

Experimental characterization of oscillatory DBD plasma-actuator arrays in quiescent air and a turbulent channel flow

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Abstract

The present work investigates plasma-based oscillatory flow forcing aimed at mimicking the drag-reduction effects of laterally oscillating wall actuation in turbulent flows. For this purpose, a gapless dielectric barrier discharge plasma actuator (DBD PA) array is operated in so-called beat-frequency (BF) mode. Reliable array prototypes with high durability and symmetric plasma formation across the array are achieved through hardware modifications. The spatio-temporal forcing characteristics relating underlying discharge properties and resulting flow effects are experimentally investigated in otherwise quiescent air. Despite the observation of minor local discharge and forcing irregularities, the results verify the functionality of the array operated in BF mode for the intended actuation scheme. Subsequently, the flow interaction of the plasma-based forcing with a turbulent channel flow is investigated in a parametric study for varying combinations of Reynolds number and oscillation frequency. Topological effects and the resulting drag impact are interpreted together and in comparison to the spanwise oscillating wall reference. The results indicate a drag increase, and show that the flow is dominated by the formation of three-dimensional flow and forcing parameter-dependent vortical structures above the array. These observations suggest the consideration of specific additional parameters in future investigations in order to further assess the potential of the plasma-based actuation concept. The conducted studies are based on the electrical, optical and fluid-mechanical characterization of the discharges and resulting flow effects. The suitability of various experimental diagnostic means is investigated for the application of measurement above the PA. A combined electro-optical approach by means of intensified imaging is introduced, enabling the evaluation of discharge properties throughout the plasma and oscillation cycle. The plasma symmetry across the array is examined with imaging methods using less sensitive camera sensors. Furthermore, the applicability of laser Doppler velocity profile sensor (LDV-PS), defocusing particle tracking velocimetry (DPTV) and Shake-The-Box (STB) for flow characterization is assessed. The flow measurements above the PA array and in a turbulent channel flow require a high spatial resolution in direct wall vicinity. The Lagrangian particle-tracking based measurement approaches, DPTV and STB, are found to be suitable under these conditions for the extraction of volumetric flow fields with flexible spatial resolution, and allow the evaluation of the Lagrangian particle acceleration. The conducted studies and implemented novel approaches further provide the foundation of suitable experimental methods in future investigations beyond the scope of this thesis.

Kurzfassung

Diese Arbeit untersucht plasmabasierte wandnahe Fluidoszillationen, die es zum Ziel haben, Reibungsminderungseffekte spannweitig oszillierender Wandbewegungen in turbulenten Strömungen nachzuahmen. Zu diesem Zweck wird ein lückenloses Array aus Plasma-Aktuatoren (PA) für dielektrische Barriereentladungen (DBD) verwendet. Dieses wird im so genannten Beat-Frequency-Modus (BF-Modus) betrieben, bei dem die zeitliche Oszillation der Entladungen durch die Schwebung angelegter Spannungssignale entsteht. Durch Anpassungen der zugrundeliegenden PA-Hardware konnten zuverlässige Array-Prototypen mit hoher elektrischer Widerstandsfähigkeit und symmetrischer Plasmabildung über das gesamte Array realisiert werden. Das räumlich-zeitliche Übertragungsverhalten der Strömungsanregung, welches die zugrunde liegenden Entladungseigenschaften des Plasmas mit den resultierenden Strömungseffekten verbindet, wird experimentell in ruhender Luft charakterisiert. Trotz kleiner lokaler Unregelmäßigkeiten in den Entladungen und der induzierten Strömung bestätigen die Ergebnisse die Funktionalität des im BF-Modus betriebenen PA-Arrays für das vorgesehene Anregungsschema. Anschließend wird die Interaktion der plasmabasierten Strömungsanregung in einer turbulenten Kanalströmung anhand einer parametrischen Studie für unterschiedliche Kombinationen von Reynolds-Zahl und Oszillationsfrequenz untersucht. Topologische Effekte und resultierende Wandreibungsänderungen werden gemeinsam interpretiert und mit dem Referenzfall der spannweitig oszillierenden Wand verglichen. Die Ergebnisse deuten auf eine Reibungserhöhung hin und zeigen, dass die Strömung durch die Ausbildung dreidimensionaler Wirbelstrukturen dominiert wird, deren Ausprägung von den Strömungs- und Anregungsparametern abhängt. Diese Beobachtungen legen nahe, in zukünftigen Untersuchungen weitere spezifische Parameter zu berücksichtigen, um das Potenzial des Aktuations-Konzepts weiter zu untersuchen. Die durchgeführten Studien basieren auf der elektrischen, optischen und strömungsmechanischen Charakterisierung der Entladungen und der daraus resultierenden Strömungseffekte. Die Eignung verschiedener experimenteller Diagnostikmethoden für Messungen über dem PA-Array wird untersucht. Ein kombinierter elektro-optischer Diagnostikansatz mittels intensitätsverstärkender Bildgebung wird vorgestellt, der die Auswertung von Entladungseigenschaften über den gesamten Plasma- und Oszillationszyklus hinweg ermöglicht. Die Plasmasymmetrie auf dem Array wird anhand von Messungen mit weniger sensitiven Kamerasensoren bewertet. Außerdem wird die Anwendbarkeit von Laser Doppler Velocity Profile Sensor (LDV-PS), Defocusing Particle Tracking Velocimetry (DPTV) and Shake-The-Box (STB) zur Strömungscharakterisierung untersucht. Die Strömungsmessungen über dem Array und in der turbulenten Kanalströmung erfordern dabei eine hohe räumliche Auflösung in Wandnähe. DPTV und STB beruhen auf Lagrange'schem Partikel-Tracking, wodurch sie sich unter diesen Bedingungen als geeignet erweisen, um volumetrische Strömungsfelder mit flexibler räumlicher Auflösung zu erfassen. Zudem kann damit neben der Geschwindigkeit auch die Lagrange'sche Partikelbeschleunigung ausgewertet werden. Die durchgeführten Studien und darin implementierten neuartigen Ansätze bilden zudem über den Umfang dieser Arbeit hinaus die Grundlage für geeignete experimentelle Methoden in zukünftigen Untersuchungen.

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1 Introduction

The present thesis investigates plasma-based flow-control strategies aimed at reducing skin-friction drag in turbulent flows. Such approaches contribute to more sustainable mobility solutions and support ongoing efforts in science and engineering addressing the challenges associated with climate change. This introductory chapter positions the thesis in the broader research context and outlines the specific objectives and research questions guiding the investigations.

1.1 Motivation

Skin-friction drag reduction in flows in the turbulent regime has become a major research topic on the way to more efficient transportation. Among other active flow-control concepts pursuing this goal, streamwise-traveling waves of spanwise wall motion have proven to be particularly effective, with drag reduction effects around 50 % and net power saving rates larger than 30 % achieved in direct numerical simulations (DNS) [see e.g. 76, 148]. For the specific case of infinite streamwise wavelength, the approach yields a spanwise oscillating wall [103], for which the drag-reduction potential was found to be slightly lower [see e.g. 43, 76, 146, 148] with the advantage of a simpler applied actuation scheme. Different experimental studies have verified the drag-reducing effect of the temporally oscillating wall actuation based on different mechanical actuators [26, 44, 74].

Due to the complexity of the mechanical realization of a physically moving wall and associated inertia effects, the application of dielectric barrier discharge plasma actuators (DBD PAs) appears advantageous for the practical implementation in realistic scenarios. These electro-mechanical devices can be embedded in a surface and interact with a flow by inducing a body-force distribution in the air in direct surface vicinity [see e.g. 109, 116, 156]. To mimic the effects of an oscillating wall, the plasma-based forcing has been applied in alternating spanwise directions using planar multi-electrode arrays of PAs. Particularly, oscillating plasma-based forcing was first introduced by Wilkinson [194] on a PA array comprising units of three electrode groups in spanwise direction, which are separated by gaps to avoid unintended discharges. Subsequently, drag reduction was reported for a similar DBD PA array and some variation in the detailed plasma operation by Jukes et al. [101]. To overcome the spatial forcing interruptions resulting from the gaps between the electrodes, planar gapless DBD PA arrays based on four electrode groups and two appropriate operation concepts have been developed by Hehner et al. [88, 90], which are therefore particularly promising and form the focus of the present work.

Previous investigations of the flow fields in the spanwise cross-plane above such arrays revealed the formation of oscillatory wall-parallel flow motion with a superimposed vertical flow component, forming counter-rotating vortical structures over the course of the oscillation cycle [88, 90]. The resulting drag was found to increase for the applied combination of forcing and flow parameters [87], motivating further investigation of the plasma-based flow control approach.

1.2 Objectives and procedure

The overarching objective of this work is to improve the understanding of underlying cause-effect relations of the applied plasma-based forcing as a basis for targeted development of such actuation schemes. In particular, the spatio-temporal forcing characteristics relating the applied voltage settings, occurring discharge characteristics and resulting fluid-mechanical effects is investigated. As an extension of previous studies in the actuator cross-plane, this involves the evaluation of the discharge and forcing regularity across the array to verify consistent actuation. Furthermore, the discharge formation is analyzed in detail to evaluate the functionality of the applied operation concept, which is characterized by fast temporal discharge dynamics. Subsequently, the interaction of the PA array with a turbulent channel flow is evaluated in an extended parametric study relating topological flow properties and the resulting drag impact. In addition, the streamwise development of the flow upon actuation onset is studied.

These investigations require suitable experimental diagnostics to evaluate discharge and flow characteristics. Specifically, the evaluation of electrical properties and optical emissions have been shown to offer valuable insights into the characteristics of DBDs in numerous previous investigations [see e.g. 20, 39, 63, 64, 81, 112, 131]. The determination of plasma-induced flow fields requires flow measurements directly above the non-transparent actuator surface. In addition, previous studies indicated that an increased spatial resolution in the immediate wall vicinity is required to reliably determine the wall-shear stress (WSS) from the mean-velocity profile in the viscous sublayer region in the turbulent channel flow [87].

The plasma discharge character and, consequently, the resulting forcing is determined by various parameters regarding the PA design and operation [see e.g. 20, 65, 116, 131, 177, WHP⁺24]. Geometric imperfections may therefore effect the discharge behavior and introduce deviations from the intended actuation. As a basis for the investigations outlined above, the manufacturing of the rather complex actuator-array prototypes is therefore addressed, aiming at a symmetrical plasma distribution, enhanced durability and good forcing reproducibility.

According to the outlined objectives, the following research questions are raised:

1. How can DBD PA arrays be designed to obtain a symmetrical plasma distribution across the array and improve their durability?
2. Which experimental means can be adapted and applied to investigate optical plasma characteristics, the flow response above the DBD PA and the interaction with the turbulent channel flow? What are the capabilities and limitations of the considered flow-measurement techniques in determining the WSS?
3. Which spatio-temporal relation applies between the observed plasma discharges, their footprint in the electrical current and the fluid-mechanical effect? How evenly do the discharges and forcing effects occur at different streamwise and spanwise positions of the actuator arrays?
4. How does plasma-based forcing affect the turbulent channel flow in streamwise and spanwise directions above a PA array? Which differences occur in comparison to a physically oscillating wall?

The investigation of these questions is broken down into several aspects, which are closely related to each other. In order to address the first research question, PA-array prototypes are developed, which are used in the experimental investigations throughout this work. The second question revolves around selecting and testing potentially suitable experimental methodology with which

the other questions can be answered, thus representing a central focus of this work. The third research question addresses the spatio-temporal forcing characteristics of the actuator, which is investigated under quiescent air conditions. As motivated in research question four, the interaction of the plasma-based forcing with a turbulent flow is studied in an existing turbulent channel flow facility of small channel height. These research objectives and their associated conditions introduce specific methodological requirements.

One aspect of the second research question involves the selection and development of suitable flow-measurement techniques for these investigations. Challenges are imposed by the non-transparent surface of the PA array, potentially causing laser-light scattering and reflection effects, and the limited channel height, necessitating a high spatial measurement resolution especially in the wall-near region. Three laser-based optical measurement techniques, which have been demonstrated to be capable of resolving flow fields at sub-millimeter resolution in previous studies [72, 117, 172], are thoroughly tested and adapted for the intended applications throughout this work.

A recently commercially available laser Doppler velocity profile sensor (LDV-PS) system provides a potentially suitable means for the detection of two-component velocity profiles along one axis (1D2C) and, in particular, the evaluation of the local WSS. The applicability of the measurement system in the context of the fourth research question is investigated in a turbulent channel flow and through a parametric study focused on the measurement accuracy using a specially designed test rig. The results of these experiments were presented at the *International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics* [PLE⁺22] and the *European Drag Reduction and Flow Control Meeting* [PGL⁺22], and are published in *Flow, Turbulence and Combustion* [PLG⁺24]. The findings are documented in Section 5.2 of this thesis. Shake-The-Box (STB) and defocusing particle tracking velocimetry (DPTV) are particle-tracking based measurement techniques suitable for measuring three-dimensional flow information (3D3C), enabling the extraction of particle velocity and acceleration data [70, 165]. Both measurement techniques are applied for near-wall flow measurements above the PA. To answer the fourth research question, volumetric flow measurements of the plasma-based forcing in a turbulent channel flow are conducted using the STB measurement technique. The flow topology and drag effect are analyzed throughout the oscillation cycle for varying parameter combinations of the incoming channel flow and the plasma-based forcing. Furthermore, the development of the observed vortical structures from the streamwise onset position of the PA array on is evaluated. The results were presented at the *International Symposium on Particle Image Velocimetry* [PML⁺25], and are documented in Sections 5.3 and 5.4. DPTV is used to measure the plasma-induced spatio-temporal velocity and acceleration distribution in otherwise quiescent air, contributing to the third research question. The obtained results were presented at the *International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics* [PL24] and an associated workshop on *Future perspectives on defocus particle tracking* [PL24], and published in *Experiments in Fluids* [PLLK25]. The respective advantages and limitations of the proposed flow-measurement techniques are comparatively discussed in Section 5.5 in the context of the posed research questions.

In complement to the velocity measurements, the plasma discharges are optically investigated using imaging techniques adapted to the characteristic time scales of the considered phenomena. In particular, intensified imaging is employed to capture discharge properties evolving on short time scales of fractions of the plasma cycle. Simultaneously conducted optical and electrical measurements enable the correlation of applied voltages and transferred electrical charge with discharge-light emissions in order to characterize the occurring discharges across the array. The results of this study were presented at *AIAA AVIATION Forum* [PFH⁺23], and are published in *AIAA Journal* [PFH⁺26]. To evaluate the actuator-array quality and manufacturing-related effects, a statistical evaluation of discharge light emissions evolving over multiple oscillation cycles

is conducted, using longer exposure time and conventional imaging sensors. In particular, these evaluations provide insight into the symmetry of the plasma distribution across the actuator array, supporting the hardware-related investigations motivated by the first research question. PA arrays with an advanced insulating material and different geometrical electrode configurations are considered in order to identify major influencing factors for the actuator quality. The corresponding findings are documented in Chapter 3 of this thesis.

The spatio-temporal forcing characteristics relating the applied voltages, the gas discharges and the associated flow response is evaluated by combining the electro-optical discharge characterization based on intensified imaging with the DPTV flow measurements 4.4, thereby addressing the third research question. The underlying phenomena evolve on two relevant time scales, the higher frequency plasma cycle and the lower frequency oscillation cycle. Taking this into account, the discharge characteristics are studied on both time-scales through the plasma and oscillation cycle, while the DPTV-measurements resolve the flow response throughout the forcing oscillation cycle.

1.3 Document structure and integration of the author's publications

The topics introduced above are integrated into the structure of this thesis. Chapter 1 introduces the research motivation and objectives. Chapter 2 provides background information, reviews related work and discusses the selection of applied methods. Chapter 3 presents developed workflows, applied routines and practical aspects of the constructive implementation of the plasma-based forcing. Chapter 4 introduces methodology, results and implications of the electro-optical and fluid-mechanical characterization of the applied flow-control approach under quiescent conditions. Chapter 5 presents the experimental setup and measurement results obtained in a turbulent channel flow with two different measurement techniques and discusses the interaction of the oscillatory plasma forcing with the turbulent channel flow. Finally, chapter 6 concludes the dissertation and outlines directions for future work.

Parts of this work are based on previously published work by the author, which is cited accordingly. In quotations from these publications, inserted additions are written in square brackets. Text omitted from the original publication is indicated with ellipses in square brackets. In order to ensure consistency across the document, minor formatting and stylistic modifications have been made, including adjustments to notation, abbreviations and reference formatting.

2 Fundamentals

This chapter introduces characteristics of turbulent flows and, specifically, the turbulent channel flow that serves as a reference case for studying the actuator-flow interaction as addressed in the fourth research question. In addition, related research in the field of flow control based on lateral wall motion is reviewed (see Section 2.1). The basic principles of DBD PAs for flow-control applications, as well as plasma-based approaches proposed for mimicking the effects of spanwise wall oscillations are introduced (see Section 2.2). Since this work focuses on the assessment of diagnostic methods, corresponding to the second research question, the requirements for and selection of measurement techniques for both discharge and flow characterization are discussed in detail in Sections 2.3 and 2.4. Additionally, their underlying principles and related work are introduced.

2.1 Turbulent channel flow with spanwise forcing

The present section introduces general aspects and mathematical descriptions of turbulent flows, followed by a detailed discussion of the turbulent channel flow, which serves as a common reference case for the investigation of turbulent flow-control approaches. Subsequently, a brief review of flow-control applications based on streamwise-traveling waves of spanwise wall motion, including spanwise oscillating wall forcing, is provided. The experimental investigations discussed in this section in part rely on flow-measurement techniques, which are reviewed in Section 2.4.

2.1.1 Introduction and description of turbulent flows

Since turbulent flows are associated with unsteady, three-dimensional flow behavior, a corresponding mathematical description of velocities is established using Reynolds decomposition [143, 150], which suggests to divide an instantaneous velocity $u(x, y, z, t)$ into the time-averaged velocity $\bar{u}(x, y, z)$ and an instantaneous velocity fluctuation $u'(x, y, z, t)$. Note that u refers to the velocity component in x direction here, and the same relations likewise hold for the velocity components v and w in y and z direction. The Reynolds decomposition is commonly written as

$$u(x, y, z, t) = \bar{u}(x, y, z) + u'(x, y, z, t). \quad (2.1)$$

For temporally periodic turbulent flows, the velocity fluctuations can be further divided into a periodic component and the stochastic fluctuation component due to turbulence. This concept is known as triple decomposition [2, 96], yielding

$$u(x, y, z, t) = \bar{u}(x, y, z) + \hat{u}(x, y, z, \varphi) + u''(x, y, z, t) = \tilde{u}(x, y, z, \varphi) + u''(x, y, z, t) \quad (2.2)$$

based on phase-averaged velocity $\tilde{u}(x, y, z, \varphi)$, periodic fluctuation part $\hat{u}(x, y, z, \varphi)$ and stochastic fluctuations of turbulence $u''(x, y, z, t)$.

The velocity fluctuations cause additional stress effects in the flow. These are represented by the covariances of the three fluctuation components, occurring at the same point and time, forming a 3×3 tensor

$$\begin{pmatrix} \overline{u'u'} & \overline{u'v'} & \overline{u'w'} \\ \overline{v'u'} & \overline{v'v'} & \overline{v'w'} \\ \overline{w'u'} & \overline{w'v'} & \overline{w'w'} \end{pmatrix} \quad (2.3)$$

referred to as Reynolds stresses. The diagonal tensor components represent normal stresses, and off-diagonal components shear stresses [143]. Throughout this thesis, the notation

$$u'_{\text{rms}} = \sqrt{\overline{u'u'}}, \quad (2.4)$$

with index rms referring to root mean square, is applied as a measure for the normal stresses.

2.1.2 Turbulent channel base flow

One well-documented reference case of wall-bounded turbulence is the turbulent channel flow, which is introduced in the following based on the work of Pope [143]. The turbulent channel flow is described as an internal flow in a duct of rectangular cross-section (length L , width b , height $2h$) as illustrated in Figure 2.1. The shown coordinate system introduces x as streamwise direction, y as wall-normal direction and z as spanwise direction, which is applied throughout this work. The channel length is sufficient to achieve a fully developed flow state ($L/2h \gg 1$), meaning that the velocity statistics do not vary in streamwise direction. The flow is further characterized by a high aspect ratio of cross-sectional width and height ($b/2h \gg 1$), which allows to assume the flow to be statistically homogeneous in spanwise direction z . Furthermore, the flow is statistically stationary and the mean velocity field only has a streamwise component. The mean velocity profile $\bar{u}(y)$ is only dependent on the wall-normal direction, and the bulk velocity can be calculated as

$$u_b = \frac{1}{2h} \int_0^{2h} \bar{u} dy \quad (2.5)$$

Accordingly, the flow is characterized by the Reynolds numbers

$$Re_b = \frac{u_b 2h}{\nu} \quad (2.6)$$

and

$$Re_{cl} = \frac{u_{cl} h}{\nu} \quad (2.7)$$

based on u_b and the centerline velocity $u_{cl} = \bar{u}(h)$, respectively, together with channel dimensions and the kinematic viscosity ν of the fluid, expressing the ratio of inertial and viscous forces of the flow.

2.1.3 Wall-shear stress and viscous flow scaling

Shear-stress effects are balanced by a constant negative pressure gradient in the streamwise direction of the turbulent channel. Based on the time-averaged momentum equation, this can be formulated as

$$\frac{d\tau}{dy} = \frac{dp_w}{dx}, \quad (2.8)$$

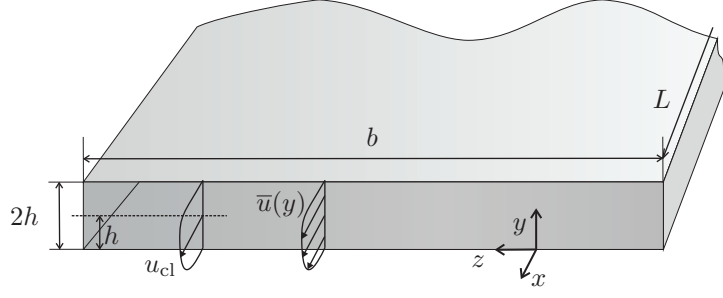


Figure 2.1: Sketch of a channel flow.

where p_w is the pressure on the channel wall and τ the total shear stress

$$\tau = \rho\nu \frac{d\bar{u}}{dy} - \rho\overline{u'v'}. \quad (2.9)$$

The latter equation shows that the shear stress depends on viscous stress $\rho\nu \frac{d\bar{u}}{dy}$ and Reynolds stress $(-\rho\overline{u'v'})$ contributions. These vary over the channel height depending on the flow characteristics. Viscous effects dominate in the wall-near region, and at the wall, the contribution of the Reynolds stress term becomes zero due to the no-slip condition. Consequently, the WSS yields

$$\tau_w = \rho\nu \left. \frac{d\bar{u}}{dy} \right|_{y=0}. \quad (2.10)$$

The skin friction coefficient can be calculated by normalizing the WSS with the dynamic pressure based on the reference velocity u_b as

$$C_f = \tau_w / (\frac{1}{2}\rho u_b^2). \quad (2.11)$$

The skin friction is higher for turbulent than laminar flows, manifesting in shape of respective mean velocity profiles. This is caused by turbulent fluctuations enhancing the mixing processes asymmetrically near the wall [98, 143].

In order to evaluate the similarity of turbulent flows in the vicinity of the wall, scaling based on outer flow quantities such as u_b is not suitable. Instead, viscous flow scales can be derived based on the WSS as friction velocity

$$u_\tau = \sqrt{\tau_w / \rho}, \quad (2.12)$$

viscous length scale

$$\delta_\nu = \nu / u_\tau \quad (2.13)$$

and viscous time scale

$$t_\nu = \nu / u_\tau^2. \quad (2.14)$$

Quantities scaled in viscous units ($u^+ = u/u_\tau$, $y^+ = y/\delta_\nu$, $t^+ = t/t_\nu$) are marked with a superscript $+$ throughout this manuscript. The friction Reynolds number is calculated as

$$Re_\tau = \frac{u_\tau h}{\nu} = \frac{h}{\delta_\nu}. \quad (2.15)$$

Viscous scaling is commonly applied to describe the flow in the region close to the wall, referred to as inner layer ($y/h < 0.1$). In the outer layer ($y^+ > 50$) flow scaling is instead based on geometric properties such as the channel half-height h . Within the inner layer, where the mean velocity profile

$\bar{u}(y)$ depends on the viscous scales, the shape of the profile suggests distinguishing characteristic flow layers in wall-normal direction, as indicated in Figure 2.2.

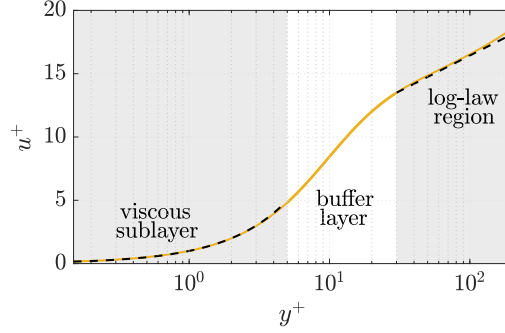


Figure 2.2: Mean velocity profile in viscous scaling at $Re_\tau = 392$ [132]. The profile curves described in Equations 2.16 and 2.17 are added as dashed lines in the regions of the viscous sublayer and log-law.

In the viscous sublayer ($y^+ < 5$), the influence of Reynolds stresses is negligible compared to viscous stress and the velocity profile is described by

$$u^+ = y^+. \quad (2.16)$$

Further up, in the log-law region ($y^+ > 30, y/h < 0.3$), the velocity profile is given as

$$u^+ = \frac{1}{\kappa} \ln y^+ + B \quad (2.17)$$

with the von Kármán constant $\kappa \approx 0.41$ and $B \approx 5.2$ [143]. The region between viscous sublayer and log-law region is called buffer layer.

In the outer layer, the shape of the velocity profile can be described through the difference between the centerline velocity and local mean velocity, which is referred to as velocity defect. The velocity defect law can be derived by normalizing the velocity defect with u_τ , yielding

$$\frac{u_{cl} - \bar{u}}{u_\tau} = -\frac{1}{\kappa} \ln\left(\frac{y}{h}\right) + B_1, \quad (2.18)$$

where the constant B_1 is flow dependent.

These considerations demonstrate that viscous scaling provides an effective means for comparing flow characteristics across different configurations, including investigations of flow-control applications. Nevertheless, the extraction of viscous scales and quantitative WSS estimates from experimental data is challenging, and various approaches have been developed and applied to obtain reliable estimates. A few methods suitable for measurements in the turbulent channel flow are briefly reviewed in the following. Firstly, the mean velocity gradient in the viscous sublayer region can be evaluated, if measured with sufficient accuracy and resolution, which enables a direct determination of the WSS (see Equation 2.10). As one alternative approach, it can be derived from Equation 2.8 that the total shear-stress profile in wall-normal direction is linear for a constant streamwise pressure gradient with $\tau(y=0) = \tau_w$ and $\tau(y=h) = 0$. Consequently, τ_w can be determined from the slope of the total stress (see Equation 2.9) derived from the measurements in a larger channel region, as applied by Hehner [87] covering approximately half the channel height. Furthermore, the streamwise pressure-drop can be measured to evaluate the WSS based on the relation given in Equation 2.8 [84]. Another method involves fitting of measurement data to a composite velocity profile description relying on combined inner and outer scaling like the one

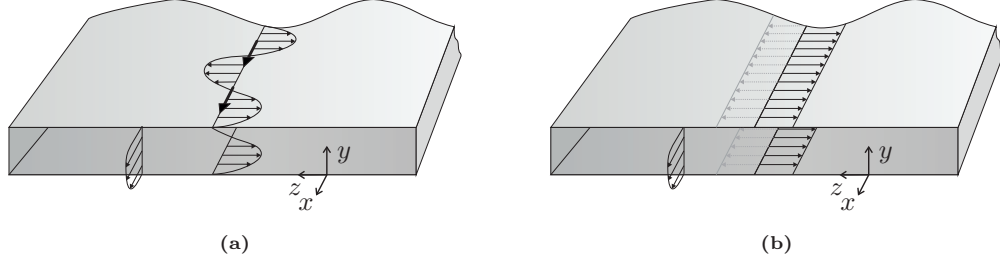


Figure 2.3: Sketch of the channel flow with imposed (a) streamwise-traveling waves of spanwise wall velocity and (b) spanwise oscillating walls.

introduced by Luchini [125] in order to estimate Re_τ and the exact wall position simultaneously [HVDS⁺21]. The latter approach is applied for the evaluation of the channel-flow experiments conducted in this work, and the applied procedure is described in the third part of Section 5.1.

2.1.4 Spanwise oscillating wall

Flow control is the application of active or passive means to manipulate a flow field aiming at specific engineering objectives [73]. Among the wide range of flow-control applications that have previously been investigated, the present work focuses on skin-friction drag reduction in turbulent flows [see e.g. 50, 145, 152]. Particularly, it was observed by Jung et al. [103] in DNS studies of a turbulent channel flow that a reduction of skin-friction drag can be achieved over a spanwise oscillating wall. Later, the favorable effects of streamwise-traveling waves of spanwise wall velocity, which represent a generalized form of the oscillating wall, on the turbulent drag were identified by Quadrio et al. [148]. Based on the classification introduced by Gad-el-Hak [73], these forcing approaches are categorized as active, predetermined and open-control-loop applications.

The streamwise-traveling waves of spanwise wall motion can be expressed as

$$w_w = A \sin(\kappa_x x - \omega t), \quad (2.19)$$

where A is the oscillation amplitude, $\kappa_x = 2\pi/\lambda_x$ is the streamwise wave number of streamwise periodicity along the streamwise wavelength λ_x and $\omega = 2\pi/T_{\text{osc}}$ is the angular oscillation frequency. T_{osc} refers to the temporal oscillation period. The velocity distribution along the streamwise direction is illustrated in Figure 2.3 (a). For $\kappa_x = 0$, i.e. $\lambda_x \rightarrow \infty$, the forcing represents the case of a spanwise oscillation wall, and the wall velocity can be written as

$$w_w = A \sin(\omega t) \quad (2.20)$$

upon changing the sign of the function. This forcing approach is shown in Figure 2.3 (b) and provides the basis for the plasma-based actuation in this work. For the sake of completeness it is worth noting that for $\omega = 0$ or $T_{\text{osc}} \rightarrow \infty$, the wall motion is described by

$$w_w = A \sin(\kappa_x x), \quad (2.21)$$

which represents a stationary spatial distribution of sinusoidal spanwise velocity [145, 148, 185].

Oscillating wall forcing (see Equation 2.20) causes the diffusion-driven spanwise velocity distribution in the fluid above the wall, resulting in the formation of a so-called Stokes layer, also referred to as second Stokes problem, described by

$$w(y, t) = A \exp\left(-\sqrt{\frac{\omega}{2\nu}} y\right) \sin\left(\omega t - \sqrt{\frac{\omega}{2\nu}} y\right). \quad (2.22)$$

The resulting velocity distribution is illustrated in Figure 2.4. The induced flow exhibits a characteristic length in wall normal direction, similar to an oscillation wavelength, which is referred to as the depth of penetration, given by

$$\delta = 2\pi\sqrt{2\nu/\omega}. \quad (2.23)$$

The thickness of the oscillating layer is specified as approximately $4.6\sqrt{2\nu/\omega}$ (see Figure 2.4) [164].

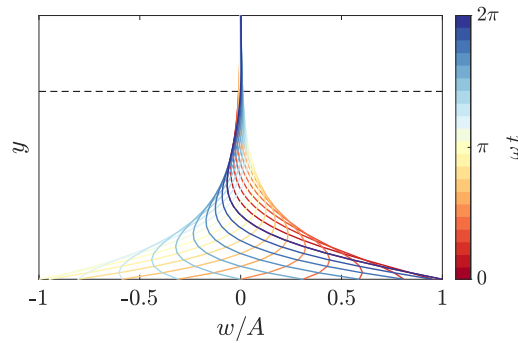


Figure 2.4: Velocity distribution above an oscillating wall with velocity amplitude A according to analytical solution in Equation 2.22. The color gradient refers to oscillation cycle phase and the dashed line indicates approximate layer thickness of $y = 4.6\sqrt{2\nu/\omega}$.

Numerous studies have investigated these flow-control approaches and their drag effect based on statistical turbulent flow quantities or the evaluation of correlations between different flow properties and observed flow structures, to shed light on underlying mechanisms. Considering the large number of studies that have contributed to these goals over the last 30 years, only a brief overview is provided in the following with a focus on reported drag reduction in relation to relevant flow and forcing parameters, as well as experimental implementations of such approaches. In particular, previous works have investigated the drag-reduction and power-saving potential as performance measures for the oscillating-wall approach for different combinations of forcing parameters A and T_{osc} , as well as for varying Reynolds numbers. As described in the review paper of Ricco [152], the percentage drag reduction is defined as the relative change of skin friction between the unforced reference flow, marked with index 0, and the flow with the application of forcing, which is given by $(C_{f,0} - C_f)/C_{f,0}$. The percentage net power saving potential represents the difference between the power saved due to the application of forcing and the power required for the actuation, normalized by the power required to move the fluid in streamwise direction. Since most studies rely on numerical flow simulations without physical actuators, the minimum required actuation power is commonly estimated as the power needed to overcome the viscous stresses in spanwise direction.

Drag reduction of up to 60 % was achieved for streamwise-traveling waves of spanwise wall velocity (see Equation 2.19) in DNS of a turbulent channel flow [148], which exceeds the observed drag reduction of spanwise oscillating wall forcing (see Equation 2.20). Despite this limitation in drag-reduction potential, the latter actuation scheme offers the advantage of moderate complexity, which also facilitates the practical implementation. In this work, the focus is therefore placed on assessing

the suitability of PA arrays in this context. In the following, previous work on oscillating-wall actuation is reviewed.

Jung et al. [103] and Baron and Quadrio [15] observed drag reduction to be most effective for an oscillation period around $T_{\text{osc}}^+ = 100$ in case of an oscillating wall, which was later confirmed in the broad parameter study by Quadrio and Ricco [146]. Furthermore, both former studies reported the attenuation of velocity fluctuations relative to the unforced flow in the wall-near flow region, as well as an outward shift of the peak in the fluctuation profiles away from the wall. In an extended numerical parametric study by Choi et al. [43], drag reduction of up to 45.4 % was observed at $Re_\tau = 150$ for $T_{\text{osc}}^+ = 150$ and $A^+ = 20$ in a turbulent channel flow. Similar results were obtained by Quadrio and Ricco [146], who reported 44.7 % drag reduction in DNS of a channel flow under similar conditions at $Re_\tau = 200$, $T_{\text{osc}}^+ = 100$ and $A^+ = 27$. A trend of increasing drag reduction with higher values A was observed for the considered parameter spaces up to $A^+ \approx 25$ [43, 76, 146]. Other studies reported that drag reduction continued to increase until A reached approximately the centerline velocity [148, 151], which is consistent with the findings of the latter three studies. Since the viscous losses associated with the actuation increase approximately quadratically with A [146], the highest saving potential occurs at lower velocity amplitudes. A maximum net energy saving of 7.3 % was found for $T_{\text{osc}}^+ = 125$ and $A^+ = 4.5$ in the parametric study of Quadrio and Ricco [146]. They further suggested that the maximum wall displacement resulting from the oscillation frequency and velocity amplitude can serve as a characterizing parameter of the oscillation. Several studies investigated the dependency of the drag-reduction effect on Re . A decrease in drag reduction was found in DNS of channel flows with spanwise wall oscillations and streamwise-traveling waves of spanwise wall motion based on extensive parameter studies by Gatti and Quadrio [75, 76]. More recently, this trend was countered by the observation of Marusic et al. [128], who reported that the drag reduction increased with larger Re based on boundary layer experiments and large-eddy simulations in a turbulent boundary layer. This inconsistency was addressed in an extended parametric DNS study of a channel flow with increased values of Re_τ by Gatti et al. [78], which confirmed the earlier findings of decreasing drag reduction with increasing Reynolds numbers. As discussed in the study, differences between the two studies arised from the distinct canonical flow cases considered, the application of continuous vs. discrete wave shape and the varying experimental and numerical methods employed in the investigations.

The phase-averaged velocity profiles in spanwise direction in a channel flow or radial direction in a pipe flow were found to be in good agreement with the analytical solution of the laminar Stokes layer described in Equation 2.22 [43, 103, 147]. In addition, the actuation was observed to be effective when the Stokes-layer thickness is in the order of a few viscous units, i.e. interacting with the near-wall flow in the characteristic region of the viscous sublayer [179].

As discussed by Quadrio and Ricco [146] and observed by Hehner [87] for plasma-based flow forcing, the local friction develops gradually in streamwise direction upon actuation, and the required adaption length depends on the forcing approach, which needs to be considered particularly in the interpretation of experimental studies. Discretized traveling wave actuation in a pipe flow [12] and a boundary layer flow [128] experimentally confirmed the drag-reduction effects associated with wall oscillations. The former experiment by Auteri et al. [12] demonstrated reductions of up to 33 % detected by means of pressure-drop measurements over the actuated region. In the latter experiments of Marusic et al. [128], drag reduction up to 25 % was evaluated using drag-balance and hot-wire anemometry (HWA) measurements. The experimental implementations relied on pipe slabs that rotated independently in case of the pipe flow and a planar surface created by individual sliding elements in case of the external boundary layer flow. A recent experiment by Knoop et al. [107] applied steady square-wave spanwise forcing using individually driven spanwise running belts. Drag reduction of up to 45 % was detected by means of stereoscopic particle image

velocimetry (SPIV). A pneumatically actuated structure moving a flow-adjacent membrane was applied to implement streamwise-traveling wave and spanwise wall oscillations by Bird et al. [26]. Drag reduction of up to $\approx 20\%$ where measured by means of HWA. Choi et al. [44] reported 45% drag reduction above an oscillating plate in a boundary layer flow using HWA. Gatti et al. [77] employed dielectric elastomer actuators to realize an oscillating surface, achieving 2.4% drag reduction as detected in pressure-drop measurements along the channel facility. Despite the success in achieving beneficial flow manipulation, the studies also demonstrate the challenges associated with the practical implementation such flow-control means. These comprise complex mechanical systems and their control [12, 26, 77, 107], often preventing direct implementation on surfaces in practical technical applications, as well as mechanical inertia and resonance effects [44, 77], partly limiting the achievable forcing parameter range.

Another approach of spanwise flow forcing aiming at reducing skin-friction drag was introduced utilizing Lorentz-force actuators. These comprise embedded electrodes and permanent magnets in the flow-adjacent surface to create an oscillating body force in spanwise direction. DNS of temporally and spatially oscillating forces in a turbulent channel flow demonstrated drag reduction up to 40% [25]. Interestingly, the approach was extended to transverse traveling wave forcing already by Du et al. [57] and Zhao et al. [201] for Lorentz-force actuation, before such approaches were discussed for spanwise wall motion. Drag reduction of up to 30% was observed by means of DNS in the former study. An experimental realization of Lorentz forcing was implemented by Pang and Choi [139], who reported drag reduction of more than 40% using a hot-film sensor 5 mm downstream of the actuation. The plasma-based forcing approaches that represent the focus of this work (thoroughly reviewed in Sections 2.2.2 and 2.2.3) are closely related to the previously discussed applications. In both cases, the main differences compared to the wall-motion based flow control arise from the stationary wall and the body-force driven actuation. The absence of moving parts may offer potentially simpler practical implementation.

2.2 Surface dielectric barrier discharge plasma actuators (PA) for active flow control

In this section, the working principle and fluid-mechanical effects of DBD PAs used for active flow-control applications are introduced, followed by a review of PA arrays for planar forcing. The discussion then focuses on the gapless arrays employed in this work and the burst-modulation (BM) and beat-frequency (BF) modes developed to operate them. The experimental studies considered in this context rely partly on flow-measurement techniques, which are reviewed in Section 2.4.

2.2.1 Working principle and fluid-mechanical effect

Plasma is an ionized state of matter that is generated through an energy supply to a gas [42, 153]. In case of DBD PAs, this is initiated by applying a high voltage (HV) signal between two electrodes separated by a dielectric layer. In this constellation alternating current (AC) voltage is required to sustain the discharges. DBDs correspond to weakly ionized, quasi-neutral gas, and the generated plasma is further classified as cold or non-thermal, with the electron temperature exceeding the temperature of ions and neutral gas [18]. DBDs can be contrasted with corona discharges between electrode configurations without separating dielectrics, which can also be operated by direct current (DC) voltage [108, 109].

The application of DBDs was firstly reported by du Moncel [58] and von Siemens [187] already in the 1850s. Since then DBDs have been used in the fields of ozone generation, pollution control, surface treatment, plasma displays, plasma medicine, flow control and others, as discussed in the review articles by Kogelschatz [108] and Brandenburg et al. [29]. Specifically, flow manipulation by means of DBD PAs was introduced by Roth et al. [155, 156] in 1995. The principle relies on the electric field acting on charged ions, which transfer momentum to neutral gas through collisional coupling [111, 156]. Plasma-based flow control for numerous applications has been investigated, as summarized in the review articles by Moreau [131], Corke et al. [51], Wang et al. [188], Choi et al. [46], Benard and Moreau [20], Kotsonis [109] and Kriegseis et al. [116].

The PAs applied throughout this work are surface DBD PAs, illustrated in a basic configuration in Figure 2.5 (a) comprising one exposed electrode shown in red and one encapsulated electrode shown in green flush-mounted on both sides of the dielectric layer shown in white. Note that the drawing shows a cross-sectional view, with the electrode expansion in out-of-plane direction being typically much larger than their width and height. If an AC HV signal of sufficient amplitude is applied to one electrode while the other is grounded, the formation of plasma can be observed above the encapsulated electrode as a blue-purple glow in air. Specifically, discharge onset occurs when the peak-to-peak voltage V_{pp} exceeds twice the breakdown voltage V_b , which characterizes the electric field strength required for self-sustaining gas ionization [67, 108, 182] (see Figure 2.5 (b)). The AC voltage-signal frequency f_{AC} defines the plasma-cycle period T_{AC} . The actuator capacitance changes throughout the discharge cycle from the purely passive (cold) capacitance to the effective capacitance, which also incorporates a contribution of the plasma itself during the discharge phases [112, 113].

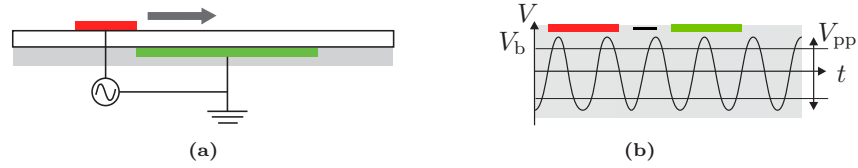


Figure 2.5: Illustration of PA in basic configuration. (a) Sketch of PA in cross-sectional view with two electrodes color-coded in red (●) and green (●), one supplied with HV signal and one grounded. The separating dielectric is shown in white and the encapsulation of the lower electrode shown in grey prevents the formation of plasma on the lower side of the actuator. (b) Potential difference of artificially generated voltage signals between both electrodes over time.

Figure 2.6 shows a detailed view of an exemplary voltage V and current I signal over approximately one and a half plasma cycles in red and black. The current is composed of a base wave portion in phase quadrature to the voltage signal, resulting from charge displacement in the actuator electrodes and connections, and current peaks, which are related to individual discharge filaments [131, 142]. Within each plasma cycle, two phases of discharges occur, separated by intervals with no discharges. The discharge characteristics are observed to differ between the two plasma half-cycles. The exposed electrode acts as cathode and anode during the negative and positive half-cycle, respectively [63]. Charge assembles on the dielectric surface during the negative half-cycle, which opposes the applied voltage and reduces the electric field initiating the discharges, exhibiting a self-limiting character of the DBD [109]. Accordingly, the discharges stop when the voltage is not continuously increased, as it is the case at the voltage peaks of a sinusoidal signal as shown in Figure 2.5 (b). It is suggested by Enloe et al. [63, 64] that therefore, in the positive half-cycle, the transferred charge is limited to the charge accumulated on the dielectric during the negative half-cycle. The current peaks occur more regular in the negative half-cycle [131], and the spatial structure of the discharge-light emission is more diffuse and more evenly distributed along the electrode [19, 81] in comparison to the positive half-cycle. The properties of discharge filaments are

further reviewed in Section 2.3 in the context of optical means for plasma characterization. Under steady actuator operation, the discussed differences and asymmetries in the two half-cycles cause a body force distribution in the wall-near fluid that produces a predominantly tangential velocity jet under otherwise quiescent flow conditions, oriented toward the direction of the encapsulated electrode, which is indicated by the dark gray arrow in Figure 2.5 (a) [e.g. 63, 64, 109, 124, 156]. In addition, smaller vertical flow velocity is observed in the region of the exposed actuator electrode [e.g. 116].

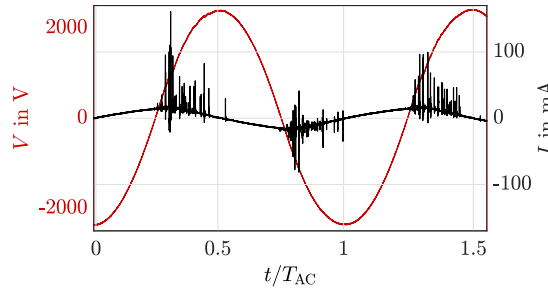


Figure 2.6: Exemplary voltage V and current I signals over time for $\approx 1.5 T_{AC}$ of a DBD PA.

The discharge properties and resulting momentum transfer characteristics depend on the operation parameters and actuator design. DBDs can be initiated in different gas species and mixtures among air, and are influenced by factors as pressure and humidity [18, 111, 140]. The DBDs can be generated at around environmental pressure in a range from 0.1 to 10 bar [61], operating voltages in the order of magnitude of $V = 1 - 50$ kV [116] and operation frequencies of $f_{AC} = 0.5 - 500$ kHz [67]. The discharges are furthermore influenced by the AC-signal shape, for which usually a sine wave is applied [131, 183]. Regarding the PA hardware, the discharge characteristics and velocity response further depend on the dielectric material and thickness, the electrode thickness and shape, and is influenced by the size of potential gap or overlap between the electrodes [20, 51, 65, 111, 116, 154, 177]. The resulting maximum plasma-induced jet velocities are reported to occur $\approx 0.3 - 1$ mm above the wall and are in the range between 0.5 m/s and 7 m/s [20, 65, 101, 110, 111, 142, 156]. Specifically, the velocities increase with increasing operation voltage and plasma frequency [65, 101, 111, 142].

2.2.2 Multi-electrode PA arrays and operating concepts for spanwise planar forcing

The plasma-based flow forcing investigated throughout this work aims at mimicking the effects of a physically oscillating wall, which has been reported to generate beneficial effects in turbulent drag but is difficult to practically implement for the application in many technical scenarios (see Section 2.1.4). The subsequent figures of PA-array configurations follow the corresponding channel coordinate system introduced in Section 2.1.2, where x denotes the mean flow direction and z the spanwise direction along which the wall motion or plasma-based forcing is applied. The plasma forcing, acting in thin stripes along the electrodes in spanwise direction, needs to be modified to generate a planar forcing scenario, and temporally oscillating forcing into two lateral directions. Several actuator configurations based on multiple electrodes next to each other and respective operation schemes have been applied for this purpose throughout the past 20 years, and an overview is provided in the following.

Plasma-based oscillatory flow forcing was introduced by Wilkinson in 2003 [194] based on a PA array with three electrode groups each supplied with a HV AC signal. The array and voltage signals are conceptually illustrated in Figures 2.7 (a) and (b). Temporally oscillating forcing is achieved by alternating discharge formations between the upper electrode group and the two encapsulated electrode groups. For this purpose, slightly different AC frequencies are supplied to the upper and lower electrode groups, which causes constructive and destructive superposition of the voltage between neighboring electrodes, as illustrated in the voltage diagrams of Figure 2.7 (b). Plasma is generated when V_{pp} exceeds $2V_b$, which defines the duty cycle D highlighted in gray in the voltage plots. Specifically, D indicates the fraction of an oscillation period T_{osc} during which the plasma forcing acts in a given direction. By applying voltages of identical plasma frequency f_{AC} at a phase shift of π to the two lower electrode groups, plasma formation occurs toward the left and right in counterphase over the oscillation cycle. The presented study investigated the induced flow under otherwise quiescent air conditions by means of HWA and Pitot-tube measurements. A coupled behavior between operating voltages and resulting D was reported for the operation concept, which limited the induced flow velocities in the experiment. The observed flow fields revealed the formation of vortices and, thus, differed from the Stokes-layer formation induced by continuous wall motion. In addition, the experimental implementation was reported to be challenged by the interaction of the electric field with applied flow-measurement techniques and frequent burn through of PAs.

Turbulent drag reduction initiated by oscillatory plasma forcing in spanwise direction was firstly reported by Jukes et al. in 2006 [101]. The studies were based on a PA array with similar construction as in the previously discussed studies of Wilkinson [194], shown in Figure 2.7 (c). The operation concept applied by Jukes et al. [101] is, however, based on direct duty cycle modulation using the voltage signals illustrated in Figure 2.7 (d). While the encapsulated electrode group is grounded, the upper two electrode groups are supplied with square-wave modulated AC HV signals. This results in temporally interrupted, alternating discharge formation between the respective upper electrodes and the encapsulated electrodes, causing temporally oscillating forcing toward both directions. The study reported up to 45 % drag reduction in a turbulent boundary layer flow at $Re_\tau = 380$ measured downstream the actuated area by means of HWA. Interestingly, drag reduction increased with decreasing oscillation period T_{osc} , and the largest drag reduction was reported for $T_{osc}^+ = 16$, which is significantly shorter than reported for cases of beneficial drag manipulation above a physically oscillating wall around $T_{osc}^+ = 100$ [15, 103, 146]. In addition, the drag was found to increase for larger spacing between the repeating units of electrodes. Additional smoke visualization of the plasma-induced flow fields revealed the formation of streamwise vortices above the electrodes. It was suggested that these flow structures might contribute to the drag-reducing mechanisms.

Several subsequent studies [45, 126, 168, 203] considered PA arrays with three electrode groups operated with pulsed forcing in alternating directions, similar to the concept introduced by Jukes et al. [101]. Mahfoze and Laizet [126] carried out a parametric DNS study based on a numerical plasma model of Suzan et al. [176], in which they considered spanwise oscillatory and unidirectional plasma forcing on a relatively sparse PA array aiming at decreasing energy input. While the drag was increased for oscillatory forcing at $T_{osc}^+ = 16$ and 100, up to 33 % drag reduction was found when the forcing was applied to only one direction. Zong et al. [203] conducted SPIV measurements in the cross-plane of a turbulent boundary layer flow at $Re_\tau = 430$ to study, among other plasma-based control approaches, the flow interaction of spanwise oscillatory forcing of a three-electrode PA array. The plasma-induced drag effect was estimated from the actuation-induced velocity changes in the near-wall region, resolved along the streamwise and spanwise direction. Drag increase was observed above the PA array, and a slight drag reduction downstream. At an exemplary streamwise

position above the PA, the maximum drag increase along the spanwise direction occurred above the upper electrodes, while drag reduction was observed in-between, above the encapsulated electrode. Note, however, that the considered parameters did not coincide with those in the experiment of Jukes et al. [101]. A recent experimental study by Serpieri et al. [168] investigated a PA array following the same actuation scheme in a turbulent channel flow at $Re_\tau = 190$ by means of PIV measurements in wall-parallel planes. It was shown that the flow topology strongly changed with the oscillation frequency and actuation duty cycle.

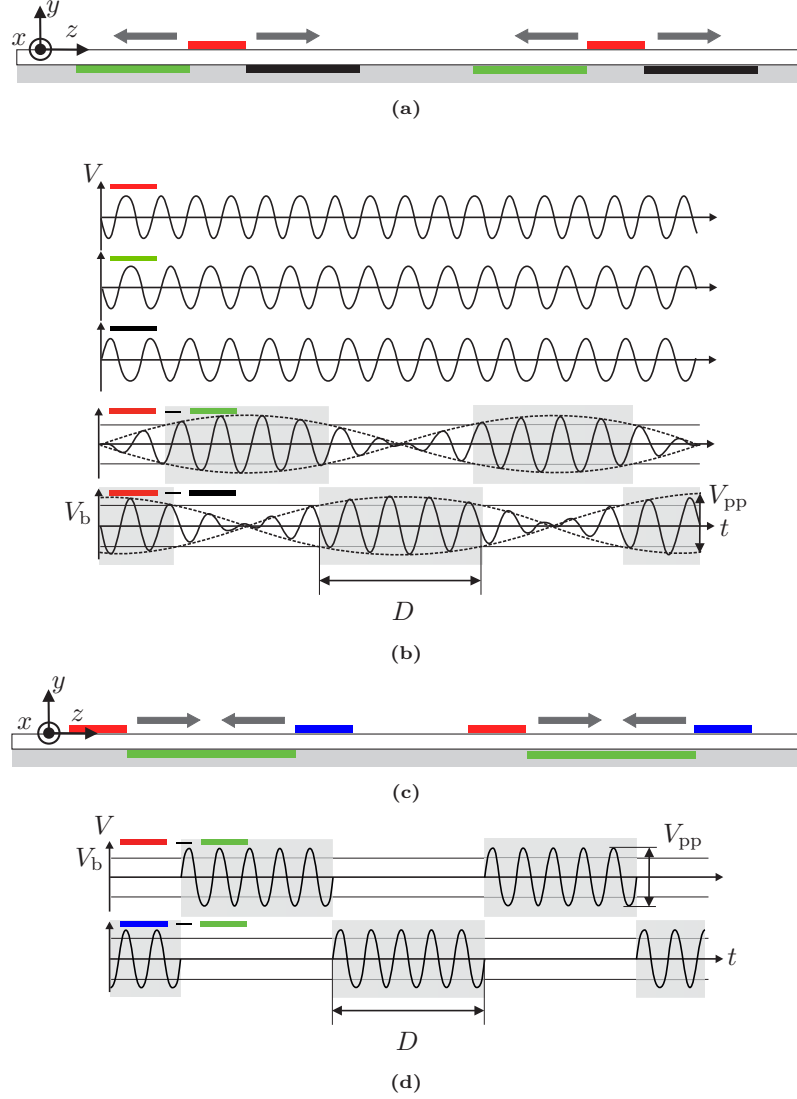


Figure 2.7: Illustration of PA arrays with three electrode groups for oscillatory plasma forcing. (a,c) Sketch of actuator arrays in cross-sectional view for the actuation concepts introduced by Wilkinson [194] and Jukes et al. [101]. All electrode groups are supplied with a voltage signal for the concept of Wilkinson, whereas for the concept of Jukes et al. the encapsulated electrode group is grounded. (b,d) Subtraction of artificially generated voltage signals of neighboring electrodes for both arrays and respective operation modes. The gray-shaded areas indicate active discharge periods between the electrode pairs based on the breakdown voltage $\pm V_b$. The top left inlays indicate the chosen (color-coded) electrode groups considered in the respective diagrams.

The operation schemes proposed by Wilkinson [194] and Jukes et al. [101] form the base for the temporally oscillating plasma on gapless PA arrays with four electrode groups, which were later

introduced by Hehner et al. [88, 90]. These arrays are used throughout this work, and are therefore discussed in detail in Section 2.2.3.

In the broader context of spanwise wall forcing, a wide range of studies investigated other plasma-based forcing strategies besides spanwise temporal oscillations [8, 23, 59, 100, 102, 122, 169, 178, 190, 197, 198, SHP⁺23]. Without aiming for completeness, the following section represents an overview of selected studies that are particularly relevant by introducing methodological or conceptual innovations. Thomas et al. [178] reported 70 % drag reduction and significant net power savings based on unidirectional and opposing simultaneous wall jets in spanwise direction generated with a novel pulsed DC DBD actuator, which later filed as a patent by Corke et al. [49]. The experiments were carried out in a boundary layer flow and rely on direct drag measurements using a force balance. Drag reduction was observed for all considered Reynolds numbers at a forcing pulse frequency of 500 Hz.

