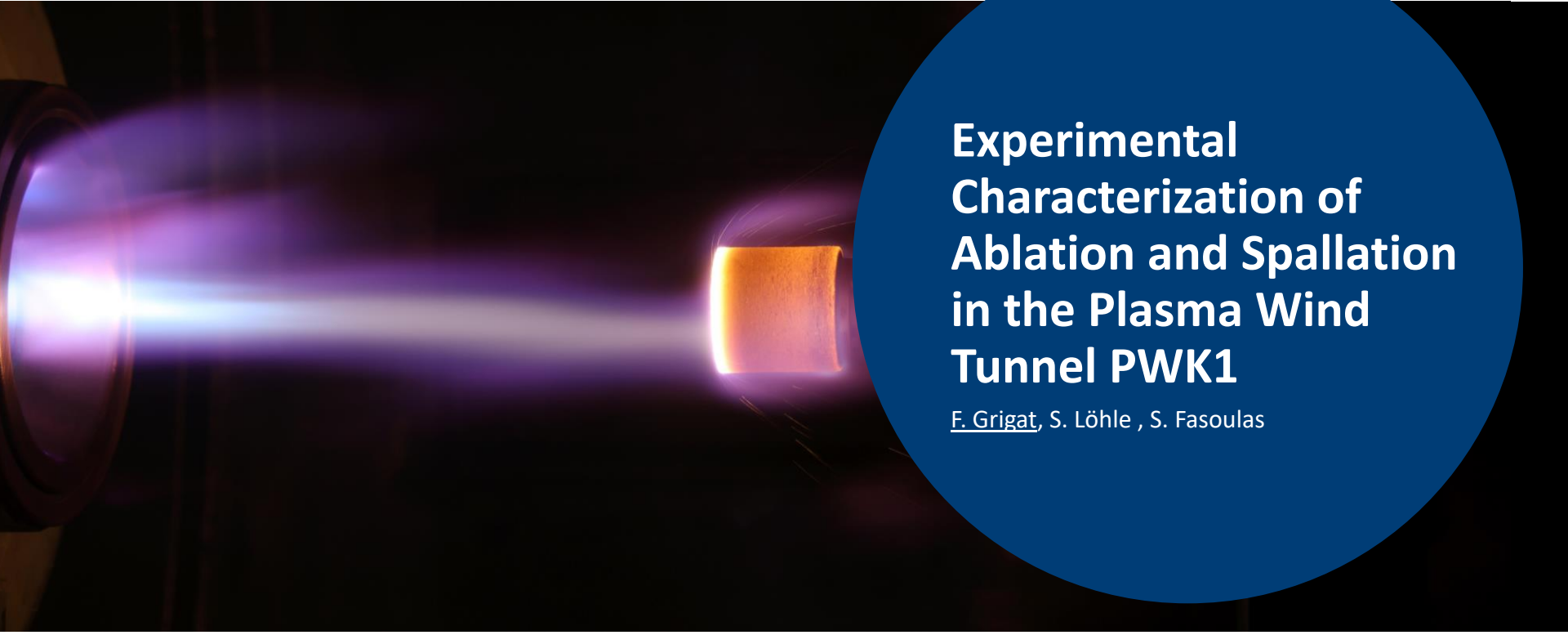
University of Stuttgart
Institute of Space Systems (IRS)

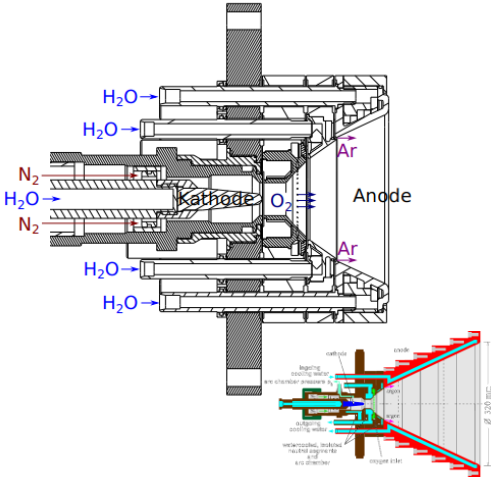


Experimental Characterization of Ablation and Spallation in the Plasma Wind Tunnel PWK1

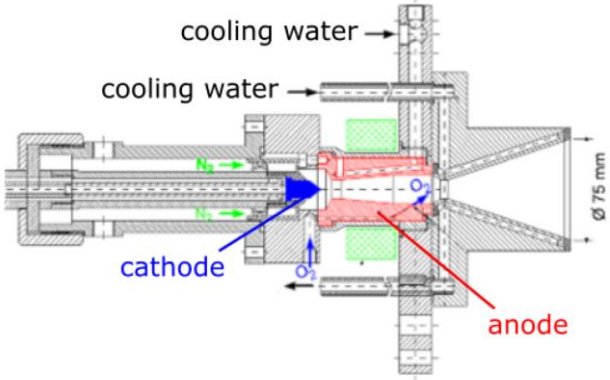
F. Grigat, S. Löhle , S. Fasoulas

IRS HEFDiG University of Stuttgart
Institute of Space Systems

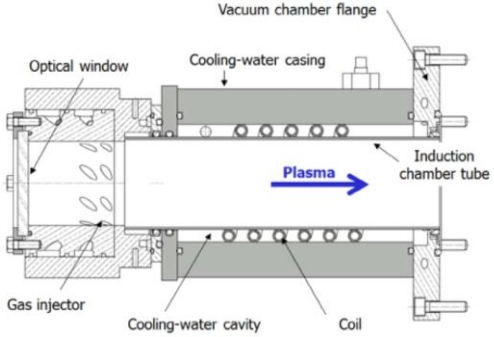
The Plasma Wind Tunnel Facilities



RD5,7 (PWK1 and 2)



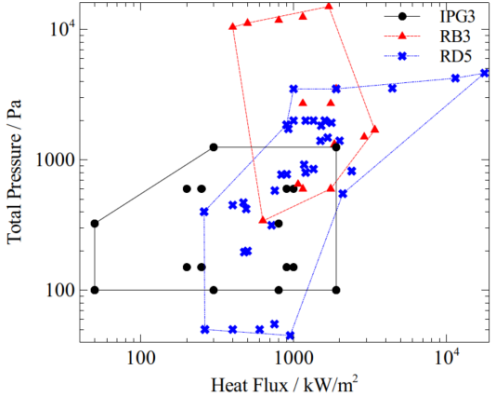
RB3 (PWK4)

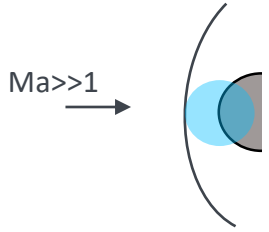


IPG3 (PWK3)

Experimental Simulation Approach

LHTS principle





Assumption:
Shock heated gas is only source of surface heating

Local Heat Transfer Simulation:
Stagnation point boundary layer streamline is the same between hypersonic flight and subsonic ground testing if:

1. $h_{Flight} = h_{Exp}$
2. $p_{tot,Flight} = p_{tot,Exp}$
3. $\beta_{Flight} = \beta_{Exp}$

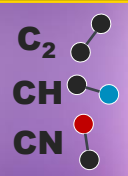
[Loehle, et al., CEAS Space Journal, 2022]
[Kolesnikov, RTO, 1999]

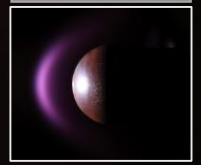
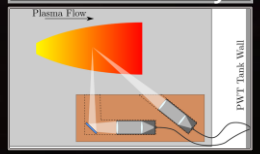
Diagnostic Methods at HEFDiG

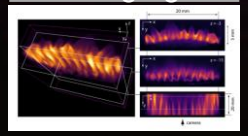
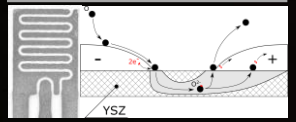
Plasma Characterization

$$h = \frac{1}{2}v^2 + \sum_i \xi_i c_{p,i} T_i + \sum_i \xi_i h_i + \sum_i \xi_i h_{el,i}$$

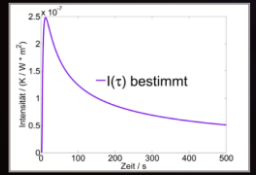
Material Response

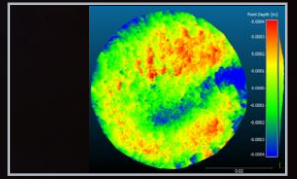
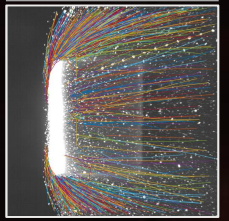


