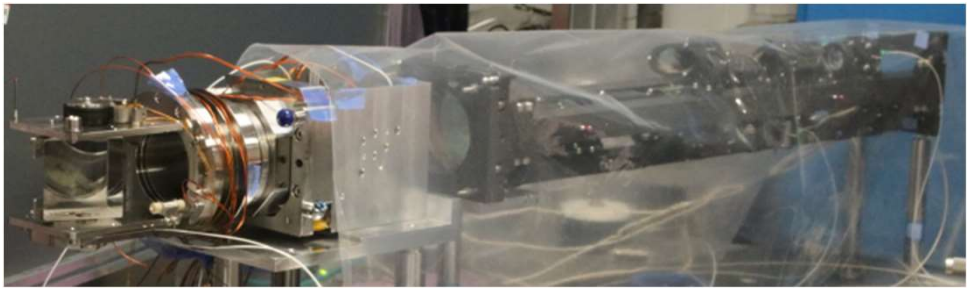
Karlsruhe Institute of Technology

Experiments on Specular Wavy Liquid Metal Surface of Selected Optical Distance Sensors from Several Meters

Björn Brenneis, Sebastian Ruck



EUROfusion

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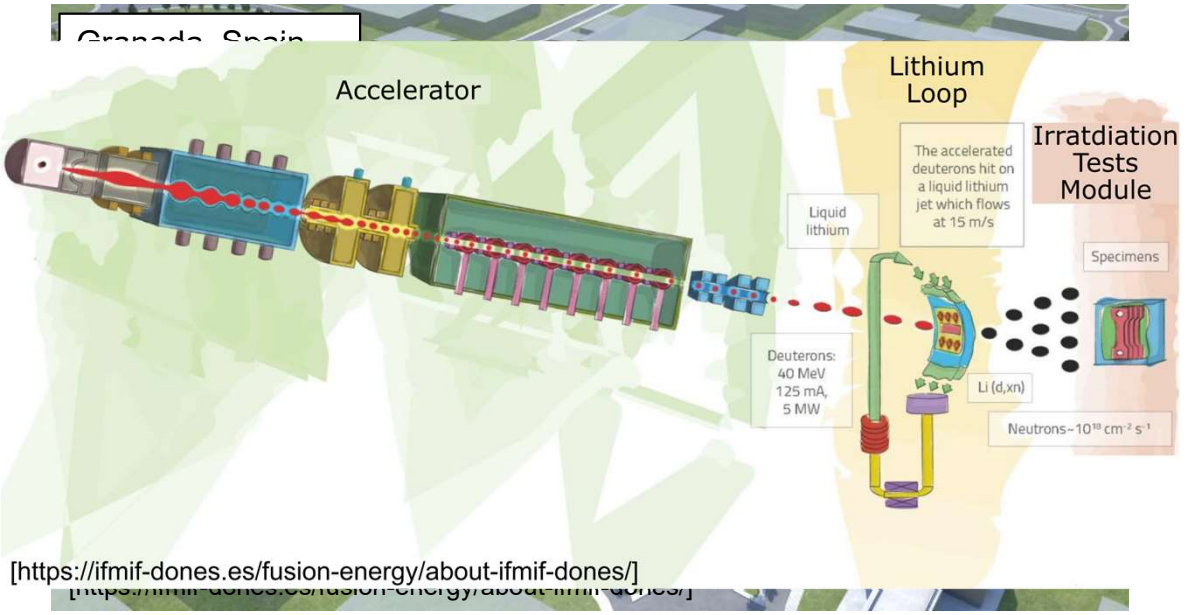
DONES

- **D**EMO **O**riented **NE**utron **S**ource (DONES)
  - Irradiation facility for fusion materials (DEMO)
  - Characterisation of irradiated structural material

- Main components
  - Deuteron linear accelerator
  - Lithium target
  - HFTM (High Flux Test Module)

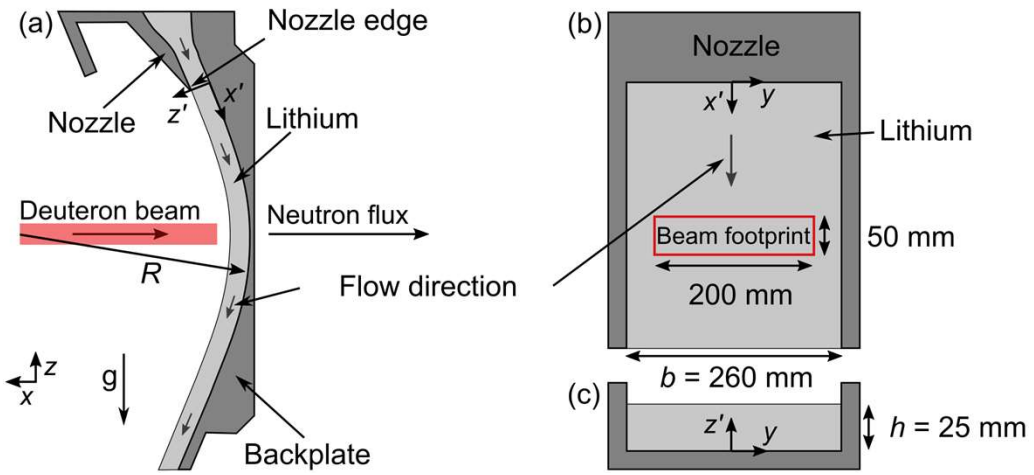
D2, 40 MeV (125 mA) ➡ n, 14 MeV
➡ 20-30 dpa in < 2.5 y (0.3 l)