Furthermore, with respect to the classification of flow-control approaches by Quadrio et al. [148] discussed in Section 2.1.4, plasma-based implementations aiming at mimicking effects of a streamwise-traveling wave of spanwise wall motion (see Equation 2.19) and stationary spatial distribution of spanwise velocity (Equation 2.21) were recently introduced. The latter case was investigated by Altintaç et al. [8] by means of DNS of a turbulent channel flow at $Re_\tau = 180$ based on a plasma model by Shyy et al. [173]. The study considered different geometrical patterns of spanwise-aligned discrete plasma areas, and drag reduction of up to 13 % was observed for the case of most dense forcing. Benard et al. [23] presented an experimental study of a similar PA array for a streamwise periodic distribution of spanwise forcing. The forcing concept was applied in a turbulent boundary layer flow at $Re_\tau = 370$, and drag reduction of up to 4 % was measured at moderate forcing amplitudes by means of hot-film measurements downstream of the actuated area. A spanwise modulation of the local drag change was observed with respect to the discrete electrode and forcing positions. Serpieri et al. [SHP⁺23] introduced a multi-model PA array named MUMO-PLA, which allows to generate spanwise forcing along a streamwise-moving, spatially-discretized waves. While temporal oscillations and stationary spatial distributions of spanwise wall velocity are restricted to $\kappa_x = 0$ or $\omega = 0$, respectively, this novel PA-array concept allows to enter the two-dimensional parameter space spanned by streamwise-traveling waves associated with increased drag reduction potential. The proof-of-concept study demonstrated the actuator functionality under quiescent flow conditions and the concept was filed as a patent [SKG⁺].

2.2.3 Gapless PA array operated in burst-modulation and beat-frequency mode

Spatial gaps between repeating electrode units introduce local interruptions of the plasma-based flow forcing, and the reduced drag-reduction of oscillatory forcing approaches was reported at increasing sizes of these gaps [101, 126]. In order to address this limitation and reduce the gap between the momentum transfer zones above the PA array comprising three electrode groups shown in Figure 2.7 (a) and (c), Hehner et al. [88] introduced a PA array with a fourth electrode group that fills the gaps, as illustrated in Figure 2.8. The modification aims at a spatially more continuous flow in spanwise direction, thereby more closely resembling the flow above the physically oscillating wall. A similar array has previously been applied by Debien et al. [55] for unidirectional forcing. However, the voltage signals applied to the four electrode groups, marked as HV1, HV2, HV3 and HV4 in Figure 2.8 (a), must be chosen to generate the spatio-temporal discharge patterns required for alternating flow forcing in opposite directions, while simultaneously avoiding undesired parasitic discharges. To this end, the BM and BF operation concepts were presented [88, 90], which are

described in the following. Note that the order of the voltage signals shown for both actuation concepts follows Figure 2.7, while the order of introduction in the text is chronological.

The BM mode [88] is an extension of the operation concept introduced by Jukes et al. [101] for the three-electrode array. One encapsulated electrode group is continuously grounded, while the upper two electrode groups are alternately supplied with square-wave modulated AC HV signals at the burst frequency $f_{\text{BM}} = f_{\text{osc}}$. For the case of $D = 50\%$, which is illustrated in Figure 2.8 (b), the additional fourth electrode group is continuously supplied with an AC HV signal of the same plasma frequency ($f_{\text{AC},1} = f_{\text{AC},2} = f_{\text{AC},4}$), phase ($\Delta\varphi = 0$) and voltage amplitude as those applied to the upper two electrode groups. As a result, plasma formation is initiated alternately toward the left and right between the respective neighboring electrode groups across the array. For smaller duty cycles, the AC HV supply to the lower electrode group HV4 must be interrupted during phases without plasma formation [87]. Consequently, for the BM concept, the oscillation frequency f_{osc} and duty cycle D are defined by the modulation of the voltage signals applied to the electrode groups HV1, HV2 and HV4. While V_{pp} can be defined flexibly, it must be matched across all HV electrode groups.

The BF concept [90] applies the same principle that was used by Wilkinson [194] for three electrode groups. Specifically, "all four electrode groups are supplied with AC HV sine waves at frequencies $f_{\text{AC},i}$ with $i = 1, 2, 3, 4$, such that the difference of the individual voltage signals result in constructive and destructive interference, as illustrated in Figure 2.8 (c). The four respective frequencies are chosen to produce a constant beat frequency f_{BF} , which is equivalent to the oscillation frequency f_{osc} as

$$f_{\text{osc}} = f_{\text{BF}} = f_{\text{AC},1} - f_{\text{AC},3} = f_{\text{AC},2} - f_{\text{AC},4} = f_{\text{AC},1} - f_{\text{AC},4} = f_{\text{AC},2} - f_{\text{AC},3}. \quad (2.24)$$

Accordingly, the upper and lower electrodes need to be, respectively, supplied with AC signals of the same frequencies $f_{\text{AC},1} = f_{\text{AC},2}$ and $f_{\text{AC},3} = f_{\text{AC},4}$. The oscillation is maintained via a phase shift of a half period $\Delta\varphi_{1,2} = \Delta\varphi_{3,4} = \pi$. The resulting frequency of the applied HV is $f_{\text{AC}} = (f_{\text{AC},1} + f_{\text{AC},3})/2$ (see Figure 2.8 (c)). In contrast to the BM concept, a feature contained in the discharge strategy of BF, is the coupled character of maximum peak-to-peak voltage $V_{\text{pp,max}}$ and duty cycle D , as elaborated extensively by Hehner et al. [90] [and already reported for the three-electrode arrays by Wilkinson [194]]. The duty-cycle periods, i.e., active discharge periods in which V_{pp} is greater than [twice] the breakdown voltage $2V_{\text{b}}$, are shaded gray in Figure 2.8 (c) to clarify onset and extinction of the discharges. [...] An increase of V_{pp} immediately implies an increase of D , and vice versa. When increasing V_{pp} , the temporal domain of the presented signals, which exceeds V_{b} increases. As a result, duty-cycle periods of opposing discharges may overlap (see overlap of gray-shaded areas marked by dashed orange box in Figure 2.8 (c)), producing detrimental bi-directional discharges and momentum transfer (see jet-vectoring efforts [144, 158, 159]). Furthermore, with the BF actuation concept, the procedure of setting the four voltages so as to equalize the resulting discharge voltages (see Figures 2.8 (a) and (c)) is very sensitive to the regularity of induced momentum on all discharge zones, as discussed [...] [by] Hehner et al. [91]." [PFH⁺26] Note that V_{pp} is continuously evolving over time in the BF mode, exhibiting highly dynamic discharge characteristics, while it is constant during plasma operation in the BM mode. Correspondingly, the BF operation is characterized by a reduced number of switch-on and switch-off events compared to the BM operation, which is associated to reduced fatigue effects of the applied hardware [90].

The plasma-induced flow developing throughout the oscillation cycle was captured using planar PIV and reported to be similar for both BM and BF operation modes. The velocity fields were observed to be dominated by the horizontal velocity component with maximum velocities in the

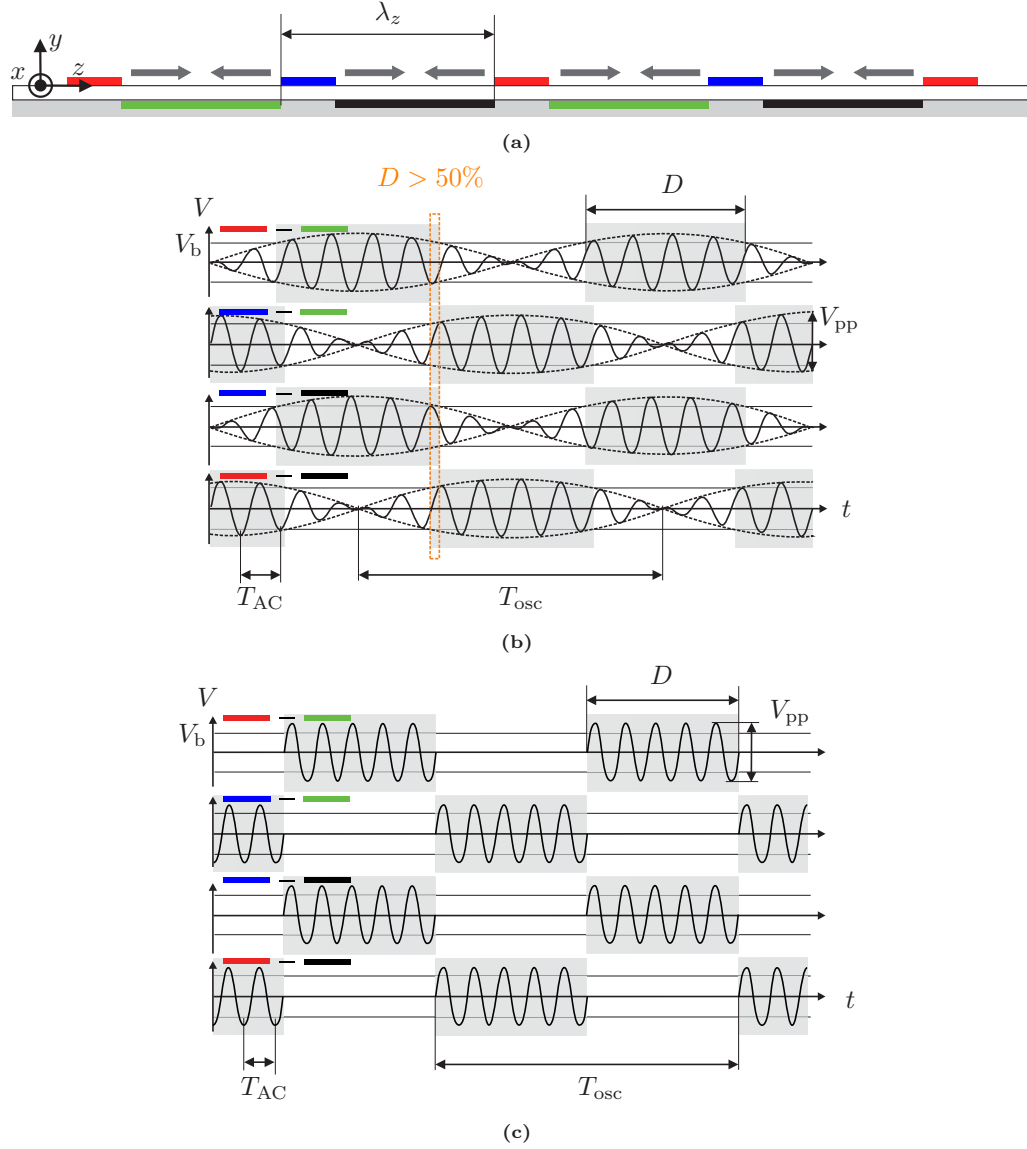


Figure 2.8: Illustration of PA array with four electrode groups for oscillatory plasma forcing. (a) Sketch of actuator array in cross-sectional view for both actuation concepts BM [88] and BF [90]. All electrode groups HV1 (●), HV2 (●), HV3 (●) and HV4 (●) are supplied with a voltage signal in BF operation, whereas in BM operation electrode group HV3 is grounded. The spanwise period λ_z is marked. (b,c) Subtraction of artificially generated voltage signals of neighboring electrodes for BM and BF modes. The gray-shaded areas indicate active discharge periods between the electrode pairs based on the breakdown voltage $\pm V_b$. The top left inlays indicate the chosen (color-coded) electrode groups considered in the respective diagrams.

order of 1 m/s occurring above the encapsulated electrodes. Furthermore, the flow fields were found to exhibit a spanwise-periodic character with wavelength λ_z (see Figure 2.8 (a)), along which the formation of vortical flow structures was observed. Comparisons of the phase-resolved wall-normal velocity profiles with the analytical Stokes-layer solution (see Equation 2.22) showed good agreement at the center of the encapsulated electrodes. Unlike the Stokes layer, the plasma-induced velocity decreases to zero velocity at the wall due to the no-slip condition [88, 90]. In an extensive parameter study, Hehner et al. [91] further characterized the BF and BM operation concepts under quiescent-air conditions. The investigated parameters included the oscillation frequency f_{osc} for both BF and BM modes, as well as the voltage amplitude V_{pp} and duty cycle D for BM operation. The so-called oscillation waveform, defined as the plasma-induced spanwise velocity evaluated at

a wall-normal distance of $y \approx 0.25$ mm, integrated over the actuator span and resolved over the oscillation cycle, was shown to be in good agreement with the analytical Stokes-layer profile for all considered f_{osc} in BF mode. This agreement was associated with the continuously evolving V_{pp} . In contrast, the BM mode is characterized by abrupt forcing discontinuities, which were found to result in an alternative waveform that varies across the investigated range of f_{osc} . The study further reported that for BM operation, the vertical motion was weaker for smaller values of D [91].

In continuation of the characterization of plasma-based forcing in quiescent air, the interaction with a turbulent channel flow was investigated for both actuation concepts at $Re_\tau = 250$ and $f_{\text{osc}} = 50$ Hz. SPIV measurements were performed in the channel cross-plane, enabling a detailed statistical analysis of the flow field. Comparisons between the phase-resolved cross-plane velocity fields in the turbulent channel flow and quiescent air revealed only minor differences. An increase in drag was observed above the PA array for both operation modes based on the evaluation of the total stress profiles (see Equation 2.9). Downstream the actuated area, a friction-drag reduction was observed. Furthermore, the flow was reported to remain in a developing flow stage over the length of the PA array [87, HVDS⁺21].

Based on these findings, Hehner [87] recommended the use of the BF mode due to its favorable properties and similarities to the oscillating wall. Despite these advantages, drag reduction has not yet been achieved, which raises several questions for further investigation. The forcing characteristics, especially for BF operation in the overlap region at $D > 50\%$, and the spatial homogeneity of both the formation of plasma and the forcing effect beyond a planar perspective remain to be clarified. Addressing these questions allows to verify whether the forcing approach performs as intended. Furthermore, the interplay of parameters characterizing the incoming flow and the forcing, which may lead to beneficial drag effects need to be investigated. In continuation of the presented efforts, this work addresses these open questions for the BF operation concept. The remaining sections of this chapter address the selection of diagnostic approaches that are employed for this purpose throughout the thesis.

2.3 Optical measurement techniques for plasma characterization

The present section introduces imaging-based measurement techniques for optical plasma characterization, which are applied in this work to evaluate the spatial and temporal discharge distribution on the PA array. The selection of suitable diagnostic means is discussed based on the respective methodological requirements and a review of previous related work. In addition, technological details of common sensor types are discussed and related to suitable exposure times for the experiments in this work.

2.3.1 Overview and selection of optical measurement techniques for plasma characterization

The investigation of optical discharge-light emissions provides valuable insights into the spatio-temporal formation, propagation and intensity of the DBD, which reflects both the underlying operation mechanisms and the coupling to fluid-mechanical effects [7, 39–41, 64, 81, 93, 110, 112]. Optical plasma diagnostics are applied in this work to characterize the BF-operated PA array. In particular, the symmetry of plasma generation within different discharge zones is assessed (see

Section 3.3). Furthermore, imaging-based diagnostics are used to investigate the working principle of the PA array in BF-mode in order to verify that the forcing concept operates as intended (see Section 4.2). The highly dynamic character of the actuation motivates a detailed analysis of discharge properties, which partly have been studied for steady DBD operation, but may differ under the unsteady forcing conditions considered here. This is complemented by the evaluation of the plasma homogeneity along the electrodes. The findings constitute a central element of the experimental characterization of the plasma-based forcing, in addition to electrical and fluid-mechanical measurements.

These measurement tasks are associated with different characteristic time scales. While the individual discharge events develop within approximately 100 ns [60, 108], the duration of a representative plasma cycle at $f_{AC} = 16$ kHz is 62.5 μ s. The oscillation cycles, occurring at frequencies between $f_{osc} = 25$ Hz and 100 Hz in this work, correspond to characteristic time scales of 10 – 40 ms (see Table 3.1 for details on the plasma parameters). This results in requirements for the imaging approach to operate at sufficiently small gate widths in order to capture the respectively occurring events. Furthermore, the emission patterns need to be spatially resolved over the region of interest on the PA array.

In the following, a concise overview of relevant work on optical plasma characterization is presented, followed by a discussion of suitable imaging approaches for the measurements in this thesis. Gibalov and Pietsch [81] investigated the macroscopic character of DBD patterns using streak photography and dust figures in a comprehensive experimental and numerical study. Specifically, the interactions of spatial discharge character and dielectric properties of the actuator itself as well as accumulated electrical charge were discussed. In the work of Enloe et al. [63, 64], a photomultiplier tube was used for time-resolved light-emission detection covering approximately one third of the PA, whereas the electric current signal was simultaneously measured. Every detected light pulse could be related to a discharge current peak. However, there were more current peaks measured that could not be associated with optical footprints of the discharge events, supposedly since they occurred out of the field of detection. Allégraud et al. [7] conducted a charge-coupled device (CCD) imaging-based analysis of DBDs to link macroscopic gas discharge character to the electrical parameters as current and applied voltage. It was found that the peak current intensity increases with the number of observed plasma filaments while with increasing applied voltage the filament length, but not its number, was increasing. Célestin et al. [39–41] investigated the spatio-temporal interaction and organization of individual, subsequently generated plasma filaments of DBDs in different configurations based on optical CCD and electrical measurements together with numerical simulations. In these studies, macroscopic characteristics such as filament length and number were discussed together with properties of simultaneously recorded electrical signals. Depositing of charge on the dielectric surface was found to majorly influence the development and structure of discharges. The spatio-temporal formation of individual discharge filaments was characterized based on synchronized imaging, spectroscopy and electrical measurements by Brandenburg et al. [28] and Höft et al. [94], even though not in context of aerodynamic active flow-control applications. Kriegseis et al. [112] studied the emitted light intensity profiles in lateral direction, i.e. perpendicular to the electrodes, by means of a complementary metal-oxide-semiconductor (CMOS) camera for different peak-to-peak voltages to characterize properties of discharge light emission such as lateral luminosity profiles, peak illumination intensity values and discharge propagation. A close correlation between the gas discharge light emission and the effective capacitance of the operated PA was observed. Measurements of the electric field accompanying DBDs have been carried out based on spectral analysis of optical emissions in order to increase the understanding of underlying discharge dynamics [97, 159], see also Goldberg et al. [82] for broader review on non-invasive optical electric field determination methods. Moreover, the application

of intensified charge-coupled device (ICCD) cameras previously uncovered various meaningful insights regarding the local and likewise spatio-temporal character of DBDs in multiple applications [11, 17, 19, 22, 28, 66, 99, 141, 181, 194].¹ [PFH⁺26]

Based on this overview and the specific measurement tasks outlined in the beginning of this section, promising imaging approaches can be identified. Streak photography and photomultiplier-based diagnostics do not provide planar spatial information and are therefore unsuitable for resolving the discharge structures across the PA array. For the characterization of the BF concept, ICCD imaging is selected due to the ability to operate at small gate widths and resolve the discharge properties within specific phases of oscillation and plasma cycle (see detailed discussion in the next section). In contrast, the assessment of plasma symmetry across the actuator array can be performed using time-averaged imaging over the duration of multiple oscillation cycles. Consequently, longer exposure times and less sensitive cameras can be employed. A scientific grayscale camera equipped with a scientific complementary metal-oxide-semiconductor (sCMOS) sensor and a comparatively low-cost consumer-grade CMOS color camera are applied in an exploratory approach. While detailed specifications of the individual camera systems used in the experiments are provided in the tables in the corresponding sections, the following section describes the relevant sensor technologies.

2.3.2 Imaging sensors for optical plasma characterization across different exposure time scales

The current section provides an overview of underlying technologies of the most common camera-sensor types, CCD and CMOS, and introduces the ICCD sensor for intensified imaging. Furthermore, relevant exposure regimes for imaging-based plasma diagnostics are discussed considering the specific requirements of the experiments conducted in this work.

The operating principle of CCD and CMOS sensors is based on the conversion of incoming photons into an electric charge within a semiconductor substrate, typically silicon [149, 184]. The built-up electric charge can subsequently be read out as an electronic signal. The individual sensor elements represent the pixels, which are organized in arrays, enabling to resolve a planar illumination distribution characterized by high sensitivity and low noise [149]. The conversion efficiency from photons to photoelectrons, also referred to as quantum efficiency, is wavelength-dependent [127]. In a CCD sensor, the charge stored in the pixels is shifted row-by-row to the readout register, where it is subsequently converted into a voltage signal that can be further electronically processed. The achievable frame rate in CCD sensors is constrained by the serial readout process [184]. While relying in the same fundamental principle of the conversion of photons to electrical charge as CCD sensors, the distinguishing property of CMOS sensors is the independent control and readout of individual pixels. Through this approach, the readout of active sub-regions of the sensor is possible at increased achievable frame rates. Additionally, electronic signals can be processed directly within the pixel array. However, the structure of CMOS sensors causes smaller photosensitive areas and decreasing signal-to-noise ratio (SNR) in comparison to CCD sensors [127, 149]. Although introduced at roughly the same time in the 1970s, CCD sensors were often preferred to CMOS sensors in the past due to the outlined characteristics. However, more recent developments of the underlying technologies allowed for improved SNR and spatial resolution in CMOS sensors, and increasingly shifted this trend in the past decades [127, 149]. Consequently, the studies on imaging-based plasma characterization described above must be seen in the context of the state of development of the applied cameras.

In 2009 sCMOS sensors were introduced, which exhibit low readout noise at high light sensitivity, frame rate and resolution. Their wide dynamic range makes them suitable for applications requiring the simultaneous detection of weak and strong signals within the same image, as it is often required for imaging-based flow-measurement techniques [149].

As outlined in Section 2.3.1, the imaging-based investigations in this thesis involve different relevant time scales, which impose requirements for suitable imaging-exposure times. At the same time, the optical emissions of the discharges is limited, which introduces a technological challenge for conventional CCD, CMOS and even sCMOS camera sensors to acquire sufficient signal levels at short exposures. In particular, the detected signal level decreases linearly with exposure time and therefore requires sufficient illumination. Further limitations for short image exposures arise from the technical implementation of the camera shutter [127, 184]. Thus, low-emission, short-exposure conditions are commonly addressed through the use of intensified imaging, specifically with an ICCD camera sensor in this work. For these sensors, image acquisition relies on a so-called image intensifier, which is positioned in front of a CCD sensor to increase light sensitivity. The components and their respective functions are briefly outlined in the following to provide an overview of the working principle. The intensifier typically consists of a photocathode, a micro-channel plate and a phosphor screen in sequential arrangement. The photocathode generates electrons for incoming photons, which are multiplied in a micro-channel plate. The phosphor screen converts the electrons back into photons, which then continue to the CCD sensor. The configuration enhances the light sensitivity of the system, which enables imaging at low illumination or under short light exposure. As a known limitation, additional noise is introduced in the process, particularly at high multiplication or gain settings. By adjusting the control voltage between photocathode and micro-channel plate, the light transmission through the intensifier can be gated, providing shutter functionality with very short response time.[184].

2.4 Optical measurement techniques for flow characterization

This section presents the measurement techniques employed to instigate the plasma-induced flow effects in quiescent air and a turbulent channel flow throughout this work. As the measurement tasks impose specific methodological requirements, the section begins by summarizing these and subsequently reviewing common experimental approaches for flow diagnostics. Related work and underlying principles of selected measurement techniques are introduced. The final part of this section discusses the potential interaction of seeding particles used in optical measurement techniques with electric fields occurring for DBD PAs.

2.4.1 Overview and selection of flow-measurement techniques

Near-wall flow measurements are fundamental in this work for both investigating the plasma-based forcing in general and assessing the interaction with turbulent flows, which motivates the methodological requirements discussed in the following. First, since the actuation predominantly affects the air within approximately 1 mm above the actuator surface [87, 109, 116], suitable measurement techniques must be capable of resolving high velocity gradients in direct actuator vicinity. Second, wall-near measurements in turbulent flows are required for studying underlying topological mechanisms of flow-control applications and assessing local drag effects. In particular, the WSS can directly be extracted from the mean velocity gradient in the viscous sublayer region if captured at sufficient resolution with a suitable experimental setup, as discussed in Section 2.1.3. Measurements of the statistical flow quantities in this region in the ISTM channel-flow facility demand a spatial

resolution in the sub-millimeter range, since a small channel height and high flow velocities are combined to achieve relevant Reynolds numbers (see Section 5.1 for details). At the same time, the PA array surface with exposed electrodes may reflect or scatters laser light applied in optical measurement techniques, which poses additional challenges to optical measurements in the wall-near flow region. For a spatio-temporal characterization of the forcing the measurement of both flow velocity and acceleration contribute valuable insights, which imposes further requirements to the choice of suitable techniques. Additionally, the electric field of the operated actuator can interact with measurement probes and seeding particles, limiting the choice of applicable diagnostics.

While a wide range of flow-measurement techniques and variations thereof exist, this section provides an overview of the most commonly applied and relevant approaches, reviews related work and evaluates the suitability for the present measurement applications. "HWA is an intrusive [point-wise] measurement technique with which flow velocities can be derived from the heat transfer of a wire probe exposed to a flow [31]. [These thermal anemometry probes have been extensively characterized and also successfully applied in numerous studies for the measurement of turbulent flow scenarios, e.g. [13, 69, 123, 137], where they are particularly advantageous due to their high frequency resolution and high measurement accuracy [138, 180]. There are, however, some factors which restrict the suitability of the measurement technique for certain investigations. In particular,] the measurement quantities are averaged over the probe length, which accordingly limits the achievable spatial resolution. [...] [Furthermore, wall-interference] can cause measurement errors, which limits the applicability of hot-wire measurements especially in the viscous sublayer [5]. Especially in complex flows as those manipulated by active flow-control techniques, HWA is sensitive to variations in ambient temperature e.g. in the near vicinity of DBD PAs. In addition, in the context of PAs [...] [reliable measurements might not be possible] due to the contamination of the hot-wire signal from electromagnetic interference as well as the danger of damaging the HWA circuit due an electrical arcing between the exposed electrode and the hot-wire probe [20, 109]." [PLG+24]

In both particle image velocimetry (PIV) and particle tracking velocimetry (PTV), flow velocities are obtained through the motion of tracer particles between consecutive image frames, providing non-intrusive optical measurements. In a basic configuration, using a thin laser light sheet for particle illumination, the measurements are planar and allow the measurement of the two in-plane velocity components. For PIV the particle images (PIs) are evaluated correlation-based within so-called interrogation areas, whose size and overlap define the spatial resolution. In case of PTV the positions of individual particles are extracted from the PIs, and matching particle pairs are identified in consecutive frames. As a result, the measured particle velocities appear as an irregular spatial distribution [1, 149]. Based on these basic working principles, extended setups and algorithms have been developed for the correlation-based measurement of three flow-velocity components (stereoscopic and tomographic PIV) and volumetric particle tracking comprising approaches such as DPTV and STB [70, 149, 162]. The latter category is referred to as three-dimensional Lagrangian particle tracking (LPT), when high numbers of particles can be tracked over a longer period of time [165]. While flow-field data is organized on a regular grid in case of Eulerian representation, Lagrangian trajectories are positioned at random locations [180]. The differences of PIV- and LPT-based approaches result in distinct strengths and limitations. As one advantage, continuous Lagrangian particle tracks allow for a direct evaluation of particle acceleration [165]. Furthermore, typical bias errors related to spatial averaging in flows with irregular seeding density or non-linear velocity profiles represent a limitation for PIV-based near-wall turbulence measurements [104, 105, 165]. However, correlation-based evaluation approaches can be more robust than particle tracking approaches depending on the PI detection and position-estimation methods. In particular, particle tracking in high-density seeded flows can represent a challenge

[71, 149]. A shared advantage of both approaches is that they avoid the uncertainties associated with traversing systems, as no intrusive measurement probes are required [48]. Generally, particle-based measurement techniques may be affected by the electromagnetic fields occurring near PAs due to possible electrical charging of tracers [20, 109]. This aspect is discussed in more detail in Section 2.4.5.

With an appropriate optical setup and processing strategy, particle-based imaging approaches have achieved sub-millimeter spatial resolution in wall-adjacent regions of turbulent flows. In particular, a long distance mirco-PIV setup was used to measure instantaneous and statistical turbulent flow quantities down to the viscous sublayer in a turbulent boundary layer flow, enabling direct extraction of the WSS [104]. Later, time-resolved PIV was employed to measure statistical turbulent flow quantities in a turbulent boundary layer down to the viscous sublayer, and the WSS could be evaluated from the mean velocity profile [195]. SPIV measurements were previously conducted for the experimental investigation of a PA array in a turbulent channel flow in the facility at ISTM with small channel height. Due to the resulting small viscous sublayer height direct determination of the WSS was not feasible [87]. Another recent study applied SPIV in a turbulent boundary layer flow for the evaluation of wall-near statistical flow quantities for the assessment of a spanwise wall-forcing approach. The drag effect was estimated from mean velocity profiles measured in the viscous sublayer region [107]. A comparison of window-correlation, single-pixel ensemble-correlation and particle-tracking evaluation methods was conducted, which focused on possible bias errors related to inhomogeneously seeded flows or non-constant velocity gradients, and only PTV based methods were identified to avoid such effects [105]. In another study [48], HWA, LDV-PS (introduced below), PIV and PTV were applied for measurements in a turbulent boundary layer and factors influencing the respective measurement accuracies were analyzed. The PTV measurement approach yielded a fine measurement resolution in the viscous sublayer. The findings of the latter studies suggest the application of PTV to complement standard PIV setups in immediate wall vicinity, where wall-related sparse and inhomogeneous seeding are present. This allows for the simultaneous measurement of flow velocities in different orders of magnitude [48, 105]. "Recently, volumetric defocusing μ PTV was successfully applied to resolve the viscous sublayer of a turbulent boundary layer through a single optical access for the WSS determination [72]. [...] The seeding of the near-wall region, which is the basis for most optical measurement applications, was reported to be challenging." [PLG⁺24] DPTV was further shown to be suitable for the measurement of turbulent flow statistics within the viscous sublayer of a turbulent channel flow with small channel height [LPK23]. In the same facility at ISTM, STB measurements were conducted, capturing near near-wall flow statistics within the viscous sublayer at increased spatial resolution [117].

Laser Doppler velocimetry (LDV) represents another laser- and particle-based flow-measurement technique enabling non-intrusive point-wise measurements. The principle is based on the evaluation of characteristics of the scattered light signal caused by a particle passing through a small, laser-illuminated volume. The corresponding particle velocity is determined based on underlying geometrical relations, such that no calibration procedure is needed. Additionally, the particle acceleration can be evaluated with extended signal processing approaches [180]. "For general LDV measurements [the particle velocity can be determined with high accuracy, while] the spatial resolution is limited to the size of the measurement volume in the order of magnitude of several hundreds of μm [180], since the positions at which tracer particles cross the measurement volume cannot be distinguished. In consequence, the [...] [scattered light] signals of all registered particles within the measurement volume are converted into a single velocity value for the entire measurement volume – independent from the variety of individual particle trajectories and velocities. Furthermore, various bias errors might occur with this measurement technique, as elaborated in the treatise of

Albrecht [3]. One of these is caused by an uneven distribution of particles passing the measurement volume at different velocities, as a higher number of particle occurrences may be expected in regions of higher mean velocity. Another possible bias error is related to the elliptical shape of the measurement volume and the velocity gradient within it, as the measurement volume is wider at its center such that more particles might be detected in this region." [PLG⁺24] Due to these characteristics, LDV measurement technique is not immediately suitable for resolving statistical flow fields within a narrow viscous sublayer. To overcome the mentioned limitations, however, the LDV-PS measurement system was developed based on the modification of classic LDV measurement technique. In particular, this measurement principle enables the determination of the axial position within the measurement volume at which the individual particles cross [52], raising the dimension of measurements from point-wise to linear. Exemplary applications reported in literature, including measurements of velocity profiles in turbulent flows [171], demonstrated the potential of LDV-PS measurements for local velocity profile measurements and WSS determination.

"Other techniques related to time-resolved measurements in the viscous sublayer have recently been reviewed in [138] highlighting that state-of-the-art techniques are faced with various challenges besides temporal and spatial resolution, or limitations in their dynamic range." [PLG⁺24]

Based on the discussed advantages and limitations in the context of measurements above PAs and wall-bounded turbulent flows under consideration of previous studies, time-resolved particle-tracking and LDV-PS techniques appear advantageous for the intended flow characterization in this work. The latter has specifically be suggested as an additional means for local WSS-measurements by Hehner [87]. In the following, the selected measurement principles, i.e., DPTV, LDV-PS and STB, are introduced. The level of detail varies according to the role each method plays in the present investigations. For the LDV-PS, particular attention is placed on the signal evaluation, which is focus of the analysis of unexpected measurement behavior. DPTV is discussed in depth as well, since the measurement technique is operated without a commercial evaluation software and novel concepts are implemented, extending the general applicability beyond the present study. The STB measurements are based on a comprehensive commercial software and are conducted with a rather user-oriented perspective. Thus, the measurement technique is described more briefly. The respective scope of investigations is summarized in the introduction of each measurement technique for increased clarity.

2.4.2 Defocusing particle tracking velocimetry (DPTV)

The present section introduces the DPTV measurement technique in detail. As already outlined above, DPTV is an optical particle-tracking based measurement technique for 3D3C flow measurements in thin measurement volumes at rather low seeding density using only one camera. DPTV is applied in this work to measure flow velocity and acceleration above the PA array under otherwise quiescent air conditions as described in Section 4.3. Novel approaches for the calibration and uncertainty quantification are implemented, establishing the applicability of DPTV for measurements of the plasma-induced flow. On that basis, the study contributes to the characterization of the plasma-based oscillatory forcing. The time-resolved measurements enable a combined evaluation of continuous Lagrangian tracks and extracted Eulerian flow fields.

State of research

"DPTV is based on the work of Willert and Gharib [196] and enables to measure three-dimensional particle positions and velocities by associating features of a defocused PI such as shape or size with

the particle position along the optical axis. Commonly applied mechanisms include astigmatism and out-of-focus imaging with and without an aperture using geometrical masks [47], out of which the latter is used here. Specifically, Fuchs et al. [70] introduced an in-situ calibrated DPTV approach for wall-bounded volumes of a few millimeters thickness, where the depth location of the tracer particle is extracted from the PI diameter. A locally adaptive intensity filter is applied for particle detection, while the PI diameter is coupled to the physical depth dimension through in-situ calibration. This work forms the basis for the present measurements, as discussed later. Various alternative detection mechanisms exist in literature, such as a comparison to a calibration stack [14] or a detection via deep convolutional neural networks [56].

An in situ calibrated DPTV approach was successfully applied by Leister et al. [119, 120] for measurements of the oil-flow structure in an open wet clutch gap of a few hundred micrometers height. [...] [As mentioned in the measurement technique overview above], the suitability of DPTV for measurements in a turbulent channel flow [LPK23] and the determination of wall-near turbulent flow structures and WSS in a boundary layer flow [72] was shown." [PLLK25]

Measurement principle

"Figure 2.9 shows the measurement principle for two particles — both positioned at different distances from the camera focal plane. The diameter of their out-of-focus PIs on the camera sensor contains the explicit distance information of each particle to the focal plane. Note, the intensity of the image might be several orders-of-magnitude lower, compared to an in-focus image as the same amount of light is distributed across a larger area on the camera chip. Olsen and Adrian [136] derived a mathematical equation of this defocusing behavior under absence of optical aberration effects, which quantifies the interrelation between the PI diameter d_i on the sensor and the physical diameter size of the particle d_p as

$$d_i^2 = M^2 d_p^2 + 5.95(M+1)^2 \lambda^2 f_{\#}^2 + \frac{M^2 y^{*2} D_a^2}{(s_o + y^*)^2}. \quad (2.25)$$

The first term describes the geometric PI with the parameter M as magnification. The second term represents the diffraction of light on the aperture, with λ as wavelength of the light and $f_{\#}$ as focal number of the lens. The third term describes the diameter change of d_i caused by the distance y^* of the particle to the focal plane, the opening diameter of the aperture D_a and the focal distance s_o . Figure 4.8 (a) shows a graphical implementation of this equation for d_i over y^* for two different particle diameters d_p . With increasing y^* , the geometrical PI size and diffraction effects are not effected, while the third term, representing defocusing effects, increases. Consequently, as shown in the figure, the third term of the equation becomes the most dominant when considering particles at a specific distance from the focal plane, which applies in the current measurements. For this case, Equation (2.25) can be simplified to gain the linear interrelation

$$d_i = m_d y^* + d_0 \quad (2.26)$$

with d_0 being the PI diameter at a known position, corresponding to the wall and actuator surface in the present case. The second parameter m_d represents the slope of the defocusing function. [...] Equation 2.26 is applied as calibration function based on the calibration parameters m_d and d_0 obtained in a calibration procedure for the respectively used measurement setup." [PLLK25]

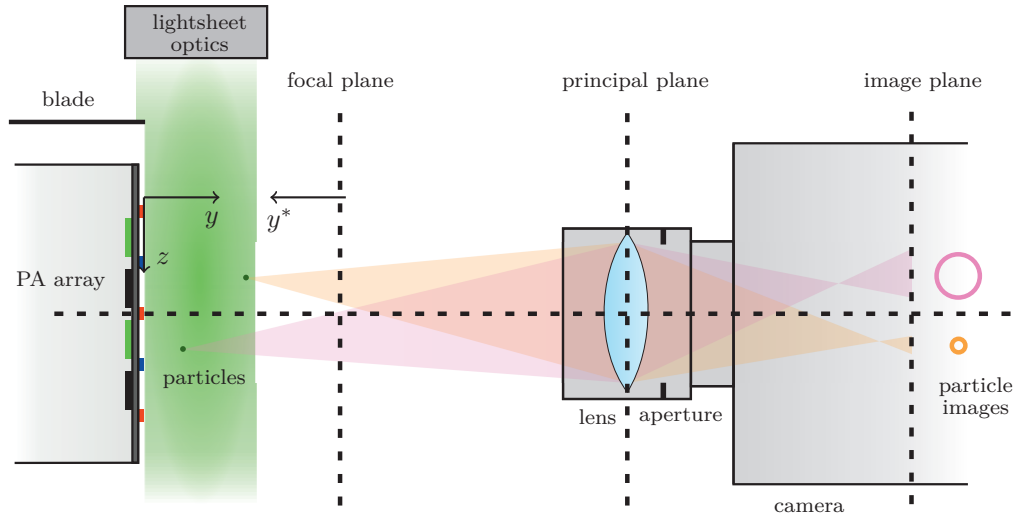


Figure 2.9: Detailed, not-to-scale sketch of measurement volume above PA and DPTV measurement principle. Reproduced from [PLLK25].

2.4.3 Laser Doppler velocity profile sensor (LDV-PS)

As introduced in the overview of different measurement techniques, the LDV-PS measurement approach enables optical 1D2C flow measurements based on the detection of tracer particles passing a small measurement volume. The feasibility of a commercial LDV-PS system is assessed for measurements in a turbulent channel flow described in Section 5.2. However, unexpected measurement behavior at low flow velocities is found to limit the applicability for the investigation of plasma-based forcing. The observed effects are therefore further investigated using an additional setup focusing on signal-processing dependent accuracies of velocity and location estimation for various tracer object sizes. On this basis, promising next steps for making the measurement technology more accurately applicable are identified.

State of research

"The LDV-PS measurement technique, in contrast to a standard LDV [...], can spatially resolve the velocity profile within the measurement volume [52, 53]. The measurement technique was further improved and developed [16, 34, 35], and [as mentioned above] has been shown to be capable of measuring turbulent channel flow mean velocity profiles as well as fluctuations in the main flow direction [171, 172]. As additional fields of application, an LDV-PS was used to measure the acoustic particle velocity [86], the flow in a fuel cell stack [36] and a microfluidic air flow [37]. Recently, Bürkle et al. [38] reported the flow characterization of a the gas flow in a model experiment for crystal growth by means of combined PIV and LDV-PS measurements for large- and small-scale investigations. In the present work, a recently introduced commercial *ILA R&D* LDV-PS system with an integrated 5 MHz Bragg shift is employed, which was recently shown to allow measurements in a laminar Couette-like oil flow in a clutch test rig [LPK22]. The commercial measurement system has furthermore been successfully applied to measure the turbulent flow in the wake of a droplet with a spatial resolution of $10\ \mu\text{m}$ [33] and the flow topologies appearing in rotary pumps used for blood [175]." [PLG⁺24]

Measurement principle

"The LDV-PS builds upon the LDV measurement concept: two laser-beam pairs $i = 1, 2$ with different wavelengths λ_i cross building overlapping interference fringe systems in the same plane. In contrast to a general LDV arrangement, the intersection points of the pairs are shifted from their respective beam-waist positions to the converging and diverging parts of the beams to purposely span two overlapping counter-oriented fan-shaped fringe patterns [52]. Consequently, the fringe distances d_i with $i = 1, 2$ of the resulting interference patterns are a function of the y -position as illustrated in Figure 2.10 for one beam pair. Since the registered Doppler-burst signals of a single particle – while simultaneously crossing both fringe patterns accordingly – rely on the location within the ellipsoid, the y -position can be determined with the quotient q of the received scattered light frequencies f_i of both fringe systems, i.e.

$$q(y) = \frac{f_2(y, u)}{f_1(y, u)} = \frac{u/d_2(y)}{u/d_1(y)} = \frac{d_1(y)}{d_2(y)}, \quad (2.27)$$

as elaborated by Czarske et al. [53]. [The frequencies f_i of the particle scattered light are determined from the measured signal by means of fast Fourier transform (FFT) transform.] The fringe distances $d_i(y)$ of either beam pair and the resulting quotient function $q(y)$ according to Equation 2.27 are shown in Figure 2.11 as green solid and gray dashed lines, respectively. Furthermore, a linearized version of the frequency quotient, i.e. q^* , is added to the diagram as black solid line, which serves as calibration to assign a y -position value to the measured frequencies in pre-calibrated set-ups as used in the present study. The uncertainty of the y -position-estimation procedure 2.27 has been derived theoretically in terms of standard deviations for the y -position

$$\sigma_y \approx \sqrt{2} \left\| \frac{\partial y}{\partial q} \right\| \frac{\sigma_f}{f} \quad (2.28)$$

and corresponding velocity

$$\frac{\sigma_u}{u} \approx \sqrt{\frac{3}{2}} \frac{\sigma_f}{f} \quad (2.29)$$

[...] [(see [53]),] assuming similar frequency levels and standard deviations in both fringe systems. It is consequently concluded, that the LDV-PS measurement accuracy depends on the accuracy at which the Doppler frequencies f_1 and f_2 are captured, the slope $\partial q / \partial y$ of the calibration curve and the accuracy of the calibration curve." [PLG⁺24]

2.4.4 Shake-The-Box (STB)

STB is an optical LPT-based measurement approach for 3D3C flow measurements at high seeding density, as already classified in the measurement-technique review. The principle follows an iterative triangulation-based procedure for particle localization using typically three or four cameras. In this work STB is applied for time-resolved flow-velocity measurements in a turbulent channel flow with and without plasma-based forcing. The conducted measurements are described in Sections 5.3 and 5.4 and rely on a comprehensive commercial software for data acquisition and processing. Flow velocity fields are extracted from the measured Lagrangian particle tracks and evaluated from a Eulerian perspective.

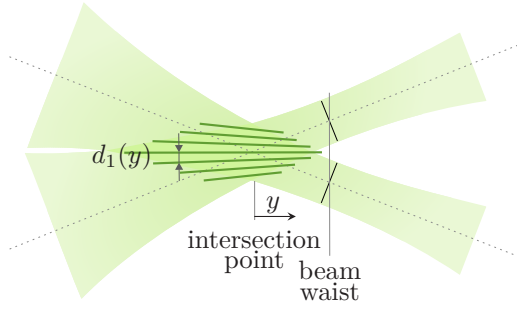


Figure 2.10: Convergent fringe pattern of one laser-beam pair with intersection point shifted from the beam waists. Reproduced from [PLG+24].

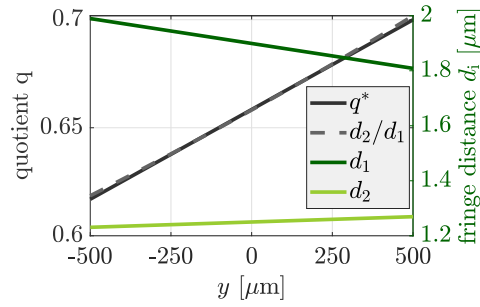


Figure 2.11: Linearized calibration curve $q^*(y)$ and the associated fringe spacings $d_i(y)$. Reproduced from [PLG+24].

State of research

STB represents an advanced particle-tracking algorithm [162], which incorporates immediate particle-position optimization by means of iterative particle reconstruction [192]. Consequently, STB advances beyond three-dimensional PTV approaches based on single-pass PI detection and three-dimensional triangulation in terms of accuracy and simultaneously trackable particle density, while yielding continuous Lagrangian particle tracks instead of voxel-resolved flow fields measured using tomographic PIV. As a result, STB allows to capture high flow velocities at fine spatial and temporal resolution [165]. Note that the development of this method relies on rather recent advancements in the underlying hardware of high-speed lasers and cameras [24].

The discussed advantages make the STB measurement technique particularly promising for the challenging task of investigating (wall-near) turbulent flows. This has been proven in different feasibility studies for the measurement of canonical flow cases over the last years. In particular, the suitability of STB for measurements of instantaneous and statistical flow quantities, including the detection of backflow events and the determination of viscous flow scales from the mean velocity gradient at the wall, was shown [166]. Later, STB was applied to measure instantaneous velocity distributions and statistical flow quantities resolving the viscous sublayer in a turbulent boundary layer flow from multi-exposed recordings at increased flow velocity of up to 30 m/s [134]. As already mentioned in the review in Section 2.4.1, STB measurements were recently employed to measure statistical flow quantities down to and within the viscous sublayer of a turbulent channel flow at the facility at ISTM with a small channel height [117].

Currently, STB is gradually finding its way into the application in different research fields, with large-scale flow measurements representing one focus point. Particularly, it has been applied in flow measurements in water in the wake of a marine propeller [68, 189] and around a moving wing [163]. Furthermore, the air flow driven by thermal convection above a radiator inside a building [130] and caused by an air conditioning unit inside a car was investigated using STB [79]. The measurement technique was further applied in measurements of the far field of a turbulent jet for the investigation of coherent flow structures and statistical quantities [32]. Other studies show the application of STB for the investigation of wall-near and smaller-scale turbulent flows. In particular, it was used to characterize the flow above superhydrophobic surfaces in a water channel [157] and the flow in a transparent left ventricle model during a cardiac cycle [199]. The latter study reported particularly good representation of wall-near velocities by means of STB measurement technique in comparison to tomographic PIV. Generally, it is interesting to note that the interpretation of STB measurement results is, up to the present time, predominantly based on

an Eulerian perspective rather than Lagrangian track properties (see also the recent review article by Schröder and Schanz [165]).

Measurement principle

Three-dimensional LPT by means of STB requires PI detection in multiple camera views, the triangulation-based determination of the particle position in object space and the matching of particles in consecutive frames. In this context, the performance of the STB algorithm benefits from methods for highly accurate particle localization and the applicability in densely seeded flows. In the following, the underlying procedures will only be briefly introduced, since the STB measurements conducted in this work rely on the implementation in Davis user software (*LaVision*). Note that modified approaches have been introduced for temporally interrupted multi-pulse tracking [134, 135], while the following description refers to the algorithm for time-resolved STB.

In that case, the particle motion in previous time steps is considered by applying extrapolation functions to calculate a first estimate for a particle position in the next time step, which is why STB is sometimes called 4D PTV, with the fourth dimension being time [165]. Subsequently, an iterative approach is applied for the optimization of particle-position reconstruction. Therefore, three-dimensional particle positions in object space are reprojected into two-dimensional image space and compared to the PI distributions, which allows to correct the particle location successively. This adjustment is therefore referred to as "particle shaking". This scheme is inspired by methods introduced for tomographic PIV ([62, 160]), where PIs are projected into voxels in the object space based on an iterative adjustment of reconstructed voxel intensities in the image space to match the recorded images as close as possible [192]. The method requires high calibration accuracy, which is achieved by applying the volume self-calibration method in order to refine the initial target-based calibration. This procedure considers local disparity values, i.e. residual triangulation errors, between the backprojection of triangulated particles and the measurement images for the correction of the initial mapping function [192]. Additionally, the calibration considers varying imaging conditions throughout the measurement volume, potentially influencing the PI shape, by means of optical transfer function calibration [161].

The iterative particle-localization scheme described above is repeatedly applied for individual time steps on residual images after subtracting the two-dimensional projections of already detected particles. This approach simplifies the reconstruction of the remaining particles in less populated images, enabling the STB algorithm to operate at high particle densities [165].

2.4.5 Seeding particles and their interaction with PAs

Optical flow-measurement techniques, such as DPTV, LDV-PS and STB applied in this work, rely on the application of tracer particles to display the motion of fluid. The ability of a particle to follow the flow closely can be approximated through the ratio of typical time scales of the flow τ_f to the particle response time τ_p , quantified by the Stokes number

$$Stk = \frac{\tau_p}{\tau_f}. \quad (2.30)$$

The particle response time can be calculated as

$$\tau_p = d_p^2 \frac{\rho_p}{18\mu} \quad (2.31)$$

with the particle diameter d_p , particle density ρ_p and fluid dynamic viscosity μ . For τ_f the quotient of a characteristic length scale and velocity of the investigated flow can be evaluated. For $Stk < 10^{-1}$ the ability of tracer particles to follow the flow is considered sufficient [149]. In this work, the experiments are carried out in air, and di-ethyl-hexyl-sebacate (DEHS) droplets are applied as seeding. Assuming a droplet diameter of $1\text{ }\mu\text{m}$ [149] results in $\tau_p \approx 2.74 \times 10^{-6}\text{ s}$. The measurements above the PA array in otherwise quiescent air (see Section 4.3) are characterized by the spanwise wavelength λ_z and typical forcing-induced velocity amplitudes, while for the channel flow measurements (see Sections 5.2, 5.3 and 5.4) the channel dimension h and characteristic velocities u_{cl} of the experiments are considered. Based on these quantities, the Stokes number yields $Stk \approx 1,5 \times 10^{-3}$ and, thus, sufficiently precise flow tracing can be assumed.

In order to additionally avoid interference of the particle supply with the investigated flow, as outlined by Kotsonis [109] in the context of plasma-based flow control, the seeding is added to the air in the employed channel-flow facility directly after the drive and before the settling chamber (see also Section 5.1). During the DPTV experiments under quiescent conditions, a PMMA housing is used around the measurement setup to reduce influences of ambient-air movement. After adding the seeding and closing the housing, the air is left to rest for several minutes, as described in Section 4.3.

Despite these careful considerations of the fluid-mechanical interaction of tracer particles in the investigated flow scenarios, additional plasma-related influence on the particle motion can occur due to charging or magnetization of particles [20, 109]. Consequently, particles might move in response to the electric field surrounding the PA. Only few studies have been conducted to investigate such effects. A comprehensive study analyzed tracing properties of different solid particles in a flow generated by a corona discharge and identified titanium dioxide, silicon dioxide microballoons and incense smoke as suitable tracers [85]. Other works investigated effects on solid tracer particles in electric fields of surface DBD PAs. Negligible electrophoretic effects on $0.3\text{ }\mu\text{m}$ diameter alumina particles were reported based on the comparison of the seeding-density distributions found in the absence and presence of discharges [106]. In another study, solid particles of smaller size were found to be generally less affected by the plasma than larger particles, while the importance to separately evaluate the effects for oil-droplet tracers was further emphasized [129]. LDV-based measurements based on olive oil, DEHS and incense seeding above a DBD PA were compared to those of a pitot tube in the absence of seeding [27]. While the pitot-measured velocities were the highest, the incense-based velocities are lower than the other seeding-based measurements. Thus, the study indicates a certain effect from the choice of seeding on the measurement result without investigating the underlying mechanisms in detail.

Unfortunately, the findings made for corona discharges can not be fully transferred to DBD PAs, and the solid tracer particles suggested in some of the studies are not practically applicable in the facilities used in the present work. Particularly, large amounts of seeding are required to supply the blower-type turbulent channel flow facility (see Section 5.1), and the open circuit does not provide for filtering the air at the outlet. Finally, possible influences of the plasma on the particle motion can not be completely ruled out or quantified based on the reviewed literature. The present work therefore relies on the application of liquid seeding, which is commonly employed in experimental studies on plasma-based flow control [87, 90, 114, 118, 167]. Furthermore, the potential impact of an electric field on the tracer particle motion must be related to the velocity amplitudes under investigation. Consequently, for measurements at small flow velocities, especially under quiescent-air conditions, water-based tracer particles are avoided in this work due to their polar molecule structure and associated response characteristics. Instead, all experiments employ DEHS particles as tracers.

3 Constructive implementation of PA arrays

The present chapter documents constructive developments and operational details of the applied PA arrays. First, in Section 3.1, the hardware components and the procedure used for plasma generation in the experiments in this work are presented. The maximum length of PA arrays, which can be operated with this equipment, is determined in an iterative procedure. Furthermore, in Section 3.2, a routine and infrastructure developed for PA-array prototype fabrication in small batch sizes under laboratory conditions is presented. In the context of the first posed research question, addressing the actuator durability, the design is improved in comparison to previously used arrays by changing the electric isolation of the lower electrodes. Finally, the plasma symmetry and regularity are considered by means of CMOS/sCMOS imaging described in Section 3.3, which falls into the context of identifying suitable diagnostic methods for the plasma characterization as motivated in the second research question. A quantitative evaluation provides insights into how design details of the electrical connections influence of discharge characteristics and design recommendations are derived.

3.1 Hardware for plasma generation and electrical operation parameters

This section introduces the hardware and procedure for plasma generation applied throughout this work. The achievable plasma length, i.e. length and number of simultaneously operated electrodes, depends on the used hardware. A simple approach is introduced to iteratively evaluate these limitations for the applied components and actuator arrays.

PA-array operation

The oscillatory plasma-based forcing is achieved in BF mode in the present experiments. While details on the working principle and the advantages of this operation mode are described in Section 2.2.3, the present section introduces the used hardware for plasma generation together with electrical operation parameters selected to achieve the intended forcing.

Two Minipuls 1 HV transformers provide the voltage signals for the upper electrode groups (blue and red in Figure 2.8), whereas two Minipuls 2 HV transformers supply the encapsulated electrodes (shown in green and black). The Minipulses (*GBS Elektronik GmbH*) are connected to DC power supplies (VLP-2403 Pro, VSP-2410, *VOLTCRAFT*). Note that the voltages supplied to the electrode groups cannot be set directly in this setup but instead depend on the DC power supply settings. This makes the voltage adjustment a manual and challenging task, particularly for BF operation, where the duty cycle is directly linked to the voltage amplitude. The signal frequencies applied to the individual electrode groups are defined in the synchronizer software (Synchronizer control unit operated using sigma software, *ILA 5150 GmbH*). The software allows the definition of a signal in repeating temporal units, i.e., in the present case rectangular-signal units of length $T_{AC}/2$, which can be defined in steps of 0.05 μs . On this basis the signal settings are chosen to

approximately yield the intended oscillation frequencies of 25, 50, 100 Hz depending on the respective experiment. The plasma frequencies applied to the upper electrode groups is $f_{AC,12} = 16$ kHz and the plasma frequency of the lower electrode groups is adjusted accordingly. As shown in Table 3.1, the resulting beat frequencies differ slightly from the target oscillation frequencies due to the limited setting options and resolution in the synchronizer software. Throughout this work, the nominal frequencies refer to the respective target frequencies if not specified differently.