- Enthalpy
  - Mass injection probe
    
- Velocity
  - Fabry-Perot interferometry
    

- Temperatures: T_{trans}, T_{rot}, T_{vib}, T_{el}
  - **Optical emission spectroscopy**
    - Echelle
    - Czerny-Turner
    - High-speed spectroscopy
- Species in the flow field: Free stream + Ablation
  - Plenoptic imaging
    
  - Solid electrolyte sensors
    

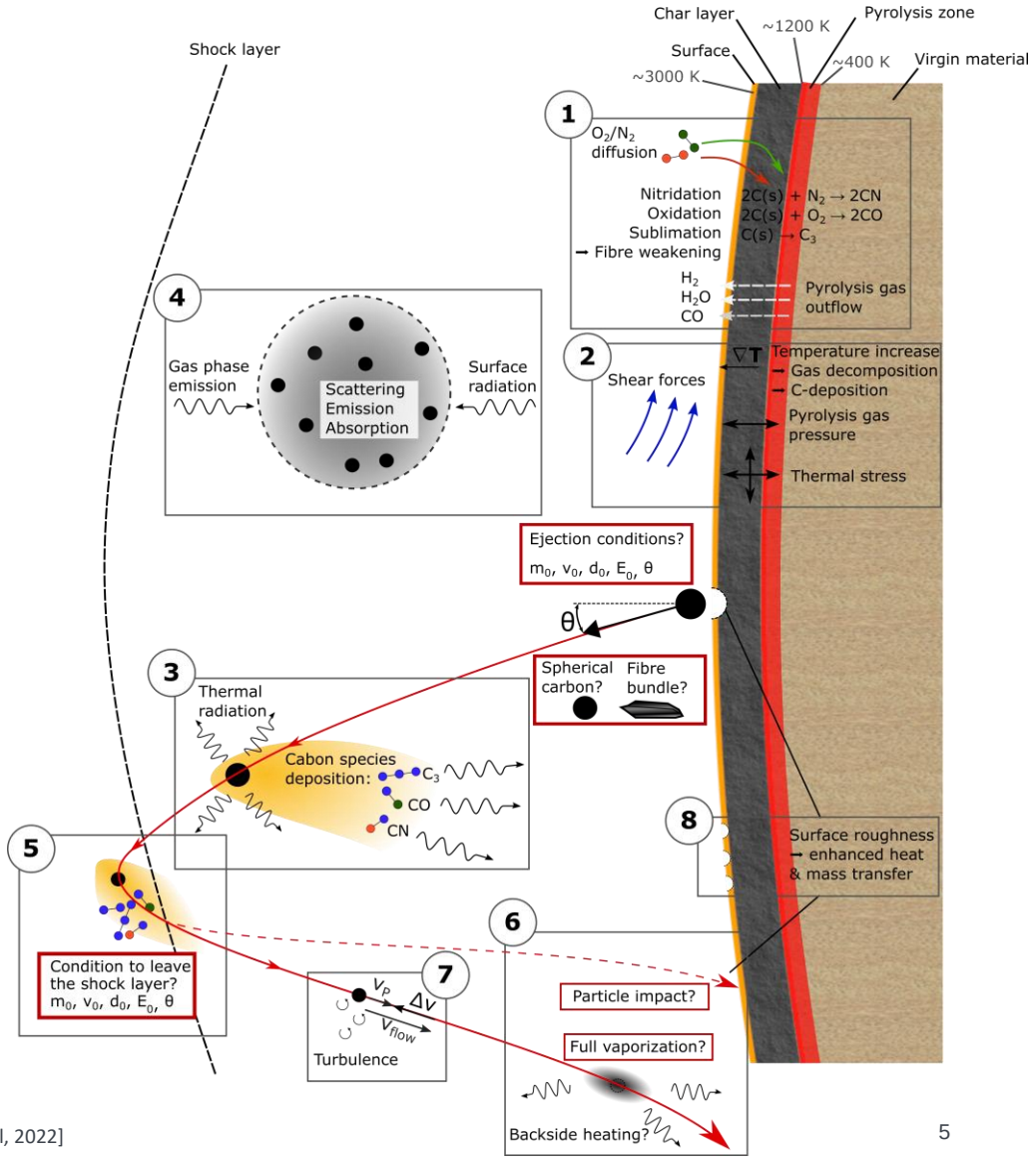
- Heat flux
  - Calorimetric probes
    

  - NISI method
    

- Surface recession
  - Photogrammetry
    
- Spallation rate
  - High-speed imaging
    
- Surface temperature
  - IR & Pyrometry
- In-depth temperature
  - Thermo-couples

Spallation of Carbon Ablators

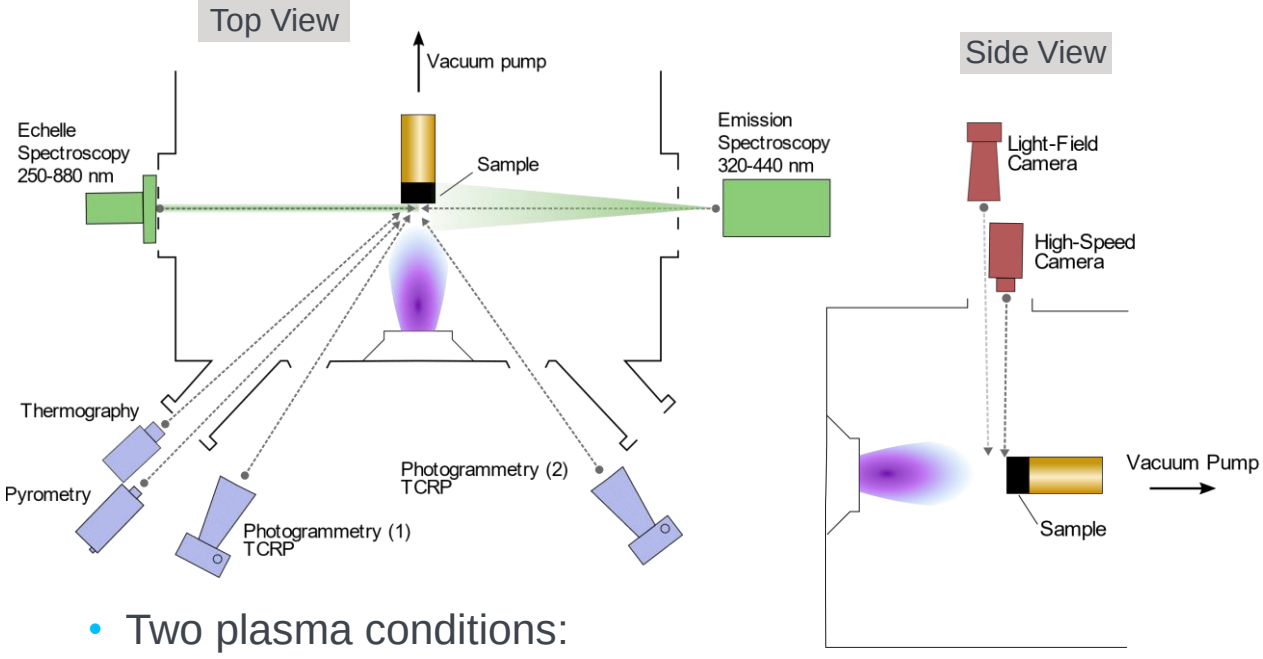
- Spallation: Ejection of solid particles from ablator surfaces
- Undesirable phenomenon, as spalled material is not decomposed at the surface
- Ablation tests of carbon preforms and carbon-phenolics were conducted at plasma wind tunnel PWK1



[Grigat, et al., AIAA Journal, 2022]