[https://ifmif-dones.es/fusion-energy/about-ifmif-dones/]

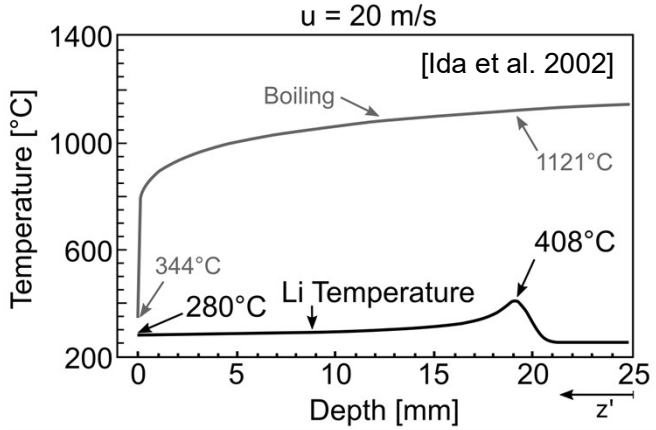
Lithium Target

- Neutron flux production
- Heat removal (5 MW)
- Film thickness 25 ± 1 mm
  - Film thickness < 22 mm
    - ➡ Heat introduced in the backplate



Measurement system necessary to monitor the film thickness:

- Protection of the plant from damage
- Guarantee a stable operation



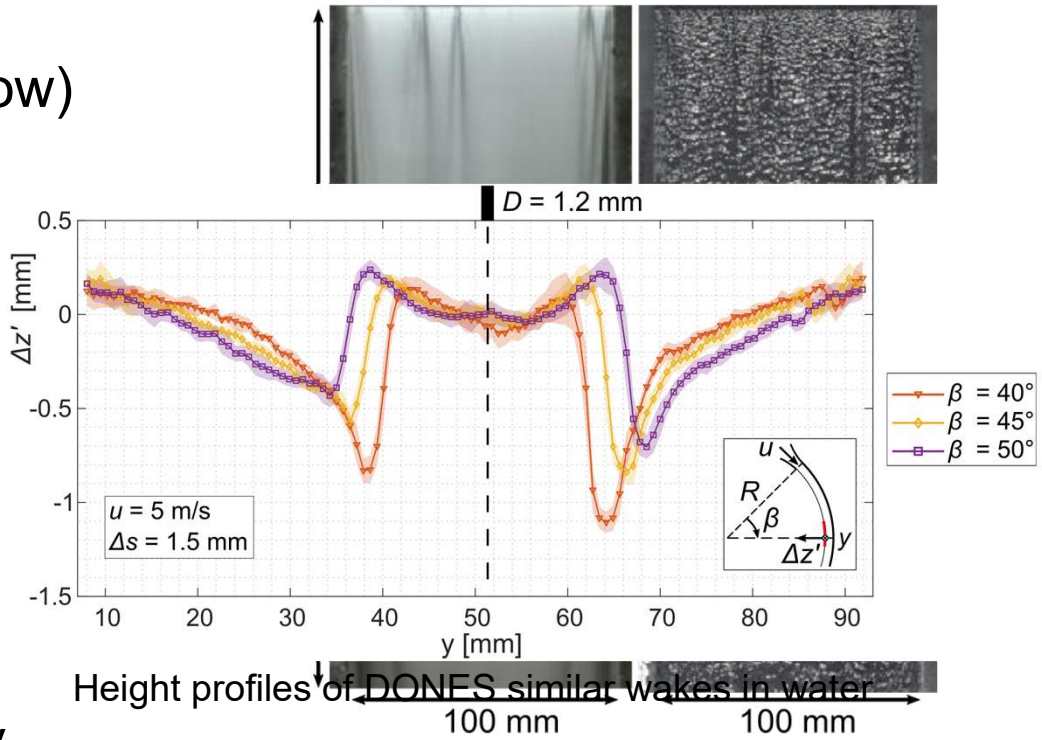
Lithium surface fluctuation

General thickness loss (e.g. loss of mass flow)

Surface waves
- Average wave amplitude < 1 mm
- Time averaged height change is zero

Wakes
- Temporal and spatial stable
- Potential local thickness loss > 1 mm
  - ➡ Monitoring during operation necessary

➡ Select two systems to measure the film thickness



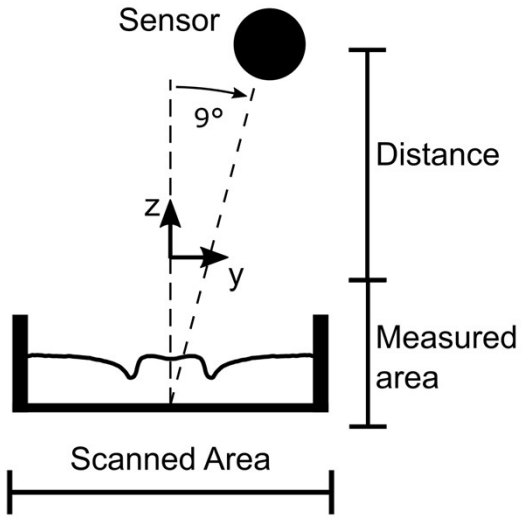
Height profiles of DONES similar wakes in water

Picture of a lithium flow in ELTL taken with 2s und 10µs exposure time
[Kondo et al. (2015), Wakai et al. (2016)]
ELTL (EVEDA lithium test loop)

Specifications

- Selecting two optical systems to measure the distance to a wavy specular liquid metal surface.