Table 3.1: Synchronizer settings for different oscillation frequencies in BF operation.

Target oscillation frequency	Upper electrodes plasma frequency		Lower electrodes plasma frequency		Actual beat frequency
f_{osc} [Hz]	$T_{AC,12}$ [μs]	$f_{AC,12}$ [kHz]	$T_{AC,34}$ [μs]	$f_{AC,34}$ [kHz]	f_{BF} [Hz]
50	62.5	16	62.7	≈ 15.949	≈ 51
100	62.5	16	62.9	≈ 15.898	≈ 102
25	62.5	16	62.6	≈ 15.974	≈ 26

Determining the maximum plasma length

Previous experiments investigating the development of the flow above a PA array in the channel flow facility at ISTM confirmed that the flow is fully developed before entering the actuated region. Above the actuator, however, the actuated flow remained in developing state in streamwise direction over the entire array length of 80 mm [87]. Accordingly, the present experiments aim to increase the PA-array size to study the further flow development above the actuator in the turbulent channel flow in Section 5.4. For this purpose, a procedure to identify the maximum array size for which electrical power can be provided in BF operation is found. PA arrays with seven upper and six lower electrodes are fabricated with the materials and process described in Section 3.2. The initial length of the upper and lower electrodes is 200 mm. Subsequently, the PA array is connected to the hardware specified above and, following the described procedure, an attempt is made to generate plasma. Iteratively, this step is repeated while reducing the upper electrode length by wiping off segments of the spray-painted electrodes with isopropanol. Finally, the maximum electrode length in the chosen actuator configuration for BF operation with the used equipment is found to be 110 mm. In consequence, the used actuators could not be sufficiently extended, and the (potentially flow- and forcing-parameter-dependent) streamwise development length required for a fully converged flow state remains to be determined. This result clarifies the need for equipment that can deliver increased electrical power while being compatible with BF operation to provide plasma over a sufficiently large streamwise section ($l_{AC}^+ = 3000\delta_\nu = 150$ mm at $Re_\tau = 250$ suggested for the used channel [87]) to achieve a fully-developed flow state upon actuation.

3.2 PA-array material selection and manufacturing routine

The present section describes the applied PA manufacturing routine and respectively used materials. Firstly, the general procedure is introduced and, in the second part, technical hands-on details for the individual steps are documented.

PA-array manufacturing procedure

For the experimental investigations of the plasma-based forcing effects, suitable PA-array prototypes are required. Since the previously applied actuators [87] were fabricated externally at TU Delft [200], an infrastructure and procedure for manufacturing small batches of prototypes in the laboratory at ISTM at KIT is developed on basis of the previously used routine, aiming at continuity and comparability with previous experiments. Additionally, specific requirements of the present application are considered, which are introduced in the following.

In the present work, the length and number of electrodes on the PA arrays vary for the respective experiments. Generally, the design comprises four groups of electrodes, respectively connected to the same voltage, following the scheme introduced in Figure 2.8 (b). The electrode geometries and connections are additionally shown from a top view in Figure 3.1 with the same color-coding for the four electrode groups. The width of the lower electrodes (HV3 (●) and HV4 (●)) of 3 mm and upper electrodes (HV1 (●) and HV2 (●)) of 1 mm from the previous actuators [87] are kept constant throughout all experiments, yielding a repeating pattern of electrodes along the spanwise wavelength of $\lambda_z = 4$ mm. Further manufacturing requirements are precise alignment of the upper and lower electrodes to avoid gaps or overlap, which could cause forcing irregularities. Furthermore, an increased durability and robustness are pursued, which is particularly challenged by the dynamic operation of the multi-electrode arrays in the present work. The upper electrodes should exceed the dielectric surface as little as possible to minimize their aerodynamic influence. The selection of suitable materials is based on an extensive study on durability aspects [WHP⁺24] under consideration of availability and compatibility with the manufacturing process and previous studies [87].

The actuator manufacturing routine used in this work resembles the procedure applied at TU Delft, and the individual steps are shown in Figure 3.2. Specifically, adhesive foil shown in light yellow is applied to both sides of a glycol-modified polyethylene terephthalate (PET) foil (*Vivak*) which acts as a dielectric and is shown in white. The electrode geometries are laser-cut into the foil so that it can be used as a stencil (see step (1)). Conductive silver paint (*Holland Shielding Systems BV*) is applied to the PET foil with an air-brush pistol, forming the electrodes shown in red, blue, green and black associated with the four electrode groups in step (2). After the removal of the stencil foil in step (3), a 3D-printed frame shown in orange is glued on the lower side of the PET foil in step (4). Unlike for the previously used actuators, polymer resin shown in gray (*R&G 888658 HT2*) serves as electrical isolation for the lower electrodes, which is casted into the frame in step (5). This changed approach aims at avoiding local defects such as air pockets, which may lead to malfunction in electrical isolation and early breakage of the arrays, which had previously occurred, when multiple layers of *Kapton* tape served as isolation. An increased actuator durability is observed throughout the experiments with the resin-based isolation. Adhesive copper tape is applied on the PET surface covering the ends of the individual electrodes belonging to the same electrode group to connect them together and to the power supply hardware. For clarity, these electrode connections are indicated by the green and pink areas in Figure 3.1. Detailed findings on different connection configurations are described in Section 3.3.

Technical details for manufacturing

In the following, further hands-on procedural details on the manufacturing process outlined above are documented. The individual steps are additionally shown in Figure 3.3 for an actuator array employed in the STB measurements in the turbulent channel flow described in Section 5.4. The PET foil exceeds the electrode area for these actuators to allow a smooth integration into the

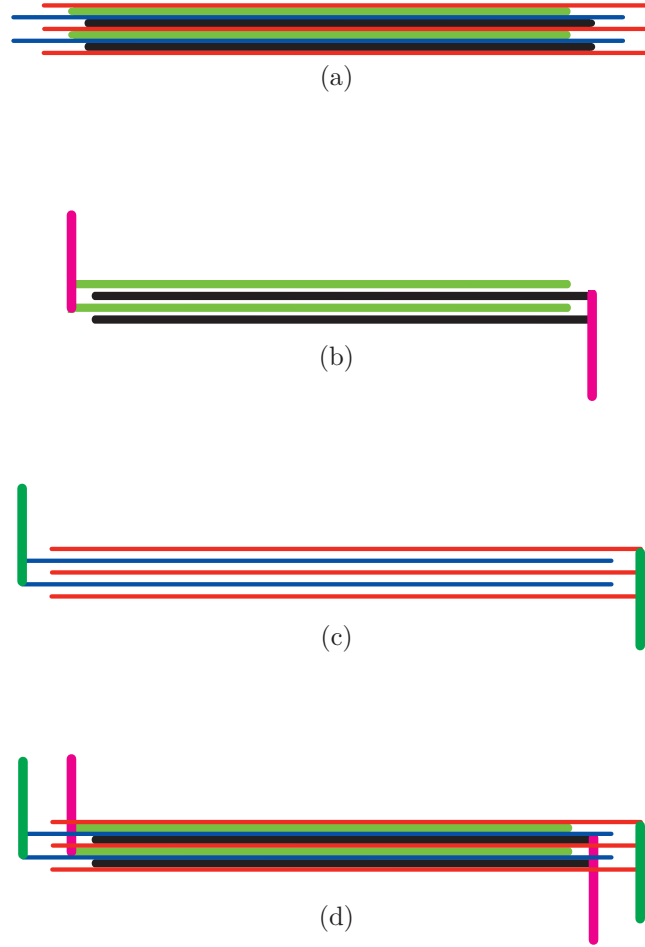


Figure 3.1: PA array electrode geometries color-coded according to voltage group with voltage connections on upper and lower dielectric surface from top view. (a) Electrodes of all groups without connections. (b) Lower electrode groups with respective connections in pink. (c) Upper electrode groups with respective connections in dark green. (d) All electrodes with connections of lower electrode groups in pink and upper electrode groups in darker green.

channel flow facility (see Section 5.1 for details). The electrode geometries for the upper and lower electrodes illustrated in Figure 3.1 (b) and (c) are defined separately using a graphic-design software (CorelDRAW) and exported as vector-graphic files. A laser cutter (operated with LightBurn software) is applied to cut the electrode shape into the stencil foil adhered to the PET. For this process, the laser intensity and velocity are iteratively adjusted to obtain smooth edges of the cut geometries without damaging the PET. Since the final electrode width and, thus, potential regions of gaps or overlap, depend on the laser beam thickness at cutting, the underlying drawing of the electrode geometries, i.e. the exact electrode width, is also iteratively adjusted. After the cutting, the cut-out parts of the adhesive stencil foil are removed and the PET surface underneath is cleaned of adhesive residues using isopropanol.

The precise alignment of upper and lower electrode geometries is a critical aspect of the actuator fabrication, for which two strategies have been developed and applied throughout this work. One is the positioning of the PET for cutting on the upper and lower side via holes punched into an

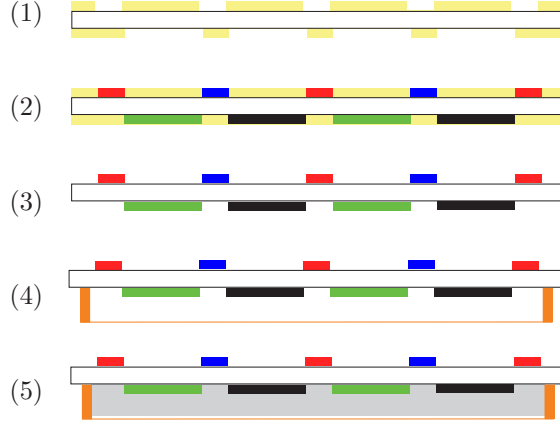


Figure 3.2: PA array manufacturing procedure shown in cross-sectional view (not to scale). (1) PET foil used as isolating dielectric in white with electrode-stencil foil with cutouts for upper and lower electrode geometries in light yellow. (2) Spray-painted electrodes color-coded according to voltage group in the stencil-cutouts on the PET foil. (3) PET foil with electrodes after stencil foil removal. (4) PET foil with electrodes and 3D-printed frame in orange. (5) 3D-printed frame filled with polymer resin shown in grey to isolate lower electrodes.

protruding edge region of the PET and centering pins attached to the laser cutter stationary frame. This procedure allows for very reproducible positioning, while the fine adjustment of upper and lower electrodes without any relative rotation remains challenging, especially for longer electrodes. The PA arrays applied in the ICCD and DPTV measurement studies described in Sections 4.2 and 4.3 are manufactured following this routine. Since the plasma length was limited to 41 mm to match the ICCD-camera field of view (FOV), strong misalignment along the electrodes was avoided. For the second approach, relying on more manual work steps, the laser cutter is only applied to cut the lower electrode stencil, which comprises the 3 mm wide cut-out regions alternating with 1 mm wide regions of left-over adhesive foil. For the upper electrodes, stripes of 3 mm wide adhesive paper tape (*mt masking tape*) are positioned by hand above the cut-out regions of the laser-cut stencil, which is visible through the transparent PET. Gaps of 1 mm width in-between the paper tape strips are created, which serve as a stencil for the upper electrodes. Despite occurrences of slight local misalignment causing spots of small gaps and overlaps, this approach yields very good electrode positioning at the cost of an increased manufacturing effort. This procedure was applied for the longer PA arrays for the STB measurements discussed in Section 5.4. The stages of electrode manufacturing are shown in Figure 3.3 for a laser-cut stencil in the left column and a paper-tape stencil in the middle column.

Before applying the conductive silver paint, all PET-foil regions that are not covered by the stencil should be covered by tape or paper. The silver paint is mixed with additional solvent (methyl ethyl ketone) for the application with an air brush pistol. Furthermore, the air brush should be moved uniformly by hand over the stencil to create an even paint layer (see lower left and middle photos in Figure 3.3). A protection mask against organic fumes and particles and good ventilation are recommended while spray-painting the electrodes. Smooth electrode edges have been obtained when the adhesive stencil foil and tape were removed from the PET after a short drying-off period of approximately 10 min.

The electrodes should dry completely before adding the copper-tape electrode connections and isolating epoxy layer on the lower PET side. A 3D-printed filament with a recommended height of 5 to 8 mm is glued on the PET foil as resin mold using superglue and avoiding any gaps through which resin could leak (shown in right column of Figure 3.3). The frame width and length are chosen to cover the entire area of electrodes that needs to be isolated. The adhesive copper



Figure 3.3: PA array fabrication stages. Left: laser-cut stencil on PET foil with lower electrode geometries without and with silver paint. Middle: paper-tape strips as stencil on PET foil with upper electrode geometries without and with silver paint. Right: spray-painted silver electrodes on PET foil with electric connections made from adhesive copper taper without and with 3D-printed frame for epoxy resin.

tape strips for the electrical connections are attached directly to the dielectric and run outwards below the frame and resin layer. The selected epoxy resin is of rather low viscosity and the two components should be stirred thoroughly but smoothly in order to achieve complete curing while avoiding the formation of bubbles. These might change the dielectric properties locally and cause actuator breakage. Trapped bubbles can be removed using a hot air gun. However, excessive thermal input should be avoided, since the PET foil might deform. Such deformed surfaces change the aerodynamic interaction and make the alignment of a laser-light volume challenging during flow measurements. The resin layer is approximately 2 – 4 mm thin.

3.3 Optical plasma-symmetry analysis of different electrode-connection schemes using conventional imaging

The present section serves a twofold purpose. First, a CMOS consumer camera and an sCMOS scientific camera are applied in an exploratory approach as diagnostic means for investigating the spatial distribution and symmetry of plasma discharges on the arrays. On this basis, the applicability of the comparatively inexpensive consumer camera is evaluated. Second, the obtained results are employed for a quantitative analysis of the effects of different electrical connection configurations on the plasma regularity between different discharge zones on the arrays.

Plasma symmetry across the array

Balancing the voltage levels set to the individual electrode groups is essential for generating symmetrical oscillatory plasma forcing in BF or BM mode (see Section 2.2.3). In particular, if the voltage between one pair of neighboring electrode groups deviates from the others, unintended differences in forcing strength arise in the respective discharge zones. Such asymmetries represent a deviation from the intended actuation scheme, which complicates the assessment of the applied flow-control approach.

While setting the voltages for the PA array, it has been observed that coupling of the voltage levels of different electrode groups can occur, appearing as a raise in the voltage level of one group when another is increased. This prevents balanced voltage levels and, consequently, regular distribution of plasma discharges and forcing. Further investigation revealed that the phenomenon was related to the positioning of the electrode connections to the power supply units. Figure 3.4 (a) and (b) illustrates the two different configurations. The initial design with voltage leveling issues is shown on the left and the reworked setup on the right.

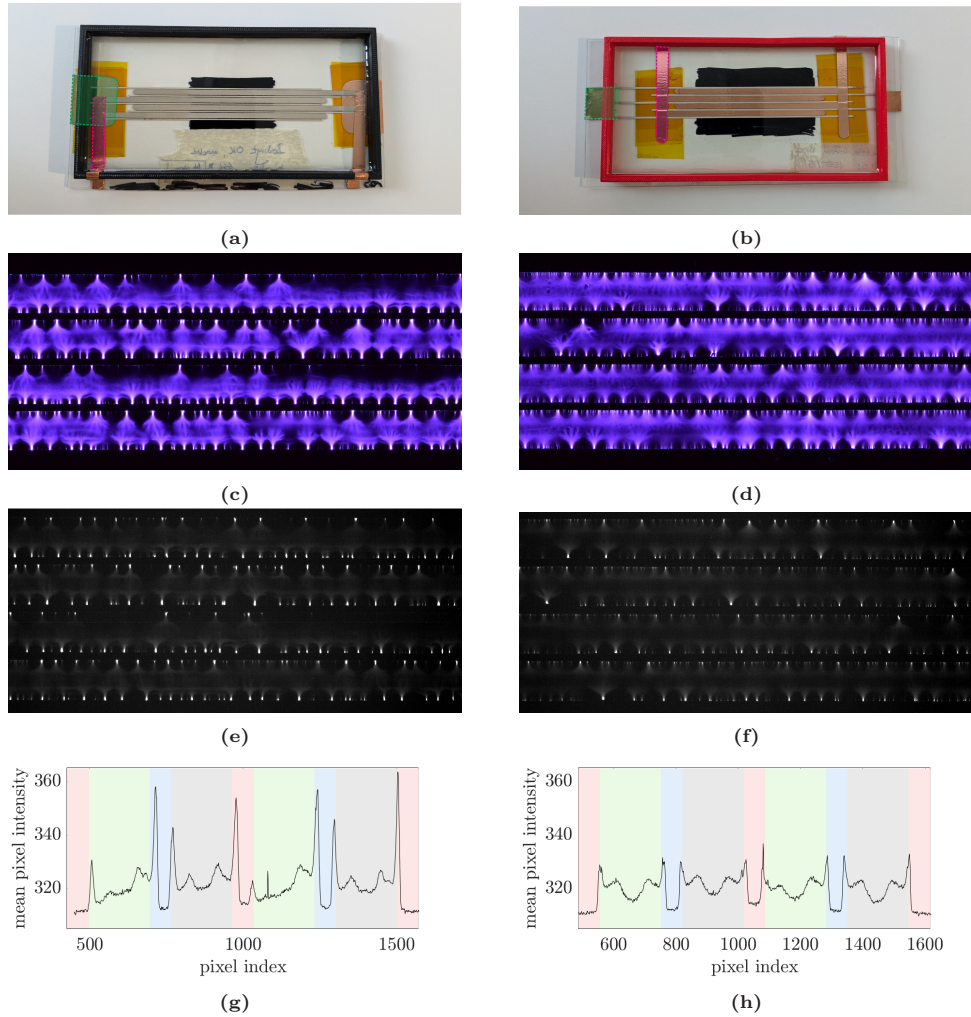


Figure 3.4: Comparison of PA arrays with different electrode connection configurations, exemplarily shown in (a) and (b). Images taken of respective PA discharges with *Nikon D5300* CMOS camera (c, d) and *PCO edge sCMOS* camera (intensified e, f) and average illumination profiles in vertical image direction for sCMOS images (g, h).

As previously described, electrical connections to the power supply units are implemented through adhesive copper tape that is applied to the PET foil acting as the separating dielectric, covering the tips of the respective electrodes and thereby connecting them together (see also the schematic in Figure 3.1). In particular, tape pieces for connecting electrodes on the lower dielectric side are highlighted in green and connections of electrodes belonging to one group on the upper dielectric side in pink in the respective figures. The structural difference between both configurations is that these tape pieces on the upper and lower dielectric side overlap in case of the first actuator in Figure 3.4 (a), while this is avoided for the second actuator configuration 3.4 (b). Note that the actuator shown on the right is a prototype with lower electrodes made from adhesive copper tape. However, two actuators with spray-painted silver electrodes were used in the experiment described in the following. The shown prototype is included here to illustrate the differences in electrode configuration more clearly.

Imaging-based comparison of electrode connection configurations

To quantitatively evaluate and document the effects of the two electrode-connection configurations on the plasma symmetry, the optical emission of the discharges on BF-operated PA arrays is analyzed. Arrays of both configurations are operated using the routine described in Section 3.1 at nominal plasma frequency $f_{AC} = 16$ kHz, oscillation frequency $f_{osc} = 50$ Hz and maximum peak-to-peak voltages around $V_{pp} = 6.4$ kV. As discussed in Section 2.3, imaging-based diagnostics have become a well-established method for investigating plasma-discharge characteristics. While ICCD-imaging based experiments presented later in this work in Section 4.2 allow to characterize the discharges through the oscillation and plasma cycle in fine temporal steps, a time-averaged, statistical analysis is suitable here for the assessment of the plasma symmetry. A relatively low-cost consumer camera is used in addition to a scientific camera to explore the applicability of simpler optical diagnostics for this purpose. A similar approach has previously been reported for example by Hink et al. [93], who captured the lateral plasma extension at an exposure time of 10 s.

Firstly, a *Nikon* D5300 consumer camera for trichromatic images equipped with a CMOS camera sensor is applied at an exposure time of 13 s. Secondly, a *PCO* edge 5.5 camera with a sCMOS sensor for scientific applications is used at a shorter exposure time of 0.1 s. The specifications and settings of the cameras can be found in Table 3.2. For the used oscillation frequency of $f_{osc} = 50$ Hz, the images taken with both cameras cover the duration of multiple oscillation cycles. To provide some level of comparability of filament distribution, the mean of 130 images is considered in case of the latter camera, yielding the same underlying exposure time for both cameras. Note, however, that the image quality depends on the varying acquisition settings.

Table 3.2: Camera and acquisition specifications of D5300 and edge 5.5.

Device	D5300	edge 5.5
Manufacturer	<i>Nikon Corp.</i>	<i>PCO AG</i>
Sensor	CMOS	sCMOS
Pixel Pitch / Pixel Size [μm]	3.9	6.5
Dynamic Range	12 bit per color	16 bit
Applied Exposure Time [s]	13	0.1
Number of images in evaluation	1	130

Figure 3.4 shows for each electrode-connection configuration the respectively taken images of the discharge distribution with the D5300 (c, d) and the edge 5.5 (e, f). In case of the edge 5.5, a

base-intensity value was subtracted from both images and the intensity was enhanced to improve the visibility of the discharges. The electrodes are oriented horizontally in the images. The formation of plasma, i.e. regions with higher illumination levels due to the optical emissions of the discharges, is observed above the encapsulated electrodes. In between, dark stripes indicate the regions of the upper electrodes. The images taken with both cameras (c, d, e, f) show filamentary discharge structures originating from points of high illumination at the edge between upper and lower electrodes. In this context, the trichromatic image character additionally supports the visibility of discharge filaments. The discharges in all images show a relatively even but interrupted distribution along the electrodes. Related to this observation, the comparison of individual images and the shown mean of 130 images taken with the edge 5.5 camera furthermore reveals the tendency for repeating discharge positions, suggesting preferred spots of initiation.

In a next step, the regularity of discharges in different discharge zones is compared, related to the respectively involved neighboring electrode pairs. The D5300 and edge 5.5 images in the left column of the figure (c, e) show a less regular appearance of discharges in different zones than the images in the right column (d, f), which is for example visible when comparing the upper two discharge zones in the image. For a quantitative evaluation of this effect, the illumination-intensity distribution of the shown edge 5.5 images (e, f) is averaged in horizontal direction, i.e., along the electrodes, as previously used for example in the work of Kriegseis et al. [112] (see also Section 2.3). This procedure yields the intensity profiles shown in Figure 3.4 (g) and (h) for the two electrode connection approaches, respectively. The positions of the electrodes are represented by the patches in the background of the curves using the colors introduced in Figure 2.8 for the respective electrode groups. The comparison of the two curves pronounces the irregularity of optical discharge emissions in different discharge zones for the left actuator, displayed by different peak intensity levels (g), while these occur more regular for the right actuator (h). Therefore, it can be concluded that the voltage levels are not well-balanced for the PA array on the left side of the shown figure. Note that the difference in illumination peak intensities between both cases are caused by a difference in voltage amplitudes connected to the coupling effects. For the left actuator, the maximum peak-to-peak voltages were in the range of 6.2 kV to 7.4 kV, whereas those of the right actuator ranged between 6.2 kV and 6.6 kV.

Finally, these observations are set in the context of the underlying differences between the two actuator arrays. In case of the actuator configuration shown in the left column of the figure, overlapping of tape pieces on the upper and lower side of the PET foil occurs, while this is avoided for the configuration shown in the right column. Due to careful manufacturing, major effects of the geometrical electrode positioning irregularities (as discussed in Section 3.2) are very unlikely. Furthermore, the manual adjustment of the voltages might cause an irregular plasma distribution across the array. In order to additionally rule out possible influences of such aspects, several actuators were examined in each case, for which the same correlation between electrode connection and plasma regularity was observed. It is therefore concluded that the observed asymmetric discharge distribution and coupled voltage behavior is related to an interaction of electric fields in these overlapping regions.

In summary, both tested cameras are shown to be suitable for analyzing the plasma homogeneity along the electrodes and in between different discharge zones through statistical evaluation over multiple oscillation cycles. Based on this diagnostic approach, it is demonstrated that better regularity of the plasma in-between the discharge zones of a PA array can be achieved when overlap of the electrode connections on both sides of the PET foil for the upper and lower electrodes is avoided.

4 Forcing characteristics of an oscillatory PA array in quiescent air

This chapter investigates the spatio-temporal relations between gas discharges and three-dimensional flow patterns above the PA array operated in BF mode, as motivated in the third research question. Such evaluations are based on the experimental characterization of discharge and flow properties using suitable diagnostics addressed by the second research question. In particular, combined electro-optical measurements by means of ICCD imaging are applied, allowing to relate electrical current and voltage signals to the optical discharge emissions throughout the plasma and oscillation cycle (see Section 4.2). Such analysis is complemented by a fluid-mechanical characterization of the plasma-induced velocity and acceleration fields throughout the oscillation cycle using DPTV measurement technique, which is described in Section 4.3. Finally, the optical discharge emission, transferred electrical current and resulting fluid-mechanical effect are related to evaluate the plasma-based forcing characteristics in Section 4.4. In addition, on the basis of the conducted experiments, the spatial homogeneity of discharges and forcing are evaluated as an indicator for the balance of operation voltages and manufacturing quality.

4.1 Quiescent air experimental facility

In the course of this work, a test rig for plasma-related setups without a superimposed flow is designed. It is intended to ensure both favorable measurement conditions and occupational safety with respect to ozone production and potentially involved seeding particles. Additional technical details, which extend the scope of the scientific discussions of the DPTV and ICCD measurements, are documented here for completeness.

As a basis for experimental plasma setups, an optical table with pneumatic vibration damping (M-INT3-36-8-A, *Newport Corp.*) was installed. It is employed in both studies described in this chapter and accommodated the plasma generation hardware and respective measurement setups shown in Figures 4.1 (a) and 4.9 (b). The room ventilation can be used for the entire room or connected to an extractor hood that was built for the use on the optical table, which is visible in the latter photo of the DPTV experimental setup. To ensure good accessibility for setup adjustment, it consists of a metal-profile frame and removable polymethyl methacrylate (PMMA) panels. The closed extractor hood allows to operate the measurements from inside the room, while masks with respirator filters against organic gases and particles were added for manual steps with ozone or seeding exposure, such as voltage-level adjustment for symmetric plasma (see discussion in Section 3.3). Additionally, the extractor hood represents an enclosed space which is intended to reduce the influence of external air flow in the lab on the flow measurements. In case of ICCD experiments, to avoid illumination from any external sources other than the plasma discharges, such as displays, the measurements are controlled from outside the lab, and the windows are covered with black foil from the outside and black fabric from the inside. The extractor hood is therefore not needed during these experiments.

4.2 Optical discharge characterization using intensified imaging

The present section introduces combined electro-optical measurements using ICCD imaging and electrical monitoring, as described in a previous publication [PFH⁺26]. Throughout this section, the coordinates $\hat{x}, \hat{y}$ indicate the physical position on the actuator, while x, y refer to pixel indices in the images. The experiments capture the spatio-temporal development of discharges across the array on time scales of the oscillation and plasma cycle. This enables the characterization of the highly dynamic BF concept, which is influenced by a continuously varying peak-to-peak voltage, operation just above the breakdown threshold and opposing discharges during the overlap region for duty cycles $D > 50\%$. The investigations focus on structural discharge properties and relate the optical emissions with the transferred electrical current.

4.2.1 Experimental methodology

The measurements are conducted in the quiescent air facility described in Section 4.1, providing ventilation and a vibration-damped optical table, on which all components are installed (see Figure 4.1 (a)). "The applied PA array shown in Figure 4.1 (b) comprises five upper 1-mm-wide and four lower 3-mm-wide electrodes, thus yielding eight discharge zones. [...] [The actuators are manufactured according to the routine described in Section 3.2 and operated in BF mode following the procedure described in Section 3.1 at nominal frequencies $f_{AC} = 16$ kHz and $f_{osc} = 50$ Hz with $D = 62\%$.] Kapton tape is applied to cover parts of the upper electrodes in order to define the size of the PA-discharge region, as shown in Figure 4.1 (b). In this way, the electrode length is reduced to 41 mm to match the camera FOV so that current traces feature exclusively discharges within the FOV.

[...] [The electrical measurements rely on the equipment applied in previous studies by Hehner [87].] The current signals are measured by means of a Rogowski coil due to the lack of grounded electrodes (see Ashpis et al. [10] for further explanations on the electrical signal measurements)

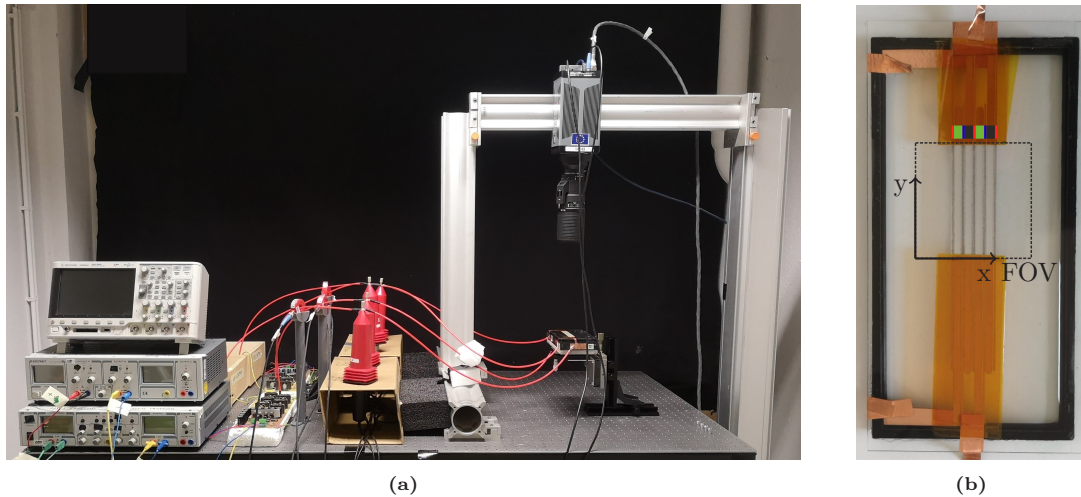


Figure 4.1: (a) Measurement setup comprising DC power supplies, HV transformers, coils for current measurements, HV probes for voltage measurement, ICCD camera and PA array. (b) Detailed view of PA array (17 mm wide $\times$ 41 mm long). The electrode horizontal positions and widths are shown by the color-coded blocks in accordance with Figure 2.8 (a). The FOV (43 mm $\times$ 43 mm) is marked by the dashed line and the coordinate axes are indicated. Reproduced from [PFH⁺26].

together with the voltage signals using an oscilloscope (not the one shown in Figure 4.1 (a); see Table 4.1). The discharge light emissions are captured using an ICCD camera equipped with a 200 mm lens and an additional teleconverter with a magnification factor of two. Note that the optical transmission of the lens limits the effective spectral range of the camera, possibly influencing the spectral representation of the plasma emissions in the images. The images of 1024×1024 pixels are taken in 16-bit resolution. For the chosen FOV of $43 \text{ mm} \times 43 \text{ mm}$ and scaling of 23.8 pixel/mm , the magnification is $M = 3.23$. All components and corresponding manufacturers are listed in Table 4.1.

Table 4.1: Components used in the ICCD experimental setup sorted by subsystems. Adapted from [PFH⁺26]

Setup component	Device and manufacturer
Plasma generation	
Function generator	Synchronizer control unit <i>ILA 5150 GmbH</i>
Power Supply	VLP-2403 Pro, VSP-2410, <i>VOLTCRAFT</i>
HV transformer	$2 \times$ Minipuls 1, $2 \times$ Minipuls 2, <i>GBS Elektronik GmbH</i>
Electric measurements	
Oscilloscope	Waverunner HRO 64Zi, <i>Teledyne LeCroy Ltd.</i> bandwidth: 400 MHz
HV probes	Pintek HVP-39pro, <i>Pintek Electronics Co., Ltd.</i> bandwidth: 50 MHz
Current transformer	Magnelab CT-C1.0 Rogowski coil, <i>Magnelab Inc.</i> bandwidth: 500 MHz
Optical measurements	
Lens	Nikkor $f = 200 \text{ mm}$, $f\# = 4$ <i>Nikon</i> and teleconverter, $M = 2$
Camera	PI-MAX [®] 4:1024 EMB, <i>Teledyne Princeton Instruments</i> photocathode: Gallium Arsenide, phosphor: P43, gain value: 800
Mechanical equipment	
Vibration damping	Optical table M-INT3 series <i>Newport Corp.</i>

The measurement data are acquired at twelve equally distributed phases of the oscillation cycle, as illustrated in the top plot of Figure 4.2. For each of the twelve samples, 21 individual measurements of $\Delta t_{\text{gw}} = 3 \mu\text{s}$ gate width are taken in direct phase sequence to cover the duration of one plasma cycle, with the gain value set to 800. Simultaneously, the current and voltage measurements are conducted with a sampling rate of 0.5 GS/s . Due to the limited number of channels of the oscilloscope, the measurement data of each sample are acquired in three repeated runs. Following this approach, the peak-to-peak voltage between the electrodes HV1 (●) and HV3 (●) ΔV_{13} , together with the according current of electrode HV1 (●) $I_{1(13)}$, the peak-to-peak voltage between the electrodes HV1 (●) and HV4 (●) ΔV_{14} , together with the according current of electrode HV1 (●) $I_{1(14)}$, and the currents of electrodes HV 1 (●) $I_{1(12)}$ and HV2 (●) $I_{2(12)}$ are measured. ICCD images are taken during all three runs." [PFH⁺26]

4.2.2 Evolution of the discharge structure throughout the plasma and oscillation cycle

"Insights into the temporal evolution of plasma-based oscillatory discharge phenomena can be gained from simultaneous electric (voltage and current) signal measurements together with the observation of light-emission characteristics during the oscillation cycle. An overview over these

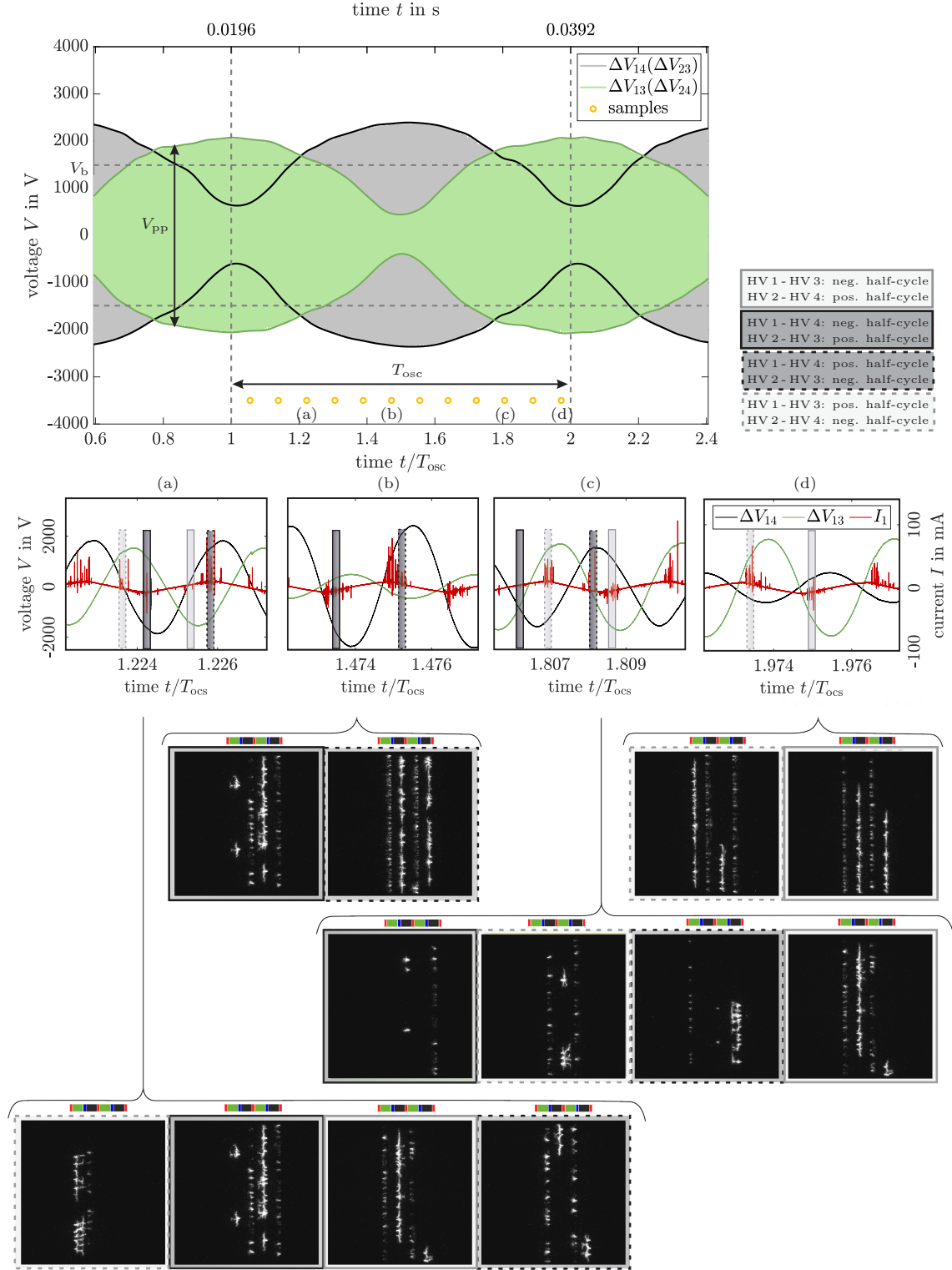


Figure 4.2: Top: Voltages between neighboring electrode pairs and peak-to-peak voltage envelope curves over time. The individual sampling points distributed over the oscillation cycle and the overlap region are marked in yellow (•). Middle: Detailed voltage and current curves of individual plasma cycles at different phases of the oscillation cycle. Bottom: Corresponding ICCD images framed by gray or black, dashed or solid lines according to the discharge pattern of the respective plasma and oscillation cycle phases. The electrode horizontal positions and widths are shown by the color-coded blocks in accordance with Figure 2.8 (a). Reproduced from [PFH⁺26].

characteristics is provided in Figure 4.2. The plot in the top shows an overview of the discharge-driving peak-to-peak voltages ΔV_{13} and ΔV_{14} , which occur between the upper HV electrode 1 (●) and the neighboring lower HV electrodes 3 (●) and 4 (●) along two oscillation cycles. Note that the envelopes of ΔV_{23} (i.e. between the upper HV electrode 2 (●)) and the lower HV electrodes 3 (●) and ΔV_{24} (i.e. between upper HV electrode 2 (●) and lower HV electrode 4 (●)), not shown, are synchronous with the envelopes of ΔV_{14} and ΔV_{13} , respectively. The signals of ΔV_{13} and ΔV_{24} , as well as ΔV_{14} and ΔV_{23} , have a phase shift of $\varphi = \pi$ as a result of the individual voltages with frequencies $f_{AC,i}$ applied to the four HV electrode groups described above.

The detailed courses of ΔV_{13} and ΔV_{14} are shown in the middle part of Figure 4.2 for the duration of approximately one single plasma cycle together with the current signal corresponding to HV electrode 1, i.e. either to discharges generated between HV electrodes 1 and 3 (● and ●, respectively) or 1 and 4 (● and ●, respectively). To characterize the discharges of a BF-operated PA at $D > 50\%$, four different characteristic phases throughout the oscillation cycle, marked (a) to (d), are considered. Two phase positions are related to the region of duty-cycle overlap of opposing discharges ((a) and (c)), whereas the other two phase positions refer to $V_{pp,max}$ ((b) and (d)), where ΔV_{14} and ΔV_{13} , respectively, accommodate a maximum. The voltage curves ΔV_{13} and ΔV_{14} reveal a shift relative to each other over the oscillation cycle. Correspondingly, in detailed view (a) (positioned in the first overlap zone at time/ $T_{osc} \approx 1.25$), ΔV_{14} is approximately $\pi/2$ ahead of ΔV_{13} , while in (c) (the second overlap zone at time/ $T_{osc} \approx 1.8$) the opposite arrangement of shifts is observed.

The lower half of Figure 4.2 shows the ICCD images of the discharges occurring at particular phase positions of the oscillation cycle and plasma cycle with increased intensity. The respectively covered period within the plasma cycle is marked by the shaded boxes with gray and black dashed and solid frames in the detailed voltage and current signals of (a) to (d). The frame color and line style match the frame box enclosing the respective ICCD image. The different line styles represent four different discharge patterns, which can be distinguished throughout the oscillation and plasma cycle according to the two forcing directions and two half-cycles, as will be discussed in detail below. The patterns are introduced in the legend right to the voltage plot in the top of Figure 4.2 and the markings will be used throughout the manuscript. Above each image, a bar with color-coded areas indicates the position of the HV electrodes 1 (●), 2 (●), 3 (●) and 4 (●) running vertically through the ICCD images, as already introduced in Figure 4.1 (b). The occurrence of discharges observed in the ICCD images can be related to captured current peaks I_1 of HV electrode 1, while dark images were taken in plasma-cycle phases that show no current peaks.

Generally, two types of gas discharges occur throughout a plasma cycle which can be distinguished according to their propagation characteristics. For the positive-going half-cycle, during which the exposed electrode represents the anode, high-intensity filaments occur. In the negative half-cycle, with the exposed electrode as cathode, the filament structures are weaker and more evenly distributed. In previous works, these discharge patterns have also been referred to as 'channels' or 'filaments' and 'diffuse' or 'uniform' (e.g. [7, 81, 174]), as well as 'streamer' and 'glow' types of discharges [20, 116]. To improve clarity across contexts, the terms positive half-cycle discharge and negative half-cycle discharge will be used throughout this work.

The presented ICCD images show both types of discharges, as is clearly visible in the enlarged image in Figure 4.3, which was added for the reader's convenience. Further, a tendency for discharges to occur repeatedly in preferential locations on the actuator over different cycles can be observed. This effect has been observed especially for lower voltage levels [93], which is the case for the BF mode. Moreover, this trend is likely connected to the actuator constructions with small

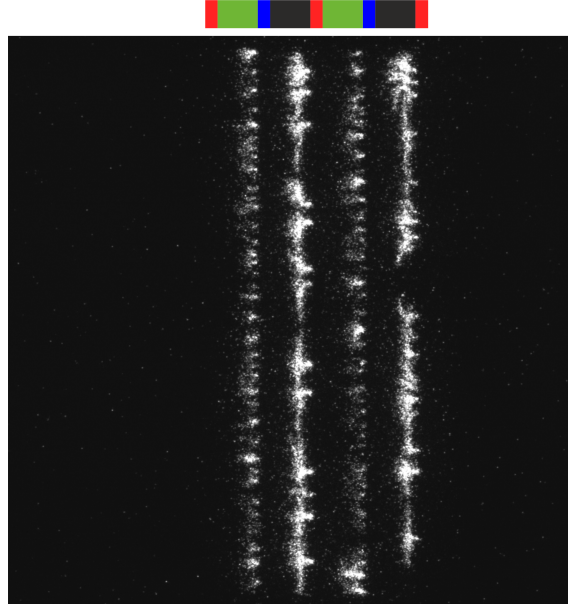


Figure 4.3: Example ICCD image capturing negative half-cycle discharge discharges between electrode group 2 (●) and 3 (●) and positive half-cycle discharge discharges between electrode group 1 (●) and 4 (●). The electrode horizontal positions and widths are shown by the color-coded blocks in accordance with Figure 2.8 (a). Reproduced from [PFH⁺26].

remaining imperfections along the electrodes, thus leading to variance in the local electric field concentration. The discharge positions and directions on the four available discharge zones of the PA vary depending on the phase of their occurrence in the discharge cycle. As such, the two images assigned to the oscillation phase (d), for example, show opposite discharge patterns of alternating positive half-cycle and negative half-cycle discharges directed to the right side. Between electrode 1 and electrode 3, positive half-cycle discharges are observed (●●, first and third discharge stripes from the left) and, at the same time, negative half-cycle discharges appear in between electrode 2 and electrode 4 (●●, second and fourth discharge stripes from the left). This characteristic of the BF operation occurs since ΔV_{13} and ΔV_{24} , and V_{14} and ΔV_{23} are by definition in counterphase (see the left image framed with a gray dashed line). Half a plasma cycle later, negative half-cycle discharges toward the right can be observed between electrode 1 and electrode 3 and positive half-cycle discharges toward the right between electrode 2 and 4 (see right image framed with gray solid line, again of case (d)). Vice versa, in case (b), the same pattern occurs for discharges propagating toward the left side, further clarifying the discharges' direction to be oscillating. Correspondingly, the images are framed with black solid and dashed lines as introduced in the legend of the figure.

During duty-cycle overlaps as for the cases (a) and (c), the afore-described four characteristic discharge patterns occur alternately, leading to opposing discharges within a plasma cycle at an accordingly high frequency. In this connection, the discharges are observed to be clearly less regular, which may indicate that they are not fully developed as peak-to-peak voltage is rather low, i.e., close to $2V_b$. This could also be related to the small time scales within which the electric fields develop. Further analysis of the occurring effects and underlying mechanisms is, though, to be carried out in future investigations on the basis of samples taken to resolve the overlap region in particular with increased temporal resolution or experiments at constant levels of V_{pp} under the absence of oscillations e.g. using the BM oscillation concept. It should be noted that the phase shift of approximately $\pi/2$ between the voltages related to opposing discharges (i.e., ΔV_{13} and ΔV_{14}) reveals another relevant characteristic of the BF operation. That is the overlap of duty cycles generating counter-directed discharges, the positive half-cycle and negative half-cycle

discharges along opposite directions occur successively and not simultaneously. Consequently, the discharges never directly oppose each other. "[PFH⁺26]

4.2.3 Relation between light emission and peak voltage amplitude

"In the following, a closer look is taken at the light-emission characteristics of positive and negative half-cycle gas discharges, and a relation to the applied peak-to-peak voltages varying throughout the oscillation cycle is established. Also, the observations will be related to earlier studies of DBDs at steady operation summarized above. In continuation of previous luminosity studies [112], therefore, the gray-scale image pixel intensity $G(x, y)$ with indices x and y (see Figure 4.1 (b)) for corresponding coordinate directions) is interpreted as a function of the spatio-temporal luminosity distribution $L(\hat{x}, \hat{y}, t)$ on the actuator surface integrated over the gate width of the ICCD camera Δt_{gw} according to

$$G(x, y) \hat{=} \int_{\Delta t_{\text{gw}}} L(\hat{x}, \hat{y}, t) dt. \quad (4.1)$$

On this basis, the mean pixel intensity profile along a horizontal pixel row, and thus across the electrode array, can be calculated as

$$G_y(x) = \frac{1}{N_y} \sum_{n=1}^{N_y} G(x, y_n), \quad (4.2)$$

where N_y is the number of considered pixel rows. For the conducted measurements, three images with 1024×1024 pixels captured at the same oscillation and plasma phase are evaluated respectively together. For each image, a profile was extracted individually along all pixel rows, yielding $N_y = 1024$, and the averages of these three profiles are calculated. The procedure is illustrated in Figure 4.4, where three ICCD images taken at the same phase are shown together with the corresponding horizontal mean intensity profile shown as gray solid line. At first glance, a common, repeating discharge pattern can be observed in all three images, whereas the instantaneous structures differ between the three images. As such, the mean intensity profiles serve as an exemplary representation of the discharge characteristics and do not show a statistically converged state.

The electrode positions are illustrated by the colored patches in the background of the graph in Figure 4.4. The four peaks of the gray solid curve result from the four discharge regions that are visible in the ICCD images. These are positioned on the right side of the upper, narrow electrodes HV1 and HV2 color-coded in red (●) and blue (●). Accordingly, the gas discharges and forcing effects are oriented toward the right. The approximate shape of observed illumination profiles with its peak value close to the upper electrode is in accordance with the observations made in previous works [7, 112, 174]. The positive half-cycle discharges can be assigned to the larger intensity peaks and the negative half-cycle discharges to the smaller peaks. This characteristic resembles the observations made by Allégraud et al. [7] for surface DBDs operated at constant peak-to-peak voltages. The gray dashed profile represents the opposite phase in the same plasma cycle, i.e., same oscillation phase. The smaller and larger peaks are reversely arranged but still on the right side of the upper electrodes due to the positive and negative half-cycle characteristics of the gas discharges discussed above.

Analogous to the use in Figure 4.2, the black intensity profiles represent the opposite oscillation phase, as illustrated in the sketch on the right side of the figure showing the peak-to-peak voltage envelope curves introduced in Figure 4.2. The respective oscillation phases considered for the shown intensity profiles are color-coded in black and gray to match the intensity profile curves. The intensity peaks of the black curves are accordingly positioned on the left side of the upper

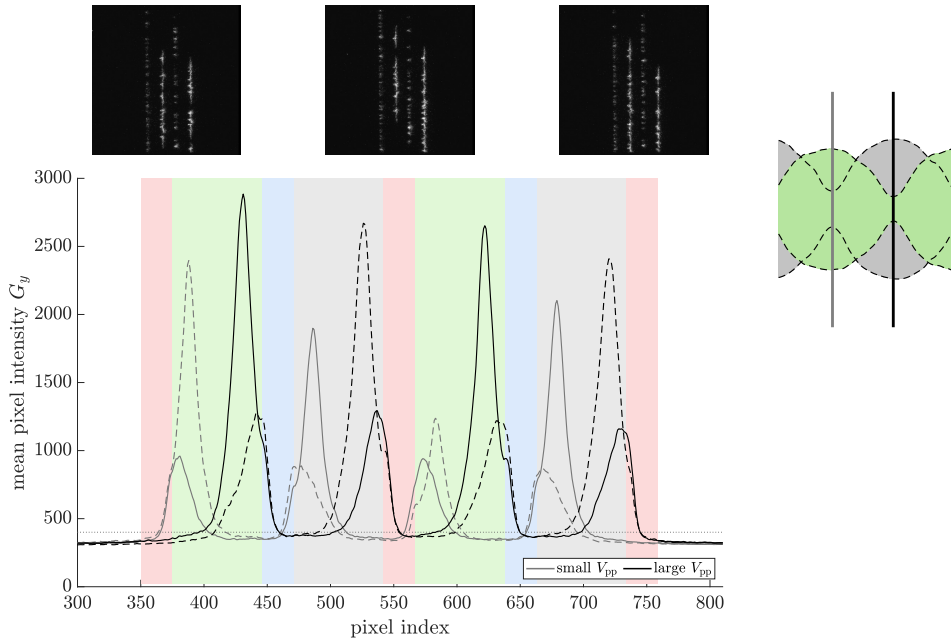


Figure 4.4: Top: Three exemplary ICCD images representing the same oscillation and plasma phase. Bottom: Horizontal mean intensity profiles of small and large peak-to-peak voltages at opposite oscillation phases (gray and black lines) and opposite plasma phases (solid and dashed lines), respectively based on three images. Color patches indicate electrode positions and horizontal dotted line marks intensity threshold for lateral discharge propagation. Plot line style indicates discharge patterns as introduced in Figure 4.2. Right: Sketch of peak-to-peak voltage envelope curves adapted from Figure 4.2 showing ΔV_{14} in gray and ΔV_{13} in green. Reproduced from [PFH⁺26].

red and blue electrodes, indicating plasma-based forcing toward the left side. Again, two opposing phases in one plasma cycle are shown, and the footprints of discharges in positive and negative half-cycles can be recognized.

The profiles show the phases of maximum light emission within the respective plasma cycle. It is therefore striking that the black curves exceed the gray curves. This effect can be related to the difference in peak-to-peak voltage values ΔV_{13} and ΔV_{14} , which are visible in the overview diagram in Figure 4.2 and imply an asymmetrical actuation character both in space and time probably occurring due to slightly unbalanced voltage settings. However, this asymmetry allows for a more rigorous analysis of the influence of the applied peak-to-peak voltage as follows.

Figure 4.5 shows the four maximum values of the intensity profile peaks and the lateral discharge propagation for the respective V_{pp} value. The plasma propagation Δx_{bf} is the lateral extension of the discharge filaments perpendicular to the electrodes averaged for three images capturing the same oscillation and plasma phase, respectively, of the BF-driven PA array. Therefore, the sections in which the light emission exceeds the average image-illumination level marked with the dotted line in Figure 4.4 are evaluated. The data are shown color-coded in gray and black and marked with a triangle for positive half-cycle discharge appearance or an asterisk in case of negative half-cycle discharge character related to the positive and negative discharge half-cycle discussed above. For a higher value of V_{pp} , larger peak values occur in the mean horizontal pixel intensity profiles for all four discharge regions (see Figure 4.5 (a)). As already discussed above, the mean intensity peaks associated with discharges of the positive plasma half-cycle systematically exceed those of the discharges in the negative half-cycle. As shown in Figure 4.5 (b), larger gas discharge propagation is observed for larger peak-to-peak voltage values, along with a trend of increased

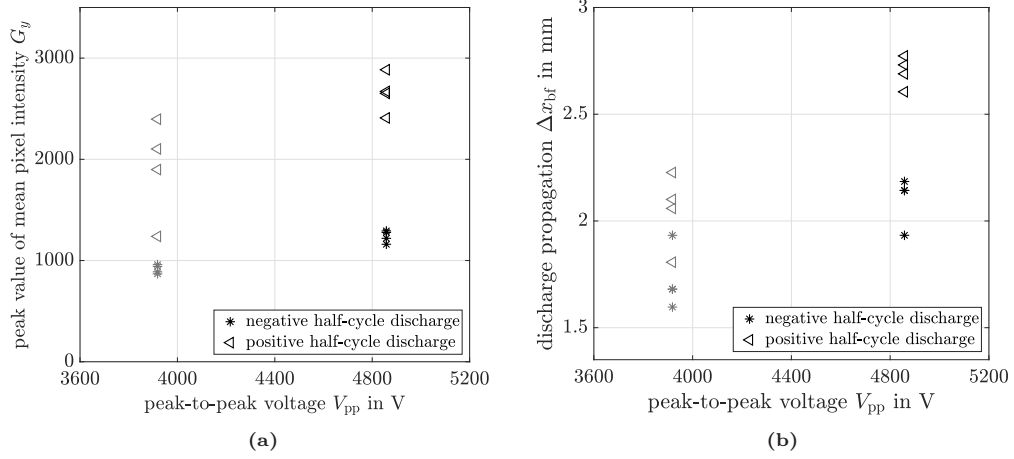


Figure 4.5: Discharge characteristics maps: (a) peak values of horizontal mean pixel intensity profiles over peak-to-peak voltage value for positive and negative half-cycle discharge states, and (b) Averaged lateral discharge propagation over peak-to-peak voltage value for positive and negative half-cycle discharge states for both forcing directions. Reproduced from [PFH⁺26]

discharge propagation for positive half-cycle discharges. This demonstrates that the observed relationship, which has been reported in previous studies on actuators in basic configurations [7, 39, 81, 112], is also evident in PA arrays with a continuously varying applied voltage at 50 Hz." [PFH⁺26]

4.2.4 Correlation of integrated light emission and transferred electrical charge

"As a next step, the electrical characteristics and discharge morphology of the observed discharges can be related due to the simultaneously conducted measurements. The mean pixel intensity can be calculated as

$$G_{xy} = \frac{1}{N_x N_y} \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} G(x_m, y_n), \quad (4.3)$$

where N_x and N_y are the number of pixel rows and columns in the considered image section. The mean background illumination $\bar{G} = 312$ is evaluated by considering only the left quarter of ICCD images without electrodes, and thus discharge occurrences. Due to the chosen procedure, the dependency of the background-illumination level on the occurrence of discharges in other sections of the image is cross-checked to confirm the robustness of the chosen value as background threshold. Therefore, mean pixel intensities in the area to the left of the electrodes is evaluated for all 756 images of which 592 are with and 164 without discharges. The background intensity is found to be approximately one count higher for the images taken while discharges occurred, and it varies up to one count for different locations of the evaluated image area, which is negligible for the here-studied effects. An expression for the integral intensity of the discharge light emission of an image is given by the sum of pixel gray-scale discharge intensities

$$\hat{G}_{\sum xy} = \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} G(x_m, y_n) - \bar{G}, \quad (4.4)$$

where the mean background intensity $\bar{G}$ is subtracted from the respective pixel intensity value to evaluate only discharge-related contributions to the gray values. The number of all image pixel rows and columns is $N_y = N_x = 1024$.

