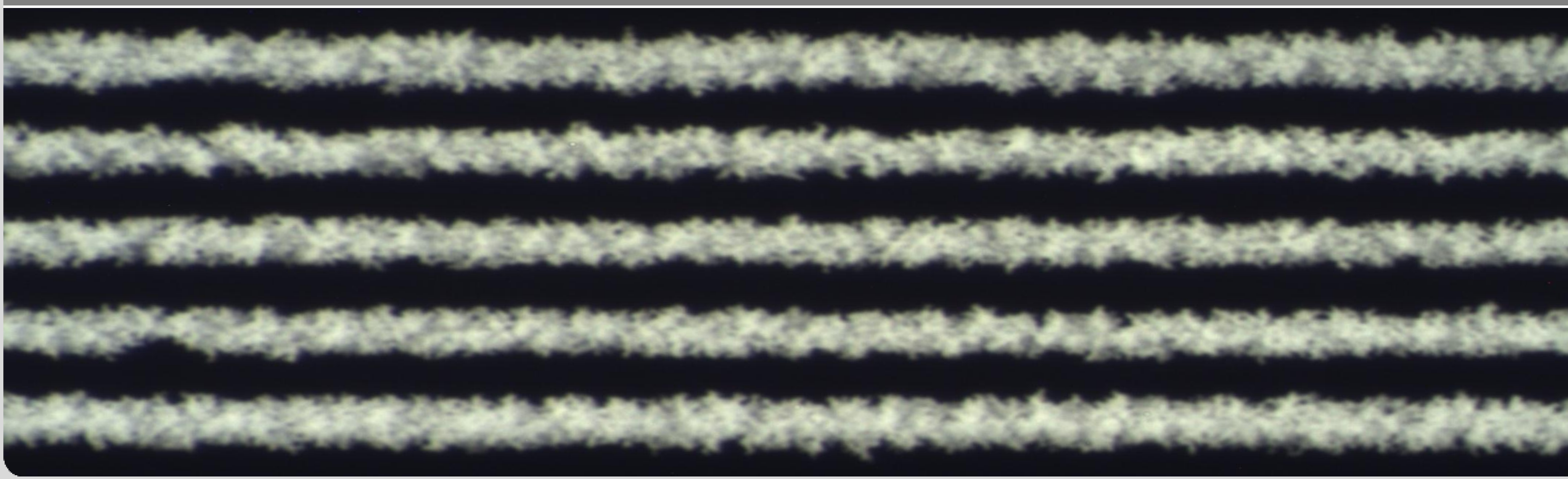
Karlsruhe Institute of Technology

Measuring the single-fiber efficiency of model fibers in parallel arrays

Loading kinetics under inertial conditions

Dipl.- Ing. Thilo Müller

Institute of Mechanical Process Engineering and Mechanics – Gas-Particle-Systems



Further contributors and sponsorship

- Dr.-Ing. Jörg Meyer
- Dipl.-Ing. Mariann Müller
- Prof. Dr. Gerhard Kasper

Karlsruhe Institute of Technology
Institute of Mechanical Process Engineering and Mechanics
Gas-Particle-Systems

Support by a grant from the Deutsche Forschungsgemeinschaft (German Research Foundation) is gratefully acknowledged

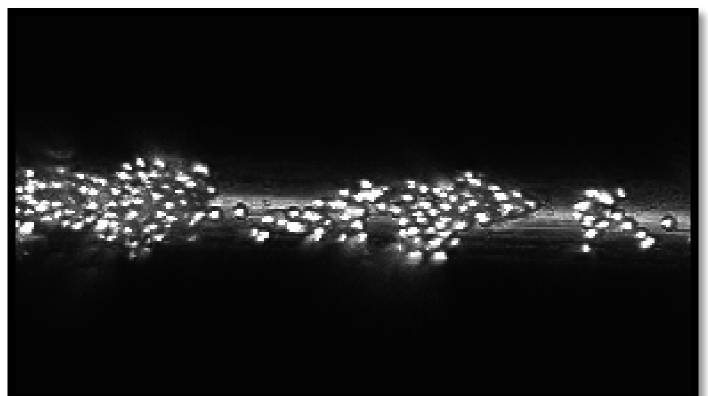
Outline

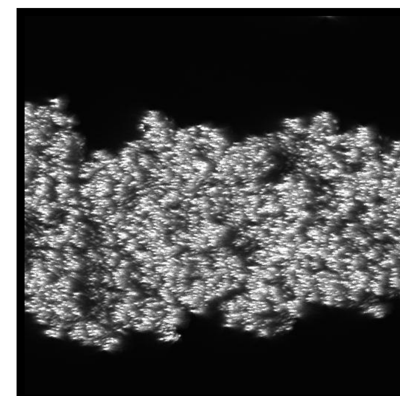
- Motivation
- Experimental setup
- Exemplary results
- Summary

Motivation

Fibrous depth filter media:

- Properties change during filtration
  - Pressure drop Δp
  - Total efficiency E
- Particle structures raise collection efficiency of fibers





Increasing particle load

Fractional efficiency of fibrous media

- Single fiber approach:
  - Fractional efficiency *T(x)*:

$$T(x) = 1 - \exp\left(-f' \cdot \eta(x)\right)$$

  - Geometry-dependent factor *f '*:

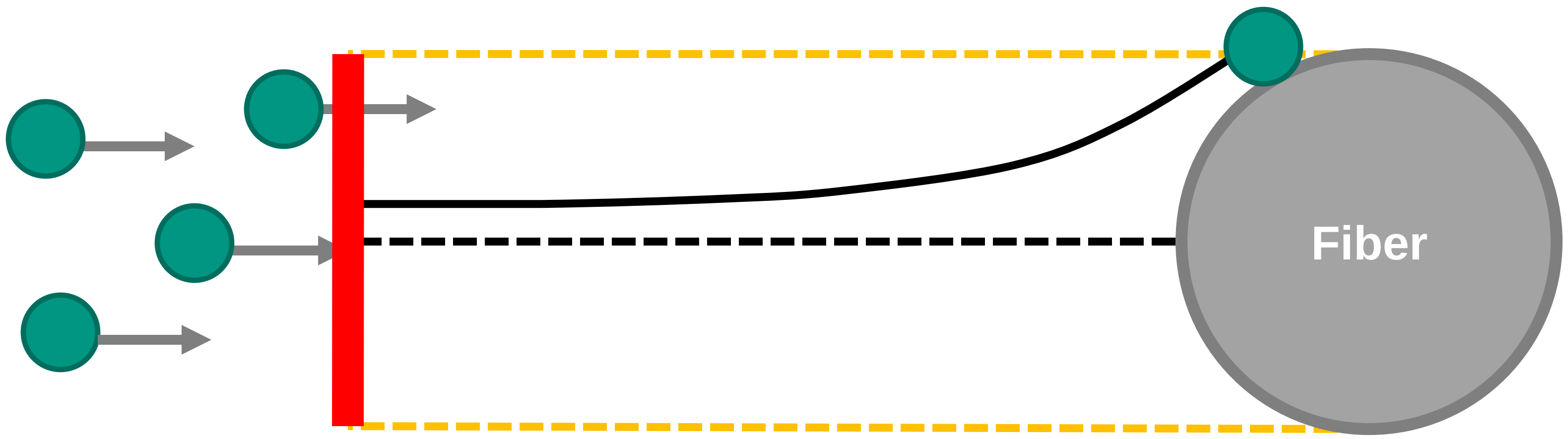
$$f' = \frac{4}{\pi} \cdot \frac{1-\varepsilon}{\varepsilon} \cdot \frac{Z}{D_F}$$