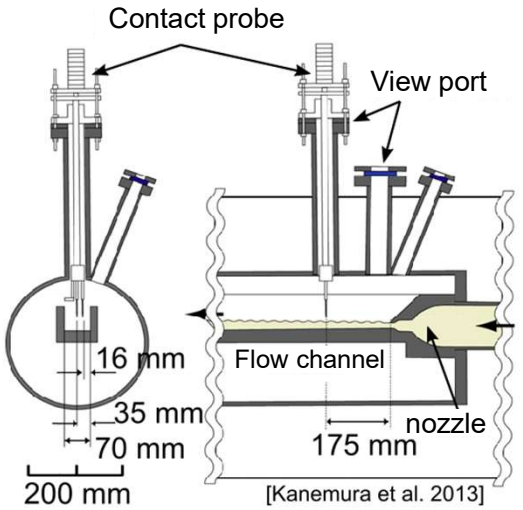
Measuring distance	> 8 m
Measured area	~ 120 mm
Vertical resolution (*z*)	< 0.3 mm
Spatial resolution (*y*)	< 5 mm
Scanned area	200 mm line (+ reference point)
Acquisition time	~ ms (per point) (< 100 ms per line)



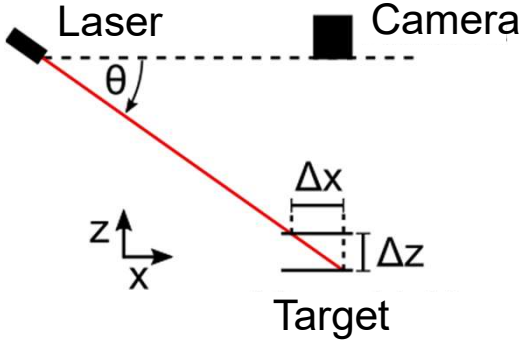
Investigated measurement systems

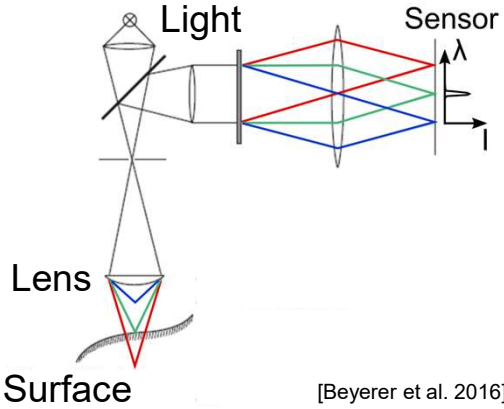
- High speed camera
  [Wakai et al. 2016]
- Contact sensor [Kanemura et al. 2012]
  - Limitation: Speed and Distance
- Triangulation
  - Distance (< 500 mm)
- Chromatic confocal
  - Distance (< 220 mm)

Measurement probe



[Kanemura et al. 2013]

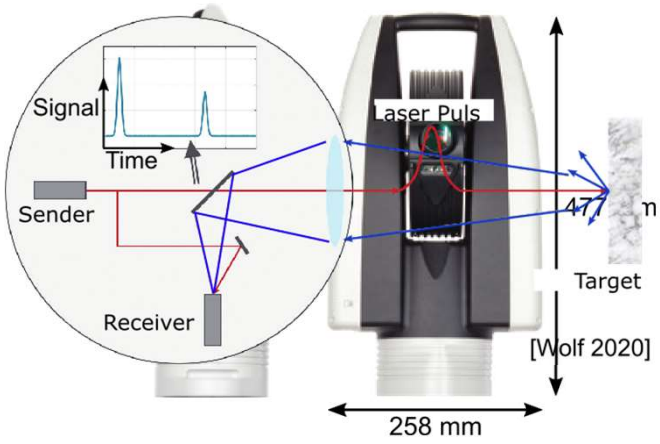


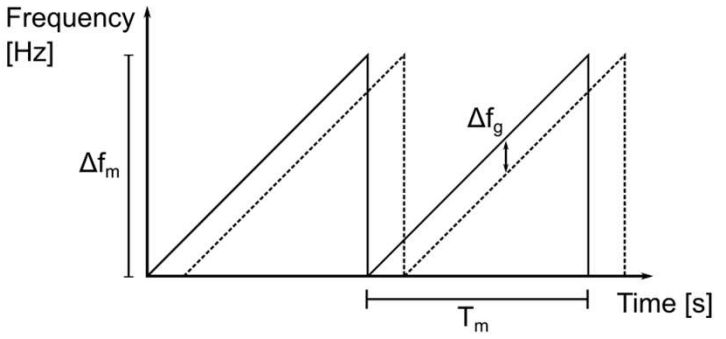


[Beyerer et al. 2016]