A representation of the gas discharge in the electric measurements is the transferred electric charge Q , which can be calculated from the current signal. The current signal, in turn, is composed of the current peaks associated with the discharges, a quasi-periodic base signal, which is aligned with the plasma cycle, and high-frequent random noise given by

$$I_{\text{total}}(t) = I_{\text{peak}}(t) + I_{\text{base}}(t) + I_{\text{noise}}(t). \quad (4.5)$$

Exemplary measured raw current signals are shown as red curves in the center plots in Figure 4.2 and in the left plots in Figure 4.6. The base signal is also referred to as capacitive component of the total current associated with the displacement of electric charge between the electrodes and connection cables due to the applied voltages of the alternating electric field and does not represent the gas discharges. The transferred electric charge is, in accordance with the second method applied by Allegraud et al. [7], calculated as

$$Q = \int_{\Delta t_{\text{gw}}} I_{\text{peak}}(t) dt, \quad (4.6)$$

where Δt_{gw} is the camera gate width time.

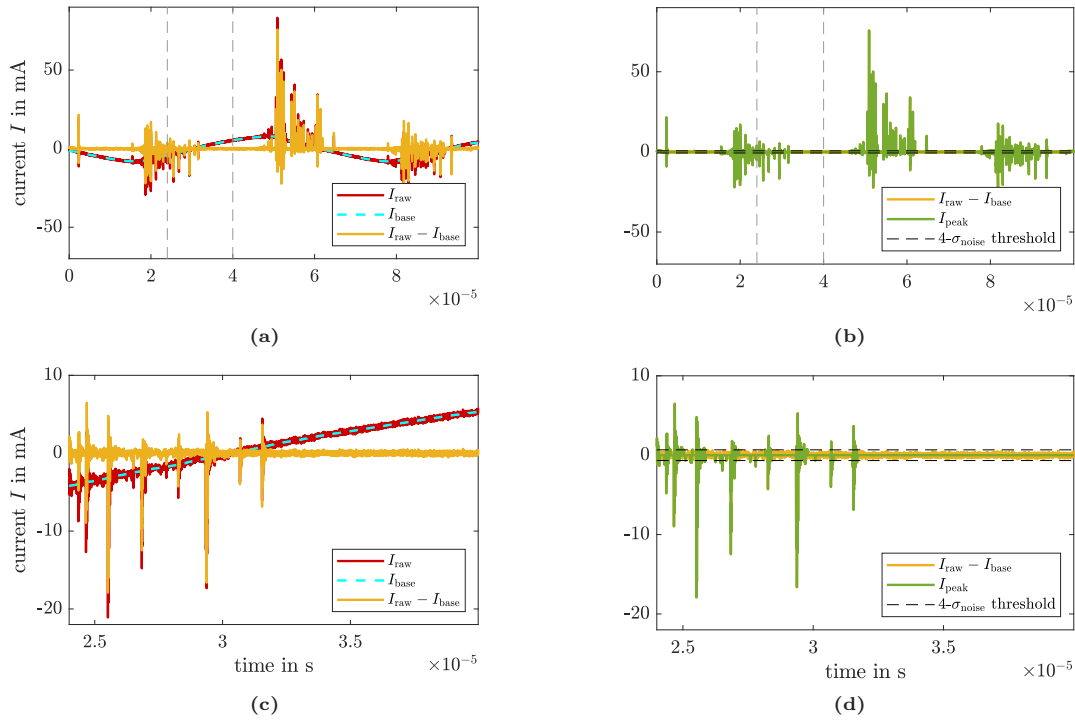


Figure 4.6: Illustration of current signal processing procedure to separate discharge-related current peaks. Top: Overview plots. Bottom: Detail plots. Reproduced from [PFH⁺26]

Accordingly, a procedure to isolate the current peaks from the raw measurement signal was developed as illustrated in Figure 4.6 for the duration of approximately one plasma cycle (see Figures 4.6 (a) and (b)) and a zoomed-in view in the range indicated by the gray dashed lines to make the course of the signal visible on a finer time scale (4.6 (c) and (d)). In a first step, a move-median filter based on 2000 consecutively measured current values is applied on the raw signal, where $I_{\text{raw}}(t) = I_{\text{total}}(t)$, to remove the high-frequent discharge peaks and noise from the signal and thus extract the base signal according to $I_{\text{filtered}}(t) = I_{\text{base}}(t) = I_{\text{raw}}(t) - (I_{\text{noise}}(t) + I_{\text{peaks}}(t))$

in accordance with Equation 4.5, as illustrated in the left plots in Figures 4.6 (a) and (c). Accordingly, subtracting the so-obtained base signal I_{base} from the raw signal I_{raw} yields the signal portion comprising current peaks and noise $I_{\text{peak}} + I_{\text{noise}}$, shown in yellow in the figures. In order to distinguish between these two proportions, the characteristic noise level of the current signal is evaluated based on a signal section without discharge events. An example for such a signal section is given between 32 μs and 45 μs in the displayed signal. Subsequently, a threshold of $\pm 4\sigma_{\text{noise}}$ with $\sigma_{\text{noise}} = 0.1686 \text{ mA}$ being the noise signal standard deviation, is applied, assuming the current peak signal I_{peak} to be zero where $I_{\text{peak}} + I_{\text{noise}}$ does not exceed the threshold value. This step prevents the current integral from increasing in the absence of discharges. The resulting current peak signal I_{peak} is illustrated in green in the plots on the right column in Figures 4.6 (b) and (d). The absolute of this signal portion is integrated over the duration of the image exposure according to Equation 4.6, yielding the cumulated charge transferred in the captured discharges.

As described above the FOV covered the entire actuator, which means that all discharges occurring on the array are visually captured. Accordingly, the electric charge transferred in all four possible discharge zones (i.e. between electrode pairs HV1 and HV3 (● and ●, respectively), HV1 and HV4 (● and ●, respectively), HV2 and HV3 (● and ●, respectively), and HV2 and HV4 (● and ●, respectively)) needs to be evaluated while avoiding to recognize individual discharges twice. Therefore, discharge peaks of the current signals of the upper electrode groups I_1 and I_2 were considered in the calculation of Q .

Figure 4.7 shows a scatter plot of the charge Q transferred in gas discharges during the 3 μs gate width of 252 individual images over the sum of their individual image discharge pixel intensities $\hat{G}_{\sum xy}$. Note that the mean background intensity is therefore subtracted from the intensity value of each pixel. This results in occasional negative discharge intensities due to statistical intensity fluctuations around the background level and the afore-mentioned bias toward slightly lower mean background intensity in images captured in the absence of discharges. As a second abscissa axis in the top, the mean image pixel intensity G_{xy} calculated based on all image pixels is added and a linear correlation fit of all displayed samples is given by the red dashed curve as a reference. A clear, approximately linear relation between transferred charge and image intensity can be observed with an R-square value of 0.934 for a linear curve fit. Accordingly, it can be assumed that a quasi-linear relation applies between transferred charge and light emission of discharges as well as a high degree of simultaneity of both characteristics smaller than the order of magnitude of the 3 μs gate width.

With regard to the early investigations by Enloe et al. [63] using a photomultiplier tube for optical measurements, enabling to temporally resolve the discharge light emissions, the present measurements represent a temporal integral of the light emissions over the ICCD-camera gate width. However, the latter measurements capture the light-emission distribution spatially (in two dimensions), whereas the photomultiplier tube signal represents a spatial integral (in zero dimensions) of the occurring discharges. As a consequence, the experiments carried out by Enloe et al. [63] allowed to relate an individual discharge peak to an optical discharge-emission peak occurring at the same time in a qualitative evaluation, while these findings can now be complemented by additional quantitative insights showing a linear relation between transferred electric charge and optical discharge emissions based on the ICCD camera measurements. Additionally, by capturing the entire PA in the ICCD camera FOV, the experiments confirm the coupled and simultaneous footprint in the electric current signal and optical emissions with guarantee of not having measured independent current peaks." [PFH⁺26]

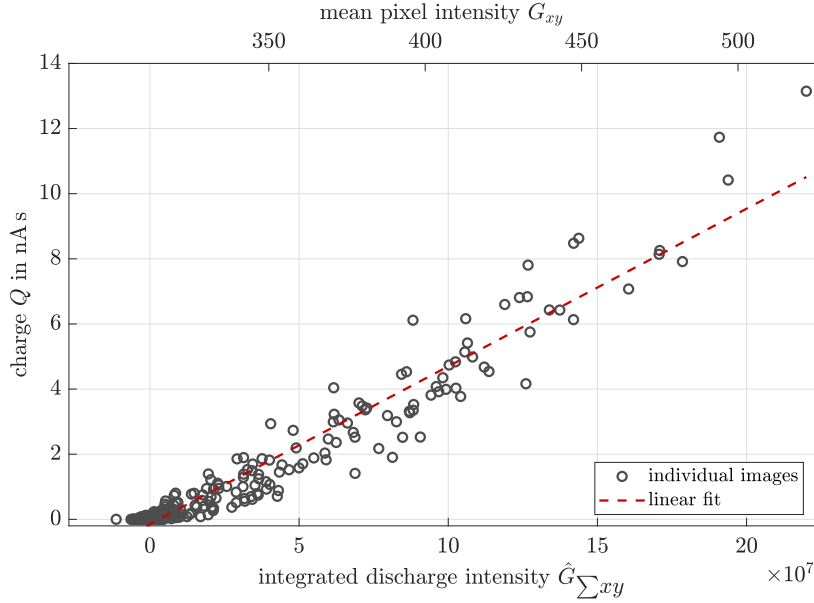


Figure 4.7: Scatter plot of plasma-transferred electric charge Q over the sum of discharge pixel intensity values $\hat{G}_{\sum xy}$ and mean pixel intensity values G_{xy} of ICCD images. Reproduced from [PFH⁺26].

4.2.5 Summary and concluding discussion

"The described results proof the suitability of the applied diagnostic methods for determining the occurring gas-discharge characteristics at different phases within an oscillation and plasma cycle. Particularly, the ICCD technology provides accessibility to the discharge phenomena on a time scale in the order magnitude of microseconds, allowing to capture phenomena that occur throughout the plasma cycle. As such, the relation between the peak-to-peak voltages applied to the electrode groups, the captured current signals, and the spatial discharge structures, or more specifically the discharge light emissions, can be investigated with the chosen measurement setup.

In the conducted study, a PA array operated in BF mode [90] was investigated, and typical discharge characteristics of the applied forcing strategy were observed throughout the oscillation cycle in order to verify whether the actuator system, comprising [...] physical PA array and [...] highly dynamic BF concept, function as intended. The temporally alternating direction of discharges required for the oscillatory forcing was assigned to the underlying electric signals, and discharge structures associated with the positive and negative plasma half-cycle were observed. Within the region of duty-cycle overlap, for which the potential differences of all neighboring HV electrodes pairs exceed V_b , insights into the presence of the opposite discharges as well as their chronological order of occurrence were achieved. Particularly, the counterplay of positive and negative half-cycle discharges was generated successively and not simultaneously. That circumstance was associated with the observed relative phase shift between the peak-to-peak voltages ΔV_{13} (and ΔV_{24}) and ΔV_{14} (and ΔV_{23}) between neighboring upper and lower HV electrode groups. A decreasing regularity of occurring discharges in the overlap region was found which might be connected to the comparatively low applied peak-to-peak voltages just above $2V_b$ or the described fast dynamics of opposing discharges. Possible relevance of these effects for the forcing performance and actuator durability are to be considered in future investigations focusing on the validation of fluid-mechanical effects and the respective drag response of the present plasma-based actuation.

The study of the optical footprint of the discharges revealed a direct response behavior of the discharges of the PA arrays to the continuously changing peak-to-peak voltages. In this context,

the lateral discharge propagation and corresponding peak luminosity increased with increasing voltage amplitudes as applied to the PA array, which is consistent with observations made for PAs in basic electrode configurations under steady operation reported in literature. The transferred charge and the spatial luminosity integral of simultaneously occurring discharge events were shown to scale approximately linear in a quantitative analysis, indicating that the light emission can provide information on the electric discharge processes without significant amounts of time lag. With regard to the findings and open questions arising from the pioneering efforts of Enloe et al. [63], the present ICCD-camera measurements confirmed earlier reports and expand the level of insight to an in-sync occurrence of optical and electric effects of the discharges from a spatial (two-dimensional) perspective capturing all occurring discharge-light emissions spatio-temporally. As a consequence of the observed effects, the optical footprint of a discharge moreover reveals implicit yet quantitative information on the electrical behavior, which can be of practical value. Particularly, the balance of the applied voltages can be estimated based on the homogeneity of luminosity, which can be advantageous for the adjustment of the applied voltage levels. In addition, it was shown that changes in transferred charge can be detected using imaging-based techniques, which can be advantageous if its derivation from electrical measurements is more complex and time-consuming. While electrical diagnostics remain essential for a detailed and quantitative discharge analysis, the presented results demonstrate that optical means can provide a powerful complementary approach. As an additional case of application, optical diagnostics offer direct access to quantities such as the spatial distribution of transferred charge in DBDs, which in turn also reveal insight into the corresponding variation of momentum-transfer locations.

The advancements discussed above also provide a solid foundation for a range of promising future investigations of the proposed flow-control concept, as well as plasma-discharge characteristics in general. While the study has shown homogeneity in the discharges across different discharge zones with respect to the applied voltage levels for most of the oscillation cycle, a broader statistical analysis, focusing on phase positions in the overlap region of the oscillation cycle and a wider range of actuation parameters, could offer further insights into the occurring effects and potential of the BF-based flow-control concept. In continuation, the corresponding fluid-mechanical response related to the plasma-based forcing can be considered together with the electrical and optical footprint of the discharges regarded in this work. Therefore, the authors rate the combined, simultaneous analysis of gas discharges with both ICCD imaging and electric discharge characteristics a promising tool especially for the development of complex actuation strategies." [PFH⁺26]

4.3 Plasma-induced flow characterization with DPTV

This section introduces DPTV measurements conducted to study plasma-induced flow structures based on a previous publication [PLLK25]. Before providing an overview of the experiments, two aspects regarding coordinate system and notation should be noted.

First, the coordinate system used in the ICCD experiments in Section 4.2 differs from that employed in the DPTV experiments in this Section. The first experiment relied on a two-dimensional imaging approach with coordinate axes defined as x and y in continuation of earlier work introducing the applied methods [112]. In contrast, the second experiment presents volumetric flow measurements and therefore adopts a three-dimensional coordinate system. Because later chapters introduce additional volumetric experiments in a turbulent channel flow, where axis definition in accordance with the work of Pope [143] is firmly established (see Section 2.1.2), the same convention is applied here to maintain consistency across all volumetric datasets. Accordingly, in this chapter x is used for the direction along the electrodes, z in lateral electrode direction, and y in wall-normal direction.

Second, to ensure a distinction between the two quantities, the mathematical symbol for the lateral extent of the body-force induced momentum transfer extracted from the particle acceleration Δz_{bf} , used in the previous publication of the DPTV experiments [PLLK25], was adjusted and is now written as $\Delta z_{a,\text{bf}}$. Δx_{bf} introduced in Section 4.2 refers to the lateral extension of the discharge-filaments optical emissions for the BF-operated array. These changes are not explicitly marked in the cited text, and the used symbols can be found in the acronyms and symbols directory.

The DPTV measurements are performed in a thin volume above a PA array operated in BF mode in otherwise quiescent air. Oscillation-cycle phase resolved, "3D3C velocity and acceleration data is extracted by introducing a continuous particle-tracking approach and an extended ex situ calibration procedure[. The latter is] based on the detection of solid particles directly applied to a wall boundary, for which no prior knowledge of the flow topology or velocity data in the direct vicinity of the wall is required. A novel method for estimating measurement uncertainty in this context is introduced, and the influencing factors are discussed from an application perspective." [PLLK25] "The tracking-based nature of the chosen measurement approach allows for a combined Lagrangian and Eulerian evaluation, enabling both the analysis of spatially resolved flow fields as well as individual particle trajectories. This dual perspective offers complementary insights into the forcing-induced flow topology and allows for the exploration of new Lagrangian viewpoints, which represents a valuable aspect of the investigation itself." [PLLK25]

4.3.1 Novel approaches for calibration and measurement uncertainty evaluation

"As described in detail in Section 2.4.2, calibration is a sensitive aspect of DPTV, and, due to the still relatively recent and specialized nature of the measurement technique, the quantification of measurement uncertainty is of particular importance. Calibration procedures and uncertainty-estimation methods for DPTV measurements applied in earlier works are mainly based on flow measurements in direct wall vicinity, which is found to be rather challenging above the PA array. Consequently, an adapted calibration procedure is implemented as an extension of an existing method, and a novel approach for a posteriori uncertainty quantification is developed for the present application. The specific limitations and introduced procedures are discussed below. Furthermore, [...] continuous i.e. time-resolved Lagrangian tracking is implemented.

The conducted experiment represents an additional benefit as a proof-of-concept experiment for future applications of DPTV for investigating the interaction of plasma-based forcing with a turbulent flow in direct wall vicinity, which has been shown to be challenging in previous works [87, PLG⁺24], as well as wall-bounded flows, wall-near flow-control applications and microfluidic flows in general." [PLLK25]

Calibration

"Following the in-situ [calibration] approach of Fuchs et al. [70], the two parameters of Equation (2.26) are found empirically in a calibration procedure based on a linear fit of detected particle displacements in the near-wall flow region, identifying the particle wall diameter representing zero displacement. Depending on the experimental setup, either information at two walls [70, 119, 120] is considered or the distance of the camera to a single wall [72, LPK23] is varied by means of traversing. Background illumination effects from flow-exposed surfaces make it difficult to detect particles and obtain reliable velocity data, particularly in the near-wall region. Applying DPTV directly above the PA array, i.e. the dielectric material and exposed silver electrodes,

therefore, requires a modified calibration approach. To overcome these challenges, the calibration is performed in a separate step using solid particles, which are directly applied to the PA-array surface. For this purpose, *Lycopodiaceae* spores are used, which are advantageous due to their known, relatively constant size of around $30\text{ }\mu\text{m}$ [80], providing an increased PI light intensity. The transferability of the calibration with spores to the measurements with the $1\text{ }\mu\text{m}$ DEHS particles is feasible, as the influence of the particle diameter on the size of the PI is negligible with sufficient defocusing. This effect is shown in Figure 4.8 (a), where the PI diameter is plotted over the distance of the particle to the focal plane for particle diameters of $1\text{ }\mu\text{m}$ and $30\text{ }\mu\text{m}$ according to Equation (2.25). The distance range considered in the calibration and the measurement are marked in the plot in gray. Instead of evaluating PI diameters representing different wall-normal positions within the measurement volume in the calibration, the camera is moved along the optical axis as performed by Fuchs et al. [72] and [LPK23], while the PA array and the laser-light volume can be kept stationary. For the measurement shown here, the respective median diameter of PIs taken at four camera positions at 0.5 mm distance from each other are evaluated to find the calibration function by means of a linear fit as shown in Figure 4.8 (b)." [PLLK25]

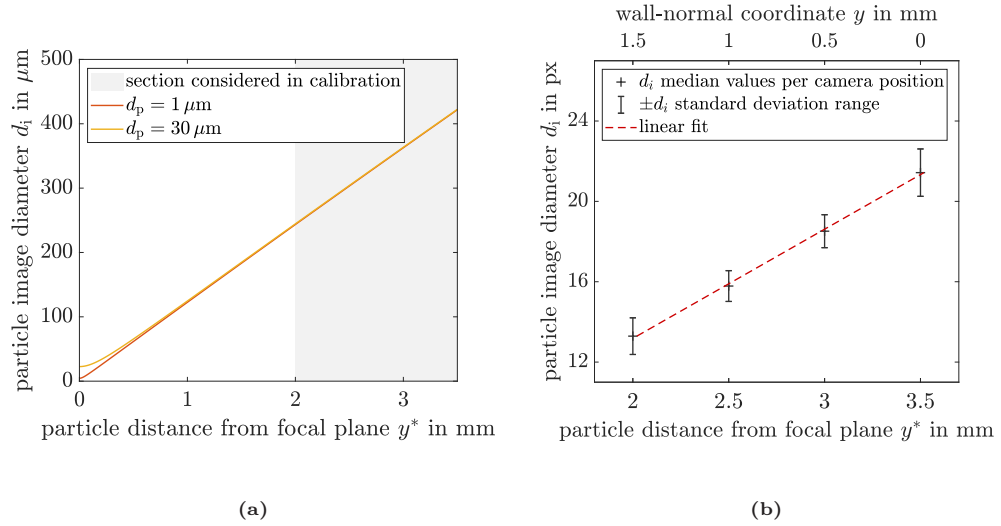


Figure 4.8: (a) PI diameter over distance of particle from focal plane according to equation introduced by Olsen and Adrian [136] for particle diameters of DEHS ($1\text{ }\mu\text{m}$) and *Lycopodiaceae* ($30\text{ }\mu\text{m}$). (b) Empirically-determined calibration curve yielding a defocus sensitivity S^y of $184\text{ }\mu\text{m}/\text{pixel}$, calibration function slope $m_d = -0.74\text{ pixel}/\text{mm}$ and $d_0 = 7.85\text{ pixel}$. Note that the ordinate axes display PI diameter in different units. Reproduced from [PLLK25].

Uncertainty evaluation

"For DPTV the spatial measurement accuracy depends on the detection of the PI diameter, in case of the out-of-plane coordinate along the optical axis, and position determination for the in-plane coordinates. Generally, a larger uncertainty is observed for the out-of-plane velocity component in previous works, see e.g. [70]. In order to evaluate the measurement uncertainty quantitatively, the deviation of observed particle movement from an expected flow behavior or a theoretical solution was evaluated by Fuchs et al. [70] and Leister et al. [119] for the measurement of planar flows. As an alternative, [120] considered the detected particle displacement at a stationary wall, where zero displacement is assumed. The latter approach can not be applied for the present measurements due to the challenges to measure in the immediate vicinity of the wall. Additionally, the flow above the PA array is characterized by forcing irregularities, such that the flow can not be assumed to be planar or follow a known profile.

An alternative procedure is therefore introduced here, based on a separate measurement in which tracer particles are tracked in quasi-quiescent air at flow velocities close to 0 m/s. The measurement uses the same setup and measurement parameters as the main measurements described later on in Section 4.3.2 without the application of forcing. Over the duration of a short measurement (see Section 4.3.4 for the parameters of the here-conducted measurements), the particle movement is approximated as a straight path. The observed deviations are expected to mainly represent particle detection inaccuracies. While residual fluctuations and random motion cannot be fully avoided, they are captured in the uncertainty estimate, which therefore represents an upper bound value. The observed low average particle velocity and homogeneous velocity distribution in the measurement volume [...] support the presented procedure. The standard deviation of in-plane and out-of-plane particle displacement is determined as an estimation for the velocity measurement uncertainty, which will be further discussed in Section 4.3.4." [PLLK25]

Lagrangian tracking

"In order to characterize the spatio-temporal [...] [forcing characteristics under consideration of] the optical and electrical footprint of the underlying plasma discharges, flow velocity and acceleration data is extracted from the measurements. For this purpose, the evaluation algorithm based on the work of Leister et al. [119] is adapted to track individual particles in multiple consecutive frames, and the used measurement equipment and procedure (see Section 4.3.2 for details) is accordingly chosen to enable time-resolved measurements. In particular, a laser with a smaller pulse intensity and a camera with lower pixel resolution were used compared to the previous work of Leister et al. [119, 120, LPK23] to enable the required increased operation frequencies at the price of reduced SNR. Consequently, continuous Lagrangian particle tracks can be detected and the fluid acceleration can be determined if two particle velocities or, respectively, three particle positions are evaluated." [PLLK25]

4.3.2 Experimental methodology

The applied PA array is fabricated following the procedure described in Section 3.2. It comprises five upper and four lower electrodes with eight discharge zones as illustrated in Figure 4.9 (a). Note that, unlike for the depicted actuator, the encapsulated electrodes are made out of copper tape for the used actuator instead of silver paint. The PA array is operated in BF mode at nominal frequencies $f_{\text{osc}} = 50 \text{ Hz}$ and $f_{\text{AC}} = 16 \text{ kHz}$ using the hardware and operational settings introduced in Section 3.1. All components used in the present experiment for plasma generation and measurements are summarized in Table 4.2.

"Voltage, current and trigger signals are captured simultaneously to the DPTV measurements, enabling the assignment of the exact phase within the plasma cycle of each measurement. The equipment for the plasma generation and the electrical measurements is accommodated on the left side of the optical table that accommodates the test rig and damps possible vibrations as shown in Figure 4.9 (b).

Figure 4.10 shows the course of measured voltages ΔV_{13} and ΔV_{14} applied to the respective electrode groups, illustrating the beat-driven oscillation of voltage amplitude introduced in the schematic in Figure 2.8. Note, that the envelope voltages ΔV_{24} and ΔV_{23} (not shown in the figure) are in phase with ΔV_{13} and ΔV_{14} , respectively. Accordingly, all particle positions along a detected three-dimensional trajectory can be assigned a phase φ between 0 and 2π within the

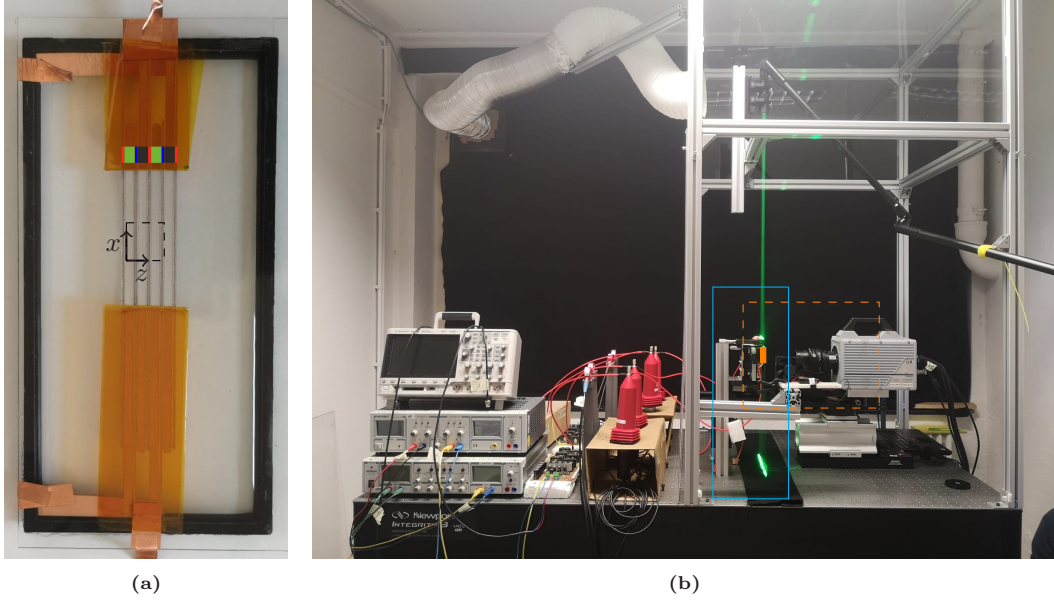


Figure 4.9: (a) Detailed view of a similar PA array. The electrodes are shown by the color-coded blocks according to Figure 2.8 and the camera FOV is marked by the dashed line. Note, that the array is mounted with the x axis oriented horizontally and the z axis vertically, so that the coordinate system is rotated in following figures. (b) Measurement setup comprising DC power supplies, HV transformers, coils for current measurements, HV probes for voltage measurement (left table side) and laser light sheet optics, camera, PA array (right table side). The small filled orange box shows the MV position and the larger dashed orange box indicates the immediately surrounding area comprising the optical components shown in the technical sketch in Figure 2.9. The framework on the right side of the table is connected to an extractor hood and can be closed with plexiglass walls. A smaller box was inserted to shield the measurement area against influence of ambient air, which is indicated by the blue box. Reproduced from [PLLK25].

forcing oscillation cycle based on their frame of detection and the simultaneously conducted electrical measurements. Due to the strict periodicity of the forcing and its synchronization with the camera acquisition, this phase assignment is repeatable across cycles. The reference phase $\varphi = 0$ is defined as the phase of minimum peak-to-peak voltage between electrode groups 1 and 3 which corresponds to the maximum peak-to-peak voltage between electrode groups 1 and 4. This enables the construction of phase-averaged velocity and acceleration fields by grouping data from multiple cycles." [PLLK25]

"The DPTV measurement setup illustrated in detail in Figure 2.9 is positioned on the right side of the optical table shown in Figure 4.9 (b) inside an extractor hood for the removal of the applied DEHS tracer particles ($1\text{ }\mu\text{m}$ diameter [149], Stokes number $Stk \approx 1,5 \times 10^{-3}$) and generated ozone. An additional, smaller PMMA box, which is not shown in the figure, with an opening on the side facing the camera is positioned around the PA to reduce the influence of external air flow in the room on the measurement results. The PA array is attached to a vertical mounting platform with precision screws for fine adjustment of the pitch angle and horizontal position. The laser beam enters the measuring chamber via a mirror arm and is expanded using light sheet optics with an 8° cylindrical lens. The resulting laser light volume is positioned parallel to the PA array, with in-plane expansion in the x and z directions being much larger than the thickness in the y direction, yielding a measurement volume size of $14\text{ mm} \times 1\text{ mm} \times 14\text{ mm}$ in x , y and z direction. A horizontal blade is inserted above the PA mounting platform and can be fine-adjusted in y direction to align the laser volume with the actuator surface.

A Nd:YLF laser with a wavelength of $\lambda = 527\text{ nm}$ and a pulse width of $< 210\text{ ns}$ is operated in double-pulse mode. To increase the illumination intensity for the measurements, both laser cavities are fired simultaneously rather than in alternating sequence at a constant pulse frequency of

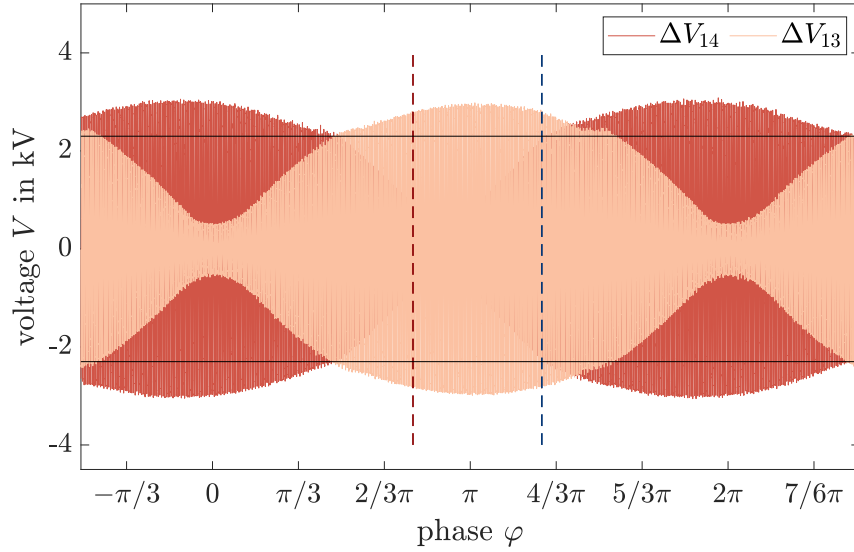


Figure 4.10: Applied voltages ΔV_{13} and ΔV_{14} between upper electrode group 1 (●) and lower electrode groups 3 (●) and 4 (●) over oscillation cycle phase φ measured during the experiment. Dashed lines mark the oscillation phases $\varphi = 0.78\pi$ (red) and $\varphi = 1.28\pi$ (blue) and black horizontal lines show the breakdown voltage. Reproduced from [PLLK25].

1837 Hz (corresponding to a pulse distance of $\Delta t = 544.270 \mu\text{s}$), resolving the oscillation cycle in 36 phases. The camera is positioned opposite the PA array using an electrical fine traverse for horizontal adjustment of the distance. An adjustment screw for the PA-array yaw orientation allows to align the actuator surface with the optical axis of the camera. The focal plane is positioned approximately 3.5 mm in front of the PA array, causing particles closer to the actuator to appear more defocused and accordingly larger. The camera (evaluated sensor section size of 512×512 pixel, 12 bit resolution) is equipped with a $f = 50 \text{ mm}$ lens at $f_{\#} = 2$ aperture, and an additional distance ring of 12 mm. The measurements are taken at a magnification of 0.74, yielding a reproduction scale of S^{xz} of $27 \mu\text{m}/\text{pixel}$. Table 4.2 provides a detailed list of model specifications and corresponding manufacturers for the used components. An additional detailed image of the PA array with measurement setup is shown in Figure 7.1 in Appendix A.

A parameter study is conducted to optimize the setup, balancing surface illumination effects due to scattering and reflections and the shielding of particle illumination near the wall. Therefore, the light sheet optics distance from the actuator in the negative z direction (and, thus, the light volume width in the measurement volume) and the y position of the blade cutting the light sheet are systematically varied. The camera-to-PA distance is maintained constant to ensure a consistent defocusing level. Additionally, the PA-array surface is coated with a thin black layer applied by a brush pen to reduce background illumination effects due to scattered and reflected laser light." [PLLK25]

4.3.3 Raw data processing routine

"Before detecting and tracking individual PIs, a pre-processing routine illustrated in Figure 4.11 is applied to enhance the SNR and reduce background illumination artifacts from dust and the borders of the upper electrodes which occur when laser light reaches the PA surface. This is caused by diffraction of the light around the knife edge, beam divergence effects and the light intensity distribution within the light volume, despite the careful adjustment of the setup components described in Section 4.3.2. First, a background image is subtracted, generated from a moving median of consecutive frames. Note that the number of frames considered is aligned with the velocity

Table 4.2: Components used in the DPTV experimental setup sorted by subsystems. Reproduced from [PLLK25].

Setup component	Device and manufacturer
Plasma generation	
Function generator	Synchronizer control unit <i>ILA 5150 GmbH</i>
Power Supply	VLP-2403 Pro, VSP-2410, <i>VOLTCRAFT</i>
HV transformer	$2 \times$ Minipuls 1, $2 \times$ Minipuls 2, <i>GBS Elektronik GmbH</i>
Electrical measurements	
Oscilloscope	Picoscope 4424, <i>Pico Technology Ltd.</i>
HV probes	Pintek HVP-39pro, <i>Pintek Electronics Co., Ltd.</i>
Current transformer	Magnelab CT-C1.0 Rogowski coil, <i>Magnelab Inc.</i>
Optical measurements	
Laser	Darwin-Duo 527-100-M <i>Quantronix Corp.</i> , energy per puls: 60 mJ
Laser beam propagation	Articulated Mirror Arm <i>ILA 5150 GmbH</i>
Light sheet optics	Standard Light Sheet Optics with cylindrical lens with effective focal length of 125 mm <i>ILA 5150 GmbH</i>
Lens	<i>Zeiss</i> $f = 50$ mm, $f^\# = 2$ and 12 mm distance ring
Camera	FASTCAM SA4, <i>Photron Deutschland GmbH</i> , pixel size: $20 \mu\text{m} \times 20 \mu\text{m}$
Seeding particles	DEHS
Seeding generator	PIVlight30 <i>PIVTEC GmbH</i>
Mechanical equipment	
Traverse system for camera	Linear Translation Stage w. Integrated Controller, Stepper Motor <i>Thorlabs, Inc.</i>
Vibration damping	Optical table M-INT3 series <i>Newport Corp.</i>

dependent particle displacement in-between frames to avoid the removal of slow particles. The so-generated background images are weighted by the instantaneous illumination level of each frame. A contrast enhancement is then applied to further improve the images.

For the flow measurements, the average PI pixel illumination is approximately 254 counts and the illumination of the brightest pixels of a PI 614 counts (12-bit depth, maximum count 4096), depending on local illumination and in-depth particle position, which was partly exceeded by the intensity of background artifacts from the electrodes. The average image intensity of an exemplary raw image for the given experimental settings was at 216 counts, resulting in a typical SNR for the brightest pixels of a PI of approximately 2.8. After applying the pre-processing, the visibility of the PIs and their contrast to the background are clearly enhanced.

As a next step, the PI positions and diameters are identified for each individual image. The procedure and implementation for the PI recognition are based on the Hough transform [95], as implemented in the MATLAB function *imfindcircles*. An example for the detected circles for two PIs is shown in Figure 4.11 (c). For the implementation of Lagrangian DPTV, a tracking algorithm for the reconstruction of particle motion across multiple frames is developed, generating trajectories of varying lengths.

Velocity values are based on the particle displacement between two consecutive frames as $\vec{u} = \Delta\vec{x}/\Delta t$. Two successive particle displacements, or correspondingly three particle positions, result in one acceleration value $\vec{a} = \Delta\vec{u}/\Delta t$. In order to assign velocity and acceleration values to a given phase within the oscillation cycle, a symmetric set of five consecutive particle positions along a time-resolved track, corresponding to four velocity and three acceleration values is used.

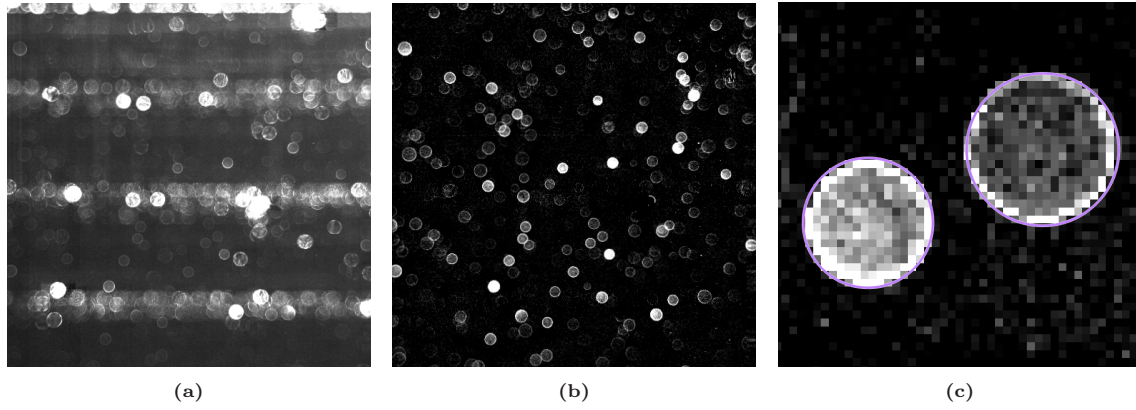


Figure 4.11: Illustration of image pre-processing and processing routine: (a) raw image, (b) image after background subtraction and contrast enhancement, (c) zoomed-in view of image section with two PIs with purple visualizes of the result of the PI recognition using the Hough transform. Reproduced from [PLLK25].

The particle recognition and tracking algorithms are based on the methods used by Leister et al. [119]. For each PI that is detected in one frame, a search is conducted in the subsequent frame within a defined maximum displacement range, similar to a nearest-neighbor approach. The expected displacement range is adjusted iteratively to the given flow and therefore chosen smaller for the quiescent air measurements than for the main experiments. If a match is found, the respective three-dimensional particle position is added to the track. The process is then repeated for the next frame. The track terminates if no suitable PI is found or if multiple potential matches are detected. The outcome of this approach is the generation of trajectories of varying lengths. The procedure is performed for all PIs in all frames, that are not assigned yet to a track starting in previous frames." [PLLK25]

4.3.4 Measurement uncertainty analysis

"As described in Section 4.3.2, a new approach has been developed to evaluate the measurement uncertainty for the present experiment. In order to reduce air movement due to the influence of ambient air, the test-rig housing is closed and then allowed to rest for several minutes before the measurements are carried out. While the procedure is found to improve the conditions for the presented uncertainty-estimation approach, perfectly still air conditions are not achievable. To acknowledge this limitation, the resulting state is referred to as quasi-quiescent air.

As shown in Figure 4.12, the particles are observed to move slowly along seemingly straight tracks in the described setting. A closer look (see detail view of exemplary track in a volume of size $0.19 \text{ mm} \times 0.35 \text{ mm} \times 0.53 \text{ mm}$ in x , y and z direction), however, reveals that the detected particle positions fluctuate along these linear paths. From the particle tracks identified in the uncertainty evaluation measurement, 70 tracks with particles detected in 50 to 100 consecutive frames are evaluated.

The mean PI displacements between two frames are found to be 0.05 pixel in negative x direction, 0.12 pixel in negative z direction and the mean PI diameter change between two frames was 0.00008 pixel. This yields an approximate absolute flow velocity of 6.4 mm/s for the reported reproduction scale S^{xz} , the defocus sensitivity S^y and the temporal delay between two consecutive frames Δt .

The measurement uncertainty is estimated based on the PI displacement and diameter change standard deviations within individual particle tracks. The evaluated mean values are $\sigma_{\Delta x, \Delta z} =$

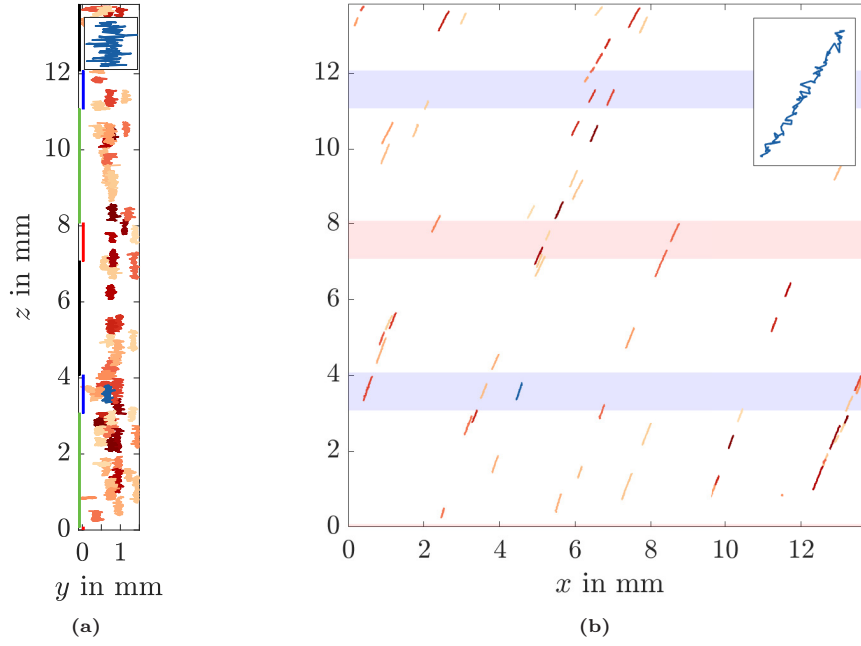


Figure 4.12: Particle tracks in almost quiescent air, (a) in y - z plane, (b) in x - z plane and zoomed-in view of particle track highlighted in blue. Colors are chosen to distinguish different tracks and indicate the information of a separate track. Electrode positions are shown for clarity, with color-coding based on electrode groups as defined in Section 2.2.3. Reproduced from [PLLK25].

0.33 pixel for in-plane PI displacements and $\sigma_{\Delta y} = 0.46$ pixel for out-of-plane PI diameter change. Based on the reproduction scale for the in-plane displacements S^{xz} and the defocus sensitivity for out-of-plane displacements S^y and the temporal delay between two consecutive frames Δt , the estimated velocity measurement uncertainty yields $\sigma_{u,w} = 0.016$ m/s for in-plane motion and $\sigma_v = 0.156$ m/s for out-of-plane motion, while the maximum flow velocities induced by the plasma-based forcing are in the order of magnitude of 1 m/s.

The estimated measurement uncertainty, especially of the out-of-plane displacement, which is reconstructed based on the change of the PI diameter, is found to be comparably large [70, 119]. However, note that different methods were used for determination, but both would tend to overestimate the measurement uncertainty, as flow-induced deviations of fluctuations and random motions cannot be entirely avoided and are included in the value.

To investigate the observed effect further, possible influencing factors and further potential are analyzed starting from the calibration curve slope, which indicates how many different out-of-plane positions can be distinguished. A given measurement volume depth Δz is represented by a range of detectable PI diameters Δd_i , where the largest possible d_i is limited by the image intensity at which PIs can still be distinguished from camera noise and be detected. This effect is a specific issue in DPTV, since the scattered light is spread over a larger area on the camera chip when defocused stronger. Accordingly, the largest, still detectable size of PIs is majorly limited due to the physical particle size and corresponding scattering properties, as well as the available laser light intensity. It further depends on the camera-specific illumination sensitivity and noise level, as well as the lens-dependent PI shape in combination with the image evaluation algorithm. On the other hand, the evaluation of smaller PI diameters is, again, limited by the detectability of the applied image evaluation algorithms, particularly the use of the Hough transform in the present measurements. Additionally, it must also be ensured that the linearization assumption for the calibration function still applies. Considering the image evaluation algorithm, the interplay of the

camera sensor physical pixel size and the image magnification is crucial for the pixel resolution of the ring-shaped PIs. Since the pixel size of 20 μm of the here-used camera is comparatively large, the brighter PI edge is represented by fewer pixels (see Figure 4.11), likely limiting the algorithm performance and PI size detection accuracy.

Consequently, several practical measures can be implemented to enhance the accuracy of DPTV measurements. Initially, the size of the measurement volume is specified by the investigated problem and the tracer particles should be sufficiently small to ensure they track the flow dynamics accurately, requiring comparably small particles for measurements in air. However, increasing the laser light intensity and applying a camera which allows for an increased sensitivity and/or SNR enhances the PI quality. A reduced camera pixel size increases resolution of PIs, providing finer information for determining their position and size when the SNR is sufficient. However, such adjustments need to be carefully balanced with the interplay of magnification, the lens-specific imaging characteristics, and the performance of the applied image-processing algorithms.

As shown below, the Lagrangian measurement data can be sorted onto a spatial grid by means of local averaging, enabling the construction of velocity and acceleration fields. This spatial organization allows the application of a different statistical approach to express the uncertainty of a bin-averaged quantity $\bar{x}$, called the standard error of the mean [9] which is given by

$$\sigma_{\bar{x}} = \sigma / \sqrt{N} \quad (4.7)$$

with standard deviation σ and sample size N . The standard error of the mean represents the uncertainty in this context because the values within each bin are derived from multiple independent samples, providing a more robust estimate of the field's statistical uncertainty.

The corresponding values for the present experiment, listed in Table 4.3, are based on a binning procedure and applied field resolutions that will be introduced later with a minimum of $N = 25$ or $N = 40$ samples per bin, respectively. The standard error of the mean for in-plane displacements $\sigma_{\Delta x, \Delta z}$ is based on the PI position uncertainty $\sigma_{\Delta x, \Delta z}$ and the reproduction scale S^{xz} . For the standard error of the mean for out-of-plane displacements $\sigma_{\Delta y}$, the out-of-plane displacement uncertainty $\sigma_{\Delta y}$ and the defocus sensitivity S^y are evaluated. It is shown that the uncertainty of the averaged quantities induced by the measurement technique is in the order of magnitude of only 1 to 20 μm for the chosen grid cell sizes specified below." [PLLK25]

Table 4.3: Standard error of the mean for in-plane and out-of-plane displacement between two consecutive frames for sample size $N = 25, 40$. Reproduced from [PLLK25].

N	$\sigma_{\Delta x, \Delta z}$ in μm	$\sigma_{\Delta y}$ in μm
25	1.78	16.93
40	1.41	13.38

4.3.5 Flow topology in particle tracks – the Lagrangian perspective

"Based on the experimental setup and methods described in the previous sections, velocity and acceleration data along individual particle tracks were detected above the PA array. In total, approximately 43 000 images representing 1200 oscillation cycles were evaluated, yielding 190 000 particle tracks. On average, 40 particles were detected in each image, yielding a PI density (also referred to as source density N_S) of 0.036 based on the ratio between the sum of PI areas and the full image area [14, 47].

It is important to note that the determined acceleration from the Lagrangian tracks represents the material acceleration experienced by the individual particles, i.e. $\vec{a} = \Delta\vec{u}/\Delta t = D\vec{u}/Dt$. If multiplied with a density ρ this term states the left-hand side of the momentum equation without any requirements of spatial derivatives for the convective term. Accordingly, the determined acceleration $\vec{a}$ automatically provides immediate insight into the sum of specific forces $\sum \vec{F}/\rho$. For the case of steady PA operation in quiescent air, this sum has been demonstrated to be predominated by the applied PA-based body force, i.e. $\sum \vec{F}/\rho \approx \vec{f}_{bf}$ [see e.g. 21, 115]. As such, the below discussion on acceleration in turn also indicates a valuable spatio-temporal footprint of the applied body force to the observed flow topology." [PLLK25]

"Figures 4.13 (a) and (b) show 500 and 3000 exemplary tracks color coded according to their local acceleration a_z in the y - z plane and x - z plane, respectively. In accordance with the expected effect of the plasma-based forcing and earlier investigations [89], the particle movement is observed to mainly occur in z direction, perpendicular to the electrodes. The figures clearly show that particles experience high acceleration close to the wall above the lower electrodes and next to the respectively involved upper electrodes, where the strongest forcing effect of the PA is located. In this context, the regions of maximum accelerations in positive and negative z direction occurring throughout the oscillation cycle, represented by the red and blue color-coding, do not perfectly overlap but are instead shifted to different z positions. The figure visualizes the local density of particle detection decreasing near the wall and especially above the upper electrodes, likely due to increasing PI size at larger distances from the focal plane and background-illumination effects especially above the exposed silver electrodes exceeding the dielectric surface. Despite this irregularity in spatial particle detection distribution, it is shown that particles were generally found over the entire measurement volume, proofing suitability of DPTV measurement technique and the chosen setup for an investigation of the plasma-induced flow directly above the wall." [PLLK25]

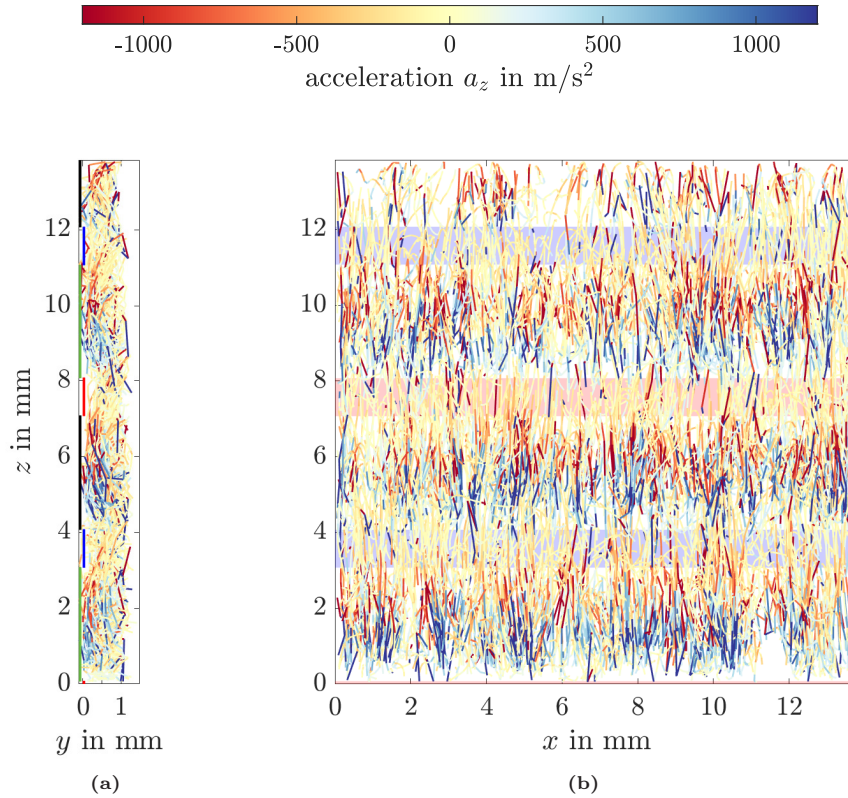


Figure 4.13: Particle tracks under oscillating forcing (a) in y - z plane, (b) in x - z plane color-coded according to their z acceleration. Electrode positions are shown for clarity, with color-coding based on electrode groups as defined in Section 2.2.3. Reproduced from [PLLK25].

In the following, a closer look is taken at the paths of individual particles. 40 tracks are considered that pass the same z position range between $z = 5$ mm and $z = 6$ mm in the chosen coordinate system during the same oscillation cycle phases $\varphi = 0.78\pi$ and $\varphi = 1.28\pi$, respectively, corresponding to phases 14 and 23 out of 36. The spatial range represents the center region above one of the encapsulated electrodes, where maximum cumulative forcing impact is expected throughout the oscillation cycle. The phases are $1/4$ of the oscillation cycle apart from each other and arranged symmetrically around the phase of maximum voltage as marked in the voltage diagram in Figure 4.10 with vertical dashed lines. The particle tracks representing these phases are shown in Figure 4.14 (a) in red and blue shades, where the intensity gradient indicates the progression of time or, correspondingly, direction of movement from light to dark. The potential differences ΔV_{13} and correspondingly also ΔV_{24} increase during phase $\varphi = 0.78\pi$, reach their maximum shortly after and decrease again during phase $\varphi = 1.28\pi$. Thus, the considered phases are associated with forcing in positive z direction. In accordance with this, it can be observed that most red particle tracks starting in phase $\varphi = 0.78\pi$ reverse from negative to positive z direction during the first frames of observation. Most particle tracks marked in blue move predominantly in positive z direction in phase $\varphi = 1.28\pi$ and the upcoming frames while a change of direction can be observed in later frames of the longest particle tracks.

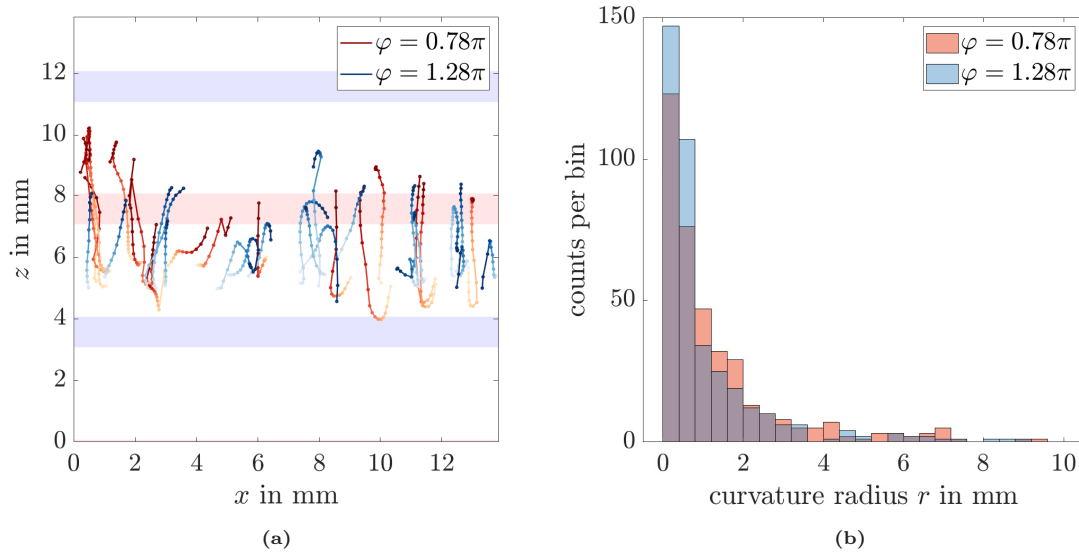


Figure 4.14: (a) Particle tracks in the x - z plane which have crossed z -positions between $z = 5$ mm and 6 mm during the same oscillation phases $\varphi = 0.78\pi$ (red) and $\varphi = 1.28\pi$ (blue). Color gradient indicates particle direction from light to dark shade of color. Electrode positions are shown for clarity, with color-coding based on electrode groups as defined in Section 2.2.3. (b) Histograms of particle track curvature radii $r = 1/\kappa$ according to Equation (4.8) in the y - z plane determined from tracks passing the same volume in oscillation phases $\varphi = 0.78\pi$ (red) and $\varphi = 1.28\pi$ (blue). Reproduced from [PLLK25].

