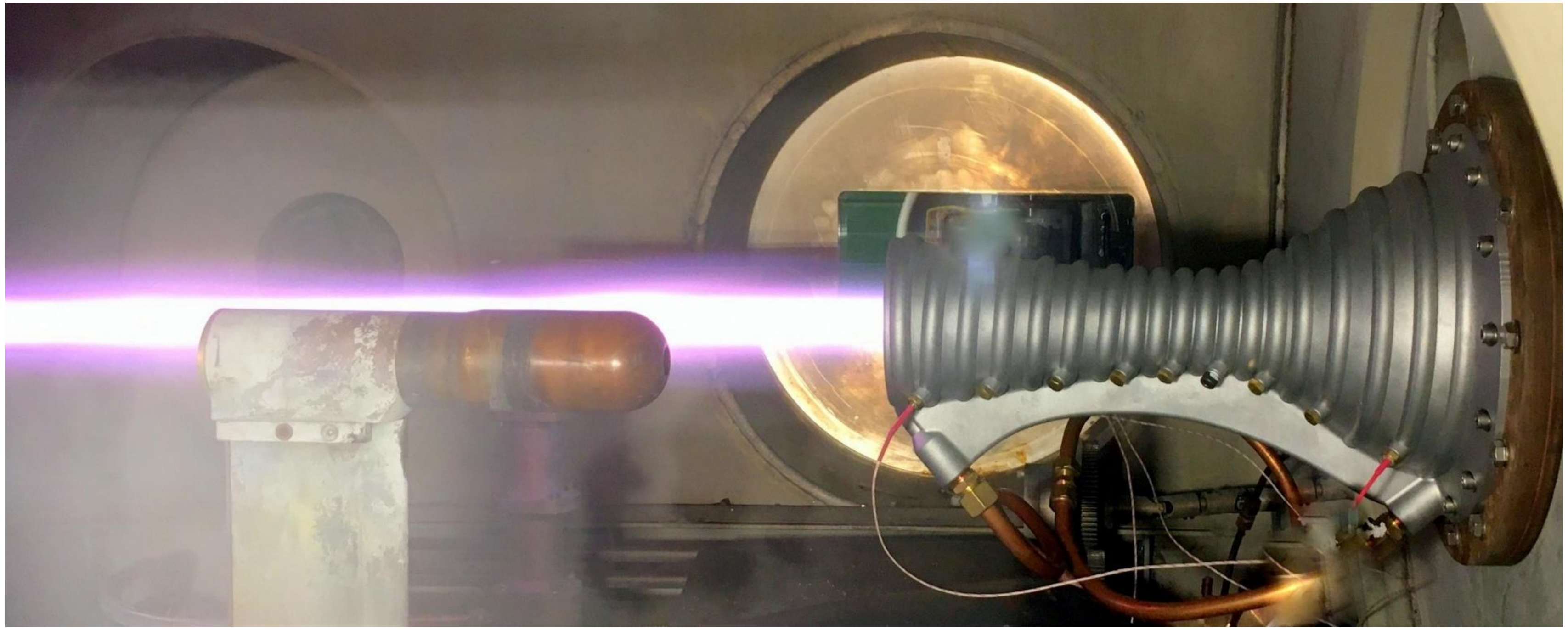
Advancements in demise testing at VKI: Sub- and supersonic experiments of titanium, Zerodur and quartz



B. Helber, A. Fagnani, A. Turchi, B. Dias, A. Viladegut, L. Sombaert, T. E. Magin, O. Chazot
von Karman Institute for Fluid Dynamics
P. Schrooyen
Cenaero
L. Walpot
ESA

02 December 2021

von Karman Institute for Fluid Dynamics

Background: Belgian GSTP

Validation of Space Debris Demise Tools using Plasma Wind Tunnel Testing and Numerical Tools

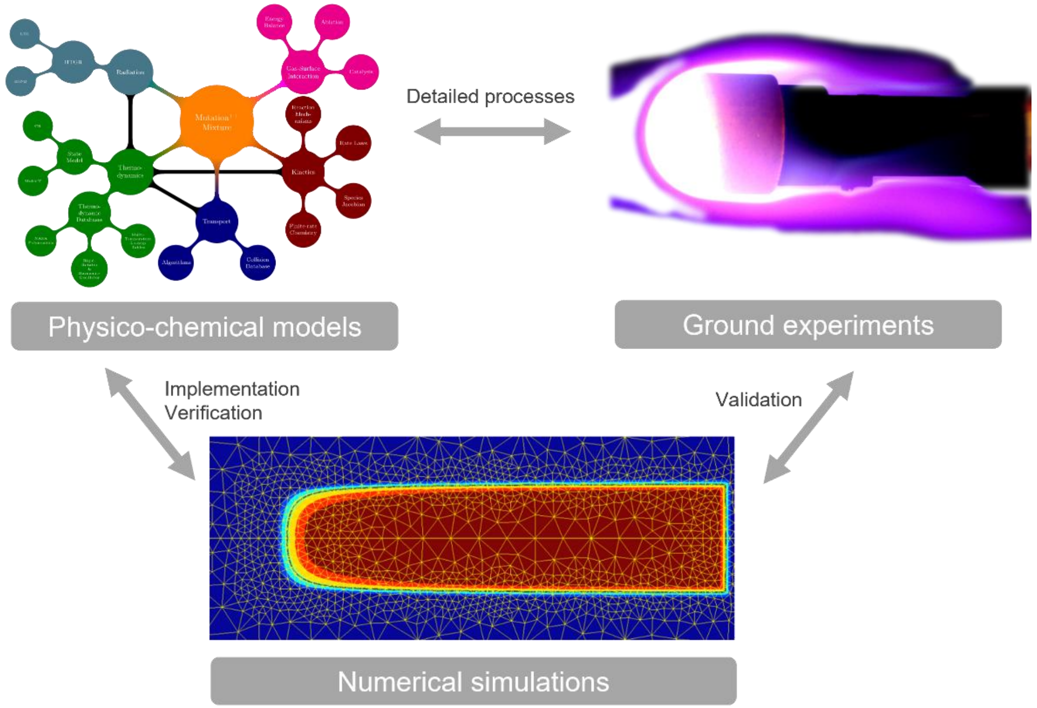
Objectives:

VKI (Plasmatron, Mutation^{++}) : High-enthalpy experiments of problematic space debris materials

Cenaero (*ARGO*) : High-fidelity models and numerical simulations

→ strengthening our understanding of demise phenomena

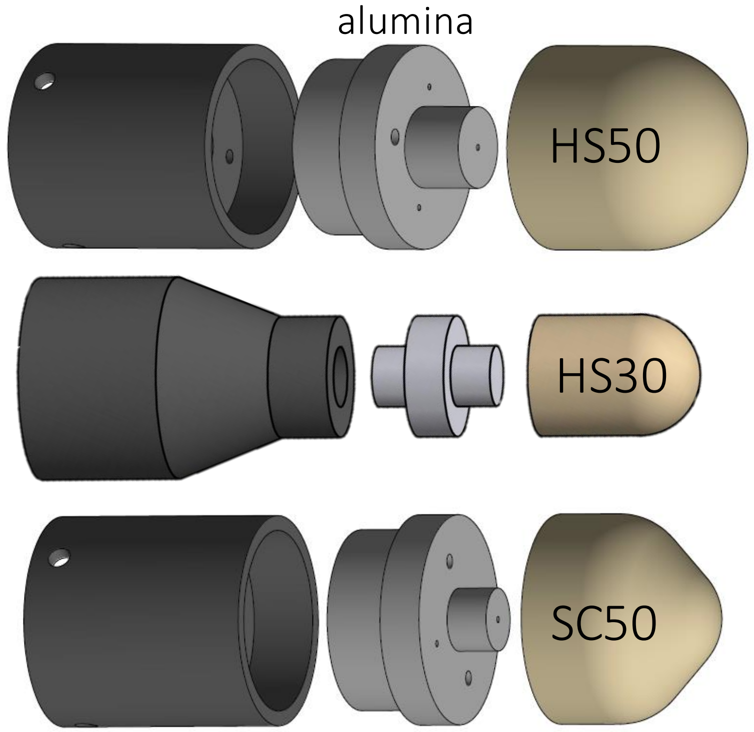
→ produce engineering correlations from high-fidelity simulations



→ engineering correlations for ground casualty risk prediction

Background: Extensive sub- and supersonic demise experiments

The variety of materials make their demise prediction difficult



Complicated oxidation mechanisms

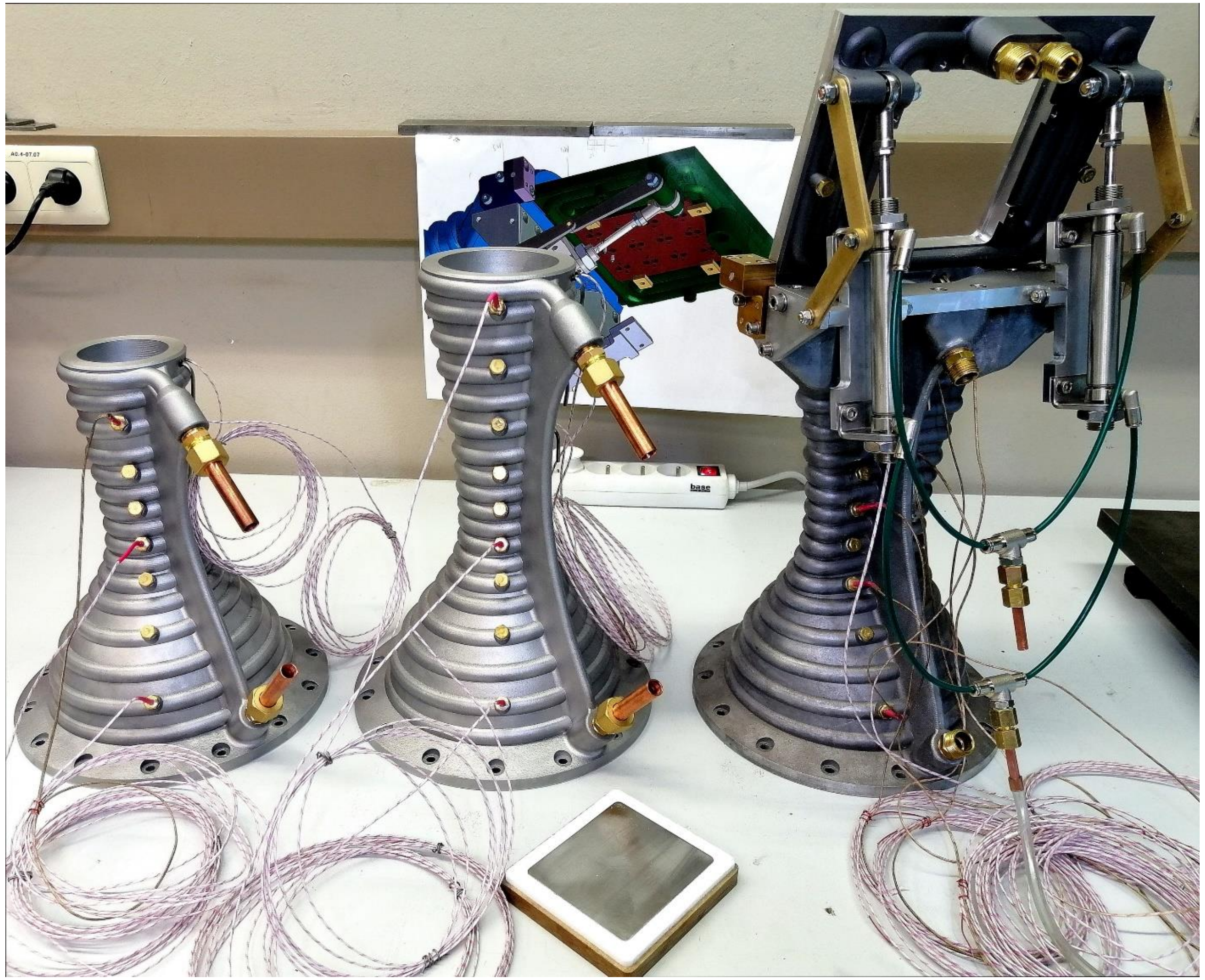
More complicated chemistry
Partial evaporation