Spallation Test Campaign

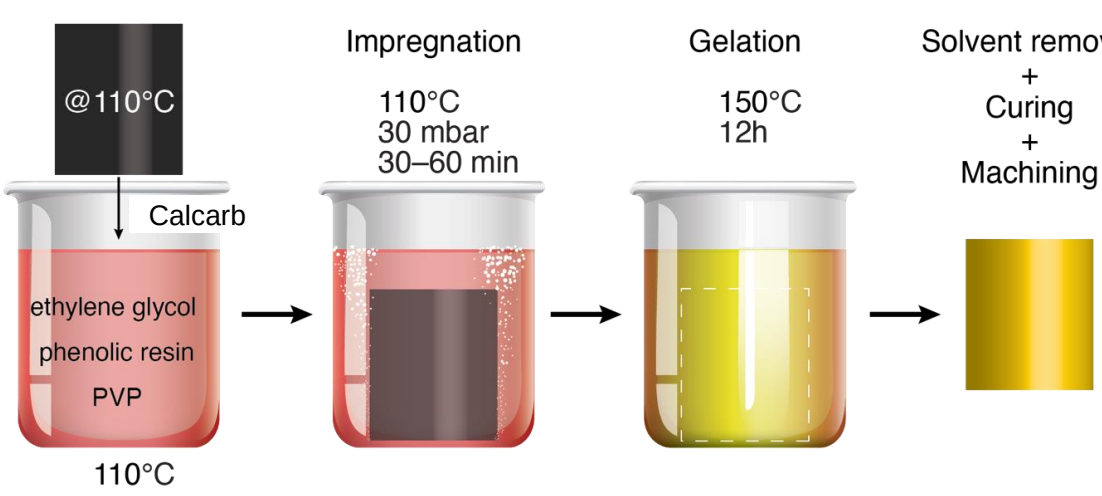
Plasma Wind Tunnel PWK1 & Diagnostic Setup

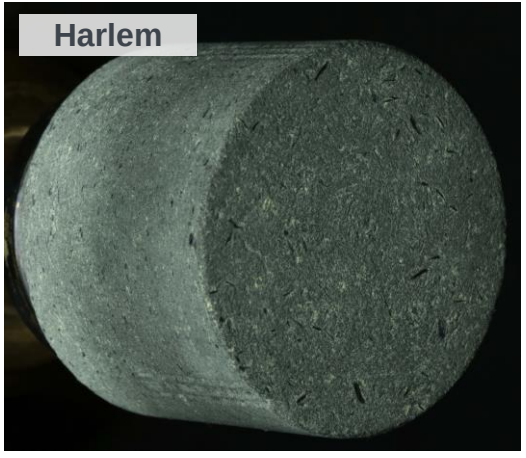


- Two plasma conditions:
  - Air (Hayabusa reentry at 78 km)
  - N2 (no oxygen, similar cold-wall heat flux)
- Samples:
  - Carbon preforms: **Calcarb** & **FiberForm**
  - Carbon-phenolics: **ZURAM** & **HARLEM**

HEFDiG Ablator Material for Research

Carbon-phenolic ablator HARLEM





HARLEM is the new ablator material that we produce in our lab at HEFDiG

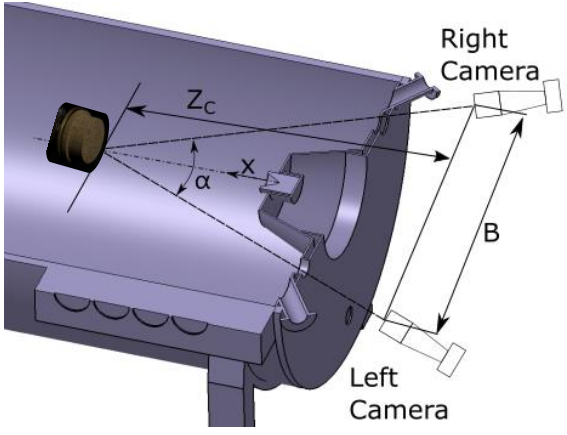
The idea is not to develop ablators but to have representative carbon-phenolic ablators available for rapid testing and **development of diagnostic methods for ablation**.

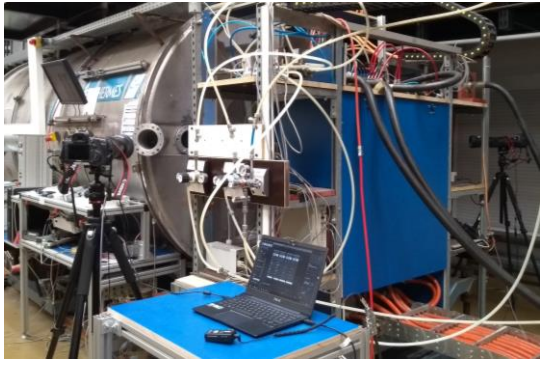
Note about the samples in this test campaign:
Harlem1_**FF**: **FiberForm** as carbon preform
Harlem2_**CC**, Harlem3_**CC**, Harlem4_**CC**: **Calcarb** as carbon preform

[Poloni, et al., Carbon, 2022]

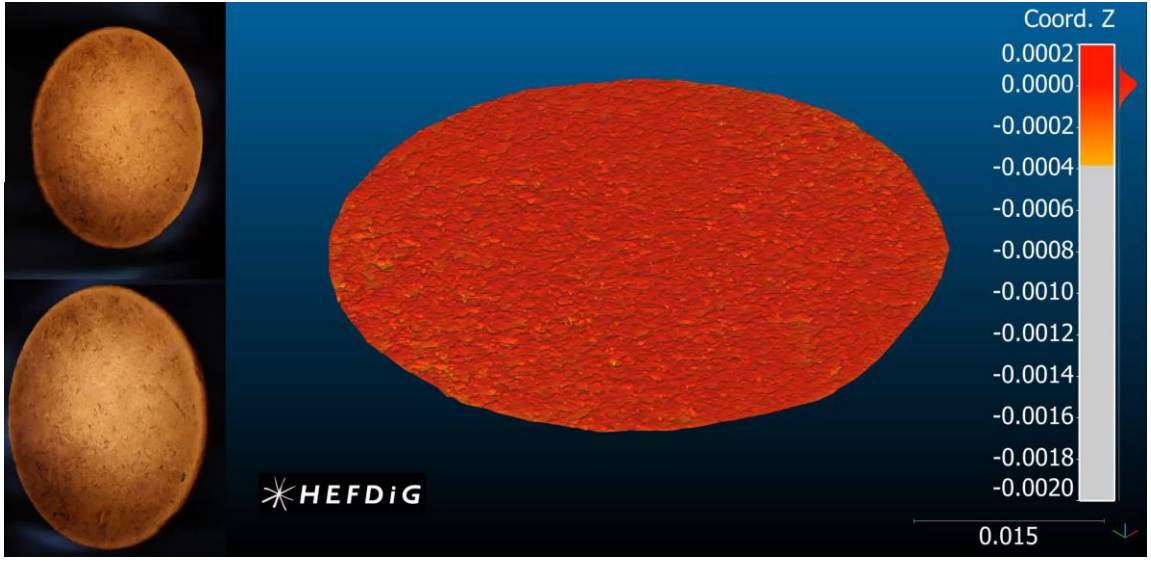
Photogrammetry

Surface Recession Measurements



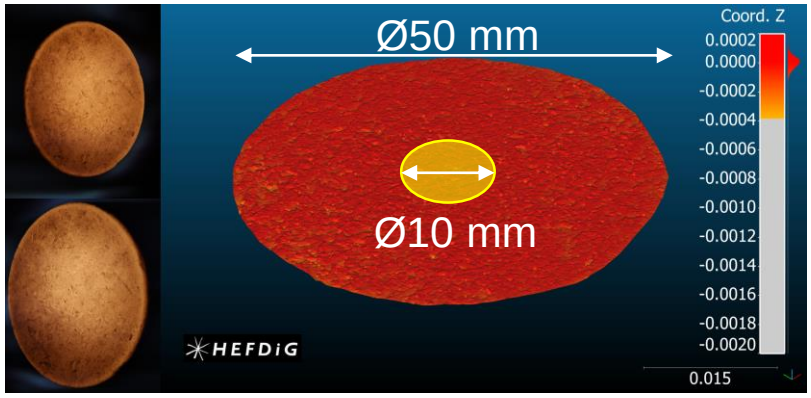


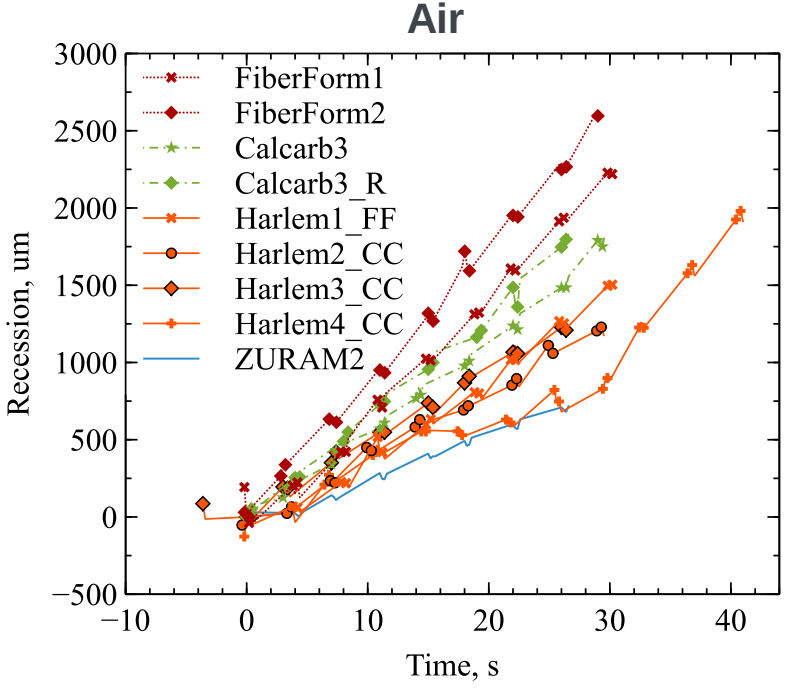
Method:
Non-intrusive 3D measurement of the ablator surface from simultaneous images from two or more DSLR cameras.