The reversal of the direction of particle movement is often accompanied by a seemingly non-systematic lateral drift in x direction. This may indicate an instability in the movement when the z velocity component becomes very small, potentially caused by superimposed convective effects near the actuator caused by forcing distribution irregularities or wavering of the surrounding air. At the same time, most observed particles of both starting phases experience a downwards movement in negative y direction, which is not visible in the shown topview perspective.

Generally, tracks passing through the same volume during the same oscillation phase resemble each other, indicating coherent forcing-based flow behavior. However, the Lagrangian perspective allows the evaluation of individual events and their deviations, which would otherwise only occur

in statistical flow quantities. Thus, a physical interpretation of individual particle behavior and, on this basis, a distinction of flow-driven events and measurement noise are possible. [30] identify the curvature of a particle path given by

$$\kappa = \frac{1}{r} = \frac{|\vec{u} \times \vec{a}|}{|\vec{u}|^3}, \quad (4.8)$$

as one aspect for the intrinsic geometric characterization of a curve in three-dimensional space, where r is the respective curvature radius.

Figure 4.14 (b) shows histograms of respectively 400 curvature radii values observed within the considered tracks. Note that for this evaluation only the curvature in the y - z plane is considered to avoid any possible impact of the afore discussed drifts occurring in x direction. It is observed that within tracks passing the same z range at earlier oscillation cycle phase $\varphi = 0.78\pi$ (red) the radii tend to be slightly larger than for those passing at $\varphi = 1.28\pi$ (blue). The effect can be associated with the temporal evolution of vortical structures over the course of the oscillation cycle, which result from the forcing-induced motion in z direction and superimposed downward motion toward the electrodes, leading to the formation of vortical structures of varying expansion at different phases.

These results highlight the effectiveness of the Lagrangian measurement approach in accessing topological features – such as the formation of vortical structures – from spatially sparse data, where Eulerian field information would suffer from coarse spatial (discretized) resolution. Particularly, the particle track curvature provides a quantitative measure for characterizing vortical motions as a result from the PA-force. This allows individual particle tracks to be compared or grouped based on flow features, helping to organize and better understand complex flow patterns directly from the particle motion.

In summary, particle tracks are detected over the entire measurement volume, demonstrating the suitability of DPTV for near-wall flow measurements above the PA. The extracted velocity and acceleration values characterize the particle motion throughout the oscillation cycle, showing the formation of vortical structures and a spatial decoupling of acceleration zones toward both directions for the present geometrical actuator parameters. At the reversal of the forcing direction a tendency of the particles is observed to laterally drift in the x direction along the electrodes. The evaluation of Lagrangian tracks is shown to offer an analysis of individual flow events and their coherence, offering new insights for the identification and interpretation of topological features." [PLK25]

4.3.6 Flow topology in flow fields – the Eulerian perspective

"In a next step, the captured flow data is projected on a grid by calculating mean velocity values within each grid cell. The Eulerian perspective allows a statistical evaluation of the observed particle tracks in order to link the flow data to the above-mentioned electrical-optical measurements [...] [(see Section 4.2)].

The applied particle tracking algorithm requires a low particle density, yielding sparse instantaneous data. The binning is based on a phase-averaging approach aligned with the cyclic character of the oscillating flow forcing. Accordingly, all values assigned to the same grid cell and phase are averaged, resulting in near-continuous, volumetric, phase-resolved velocity and acceleration fields. As applied in the later evaluations, the spatial grid and phase resolution of the binning allow to display the measurement results from different perspectives, demonstrating the flexibility

achieved through the Lagrangian measurement approach with the measurement time and corresponding data statistics being the limiting factor. Accordingly, the local data density needs to be considered, which depends on the illumination distribution, imaging effects and the algorithm performance. As already discussed above, the statistical convergence of averaged data depends on the measurement noise as well as the deviation of occurring physical events.

First, the measurement volume is divided into 15 bins in y and 40 bins in z direction, yielding respective spatial resolutions of 0.1 mm and 0.35 mm. No partition of the measurement volume in x direction is considered, as the forcing is applied continuously along this direction. A velocity or acceleration value is assigned to a grid cell when at least 40 data points were detected in the respective cell, which is determined empirically to allow for statistical convergence of the mean values. The expected displacement uncertainty based on the measurement technique is given in Table 4.3. Figure 4.15 shows the z -component acceleration distribution in the y - z plane as contour plot and the in-plane velocity fields as vector arrows for six out of 36 phases within the oscillation cycle.

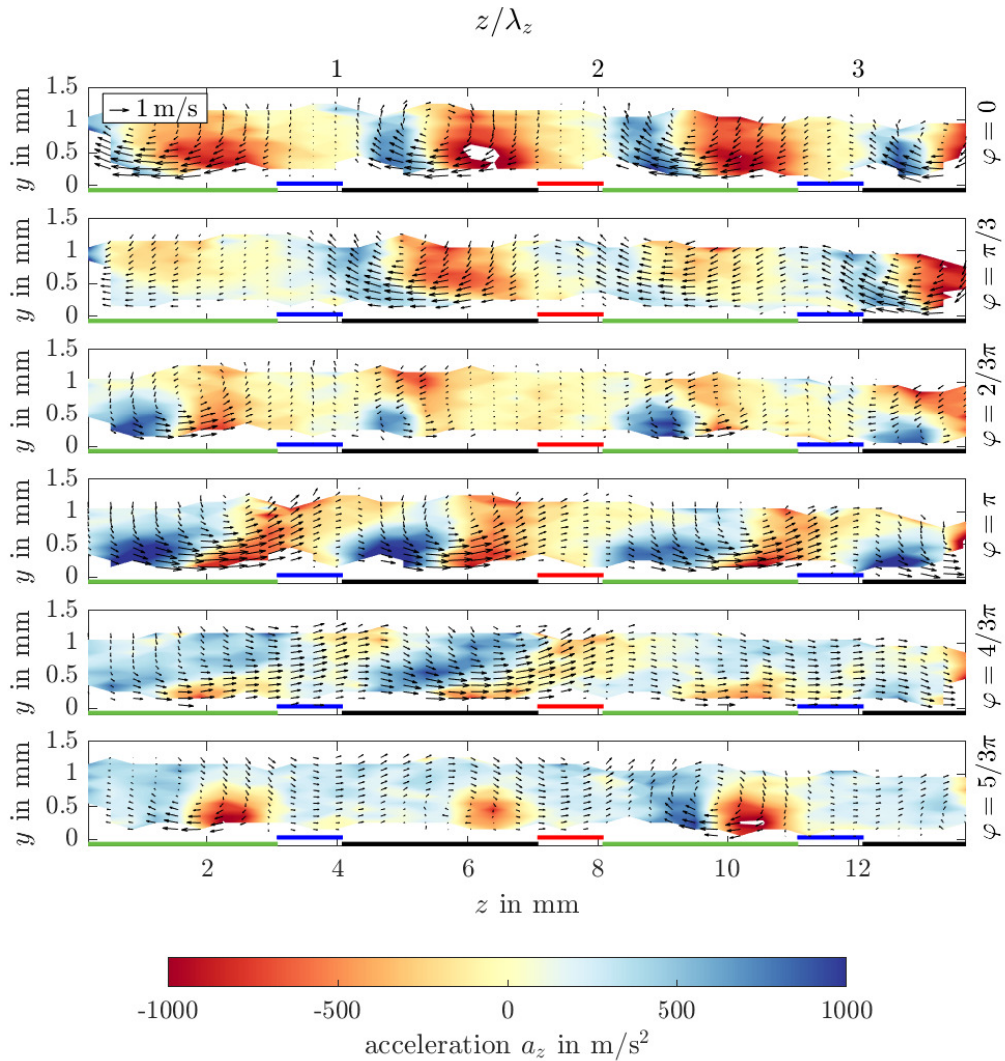


Figure 4.15: Distribution of z acceleration as surface plot and in-plane velocity as quiver plot in y - z plane for six exemplary oscillation phases. More intense shades of colors indicate higher z acceleration. Electrode positions are shown for clarity, with color-coding based on electrode groups as defined in Section 2.2.3. A scale vector representing $w = 1 \text{ m/s}$ is added as reference. Reproduced from [PLLK25].

Flow fields in the x - z plane are shown in Figure 4.16, where the same procedure is applied for a grid with 14 cells in x and z direction and a corresponding spatial resolution of approximately 1 mm in both directions. Different from the approach above, the shown flow field represents only the lower third of the measurement volume from the PA array up to 500 μm above it, as the flow field is known to deviate strongly along the wall-normal direction (see Figure 4.15). For this choice of spatial resolution the total number of grid cells increases, while less particle track data is considered in the binning. At the same time, a large velocity gradient occurs in wall-normal direction. To yield a mostly continuous flow field representing the near-wall flow layer the minimum number of values per grid cell is reduced to 25. These aspects are considered in the interpretation of the flow fields.

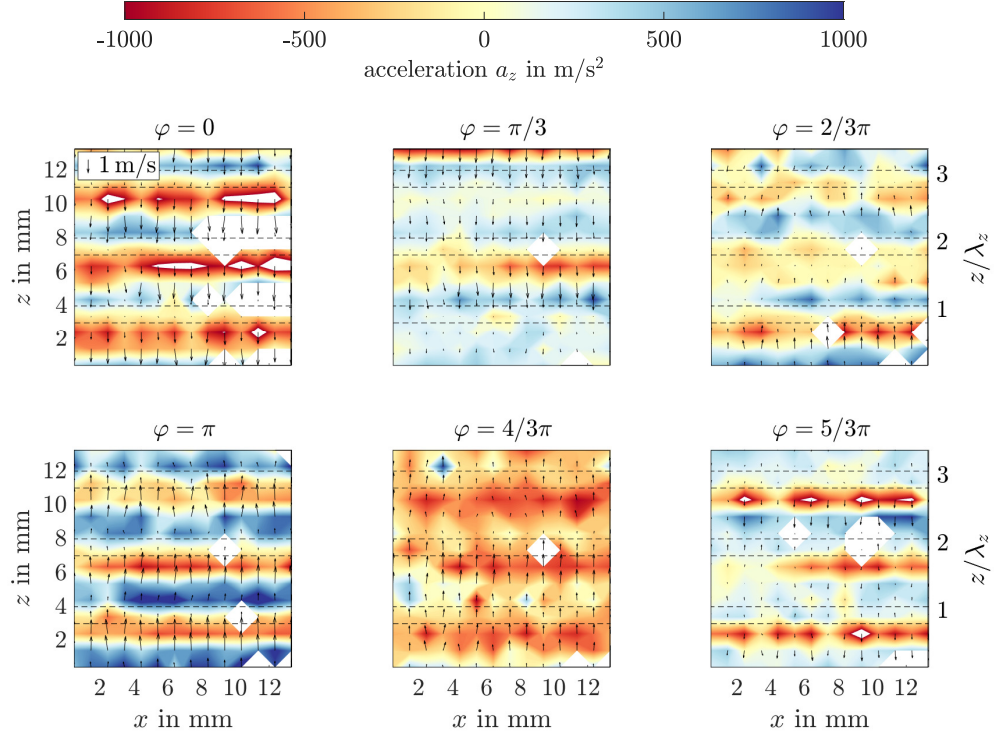


Figure 4.16: Distribution of z acceleration a_z as surface plot and in-plane velocity as quiver plot in x - z plane representing the velocity data detected in a 500 μm thick volume above the PA array for six exemplary oscillation phases. More intense shades of colors indicate higher z acceleration. Electrode positions are indicated with dashed lines for clarity. A scale vector representing $w = 1 \text{ m/s}$ is added as reference. Reproduced from [PLLK25].

The surface plots in Figure 4.15 shows that particles experience high acceleration in horizontal direction in the region above the encapsulated electrodes on the side of the respectively involved upper electrodes due to the plasma-based forcing. Subsequently, deceleration is observed further downstream along z , where the particle velocity decreases again (see phases 1 and 3 in Figures 4.15 and 4.16, respectively). The maximum occurring flow velocities are in the order of magnitude of 1 m/s, with the maximum acceleration being around 1000 m/s^2 . Over the course of one oscillation cycle, the forcing strength toward one direction can be observed to increase, e.g. between $\varphi = 2/3\pi$ and $\varphi = \pi$, and then decrease, e.g. between $\varphi = \pi$ and $\varphi = 4/3\pi$. Eventually, the forcing in opposite direction begins, as visible in phase $\varphi = 5/3\pi$ and the reverse process takes place. The velocity field that develops under the influence of the described oscillating forcing indicated by the quiver plot is predominantly horizontally oriented. The flow direction is observed to reverse shortly after the forcing direction changes. The average flow velocities in x direction in Figure 4.16 are mostly very small, indicating that the drift events at flow direction reversal in Figure 4.14

(a) cancel out statistically and do not represent dominant local flow structures. In addition to the desired horizontal flow, a downwards motion can be observed above the regions of strongest forcing, which induce the already mentioned vortical flow structures. These can be associated with a potential increase in skin friction drag, since high-momentum fluid is pulled toward the wall in these structures in a (turbulent) shear flow.

Both perspectives on the plasma-induced flow fields in Figures 4.15 and 4.16 emphasize the symmetric character of the forcing throughout the oscillation cycle. In particular, the phases opposite to each other in the oscillation cycle, separated by $\Delta\varphi = \pi$, exhibit phenomenologically similar yet oppositely oriented behavior. This indicates that the applied voltages are balanced and the actuator geometry is manufactured with sufficient precision, which are important requirements for the development of the plasma-based implementation of the oscillating wall effects. Small irregularities can for example be observed in phase $\varphi = 1/3\pi$, where the forcing effect is stronger between the electrode groups marked in red and black than those shown in green and blue. A study of forcing homogeneity along electrodes is limited by the achieved resolution in x and z direction in the context of statistical convergence of the data shown in Figure 4.16 especially near the wall for the reasons discussed above. However, some local deviations are indicated, e.g. in the acceleration field shown for phase $\varphi = 5/3\pi$ in the region of z between 5 and 7 mm.

The presented results demonstrate that phase-resolved, nearly continuous, volumetric Eulerian velocity and acceleration fields can be derived from the instantaneously, rather sparse particle tracks captured using DPTV. The spatial grid resolution can be adjusted flexibly, allowing to focus on different aspects on the flow, though it remains constrained by the statistical convergence at the available data density. It is shown that the particles experience a strong acceleration near the edge of the upper electrodes and decelerate further downstream before the subsequent upper electrode. The periodically regular formation of vortical structures, characterized by downward motion toward regions of strong forcing and upward motion thereafter, is observed. Compared to the Lagrangian perspective, the Eulerian field data offers a more statistical representation of the flow above the oscillating PA array, enabling an evaluation of the forcing regularity and homogeneity. A regular distribution of velocity and acceleration along multiple discharge zones, as well as symmetrical behavior of opposing discharge zones, is observed. Despite minor local deviations, these findings support a good balance of applied voltages for the electrode groups and sufficient manufacturing precision." [PLLK25]

4.3.7 Interplay of acceleration and velocity

"In order to investigate the spatio-temporal [...] [characteristics] of the plasma-based oscillating forcing from a quantitative perspective, the relation between velocity and acceleration fields is investigated. As a measure for the respective footprints in the flow, the mean of velocity and acceleration profiles shown in Figure 4.15 are considered in wall-normal direction up to 0.7 mm. The respective mean values over the spanwise z direction and oscillation cycle phase φ are illustrated in Figure 4.17 as surface and contour plots for velocity u_z and acceleration a_z , respectively.

The distribution of mean acceleration values over z for phases between approximately $\varphi = 0.5\pi$ and $\varphi = 1.5\pi$ shows well how the flow is accelerated by the forcing in the region next to the upper electrode in shades of blue and decelerated further downstream in positive z direction in shades of red. The z extension of high acceleration values is shown to first increase gradually over the phase and then decrease more abruptly when the forcing direction changes. The acceleration strength increases and decreases evenly over the phases with the maximum value approximately in the middle of the forcing period at potential difference peaks $\varphi = \pi$, where the applied voltage

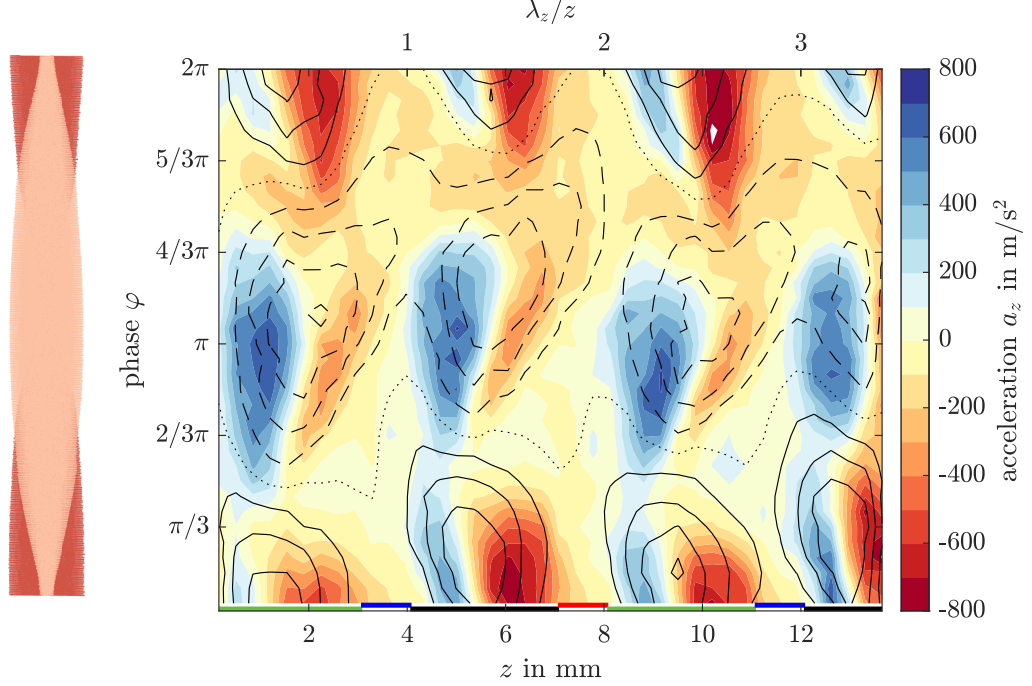


Figure 4.17: Distribution of mean z acceleration profile values as surface plot with red shades representing negative and blue positive values and mean velocity profile values as contour plot with solid lines representing negative values, dashed lines representing positive values and dotted line indicating zero over oscillation phase φ and z direction. The z velocity iso lines represent 0.25 m/s steps. Electrode positions are shown for clarity, with color-coding based on electrode groups as defined in Section 2.2.3. The voltage signals over phase from Figure 4.10 are replotted on the left for orientation. Reproduced from [PLLK25].

amplitude is at its maximum (see Figure 4.10). The mean velocity distribution reveals a similar spatio-temporal pattern as the forcing-based acceleration distribution but appears shifted in space and time. As such, the maximum mean velocity value is located approximately 1 mm downstream in z direction and $1/6\pi$ later within the oscillation cycle, being equivalent to $1/4\lambda_z$ and $1/12T_{\text{osc}}$, quantifying the convective shift and inertial delay of the flow response to local acceleration. Similar effects are observed for the opposite forcing direction across the other phases of the oscillation cycle.

The temporal evolution of the oscillatory flow pattern along z , in contrast, can be related to the rate of change of the estimated plasma length $\Delta z_{a,\text{bf}}$ [which is the momentum transfer length, see 115] on the dielectric, i.e. $\partial\Delta z_{a,\text{bf}}/\partial t$, which is known to increase with increasing voltage amplitude [20, 116]. This term corresponds to the inverse of the slope $\partial\varphi/\partial z$ in the interplay-map of Figure 4.17, which is particularly salient in the range around $\varphi = \pi$ separating the force-driven acceleration on the plasma and the drag-dominated deceleration next to the plasma. As obvious from the diagram, the sign flip between acceleration and deceleration coincides with the location of velocity peak. This spatio-temporal interplay between acceleration and velocity therefore provides evidence in the above-outlined cause-effect relation between body-force input $D\vec{u}/Dt = \vec{a} \doteq \vec{f}_{\text{bf}}$ and the flow response $\vec{u}$ during acceleration.

The evaluation described above characterizes the [...] plasma-induced oscillating forcing quantitatively by relating the flow acceleration and velocity distributions, both spatially in spanwise direction and temporally throughout the oscillation cycle. The acceleration distribution over spanwise direction and oscillation cycle peaks symmetrically at phases of maximum applied voltages while the velocity follows a similar pattern but is shifted in time and space, quantifying the transmission inertia and convection of the flow response to the applied forcing. The spanwise expansion of the region of acceleration, indicating the momentum transfer zone, increases over the course of

the oscillation half-cycles with the resulting slope in the φ - z map coinciding with the maximum of the velocity distribution, confirming the direct, causal link between body force input and resulting flow velocity." [PLLK25]

4.3.8 Summary and concluding discussion

"The DPTV measurement technique is applied to measure the periodic airflow in a wall-bounded region above a PA array using a setup with only one camera. It is shown that 3D3C velocity and acceleration data can be determined by introducing a continuous tracking approach and a novel ex situ calibration procedure based on an established method by Fuchs et al. [70], for which no prior knowledge of the flow topology or velocity data in the direct vicinity of the wall is required. For these conditions, a new procedure for the estimation of the measurement uncertainty is presented based on separate measurements in quasi-quiescent air. Since calibration and uncertainty estimation must be carried out in additional steps, the overall experimental effort increases. At the same time, the described adaptations significantly enhance the practical applicability of the measurement technique in unknown, complex flow situations. As such, great potential is shown for further studies of wall-near flow-control applications, including plasma-based approaches, and (turbulent) boundary layer flows for which the region of interest is characterized by large length-to-width aspect ratios.

The measurement uncertainty is found to be strongly influenced by the choice of setup and equipment, in interaction with the processing algorithm. A compromise was made in selecting the laser, balancing available illumination with the need for high pulse frequency for time-resolved measurements. Measurement accuracy can be improved by increasing laser-light intensity and camera sensitivity under consideration of the SNR, which improves PI quality and extends the range of usable PI diameters, thereby in turn enhancing the range of viable defocus sensitivities. Additionally, increasing pixel resolution is expected to further improve algorithm performance and reduce uncertainty.

The Lagrangian particle tracks are shown to allow an analysis of individually occurring events in the flow, as well as statistical effects based on extracted field data with flexible spatial and temporal resolution representing an additional benefit of DPTV as a volumetric, tracking-based measurement technique. On this basis, physical deviations of flow behavior and measurement noise can be distinguished, offering valuable insights into the coherence of the flow behavior over multiple oscillation cycles of the applied plasma-based forcing. In this context, a lateral drift in x direction is often detected during the reversal of the forcing direction, when the particle velocity becomes very small.

The distinct electrode positions cause a discontinuous forcing along the z direction, which is observed to induce vortical motions. Moreover, the conducted measurements reveal spatially decoupled forcing impact zones for both forcing directions, which appear to be correlated in space to the oscillatory discharge [momentum-transfer] extent $\Delta z_{a,bf}$. The forcing impact and the subsequently developing velocity fields are found to be regular between the discharge zones of the different neighboring electrode groups, indicating the applied operating voltages to be balanced across the discharge zones and the PA arrays to be manufactured with reasonable precision. However, some remaining irregularities in the distributions of velocity and acceleration uncover small effects of local forcing irregularities along the discharge zones during specific phases. Generally, the findings verify the plasma-based forcing to be capable of inducing spatially and temporally well-organized

flow responses despite the highly dynamic character in the time scales of the oscillation and therefore support the application of the used PA arrays and operation concept for further parametric studies of the drag impact in turbulent flows as a next step.

The spatio-temporal relation between acceleration and velocity is evaluated quantitatively, revealing the inertia- and convection-driven forcing [...] behavior of the PA-array. This analysis confirms the cause-effect relation between the plasma-induced body force input and the resulting flow response. Moreover, the inverse of the slope of maximum velocity $\partial\varphi/\partial z$ is identified to resemble the rate of change of spatial body-force extent, $\partial\Delta z_{a,bf}/\partial t$, leading to significant spanwise displacement of the resulting velocity peak during oscillation.

These insights lead to the conclusion that oscillation frequency and body-force magnitude appear to span a two-dimensional parameter space, which allows to control the spatio-temporally oscillatory location of maximum spanwise velocity. Despite the observed drawback of spatially interrupted forcing with PAs, this parameter space is envisioned to introduce an additional degree of freedom for the conceptualization of PA arrays and controller conception to achieve turbulent drag reduction by means of plasma-based oscillatory forcing." [PLLK25]

4.4 Connecting discussion on spatio-temporal forcing characteristics

The previous experiments describe the spatio-temporal forcing characteristics of a BF-operated PA array in quiescent environment. In particular, the ICCD-imaging study provides insights into structural and electrical discharge properties, while the DPTV experiments present complementary insights into the fluid-mechanical forcing effects manifesting in volumetric velocity and acceleration fields. The results of both experiments are linked using the oscillation cycle phase derived from the measured voltage signals.

The simultaneously conducted electro-optical measurements allow to investigate the occurring discharges on the time scales of the plasma and oscillation cycle. A linear relation between optical emissions and transferred electrical charge is confirmed. In addition, both effects are found to occur simultaneously, with the possible temporal offset of these characteristics limited to time scales $\ll 1 \mu\text{s}$. The investigations additionally demonstrate that the BF-operated PA array functions as intended by revealing the characteristic discharge structures of positive and negative plasma half-cycle over the course of the oscillation period. In particular, it is verified that the discharge characteristics immediately respond to the continuously changing level of the applied peak-to-peak voltages V_{pp} . Thus, no deviation in the behavior of the highly dynamic concept compared to steady PA operation is observed. Consistently, the lateral discharge propagation length Δx_{bf} is observed to increase for larger V_{pp} within the oscillation cycle. Furthermore, opposing discharges in the overlap region of a duty cycle $> 50\%$ occur successively and not simultaneously within individual plasma cycles related to a phase shift between respectively applied voltages.

The DPTV experiments resolve volumetric velocity and acceleration fields throughout the oscillation cycle. It is observed that the acceleration in lateral direction is at its maximum around $V_{pp,max}$ (see Figure 4.17), indicating that no temporal offset exists between the occurrence of the discharge and the forcing effect. As shown in the same figure, from the phase of directional reversal on, e.g. at $\varphi \approx 5/6\pi$, the lateral z extension affected by the body-force $\Delta z_{a,bf}$ increases over the phase until the maximum voltage $V_{pp,max}$ is reached. The observation can be related to an increase of the filament length Δx_{bf} at increasing V_{pp} observed in the ICCD measurements, indicating a spatial correlation of the optical discharge emissions and fluid-mechanical acceleration effects in

addition to their temporal simultaneity. As discussed for the DPTV experiments, the development of velocity field is influenced by convective and inertia effects, causing the maximum velocity amplitudes to occur approximately 1 mm downstream the position of maximum acceleration, and 1.67 ms or $1/12 T_{\text{osc}}$ later.

In addition, both experiments offer insights into the spatial plasma regularity on the array. The ICCD experiment captures the spatial distribution of discharges, which can be associated with the locally transferred charge. Discharges are captured repeatedly at the same distinct positions along the electrodes, introducing spatial irregularities especially in the overlap region at lower V_{pp} . The DPTV experiment also shows local irregularities of the forcing effect in the velocity fields in Figure 4.16. A direct correspondence between discharge locations and flow responses cannot be shown with the present spatial resolution of the flow measurements. Despite this limitation, the repeated observation of such irregularities indicates a deviation of the present actuation from an ideally homogeneous forcing distribution. However, the resulting velocity-field inhomogeneities are of limited magnitude, and the regularity of the plasma-induced flow field is therefore considered sufficient to support the subsequent investigations of the array interaction with a turbulent channel flow addressed in the following chapter. Furthermore, the plasma is observed to be more symmetric in-between different discharge zones in case of the DPTV measurements (see Figure 4.10), which can be associated with better voltage symmetry in comparison to the ICCD experiments (see Figure 4.2 top). This observation emphasizes the importance of precise array layout and manufacturing along with careful adjustment of operating voltages (see Chapter 3).

5 Flow interaction of an oscillating PA array with a turbulent channel flow

The turbulent channel flow is commonly employed as canonical reference case for the investigation of flow-control strategies, facilitating comparisons between actuated and non-actuated flow states across experimental and numerical studies. In this context, this chapter focuses on identifying suitable measurement techniques for the experimental characterization of the channel flow and the drag effect above a PA array for oscillatory flow forcing, addressing the second research question. Both the channel flow and the plasma-based flow-control application impose requirements on the flow-measurement technique, which are discussed in Section 2.4.1. Subsequently, the interaction of a BF-driven PA array with the turbulent channel flow is investigated in the context of the fourth research question

After introducing the experimental channel flow facility in Section 5.1, measurements conducted with a recently developed commercial LDV-PS measurement system are presented in Section 5.2. The investigations comprise measurements of statistical flow quantities in the channel and analyze the underlying signal-processing accuracy in an extended feasibility study [PLG⁺24]. The results reveal limitations in the achievable measurement accuracy at low flow velocities, thereby restricting the applicability of the sensor for the intended measurements of near-wall velocity distributions above the PA. STB represents a more proven but also more complex measurement technique, which has been previously applied for measurements in the present experimental facility. Consequently, to determine the suitability under the given specific conditions, STB measurement technique is used to investigate, first, the channel base flow above a built-in PA array without forcing operation (Section 5.3) and, subsequently, the interaction of the oscillating plasma-based forcing with the channel flow (Section 5.4) in a parametric study. Finally, different flow-measurement techniques are comparatively discussed in Section 5.5.

5.1 Channel flow facility and constructive integration of PA arrays

The present section introduces the channel-flow facility used for the LDV-PS and STB experiments, along with the constructive integration of the PA arrays into the measurement section. In addition, the applied routines for adjusting the channel drive settings for a target friction Reynolds number, as well as post-measurement refinement of friction Reynolds number and wall-position estimation based on the measurement data are described.

Channel construction and measurements

The used turbulent channel flow (see also Section 2.1.2) experimental facility at ISTM is an open-circuit blower-type wind tunnel in subsonic range. It was built as a twin to an existing channel for testing flow-control approaches for turbulent drag reduction based on measurements of the stream-wise pressure gradient (see Equation 2.8 and [84]). The static pressure along the channel directly

reveals small changes in flow resistance due to surface friction directly, while the investigation of the underlying mechanisms requires a more detailed flow analysis. Precise knowledge of flow structures and statistical flow quantities such as mean-velocity and Reynolds-stress profiles therefore provides valuable insights for the investigation of flow-control mechanisms. This motivates the experimental determination of flow fields in the turbulent channel particularly above the flow-control applications, requiring flow-measurement techniques suitable for the present channel flow operation conditions and flow-control application (see Section 2.4.1). Common optical flow-measurement techniques typically require adding seeding particles to the flow, which tend to deposit on surfaces over time. Since the first channel-flow facility relies on a highly precise geometric construction and fine pressure taps along the wall to maintain high measurement accuracy, particle contamination must be avoided. Therefore, the second twin-channel facility with similar design and the same measurement-section size was built specifically intended for the use with seeding particles in optical measurements. Note that, due the optimization of the channel design for the described pressure-drop measurements, the intended Reynolds numbers are achieved with a small channel height and high flow velocities. A small channel height, however, results in small characteristic length scales of the flow, and high velocity gradients need to be captured experimentally in flow topology studies.

The channel-flow facility is shown in Figure 5.1 and comprises the settling chamber with flow straighteners and grids and the channel section with flow tripping at the inlet. Instead of an internal drive and the nozzle shown in the rendering, the facility is equipped with an external drive during the present experiments, which is connected to the settling chamber. Seeding particles for optical measurements are added immediately after the drive to avoid any fluid-mechanical impact of the particle supply on the measurements. The channel length is 4000 mm and the channel half-height is $h = 12.6$ mm at a height-to-width aspect ratio of 1:12. Continuous steel beams serve as channel side walls, and the upper and lower walls consist of four removable segments of precision-milled aluminum plates. The plates near the outlet are modified for the respective measurement setup. In particular, an anti-reflection coated float-glass window of 11 mm diameter and 1 mm thickness is installed flat-mounted in the upper channel-wall segment centered 8.5 mm upstream the outlet (modification is not shown in Figure 5.1), serving as an optical access, and the lower channel wall is replaced by an electrically isolating PMMA plate of 15 mm thickness, which allows the installation of a PA array. A fully developed flow state was measured at the outlet for $Re_b = 3500$ for the pressure measurement channel flow facility [84], for which Re_τ can be estimated to be ≈ 220 based on the correlation by Dean [54]. Since the distance of the measurement position of the present experiments to the outlet is small in comparison to the channel length, a fully developed flow state is assumed for the considered Reynolds numbers of $Re_\tau = 250$ and 350. The channel flow facility was previously used by Hehner et al. [87] and von Deyn et al. [186] for the investigation of active and passive flow-control applications by means of stereo PIV measurements in the cross-plane of the channel.

PA integration

For the STB measurements described in Sections 5.3 and 5.4, a PA array is installed flat-mounted to the surface of the lower channel wall as shown in Figure 5.2 for one PMMA channel segment. In the following, some technical details are provided on the PA integration, which builds upon the descriptions of the array design and manufacturing in Section 3.2. A pocket is milled into the PMMA channel-wall plate to accommodate the PA with the 3D-printed frame. Additionally, a PET foil exceeding the area of actuation is used as dielectric layer between the upper and lower electrodes, which covers the entire channel-wall plate in order to avoid any additional gaps that

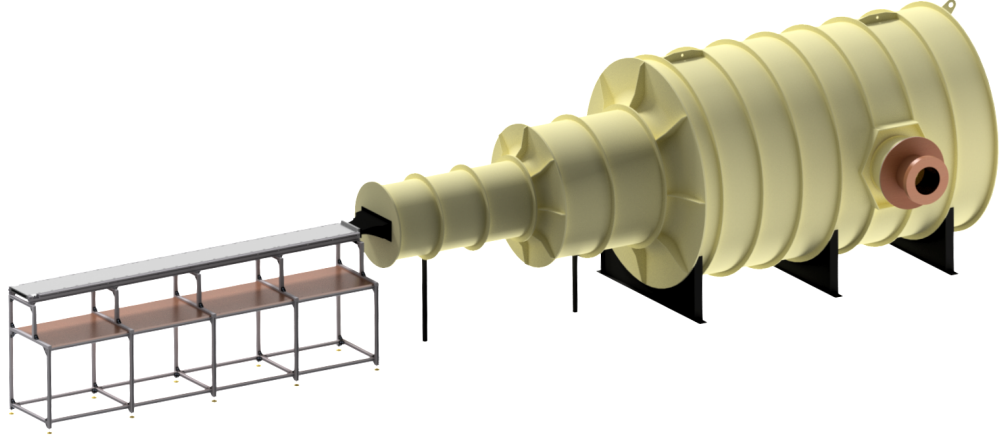


Figure 5.1: Model rendering of channel flow facility for optical flow measurements at ISTM comprising channel test section and settling chamber.



Figure 5.2: PA array integrated in channel wall plate with silver electrodes and copper electrode connections. The wide copper stripes connect the lower electrode groups and the narrow copper stripes the upper two electrode groups to the channel segment front edge.

could represent a fluid-mechanical obstacle to the flow. The edges of the PET foil are attached to the channel segment using strong double-sided adhesive tape. The electrodes are made out of a thin layer of conductive silver paint that is applied with an airbrush pistol, which minimizes the thickness of the the upper electrodes exposed to the channel flow and reduces their geometric interaction with the flow. The electrical connections of the lower electrode groups are implemented by means of adhesive copper-foil strips running on the backside of the PET-foil toward the segment front edge, i.e., lower edge in the figure. As visible in the bottom center of the figure, additional thinner stripes of adhesive copper tape are used on the PA surface to extend the upper electrodes in downstream direction to the channel section front edge for electrical connection. Finally, the electrode groups are connected to the electrical components providing the voltage signals for the plasma generation using adhesive copper tape and wires (see the photo in Figure 7.2 (b) for details). Black color is applied with a marker pen to the spaces between the exposed electrodes for the STB measurements to reduce effects of surface scattering and reflections (not shown in Figure 5.2).

To position the actuator array in streamwise x direction under the optical access window and relative to the stationary measurement setups, the channel-wall plate is moved to different downstream positions by inserting additional smaller channel-wall segments upstream the last channel segment. The concept is described in detail in the work of Hehner [87]. Furthermore, the electrodes of the

array are carefully adjusted with flow direction to ensure for the intended spatial orientation of the induced forcing in spanwise direction.

Routine for setting the channel-flow operation at targeted Reynolds number

Prior to conducting the experiments, the frequency of the external drive of the channel flow facility needs to be set to match the target friction Reynolds number Re_τ (see parameters in Table 5.2 for STB measurements). In a first step, the centerline velocity u_{cl} for the respective friction Reynolds number is estimated based on physical equations and empirical correlations using the first Matlab script in Appendix B. The procedure is briefly described in the following. Specifically, τ_w is computed for the target Re_τ considering the channel half-height $h = 12.6$ mm and reference values for air viscosity and density at the approximate experiment air temperature. Further, the definition of the bulk Reynolds number and skin-friction coefficient (see Equations 2.6 and 2.11) are applied together with the correlation

$$C_f = 0.073 Re_b^{-0.25}, \quad (5.1)$$

by Dean [54] to relate the friction Reynolds number and a bulk velocity u_b . Finally, a matching centerline velocity can be calculated as

$$u_{cl} \approx 2.4u_\tau + u_b \quad (5.2)$$

based on integrating the velocity defect law (see Equation 2.18 with $B_1 = 0$ for consistency at $y = h$) over the channel height [143].

In the second step, a Prandtl tube is used to evaluate the dynamic pressure as the difference between stagnation pressure p_s and static pressure p_0 in the channel center shortly before the outlet where the measurements are conducted. Based on these measurements, the centerline velocity is calculated as

$$u_{cl} = \sqrt{2(p_s - p_0)/\rho}. \quad (5.3)$$

The drive frequency is gradually adjusted until it approximately matches the calculated target centerline velocity.

Routine for estimating the Reynolds number and wall position from measurement data

Validating the measurement results against DNS reference data requires the conversion into non-dimensional viscous units based on viscous flow scales (see Equations 2.12 to 2.14), as well as knowledge of the exact position of the flow-adjacent wall. Since Re_τ is set using the correlation-based procedure described above and the drive frequency can only be adjusted in discrete steps, a finer a posteriori estimation of the viscous flow scales is conducted based on the measurement data itself. Among other methods discussed in Section 2.1.3, this can be achieved through a comparison of the measured mean velocity profile with a composite reference profile. In the present work, a fitting procedure based on the formulation by Luchini [125] is applied to simultaneously refine the wall position and friction Reynolds number Re_τ . The Matlab function implementing this procedure developed for the present study is included in Appendix B, and the procedure is briefly outlined in the following.

The mean velocity profile extracted from measurement data is shifted in wall-normal direction and transformed into viscous units for different combinations of wall-offset values and Re_τ to optimize

these two in a combined manner. The latter step is, again based on the channel half-height $h = 12.6\text{ mm}$ and reference values for air viscosity and density at the approximate experiment air temperature. The best combination of values is found as the minimum cumulated difference between the measured profile and the reference profile calculated with the approach described by Luchini [125] by means of a least-square fit. For the STB experiments, the method was modified by weighting the wall-near samples more than those in the region farther away from the wall. The applied method for the determination of the viscous scales does not require the measurement of the mean flow velocity gradient in the viscous sublayer region. Note, however, that the procedure can only be applied for the base flow without flow manipulation, since it relies on the profile reference.

5.2 Channel base flow characterization with LDV-PS

The present section presents measurements with an LDV-PS system in a turbulent channel flow based on a previous publication [PLG⁺24]. For maintaining consistency throughout the thesis manuscript, some of the mathematical symbols have been adjusted. In particular, the centerline velocity is written as u_{cl} , the mean velocity profile in wall-normal direction as $\bar{u}$ and the Reynolds stresses as u'_{rms} . These changes are not explicitly marked in the cited text and the used symbols can be found in the acronyms and symbols directory.

A recently developed, commercial LDV-PS system is employed to measure a turbulent channel flow without the application of plasma-based forcing, in order to assess its feasibility. "Additionally, the measurement and signal-processing accuracies of velocity and location are evaluated for various tracer-object sizes and velocities [in a separate experiment]. On this basis, the turbulent channel-flow measurements are evaluated and compared to reference data from DNS. Thus, potentials of the LDV-PS are investigated for different regions of the flow and various data processing routines as well as the experimental practice are discussed from an application perspective." [PLG⁺24]

5.2.1 Experimental methodology

This section introduces two experimental setups and procedures employing the LDV-PS system. "The commercial LDV-PS used in this work combines all laser light sources, optical components and the photo multiplier detecting backwards-scattered light in one device, as shown in Figure 5.4 and 5.5. Accordingly, an optical access in one dimension is sufficient and the measurement unit can be traversed without the need to readjust individual components, making an extend FOV larger than the measurement volume length accessible at moderate effort. The measurement volume length is specified as about $500\text{ }\mu\text{m}$ to $3000\text{ }\mu\text{m}$ by the manufacturer depending for the focal length, i.e. 500 to $1000\text{ }\mu\text{m}$ for the here-used system." [PLG⁺24]

Setup of the turbulent channel-flow measurements

The LDV-PS is positioned above the optical access window, entering the "measurement domain 100 mm upstream the channel outlet [...] [from above, as shown in Figure 5.3. T]he measurement system and corresponding fringe patterns are oriented to measure the wall normal profile of the main velocity component, i.e. $u(y)$. To avoid [scattering and] reflection issues at the lower wall, the sensor is furthermore tilted by $\alpha = 20^\circ$ around the x axis as shown in Figure 5.4 and the measured position values y' are subsequently corrected by means of trigonometric relations to determine y . In the channel flow, the measurement volume is traversed in $500\text{ }\mu\text{m}$ steps [in y' direction] to capture

the velocity profile continuously in the lower channel half and the measurements are conducted through the transparent top wall in the lower half of the cross section.

The y -value measurement range per measurement volume location is limited to $2000\text{ }\mu\text{m}$ within each individual measurement to limit the increasing measurement uncertainty at increasing distance from the measurement volume center. The [...] sampling frequency is chosen to 100 MHz with a sample number of 2048 for the velocity [FFT] evaluation of the individual burst-event [scattered light] signals." [PLG⁺24]

The LDV-PS measurements in the turbulent channel flow were conducted at a Reynolds number of $Re_\tau = 350$. Thus, the centerline velocity is $u_{cl} \approx 8.4\text{ m/s}$ and the height of the viscous sublayer, resembling a wall distance of $y^+ = 5$ is $180\text{ }\mu\text{m}$ in physical coordinates.



Figure 5.3: Model rendering of channel flow measuring section with LDV-PS measurement setup near the outlet.

Setup of the wire characterization experiment

"The characterization experiment is conducted on a modified existing test rig for clutch-flow investigations [see 119, LPK22, for rig details] equipped with a precise [...] [Nanotec Electronic GmbH & Co. KG] ST11018L8004 stepping motor. Wires of $5\text{ }\mu\text{m}$, $10\text{ }\mu\text{m}$, $13\text{ }\mu\text{m}$, $20\text{ }\mu\text{m}$, $40\text{ }\mu\text{m}$ and

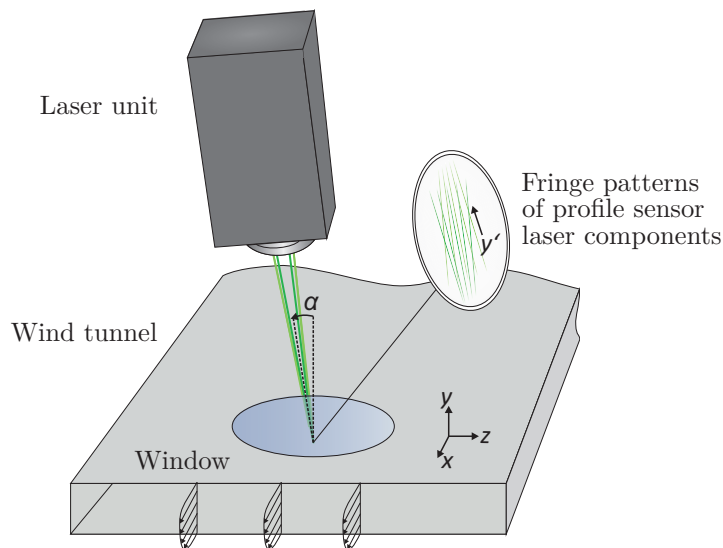


Figure 5.4: Experimental Setup: LDV-PS on top of the wind tunnel, only the laser beam pairs of the LDV-PS are displayed. The detailed view shows convergently-divergently oriented interference fringes that form in the measurement volume in the $x - y$ plane. Reproduced from [PLG⁺24].

80 μm diameter are attached radially along the perimeter of a 3D-printed circular frame, which is mounted on the test rig to ensure a constant and identical circumferential velocity $u_\phi = \Omega r$ for all wires at the investigated angular speeds Ω ; see Figure 5.5. Tungsten wires are used for the study, as these wires are available across a wide range of small diameters with a good geometrical accuracy of $\pm 10\%$ down to the size range of seeding particles. A light barrier sensor ([SICK AG] WL100L-F2231) enables the retro-active determination of the rotation angle to distinguish the measurement data of the individual wires and thus allocate the recorded Doppler bursts to the respective wire diameters. As the frame radius is large compared to the size of the measurement volume, the trajectory of the wires through the measurement volume is approximated as linear. The sensor faces the wire frame, and is operated at a 5 MHz Bragg shift and tilted toward the axis of rotation for reflection prevention.

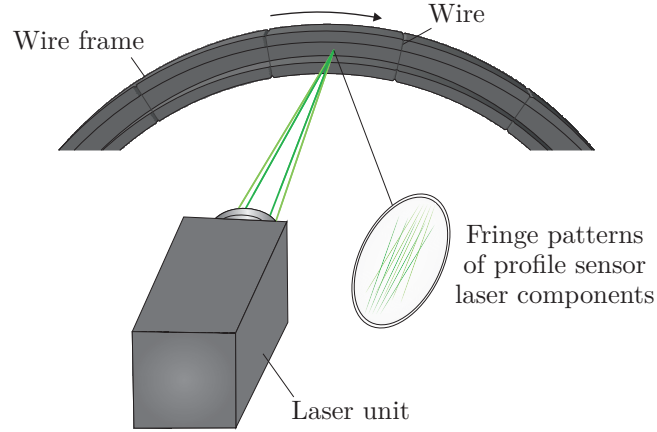


Figure 5.5: Experimental Setup: LDV-PS facing the rotating wire frame, only the laser beam pairs of the LDV-PS are displayed. The detailed view shows convergently-divergently oriented interference fringes. Reproduced from [PLG⁺24].

The theoretically derived expressions for the quantities in Equations 2.28 and 2.29 imply an influence of the relative frequency uncertainty of a burst signal evaluation. Therefore, the sample rate and sample number of the FFT [determining the scattered light signal frequencies] are varied systematically in coordination with four different angular velocities Ω as listed in Table 5.1 and illustrated in Figure 5.6. FFT sample rate and sample number are defined as constant values for each individual measurement in the *ILA R&D* LDV-software. For the first investigated acquisition mode, the acquisition rate and number of samples used for the FFT is held constant as indicated in the upper part of Figure 5.6. This acquisition mode is especially advantageous, when the velocities of the investigated flow field are unknown. Furthermore, the measurement effort is comparatively small as all data can be acquired straight forwardly with the same set of parameters in one individual run. Then, for the second acquisition mode, the sample number per burst is kept constant and the sample rate is adjusted accordingly to record the constant number of samples across the same period length of a burst independent of the wire velocities; see lower part of Figure 5.6. It is worth to mention that for this latter acquisition case the settings have to be adjusted to the measured velocity level, which makes flow measurements of velocity gradients and turbulent fluctuations more complex." [PLG⁺24]

Table 5.1: Acquisition settings of the individual measurements; reference case appears in **bold** font. The sample number was 2048 for all shown cases. Reproduced from [PLG⁺24].

Rotation frequency [Hz]	Velocity [m/s]	Sample rate [MHz]
1	0.55	50
		25
2	1.1	50
4	2.2	50
		100
8	4.4	50
		130*

* chosen value (below the desired $4 \times 50 = 200$ MHz) due to hardware limitation of the applied sensor

5.2.2 Raw data and processing routine

In this section, the measurement data of the turbulent channel flow is presented, focusing "on the chosen post-processing routines for the scattered data. This comparative discussion on appropriate post-processing strategies rises further, more measurement-scientific, questions, which are particularly addressed in Section 5.2.3. In a final step, on basis of the insights derived from the characterization study, the experimentally obtained channel flow data set is further evaluated in Section 5.2.4 by means of a comparison to reference DNS data.

Figure 5.7 shows a scatter plot of velocity and position of approximately 624 000 particle bursts that were detected in the lower channel half with the settings described in Section 5.2.1. The alternation of lighter and darker shades in the diagram refer to each of the measurement series obtained at different traverse positions of the sensor, and thus of the measurement volume. The black asterisk indicates the channel half-height position and velocity, estimated as the maximum velocity from averaged measured velocity values in y -position bins in the central channel region. At small flow velocities, an increased scatter of measured values can be observed. The scattering of position values is limited to the maximum measurement range of $2000 \mu\text{m}$, corresponding to approximately four times the measurement volume length. A small amount of approximately 500

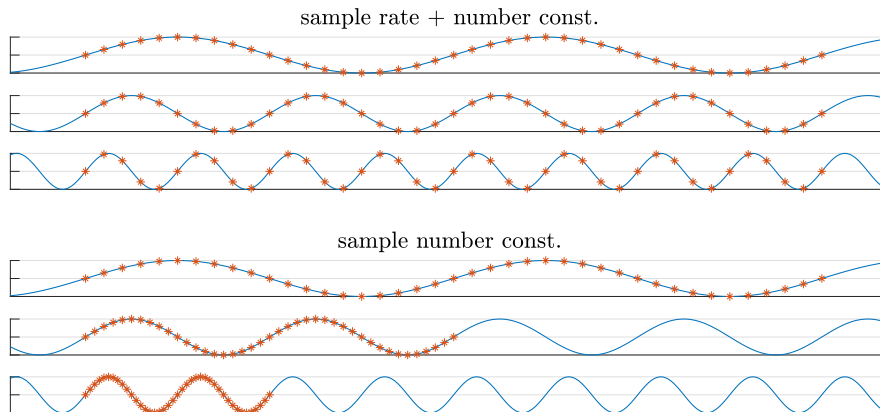


Figure 5.6: Investigated acquisition modes of the characterization experiment. Upper part: sample rate and sample number remain constant for all investigated velocities; lower part: sample number remains constant, sample rate is adjusted to maintain identical sample numbers per burst for all investigated velocities. Reproduced from [PLG⁺24].

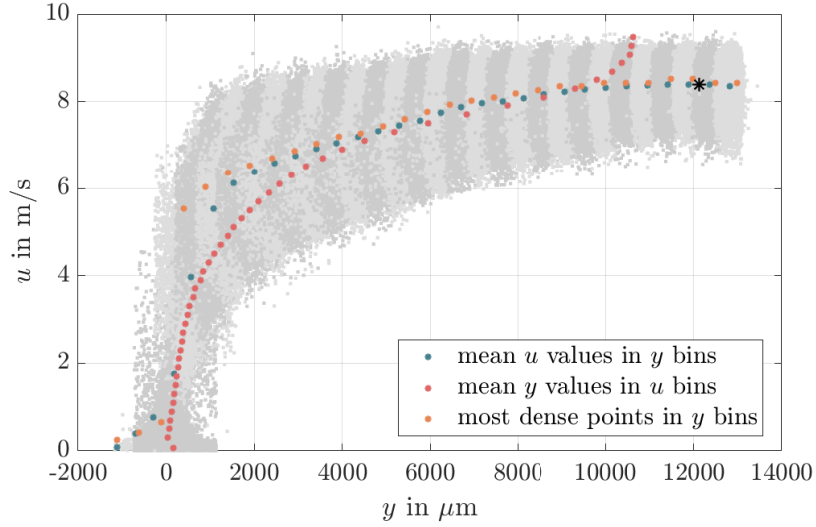


Figure 5.7: Velocity and position values of the bursts registered in the turbulent channel flow ($\bullet$) and different data averaging approaches ($\bullet$ $\bullet$ $\bullet$). Reproduced from [PLG⁺24].

bursts is registered with small negative velocities up to 0.03 m/s, which are expected in the viscous sublayer [121].

In order to achieve mean velocity profiles $\bar{u}(y)$ from the recorded scattered data, different post-processing routines have been suggested for LDV-PS measurements in the literature. Shirai et al. [171] used the averaged position and velocity of 200 neighboring particle bursts, while Neumann et al. [133] applied a so-called slotting technique to reveal spatially down-sampled gridded data from the LDV-PS raw data. This slotting has been applied by Burgmann et al. [33], who averaged the velocity values of bursts within the same 10 μm -range of detected y -positions. In an attempt to advance beyond the prescribed limits of the evaluated bins, Strauch et al. [175] proposed a post-processing routine based on the evaluation of most dense points in the velocity profile data. The maximum of the density distribution of measured velocity and position values was then evaluated within position bins.

The results of the latter two approaches are shown superimposed to the raw data in Figure 5.7, where the averaged velocity values across 470 μm -wide y bins ($\bullet$) and most dense points together with averaged position values corresponding to 0.2 m/s-wide velocity bins ($\bullet$) [are plotted]. In an additional approach tested by Fuchs et al. [72] the respective average y locations within velocity bins are analyzed, which is additionally shown for the present measurement data in Figure 5.6 ($\bullet$). This latter method serves as a straight-forward evaluation approach to interpret the recorded LDV-PS data close to the wall, where steep velocity gradients occur and, moreover, the increasing scatter margin of measurement values makes the determination of the wall position challenging. Accordingly, the absolute position values shown in Figure 5.7 build upon the wall position found with a linear fit of mean position values in 0.2 m/s wide velocity bins at flow velocities up to 2 m/s.

Consequently, the comparison of the three different post-processing strategies indicates that the mean velocity profile as well as the correspondingly expected wall position depend on the applied processing routine. As the observed distribution of detected bursts represents a superposition of the mean velocity profile, turbulent fluctuations and measurement uncertainty, the differentiation of these quantities is required for the development of a suitable data-processing routine. Considering the underlying determination procedure of a passing tracer-particle's velocity and position of the LDV-PS described in Section 2.4.3, it becomes clear that also the measurement accuracy of both quantities are mutually linked to each other. In order to investigate the effects of the internal

signal-processing evaluation together with the arising position and velocity-measurement accuracy a characterization study is conducted, where both position and velocity measurements can be investigated separately. Subsequently, on basis of the results achieved for a set of systematically varied parameters the measurement data can be further evaluated as described below." [PLG⁺24]

5.2.3 Measurement uncertainty characterization experiment

"As introduced above, the extended parametric characterization experiment investigates the interplay between the size of the scattering object, a broad range of chosen LDV-PS acquisition parameters, the velocity range within the observed measurement volume, and the accuracy of the velocity and position estimation. The conducted measurements comprise two acquisition modes, four velocities (see Table 5.1 and Figure 5.6 for details and illustration) and six wire diameters.