Low $T_{surface}$: no mass removal, validation SEB

High $T_{surface}$: validation evaporation + shear

Background: Extensive sub- and supersonic demise experiments

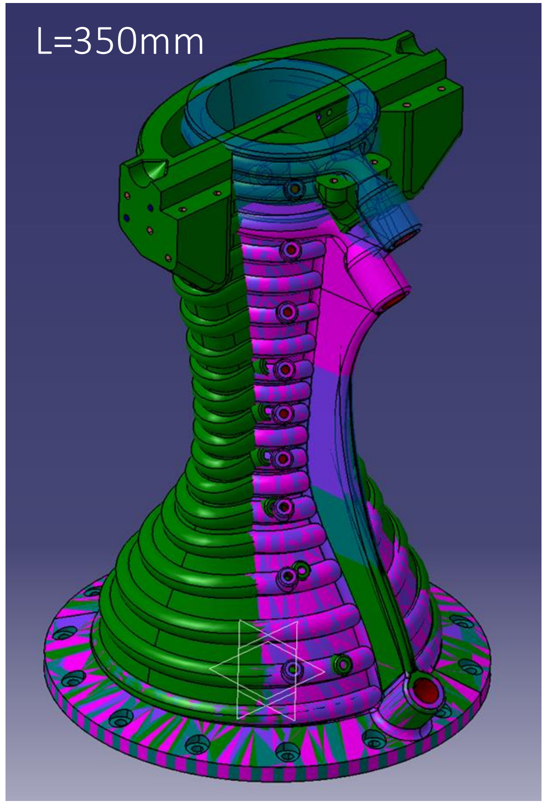
Design and commissioning of conical and semi-elliptical nozzles (additive manufacturing)

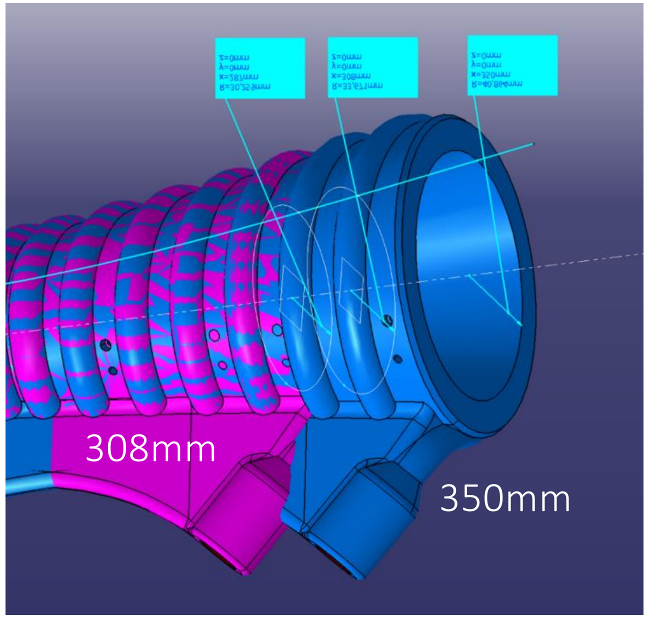


identical length, area ratio and exit area for SE and conical nozzle

Identical cooling loop design

Shorter nozzle for less expansion





Overview

Experimental methods

- Plasmatron facility
- Instrumentation setup and new hardware

Experiments

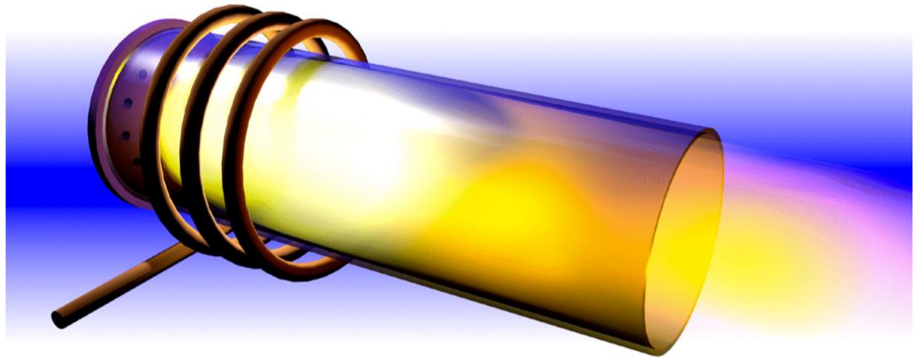
- Quartz
- Zerodur
- Titanium
- Supersonic

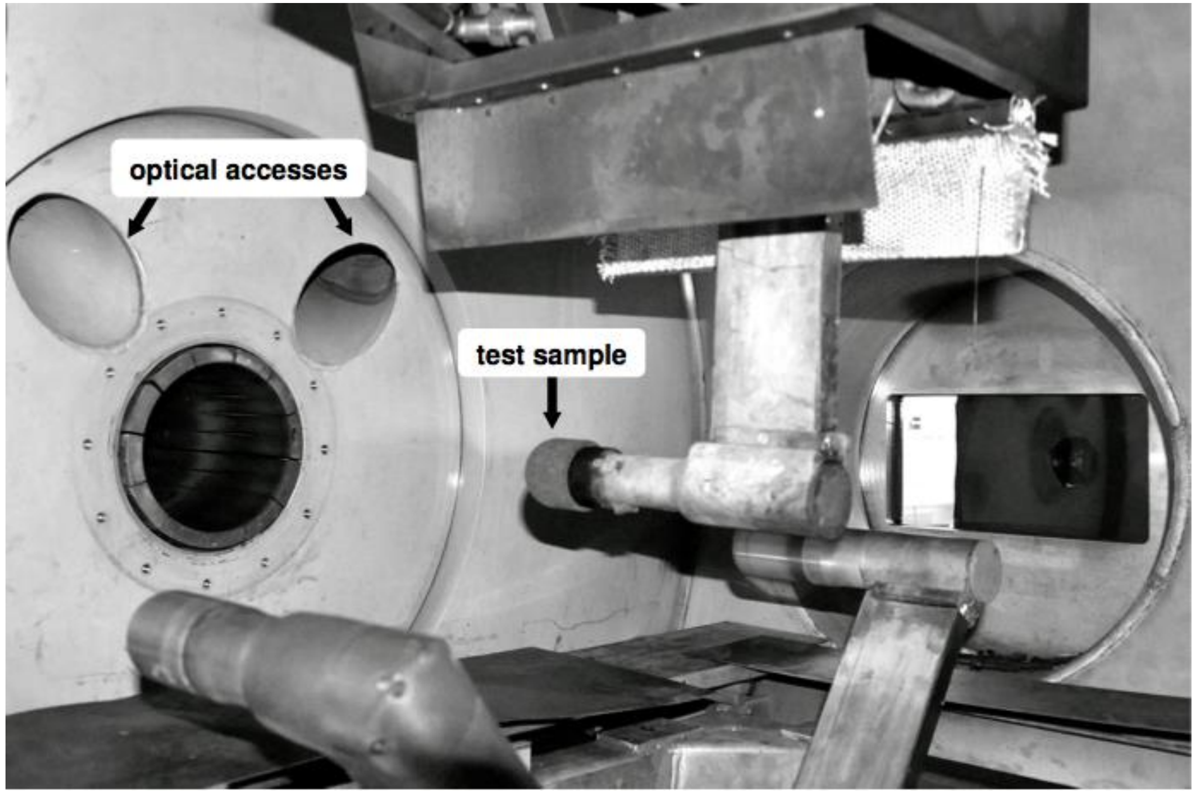
Numerical simulations outlook

- Mutation^{++}
- 1D-stagnation line code with melting model
- High-fidelity *ARGO* simulations

1.2 MW Inductively Coupled Plasmatron

A subsonic test bed for re-entry flow reproduction

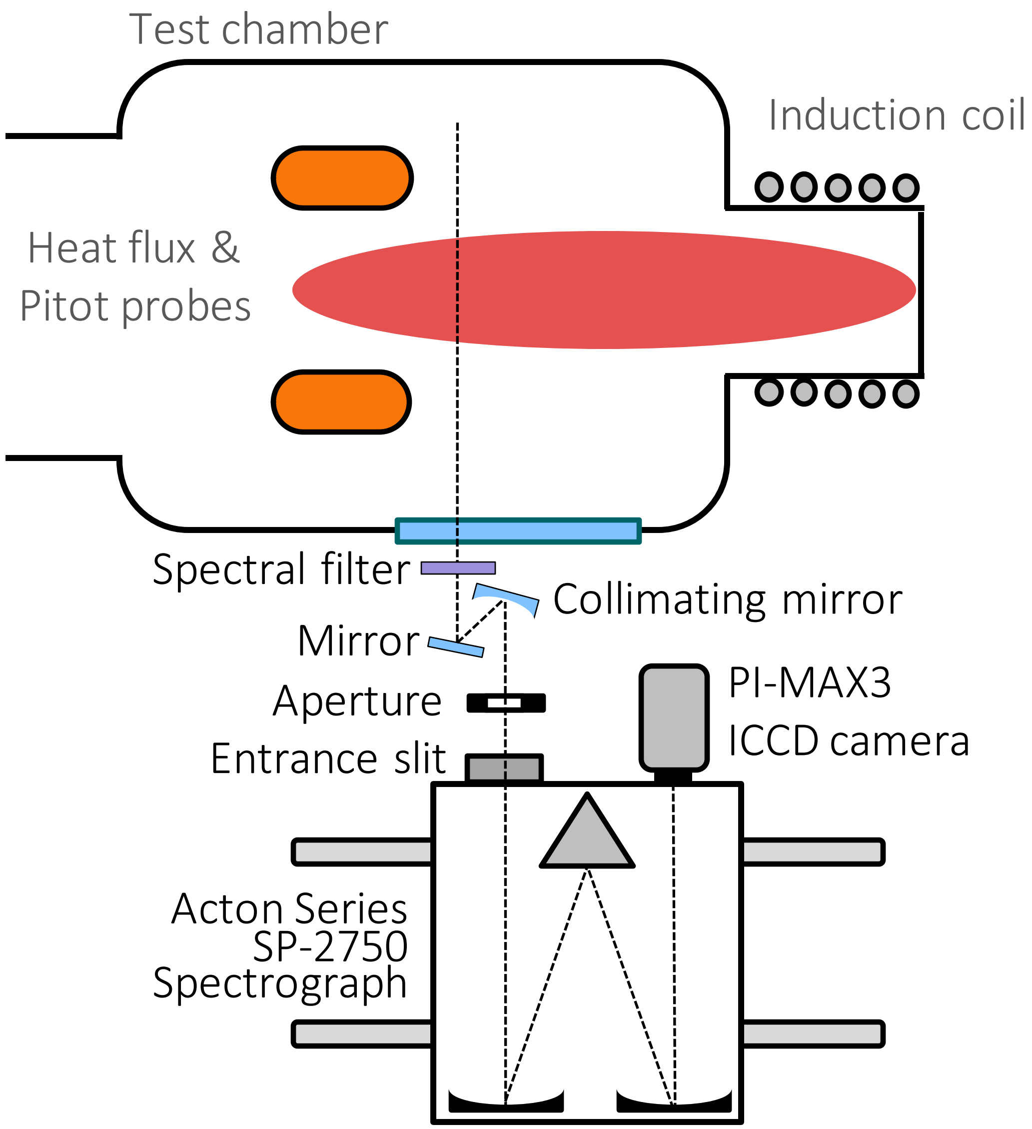


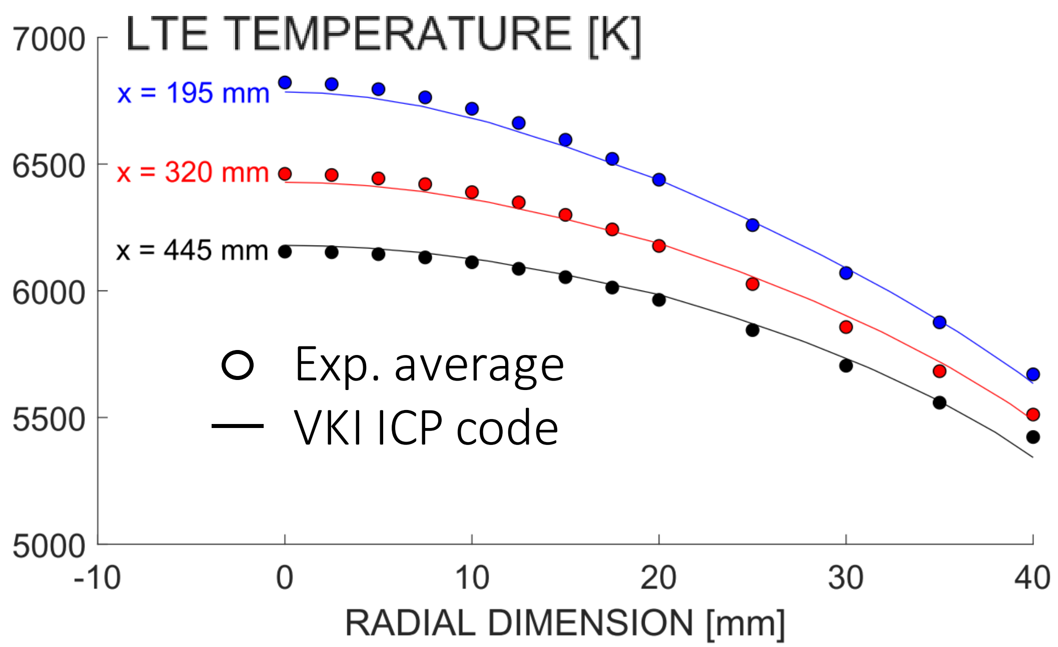


Gas	air, N_2, CO_2, Ar
Power	1.2 MW
Max. heat flux	15 MW/m^2
Pressure	10 hPa - 400 hPa