Proposed sensors

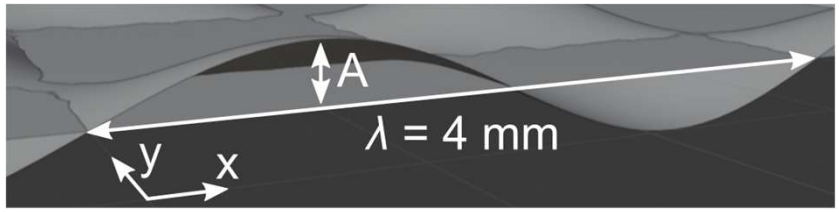
- ATS600 (HEXAGON)
  - Wave Form Digitizer (“Enhanced” Time of Flight measurements) [Wolf 2020, Maar 2014]
    - Accuracy (vertical resolution) < 0.3 mm up to 30 m
    - Spatial resolution 0.5 mm @ 7 m
    - Acquisition rate 1 kHz
- ITER In Vessel Viewing System (IVVS)
  - Prototyping by Bertin technologies for F4E
  - Frequency Modulated Measurement System FMCW
    - Accuracy 0.3 – 0.5 mm @ 1 – 15 m
    - Spatial Resolution 1.2 mm @ 8 m
    - Acquisition rate 5 kHz (per point)
    - Total dose 10 MGy (8y in DONES), Vacuum and 8 T





Blender Simulation

- IVVS Simulator Add-on for Blender (F4E)



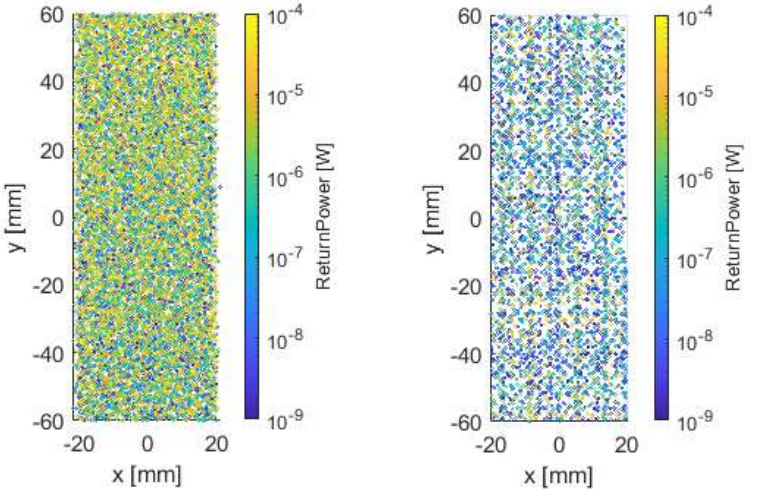
- Input:
  - Position of the optical head, spatial resolution, laser power
  - Model surface 9° inclination, 3D sinus wave as surface normal (4 mm wavelength with different amplitudes *A* (normal map))
- Approach:
  - Ray Tracing ➡ Angle of incidence
  - ➡ Calculate the reflected power (Ashikhmin-Shirley Reflection model)
- Evaluation:
  - Threshold value for the reflected power ($0.5 \cdot 10^{-9}$ W) needed
  - ➡ Flat specular surface was not detected

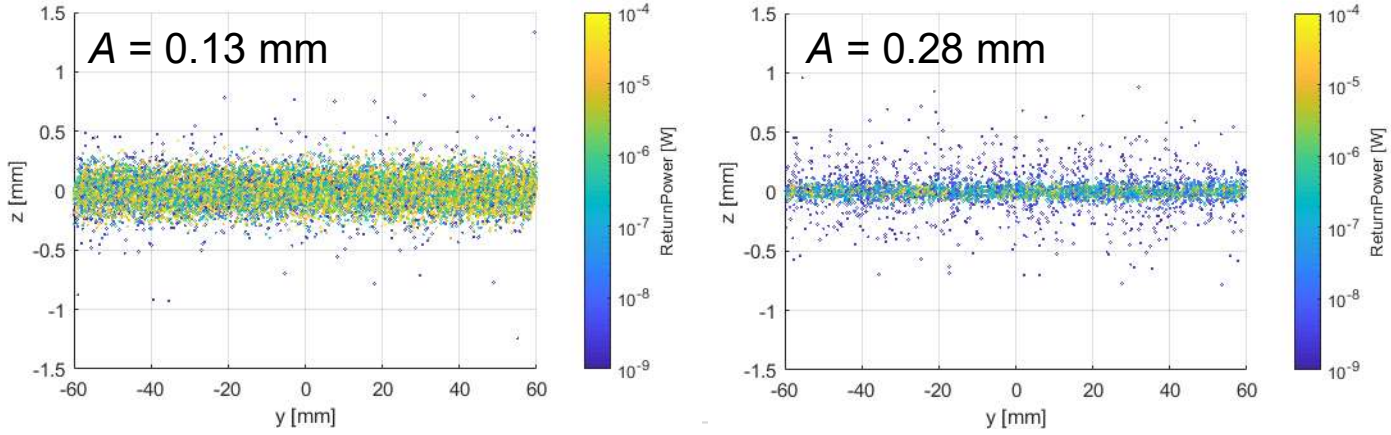
Simulation results

- Plane 120x40 mm, 9° inclination, 7 m measuring distance,
- Specular metallic surface
- A = 0.13 mm, 15862 points (~ 40%)
- A = 0.28 mm, 4802 points (~ 12%)
- Standard deviation < 0.12 mm