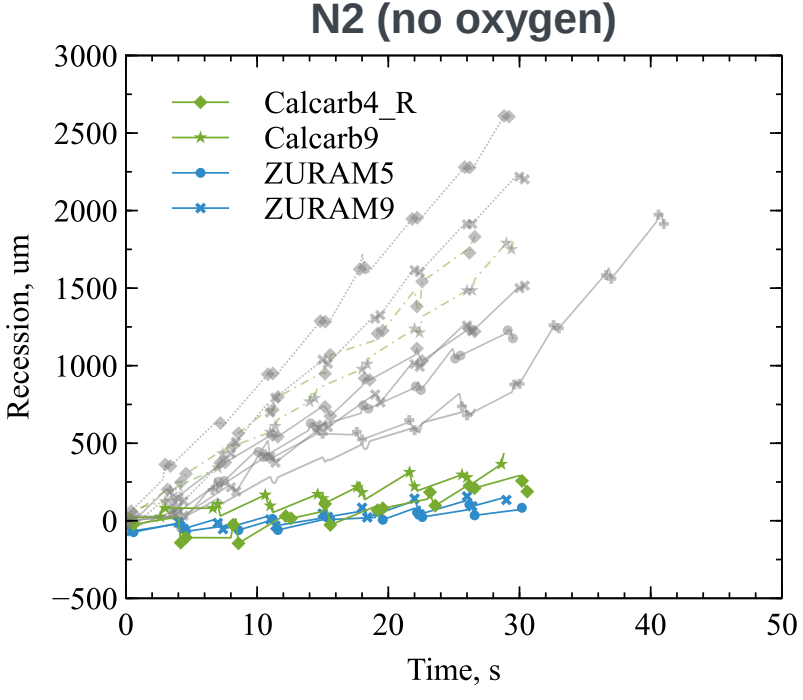


Photogrammetry

Surface Recession in the Stagnation Region

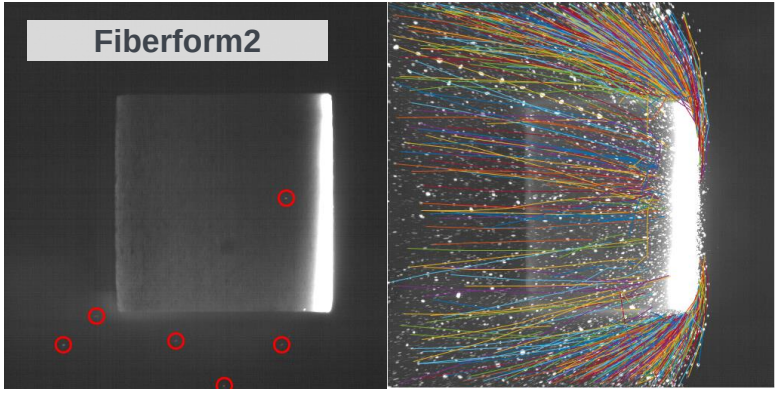


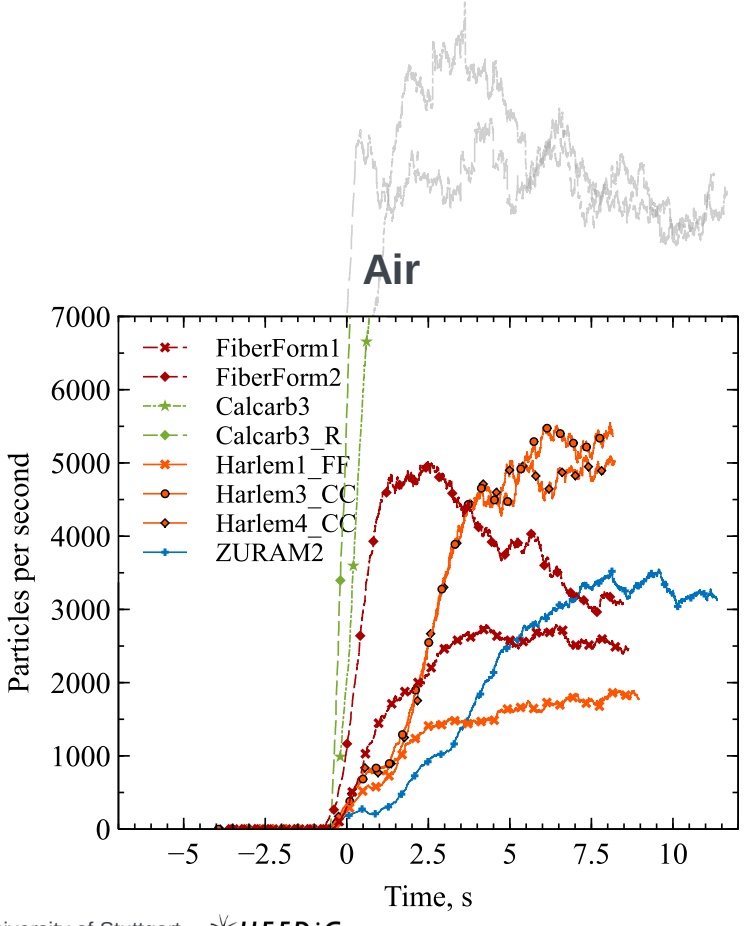


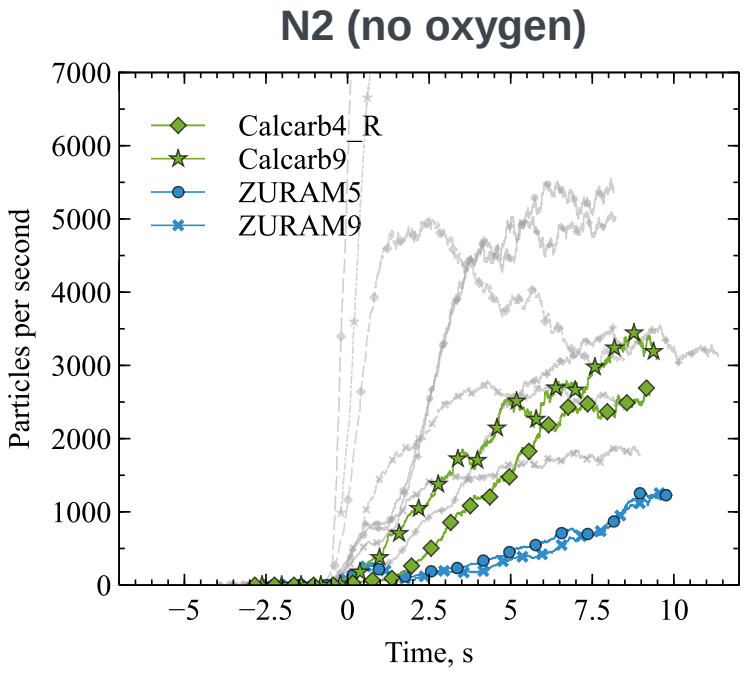


High-Speed Imaging

Particle Detection & Linking

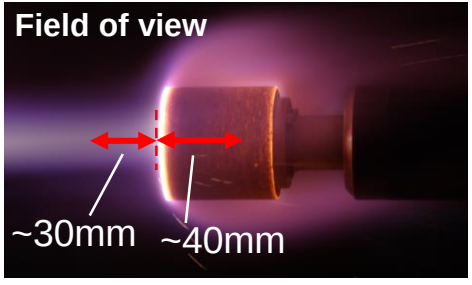


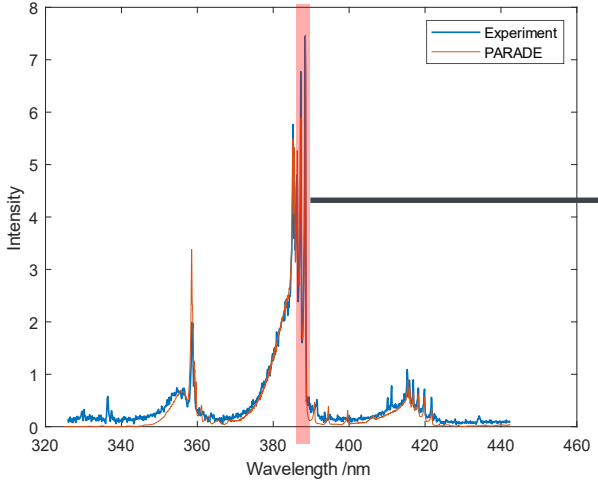