ε: porosity

Z: media thickness

D_F: fiber diameter

Single fiber collection efficiency



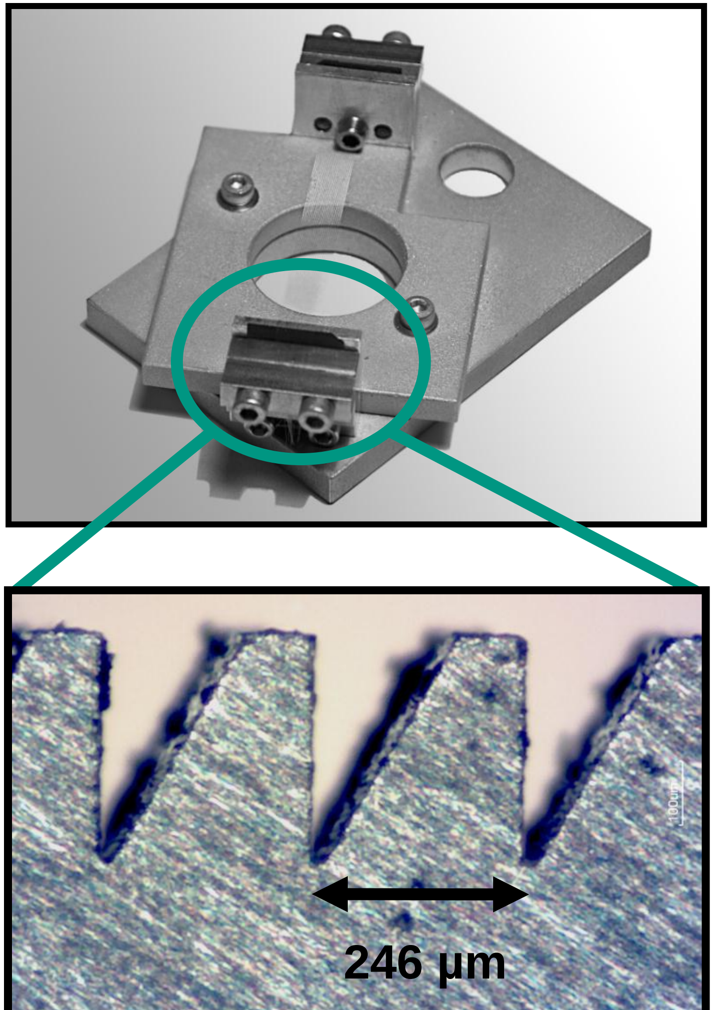
- Single fiber collection efficiency η:

$$\eta = \frac{N_C}{N_A} = \frac{collected\ particles}{incoming\ particles^*}$$

*: only particles entering through the projected area of the fiber (red) are considered in this definition

Experimental setup

Fiber arrays



- Mounting: Micro-combs
  - Precise fiber position
  - 25 parallel fibers
  - Sufficient fiber tension applicable

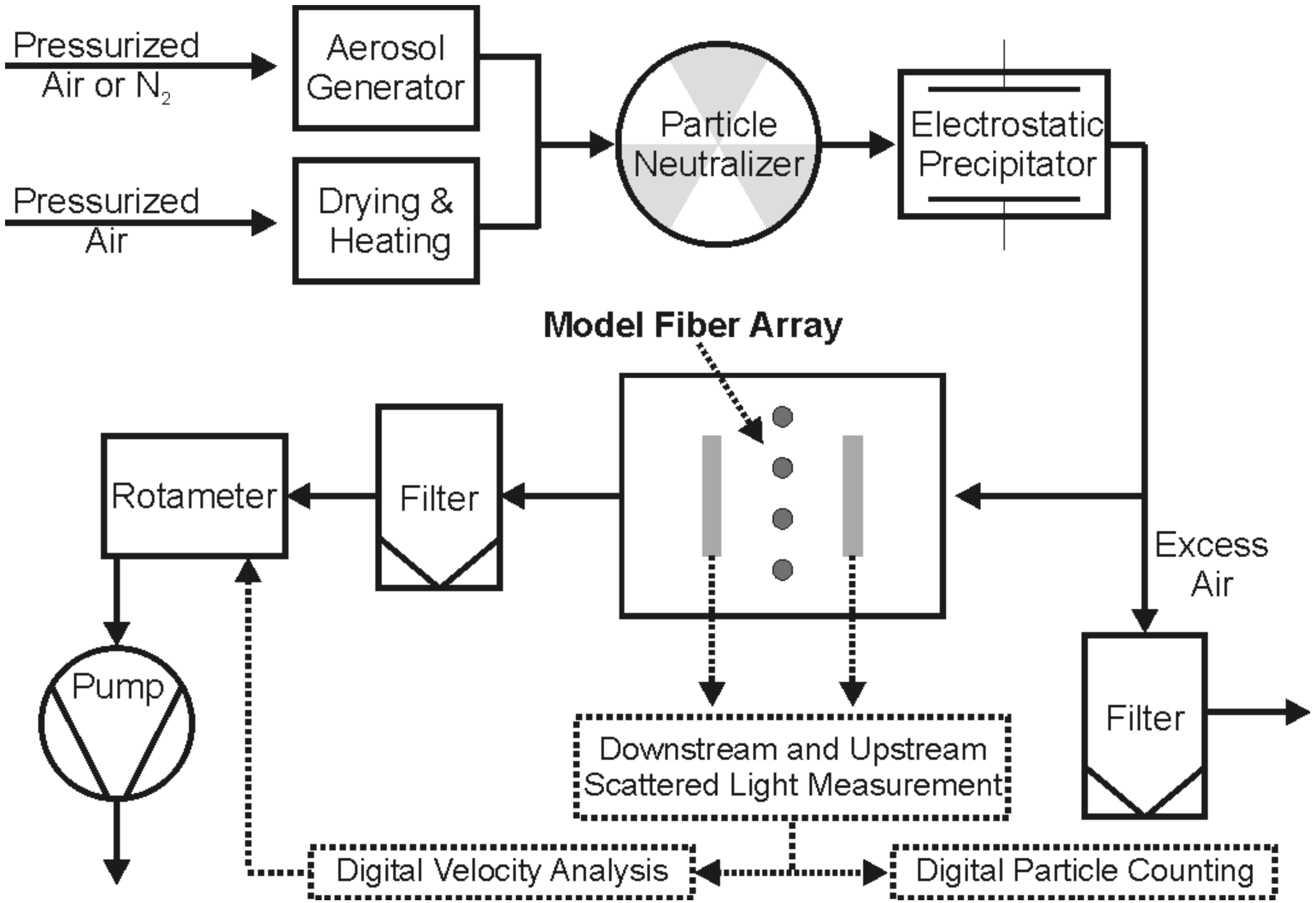
- Variable fiber distance (< 246 µm)

Real fibrous media:

- Flow field influenced by nearby fibers

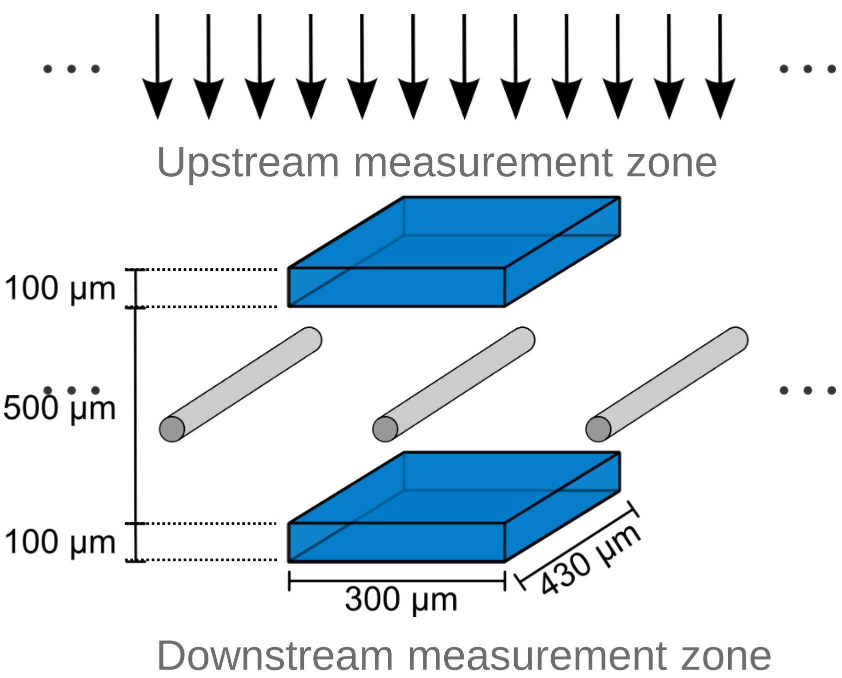
➔ Calculations based on single fiber efficiencies of fibers arranged in parallel arrays lead to more realistic efficiencies [Hoferer, 2011]

Experimental setup



Institute of Mechanical Process Engineering and Mechanics

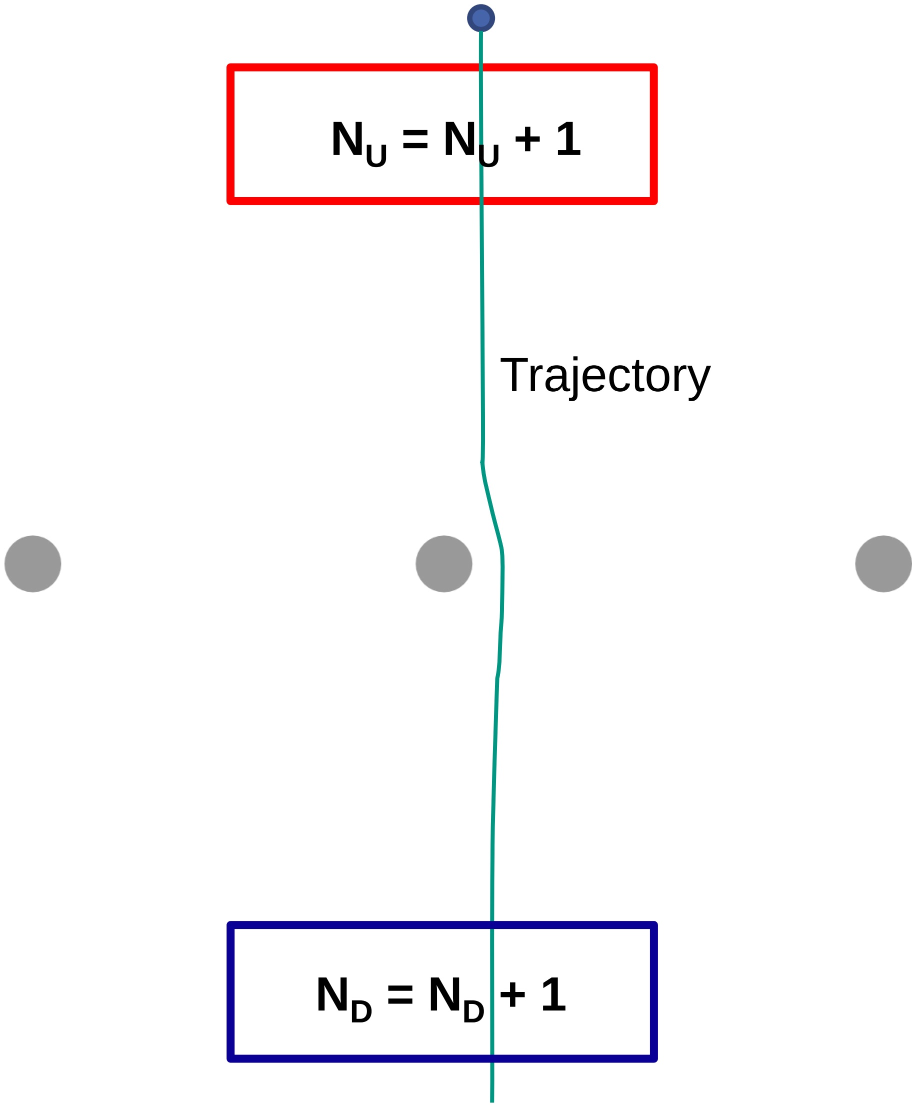
Dual scattered light measurement



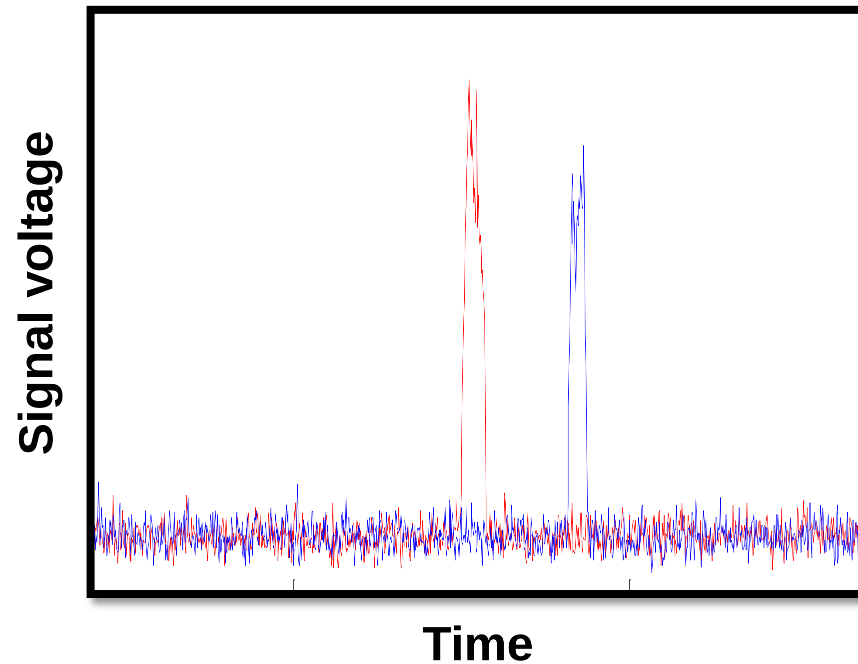
- High-intensity rectangular light beams
- Scattered light detection at 90°