➡ Detection of the wavy Surface feasible

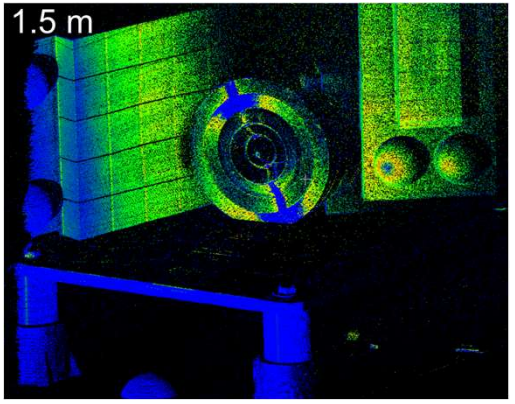
➡ Significant influence of waviness

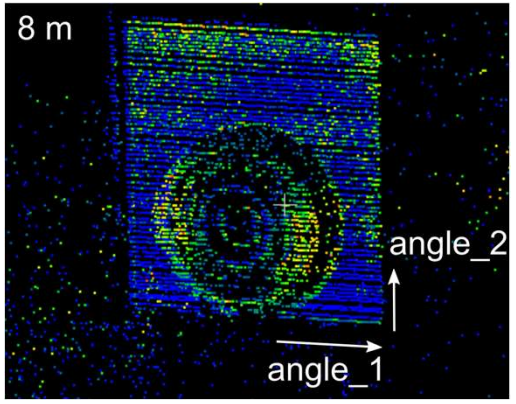


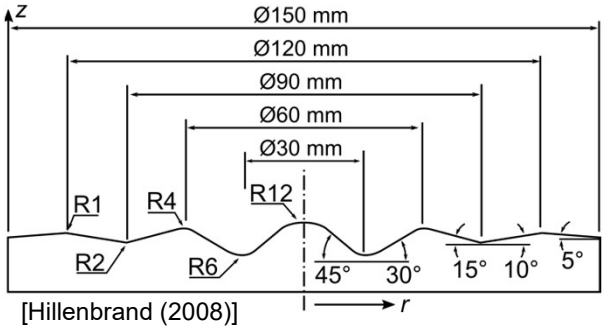


Solid model IVVS measurements

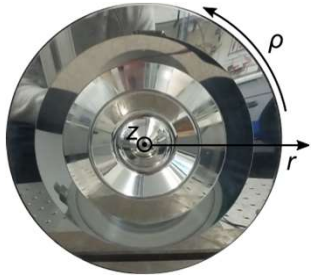
- Point to point distance 1.2 mm @ 8 m
  ~ 60% points lost





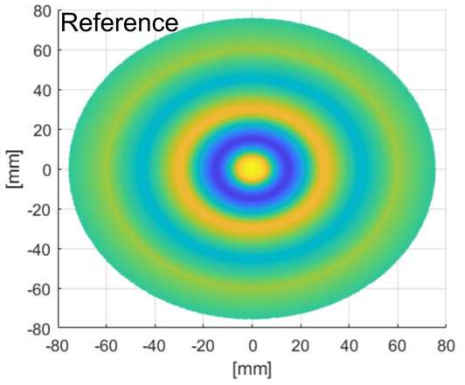


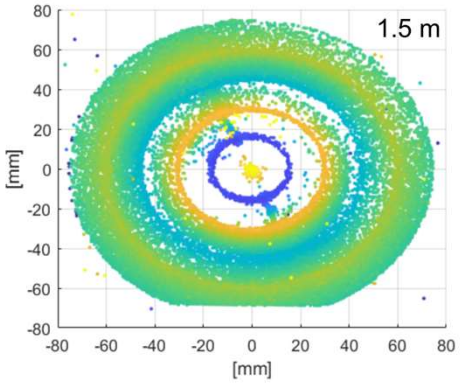
[Hillenbrand (2008)]

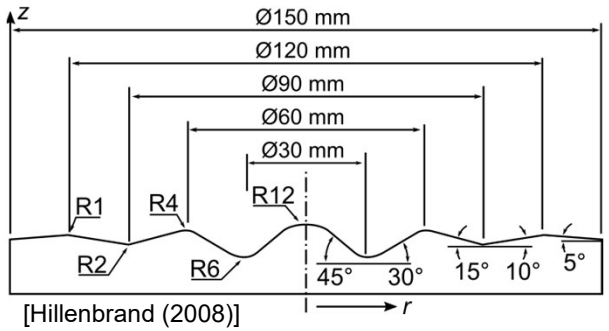


Solid model IVVS measurements

- Point to point distance 1.2 mm @ 8 m
  ~ 60% points lost
- Evaluated with a 2 mm window in radiale direction
- Points mainly lost on slopes
  Minima and Maxima detected
  - Slopes < 15° detected







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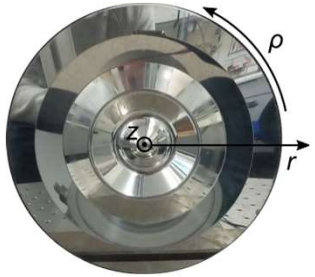