1.2 MW Inductively Coupled Plasmatron

Plasma flow characterization by emission spectroscopy

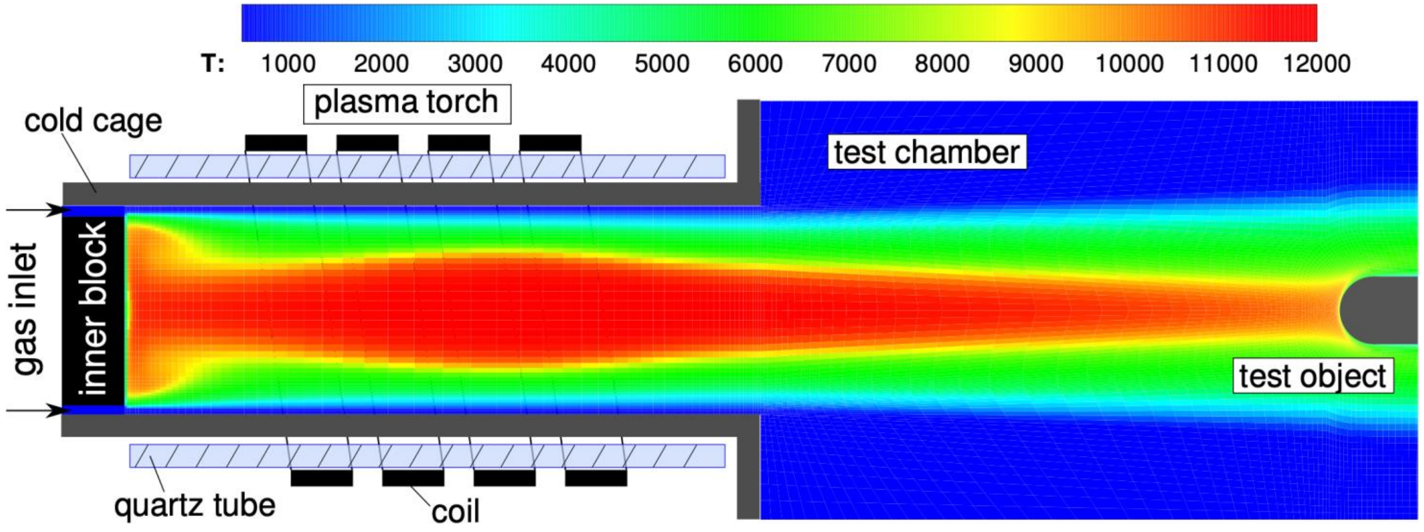


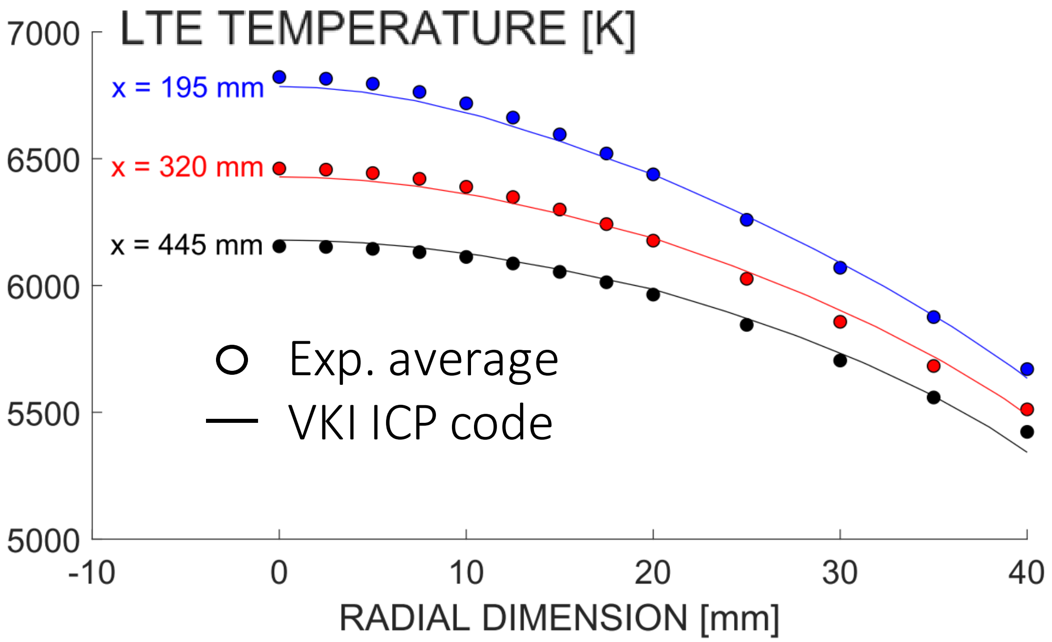


A. Fagnani et al., AIAA 2020-0382

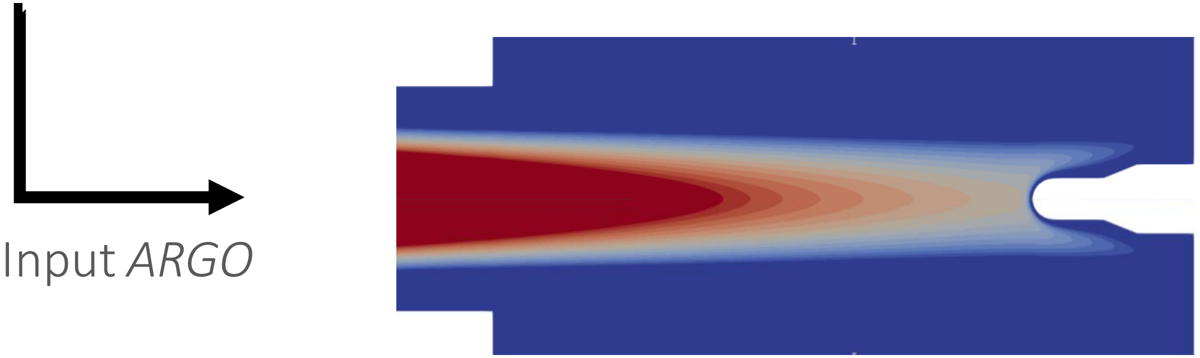
1.2 MW Inductively Coupled Plasmatron

MHD-CFD simulations: Serving as input to material simulations



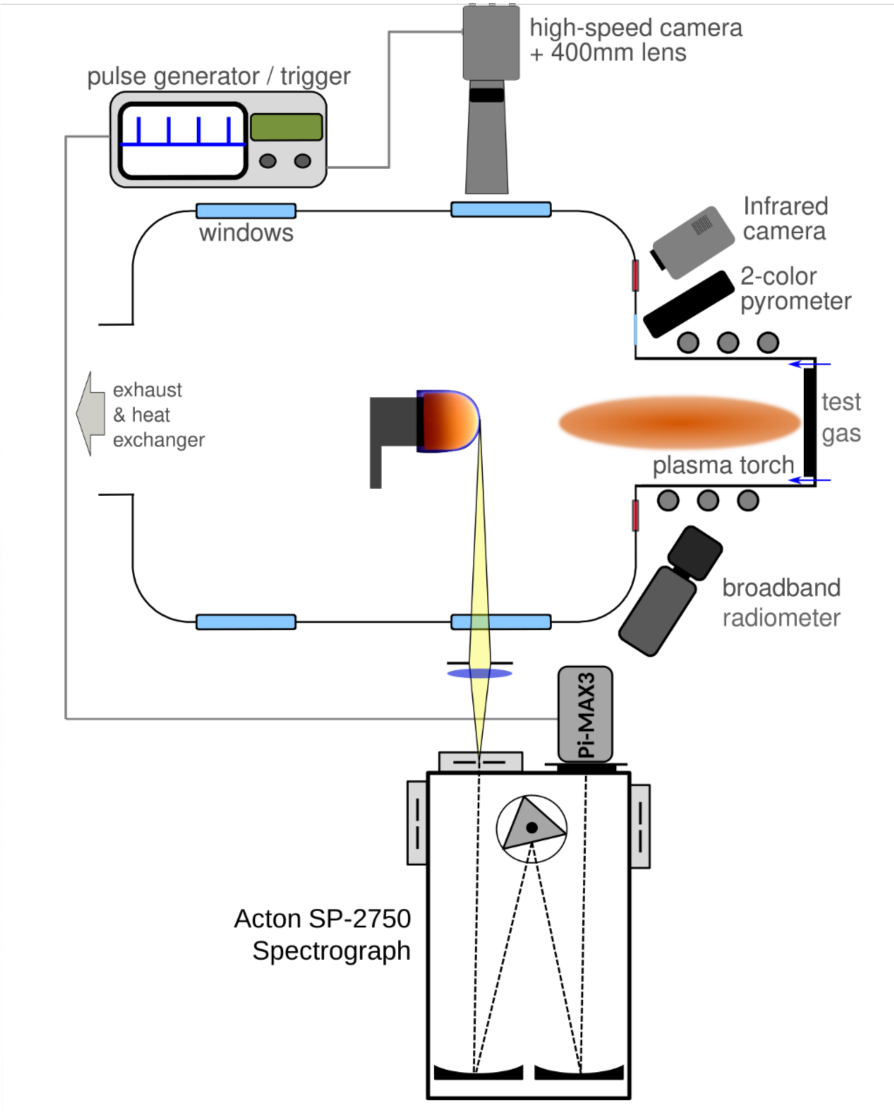


A. Fagnani et al., AIAA 2020-0382



In-situ material response characterization

Comprehensive high-temperature experimental setup



FLIR A6750sc MWIR (3-5µm)
450 - 3270 K calibrated (FLIR)

2-colour pyrometer (0.75-1.1µm)
1300 - 3270 K calibrated (NPL London)

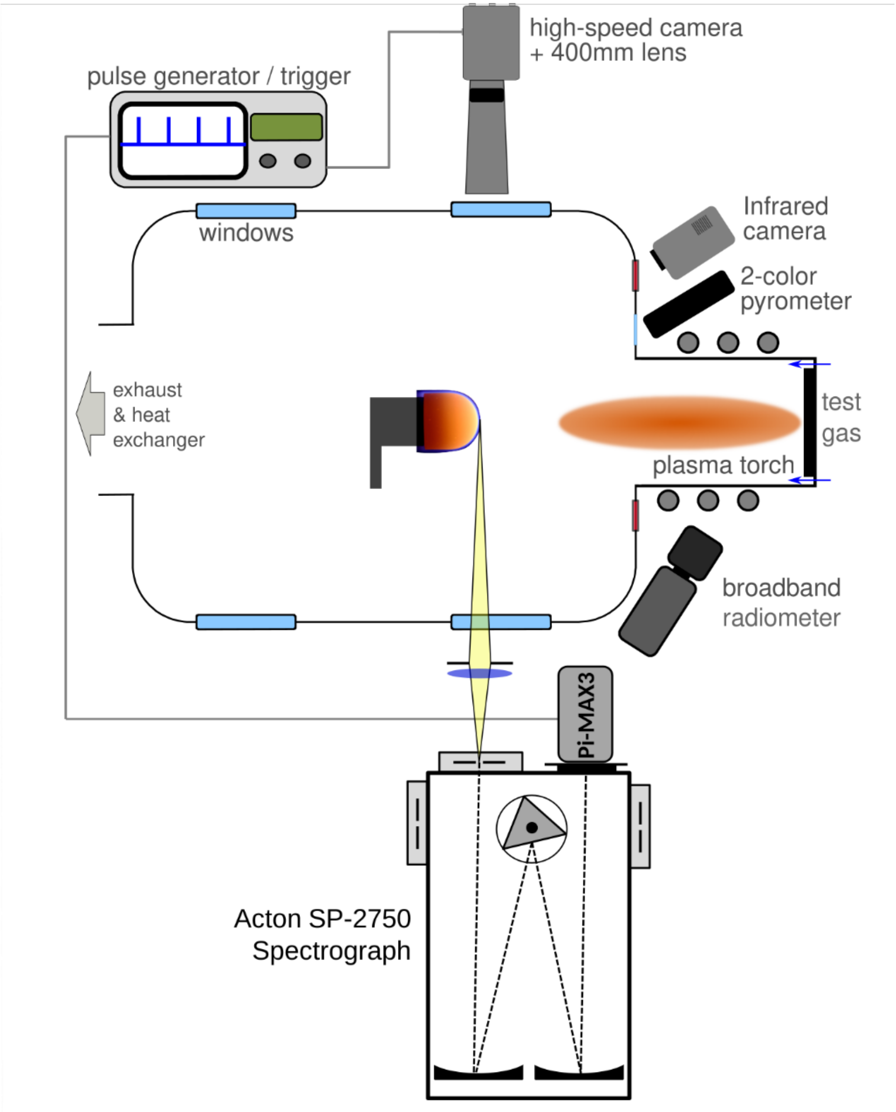
Broadband radiometer (0.65-39µm)
RT - 3270 K calibrated (NPL London)