  ➔ Voltage signal
- Fibers are positioned between the measurement zones

Voltage signals

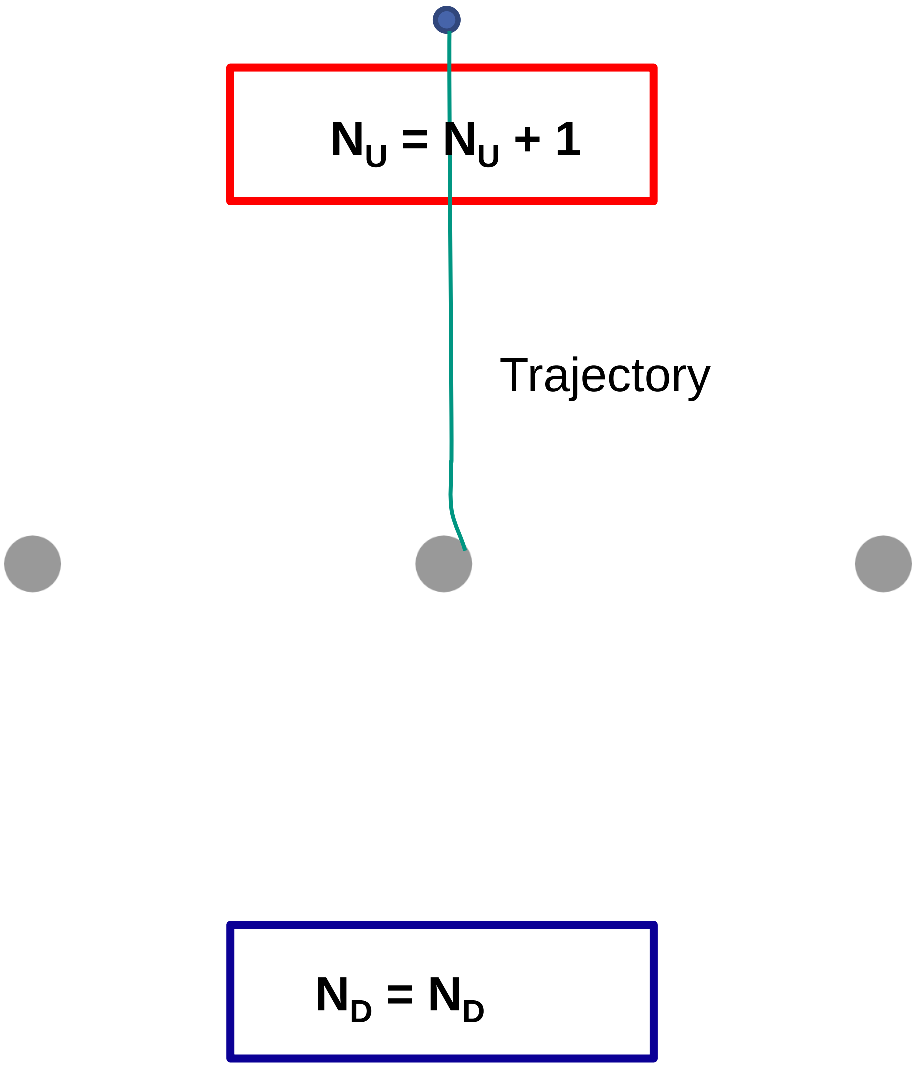


Case 1: Particle passing through array

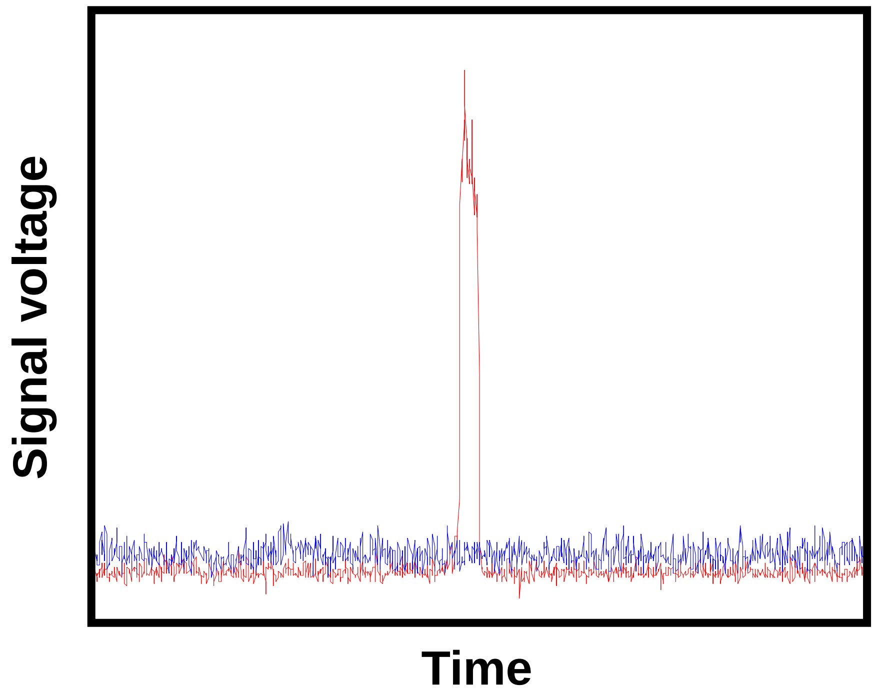


Red: Upstream voltage signal
Blue: Downstream voltage signal

Voltage signals

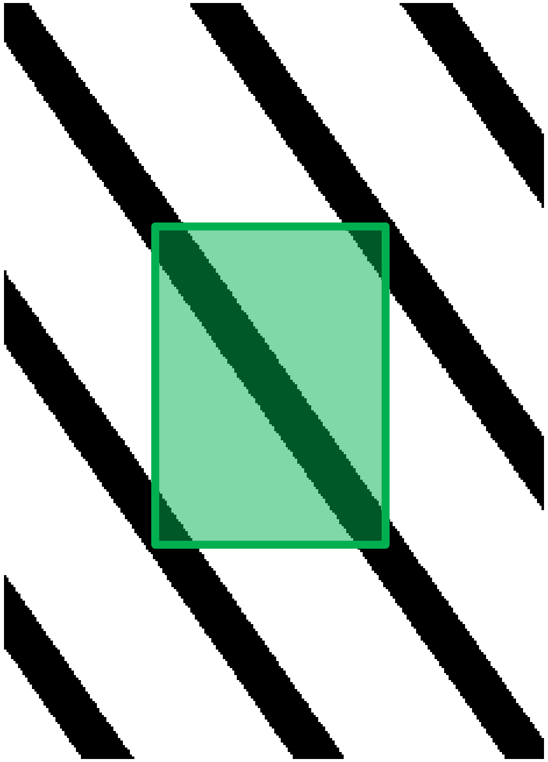


Case 2: Particle captured



Red: Upstream voltage signal
Blue: Downstream voltage signal

Calculation: single fiber efficiency



Parallel fibers / top view

$$\eta = \frac{N_U - N_D}{N_{U,f}} = \frac{N_U - N_D}{N_U} \cdot \frac{A_{SLZ}}{A_F}$$

A_{SLZ}: Projected area of the scattered light zone (green)

A_F: Projected fiber area covered by scattered light zone

Only a small fraction $\frac{A_F}{A_{SLZ}}$ of measured particles has a chance to hit the fiber. Large sample sizes have to be applied for statistical validity of the estimate

$$N_{U,F} = N_U \cdot \frac{A_F}{A_{SLZ}}$$

Advantage of fiber arrays compared to single fiber:

➔ Accurate prediction of A_{SLZ} / A_F possible

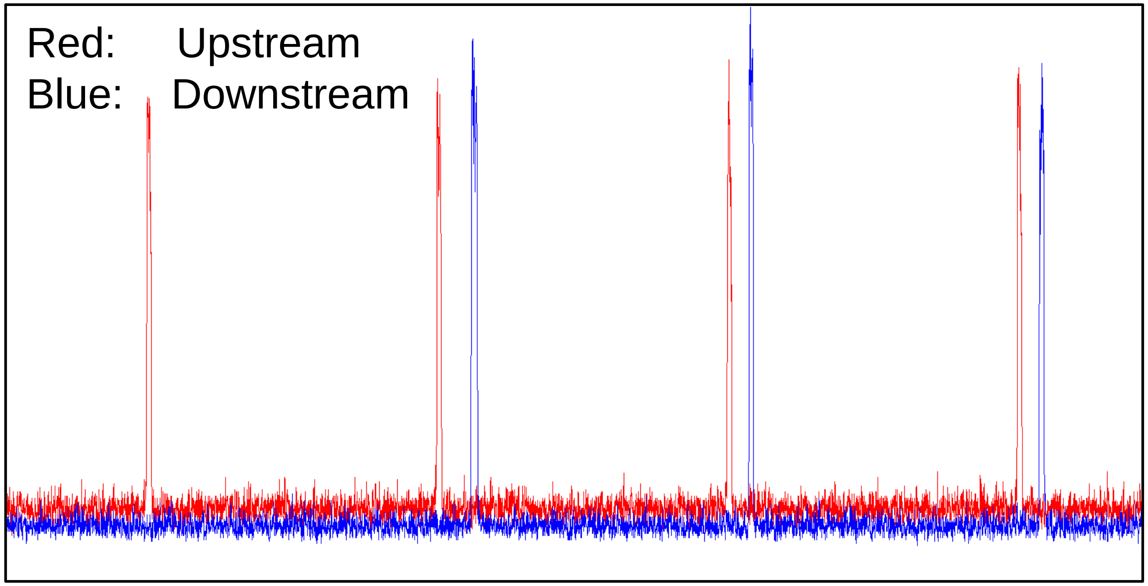
(= const., for certain geometric conditions)