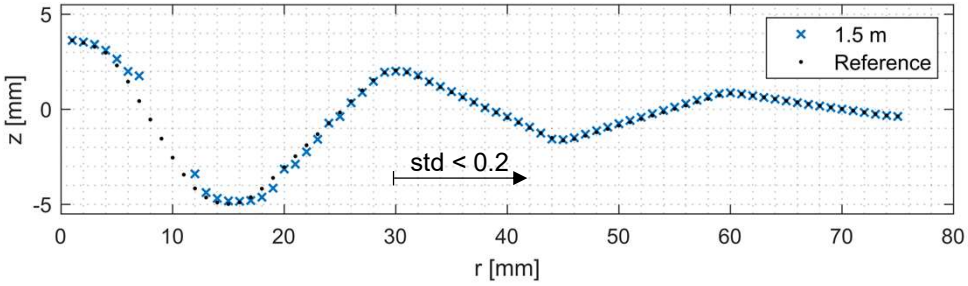

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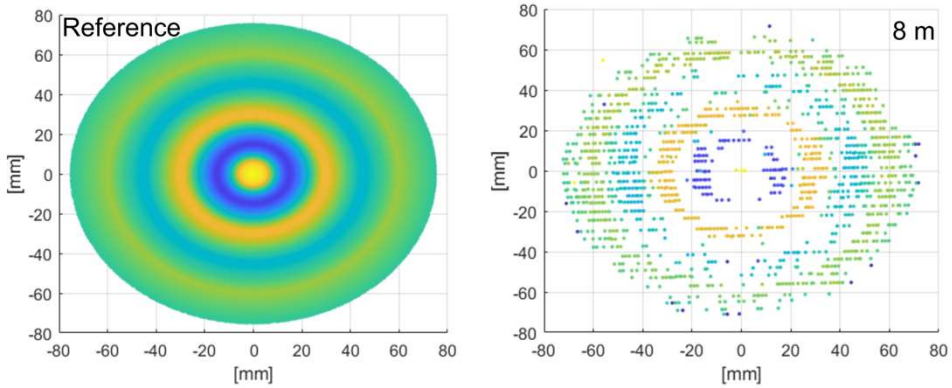

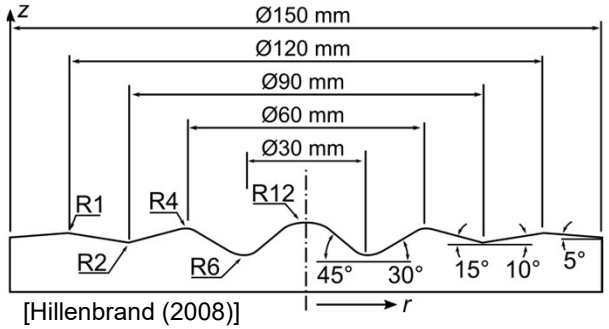

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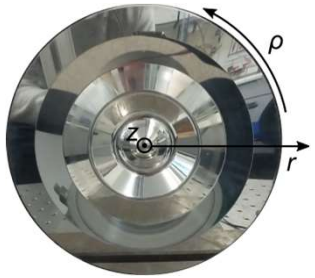
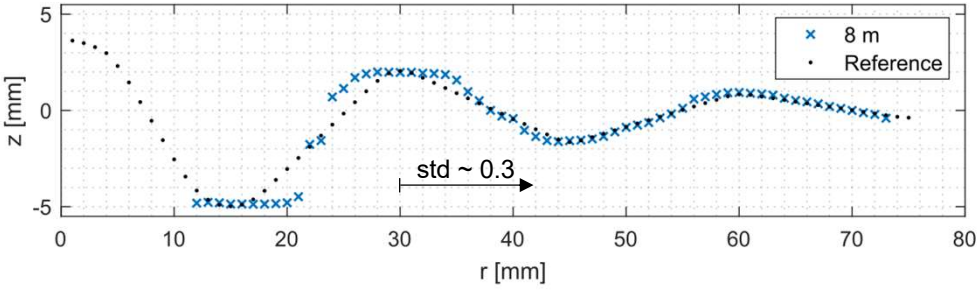
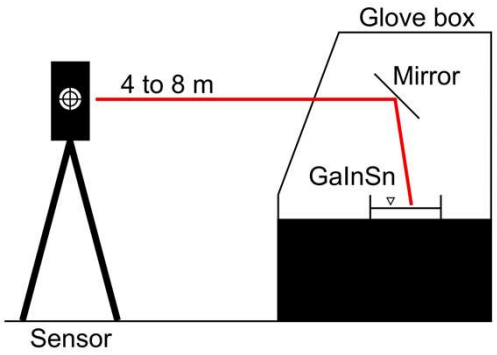


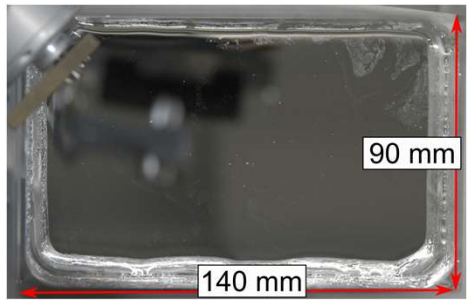


Measurement setup

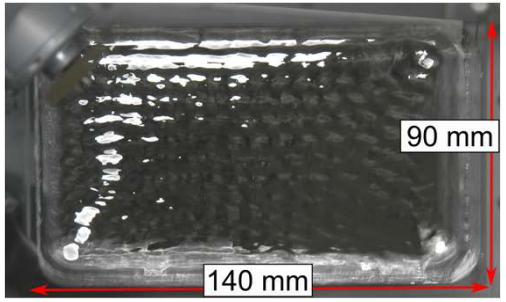
- GaInSn placed in a glove box (Ar atmosphere)
- Sensor measures through side wall of the glove box and via a mirror
- Measurement distance 4 m to 8 m
  - Reference plane (2 height levels)
  - GaInSn with oxide layer
  - GaInSn flat
  - GaInSn wavy