The distributions of detected wire velocities and correspondingly determined wire positions are shown in Figure 5.8 for the 5 μm - and 80 μm -diameter wires (top and bottom row, respectively). As to be expected, σ_y decreases for thinner wires for both acquisition cases. The relative velocity standard deviation σ_u/u is in the range of 0.4 % to 0.6 % for all wires and cases with slightly increasing relative velocity standard deviations for larger wire diameters. The scatter distribution of the obtained y -position values resembles a Gaussian distribution.

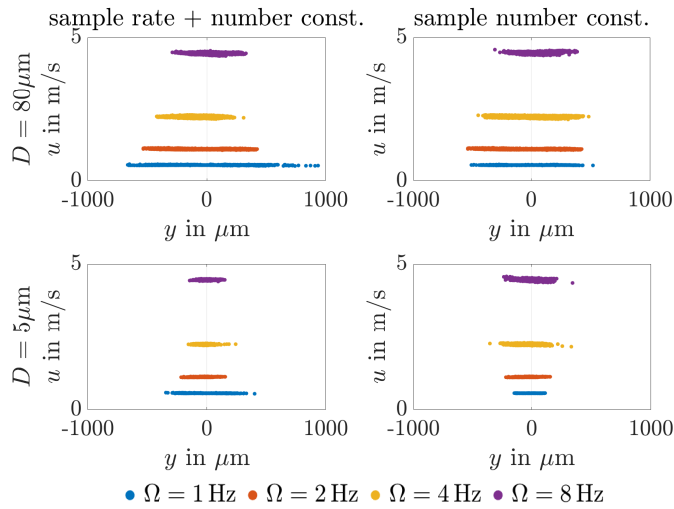


Figure 5.8: Distributions of detected wire velocities and corresponding positions for different velocity levels, wire diameters D and acquisition modes. Reproduced from [PLG⁺24].

For the first acquisition case with constant sample rate and number in the scattered light signal processing FFT (left column of Figure 5.8), the spatial uncertainty increases with decreasing velocities. This effect has been observed also in the turbulent channel flow and can be explained by the different burst-signal representations of the evaluated samples. While the temporal window size remains constant, the duration and corresponding period length of the Doppler bursts increases with decreasing velocity, which is indicated in Figure 5.9. Consequently, the excluded margin of the registered bursts increases for lower velocities so that an accordingly smaller proportion of the burst signal is evaluated at likewise diminished relative sample rate.

This truncation of the burst signal inevitably leads to a lack of information and is, therefore, expected to cause the observed measurement uncertainty to increase at low velocities. To overcome this velocity-related shortcoming, the second acquisition mode, in contrast, adapts the sample rate to the expected velocity magnitude, which accordingly renders the position-estimation uncertainty

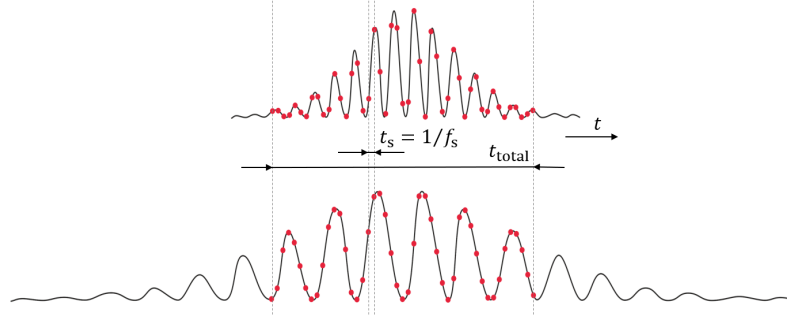


Figure 5.9: Sketch of two Doppler bursts at different particle velocities and the relative distribution of a constant sample number and rate within either burst. Reproduced from [PLG⁺24].

to become independent from the considered velocity level. The wire results for this acquisition mode of constant (relative) period resolution and period length of a burst signal for all considered wire velocities are shown in the right column of Figure 5.8, which indeed indicate the expected constant accuracy for this LDV-PS operation mode.

Furthermore, as shown in Equation 2.28, the position measurement accuracy σ_y additionally depends on the quotient-function slope $\partial y/\partial q$ and the quotient-function accuracy σ_f [see also 53]. For the used LDV-PS measurement system, this quotient function is approximated by a linear function as illustrated in Figure 2.11, which causes an increasing measurement error with increasing distance from the measurement volume center at $y = 0$ (cf. q^* and d_2/d_1). The slope $\partial y/\partial q$ of the used measurement system is $12\,041\,\mu\text{m}$, whereas a slope of $7\,143\,\mu\text{m}$ was reported for a different LDV-PS set-up by Shirai et al. [171], where the latter weaker value accordingly leads to an approximately halved calculated z -position standard deviation. This difference in the slope of the quotient function occurs due to a larger focal length of the employed commercial LDV-PS system.

An evaluation of the particle-diameter influence on the resulting position measurement accuracy σ_y is shown in Figure 5.10, which compares the linear regression curves of the y -position standard deviations σ_y for all investigated wire diameters D , all four angular velocities Ω and both acquisition modes. As indicated in the left diagram, in case of acquisition at constant sample rate and number the aforementioned velocity-dependent uncertainty leads to a quasi-constant shift of the curves, which accordingly appear sorted by the respective wire velocity, i.e. increasing standard deviation for decreasing velocities. This clear velocity-related separation is not observed for an acquisition with velocity-adjusted sample rate (right diagram of Figure 5.10), where the curves of all investigated angular velocities collapse. The slope dy/dD of the curves varies in the range from 0.67 to 1.21 with an average slope of 0.91 for both considered acquisition modes. Since this average value is approximately 1, it is consequently hypothesized that the y -position standard deviation immediately scales with the chosen tracer-particle diameter, which is mimicked by the wires in the present study. It is likewise expected that σ_y is limited to the particle diameter as a minimum, since light is scattered at the particle surface when passing the measurement volume.

It is important to note, that the observed standard deviations are additionally influenced by individual and global sources of uncertainty related to the chosen experimental setup. In the present context, these include the wire-diameter uncertainty, the hand-mounting process of the wires, vibrations of the test rig, thermo-mechanical effects on the wires caused by the laser radiation and possibly velocity dependent dynamic behaviour of the wires. Most of these factors can not be determined quantitatively for the conducted experiments, but may explain the observed scatter margin of the measurement data of individual wires in Figure 5.10. A quantitative evaluation of test-rig vibration-caused y -position fluctuations has been measured by means of a triangulation

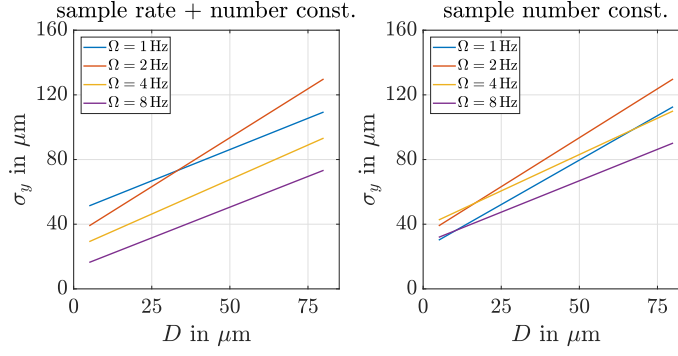


Figure 5.10: Fitted linear curves for y -position standard deviation over wire diameter D for all four velocity levels of both acquisition modes. Reproduced from [PLG⁺24].

sensor for $\Omega = 1$ Hz, 2 Hz and is found to range between $10\ \mu\text{m}$ and $20\ \mu\text{m}$. Accordingly, a vertical downward shift of the standard deviation curves shown in Figure 5.10 corresponds to the measurement uncertainty of the system without the influence of the vibrations." [PLG⁺24]

5.2.4 Channel base flow

"The LDV-PS measurement data can now be evaluated based on the findings of the characterization study. The y -position uncertainty is found to be limited to the size of the tracer particles in the characterization experiment, which is in the order of magnitude of $1\ \mu\text{m}$ for DEHS particles in the conducted measurement and, thus, small compared to the measurement uncertainty induced by the signal processing at decreasing velocities (see left diagram of Figure 5.10). The vibrations of the lower channel flow were measured by means of a triangulation sensor and did not exceed $1\ \mu\text{m}$. Furthermore, the study reveals an increasing position measurement uncertainty at decreasing velocities for constant FFT parameters, which is observed at low flow velocities (see Figure 5.7). As such, the scattering of measurement data in the near wall region of the turbulent channel flow represents a position measurement uncertainty rather than a characteristic of the flow.

To further examine this effect, the registered particle velocity and position distribution is shown in Figure 5.11, where lighter shades indicate a lower and darker shades a higher burst density. The number of detected burst events is determined in $0.2\ \text{m/s}$ wide velocity bins and $200\ \mu\text{m}$ wide position bins, and is afterwards normalized by the maximum number of bursts found at all velocity bins within the same position bin.

In order to allow an immediate interpretation of the shown data, the normalized probability density distribution of the flow velocity over channel wall distance for DNS data at $Re_\tau = 590$ [5] is superimposed to the diagram as black solid lines. The DNS results were, therefore, converted to physical units assuming the facility channel height and air viscosity to allow for immediate data comparison. This was preferred instead of converting the measured data into inner-scaled quantities due to the different mean-velocity gradients depending on the averaging methods for the PS-LDV.

A good agreement of the probability density distribution of the measurements and the DNS data is found for position values $y > 2000\ \mu\text{m}$, while closer to the wall the measurement uncertainty increases due to the factors elaborated in Section 5.2.3. Particularly for the range $y < 1000\ \mu\text{m}$ this deviation reveals a significantly larger scatter margin of the LDV-PS data due to the increasing position-estimation uncertainty for the lowest velocity range above the wall. While the velocity-fluctuation amplitude is large in this region as shown by the DNS reference data, a decrease to

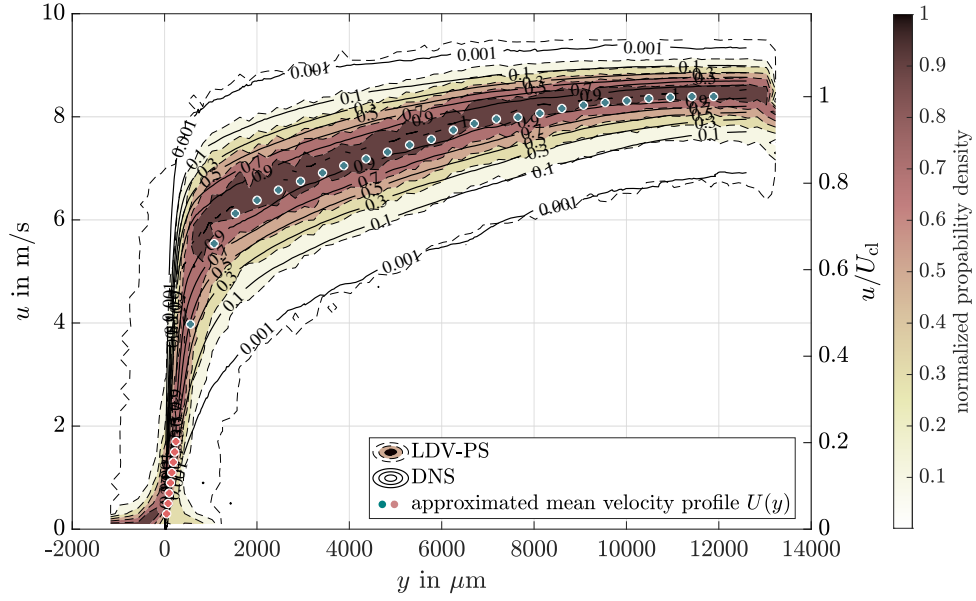


Figure 5.11: Comparison of normalized probability density distribution of the measurement results and reference DNS data at $Re_\tau = 590$ [5]. The number of bursts within 0.2 m/s wide velocity bins and 470 μm wide position bins normalized with the maximum number of bursts at the same position. The approximated mean velocity profile based on u -bin averaged velocity values close to the wall ($\bullet$) and y -bin averaged position values in the channel centre region ($\bullet$) is indicated with the circles. Reproduced from [PLG⁺24].

zero is by definition expected at the wall. In fact, the streamwise velocity PDF is known to be log-normal and therefore strongly asymmetric [5] as can also be inferred from the DNS contour lines. The reason why the LDV-PS data exhibits a near Gaussian distribution with nonphysical values is related to the inherent background noise level as also known from LDV measurements, which shows up when the absolute fluctuation level goes below the noise floor. Additionally, as the scattering of position values is found to be approximately Gaussian distributed in the characterization study, it becomes clear that a mean velocity profile based on y -bin averaging, represented by the blue circles, in fact is no suitable representation of the flow physics in the vicinity of the wall for the present measurement data.

It must be noted that the underlying approximation of the wall position from the LDV-PS measurement data as well as the relative traverse positions remain a source of uncertainty in these considerations. The so-called diagnostic plot [6] allows the comparison of turbulent shear flow data without the need to determine the wall position nor the friction velocity. Figure 5.12 shows such a diagnostic plot for the present investigation, where the ratio of the rms level of streamwise velocity to mean streamwise velocity $u'_{\text{rms}}/\bar{u}$ is plotted over the ratio of mean streamwise velocity to centerline velocity $\bar{u}/u_{\text{cl}}$. Recall from above, that – similar to the mean quantities – also the u' -rms values can only be evaluated within data bins, which in the present case has been the y -position binning as already applied for the blue data points of the mean velocity profile in Figure 5.7.

A good agreement is found with DNS reference data by Moser et al. [132] at $Re_\tau = 390$ and 590 for mean flow velocities $\bar{u} > 0.7u_{\text{cl}}$, which confirms the quality of the determined mean and rms velocity values for the outer region [...] [4]. To allow further comparison of tracer-based velocimetry approaches for the given flow scenario, the stereo PIV results of Hehner et al. [HVD⁺21] are also added to the diagnostic plot. Interestingly, the PIV data remain on the DNS curve toward lower relative velocities $\bar{u}/u_{\text{cl}}$ as compared to the LDV-PS approach [, while the LDV-PS measurements offer additional samples in the wall-near region]. This immediate comparison of the experimental

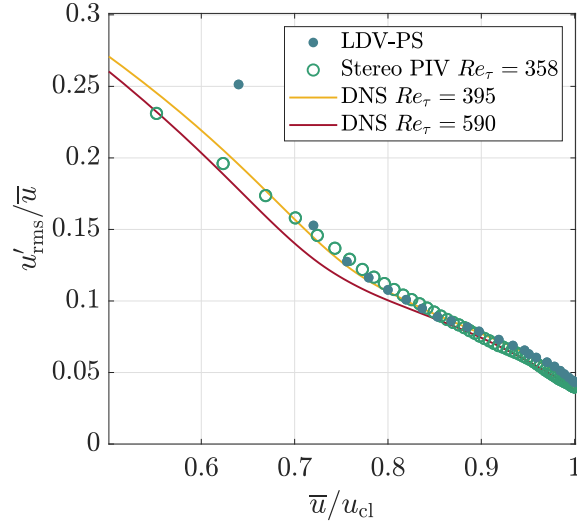


Figure 5.12: Diagnostic plot of LDV-PS measurement data evaluated in 470 μm wide y -position bins together with reference DNS data at $Re_\tau = 390$ and 590 [132] and stereo PIV data at $Re_\tau = 358$ [HVDs+21]. Reproduced from [PLG+24].

results indicates that measurement-uncertainty related contributions to the u'_{rms} level of the experimental data adversely affects the LDV-PS procedure up to larger velocities – thus wall distances – as compared to the PIV approach.

Finally, we aim to extract the mean velocity profile in inner scaling from the LDV-PS data and compare it to velocity data from DNS. In order to convert the present data into dimensionless viscous + units, different approaches are presented and discussed. Here, the superscript + indicates nondimensionalisation by the kinematic viscosity ν of the fluid and the friction velocity $u_\tau = \sqrt{\tau_w/\rho}$, where τ_w denotes the mean wall shear stress and ρ the fluid density. Firstly, as described by Hehner et al. [HVDs+21], the present data can be fitted to a composite velocity profile description such as the one by Luchini [125] in order to find the corresponding friction Reynolds number Re_τ and wall position simultaneously. Alternatively, the wall shear stress τ_w can be determined directly from the mean velocity gradient in the viscous sublayer, if it is measured with sufficient measurement accuracy and spatial resolution. Note that we abstain from using the WSS from the (global) pressure-drop measurements, since the reason for testing the LDV-PS in turbulent channel flow is the access of local wall shear stress information.

A mean velocity profile based on a combination of u -bin averaging in the near wall region ($\bullet$) and y -bin averaging in the channel center region ($\circ$) is considered, which is respectively indicated by the red and blue circles in Figure 5.11 in consistency with the color-coding of Figure 5.7. The evaluation of most dense points suggested by Strauch et al. [175] shown in Figure 5.7 is observed to overshoot the average-based mean velocity profile, which is likely to be related to the effect that more particles cross the LDV measurement volume at higher velocities [3]. The y -bin averaging is therefore expected to be less biased by this effect and accordingly to be a better representation of the flow. Additionally, correction procedures for mean velocities measured with LDV have been presented in literature [3].

Based on this combined velocity profile, first Re_τ and the wall position are estimated simultaneously by means of a least-square fit function using the general description of the dimensionless mean velocity profile by Luchini [125]. Figure 5.13 shows the mean velocity profile, where the lower abscissa axis and left ordinate axis show inner (viscous) scaling, while the upper abscissa axis and right ordinate axis present physical coordinates to also maintain direct comparability with

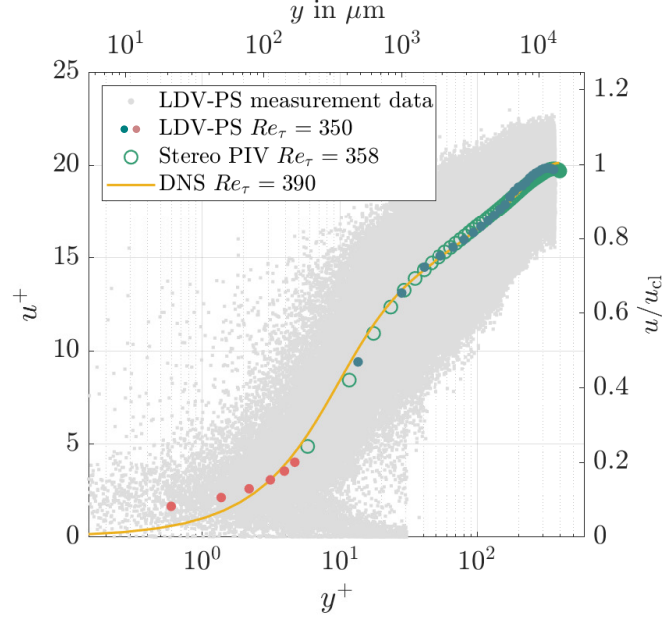


Figure 5.13: Mean velocity profile evaluated in 0.2 m/s wide velocity bins (•) and 470 μm wide y -position bins (•) of LDV-PS measurements compared with DNS data at $Re_\tau = 390$ [132] and stereo PIV data at $Re_\tau = 358$ [HVDS⁺21]. The physical coordinates on the upper and right axes refer to the profile sensor measurements at $Re_\tau = 350$. All registered velocity and position values are shown in the background (•). Reproduced from [PLG⁺24].

Figures 5.11 and 5.12. Additionally, DNS data from Moser et al. [132] at $Re_\tau = 390$ and stereo PIV measurements from Hehner et al. [HVDS⁺21] at $Re_\tau = 358$ are shown for reference and comparison purposes, respectively. The velocity and position values of all registered bursts are shown in the background (•).

The mean velocity profile overall agrees with the reference profiles. Nevertheless, deviations occur in the near-wall region. Accordingly, the determination of the viscous scales based on the evaluation of the wall shear stress using the velocity gradient in the wall near region of the viscous sublayer leads to an underestimation of the friction Reynolds number and, thus, does not lead to an appropriate scaling for the largest portion of the profile, even though a sufficient amount of particle bursts was detected in the region of the viscous sublayer. For the stereo PIV measurements, in comparison, the first measurement point is at $y^+ = 6$ for a similar Re_τ , while the first LDV-PS sample represents $y^+ < 1$. The deviation of the LDV-PS velocity profile from the references in the wall near region is represented by overshooting velocity values close to the wall. This effect might be associated with decreasing particle density toward the wall and the occurrence of the LDV-typical bias to detect more particles at higher velocities [3], which is especially pronounced at high velocity gradients. Based on such a shifted particle density distribution, the mean position values are underestimated within velocity bins, as can be observed in Figure 5.13.

The comparison of the mean velocity profile of the flow emphasizes the findings revealed in the diagnostic plot. Good agreement of the measured mean and rms velocity profiles with reference data is shown at larger mean velocities toward the channel center, where the measurement system related uncertainty is small. Though, since the effect of slightly overshooting mean velocity values is less pronounced in the diagnostic plot (see Figure 5.12), the measured rms values in the center region are found to be slightly overestimated as well. Overall, Figure 5.11 confirms the accordance of the probability density distribution of the measurement data with DNS data over the entire outer region of the channel flow. In the direct proximity of the wall, in contrast, the increasing

position-determination uncertainty at low velocity levels together with the large velocity gradient lead to large deviations of the rms and probability density distribution values from the reference data. As such, the distinction of turbulent velocity fluctuations and measurement uncertainty remains a challenge for LDV-PS measurements in unknown flows. None of the suggested processing approaches allowed the direct measurement of the wall shear stress from the shown measurement data." [PLG⁺24]

5.2.5 Summary and concluding discussion

"The employed LDV-PS measurement system was found to provide spatially and temporally resolved velocity data in the outer region of the turbulent channel flow based on the statistical evaluation of the measurement data shown in Figure 5.12. As such, it is a beneficial tool for flow measurements especially in facilities with limited accessibility for intrusive probes or multiple optical components. The evaluation of the measurement data gathered in the inner region and a separate characterization experiment showed an increasing measurement uncertainty at decreasing velocity levels, thus indicating limited suitability of the measurement system in low-velocity flow measurements. Particle bursts could be detected over the whole channel height with the chosen setup, proving that the region of the viscous sublayer is in principle accessible with the measurement system. [While the measured mean velocity profile follows the reference data relatively close with a slightly smaller velocity gradient in the direct wall-vicinity, the velocity fluctuation profile is strongly influenced by the increasing measurement uncertainty in this region.] The observed velocity-dependent scatter margin of the location estimation has been identified to be dominated by the internal signal processing of the scattered light signal of the measurement system. It has to be concluded accordingly, that a flow-velocity dependent choice of FFT parameters is required to achieve constant (low) measurement uncertainty, allowing the evaluation of turbulent statistics at small local flow velocities. [These findings, however, demonstrate further potential for measurements at increased accuracy based on an improved signal evaluation strategy, as previously implemented for a non-commercial profile sensor [170].] Additionally, possible sources of measurement inaccuracy arise from the dynamic behavior of the test setup during the experiments as well as the scattering object size, as evidenced by the increase of the wire diameter in the characterization experiment, which caused an increase of the measurement uncertainty of approximately the same value. The latter factor might complicate measurements in liquid with overall larger particles.

The determination of turbulence statistics is directly influenced by the particle density distribution of measured velocity and position values, which depends on the choice of traversing steps and respective measurement durations. A continuous, homogeneous burst distribution, therefore, requires fine traversing of the LDV-PS in the order of magnitude of the measurement volume length and increased measurement times at high velocity gradients, which might be accompanied by an increased measurement effort. Additionally, the reduced amount of particles near the wall and a potentially decreasing SNR due to light scattered at the wall need to be considered in the interpretation of data. The possibility of limiting the position measurement range in the LDV-PS software can reduce the position scattering of a measurement. Though, this might make the statistical processing of the data more difficult, as the scattering of detected particles is not captured as a whole anymore. Furthermore, general LDV-specific bias errors occur due to the measurement volume shape with regard to the velocity-profile slope as well as the higher number of faster particles passing the measurement volume, which could be corrected based on the individual particle passing time.

It was shown that different data-evaluation approaches used in the literature led to varying results for the introduced measurement data, which demonstrates the need for consistent and comprehensible documentation. As a final remark toward future LDV-PS-based flow investigations, a transparent, uniform and robust data processing routine seems mandatory, to ensure an objective analysis of flow statistics and measurement uncertainties.

The work summarized in this [...] [section] was initiated to document the capability of the commercially available LDV-PS to measure a turbulent channel flow and corresponding near-wall turbulence statistics. However, as described above, this step indicates that further work is needed to be able to use the LDV-PS as a reliable off-the-shelf technique for measurements in flows with large velocity gradients. Especially after performing comprehensive analyses of the observed measurement characteristics, this otherwise preliminary verification step is considered important knowledge to share with the scientific community." [PLG⁺24]

Accordingly, the LDV-PS measurement system is not applied to measure the interaction of the oscillatory plasma forcing in a turbulent flow. Since the results clarify the need for a different measurement technique to measure statistical flow quantities close to the wall, STB measurement technique is comparatively applied to measure the same turbulent channel flow as a next step.

5.3 Channel base flow characterization with STB

A STB measurement setup with a commercial software for data acquisition and evaluation is employed for turbulent channel-flow measurements in a feasibility study. To account for the challenges of conducting such optical measurements directly above a flow-control application, a non-operated PA array is installed in the channel. The assessment of the measurement approach is based on the analysis of data quality and a broad comparative study considering results from DNS and multiple previous experiments.

5.3.1 Experimental methodology

This section describes the measurement setup used in both the channel base flow measurements described in Section 5.3 and the subsequent forced flow measurements in Section 5.4. The measurements are conducted at $Re_\tau = 250$ and 350 , such that the viscous sublayer height of $y^+ = 5$ resembles $250\ \mu\text{m}$ and $180\ \mu\text{m}$ in physical coordinates in the present facility. For reference, the viscous scales are $u_\tau = 0.31\ \text{m/s}$, $0.43\ \text{m/s}$ and $\delta_\nu = 50\ \mu\text{m}$, $36\ \mu\text{m}$ for $Re_\tau = 250, 350$. The respective mean centerline velocities are $u_{cl} \approx 5.0\ \text{m/s}$ and $u_{cl} \approx 8.4\ \text{m/s}$.

The applied PA array (see Figure 2.8 (a)) comprises seven upper and six lower electrodes with a spanwise wavelength of $\lambda_z = 4\ \text{mm}$ and streamwise length of $L_x = 110\ \text{mm}$. In viscous scaling, the spanwise wavelength resembles $\lambda_z^+ = 80$ and 111 and the streamwise length $L_x^+ = 2200$ and 3000 for $Re_\tau = 250$ and 350 . The actuator is permanently positioned in the channel during the measurements of the base flow without actuation and the forced flow cases. For the latter measurements, the PA array is operated at nominal frequencies $f_{AC} = 16\ \text{kHz}$, $f_{osc} = 25, 50$ and $100\ \text{Hz}$ and maximum voltage of $V_{pp} = 5\ \text{kV}$ in BF mode (see Section 3.1) at different Reynolds numbers and streamwise positions as specified in Table 5.2. Details of the BF-operation concept were elaborated by Hehner et al. [90] and summarized in Section 2.2.3. As described in Section 5.1, the PA can be moved in streamwise direction relative to the stationary setup and measurement volume.

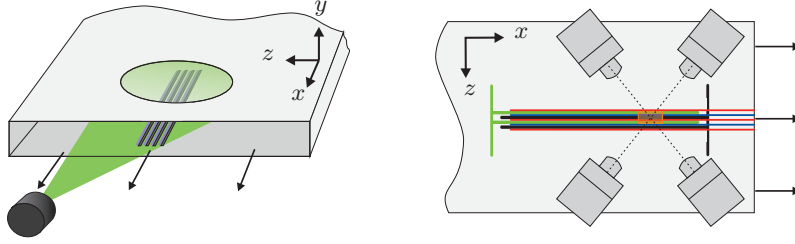


Figure 5.14: Experimental STB setup (not to scale) with measurement volume position in x - z plane in orange above the PA array shown with color-coded electrodes in the right image.

Table 5.2: Measurement flow and forcing parameter combinations: Reynolds number (Re), oscillation frequency (f_{osc}), oscillation period in viscous scales (T_{osc}^+) and downstream distance of the measurement volume center from the plasma-forcing onset position in physical units (ΔX_{onset}) and viscous scales (ΔX_{onset}^+). Blank space for f_{osc} indicates measurement without active forcing.

Re [-]	f_{osc} [Hz]	T_{osc}^+ [-]	ΔX_{onset} [mm]	ΔX_{onset}^+ [-]
250			30	600
250	50	120	30	600
250	25	240	30	600
350			30	830
350	50	240	30	830
350	100	120	30	830
250	50	120	0	0

Figure 5.15 shows the STB measurement setup together with the measurement section of the channel-flow facility, which is the same for the measurements of the channel base flow without forcing discussed in this Section and the forced flow case discussed below. A window in the upper channel wall serves as optical access for the four cameras positioned above the channel in pyramidal formation to capture the particles in the flow under Scheimpflug conditions. A thin laser light volume is positioned directly above the lower channel wall with embedded actuator array (see Section 5.1 for details of the constructive integration), entering through the channel outlet. A laser mirror arm and a blade are used to adjust the laser volume position and boundaries, aiming at reducing scattering and reflection effects on the channel wall and actuator surface due to imperfect flatness of the laser sheet induced by beam divergence and intensity gradients. The camera frame rate, magnification and accordingly required sensor crop are adjusted to enable particle tracking at the expected flow velocities of up to ≈ 10 m/s, while achieving a sufficiently large measurement volume. Based on these considerations, the measurement-volume size is approximately $20 \text{ mm} \times 4 \text{ mm} \times 10 \text{ mm}$ in main flow direction (x), wall-normal direction (y), and spanwise direction (z), covering the region above three upper and two lower electrodes as indicated in orange in Figure 5.14. DEHS tracer particles ($1 \mu\text{m}$ diameter [149], $Stk \approx 1, 5 \times 10^{-3}$) are added to the flow at the inlet into the settling chamber behind the channel drive. Table 5.3 lists the specifications of the used components, along with their respective manufacturers and operation settings. In addition to the drawings of the setup shown in this section, Figure 7.2 in Appendix A provides photos to document technical details of the experiments.

For each measurement run, data is recorded over a duration of 1.2 s at an acquisition frequency of 25 kHz allowing for time-resolved particle tracking. At least five runs are taken of each considered parameter combination with varying seeding density to ensure good particle detection and allow improved measurement statistics based on the evaluation of multiple runs. For the measurement calibration a dual plane calibration plate is used.

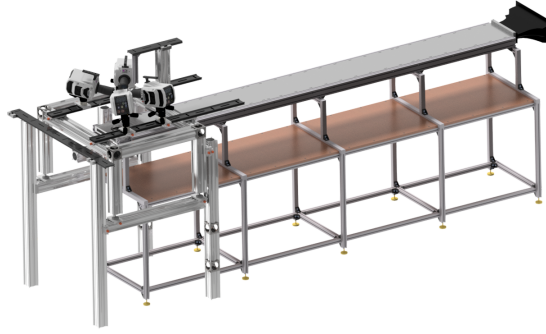


Figure 5.15: Model rendering of channel flow measuring section with STB measurement setup near the outlet.

Table 5.3: Components used in the STB experimental setup sorted by subsystems.

Setup component	Device and manufacturer
Plasma generation	
Function generator	Synchronizer control unit <i>ILA 5150 GmbH</i>
Power Supply	VLP-2403 Pro, VSP-2410 <i>VOLTCRAFT</i>
HV transformer	2× Minipuls 1, 2× Minipuls 2 <i>GBS Elektronik GmbH</i>
Electrical measurements	
Oscilloscope	Picoscope 4424 <i>Pico Technology Ltd.</i>
HV probes	Pintek HVP-39pro <i>Pintek Electronics Co., Ltd.</i>
Current transformer	Magnelab CT-C1.0 Rogowski coil <i>Magnelab Inc.</i>
Optical measurements	
Laser	DM2-100-532-DH <i>Photonics Industries</i>
Laser beam propagation	Laser Guiding Arm <i>LaVision</i>
Volumetric laser optics	Sheet Optics (divergent) <i>LaVision</i>
Lens	4× Milvus 2/100M <i>Zeiss</i> $f = 100$ mm, $f^\# = 6.7$
Scheimpflug adapter	4× Adapter v3 <i>LaVision</i>
Camera	4× Phantom v1840 <i>Vision Research</i> cropped sensor size: 639 pixel × 303 pixel magnification: 26.13 pixel/mm at $y = 0$ mm
Calibration plate	053-1-1 <i>LaVision</i>
Seeding generator	PIVlight30 <i>PIVTEC GmbH</i>
Seeding fluid	DEHS

5.3.2 Raw data and processing routine

Prior to discussing the measurement results from a fluid-mechanical perspective, the present section introduces the applied data processing routine and provides insight into the measurement statistics and quality.

Data processing

Continuous, three-dimensional particle tracks are reconstructed from the images taken with the routine described above based on the STB algorithm [193] using DaVis 11 (*LaVision*) software. Reflection and scattering artifacts occur in the raw images particularly in the regions of the upper silver electrodes (see Figure 5.16 (a)) related to the positioning of the laser light volume and possibly diffraction effects around the inserted blade. To enhance the image SNR, a pre-processing

routine for background removal based on conventional image processing steps considering spatial and temporal effects is applied prior to particle detection and tracking, as illustrated in Figure 5.16 (b). These include subtraction of a sliding intensity image calculated for consecutive frames, subtraction of local minimum intensity, normalization with local intensity average and sliding Gaussian smoothing. The resulting particle density is 0.03 particles per pixel for an exemplary measurement run. Volume self-calibration [192] is applied to complement the image calibration achieved using a calibration plate.

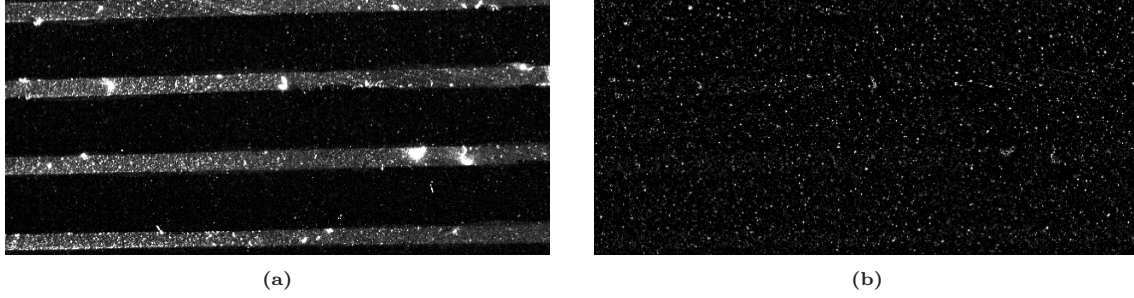


Figure 5.16: (a) Exemplary raw image. (b) Image after pre-processing (shown with scaled intensity).

The average measurement uncertainties of individual samples calculated in Davis are evaluated for an exemplary measurement. The average position uncertainty in wall-parallel direction is approximately $\sigma_{x,z} = 0.0035$ mm and $\sigma_y = 0.006$ mm in wall-normal direction, and the average velocity uncertainties yield $\sigma_{u,w} = 0.06$ m/s for the wall-parallel components and $\sigma_v = 0.1$ m/s for the wall-normal component. The reconstructed particle tracks are further processed using Matlab. A spatial binning is applied allowing to determine fields of statistical flow quantities. For the channel base flow without forcing, simple mean values of measurement quantities detected in the same spatial bin over all time steps are considered. Based on the procedure described above in Section 5.1, the wall position and viscous scales are determined for individual channel base flow measurements from spatially and temporally averaged mean velocity profiles $\bar{u}(y)$. The achievable spatial resolution of the flow fields depends on the local convergence of the considered measurement data [165], as will be discussed for an exemplary grid in the following.

Measurement statistics and quality

The evaluations discussed in this subsection are based on one exemplary measurement run taken at $Re_\tau = 250$. Figure 5.17 (a) shows the average detected number of tracked particles per bin in the channel cross-plane for a grid containing 15 bins in x , 80 bins in y and 20 bins in z direction, yielding a spatial resolution of 1240 μm , 50 μm and 470 μm in x , y and z direction. The bins are chosen to be smaller in y direction in order to achieve a higher spatial resolution in the wall-normal direction. The plot shows the maximum number of detected particles in the cross-plane center with fewer detections especially in the region above the wall. This effect might be related to the removal of PIs with the image background during image pre-processing, a decreasing laser light illumination at the wall due to the Gaussian laser beam profile or a general tendency of seeding particles not to enter the wall-near flow regions. More detections are observed in the wall-near bins at the upper electrode positions (i.e. z -bin index in the range from 3 to 6 and 11 to 14), possibly occurring due to surface reflection or scattering of laser light enduring the image pre-processing being falsely interpreted as particles. Consequently, interpretation of flow data measured in the first bin near the wall is performed with particular care to account for such effects of measurement malfunctions.

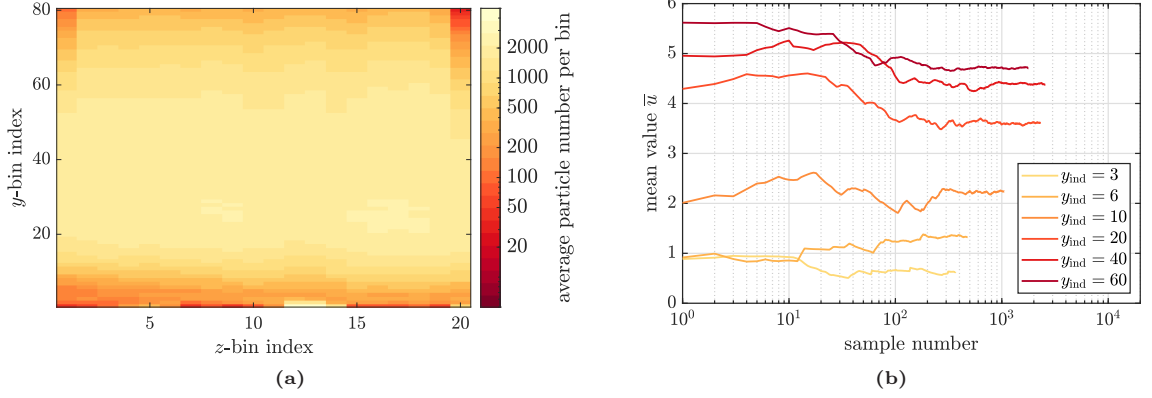


Figure 5.17: (a) Data-density distribution and (b) local converge curves at $x_{\text{ind}} = 10$ and $z_{\text{ind}} = 10$ for a grid with 15 bins in x , 80 bins in y and 20 bins in z direction for individual run at $Re_\tau = 250$ without plasma-based forcing.

In Figure 5.17 (b) the convergence curves of mean $\bar{u}$ velocity values are shown for bins with x and z bin indices 10 and multiple y bin indices or wall-normal distances, respectively, for the same grid. Even though a smaller number of samples per bin was detected at positions closer to the wall, all curves converge from approximately 200 samples on. Following up on the discussion in the end of Section 5.1, the height of the viscous sublayer resembles the position of the 6th bin in wall-normal direction for the present Reynolds number of $Re_\tau = 250$. Thus, the number and distribution of samples of the considered measurement are sufficient for the chosen grid resolution and the viscous sublayer is resolved locally based on time-averaged measurement data.

Further, a preliminary qualitative analysis of the flow fields is carried out to provide an overview of the flow in the channel flow facility and potential irregularities. Figure 5.18 shows the three-component time-averaged flow field in the channel cross-plane at decreased resolution in wall-normal direction for better visibility with the mean flow velocity $\bar{u}$ as contour plot and the mean in-plane flow velocities $\bar{v}$ and $\bar{w}$ as a quiver plot. As to be expected for the studied flow case, the flow is homogeneous in spanwise direction with increasing flow velocity at increasing wall distance and very small resulting in-plane velocity contributions over the entire cross-plane. As an additional indicator for the data quality, the flow field divergence is calculated and found to be around zero over the entire measurement volume.

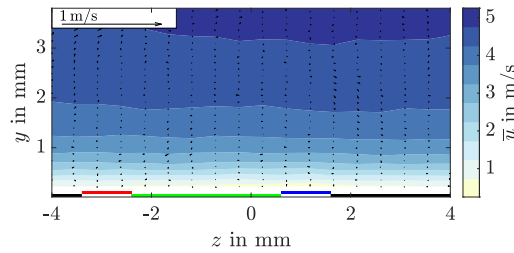


Figure 5.18: Time-averaged velocity fields in channel cross-plane as contour plot for $\bar{u}$ and quiver plot for $\bar{v}$ and $\bar{w}$ for data of individual run in a grid with 15 bins in x , 30 bins in y and 20 bins in z direction evaluated over the x range between $x = -7.4$ mm and $x = -5.0$ mm at $Re_\tau = 250$.

The $\bar{u}$ velocity distribution in the wall-parallel planes of the first six bins near the wall, representing the viscous sublayer region for the chosen grid with 80 bins in wall-normal direction, is shown in Figure 5.19. In the first three layers shown in the top row of the figure, a diagonal stripe of high mean flow velocity is detected. Since the spatial orientation is found to be aligned with the angle of incidence of the laser light and the raw images show areas of higher illumination in this region, the effect is likely to be related to the detection of scattered or reflected light rather than representing

an unexpected flow phenomenon. Accordingly, the area is masked out for the fitting procedure applied to identify the wall position and viscous scales (see Section 5.1) and further evaluations of the present measurement. Over the remaining area in the shown planes, the velocity distribution is homogeneous and the respective velocity levels gradually increases with increasing wall distance.

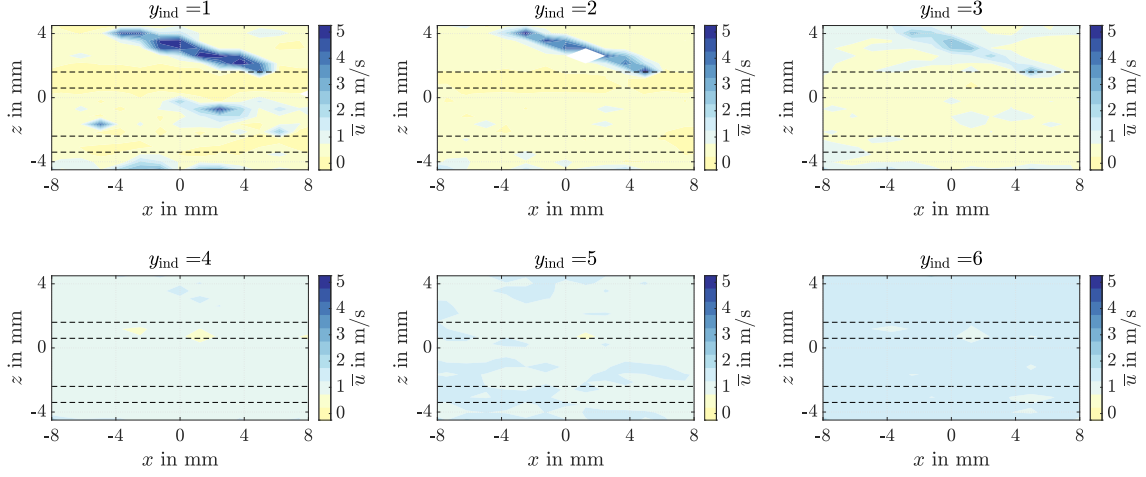


Figure 5.19: Distribution of time-averaged velocity $\bar{u}$ in wall-parallel planes in near-wall bins at $y_{\text{ind}} = 1$ to 6 representing wall distances of 0.008 mm to 0.258 mm in a grid with 15 bins in x , 80 bins in y and 20 bins in z direction for individual run at $Re_\tau = 250$ without plasma-based forcing. Electrode positions are indicated by dashed lines.

5.3.3 Channel base flow

Analogous to Section 5.2.4, a quantitative validation of the measurement data against data from DNS at $Re_\tau = 180$ and $Re_\tau = 390$ is carried out for the present STB measurements, characterizing the suitability of this flow-measurement technique in the current setup for the application above a PA array. Additionally, the results obtained with different measurement techniques in the same channel flow facility are compared against each other. For this purpose, the plots in Figures 5.20 and 5.21 resume the information shown in Figures 5.12 and 5.13 for the afore-discussed LDV-PS measurements [PLG⁺24] in Section 5.2 in an extended context. Furthermore, measurement results based on Stereo PIV [87, HVDS⁺21], DPTV [LPK23, LPK24] and STB [117] at Reynolds numbers around $Re_\tau = 350$ are considered.

Figure 5.20 shows wall-normal profiles of the mean velocity $u^+ = \bar{u}/u_\tau$ and Reynolds stress components $u'^2_{\text{rms}}/u_\tau^2$ and $w'^2_{\text{rms}}/u_\tau^2$ obtained with DNS and different measurement techniques. The results of the present STB measurements above the non-actuated PA array for $Re_\tau = 250$ and $Re_\tau = 350$ are shown as blue and orange triangles, respectively. The data is based on the same measurement run considered in Section 5.3.2 taken at $Re_\tau = 250$ and an additional run at $Re_\tau = 350$. The curves are obtained through temporal and spatial averaging of the measurement data over all time steps of one measurement run and all bins in the z range between -4 mm and 4 mm and the x range between -9 mm and -5 mm. This choice considers the observed local irregularities described in the previous section and full sections of the spanwise wavelength. The plot shows the profiles from the second bin in wall-normal direction corresponding to $50 \mu\text{m}$ wall distance on. The upper and right axes in the plot show the physical coordinates for a scaling according to $Re_\tau = 350$.

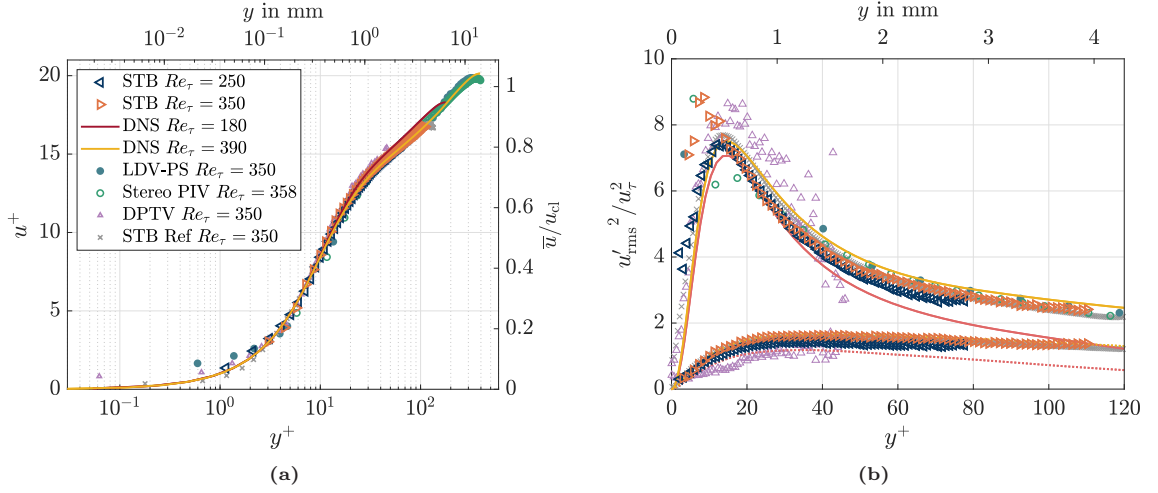


Figure 5.20: Profiles of (a) mean velocity u^+ and (b) Reynolds stresses u'^2_{rms}/u_τ^2 (upper, solid-line curves) and w'^2_{rms}/u_τ^2 (lower, dotted-line curves) from different measurement techniques and DNS in Re_τ range from 250 to 390. The upper (and left) axes are scaled for $Re_\tau = 350$.

The comparison of the mean velocity profile in Figure 5.20 (a) against the DNS data from Moser et al. [132] shows good agreement throughout the whole y measurement range down to $y^+ = 1$ and 3, respectively, for $Re_\tau = 250$ and 350. The viscous sublayer region is represented by four sample points in case of the lower and two sample points for the higher Reynolds number. Consequently, a direct extraction of the WSS and, thus, viscous flow scales based on the mean velocity gradient in this region is feasible. With this method, the estimated friction velocity for the measurement at the lower Reynolds number is found to be $u_\tau = 0.29$ m/s, while the applied profile fitting approach described in the end of Section 5.1 yields $u_\tau = 0.31$ m/s.

The comparison of measurement results shows that in the current STB measurements the wall-near flow region could be resolved down to lower heights in viscous units in comparison to the SPIV measurements [HVDS⁺21]. The LDV-PS measurements [PLG⁺24] yield additional samples near the wall which, however, tend to systematically overshoot the reference profile in this region. The DPTV and reference STB measurements, both conducted under a transparent glass window instead of an opaque wall or PA surface, are shown to capture the mean velocity profile beyond the region accessed in the present STB measurements in direct wall vicinity. In the context of this comparison, it is also important to note that, in addition to the improved optical conditions, the reference STB measurements are based on an increased sample number, since 300 000 consecutive time steps were evaluated together and the whole measurement domain could be considered without the need to mask larger areas due to surface illumination effects. Generally, these results imply further potential for increased achievable measurement resolution as well as larger Reynolds numbers of the flow in the immediate wall vicinity using STB measurement technique. The convergence of velocity data within the individual bins is considered the limiting factor for the spatial resolution and achievable minimum wall distance of the present STB measurements [165]. The ability of STB to flexibly define the spatial resolution represents a general advantage against correlation-based PIV, in which parameters such as seeding density must be adapted to the chosen interrogation area size.

A good agreement of the Reynolds stress profiles captured in the current STB measurements with the DNS data is shown in Figure 5.20 (b) for $Re_\tau = 250$, indicating only slight overestimation in the wall-near region. In case of $Re_\tau = 350$ the u'^2_{rms}/u_τ^2 values show more scattering and overshoot the DNS reference stronger in the bins close to the wall. Strong deviation between DNS

and measurement data is observed for other measurement techniques, i.e. LDV-PS, SPIV and DPTV, particularly in the wall-near region. The reference STB profile is observed to follow the DNS data closely. Out of the measured profiles, only the STB reference measurements, DPTV measurements and the present STB measurements at $Re_\tau = 250$ represent the decrease in velocity fluctuations close to the wall. For the sake of completeness, Figure 7.4 in Appendix A includes the $v_{\text{rms}}'^2/u_\tau^2$ component of the Reynolds stresses at decreased color saturation for the measurements and dashed line for the DNS profiles. Interestingly, the current STB measurements overestimate these values particularly near the wall, while the mean values of the v -velocity component, as shown exemplarily in Figure 5.18, are close to zero. This observation indicates an increased scattering of detected wall-normal velocity values, which does not represent the physical flow behavior in a turbulent channel flow. While the underlying mechanisms leading to the shown behavior remain to be understood in future investigations, it can be noted that the effect occurs in the out-of-plane direction and might therefore be related to the particle triangulation.

As discussed previously for the LDV-PS measurements in Section 5.2, the agreement of the measured mean velocity and Reynolds stress profiles with the DNS references depend on the applied viscous scaling and estimated wall position. To overcome possible influences of these factors, the diagnostic plot introduced by Alfredsson et al. [4] is considered in the following, which shows the ratio of $u_{\text{rms}}'/\bar{u}$ at different wall-normal positions over the respective values of the ratio $\bar{u}/u_{\text{cl}}$. Figure 5.21 shows the plot over the full occurring range of values for $\bar{u}/u_{\text{cl}}$ and a zoomed-in detail for $\bar{u}/u_{\text{cl}}$ between 0.4 and 0.9 marked by dashed lines in the full plot for the same measurement and DNS cases discussed before in the context of Figure 5.20. Since the DNS profiles are given in viscous units, the respective ratios of mean velocity and rms values are used. For all plots showing measurement results there is a tendency to overshoot the curves of numerical simulations in the left region representing the wall-near flow. As the velocity mean values and average fluctuations both approach zero in this region, the observed deviation of the measurement results in comparison to the DNS data indicates an overestimation of velocity-fluctuation rms values near the wall. This effect is therefore likely to represent additional fluctuations related to the measurement itself, thus not representing physical flow behavior, or unexpected superimposed effects influencing the flow such as possible wall vibrations. In the outer region, represented by the detail plot in Figure 5.21 (b), good agreement of the data from the present STB measurements with the DNS data for the respectively similar Reynolds numbers and the reference STB measurements is found, while the values from the DPTV, SPIV and LDV-PS measurements tend to scatter and deviate more.

The shown mean velocity profiles, Reynolds-stress profiles and diagnostic plot (Figures 5.20 (a) and (b), 5.21) of the different measurement techniques together with results of numerical simulations can be found in full-page format for better visibility of details in Appendix A of this work (Figures 7.3, 7.4, 7.5).

5.3.4 Summary and concluding discussion

Volumetric STB measurements are conducted in the wall-adjacent region of a turbulent channel flow at $Re_\tau = 250$ and 350 above a non-operated PA array.

The extracted mean velocity profiles are found to be in good agreement with reference data from DNS throughout the whole y measurement range down to a physical wall distance of 50 μm , resembling $y^+ = 1$ for the lower and $y^+ = 3$ for the higher Reynolds number. The viscous scales determined from the velocity gradient in the viscous sublayer region agree well with those from the fitting of measurement results to a composite mean velocity profile description [125], which indicates suitability of the measurement approach for the direct WSS determination. This aspect

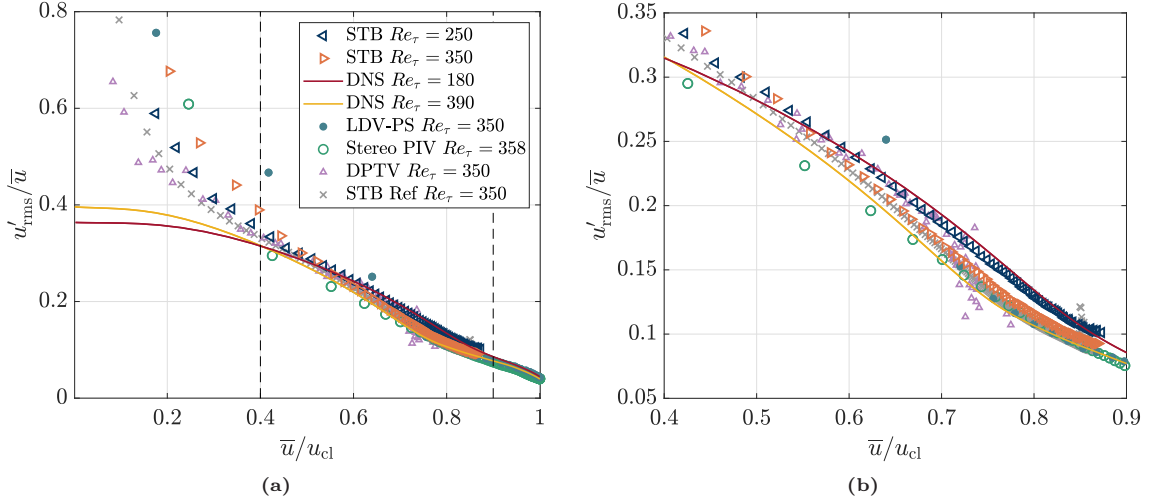


Figure 5.21: (a) Diagnostic plot and (b) detail of diagnostic plot from different measurement techniques and DNS in Re_τ range from 250 to 390.

represents an important addition to the prior STB measurements under a transparent glass plate [117] on the pathway to practical application of the measurement technique in the investigation of flow-control mechanisms in general. In accordance with previous descriptions [165], the density and distribution of underlying particle tracks is identified as limiting factor for the spatial resolution of velocity fields. Consequently, STB measurement technique also appears promising for future investigations of similar flow scenarios at increased Reynolds numbers when longer measurement times are feasible. The rms profiles of the velocity fluctuations w' in spanwise direction are in good agreement with DNS data, while those of the velocity fluctuations u' in streamwise direction show slight overestimation near the wall, with increased scattering in case of larger Re_τ .