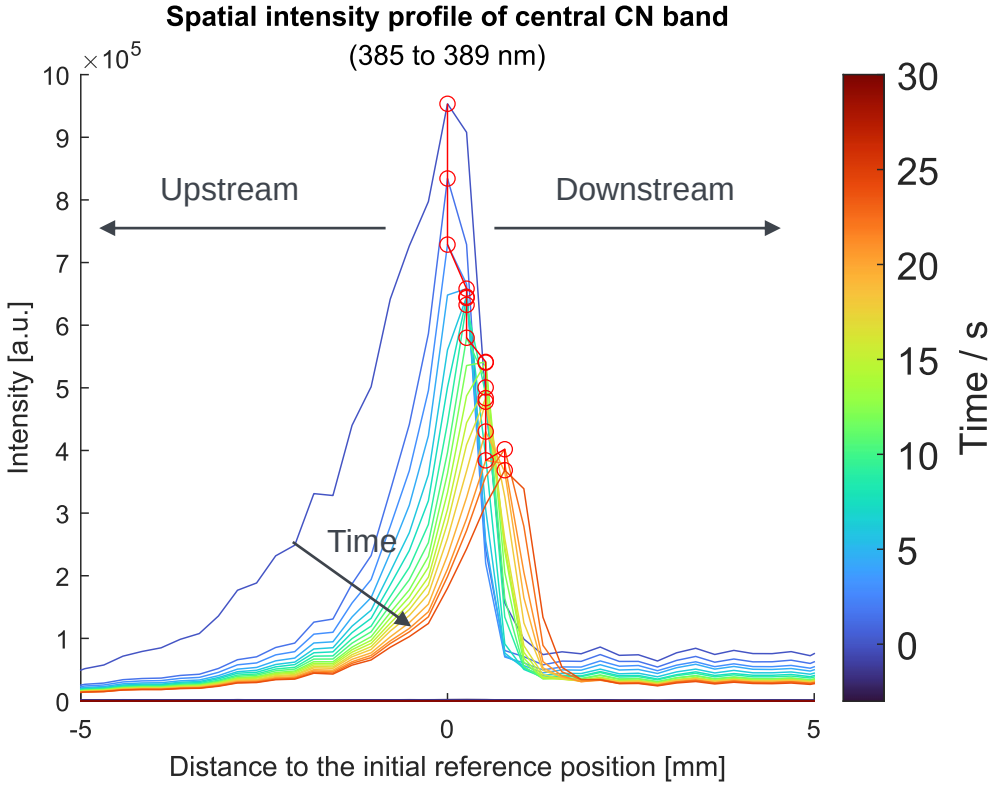


Optical Emission Spectroscopy

CN band intensity integrated from 385 nm to 389 nm

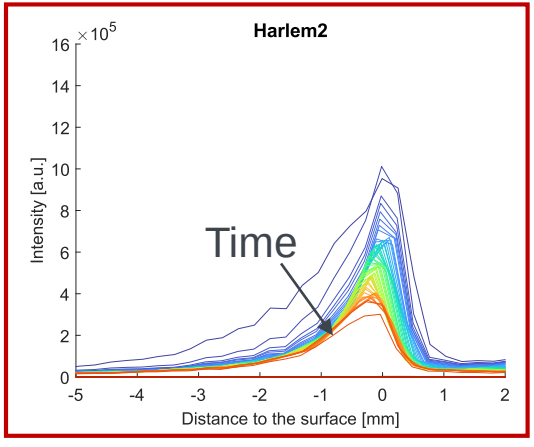


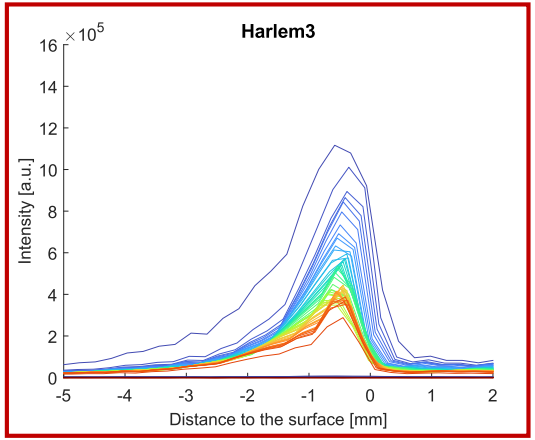


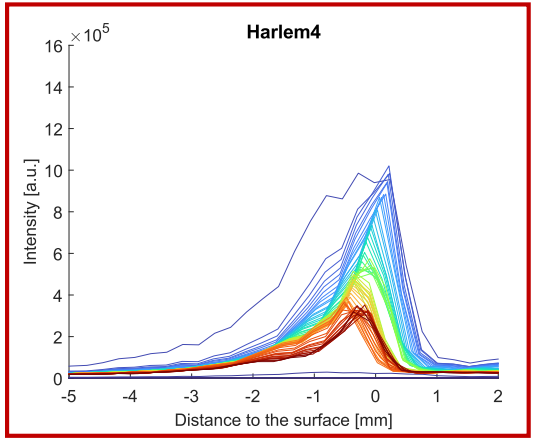


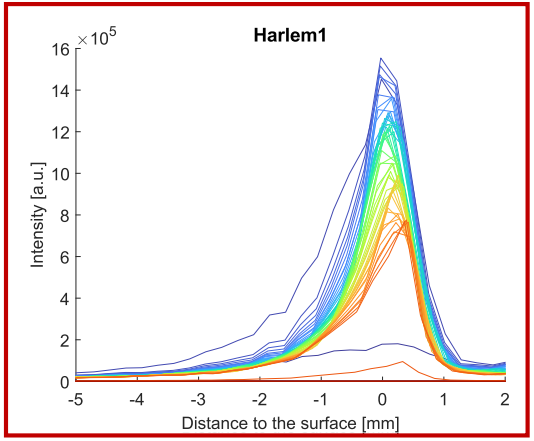
Optical Emission Spectroscopy

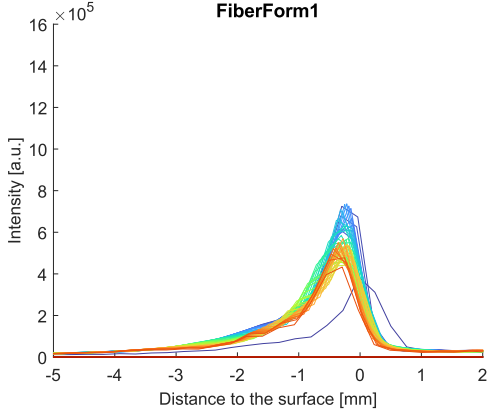
CN band intensity relative to the surface