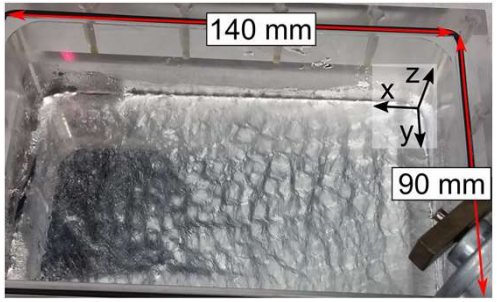
GaInSn „flat“



GaInSn „wavy“

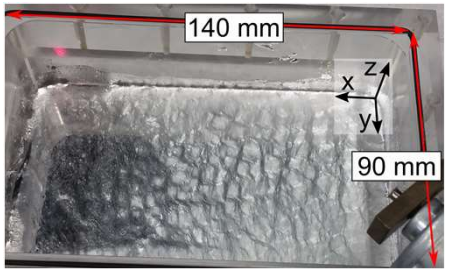


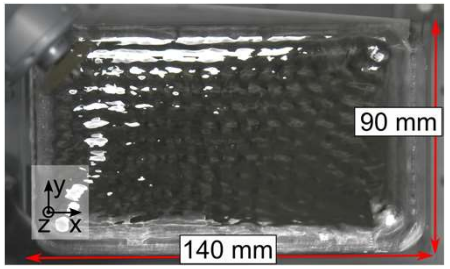
GaInSn „oxide layer“

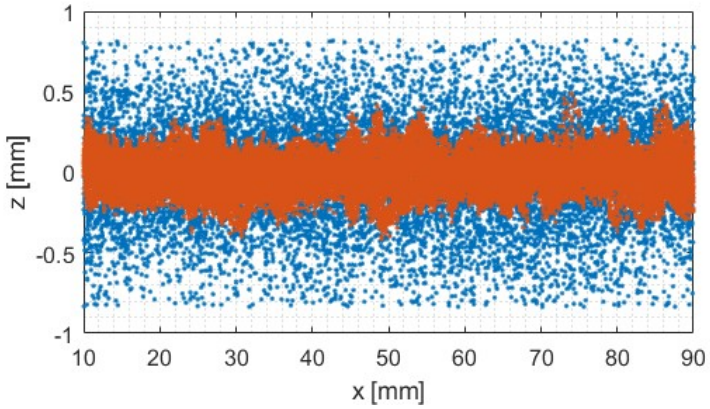


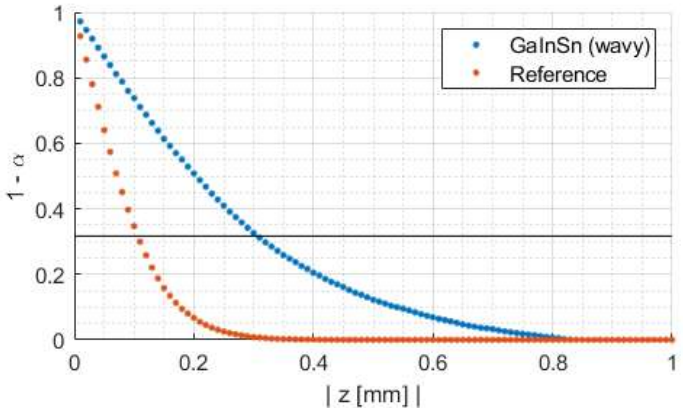
GaInSn measurements ATS600

- Measurement distance: 4.3 m
  - Measurements on diffuse surface (reference)
    - Std < 0.11
  - Measurements on wavy oxide-free GaInSn surface
    - Std < 0.33 (Filtered by intensity and 5% trimmed)
    - 36 – 56% points in comparison to reference