Institute of Mechanical Process Engineering and Mechanics

Signal processing

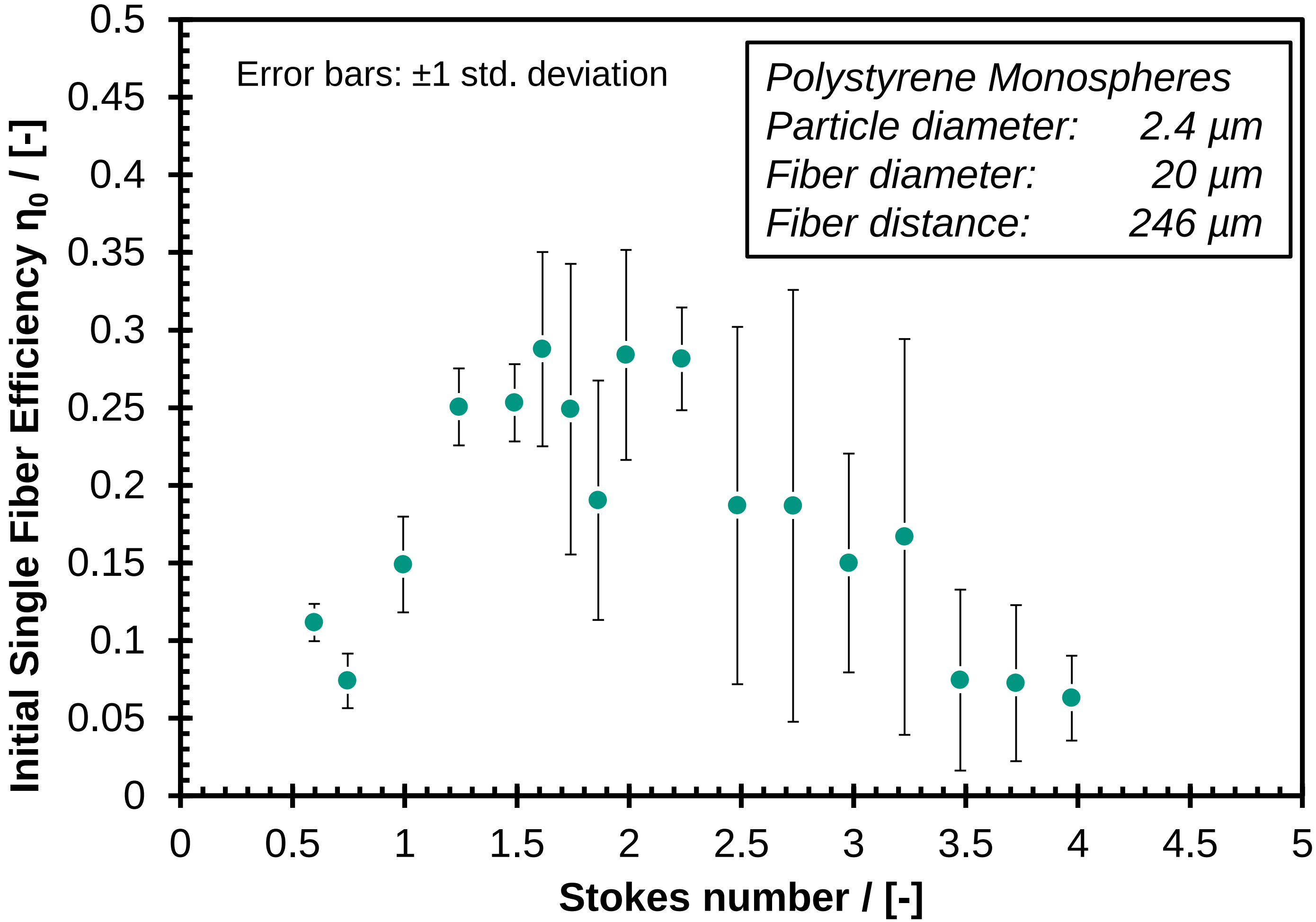
- Voltage peaks recorded using dual-channel PC-oscilloscopes

- Occurance of precipitation can be checked for each individual particle
  - ➔ Compensation of error sources possible:
    - Coincidence
    - Signal intensity variation (Shadowing, measurement border zone)