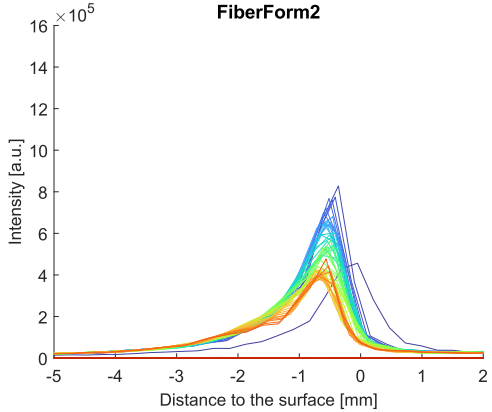


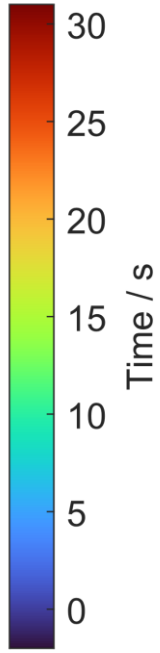






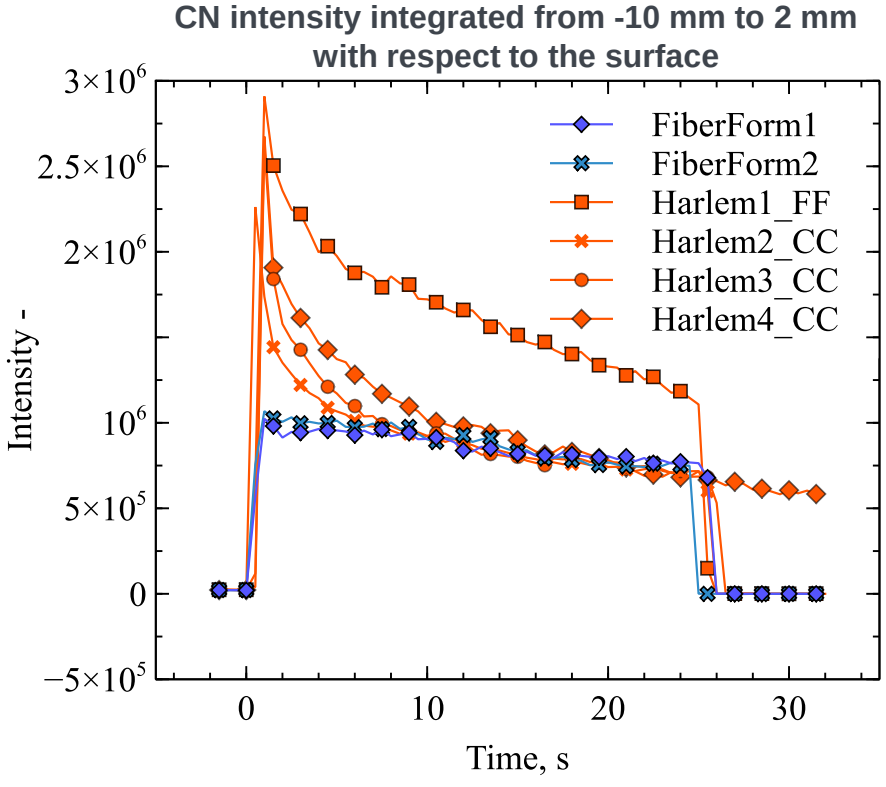


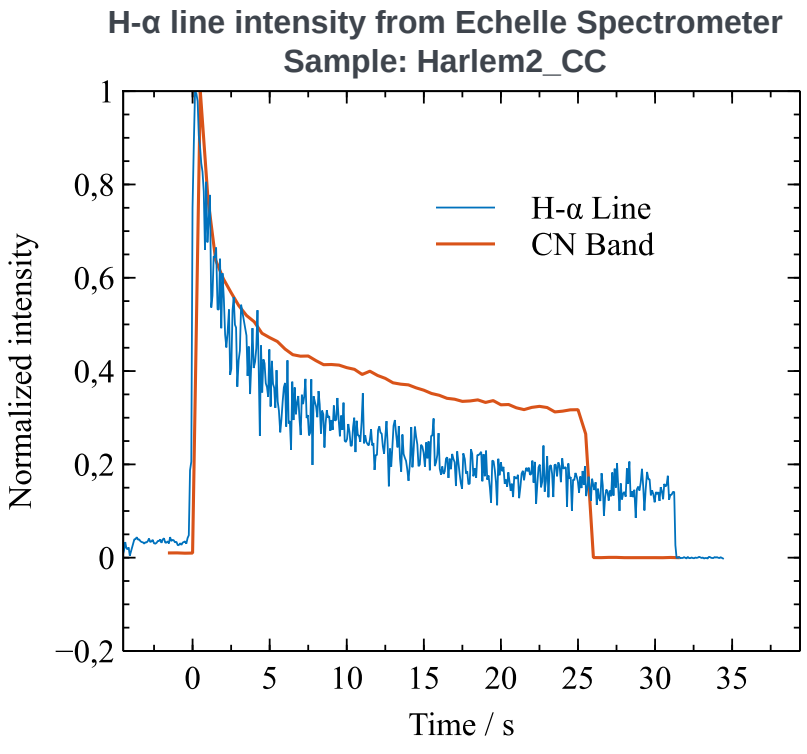




Optical Emission Spectroscopy

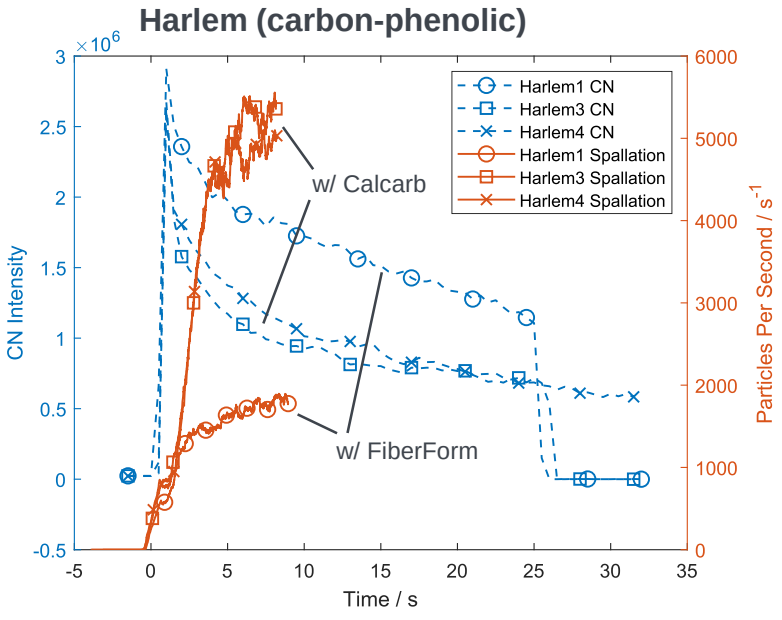
CN intensity and pyrolysis outgassing

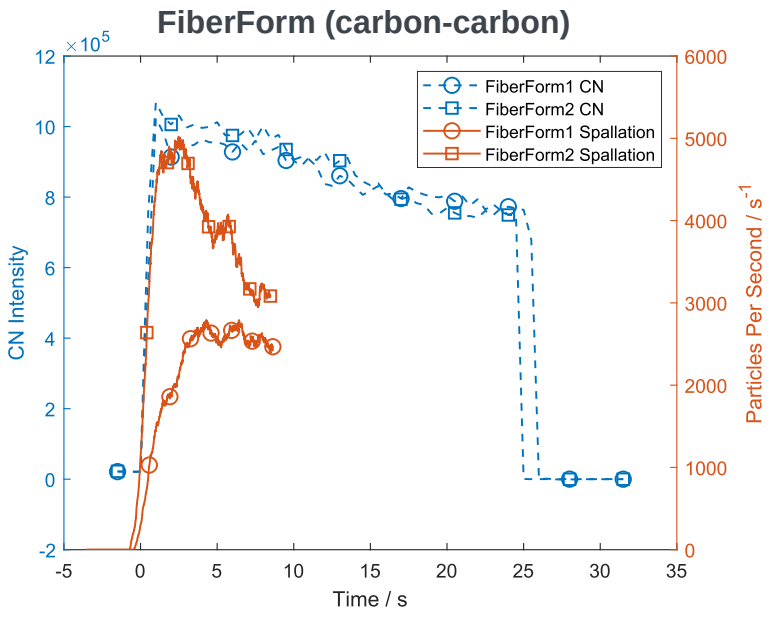




Temporal evolution of the CN intensity of Harlem samples (i.e. Carbon-Phenolics) resembles the temporal evolution of the H-α line (indicator for pyrolysis outgassing)