Optris 1C pyrometer (3-5µm)
RT - 2000 K

Type-K thermocouples (Nickel-Chromium/Nickel-Alumel)
RT - 1500 K

In-situ material response characterization

Comprehensive high-temperature experimental setup



FLIR A6750sc MWIR (3-5µm)

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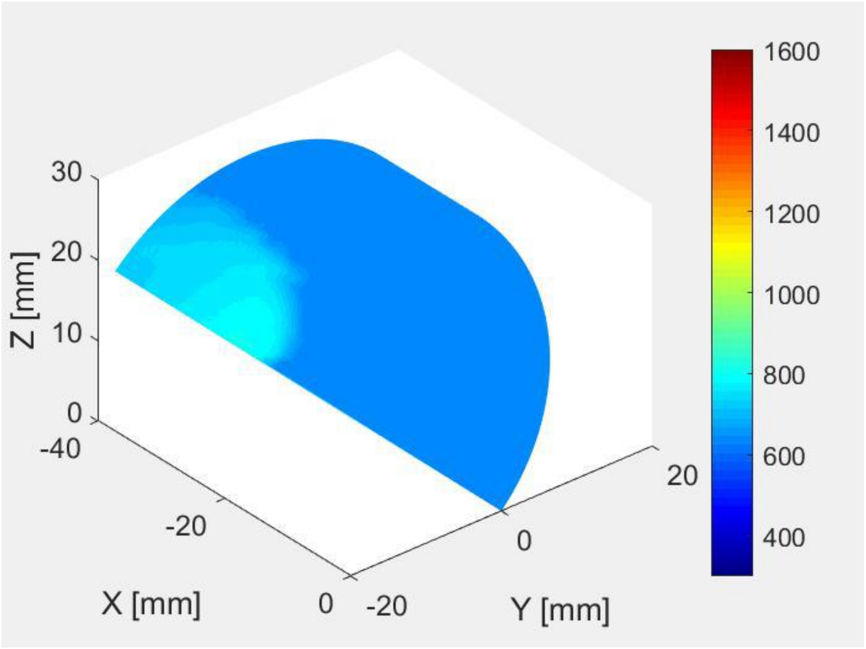
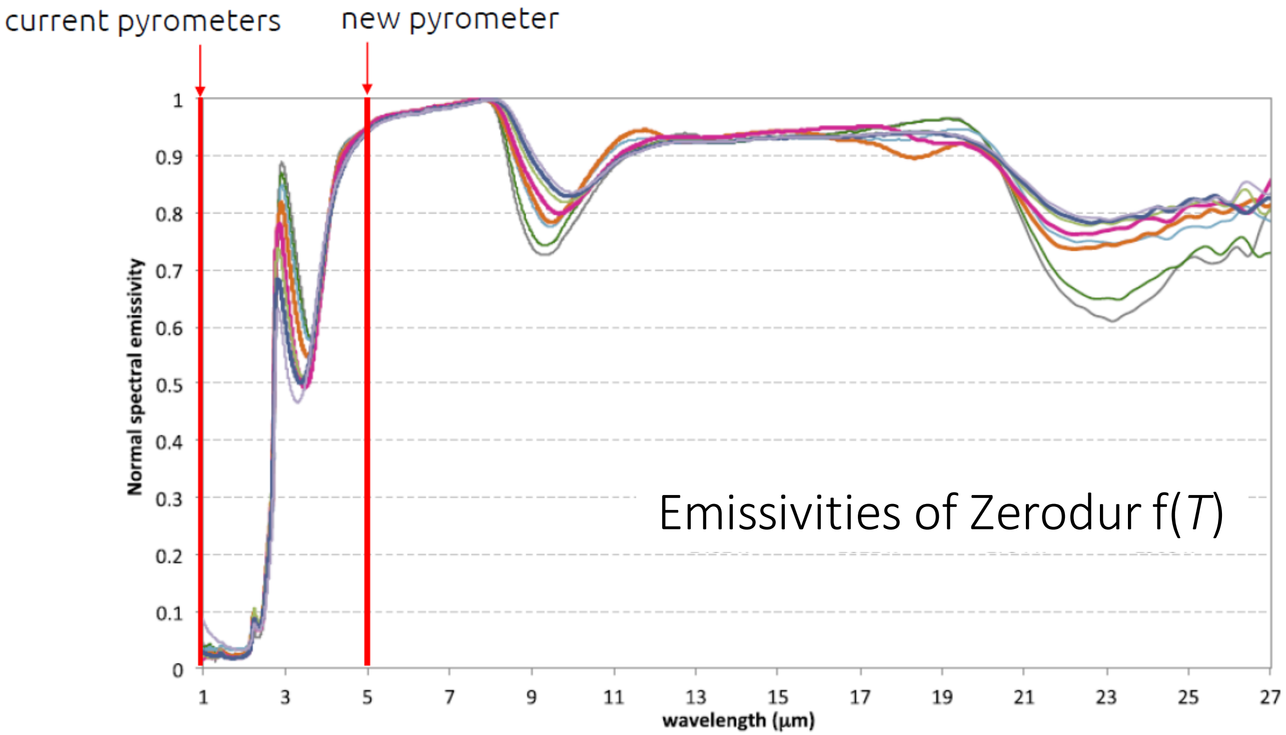


In-situ material response characterization

Quartz surface pyrometry: Problems with transmissivity

New glass pyrometer:

- OPTRIS CTlaserG5
- spectral range 5µm
- to be calibrated at VKI
- emissivity required [*Balat et al*.]



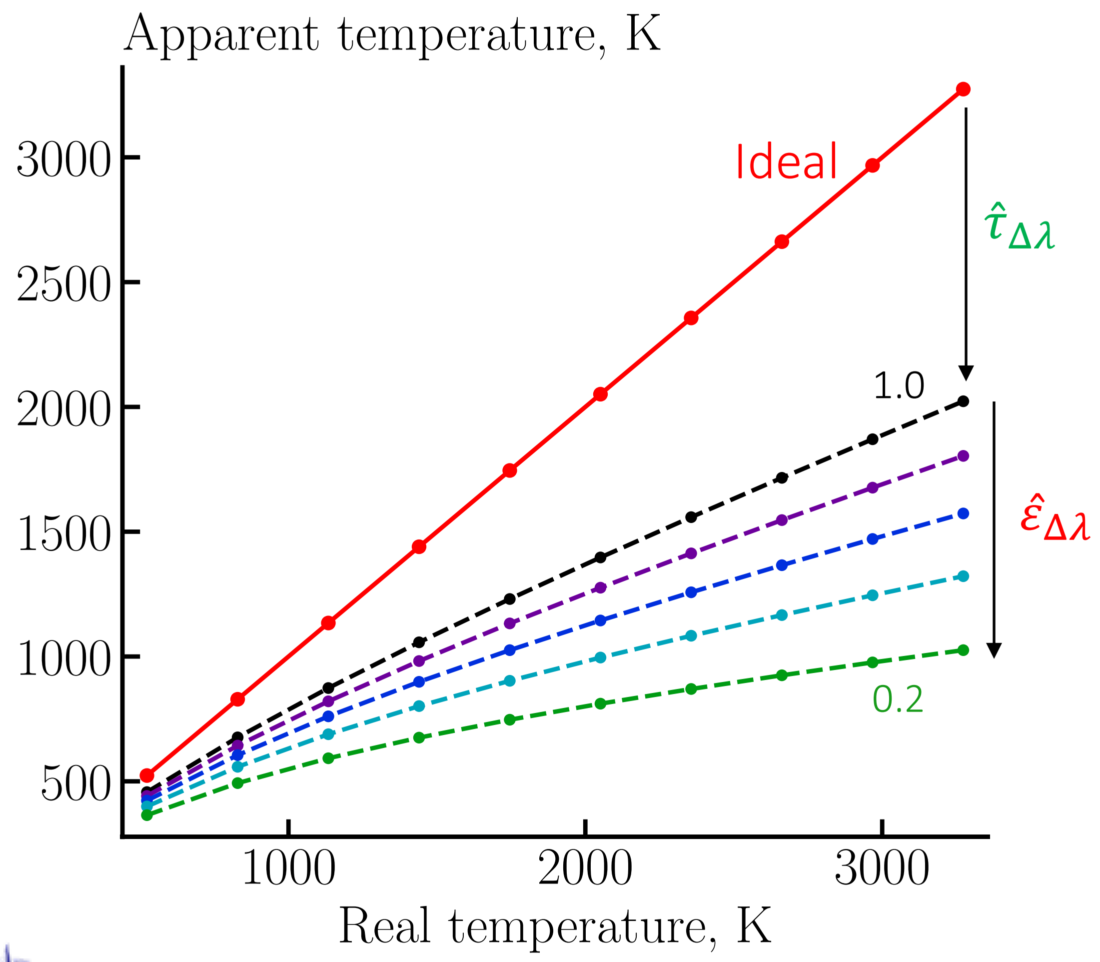
Balat-Pichelin, M., De Sousa Meneses, D., and Annaloro, J. Infrared Phys. Technol., 101, 2019 (68–77)

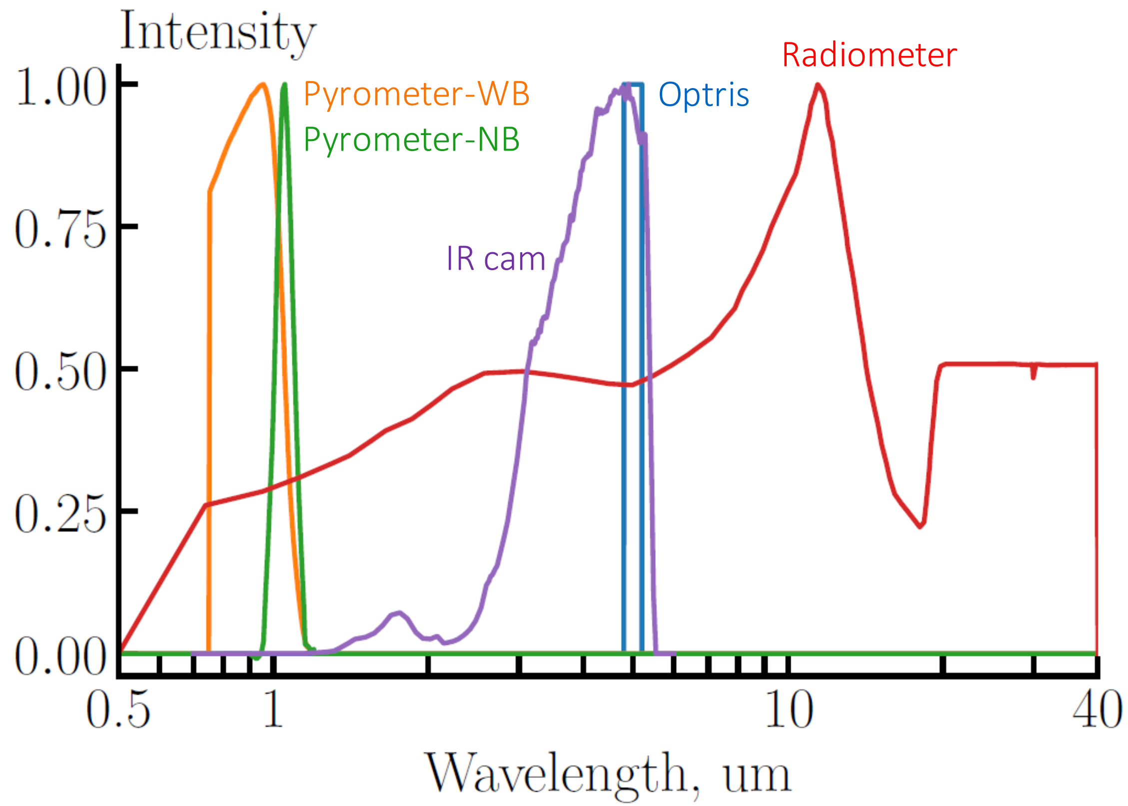
IR radiometry: calibration and emissivity measurements