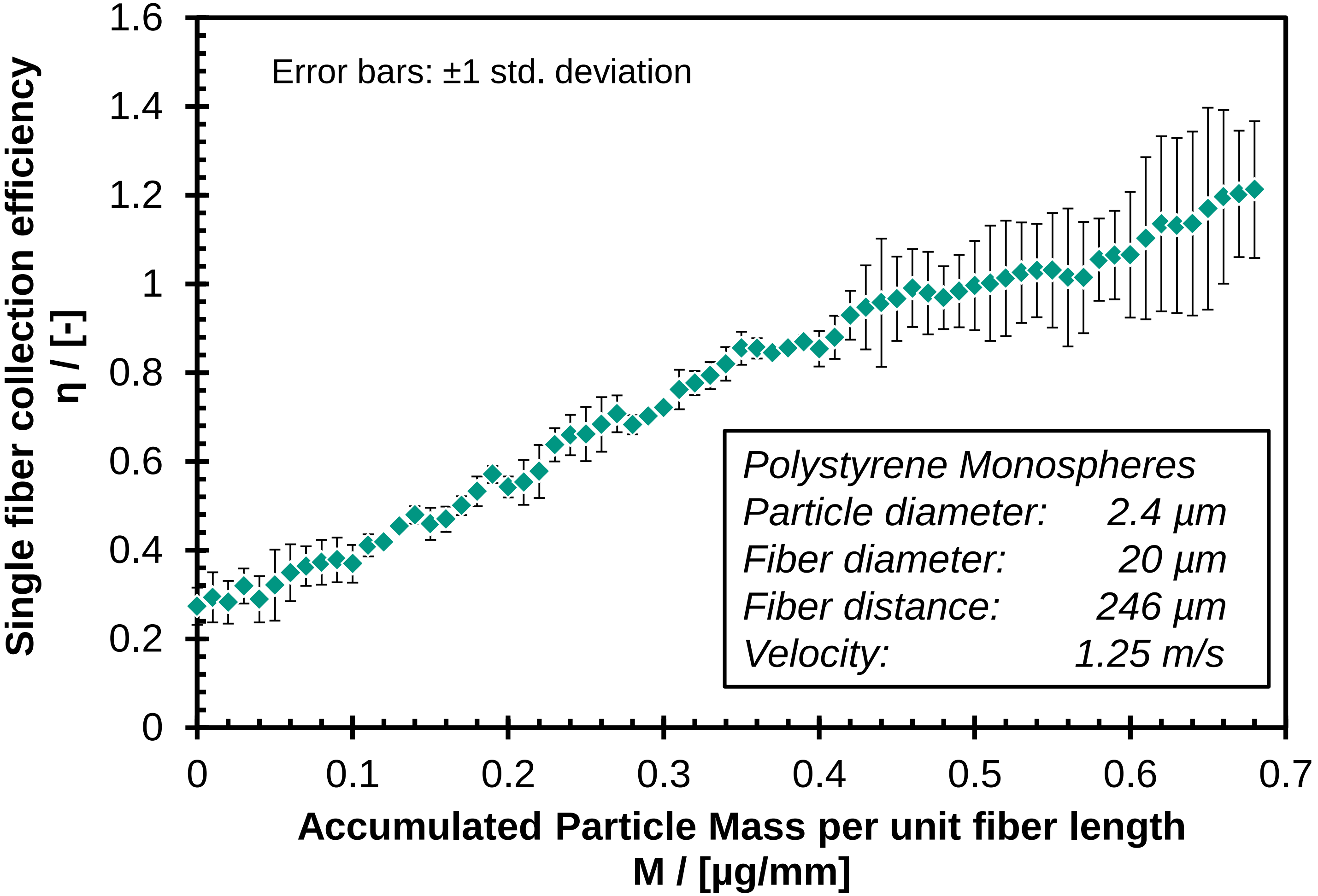
Results

Results:
Initial Single Fiber Efficiency vs. Stokes number

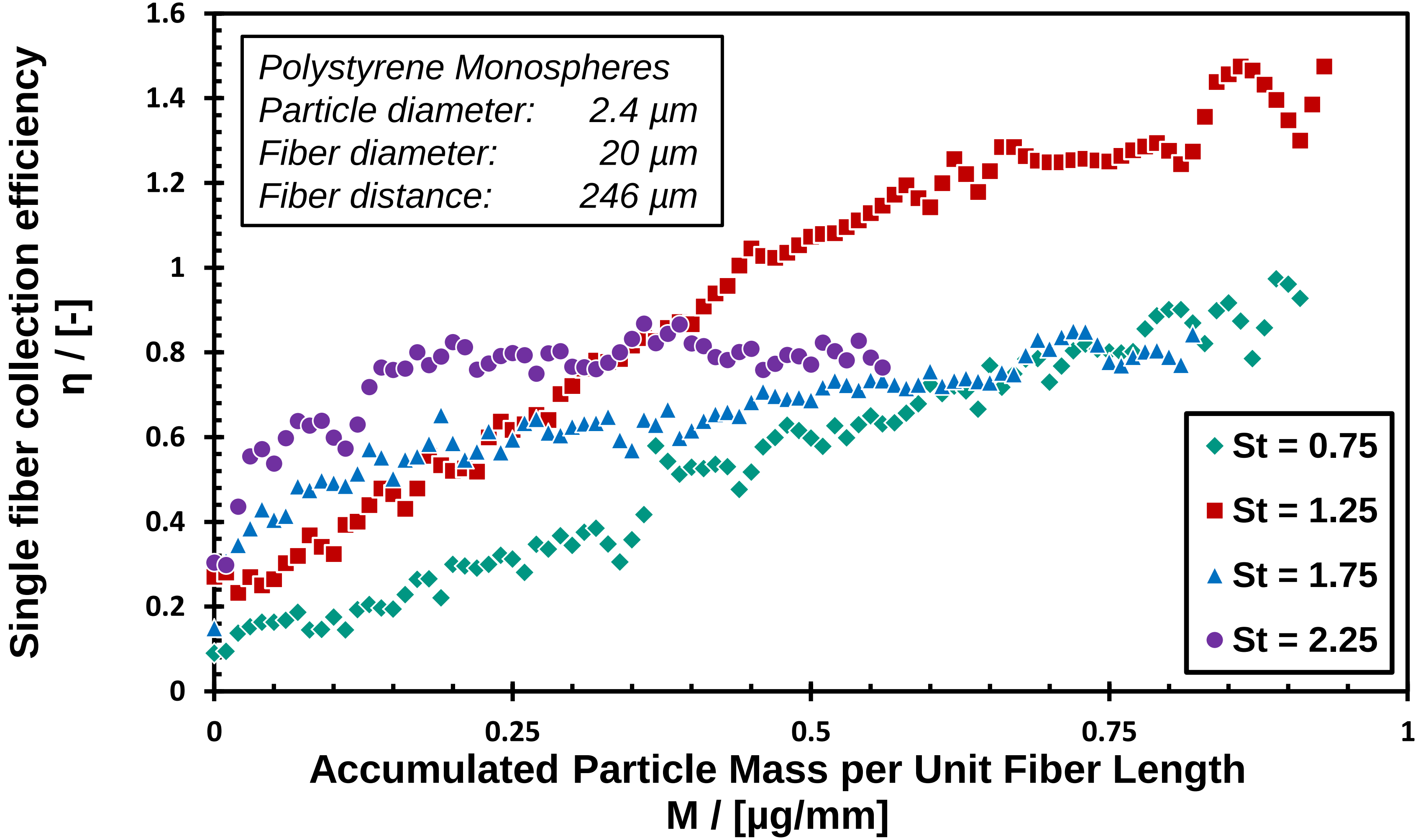


Institute of Mechanical Process Engineering and Mechanics

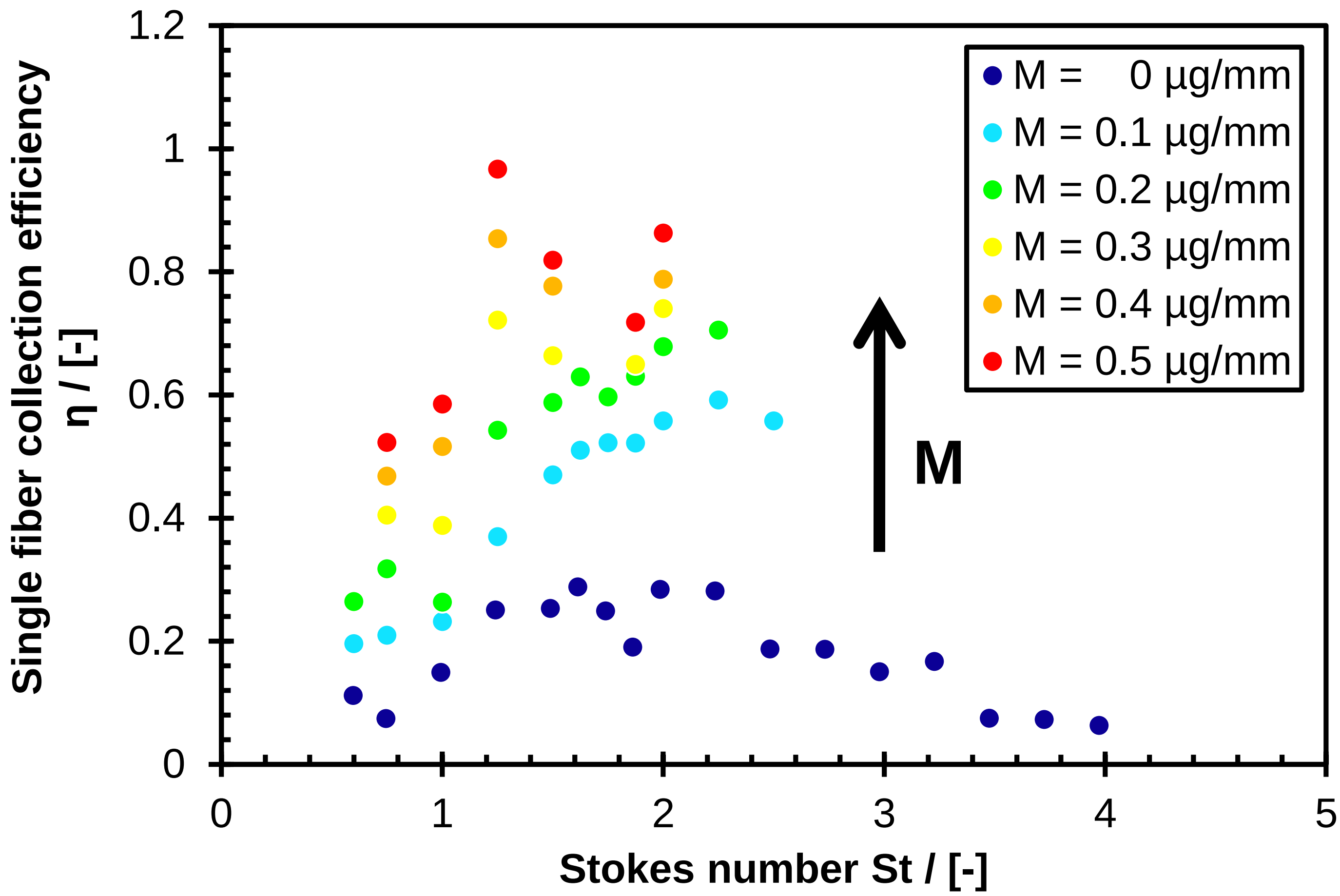
Results:
Efficiency vs. Deposited particle mass