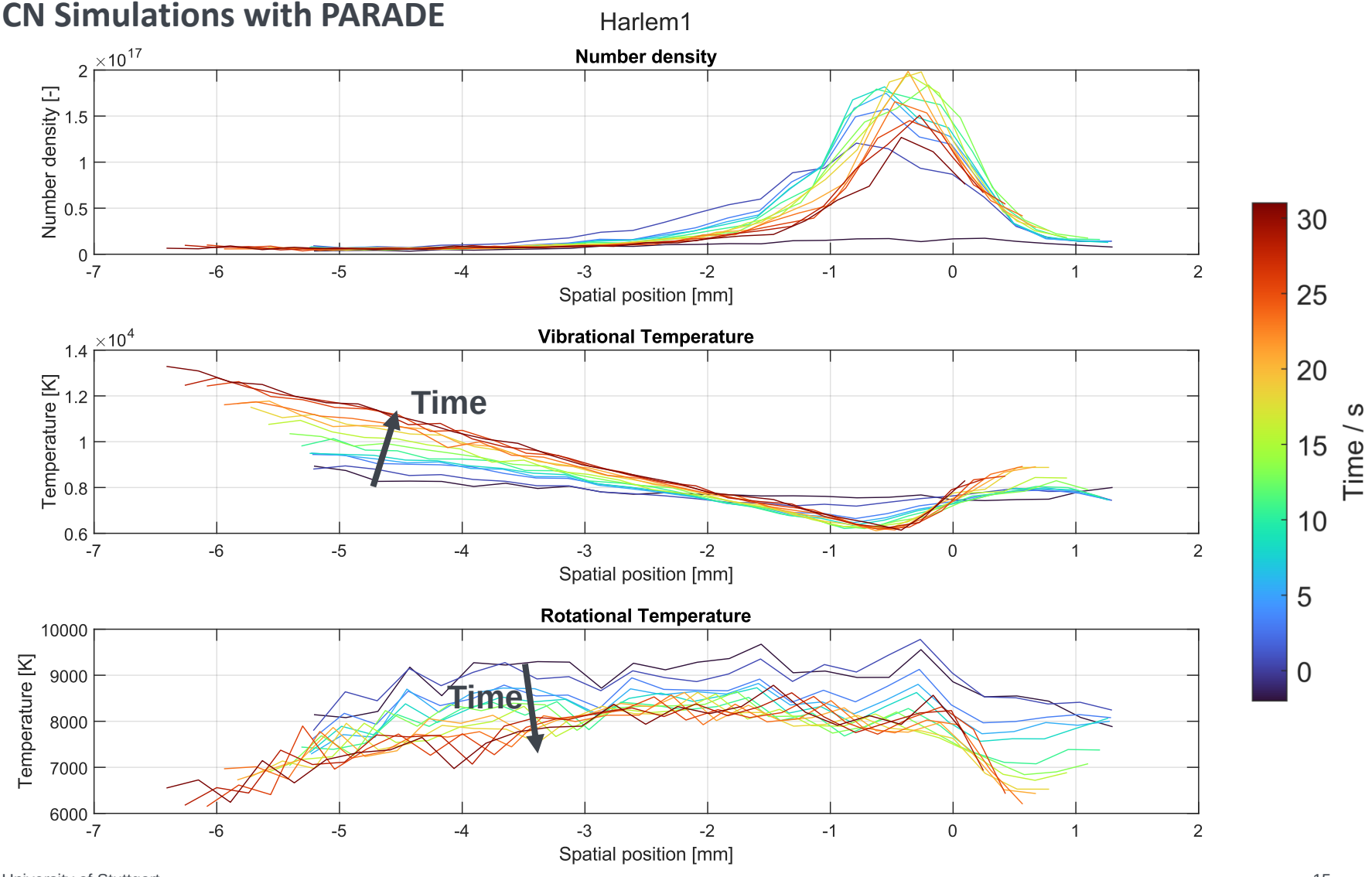
Comparison of CN intensity to Spallation



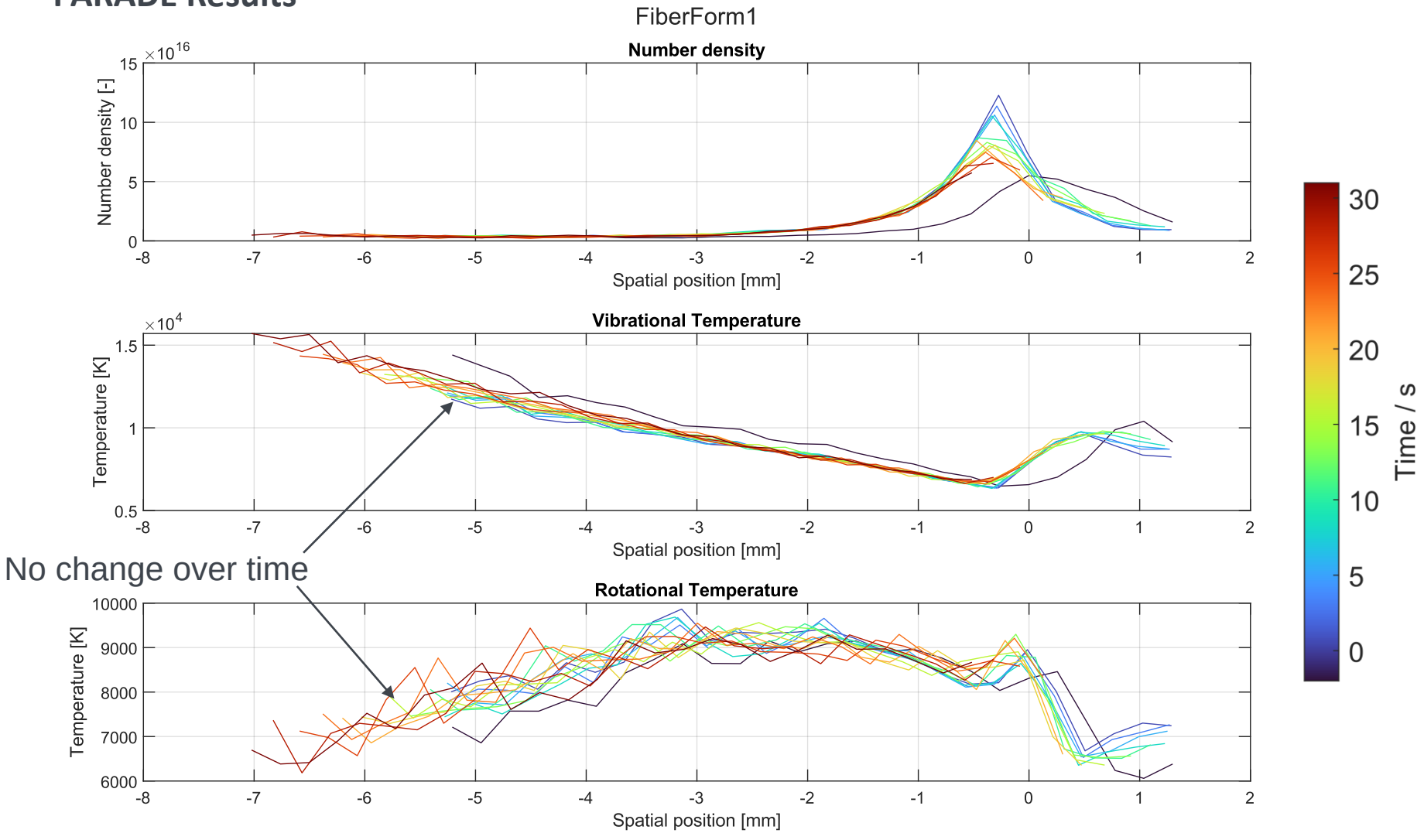


- **Harlem: No correlation visible** between the spallation rate and the CN intensity
- **FiberForm**: CN intensity and spallation rate quickly reach a maximum and then decrease steadily.
  But role of spallation vs. surface ablation is unclear