The comparison of the measurement results with those obtained using other techniques in the same channel flow above a non-transparent surface show that the STB measurement technique agrees more closely with the DNS reference data, particularly in the region near the wall, than LDV-PS and SPIV approaches. Additionally, due to the tracking-based nature, the STB algorithm yields additional flexibility in the spatial resolution of velocity fields, while covering a volumetric measurement domain. The wall-near flow fields captured with STB in the present measurements reveal unexpected regions of high velocity amplitudes which are likely related to surface illumination scattering or reflection. While the underlying mechanisms of this observation remain to be fully understood, this observation indicates the necessity for an extensive evaluation of measurement statistics and quality prior to flow-physical interpretation of the results. Furthermore, in the measurements no fluid-mechanical interaction of the flow with the spray-painted exposed electrodes on the actuator surface is detected. This finding supports the applied PA-array manufacturing described in Section 3.2.

Finally, the present measurement technique and setup are identified as promising experimental means for the intended investigation of active flow-control approaches. As such, STB is applied for the characterization of forced flow cases based on plasma-induced spanwise flow oscillations in the turbulent channel flow described in Section 5.4.

5.4 Forced flow characterization with STB

STB measurements are conducted to investigate the interaction of oscillatory plasma-based forcing in the turbulent channel flow. The same measurement setup and procedure are applied as in the STB measurements of the channel base flow described above, and the measurement quality of both experiments is discussed comparatively.

Building on previous investigations of BF-driven PA arrays in the turbulent channel flow at ISTM by means of 2D3C SPIV [87], the present experiments first aim to verify the reproducibility of the plasma-induced flow fields. In addition, the STB experiments extend the earlier study with a comprehensive topological study focused on the formation of vortical structures in the channel cross-plane throughout the oscillation cycle and their interaction with the flow field in main flow direction. A systematic comparison of different incoming flow and forcing parameters supports the identification of favorable structures and operation modes for future optimization. The measurement region of the present experiments has been extended toward the wall, aiming at resolving the viscous sublayer and characterize near-wall forcing effects. Furthermore, the volumetric character of the STB technique enables detailed observation of the transient development of flow structures upon convective actuation onset in streamwise direction, thereby complementing the previous SPIV study limited to discrete streamwise positions. Finally, the present analysis includes a comparison of the results with flow features of oscillating wall forcing.

5.4.1 Raw data and processing routine

Complementing the details provided in Section 5.3.2, the present section describes adjustments to the data-processing routine that account for the periodic forcing character. The data statistics and quality are analyzed in comparison to the channel base flow measurements.

Data processing

The data processing routine using the STB software DaVis described for the channel base flow in Section 5.3.2 is now applied for the measurements taken with active flow forcing. The estimation of the respective wall position and viscous flow scales (see Section 5.1 for details) is based on reference channel base flow measurements taken directly prior to or after the forced flow measurements to reduce the risk of components moving in the meantime.

Fields of time-averaged and phase-resolved statistical flow quantities (for example $\bar{u}(x, y, z)$ and $\tilde{u}(x, y, z, \varphi)$ for the streamwise velocity, see Equations 2.1 and 2.2) are extracted from the detected particle tracks using Matlab. This procedure relies on averaging of measurement values detected within the same bin in all time steps or selected time steps representing the same oscillation cycle phase. In case of the latter, each time step in the measurement is assigned to one of 24 equally spaced phase bins resolving the oscillation cycle. By averaging velocity values within the same phase and spatial bin, phase-resolved three-dimensional velocity fields are obtained. The individual measurement runs comprise multiple oscillation cycles depending on the set beat or oscillation frequency (see measurement and plasma parameters stated in Section 5.3.1 and Table 5.2). For an exemplary oscillation frequency of 50 Hz, approximately 60 cycles are recorded. However, since the measurement start is not synchronized with a particular phase in the forcing oscillation cycle, all time steps at the start and end of each measurement that lie outside full oscillation cycles, starting when the spanwise velocity is $\tilde{u} \approx 0 \text{ m/s}$, are discarded. This evaluation step is based on the simultaneously conducted electrical measurements of applied voltage and trigger signals prior to

the application of averaging steps. With this procedure it is avoided that time-averaged quantities are biased by longer cumulated durations of forcing into one direction due to an over-representation in samples. Furthermore, on this basis multiple runs can be stitched and evaluated together for improved statistics, as will be applied for one parameter combination in the upcoming sections.

Measurement statistics and quality

Figure 5.22 shows the distribution of the average detected particle number in the channel cross-plane and exemplary convergence curves of mean velocity $\bar{u}$ for bins at different wall-normal distances for a forced flow measurement analogous to Figure 5.17 in Section 5.3.2. The measurements are conducted at $Re_\tau = 250$ and $f_{osc} = 50$ Hz, and the origin of the x -axis, marking the center of the measurement volume in streamwise direction, is located 30 mm downstream of the convective actuation onset. The same grid resolution as for the evaluation of measurement statistics in the channel base flow is chosen. In comparison to Figure 5.17 (a), the number and distribution of particle detections over the channel cross-plane is generally similar, while less particles are detected in the bins in direct wall vicinity. This effect might be related to the plasma-based forcing and resulting flow movement carrying particles away.

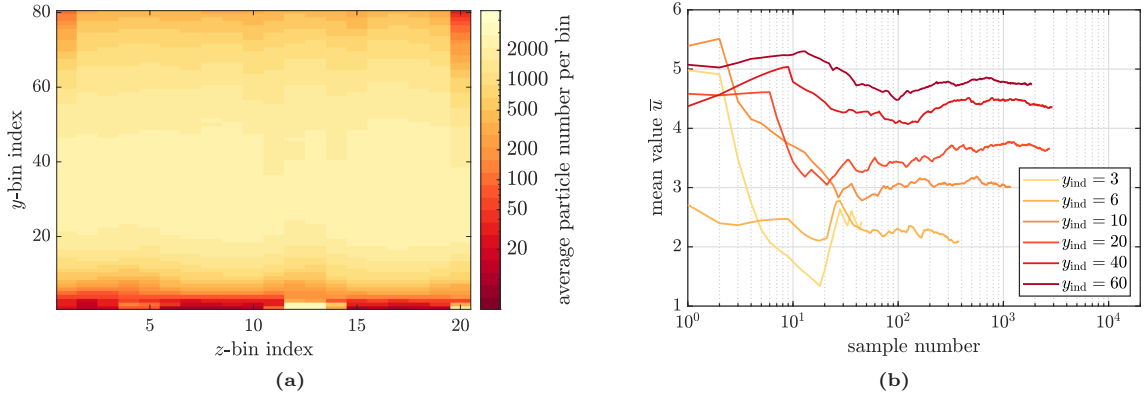


Figure 5.22: (a) Data-density distribution and (b) local converge curves at $x_{ind} = 10$ and $z_{ind} = 10$ for a grid with 15 bins in x , 80 bins in y and 20 bins in z direction for individual run at $Re_\tau = 250$ and $f_{osc} = 50$ Hz.

Figure 5.22 (b) shows that more samples are needed for the mean flow velocity values to converge especially near the wall where the plasma-based forcing is induced. This observation indicates the interaction of the spanwise oscillations with the flow in mean flow direction x , which will be discussed further in the topological flow study in Section 5.4.2. The mean flow velocity gradient in the wall-near region is of particular interest for the evaluation of the WSS, and the convergence curves show that more samples are needed to achieve local convergence of this quantity. Consequently, for a local, phase-resolved evaluation of the WSS, even more data per bin would be required. Since larger bin sizes would prevent a sufficient resolution of the viscous sublayer region, longer measurement durations or the evaluation of multiple measurement runs is required.

Prior to a combined evaluation of multiple stitched-together measurement runs, the consistency and the quality of the forcing impact is evaluated. For this purpose, Figure 5.23 shows time-averaged flow fields from full oscillation cycles from three different measurement runs ((a) to (c)) and the three runs merged together (d). The velocity amplitudes of the resulting in-plane motion are generally small (see 1 m/s reference vector in upper left corners). The observed structures are not symmetric over the spanwise wavelength λ_z . This is visible from the resulting flow motion toward the left in the region around $z = -2$ mm, which is not counteracted from a flow toward the right in the region around $z = 0$ mm. These observations indicate that the forcing is not precisely

equally strong in all plasma regions. However, the velocity amplitudes of these effects are small and no dominant in-plane motion toward either horizontal direction dominates the mean flow. The measurement results show consistent flow topologies across the individual runs, which indicates that multiple measurement runs can be merged for statistical analysis of the flow behavior.

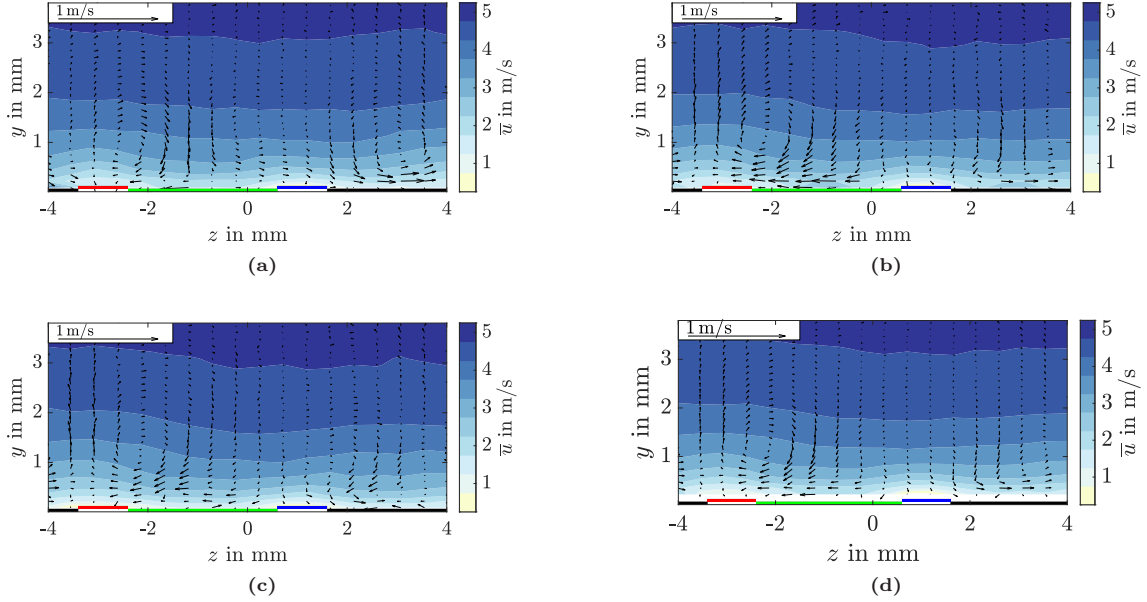


Figure 5.23: Time-averaged velocity fields in channel cross-plane as contour plot for $\bar{u}$ and quiver plot for $\bar{v}$ for data of individual runs taken at the same forcing parameters ((a) to (c)) and three merged runs (d) in a grid with 15 bins in x , 30 bins in y and 20 bins in z direction at $Re_\tau = 250$ and $f_{osc} = 50$ Hz.

Analogous to the procedure followed in Section 5.3 for the channel base flow, the data characteristics in the wall-parallel planes above the actuator are examined as a preliminary evaluation step. Figure 5.24 shows the $\bar{u}$ velocity distribution for the bins near the wall. For y -bin indices 2, 3 and 4, diagonally oriented regions with higher measured velocities are visible, similar to those observed in the channel base flow. Furthermore, in contrast to the channel base flow case, the flow velocities do not increase monotonously with increasing distance from the wall. Instead, high flow velocities around 5 m/s, which is close to the channel centerline velocity, are observed above the lower electrode regions where the plasma develops, particularly in the first, second and third bin from the wall. This observation does not represent the expected physical flow behavior. Given the regions of occurrence, some interaction of the measurements with the presence of plasma is likely to cause the effect. However, the origin of this phenomenon could not be resolved within the scope of this work and remains subject of ongoing investigation.

For the further measurement evaluation it is clear that the flow fields in the immediate vicinity of the wall cannot be reliably interpreted. Consequently, the following section focuses on the flow topology in the region further up above the actuator, which shows reasonable behavior. However, no extraction of (local or phase-resolved) WSS is feasible without the interpretation of measurement data in close vicinity to the wall. Despite this major limitation, qualitative WSS changes are still implied by the course of mean velocity profile $\bar{u}$ further away from the wall, allowing careful insights into the local drag manipulation in the present case. In addition, the diagonal region showing elevated velocities in both the measurements with and without forcing is omitted from further evaluation.

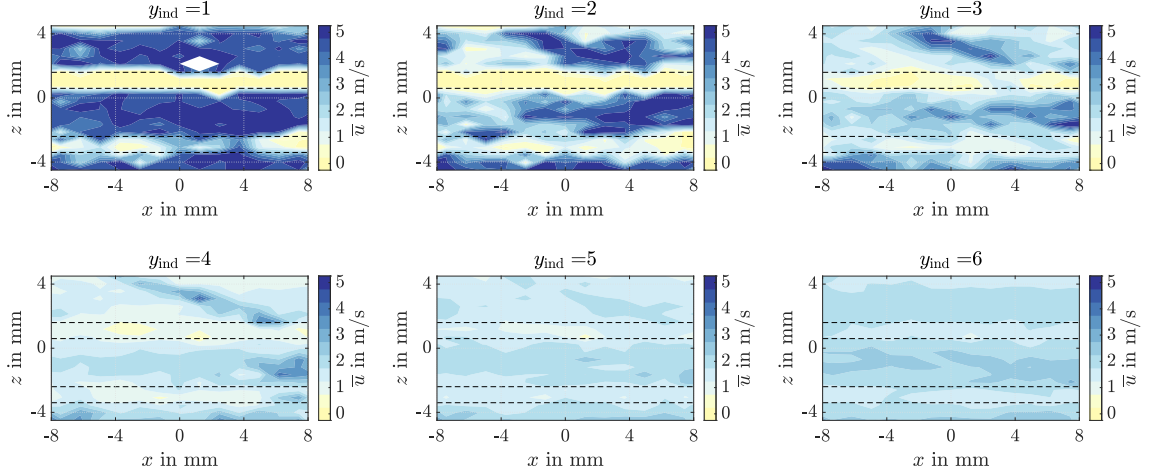


Figure 5.24: Distribution of time-averaged velocity $\bar{u}$ in wall-parallel planes in near-wall bins at $y_{\text{ind}} = 1$ to 6 representing wall distances of 0.008 mm to 0.258 mm in a grid with 15 bins in x , 80 bins in y and 20 bins in z direction for individual run at $Re_\tau = 250$ and $f_{\text{osc}} = 50$ Hz. Electrode positions are indicated by dashed lines.

5.4.2 Flow topology evolution throughout the oscillation cycle

The analysis of the measurement results in this section is focused on the flow fields the channel cross-plane, representing data collected in a thin streamwise volume of 2 mm depth positioned approximately 25 mm downstream the actuation onset. This cropped streamwise range balances statistical reliability with the need to avoid averaging over large regions of the still developing flow above the array (see Section 3.1). From this perspective, phase-resolved flow fields forming under the influence of the plasma-based oscillatory forcing are characterized. Furthermore, systematic variations of flow and forcing parameters (see Table 5.2) are considered, enabling the identification of promising adjustments to the parameter space for future investigations. Particular focus is placed on the comparison with oscillating wall actuation, for which local phase-resolved velocity profiles are evaluated.

Flow fields in the channel cross-plane

Figure 5.25 shows the phase-resolved velocity fields in the y - z channel cross-plane for every second out of 24 phase sections of the oscillation cycle. The in-plane velocity components $\tilde{v}$ and $\tilde{w}$ are shown as quiver plot, while the main flow velocity component $\tilde{u}$ is given as a contour plot. The quiver vectors indicate spanwise velocity amplitudes of up to ≈ 1 m/s. The results are based on a combined evaluation of three merged measurement runs taken at $Re_\tau = 250$, $f_{\text{osc}} = 50$ Hz and 30 mm distance of the measurement volume center and x -axis origin downstream the plasma onset.

The in-plane velocity distribution is dominated by a horizontal flow toward the left and right, thus illustrating the expected effect of the forcing throughout the oscillation cycle. Furthermore, the plots show a spanwise periodicity of the flow fields along the spanwise wavelength λ_z comprising one lower and one exposed electrode, respectively. The observation implies good forcing regularity between the individual discharge zones and, thus, precise PA-array manufacturing and balanced voltages applied to the electrode groups.

Within the spatial units of spanwise periodicity, the formation of vortical structures is observed. Such structures were already found in the DPTV measurements above the PA array at the same oscillation frequency and spanwise wavelength under quiescent air conditions described in Section

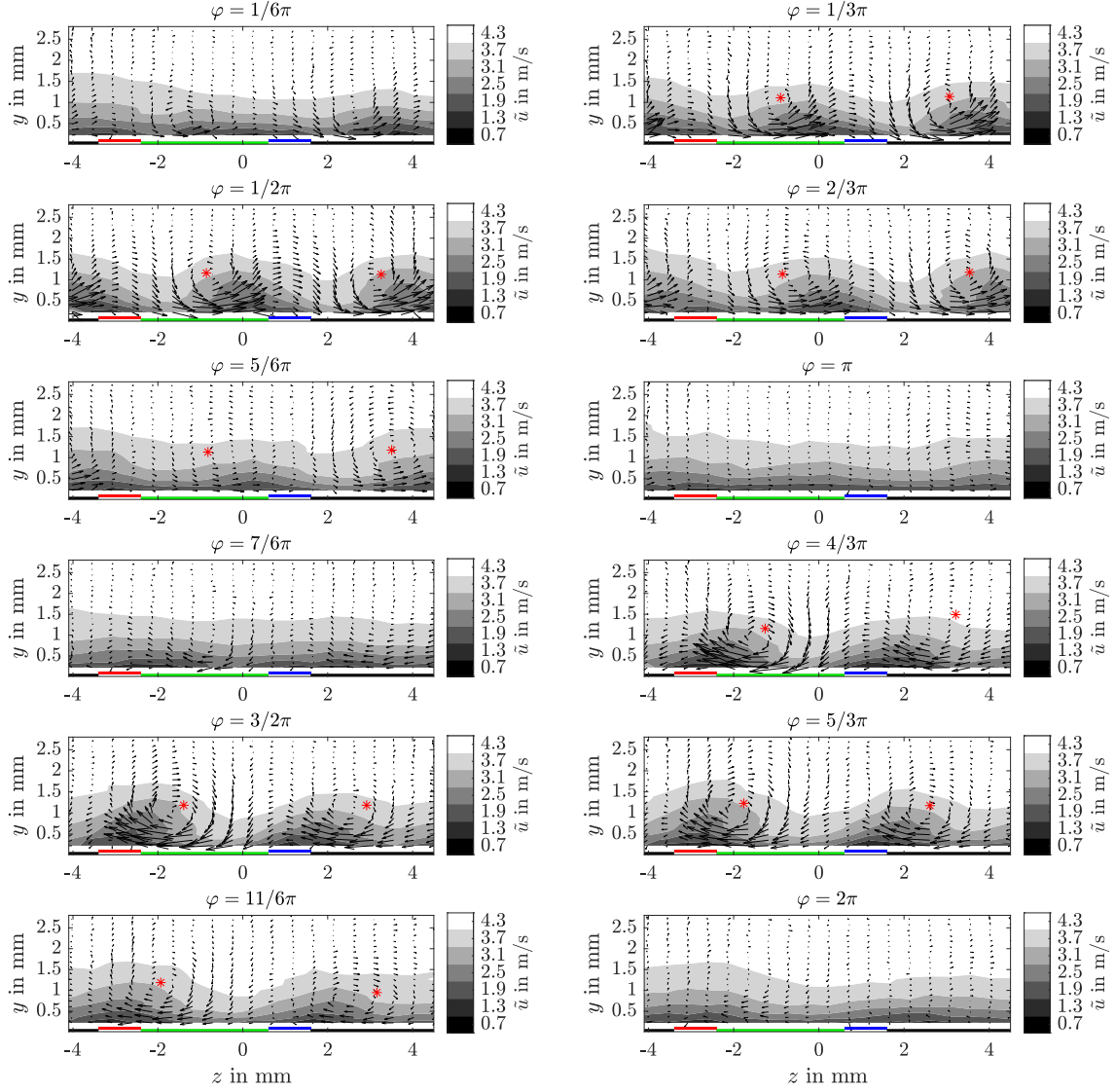


Figure 5.25: Oscillation-cycle phase-resolved velocity fields in channel cross-plane as contour plot for $\bar{u}$ and quiver plot for $\bar{v}$ and $\bar{w}$ in a grid with 15 bins in x , 30 bins in y and 20 bins in z direction for data of three merged runs at $Re_\tau = 250$ and $f_{osc} = 50$ Hz. Vortex centers identified based on Γ_1 criterion [83, 202] are shown as red asterisks.

4.3 and earlier experiments by Hehner [87, PLLK25]. They were found to be caused by the spanwise inhomogeneity of the forcing due to the discrete electrode positions along the spanwise direction and represent a fundamental difference to the purely horizontal flow motion evolving above an oscillating wall. Interestingly, however, Benard et al. [23] reported drag reduction effects for a plasma-based forcing approach mimicking the effects of a stationary spatial distribution of spanwise velocity (see Equation 2.21 and Section 2.2.2), which also induced a spanwise-inhomogeneous WSS distribution. This observation implies that such effects are not necessarily critical.

Over the course of an oscillation half-cycle the in-plane velocity amplitudes increase and the vortices show a tendency to expand in wall-normal direction and travel in the spanwise direction of forcing impact. Similarly, a horizontal displacement of the maximum spanwise velocity was observed in the quiescent-air characterization using DPTV (see Figure 4.15), associated with the spatial extension rate of the plasma-induced body force.

The motion in the channel cross-plane is also visible when considering the positions of vortex centers identified based on Γ_1 criterion [83, 202]. These are added to further illustrate the developing structures in Figure 5.25 as red asterisks. Note, that the vortex-center positions are shown for phases with distinct flow structures, for which they mark meaningful points. Rather unstructured chaotic flow behavior is observed at the reversal of forcing direction, around $\varphi = \pi$ and 2π , when the vortical structures collapse. It takes approximately $1/6 T_{\text{osc}}$ for the flow patterns to reorient after the change in forcing direction. In contrast, for an oscillating wall, the induced motion propagates diffusively in the wall-normal direction, leading to a continuous reversal of the spanwise velocity component.

The vortical structures that develop in the channel cross-plane involve a downwash of high-momentum fluid toward the wall and an upwash of low-momentum fluid away from it [87]. Correspondingly, the measurement results reveal a variation of the $\tilde{u}$ -velocity distribution at different spanwise positions and throughout oscillation cycle. During phases in which strong vortical structures are present, distinct regions of lower $\tilde{u}$ velocity develop near the wall and expand into wall-normal direction, where slower fluid moves upwards. These are spatially separated by regions of higher $\tilde{u}$ velocity, where faster fluid moves downwards to the wall. The spanwise periodicity of the in-plane motion described above is imprinted on the velocity distribution in main flow direction, implying a variation in local WSS.

Local phase-resolved velocity profiles

To gain more insights into the velocity amplitudes, and the spatio-temporal interplay of the in-plane $\tilde{v}$ and $\tilde{w}$, and out-of-plane $\tilde{u}$ velocity components, wall-normal velocity profiles are extracted from the data based on three measurement runs for Reynolds number $Re_\tau = 250$ and oscillation frequency $f_{\text{osc}} = 50$ Hz at characteristic spanwise positions along λ_z (see flow fields shown in Figure 5.25). The plots of the spanwise velocity component additionally allow for the assessment of forcing reproducibility with respect to earlier measurements conducted by Hehner [87]. As indicated in the sketch in the upper left corner of Figure 5.26, one position above the upper electrode (a) and three positions above the encapsulated electrode, particularly at the left electrode edge (b), electrode center (c) and right electrode edge (d), are considered. The 24 oscillation cycle phases are represented by the profile colors and the black dashed $\tilde{u}$ profiles show the mean velocity profile of the channel base flow.

As discussed before in the context of Figure 5.24, the plots show unexpectedly high velocity values in the direct wall vicinity for the $\tilde{u}$ and $\tilde{v}$ velocity components at the positions above the encapsulated electrodes ((b), (c), (d)), where the plasma occurs. Since these effects are likely representing a measurement technique malfunction, the regions will be excluded from the evaluation. Further, the profiles of all velocity components develop systematically over the phases as indicated by the arrangement of profiles along the continuous color gradient of the phase color bar. The amplitudes of the spanwise velocity component $\tilde{w}$ are smallest above the upper electrode at position (a), where no plasma develops, with ≈ 0.2 m/s at maximum and largest at the center of the encapsulated electrode at position (c) with ≈ 1 m/s at maximum positioned at a wall distance of 250 to 400 μm . The latter velocity amplitude represents $A^+ = 3.2$ for the given Reynolds number of 250. In previous experiments in the channel flow facility at ISTM at the same oscillation frequency and Reynolds number, phase-resolved spanwise profiles of similar shape were obtained, showing a maximum amplitude of ≈ 0.8 m/s and equivalent $A^+ = 2.5$ [87]. Considering the newly implemented manufacturing routine (introduced in Section 3.2) and complex manual voltage-adjustment procedure, the achieved agreement between the results demonstrates

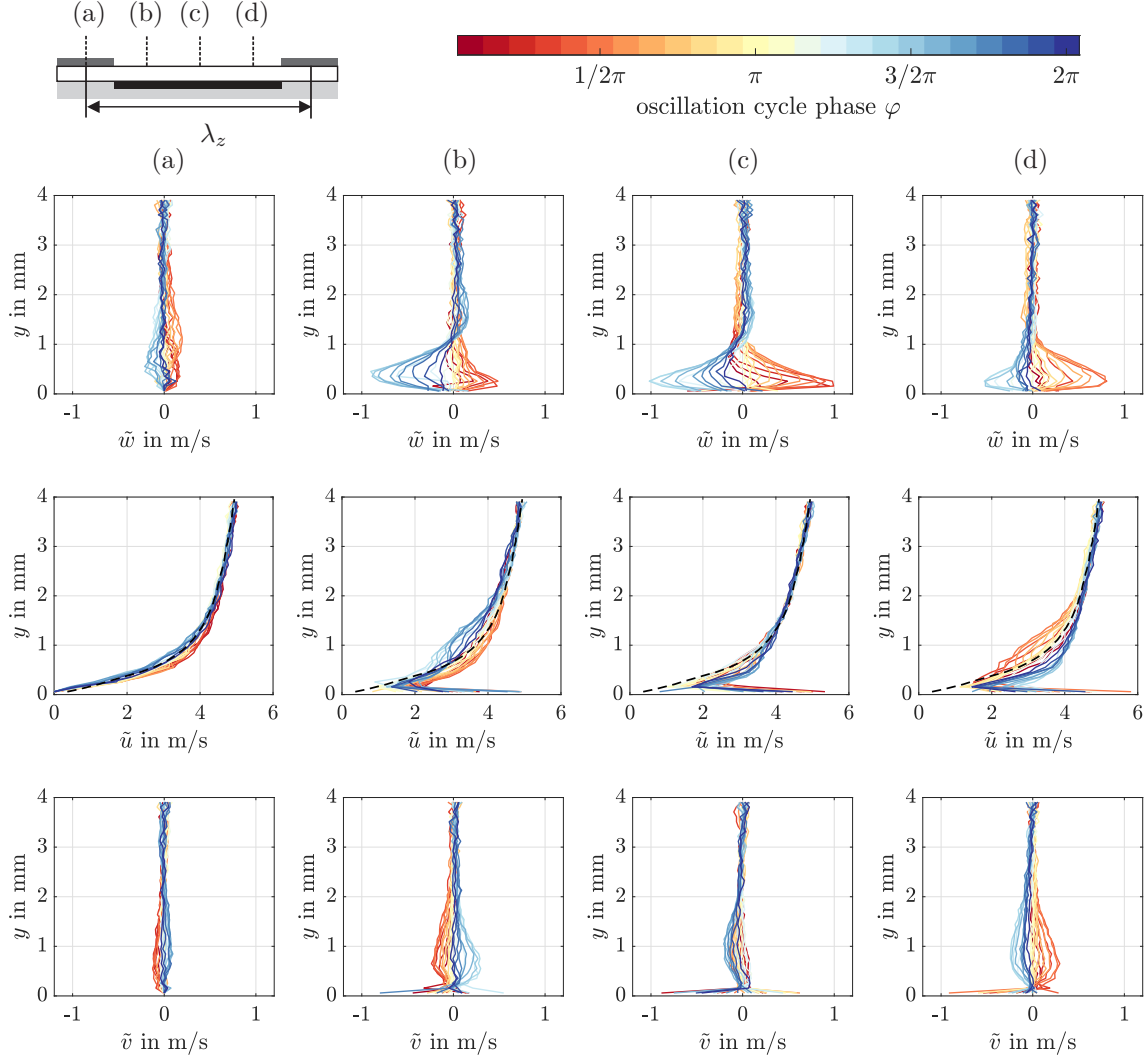


Figure 5.26: Local, oscillation-cycle phase-resolved velocity profiles measured at different positions along the spanwise wavelength λ_z for data of three merged runs at $Re_{tau} = 250$ and $f_{osc} = 50$ Hz. Dashed lines in $\tilde{u}$ profiles shows measured mean velocity profile of channel base flow.

high reproducibility of plasma-induced flow fields, representing an important validation of the experimental approach. The observed spanwise velocity amplitudes in viscous scaling fall within the range where drag reduction has been reported for oscillating-wall actuation [151]. However, larger drag reduction effects were observed at higher oscillation amplitudes, which in the present channel flow facility would require considerably higher spanwise velocity amplitudes due to the small channel height and corresponding viscous length scales. For comparison, Jukes et al. [101] reported similar plasma-induced velocity amplitudes of approximately 1.2 m/s, corresponding to $A^+ = 15$ in the considered boundary-layer flow. Asymmetric profiles are observed over the oscillation cycle at the electrode borders at positions (b) and (d) due to the lateral motion of fluid caused by the forcing. These observed locally varying spanwise velocity amplitudes and directional irregularities are two aspects that distinguish the flow structures of the present forcing application from the reference case of an oscillating wall. The profiles of streamwise velocity $\tilde{u}$ show strong deviation from the channel base flow reference profile (shown as black dashed line) throughout the oscillation cycle especially above the lower electrode edges of up to ± 1.5 m/s at $y = 0.5$ mm. This observation indicates strong WSS variations over the oscillation cycle phases depending on the spanwise position clarifying the need for spatially and temporally resolved evaluation for future

measurements. Such investigations could offer new insights into underlying cause-effect relations of the parameter-dependent, forcing-induced flow structures and resulting local and momentary drag effect. Particularly, identifying beneficial flow structures can be an important step in the development of practically applicable forcing approaches in general. In this context, the work of Agostini et al. [2] investigated the development of the skin friction coefficient and other statistical velocity quantities over the forcing cycle of a laterally oscillating wall and relates it to different statistical flow quantities, which could allow for an insightful comparison of characteristics in a beneficially manipulated flow.

The profiles of spanwise velocity $\tilde{w}$ are in phase at the different spanwise positions over the oscillation cycle, as can, e.g., be observed by the local maximum velocity amplitudes occurring in the same phases at all positions. In contrast, this does not apply for the $\tilde{u}$ and $\tilde{v}$ profiles, introducing a separation of velocity profiles in different directions over the oscillation cycle. This separation directly reflects the vortical flow structures induced by the discrete forcing input positions. However, this finding is particularly relevant for the investigation of the present flow-control approach, as it represents another critical difference to a physically oscillating wall. In this context, it should additionally be noted, that the maximum spanwise velocity amplitude occurs $\approx 300 \mu\text{m}$ above the wall in case of the plasma-based forcing.

To confirm that the observed directional separation occurs systematically over time and space, average values of the wall-normal velocity profiles between the wall-distance of 0.15 mm and 1 mm are evaluated for all 24 oscillation cycle phases and the entire spanwise measurement range. This approach provides a compact overview of the directional velocity distributions as contour plot maps in Figure 5.27. The information of one of the profiles in Figure 5.26 for one z position and oscillation phase is represented by one point in the maps in Figure 5.27, and one of the sub-figure profile plots is now represented by a vertical slice in the map.

The top map of the spanwise velocity component $\tilde{w}$ illustrates the oscillatory motion, with either positive or negative velocities spanning the entire spanwise range during the two half-cycles of the oscillation. The lateral z shift of the high-velocity regions between the two forcing directions reflects the asymmetric shape of the velocity profiles in Figure 5.26 at positions (b) and (d). The $\tilde{v}$ map shows a region of negative and positive velocity for each spanwise wavelength λ_z and oscillatory half-cycle. These patterns correspond to a downwash at the side of the plasma impact region facing the upper electrode and an upwash on the opposite side, forming part of the vortical structures in the channel cross-plane. Regions of negative velocity in the $\tilde{v}$ map coincide with regions of high $\tilde{u}$ velocities within the same φ and z range. For an oscillating wall, in contrast, the velocity would be constant over the spanwise direction z with $\tilde{v} = 0$ for all oscillation cycle phases.

The spatio-temporal evolution captured in these maps confirms that the systematic directional separation of velocity profiles is a consistent and systematic characteristic of the developing vortical structures. In addition, the patterns confirm the regularity of the induced vortices over the spanwise direction of the measurement volume.

Comparison of flow and forcing parameters

In the following, the influence of different combinations of parameters of the incoming flow and the forcing introduced in Table 5.2 is investigated. Due to the above-described limitations, the evaluation of the flow fields is confined to a small streamwise section of the measurement volume. This restriction requires the combined evaluation of multiple measurement runs to achieve statistically fully converged results, which are only achievable with substantially increased processing effort. As a compromise, a careful qualitative evaluation and comparison of measurements conducted at

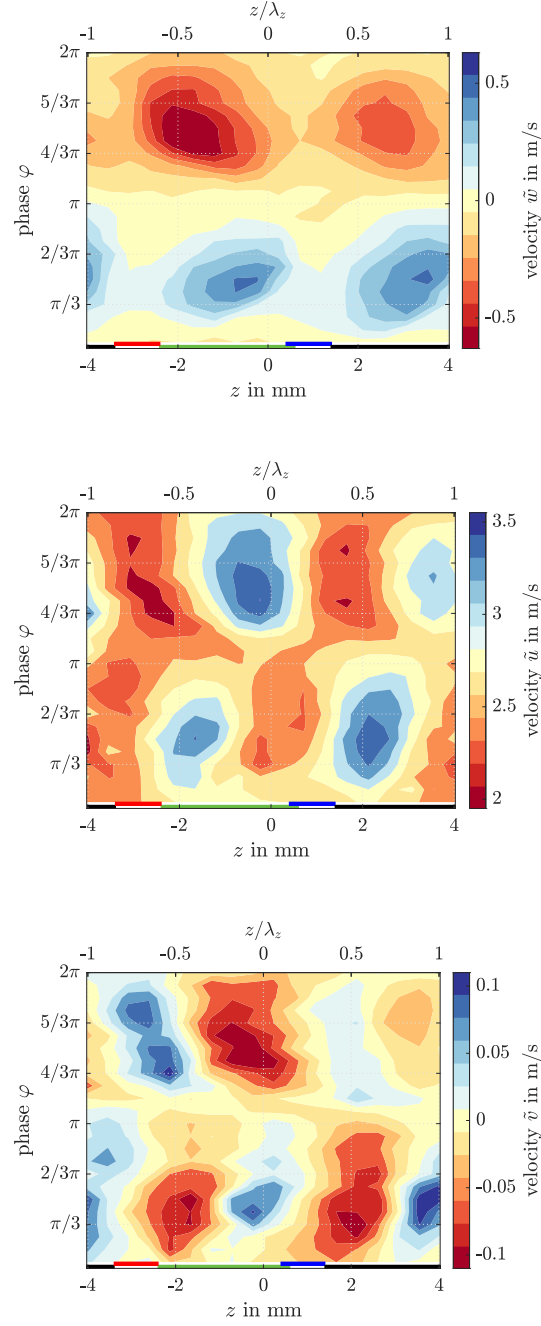


Figure 5.27: Average value of local, oscillation-cycle phase-resolved velocity profiles $\tilde{u}$, $\tilde{v}$ and $\tilde{w}$ in near-wall region from 0.15 mm up to $y=1$ mm along spanwise direction z in a grid with 15 bins in x , 40 bins in y and 20 bins in z direction for data of three merged runs at $Re_\tau = 250$ and $f_{osc} = 50$ Hz.

varying parameters is carried out, based on only one measurement run per parameter combination, respectively. The evaluation aims at providing first insights into parameter-dependent characteristics of flow structures and rather serves as a preliminary study to possible future experiments. Aspects of the evaluation of the parameter-dependent flow topology are inspired by numerical simulations of the PA-array interaction with a laminar flow [191].

For the interpretation of the measurements, it is important to note that the characteristic wall-near layers of a turbulent channel flow scale with the viscous length scale of the flow (see Section 2.1.2). Consequently, at higher Reynolds numbers, the physical thickness of these regions decreases and the plasma forcing, imposed at the same physical height [91, 92], interacts with the flow at different characteristic layers. Therefore, the relation between the thickness of characteristic wall-near layers and the impact height of applied forcing is considered in the parametric comparison. The parameters were selected to maintain a constant ratio of the oscillation frequency-dependent theoretical penetration depth δ (introduced in Equation 2.23) of the oscillating wall reference case to the Reynolds number dependent viscous length scale δ_ν of the non-actuated channel flow. The respective pairs of parameter combinations with constant ratio δ/δ_ν are additionally associated with the same dimensionless oscillation period in viscous units T_{osc}^+ , as shown in Table 5.2. In particular, δ/δ_ν and T_{osc}^+ were constant between the cases with parameters $Re_\tau = 250$, $f_{\text{osc}} = 50$ Hz and $Re_\tau = 350$, $f_{\text{osc}} = 100$ Hz, as well as $Re_\tau = 250$, $f_{\text{osc}} = 25$ Hz and $Re_\tau = 350$, $f_{\text{osc}} = 50$ Hz. Note, however, that the penetration depth represents the frequency-dependent, ideal case of Stokes-layer actuation, from which the plasma-based forcing deviates.

Analogous to Figure 5.25, Figures 7.6, 7.7 and 7.8, positioned in Appendix A to maintain the flow of the text in this chapter, show the phase evolution of three component velocity fields for different combinations of flow and forcing parameters within the same streamwise x range. Generally, the formation of vortical structures is observed in the channel cross-plane for all studied cases. The fields appear less regular when derived from reduced data density, while still displaying consistent topological structures particularly for phases with pronounced vortex formation. For the case of $Re_\tau = 250$ and $f_{\text{osc}} = 25$ Hz, no forcing effect toward the negative z direction is visible for phases $\varphi = 4/3\pi$ to $\varphi = 11/6\pi$ in the positive z region. This observation indicates a local malfunction of the PA array in this region.

The cross-plane velocity fields enable a comparison of the respectively developing vortical structures. The vortices appear most pronounced and vertically expanded for the case of $Re_\tau = 250$, $f_{\text{osc}} = 25$ Hz and least developed and vertically expanded for $Re_\tau = 350$ and $f_{\text{osc}} = 100$ Hz. Despite the clear differences between the wall-motion based and plasma-based actuation, this trend can be interpreted in the context of the penetration depth of a laterally oscillating wall (see Section 2.1.4), which also decreases for increasing oscillation frequencies. Furthermore, the spanwise distribution of the streamwise velocity $\tilde{u}$ is most homogeneous in case of $Re_\tau = 350$, $f_{\text{osc}} = 100$ Hz and least homogeneous for $Re_\tau = 250$, $f_{\text{osc}} = 25$ Hz. This is evident from the distinct semicircular regions of low $\tilde{u}$ velocities in the cross-plane above the actuator surface in the upper four plots.

The direct extraction of quantitative WSS values from the mean velocity gradient in the viscous sublayer region is not sensible based on the present measurement data as outlined above in Section 5.4.1. Despite this restriction in terms of quantitative diagnostics, a comparison of spatially and temporally averaged velocity profiles in the outer flow region farther away from the wall may still provide interesting insights. Figure 5.28 presents these profiles for the four different parameter combinations together with the respective base flow case. The curves consider complete oscillation cycles and regions of full spanwise wavelengths λ_z , while excluding areas of reflection artifacts. All profiles show a velocity increase near the wall and a decrease further up in the log-law region, which is consistent with the earlier results of Hehner at $Re_\tau = 250$ and $f_{\text{osc}} = 50$ Hz [87]. The near-wall

velocity increase suggests a global increase in WSS for all considered parameter combinations. The profiles of forced and base flow case differ only slightly at $Re_\tau = 350$ and $f_{osc} = 100$ Hz, whereas a more pronounced steepening of the velocity profiles near the wall is observed for $Re_\tau = 250$ and $f_{osc} = 25$ Hz. Particularly, the mean velocity profile plots indicate a disadvantageous drag effect of the actuation at lower oscillation frequency and Reynolds number. Based on these observations, strong vortical motion in the channel cross-plane and the related spanwise inhomogeneity of the streamwise velocity may indicate unfavorable forcing effects, as has been previously described by Jukes et al. [101]. The latter work reported increasing drag reduction at decreasing oscillation periods, which is consistent with the smaller drag increase at higher oscillation frequencies observed in the present experiment. However, the direct comparability is limited, as the earlier study considered a different array configuration and frequency range. Furthermore, drag effects were evaluated downstream the actuated region in a boundary layer flow. The flow fields and mean velocity profiles corresponding to the parameter combinations with the same ratio δ/δ_ν and T_{osc}^+ , respectively, do not exhibit distinct similarities. This observation confirms that the ratio, being derived from the theoretical penetration depth δ of the oscillating wall reference case, does not represent the dynamics of the present configuration.

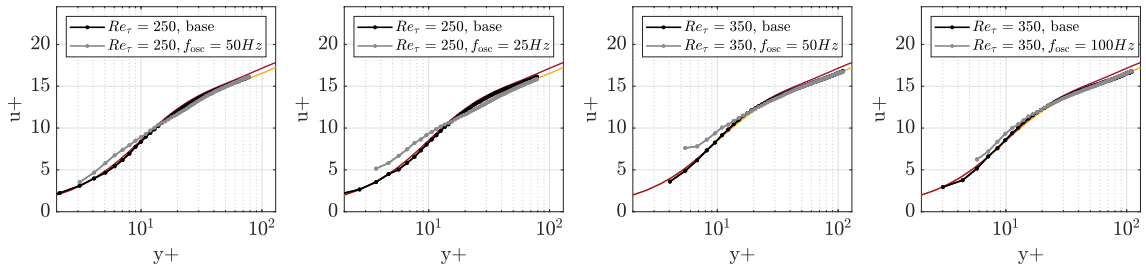


Figure 5.28: Time- and space-averaged mean velocity profiles of forced flow (grey) and respective channel base flow (black) measurement for different flow and forcing parameters. Reference profiles from DNS are added in red and yellow for $Re_\tau = 180$ and 390 .

In summary, the phase-resolved velocity fields in the channel cross-plane illustrate the interaction of the flow in streamwise direction with the formation of vortical structures in the channel cross-plane. In particular, comparing the four combinations of incoming flow and forcing parameters, the formation of strong vortical motion causes stronger spanwise inhomogeneity in the streamwise velocity distribution, which coincides with more pronounced drag increase. The underlying spanwise fluid displacement is likely determined by the interplay of the time scales of the oscillation cycle T_{osc} together with the plasma body-force magnitude and the spatial scales of the spanwise wavelength λ_z . Similarly, Quadrio and Ricco [146] suggested the maximum wall displacement as a characterizing parameter for the oscillating wall actuation, which depends on the oscillation frequency and velocity amplitude. In case of the present plasma-based actuation, air is accelerated predominately in horizontal direction in the plasma-impact zones above the lower electrodes depending on the plasma-induced body-force distribution and amplitude. The resulting velocity distribution moves the fluid in spanwise direction for a certain duration until the reversal of the forcing direction, which depends on the oscillation period T_{osc} . This causes the formation of vortical structures in the cross-plane, influenced by the available spanwise space until the next upper electrode. Based on this observation, it is suggested to investigate the influence of the λ_z and forcing or velocity amplitude (equivalent to A^+ for an oscillating wall) as additional actuation parameters in future experiments.

From the comparison of flow fields and mean velocity profiles at different flow and forcing parameters, further suggestions for future investigations can be derived. Interestingly, the flow exhibits similar, likely advantageous, modifications when either the Reynolds number or the oscillation

frequency is increased. At higher oscillation frequencies, the cross-plane vortical structures become less pronounced and extended in vertical direction, consistent with the trend of decreasing δ at higher frequencies of oscillation (see Equation 2.23). At higher Reynolds numbers the forcing interacts with the flow in characteristic regions farther away from the wall, which also appears favorable. Therefore, the parameter space should be extended toward higher Reynolds numbers and oscillation frequencies to further investigate the potential of such effects.

5.4.3 Flow behavior at convective PA-array onset

In the following, the origin of the described flow structures is studied around the convective actuation onset. The chosen perspective allows to evaluate the flow structures in streamwise direction as third dimension, complementing the observations made in the channel cross-plane discussed above. As described in Section 5.1, a fully developed flow state is achieved in the channel and reaches the PA array near the outlet. While the same Reynolds number of $Re_\tau = 250$ and oscillation frequency $f_{osc} = 50$ Hz were chosen as for the measurements described above, the PA array was moved 30 mm in downstream direction for the present investigation to align the streamwise actuator onset position in the measurement volume under the optical access window (see Table 5.2). The present evaluations are based on one measurement run.

The top six plots in Figure 5.29 show the distribution of all three velocity components $\tilde{w}$, $\tilde{v}$ and $\tilde{u}$ averaged in near-wall bins from a wall distance of 0.35 mm to 0.61 mm in the wall-parallel x - z plane for two opposing phases in the oscillation cycle. The spanwise velocity component $\tilde{w}$ is shown in the top row here to maintain consistency with previous figures. Interestingly, in contrast to the measurements discussed above, the plots show no diagonally oriented region of high velocities as observed in Figures 5.19 and 5.24. Since the measurement setup remained unchanged and only the channel bottom plate with the built-in actuator was moved, the observed effects are likely related to scattering effects caused by local unevenness of the actuator surface or local blockings of laser light from the side of the channel outlet due to the electrical connections or other components.

The actuation onset is positioned at $x = 0$ mm in the present coordinate system. Farther upstream, in the negative x range, the mean velocity distribution remains rather homogeneous with $\tilde{v}$ and $\tilde{w}$ values of approximately 0 m/s. Upon passing the actuation onset, the flow structures change immediately, initiating the generation of the previously discussed vortical flow structures. Interestingly, it requires at least the same x distance for the flow structures and velocity levels to develop in $\tilde{w}$ as in $\tilde{u}$ and $\tilde{v}$, even though the primary forcing initiating the disruption acts in the spanwise direction z . This indicates that the actuation immediately causes the formation of vortical structures from the plasma onset on, rather than vortices forming farther downstream after an initial region dominated by spanwise motion.

A direct interplay of the velocity fields in wall-normal and main flow direction is observed, as areas of positive $\tilde{v}$, i.e. upwards motion, coincide with regions of decreasing $\tilde{u}$. The distributions of both velocity components show a slightly diagonal course of high- and low-velocity regions after the convective plasma onset, which subsequently reorganize parallel to the electrodes ≈ 4 mm downstream of the onset x position.

The two plots in the bottom of Figure 5.29 show the respective cross-plane velocity distributions as contour ($\tilde{u}$) and quiver ($\tilde{v}, \tilde{w}$) plot at $x = 5.5$ mm, which is marked by the vertical red line in the above plots. Topologically, the flow fields show vortical in-plane flow structures as observed before in the measurements farther downstream above the PA array, confirming their formation directly after the convective actuation onset. The $\tilde{w}$ contour plots in the top of the figure, however,

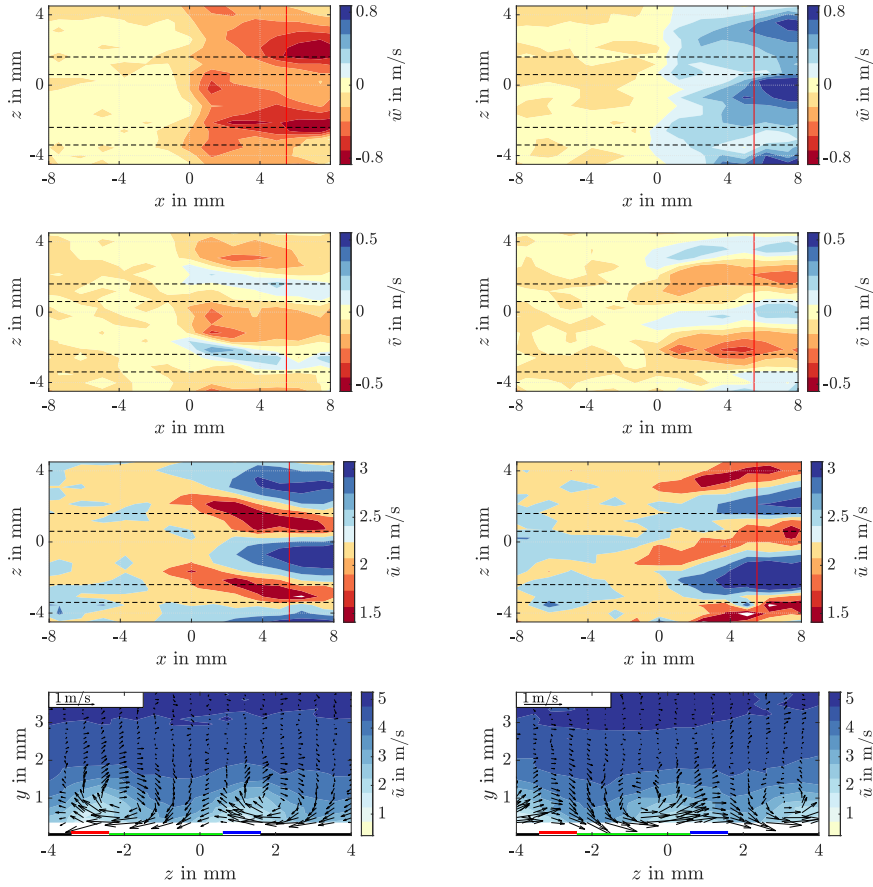


Figure 5.29: Distribution of oscillation-cycle phase-averaged velocities $\tilde{w}$, $\tilde{v}$ and $\tilde{u}$ around the start of the PA array at $x = 0$ mm in wall-parallel plane averaged in near-wall bins from a wall distances of 0.35 mm to 0.61 mm in a grid with 15 bins in x , 30 bins in y and 20 bins in z direction for individual run at $Re_\tau = 250$ and $f_{osc} = 50$ Hz for two opposing phases. The respective velocity fields in the channel cross-plane marked with the red vertical lines at $x = 5.5$ mm are shown as contour plot for $\tilde{u}$ and quiver plot for $\tilde{v}$ and $\tilde{w}$ below. Electrode positions are indicated by dashed lines.

indicate an ongoing development of the flow field, with increasing velocity amplitudes in spanwise direction farther downstream.

5.4.4 Summary and concluding discussion

The interaction of a PA array in BF operation in a turbulent channel flow is characterized by means of time-resolved 3D3C STB measurements at different incoming flow and forcing parameters. Despite experimental limitations, the measurements provide new insights into the plasma-induced flow topology developing above the array. Particularly, building on the previous work of Hehner [87] mainly focusing on statistical flow evaluations, the present study expands the investigation toward a detailed topological interpretation of the developing flow fields throughout the oscillation cycle. The use of volumetric STB measurement technique also enables the observation of the continuous streamwise evolution of flow structures upon convective actuation onset, thereby bridging the gap between the flow fields obtained at discrete downstream positions in earlier studies. In addition, the experimental parameter space was extended to include multiple combinations of Reynolds numbers and oscillation frequencies, allowing for a systematic comparison of respective flow topologies and associated drag effects.

The results confirm that the discrete forcing positions along the PA array upper electrode edges lead to a spanwise-periodic but inhomogeneous velocity distribution as already observed in previous experiments using the same PA array and operation concept [87]. In this context, reproducibility of the forcing in earlier studies and regularity of the forcing effects in-between different discharge zones and throughout the oscillation cycle phases are shown. Importantly, the conducted topological analysis of transient streamwise flow development reveals that the plasma-induced oscillatory forcing does not cause isolated spanwise flow motion, but, immediately from the convective plasma onset on, produces a system of three-dimensional flow structures. These are characterized by the well-known vortical motion in the channel cross-plane, locally interacting with the velocity distribution in main flow direction by transporting near-wall low-momentum fluid upwards and higher-momentum fluid from above downwards. This spanwise flow inhomogeneity represents an important difference to the oscillating wall actuation. The velocity distributions in the channel cross-plane 5 mm downstream of the convective plasma-forcing onset qualitatively resembles those observed at around 30 mm. In viscous length scales, these distances from the actuation onset respectively correspond to $\Delta x^+ = 100$ and 600 for $Re_\tau = 250$ and $\Delta x^+ = 139$ and 834 for $Re_\tau = 350$. The velocity amplitudes are observed to develop further within this region.

A detailed analysis of the flow topology in the channel cross-plane throughout the oscillation cycle reveals a systematic, spatio-temporal separation of velocity profiles in the spanwise and streamwise directions due the vortical structures. This aspect represents another key difference to the flow above a physically oscillating wall and clarifies the need to resolve the WSS over the spanwise direction z and the oscillation cycle phase φ .

A topological comparison of measurements taken at different parameter combinations of the incoming flow and the forcing shows a correlation between strong vortical structures and an inhomogeneous distribution of the main flow velocity component in the channel cross-plane with unfavorable drag effects. The study supports that the development of vortical structures is driven by the spanwise fluid displacement in the channel cross-plane, which depends on an interplay of the Re_τ -dependent flow characteristics, the forcing oscillation frequency, the spanwise wavelength of the array and the forcing amplitude and distribution. Consequently, the spanwise wavelength λ_z and the forcing or velocity amplitude are identified as promising additional parameters for future investigations. The forcing amplitude and height are directly linked to the BF duty cycle and array hardware, and are, therefore, less easily adjustable, although they can be modified through the PA design [see e.g. 65, 154, 177]. The qualitative assessment of the drag effect in this study allows for a careful recommendation to apply higher Reynolds numbers and oscillation frequencies in future work.

In this context, it is interesting to consider the characteristic flow scales. While the reference case of a laterally oscillating wall is based on the viscous scales of a turbulent flow and characteristic time scales of the oscillation (see Section 2.1.4), the plasma-based forcing approach additionally involves spatial scales of the plasma impact height and the spanwise periodicity of the electrodes (discussed in Section 2.2.3). It must therefore be concluded that a direct transfer of advantageous parameter combinations of the oscillating wall actuation is not necessarily sufficient, and parametric studies considering only the parameter space of the oscillating wall forcing cannot conclusively answer the question of whether advantageous plasma-based forcing is possible.