Efficiency vs. Mass for different Stokes numbers

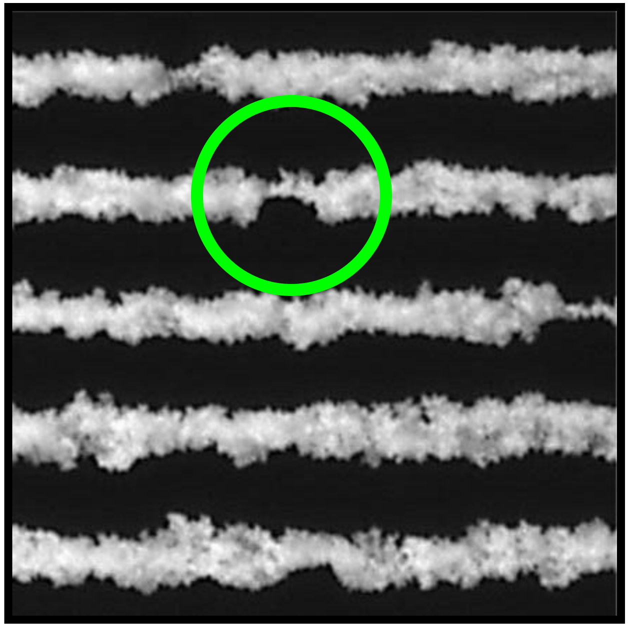


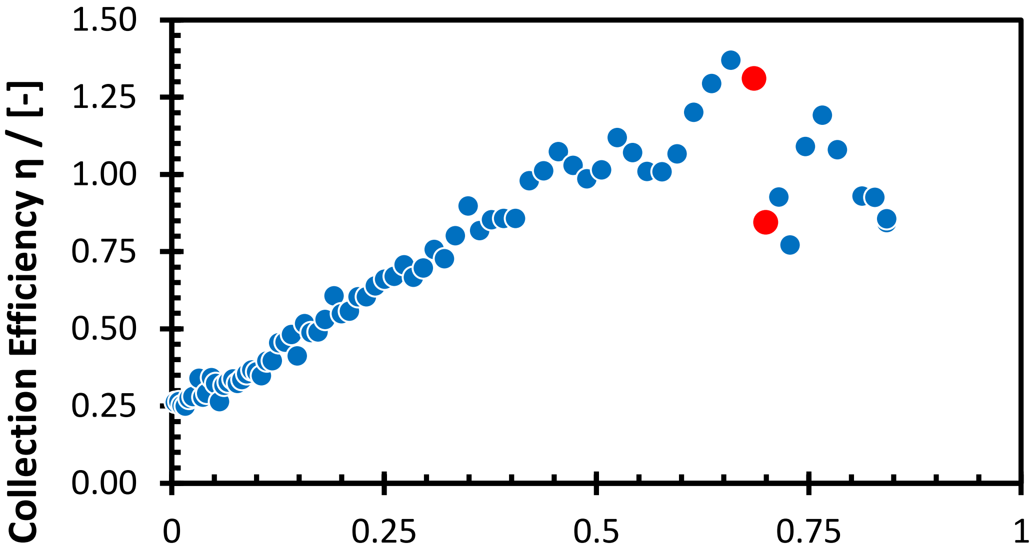
Results:
Single fiber efficiency at various mass loads



Institute of Mechanical Process Engineering and Mechanics

Problem: Acquiring data for high mass load at high Stokes number





- Increasing mass load

  ➔ Rising drag forces on particle structures

  ➔ Particle structure breakage and reentrainment

  ➔ Undefined state of loading

Efficiency evolution during loading process

- Non-linear approach:

Single fiber collection efficiency as a function of particle mass per unit fiber length [Kasper et al, 2009]:

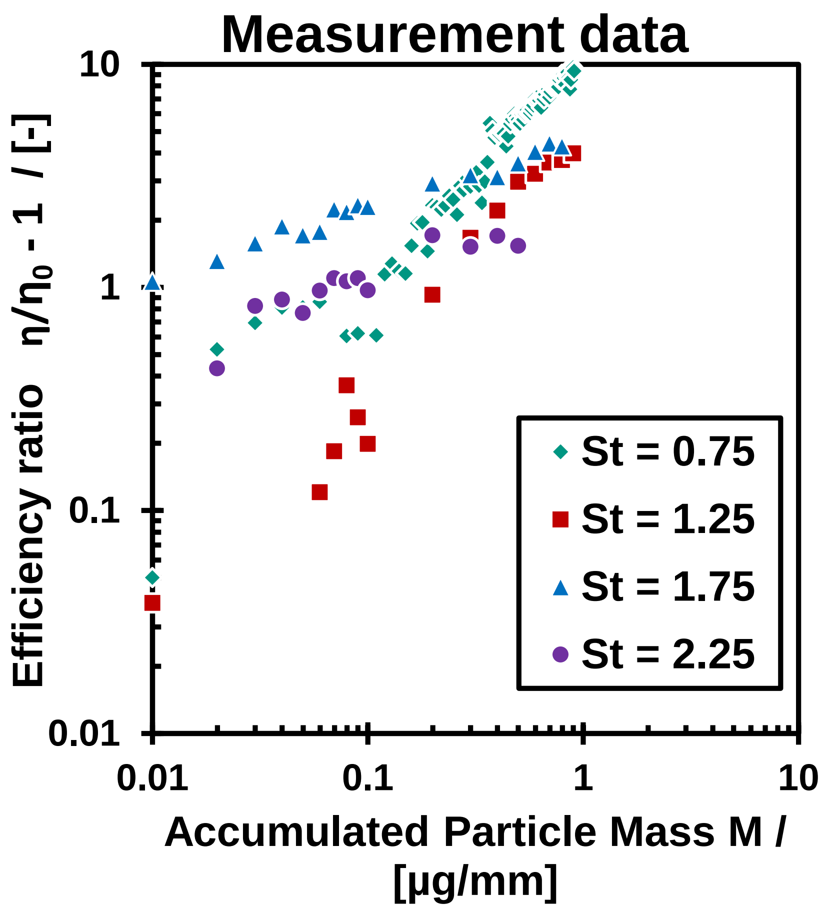
$$\frac{\boldsymbol{\eta}}{\boldsymbol{\eta_0}} = \mathbf{1} + \boldsymbol{b} \cdot \boldsymbol{M}^{\boldsymbol{c}}$$