CN Simulations with PARADE



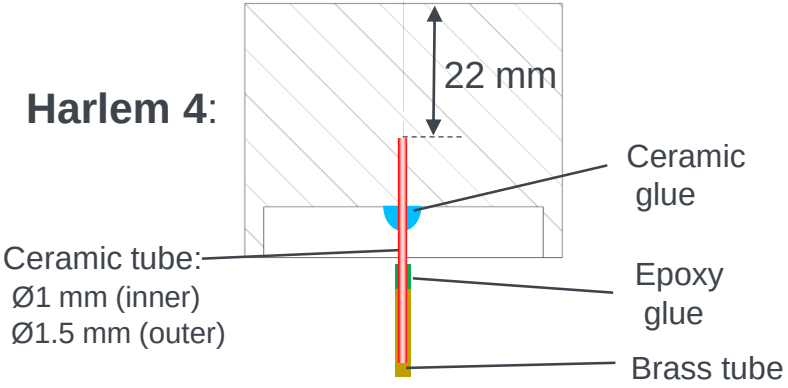
PARADE Results

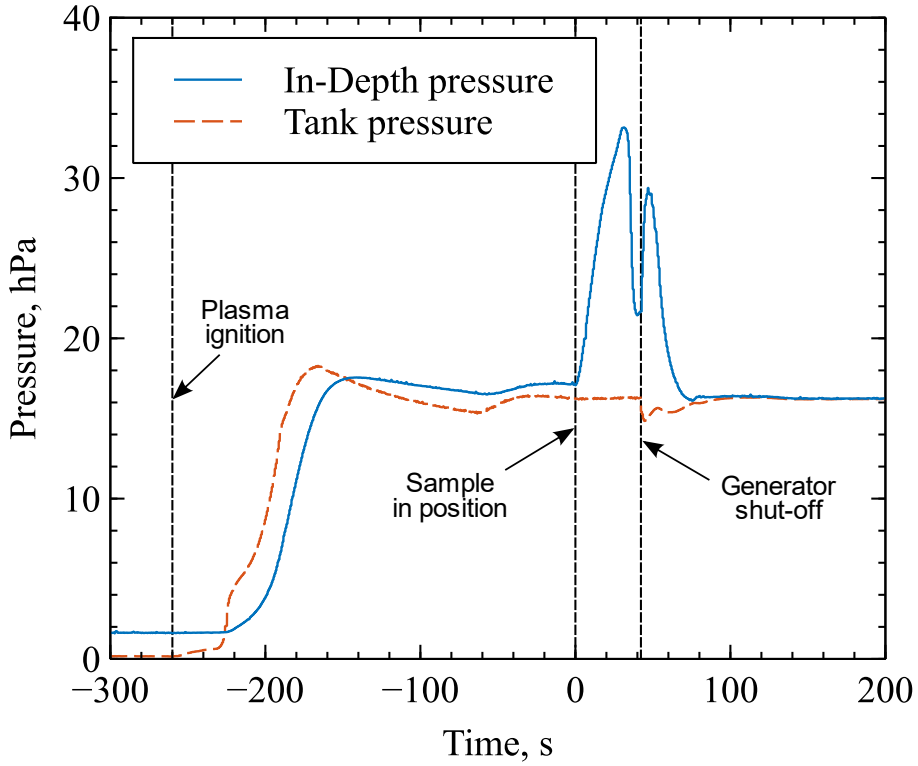


Ongoing developments: Embedded diagnostics

In-depth pressure measurements

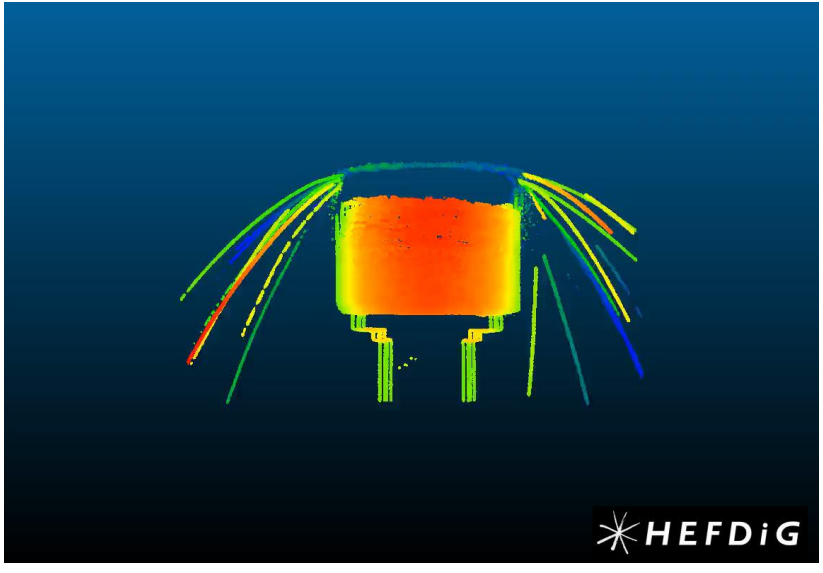
Harlem 4:

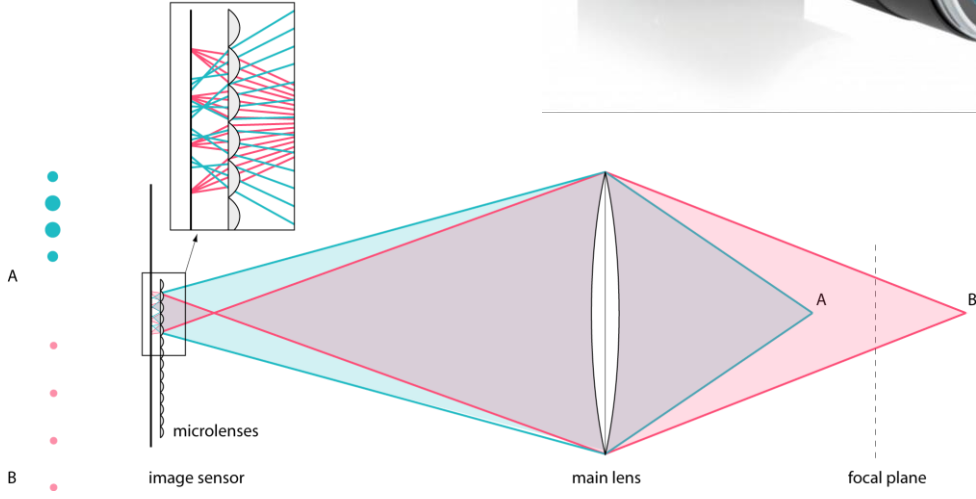




Ongoing developments: Lightfield imaging

3D particle tracking

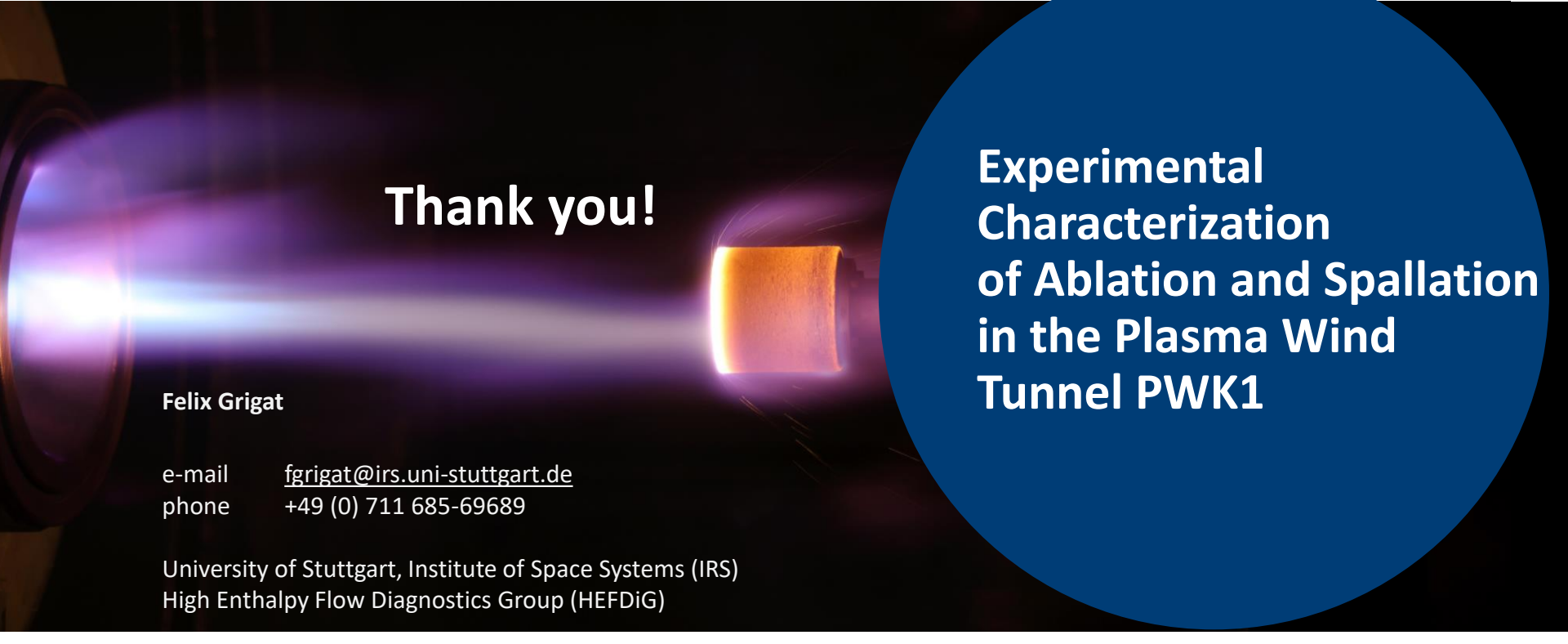




Summary

- Ablation experiments mainly conducted in plasma wind tunnel PWK1
  - Air plasma
  - N2 plasma
  - H/He plasma
- Diagnostic methods:
  - Photogrammetric recession measurements
  - Optical emission spectroscopy
    - Echelle spectrometer
    - Czerny-Turner spectrometer
  - Surface temperature measurements
  - Spalled particle tracking via high-speed imaging

- Work in progress:
  - 3D particle trajectory measurements via plenoptic imaging
  - In-depth pressure measurements



Thank you!

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