1) The instrument response can be simulated for different grey-body emissivities

2) the grey-body emissivity can be measured once the real temperature is known

$$I_{\text{det}}^{\text{RB}} = \hat{\tau}_{\Delta\lambda}\hat{\varepsilon}_{\Delta\lambda}\int_0^{inf}\tilde{R}_\lambda L_\lambda^{BB}(T)$$





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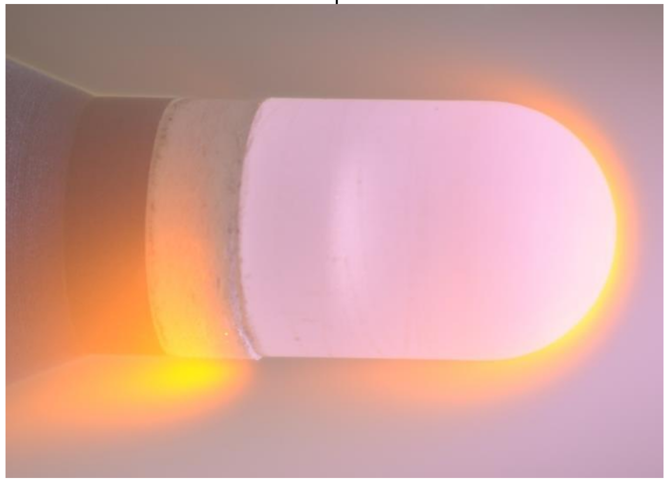
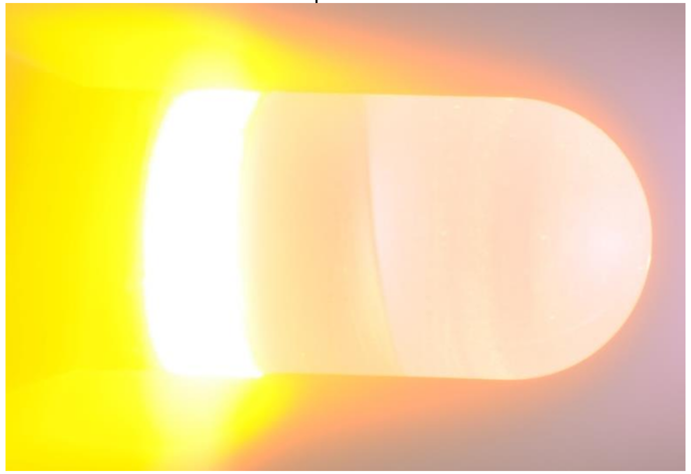
air 16 g/s, 50 mbar, 150 kW

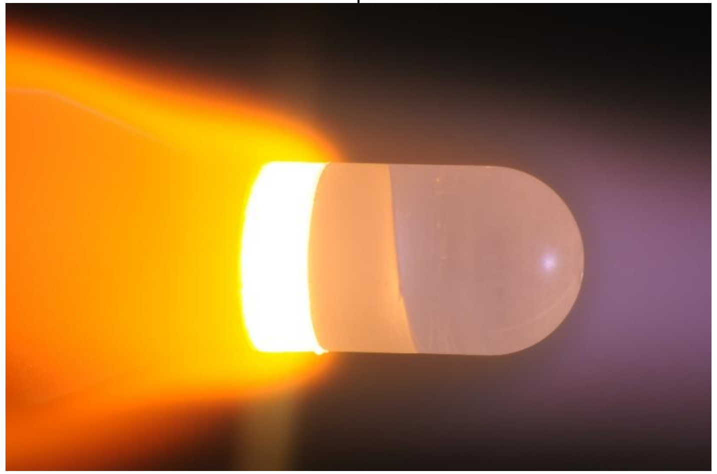
Quartz-HS30-A: no recession

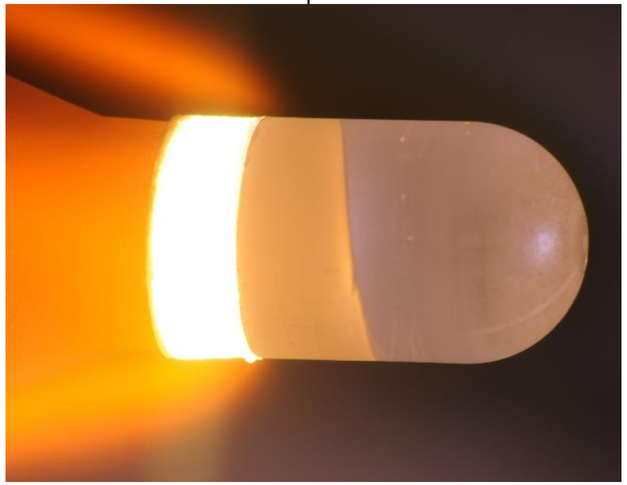
injection | crack appearing | surface steady state | test end