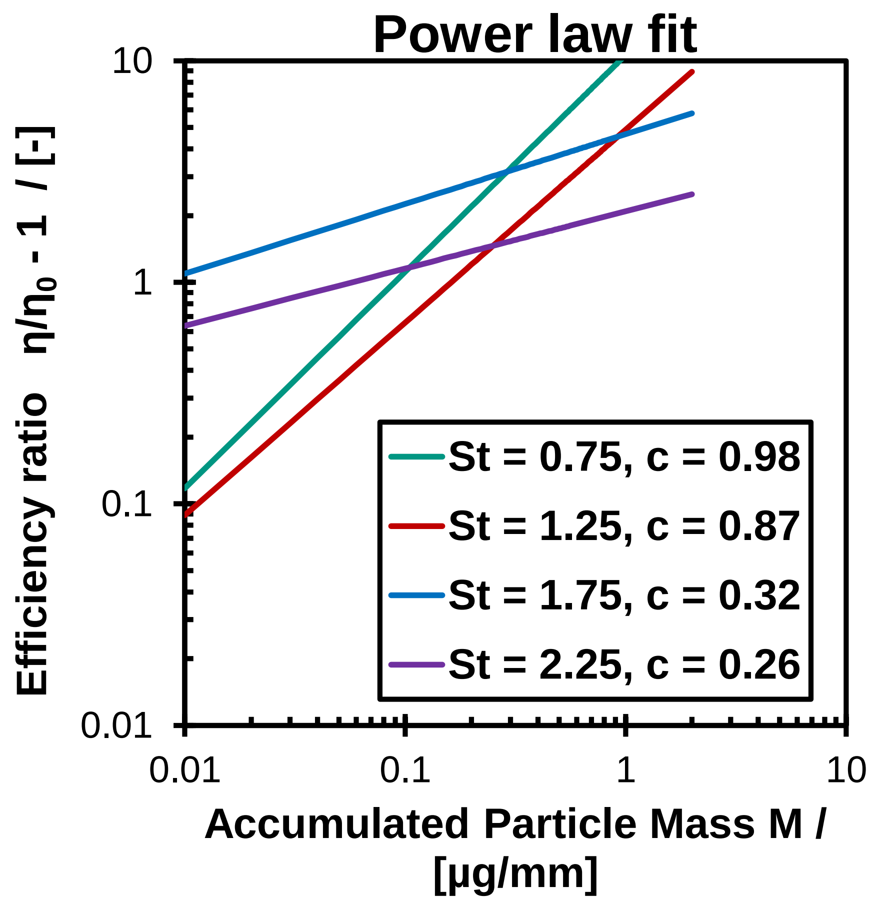
η:	single fiber efficiency
η_0:	initial single fiber efficiency
b,c:	empirical fit parameters

Institute of Mechanical Process Engineering and Mechanics

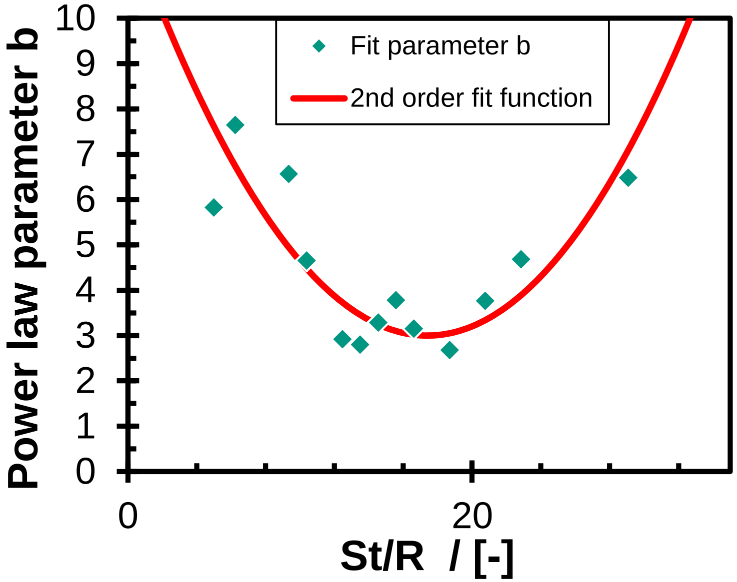
Empirical fit model

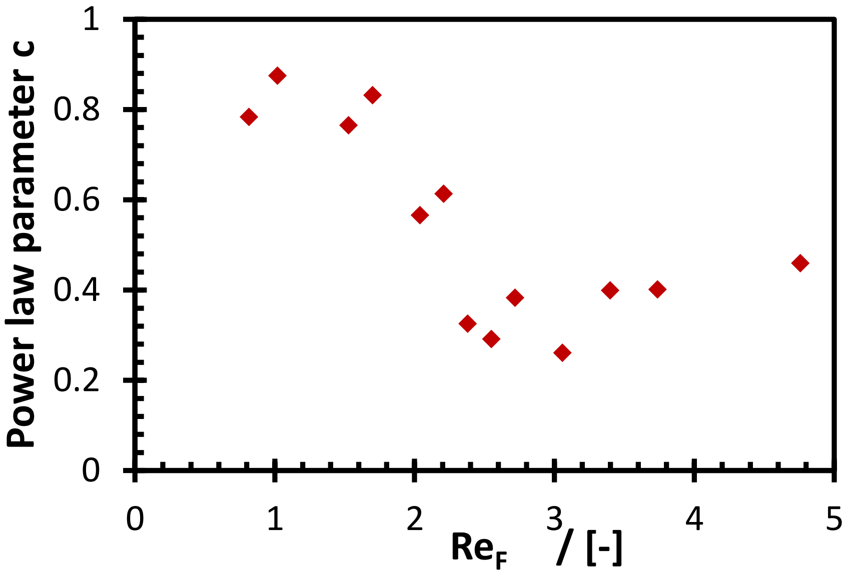
- Obvious: c decreases when Stokes number is increased





Evolution of power law parameters





- b: Distinctive minimum at approx. St/R = 17.4
- c: Evolution from unity towards 0.25 – 0.4

R: Interception parameter = d_p/d_f

Summary

- Improved measurement of the single fiber efficiency of fibers in parallel arrays
- Results for dust loading kinetics for the single fiber efficiency
- Empirical model approaches published by Kasper (2009) for isolated single fibers are also suitable for fiber arrays. Absolute values vary expectedly.

Dimensionless numbers and literature

$$St = \frac{\rho_p d_p^2 v_\infty Cu}{18\,\mu_g d_f}$$

$$Re_f = \frac{\rho_g d_f v_\infty}{\mu_g}$$

$$R = \frac{d_p}{d_f}$$

d_p:	Particle diameter
d_f:	Fiber diameter
v_∞:	Approaching velocity in the undisturbed gas
Cu:	Cunningham slip correction
μ_g:	Gas viscosity
ρ_p, ρ_g:	Particle and gas density

[Kasper et al, 2009]

Kasper G. , Schollmeier S., Meyer J., Hoferer J.,"The collection efficiency of a particle-loaded single filter fiber", Journal of Aerosol Science, Volume 40, 2009, 993-1009

[Hoferer, 2011]

Hoferer, J., “Einzelfaserbasierte Modellansaetze zur Beschreibung der Filtrationskinetik von Tiefenfiltern”, Verlag Dr. Hut, München 2011