Different measurement-related issues limit the scope of the present evaluation. In particular, local illumination artifacts and the observation of unexpected flow behavior in the wall-near flow region exposed to the formation of plasma required to exclude parts of the measurement volume from the evaluation. Thus, the direct quantification of the spatio-temporal WSS distribution is prevented for the current experiments, even though the viscous sublayer region was shown to be

generally accessible with the chosen measurement technique and setup. Consequently, remaining questions need to be addressed in future measurements upon clarifying whether and how the plasma influences the STB measurement performance. In particular, such knowledge is expected to establish a clearer connection between local, phase-resolved flow topology and drag effects, which is important for increasing the understanding of the forcing approach and assessing its potential for drag reduction. Furthermore, the evaluation of acceleration values extracted from continuous particle tracks and Lagrangian flow properties, as applied in the context of the DPTV measurements described in Section 4.3, is not yet feasible based on the present results due to the observed measurement behavior near the wall. Preliminary analyses indicate acceleration magnitudes comparable to but slightly exceeding those obtained in the quiescent air experiments, while exhibiting less uniform behavior over the oscillation cycle. Further evaluations could provide valuable complementary insights into the spatio-temporal distribution of the acceleration and the forcing characteristics of the array in a turbulent flow.

5.5 Comparative discussion of applied measurement techniques

One central objective of this work is the identification of suitable diagnostic methods for the flow measurements above a PA array in quiescent air and a turbulent channel flow. This application poses several challenges, including measurement in close proximity of the array surface, the presence of strong electromagnetic fields and the small channel height of the used facility, which requires a fine spatial resolution. In addition, the study evaluates the suitability of the applied measurement techniques to resolve the mean velocity profile in the viscous sublayer region, which would enable a direct determination of the WSS. This section compares the measurement approaches with respect to their general characteristics, applicability and performance in the conducted experiments and their future potential.

Based on these considerations, three particle-based, optical measurement approaches are investigated, namely DPTV, a LDV-PS system and STB measurement technique. These approaches, along with the specifically applied setups and procedures, differ with respect to their fundamental characteristics. While the LDV-PS system resolves flow velocities along one spatial dimension, DPTV and STB represent volumetric LPT methods. This is achieved with one camera for DPTV and, in the present case, four cameras for STB, representing significant differences regarding setup complexity and price of the respectively required components. Furthermore, a rather simple Matlab-based evaluation is employed for the present DPTV measurements, whereas STB builds upon a comprehensive commercial software for streamlining data acquisition and comprehensive evaluation algorithms suitable for higher seeding densities and larger amounts of data. For the employed LDV-PS system, optical access from a single direction is sufficient, while DPTV and STB are imaging-based techniques that require access for both laser illumination and camera views. A broader overview of experiment requirements, the selection of promising flow-measurement techniques and a comprehensive description of the measurement principles is given in Section 2.4.

In this work, DPTV is applied to capture plasma-induced wall-near flow structures in otherwise quiescent air (see Section 4.3), the LDV-PS system is tested for the application of measurement in a turbulent channel flow (see Section 5.2) and STB measurement technique is employed for measurements with and without plasma forcing in a turbulent channel flow (see Sections 5.3 and 5.4). The experimental success, limitations and potential of the individual measurement techniques is discussed in the context of the conducted experiments.

The newly-developed commercial LDV-PS measurement system allows to detect particles across the entire channel half-height down to the viscous sublayer region at $Re_\tau = 350$, while the applicability is found to be limited by an increasing position-measurement uncertainty at decreasing flow velocity. A parametric study indicates further potential to overcome this drawback based on an improved signal evaluation strategy. This would, however, require implementation within the underlying data processing software of the commercial measurement system.

Both DPTV and STB measurement technique are applied in time-resolved measurements for continuous particle tracking, allowing the evaluation of particle acceleration and Lagrangian track properties. Such perspectives remain to be further explored and established in the interpretation of flow scenarios. Since the extraction of Eulerian flow fields is based on spatio-temporal binning methods, the spatial resolution can be flexibly chosen and is primarily limited by the amount and distribution of underlying measurement data. Thus, sparse instantaneous velocity distributions can be statistically evaluated due to the cyclic character of the oscillating forcing in the present experiments. The velocity measurement uncertainties, although determined with different procedures, are of similar magnitude for both approaches. It is, however, noteworthy that the velocity amplitudes are smaller in the DPTV measurements in otherwise quiescent air than in the STB measurements in the turbulent channel flow, which potentially influences the measurement accuracy. The uncertainty of the out-of-plane velocity component, directed along the camera axis, is around ten times higher than that of the in-plane velocity components for DPTV, but only twice as high for STB.

STB measurement technique is shown to be suitable to resolve mean velocity and Reynolds-stress profiles above the PA surface within the viscous sublayer region of a channel flow at $Re_\tau = 250$, thereby enabling direct extraction of the WSS and providing improved spatial resolution compared to the LDV-PS and previous SPIV measurements in the same facility. However, unexpected measurement results are observed in the direct actuator vicinity during plasma operation, suggesting a possible influence of the plasma on the STB performance. Such effects, and their implications for the applicability of diagnostics in plasma-based flow-control applications, require further investigation.

DPTV is found to be applicable for capturing velocity and acceleration fields in a flat measurement volume down to the PA surface, using comparatively simple low-cost hardware. The achieved wall-near spatial resolution is equivalent to measurements within the viscous sublayer region at $Re_\tau = 250$ in the used turbulent channel flow facility. Further potential for increased measurement accuracy is identified through optimized component selection. The present DPTV experiments apply a not yet well-established measurement technique to an advanced application, partly enabled by modifications of the calibration, tracking and uncertainty estimation procedures. In this context it is important to note that the different measurement approaches applied throughout this thesis presently rely on varying amounts of development work.

In summary, each measurement technique presents distinct strengths and limitations for the wall-near flow diagnostics above PAs. LDV-PS measurements currently suffer from low-velocity uncertainties due to unfavorable signal processing, limiting the applicability in wall-near flows. DPTV and STB offer volumetric information and Lagrangian insights. The STB approach is particularly robust and strong for extended studies due to the commercial software, while its interaction with plasma remains to be further understood. DPTV provides successful characterization of the plasma-induced near-wall flow, although the data evaluation remains largely manual and limited to low seeding densities. Finally, the very small channel height in the experimental facility imposes critical requirements on the spatial resolution, particularly for resolving the viscous sublayer for WSS determination. Consequently, successful implementation of experiments requires careful

planning and setup refinement, since off-the-shelf measurement solutions do not sufficiently address the application requirements.

6 Summary, conclusions and outlook

The present thesis addresses PA arrays for oscillatory flow forcing operated in BF mode [90]. Particularly, the spatio-temporal forcing characteristics relating the discharges and resulting flow effects is experimentally investigated, and the interaction of the actuation approach with a turbulent channel flow is analyzed for varying combinations of incoming channel flow and forcing parameters. Such experiments require the development of precise and durable PAs along with suitable diagnostic methods for discharge and flow characterization, for which different approaches are tested, compared and applied throughout this work. Intermediate conclusions from individual studies are provided at the end of the corresponding sections, and summarized and placed into broader context in this final chapter.

The first research question addresses the practical implementation of PA arrays, focusing on spatial plasma symmetry required in subsequent investigations of discharge and flow properties. In this context, a manufacturing routine involving polymer resin as isolation for the lower electrodes increases the electrical durability and operational lifetime, while ensuring good reproducibility of the forcing effects of previous studies. Furthermore, it is found that beyond the nominal definition of the array-operation concept, the specific geometric arrangement of the electrode connections within each HV group can strongly affect the plasma symmetry in different discharge zones. In particular, large overlap regions of the conductive tape applied for this purpose on the upper and lower side of the dielectric introduce unintended coupling of the applied voltage signals and should therefore be avoided. The conducted experiments furthermore clarify that hardware providing increased electrical power is required to operate a PA array of sufficient length for achieving a fully developed state upon actuation, in which no further development occurs in streamwise direction above the actuator, in the turbulent channel flow considered in this study. In addition, using identical HV transformers might simplify the voltage balancing process.

Different diagnostic methods are tested and applied throughout this work for the characterization of discharge and flow properties, which is represented in the second research question. To resolve phenomena occurring on different characteristic time scales, imaging approaches in different exposure regimes are employed. ICCD imaging is found to be well suited for capturing optical emissions of typical discharge structures at short exposure times within the positive and negative plasma half-cycle. On this basis the discharge development throughout the plasma and oscillation cycle is analyzed using a combined electro-optical measurement approach. These experiments show a linear relation between transferred charge and spatial illumination integral of the discharges by means of simultaneously conducted electrical and optical measurements. In addition, a simpler imaging approach based on less sensitive scientific or consumer cameras with sCMOS and CMOS sensors are applied for a statistical evaluation of discharge emissions using longer exposure times over multiple oscillation cycles. The results show that both camera types enable the assessment of the discharge regularity across the array, demonstrating that such imaging approaches provide fast and cost-effective diagnostic means, complementing electrical measurements.

The applied flow-measurement techniques meet demanding experimental requirements arising from the immediate wall vicinity, the presence of the plasma and the limited actuation region. In the turbulent channel-flow measurements, the small channel height poses an additional challenge to

achieve the intended resolution of the flow with high velocity gradient in the viscous sublayer region enabling direct WSS evaluation. Three potentially suitable optical flow-measurement techniques are selected and tested throughout this work. The applicability of a commercial LDV-PS measurement system, which is used to capture wall-near flow velocities in a turbulent channel flow without plasma-based forcing, is found to be limited by an increasing position-measurement uncertainty at small flow velocities. Thus, measurement noise and velocity fluctuations in turbulent flows can not be distinguished and the measurement of mean velocities is prevented for small flow velocities in direct wall vicinity. Consequently, the application of the system for the measurements characterizing the plasma-based forcing is not feasible. However, in a separate characterization study, the observed effect is found to be related to the underlying signal-processing routine of the commercial measurement system, as demonstrated by a significant dependence of the measurement uncertainty on the employed processing parameters. This observation, together with related findings reported during initial measurement-technique development [170], suggests this technique has further potential through improved signal-evaluation strategies.

In subsequent experiments, two measurement techniques based on continuous particle tracking are identified to be well suited for the investigation of flow fields at high spatial resolution and sufficient accuracy in direct wall vicinity. STB measurement technique provides a comprehensive tool for data acquisition and evaluation based on robust particle-tracking algorithms integrated in a commercial software. The applicability for measurements of mean velocity and Reynolds-stress profiles is demonstrated in a turbulent channel base flow above a non-operated PA array at $Re_\tau = 250$, thereby establishing a measurement approach that enables the experimental investigation of wall-bounded flow-control applications in the present facility. Despite the small channel height, the mean velocity profile is resolved within the viscous sublayer region, allowing the extraction of WSS and viscous flow scales. However, unexpected measurement behavior is observed in measurements of forced flow cases during actuator operation. While the effects are characterized in detail, their underlying cause remains an open question. Further investigations are therefore required to assess the suitability of STB in the presence of plasma and clarify potential interactions, which currently limit the application to flow regions farther away from the wall. The DPTV measurement technique is successfully applied to measure the plasma-induced flow in direct wall proximity in otherwise quiescent air. Velocity and acceleration data is extracted from captured particle tracks, and additional Lagrangian properties are considered in the evaluation. In particular, information about the flow structures is obtained from the local track-curvature radius. The conducted DPTV measurements rely on the development and implementation of approaches for calibration and uncertainty estimation, which expand the practical applicability of the measurement approach toward the quantification of previously unknown flows in direct wall vicinity. Further potential to increase the measurement accuracy is identified through optimized component selection and further refinement of calibration and particle-tracking procedures. As a relatively recent approach, the technique currently involves a significant number of manual operations, which imposes additional effort especially when conducting extended measurement studies. Overall, the results demonstrate that experimental diagnostics in a channel of small height represent a critical factor in the investigation of flow-control approaches. The conducted measurements confirm the advantages of particle-tracking based methods for these applications, as they allow flexible spatial resolution of extracted flow fields and help to overcome challenges associated with a decreasing amount of detected particles near the wall [105, 165].

The experiments employing ICCD-imaging, electrical diagnostics and DPTV flow measurements collectively describe the spatio-temporal forcing characteristics of the applied plasma-based actuation approach in otherwise quiescent air, as motivated in the third research question. First, the combined electro-optical study verifies that the PA array, operated in rapidly modulated BF

mode, functions as intended regarding the spatio-temporal discharge scheme. It is shown that the structure of occurring discharges immediately responds to the continuously changing V_{pp} , and that opposing discharges in the overlap region occur successively within the time scales of a plasma cycle. Second, the velocity and acceleration fields developing throughout the oscillation cycle are captured in a thin volume above the array using DPTV, enabling the correlation of optical, electrical and fluid-mechanical effects. Specifically, the voltage settings, discharge-current peaks, optical emissions and acceleration response occur simultaneously, whereas the corresponding response in the velocity field is affected by convective and inertia effects, which are quantified in the measurements as spatial and temporal offsets. In addition, it is shown that a homogeneous distribution of optical discharge emission and plasma-induced acceleration and velocity fields in-between different discharge zones is achieved despite the highly dynamic character of the applied BF operation, provided that the voltages for all four electrode groups are balanced well. Small, statistically distributed local irregularities are observed along the electrodes, especially in the overlap region at duty cycles larger than 50 % when the voltages are close to the breakdown voltage. Since, however, no pronounced deviations between the intended and actual actuation are identified, the findings confirm the functionality of the present PA arrays operated in BF mode regarding spatio-temporal discharge patterns and flow response, thereby providing a reliable basis for further investigations.

The findings related to the fourth research question address the interaction of the BF-driven PA array with a turbulent channel flow, and examine how the resulting flow structures differ from those induced by laterally oscillating wall actuation. Volumetric STB measurements reveal the development of three-dimensional flow structures above the array in streamwise direction immediately upon convective forcing onset, which manifest as vortical patterns in the channel cross-plane. These structures are associated with the local downwash of high-momentum fluid and upwash of low-momentum fluid due to discrete forcing positions, inducing a spanwise inhomogeneity of the main-flow velocity distribution. As a consequence, the WSS varies not only over the oscillation phase but also along the spanwise direction. The spanwise forcing inhomogeneity and induced vertical motion constitute major differences between the plasma-induced flow and the Stokes-layer flow above a physically oscillating wall [164].

As collectively observed in the DPTV and STB experiments in quiescent air and the turbulent channel flow, the exact characteristics of developing flow structures are a result of fluid displacement in the channel cross-plane throughout the oscillation cycle, which is influenced by the interplay between Re_τ , f_{osc} , λ_z , forcing distribution and amplitude. Consequently, the parameters considered for oscillating wall forcing, i.e., Re_τ , f_{osc} and A^+ (see e.g. [76, 145]), are not sufficient to describe the plasma-based approach. A parametric study with varying values of Re_τ and f_{osc} indicates a drag increase in comparison to the unforced base flow for all considered parameter combinations. However, the drag increase tends to be weaker when the vortical motion and spanwise inhomogeneity of the main flow velocity distribution are smaller, which is observed for both larger Re_τ and larger f_{osc} . These results show that the drag impact of the applied forcing is strongly parameter-dependent, and demonstrate the importance of conducting a broader parametric study in future investigations, incorporating additional variables and in particular larger values of Re_τ and f_{osc} to assess the drag-reduction potential of the plasma-based forcing approach.

The extent to which the plasma-based approach can reproduce the drag-reduction mechanisms of the oscillating wall remains an open question in current research. In the present experiments it is unclear if such beneficial mechanisms occur, as they may be masked by additionally induced effects, including those caused by the strong vortical motion. Future investigations could be supported by numerical simulations as these avoid several experimental constraints, such as channel-height limitations, the practical feasibility of manufacturing and operating PA arrays of specific length or λ_z or the diagnostics requirements associated with achieving a higher spatial resolution at larger

Re_τ . The spatio-temporal Lagrangian acceleration data obtained from continuous particle tracking provides valuable reference data to support the numerical implementation and validation of the plasma-based forcing. Additionally, the application of the BM-operation concept can be considered in order to modify the velocity amplitude independent of the duty cycle and actuator construction.

Overall, this thesis provides a comprehensive experimental and analytical framework for the investigation of plasma-based flow-control approaches, linking the discharge behavior to the near-wall flow response. The combined evaluation of topological flow characteristics and the WSS effect reveal the complex, parameter-dependent character of the oscillatory flow forcing. These insights provide recommendations for parameter selection and optimization in future studies. The methodological contributions including the identification and refinement of suitable optical flow-measurement techniques establish a foundation for experimental studies in challenging experimental configurations.

7 Appendix

Appendix A: Additional figures

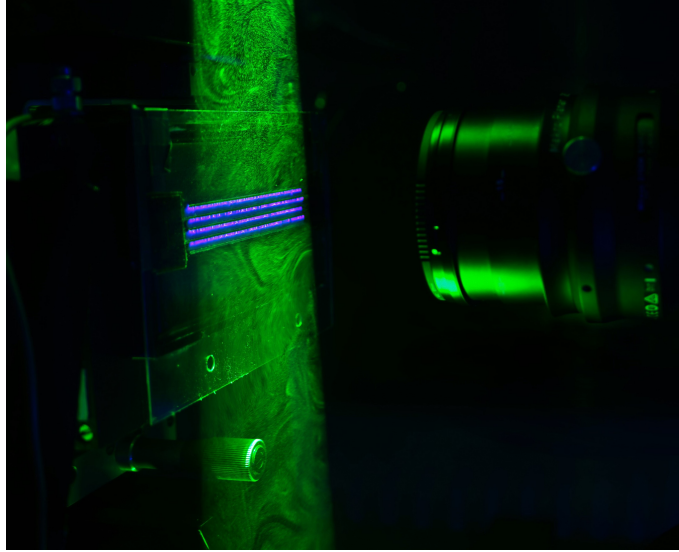


Figure 7.1: Detail photo of experimental setup for the investigation of plasma-induced flow forcing in quiescent air facility by means of DPTV.

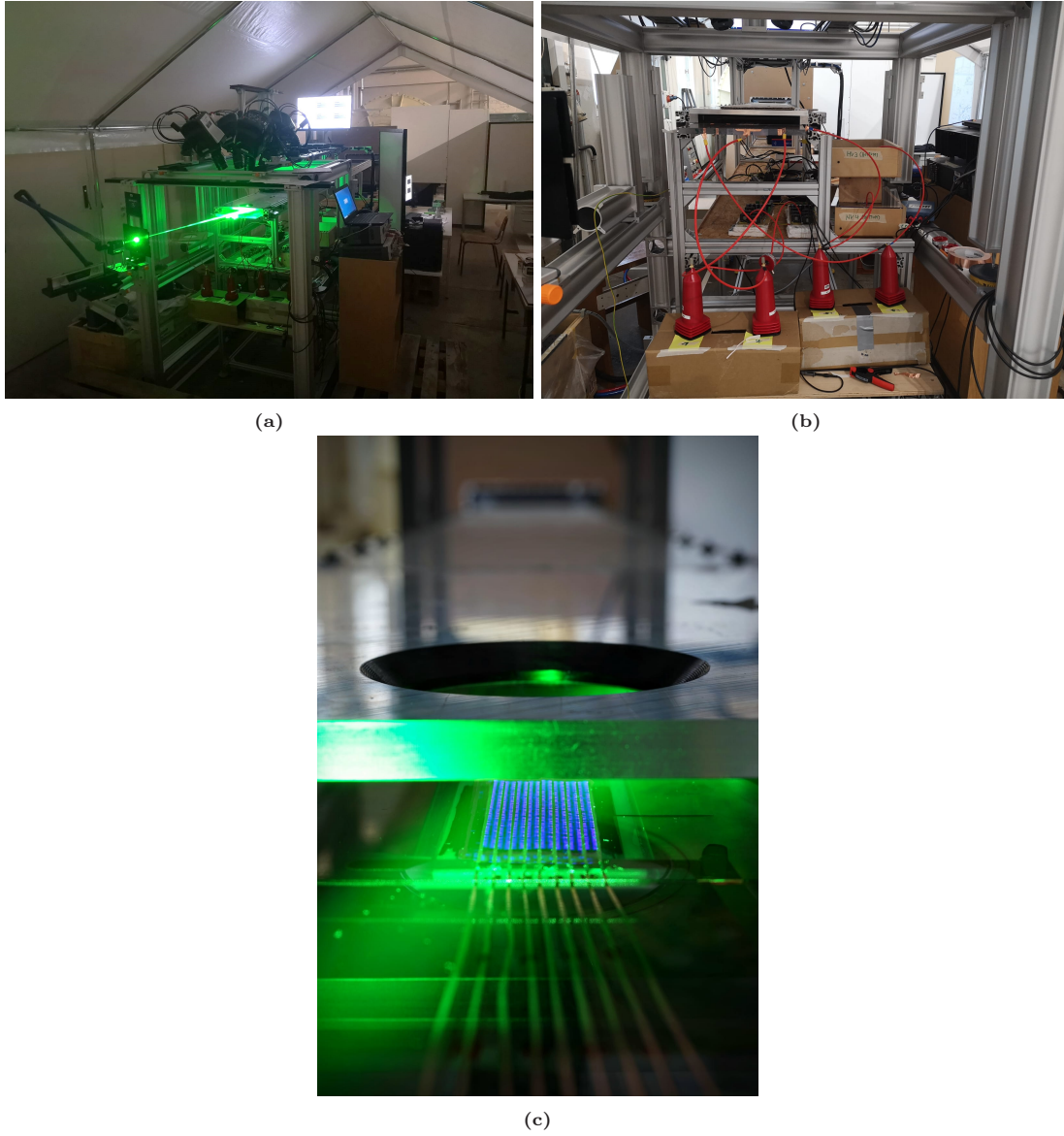


Figure 7.2: Photos of experimental setup for the investigation of plasma-induced flow forcing in turbulent channel flow facility. (a) STB measurement setup at channel test section. (b) Plasma generation setup at channel test section. (c) PA array in the channel underneath the optical access window with illustrated plasma regions along the electrodes.

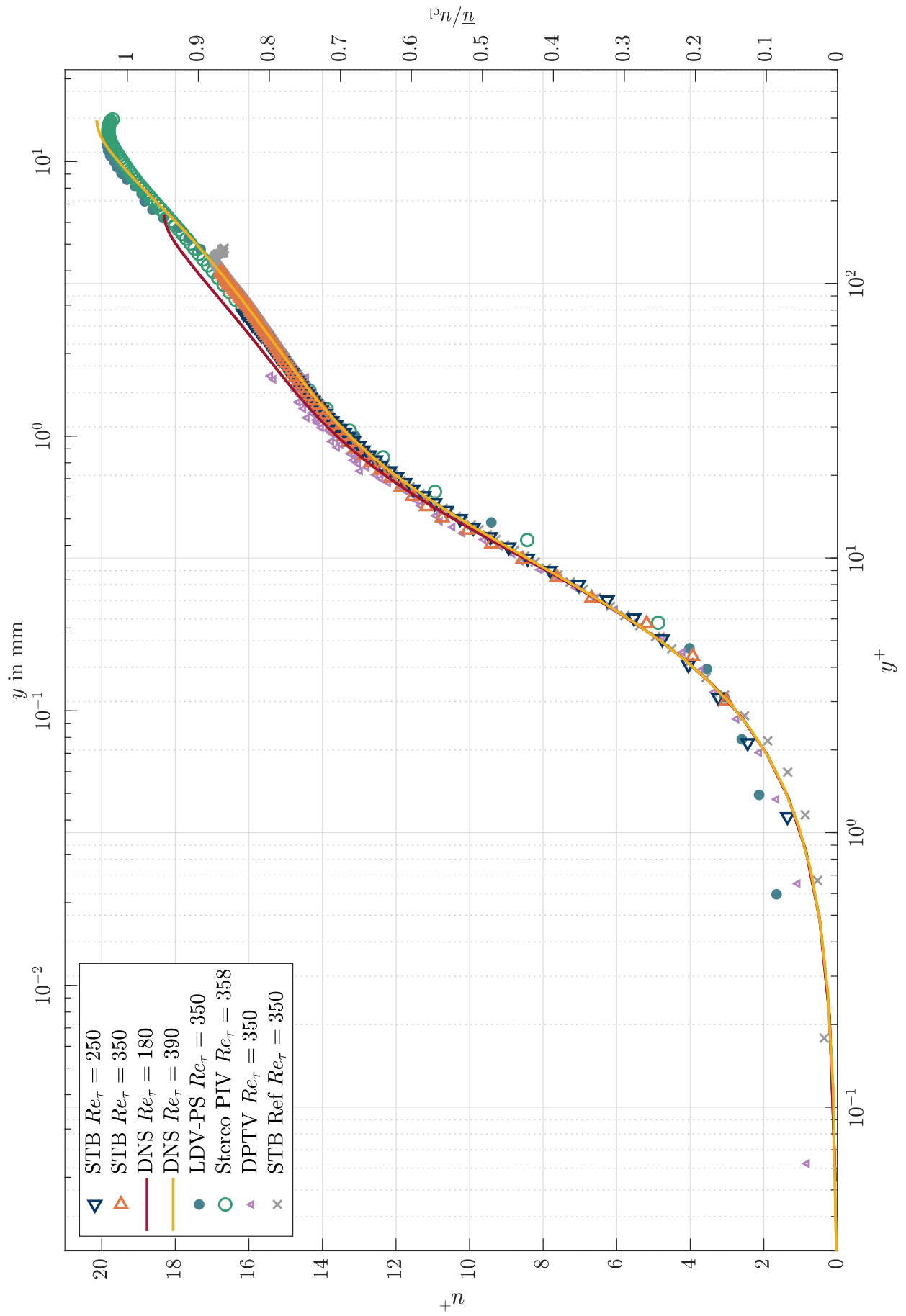


Figure 7.3: Mean velocity u^+ profiles from different measurement techniques and DNS in Re_τ range from 250 to 390. The upper and left axes are scaled for $Re_\tau = 350$.

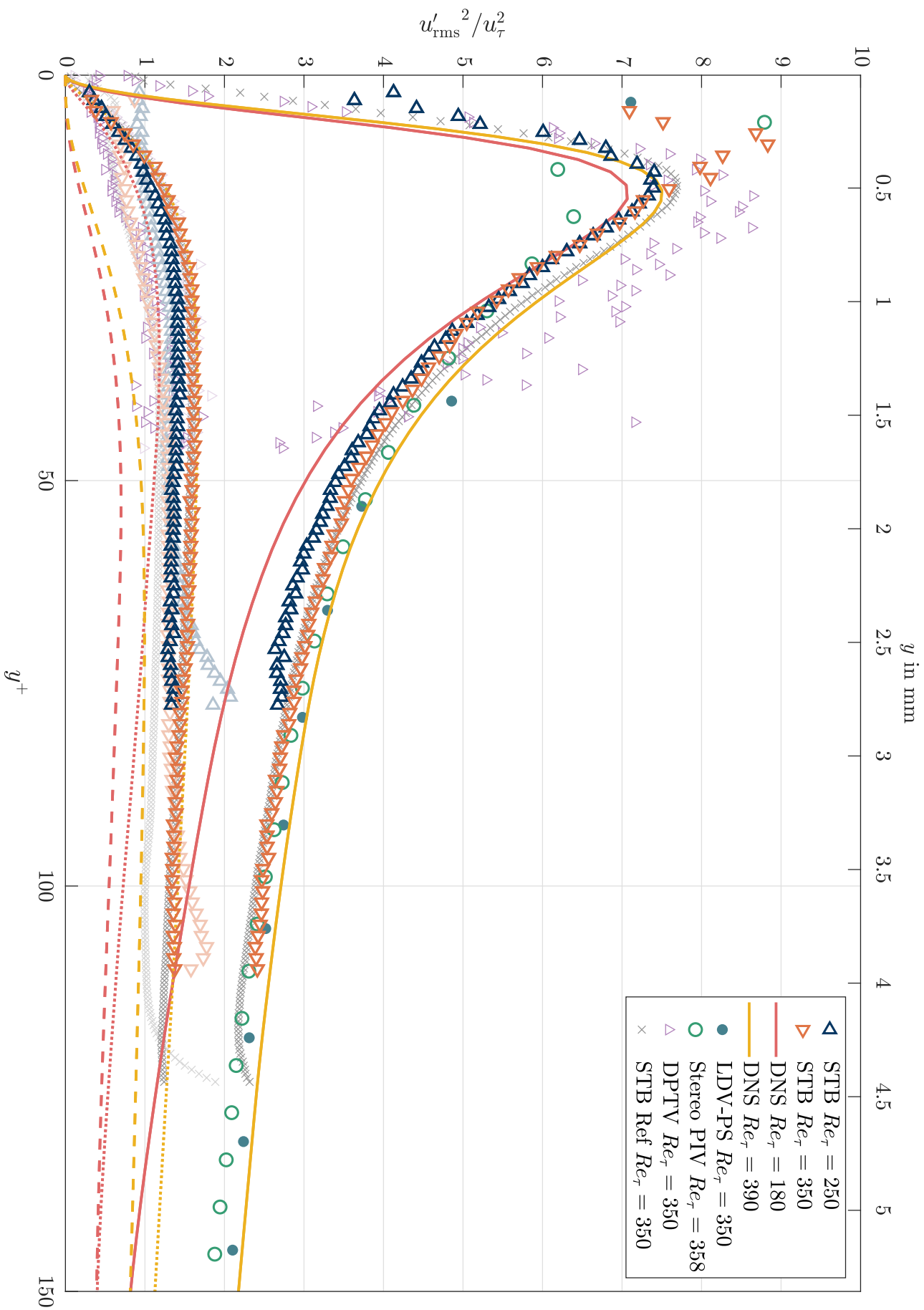


Figure 7.4: Reynolds stress profiles $u'_{\text{rms}}^2/u_\tau^2$ (upper, solid-line curves, stronger-shaded color symbols), $v'_{\text{rms}}^2/u_\tau^2$ (lower dashed-line curves, weaker-shaded color symbols) and $w'_{\text{rms}}^2/u_\tau^2$ (middle, dotted-line curves, stronger-shaded color symbols) from different measurement techniques and DNS in Re_τ range from 250 to 390. The upper axis is scaled for $Re_\tau = 350$.

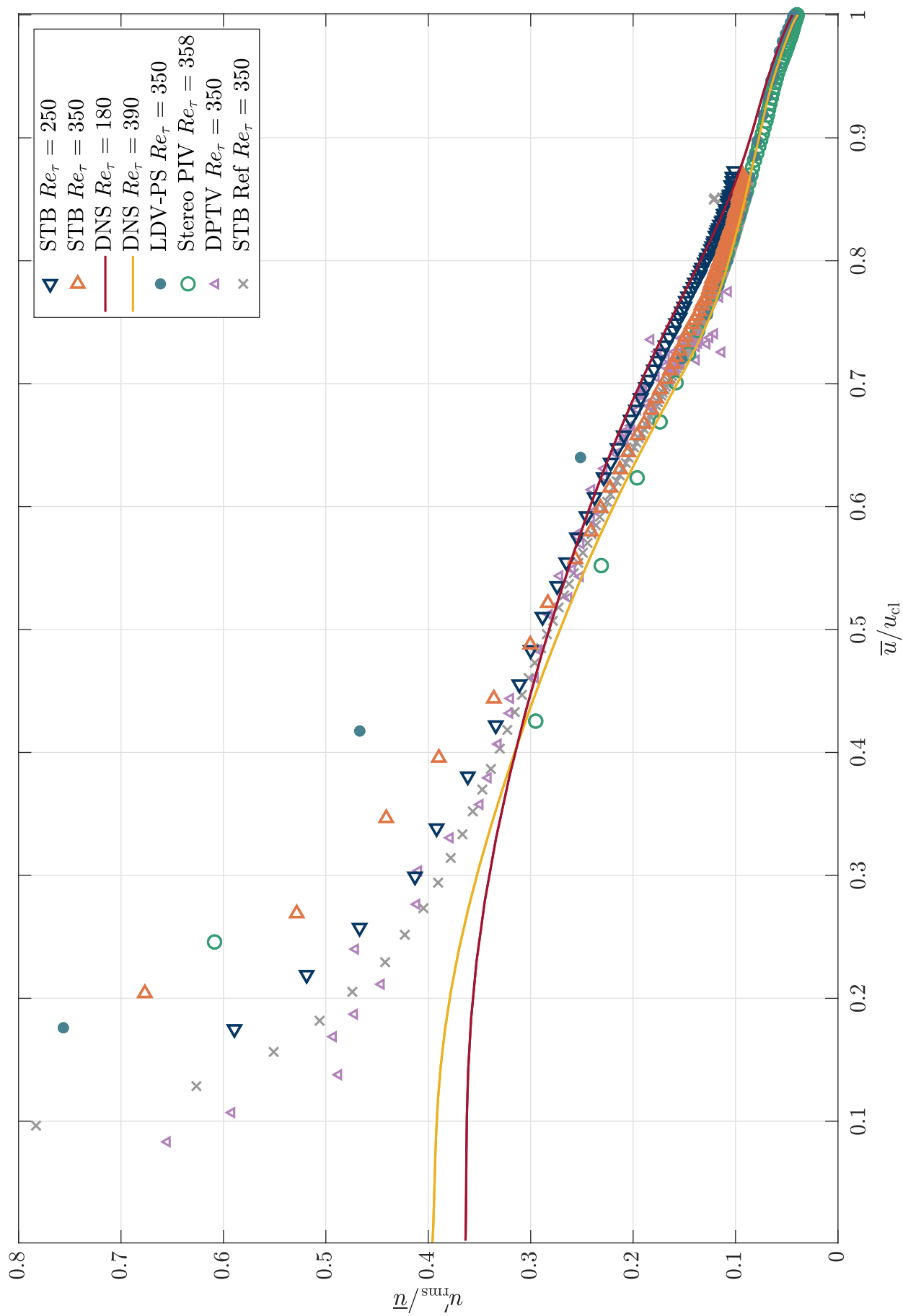


Figure 7.5: Diagnostic plot from different measurement techniques and DNS in Re_τ range from 250 to 390.

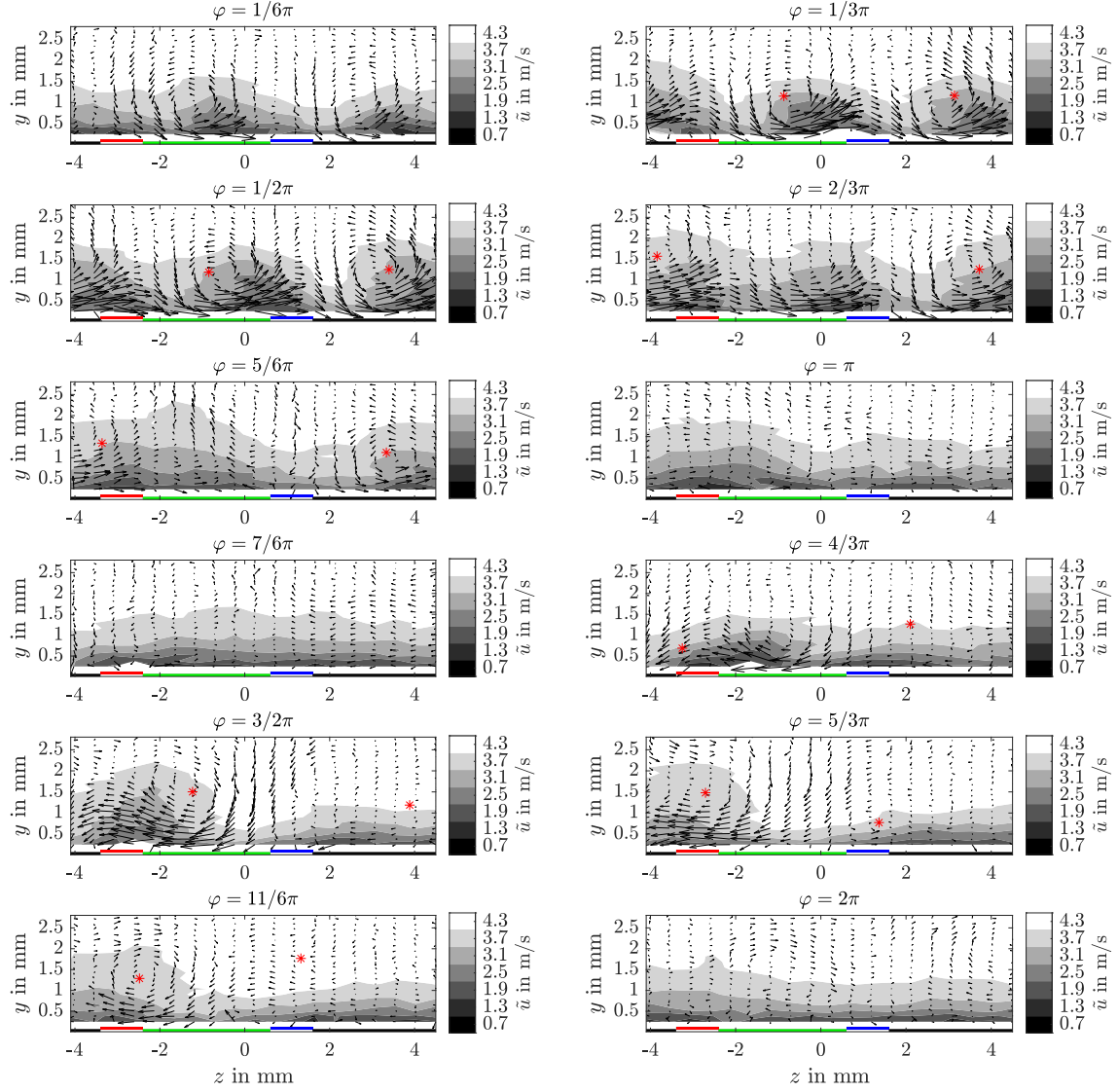


Figure 7.6: Oscillation-cycle phase-resolved velocity fields in channel cross-plane as contour plot for $\bar{u}$ and quiver plot for $\bar{v}$ and $\bar{w}$ in a grid with 15 bins in x , 30 bins in y and 20 bins in z direction for data of one individual run at $Re_\tau = 250$ and $f_{osc} = 25$ Hz. Vortex centers identified based on Γ_1 criterion [83, 202] are shown as red asterisks.

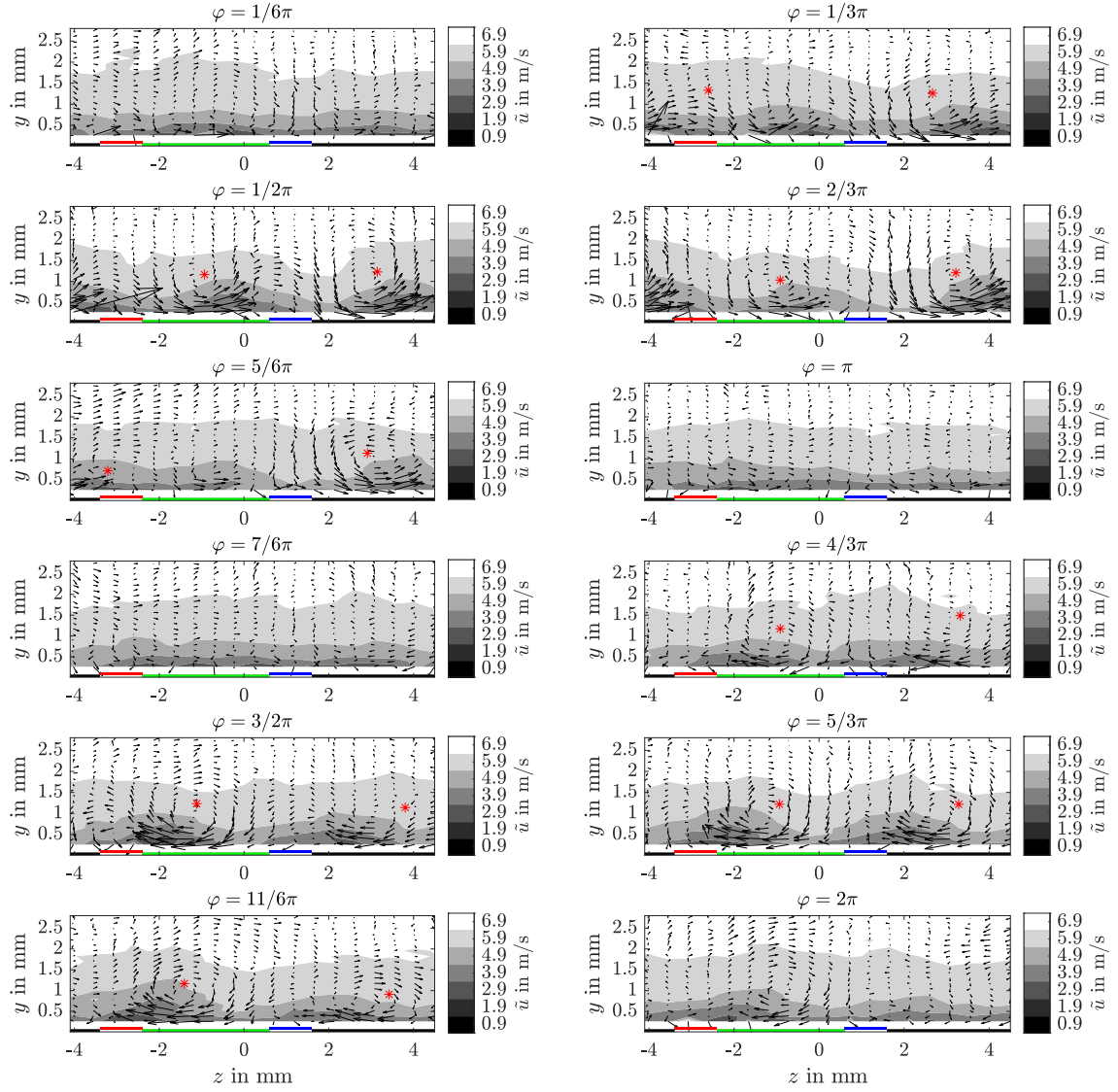


Figure 7.7: Oscillation-cycle phase-resolved velocity fields in channel cross-plane as contour plot for $\tilde{u}$ and quiver plot for $\tilde{v}$ and $\tilde{w}$ in a grid with 15 bins in x , 30 bins in y and 20 bins in z direction for data of one individual run at $Re_\tau = 350$ and $f_{osc} = 50$ Hz. Vortex centers identified based on Γ_1 criterion [83, 202] are shown as red asterisks.

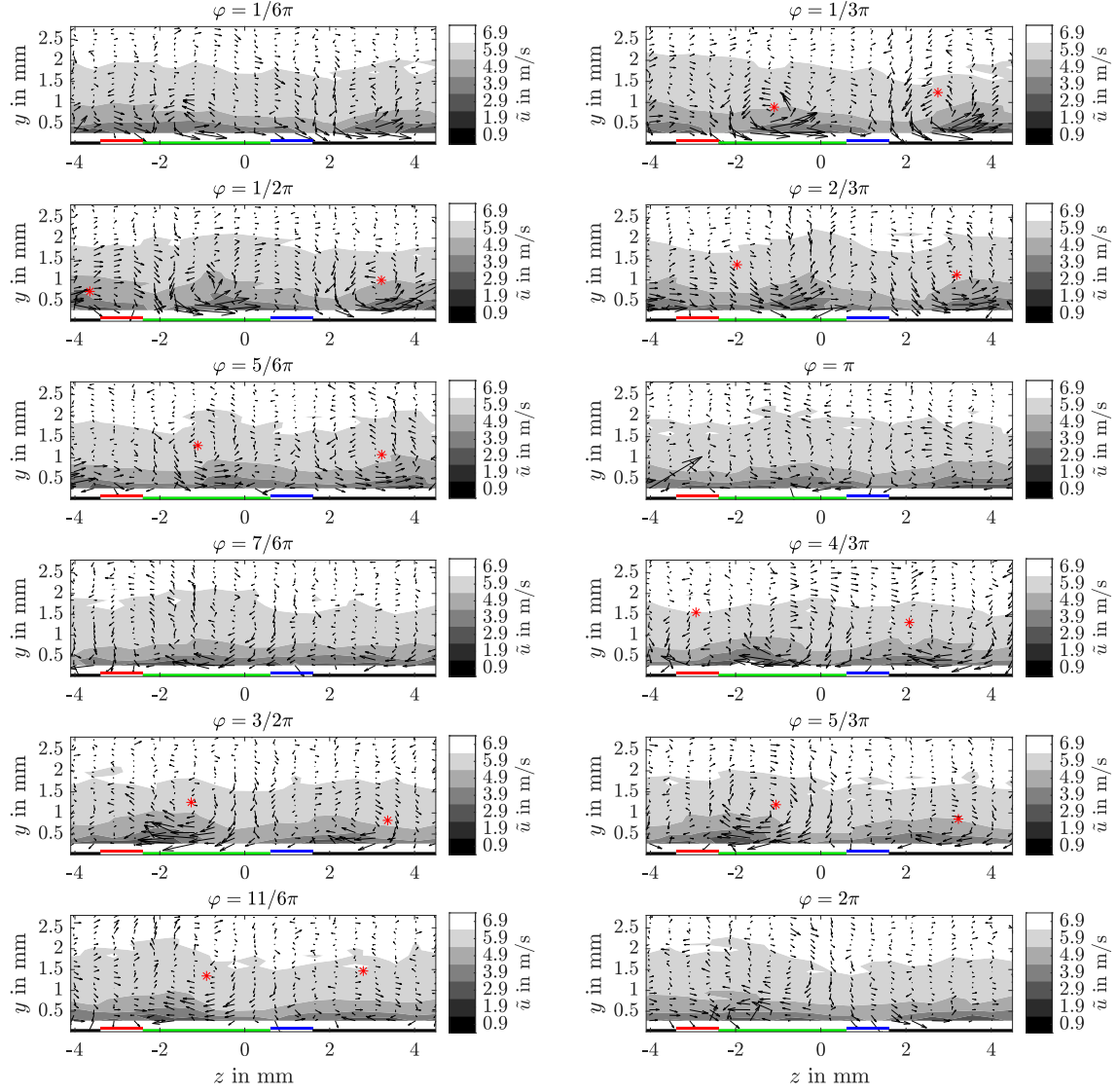


Figure 7.8: Oscillation-cycle phase-resolved velocity fields in channel cross-plane as contour plot for $\bar{u}$ and quiver plot for $\bar{v}$ and $\bar{w}$ in a grid with 15 bins in x , 30 bins in y and 20 bins in z direction for data of one individual run at $Re_\tau = 350$ and $f_{osc} = 100$ Hz. Vortex centers identified based on Γ_1 criterion [83, 202] are shown as red asterisks.

Appendix B: MATLAB scripts

The following script was used to estimate the centerline velocity u_{cl} corresponding to a target friction Reynolds number Re_τ for the channel flow:

```
% MATLAB script to estimate centerline velocity from Re_tau
Re_tau = 200;      % target friction Reynolds number

% Parameter definition
h = 12.6e-3;      % Channel half-height [m]
mu = 18.5e-6;     % Dynamic viscosity of air at 25 C [Pa s]
rho = 1.1839;     % Density of air at 25 C [kg m^-3]

u_tau = Re_tau * mu / (rho * h);
tau_w = rho * u_tau^2;

% Equating the definition of the skin friction coefficient with the Dean
% correlation and inserting the definition of the bulk Reynolds number gives:
Re_b = 0.5 * ((8 * tau_w * h^2 * rho / (0.073 * mu^2))^(1/1.75));

% Bulk and centerline velocities
u_b = Re_b * mu / (rho * h);
u_cl = u_b + 2.4 * u_tau;
```

The following function was used to find the refined channel wall position and friction Reynolds number Re_τ of the channel flow during an experiment based on a comparison of a measured mean velocity profile and a reference composite velocity profile based on the work of Luchini [125]:

```
%% Input:
% measurement data
y                % in mm
u_mean           % in m/s
% fitting parameter space
Re_Tau=linspace(240,260,5);
delta_y=linspace(-50,200,5); % in mu m

%% MATLAB function to estimate the refined wall-position and friction Reynolds
% number from a measured mean velocity profile in a turbulent channel flow

function [Re_Tau_opt,delta_y_opt] = FitProfileLuchini(u_mean, y, Re_Tau, delta_y)

% Parameter definition
h=12.6e-3; %channel half height in m
nu= 15.626e-6; %kinematic viscosity of air in m^2/s at 25 C

u_Tau=(Re_Tau*nu)/h;
delta_nu=(u_Tau).^(-1)*nu;
```

```
y=y*1e3;                                % convert unit from mm to mu m

% Implementation of composite velocity profile according to Luchini 2018
% Coefficients
A_1=1.03;
a_0=-7.374;
a_1=-0.493;
a_2=0.0245;
b_1=0.05736;
b_2=0.01101;
c=0.03385;
d=3.109;
kapa=0.392;
B=4.48;
% outer coordinate (relative height coordinate in channel)
Z=y/(h*1e6);
% corner defect function
H=-0.57*Z.^7;
% wake function
G=Z*A_1+H;

% Shift and nondimensionalize the measured velocity profiles for all
% combinations of Re_tau and delta_y, compute the reference profile based on
% composite velocity profile, evaluate the deviation for all wall-normal
% positions, visualize the results for diagnostics

counter=zeros(length(delta_y),length(Re_Tau));

figure
hold on

for j=1:length(delta_y)
    y_shift=y+delta_y(j);
    for i=1:length(Re_Tau)
        for k=1:length(u_mean)

            % nondimensionalize measured and shifted profile
            u_p_meas(j,i,k)=u_mean(k)/u_Tau(i);
            y_p(j,i,k)=y_shift(k)/(delta_nu(i)*1e6);

            % calculate u+ comparison values for composite velocity profile
            % description
            f_0(j,i,k)=((a_0+a_1*y_p(j,i,k)+a_2*y_p(j,i,k)*y_p(j,i,k))/...
            (1+b_1*y_p(j,i,k)+b_2*y_p(j,i,k)*y_p(j,i,k)))\...
            *exp(-c*y_p(j,i,k))+log(y_p(j,i,k)+d)/kapa+B;
            u_p_comp(j,i,k)=f_0(j,i,k)+G(k);

            % calculate the difference
            if u_p_comp(j,i,k)>0
```

```

        diff(j,i,k)=(u_p_comp(j,i,k)-u_p_meas(j,i,k));
        counter(j,i)=counter(j,i)+1;
    else
        %ignore negative y values due to offset shift
        diff(j,i,k)=0;
    end
end

% plot each profile
plot(squeeze(y_p(j,i,:)),squeeze(u_p_meas(j,i,:)),'-o')
plot(squeeze(y_p(j,i,:)),squeeze(u_p_comp(j,i,:)),'-k')
end
end

xlabel('y+')
ylabel('u+')

% compute sum of quadratic difference between measured and reference profiles
% for all combinations of Re_tau and delta_y

for j=1:length(delta_y)
    for i=1:length(Re_Tau)
        summ_diff(j,i)=sum(diff(j,i,:).*diff(j,i,:))/counter(j,i);
    end
end

% find minimum

ind=find(summ_diff==min(summ_diff,[],'all'));
[ind_dy, ind_re] = ind2sub(size(summ_diff), ind);
Re_Tau_opt=Re_Tau(ind_re);
delta_y_opt=delta_y(ind_dy);

```


8 References

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Acronyms and symbols

Acronyms

AC	alternating current
BF	beat frequency
BM	burst modulation
CCD	charge-coupled device
CMOS	complementary metal-oxide-semiconductor
DBD	dielectric barrier discharge
DC	direct current
DEHS	di-ethyl-hexyl-sebacate
DNS	direct numerical simulations
DPTV	defocusing particle image velocimetry
FFT	fast Fourier transform
FOV	field of view
HV	high voltage
HWA	hot-wire anemometry
ICCD	intensified charge-coupled device
LDV	laser Doppler velocimetry
LDV-PS	laser Doppler velocity profile sensor
LPT	Lagrangian particle tracking
PA	plasma actuator
PET	polyethylene terephthalate
PI	particle image
PIV	particle image velocimetry
PMMA	polymethyl methacrylate
PTV	particle tracking velocimetry
rms	root mean square
sCMOS	scientific complementary metal-oxide-semiconductor

SNR	signal-to-noise ratio
SPIV	stereoscopic particle image velocimetry
STB	Shake-The-Box
WSS	wall-shear stress
xDyC	x spatial dimensions, y velocity components

Latin letter - Upper case

A	spanwise velocity amplitude
B	constant in the log law
B_1	constant in the velocity-defect law
C_f	skin friction coefficient based on bulk velocity
D	duty cycle, wire diameter
D_a	aperture opening diameter
F	force
I	electric current
G	gray-scale image pixel intensity
G_y	mean pixel intensity profile along a horizontal pixel row
G_{xy}	mean pixel intensity
$\overline{G}$	mean background pixel intensity
$\hat{G}_{\sum xy}$	sum of pixel intensities
L	channel length, luminosity distribution on PA surface
M	magnification
N_s	particle image source density
N_y	number of pixel rows
N_x	number of pixel columns
N	number of samples
Q	electrical charge
Re	Reynolds number
Re_b	Reynolds number based on bulk velocity
Re_d	Reynolds number based on centerline velocity
Re_τ	friction Reynolds number
S^{xz}	reproduction scale
S^y	defocus sensitivity

Stk	Stokes number
T_{AC}	period length of the HV signal applied to electrode groups for the generation of plasma
T_{osc}	period length of the forcing oscillation cycle
V	electric voltage
V_{pp}	peak-to-peak voltage
V_b	breakdown voltage

Latin letter - Lower case

a	acceleration
b	channel width
d_p	particle diameter
d_i	particle image diameter
d_0	particle image diameter at a known distance from the focal plane
d_1, d_2	distances of LDV-PS interference fringes
f_{AC}	HV frequency applied to electrode groups for the generation of plasma
f_{bf}	plasma-induced body force per unit density
f_{osc}	oscillation frequency of the forcing
$f_{\#}$	focal number of a lens
f	frequency, focal length
f_1, f_2	scattered light frequency of LDV-PS interference fringe systems, Doppler frequencies
h	half channel height
l_{AC}	PA array length
m_d	slope of the defocusing function
p_w	pressure at the wall
p_s	stagnation pressure
p_0	static pressure
q	LDV-PS calibration curve
q^*	linearized LDV-PS calibration curve
r	radius
t	time
t_ν	viscous time

u	velocity
u_{cl}	centerline velocity
u_{b}	bulk velocity
u_{τ}	friction velocity
u'_{rms}	normal Reynolds stress
y^*	particle distance to focal plane
y'	tilted coordinate axis aligned with LDV-PS measurements
y_{ind}	y -bin index
$\{u, v, w\}$	velocity components
$\{x, y, z\}, \{x, y\}$	coordinates in flow measurements, pixel indices in ICCD measurements
$\{\hat{x}, \hat{y}\}$	coordinates in ICCD measurements

Greek letters - Upper case

Δt_{gw}	camera gate width
Δx_{bf}	lateral extension of the discharge-filaments optical emissions
$\Delta z_{\text{a,bf}}$	lateral extension of the momentum transfer
Ω	angular velocity
τ	shear stress
τ_{f}	characteristic time scale of the flow
τ_{p}	particle response time
τ_{w}	wall-shear stress

Greek letters - Lower case

α	tilting angle
δ	penetration depth of Stokes layer
δ_{ν}	viscous length
κ	von Kármán constant, particle-path curvature
λ	wavelength of light
λ_z	spanwise wavelength of the PA array
λ_x	streamwise wavelength of spanwise wall motion
μ	dynamic viscosity
ν	kinematic viscosity

ω	angular frequency of oscillation
φ	oscillation cycle phase
ϕ	rotation angle
ρ	density
$\rho_{\mathbf{p}}$	particle density
σ	standard deviation, measurement uncertainty
$\sigma_{\bar{\mathbf{x}}}$	standard error of the mean

Accents and operators

$\mathbf{x}^+$	viscous-scaled quantity
Δ	difference
$\bar{\mathbf{x}}$	mean
$\tilde{\mathbf{x}}$	phase-resolved mean
$\mathbf{x}'$	total fluctuations
$\mathbf{x}''$	stochastic fluctuations of turbulence
$\hat{\mathbf{x}}$	periodic fluctuations
$\vec{\mathbf{x}}$	vector

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