0s | 17s | 180s | 385s | time,





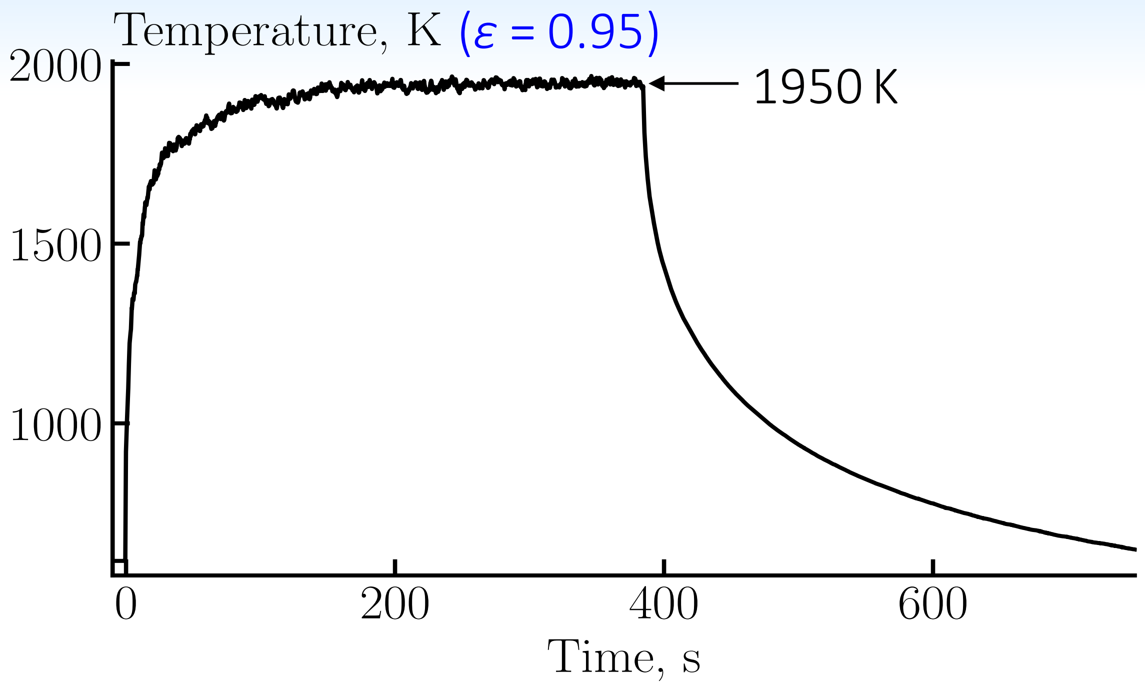


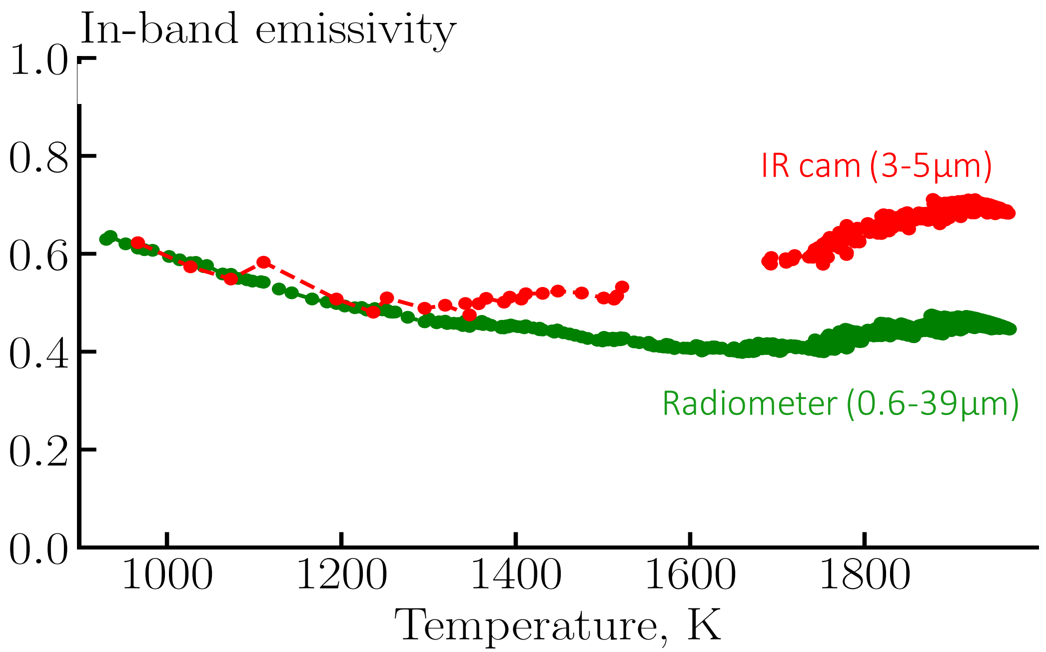


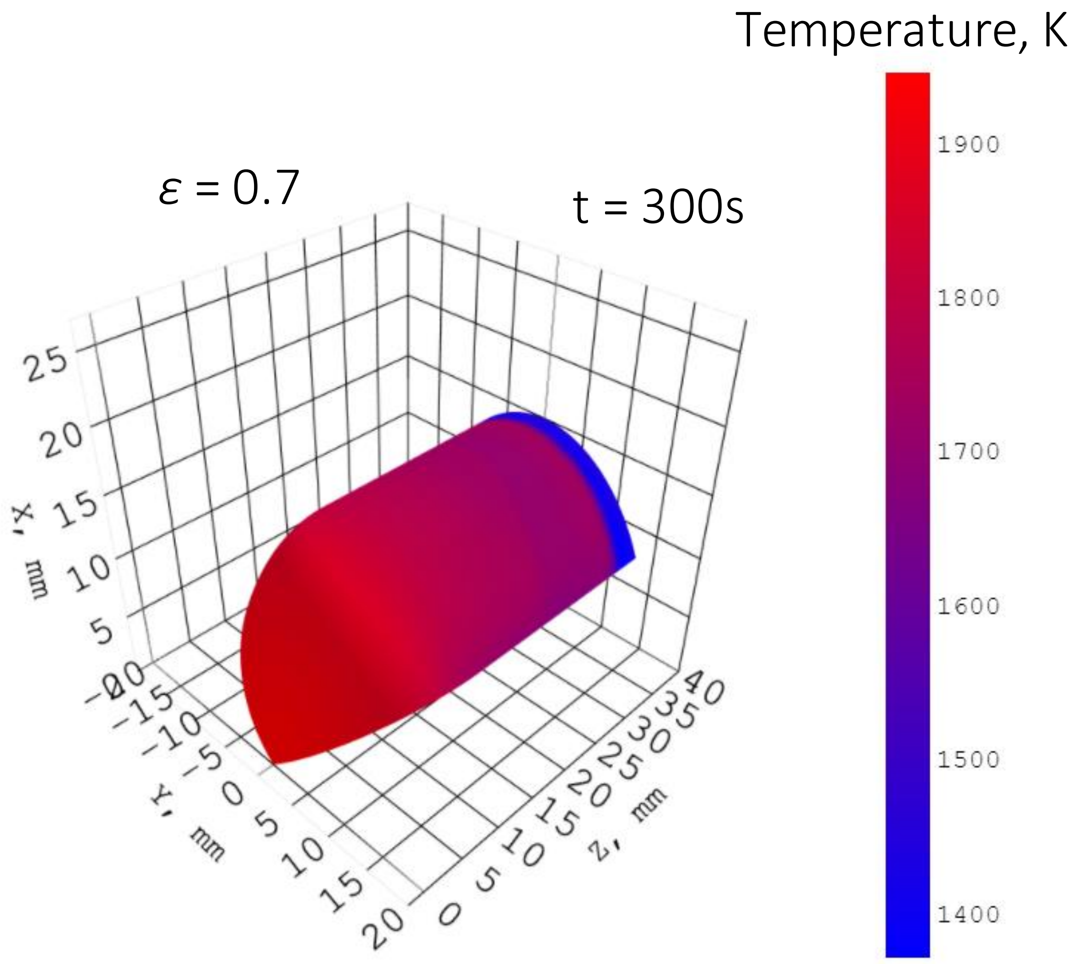
virgin

tested

Quartz-HS30-A: Surface radiometry

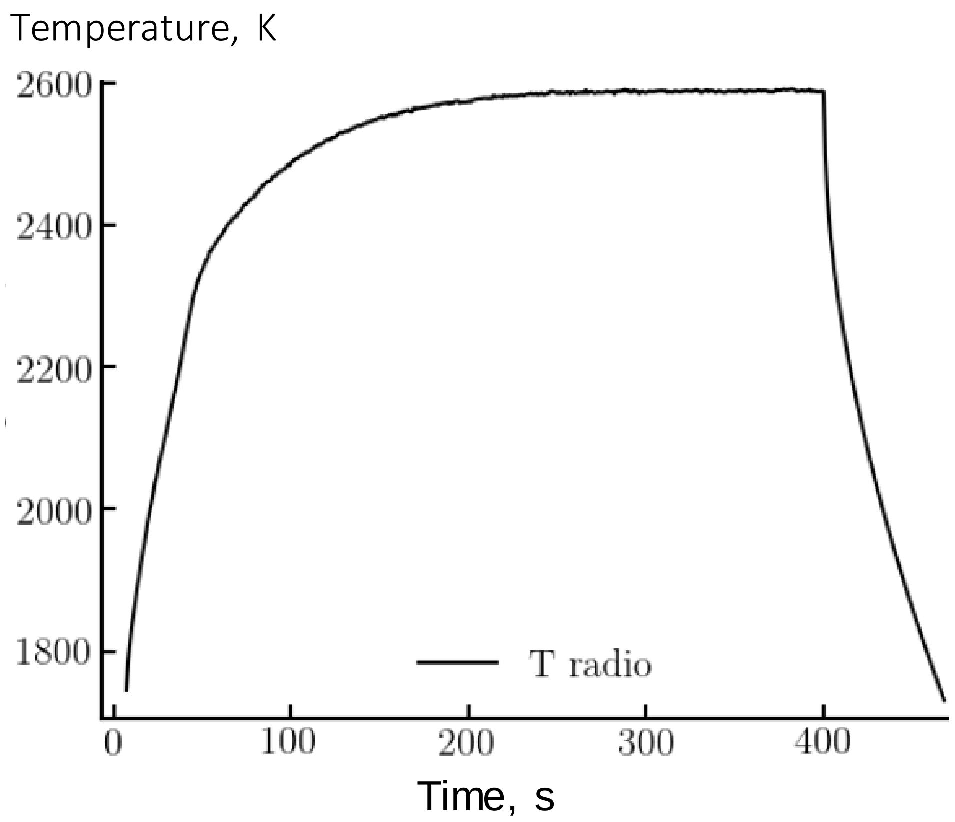


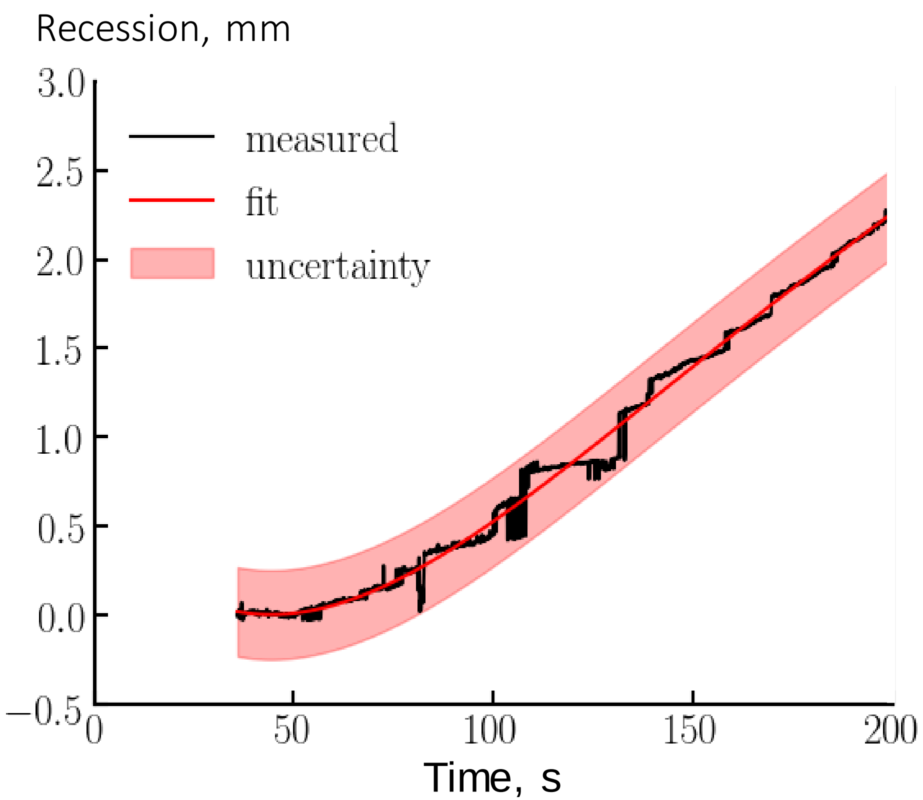




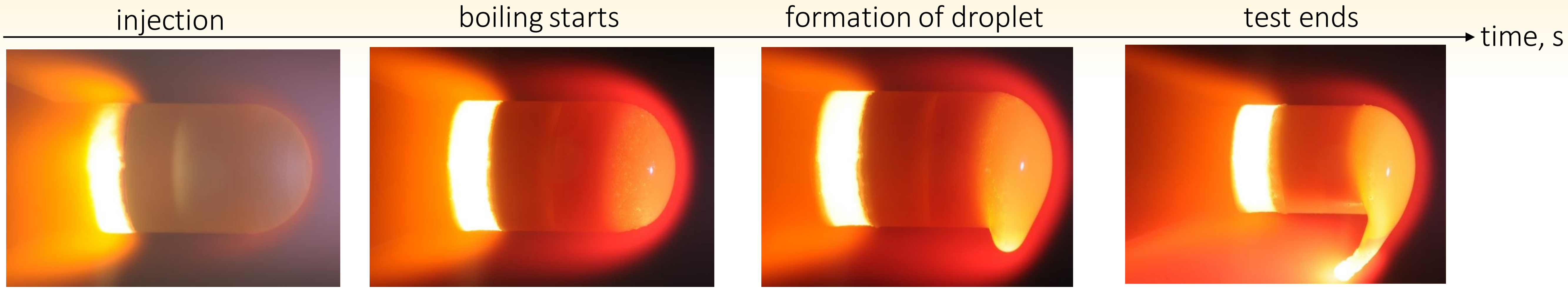
air 16 g/s, 100 mbar, 290 kW

Quartz-HS50-A: High recession