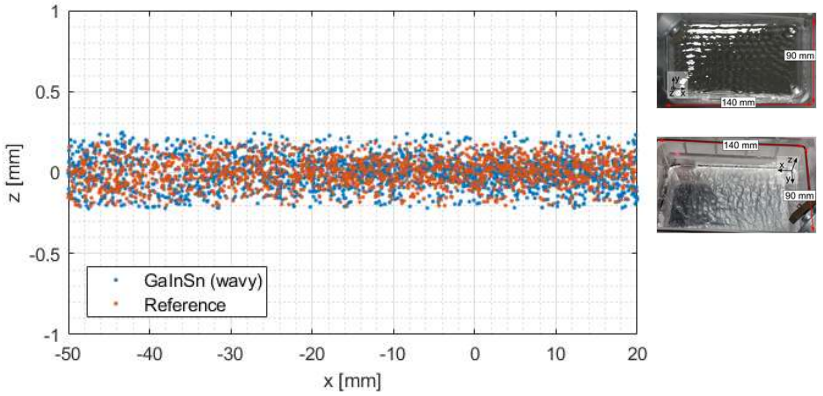


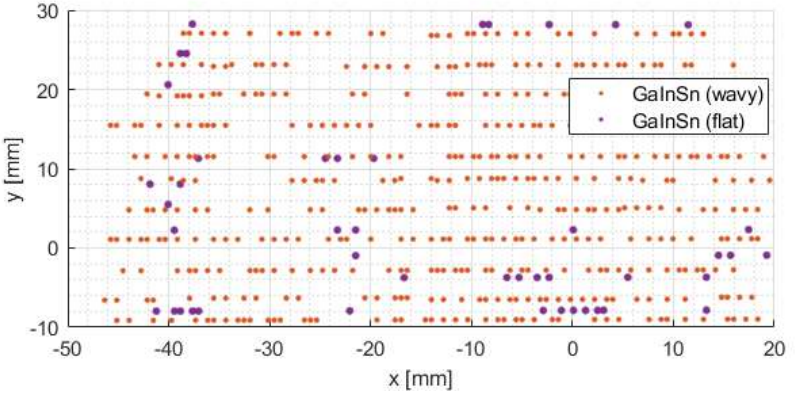


(1) 5 % trimmed

GaInSn measurements IVVS

- Measurement distance 8 m
  - Measurements on diffuse surface
    - std ~ 0.1 mm ($12\% \pm 3\%$ points lost)
  - Measurements on wavy oxide-free GaInSn surface
    - std < 0.14 mm ($21\% \pm 3\%$ points lost)





➡ Small surface waves enable measurements on the specular surface.

Summary

- Wakes as potential error source in DONES

Selection and characterization of two optical distance sensors for DONES

- Test measurements with the liquid metal GaInSn
  - Detecting the wavy specular liquid metal surface with an accuracy < 0.33 mm from 8 m distance possible
  - Surface waves enable measurements
  - Significant impact of the waviness on the measurement results

Appendix

Wake equations

- Kelvin Wake equation [Lamb1916, Kondo2004]:
  - “deep water” ($\lambda < h$)
  - Centrifugal forces > gravity
  - Dimensionless numbers
    - Froude-number (Inertia to gravity)

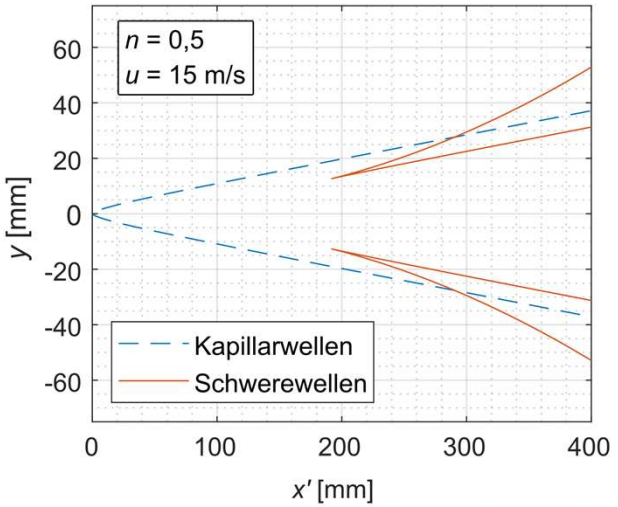
$$Fr = \sqrt{R/L}$$

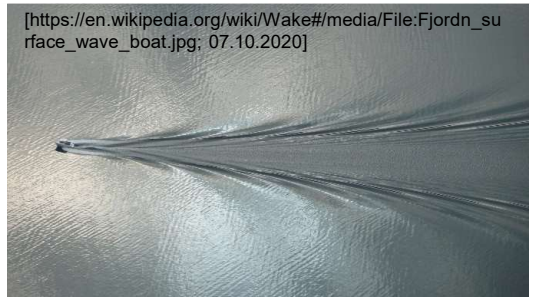
- λ Wavelength
- h Film thickness
- R Curvature radius
- L char. length

    - Weber-number (Inertia to surface tension forces)

$$We = u \cdot \sqrt{\rho \cdot L)/\sigma}$$

- ρ Density
- u Flow velocity
- σ Surface tension




[https://en.wikipedia.org/wiki/Wake#/media/File:Fjordn_surface_wave_boat.jpg; 07.10.2020]

➡ R and *We* · *Fr* constant ➡ Identical wake shapes in lithium and water

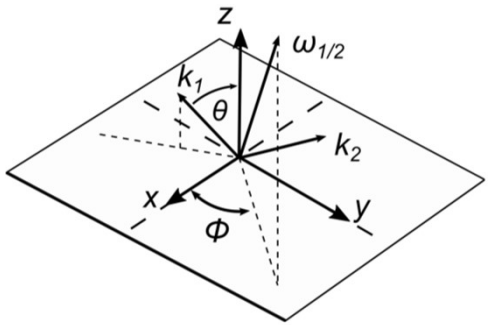
Ashikhmin-Shirley Reflection model

- Assumtions:
  - Isotropic Reflection
  - Metallic specular surface $\epsilon_d = 0$
  - Viewing angle equals Incidence angle $k_1 = k_2$

$$I_R = \epsilon \cdot \Omega \cdot I_L$$

$$\epsilon(k_1, k_2) = \epsilon_s(k_1, k_2) + \epsilon_d(k_1, k_2)$$

$$\epsilon_s(k_1, k_2) = \frac{n_{uv} + 1}{8\pi \cdot \cos(\theta)} \cdot \cos^{n_{uv}}(\theta)$$



Reflected Power I_R
Laser power I_L
Reflectivity ϵ (*s* specular, *d* diffuse)
Incidence angle θ

Simulation results

- Plane 120 x 40 mm, 9° inclination, 7 m measuring distance
- Specular metallic surface
- Measured FIDES wake

- ~10 lines necessary to scan the profile
- Estimated measurement time for DONES < 0.5 s