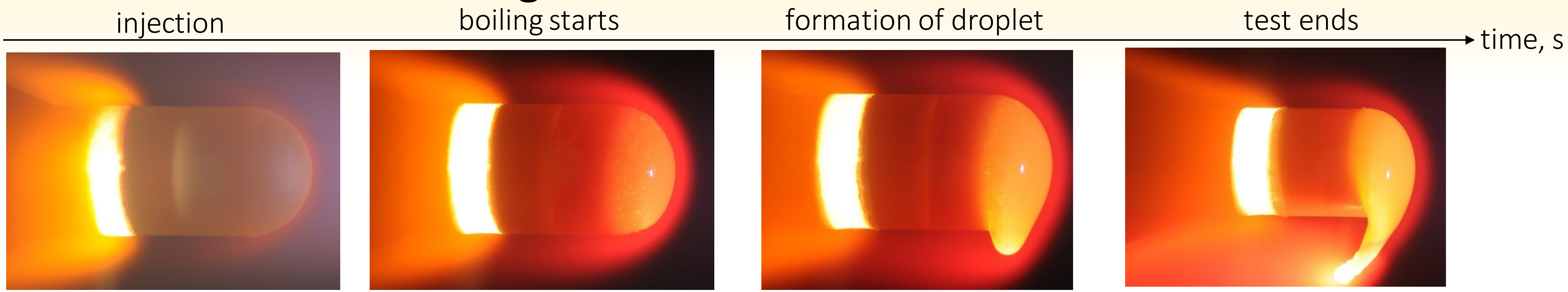


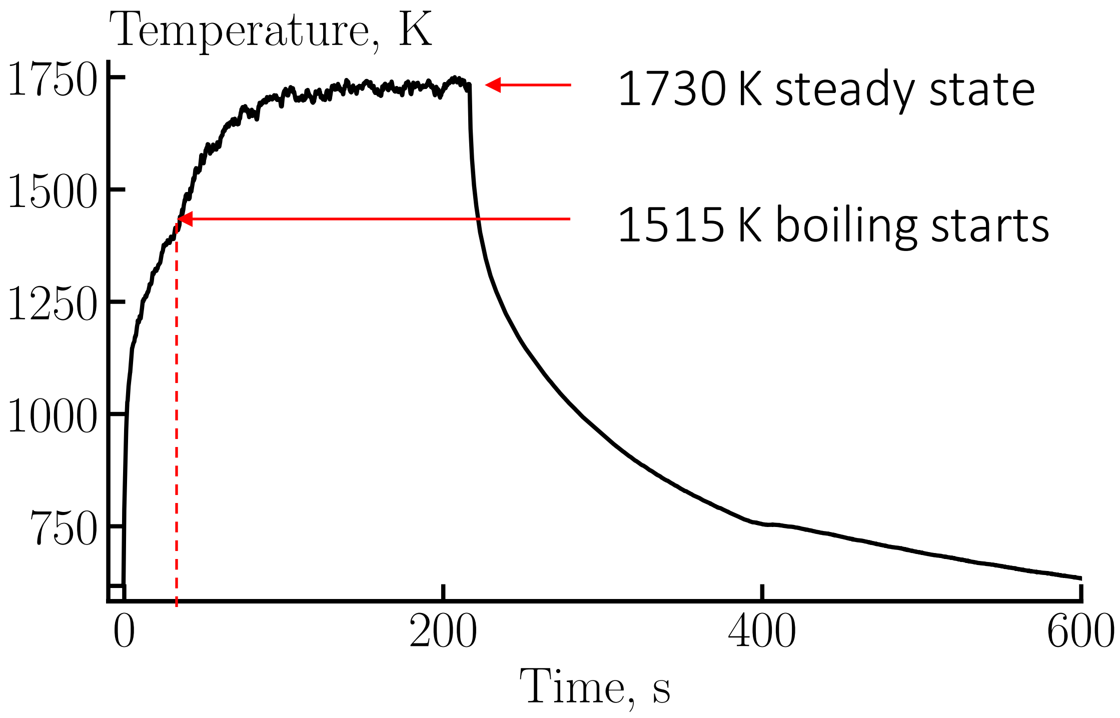
ZERODUR demise testing

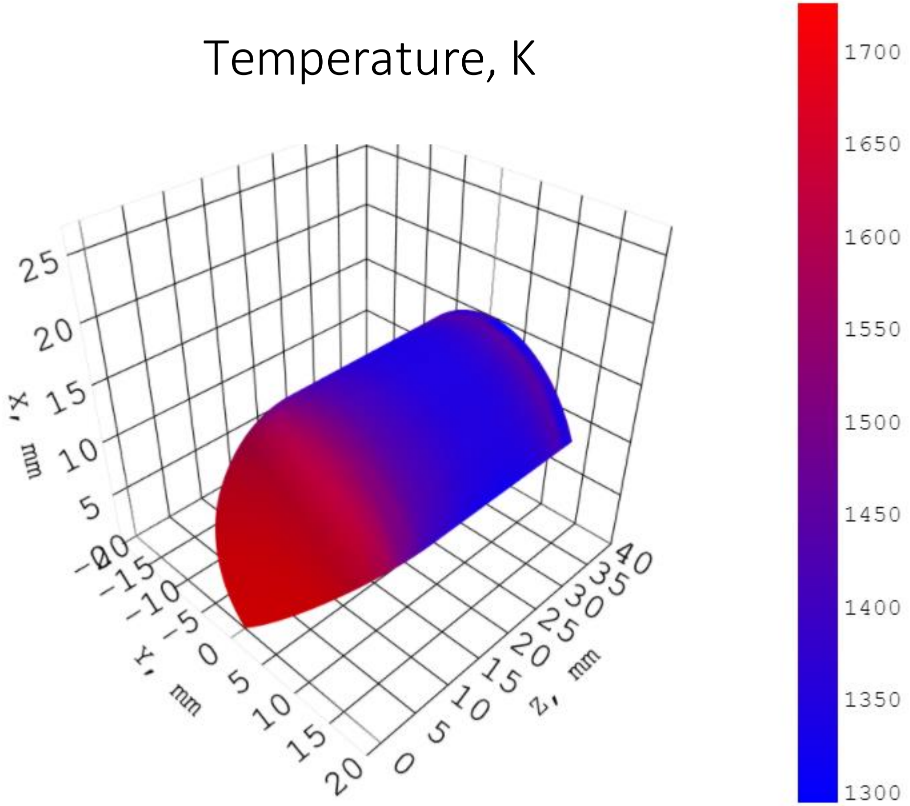


air 16 g/s, 50 mbar, 150 kW

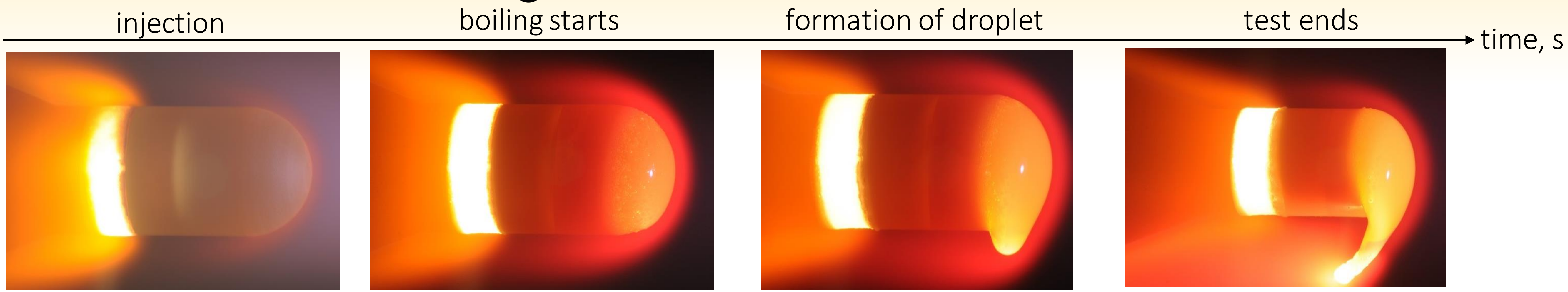
ZERODUR demise testing

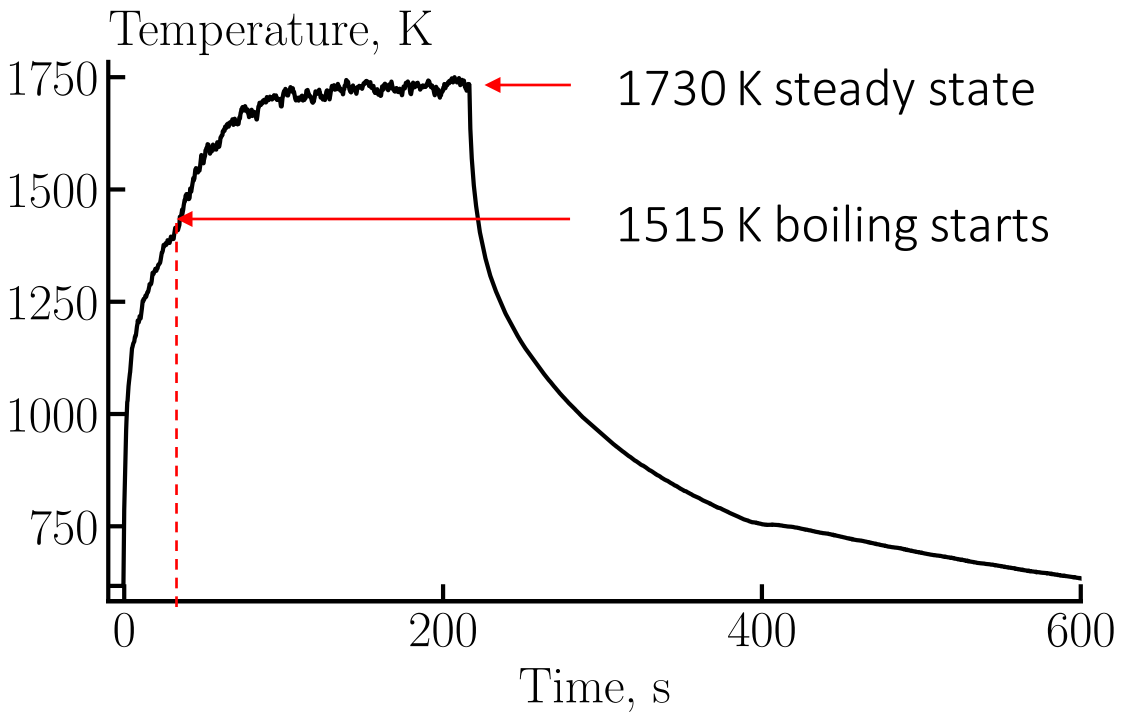


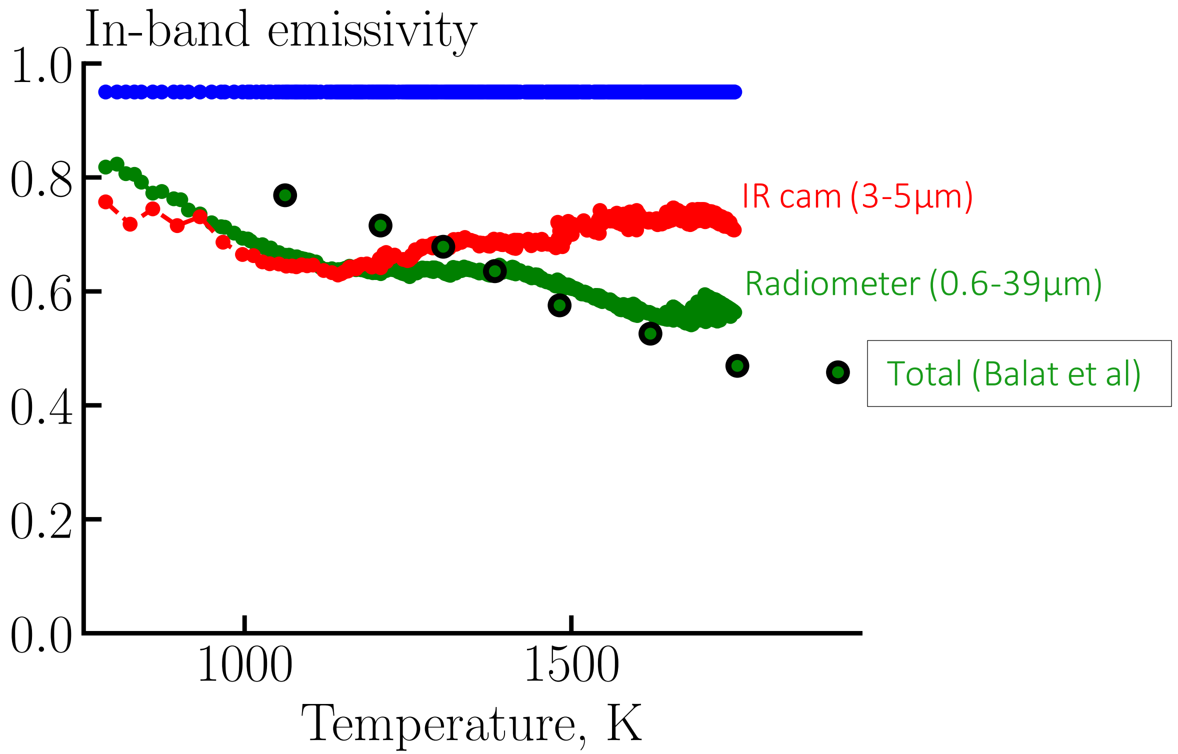




ZERODUR demise testing

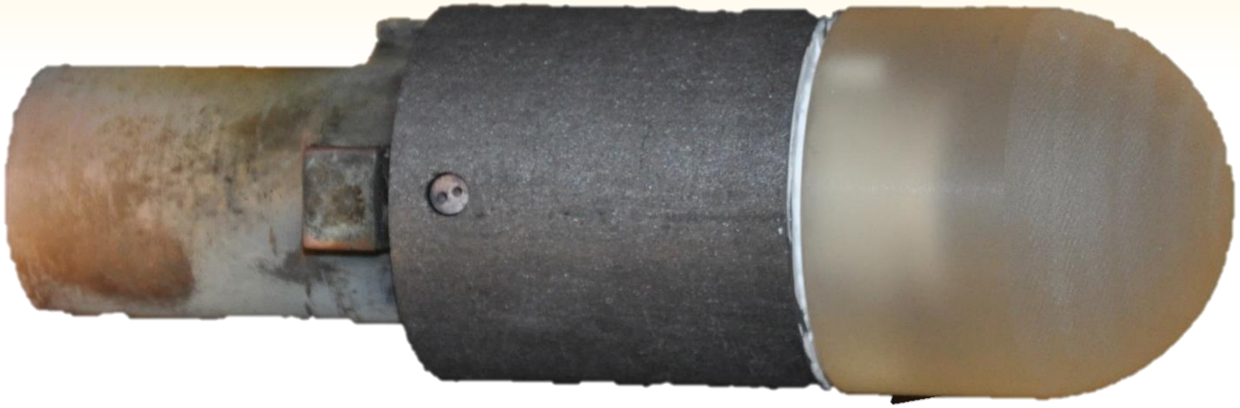


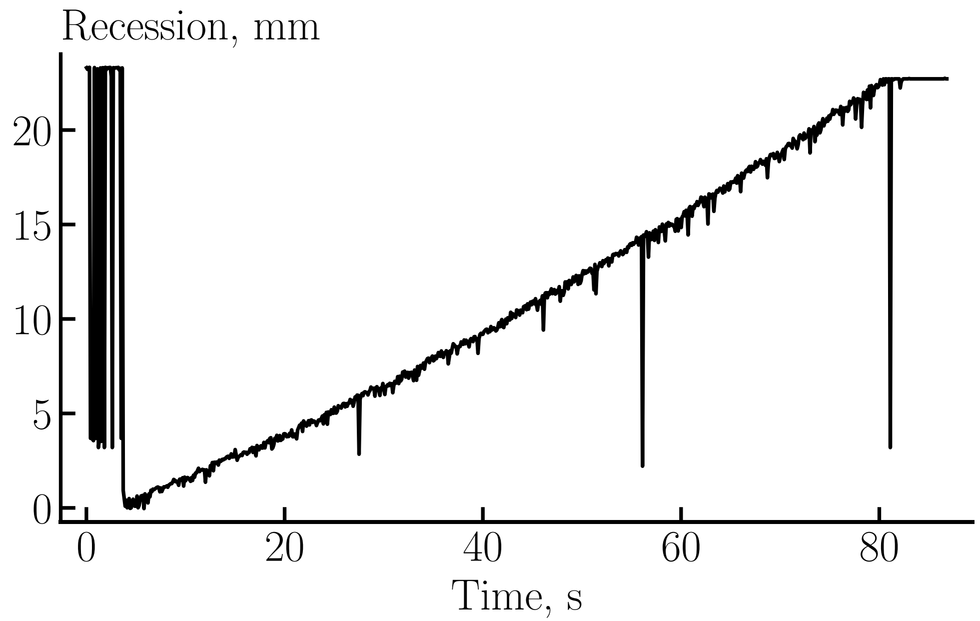




ZERODUR demise testing

air 16 g/s, 100 mbar, 390 kW





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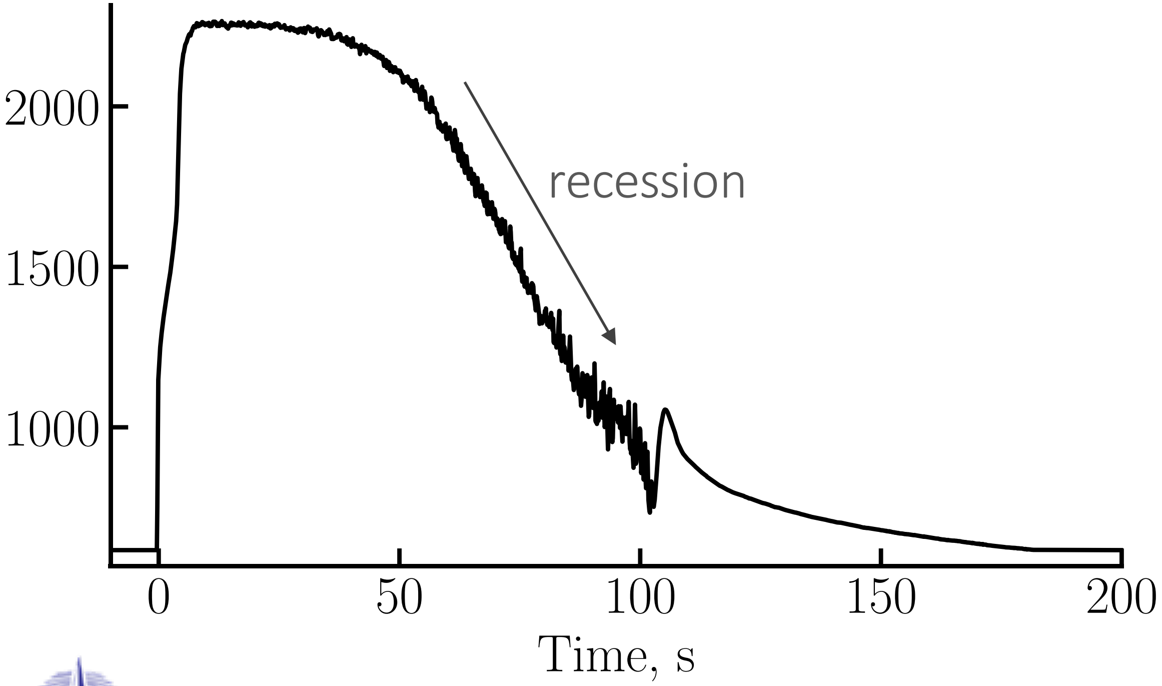
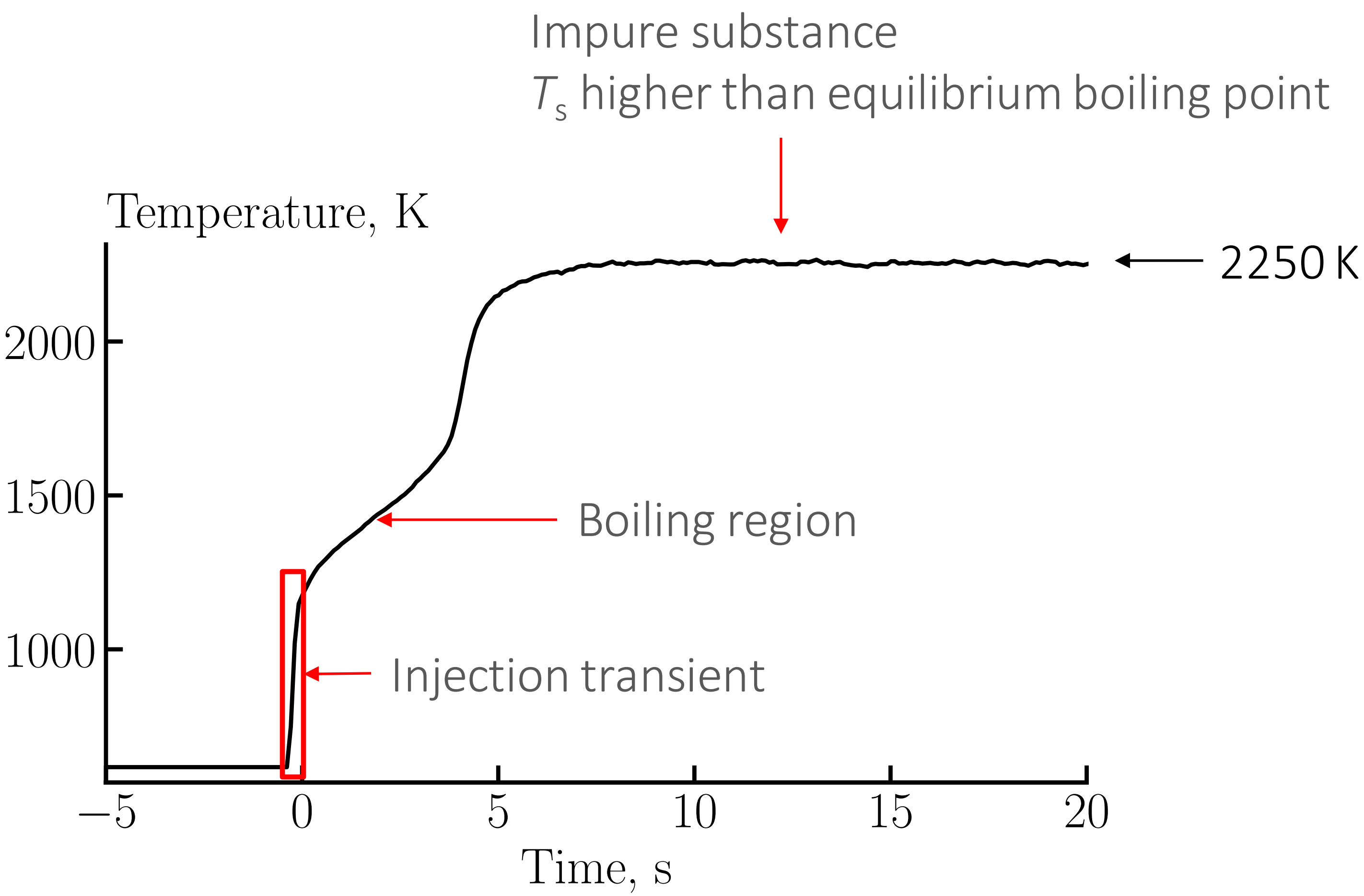
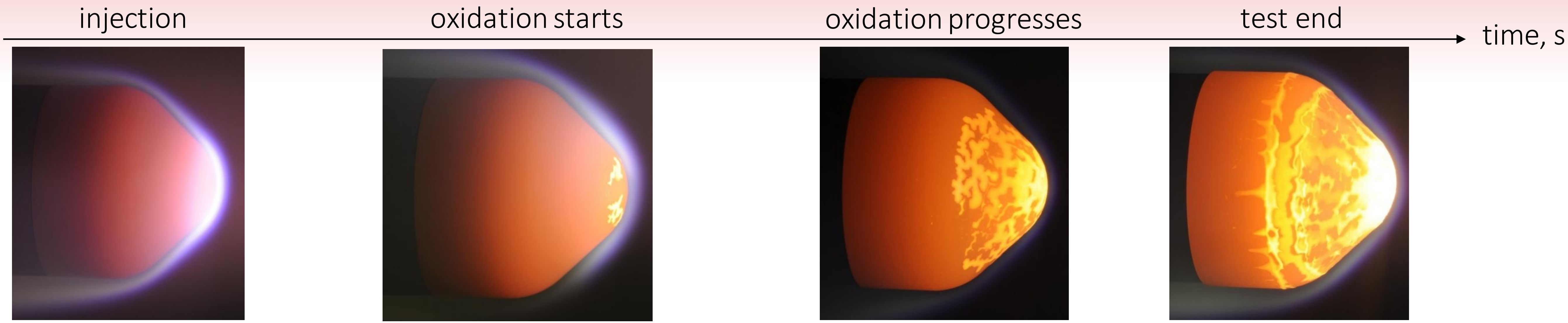
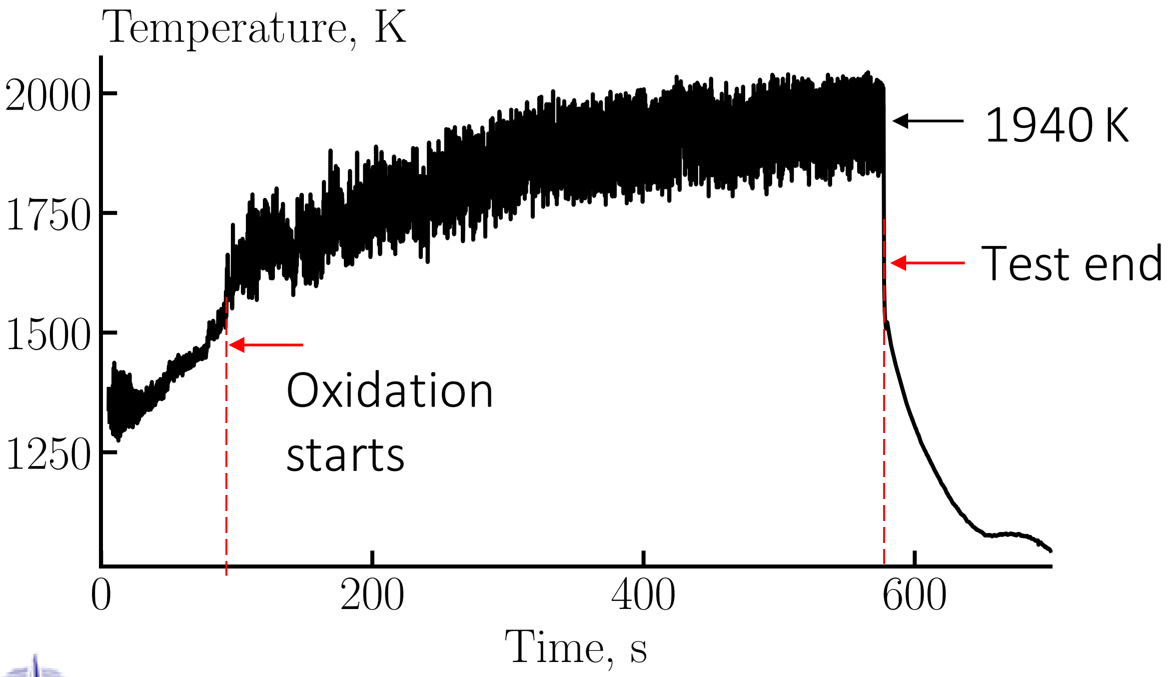


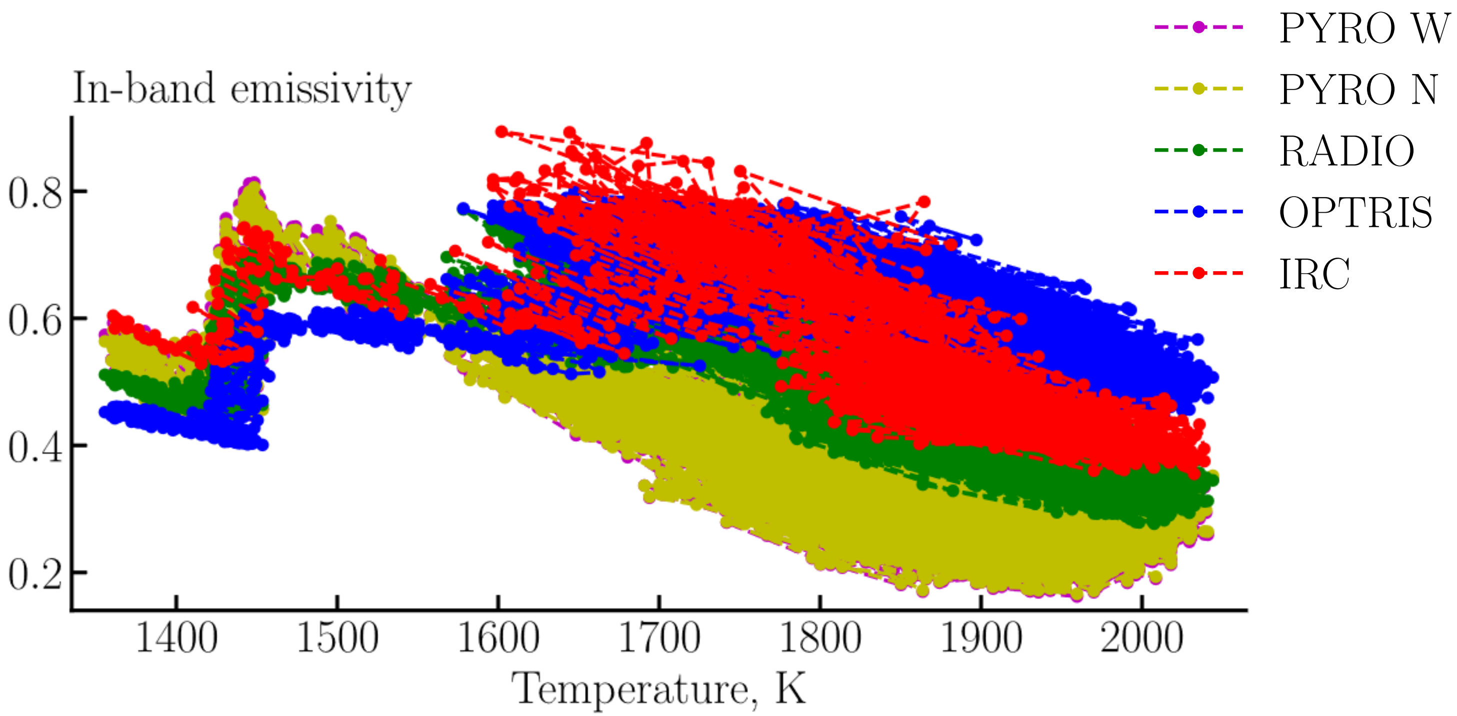


air 16 g/s, 50 mbar, 125kW

Titanium oxidation: difficult to demise and difficult to simulate



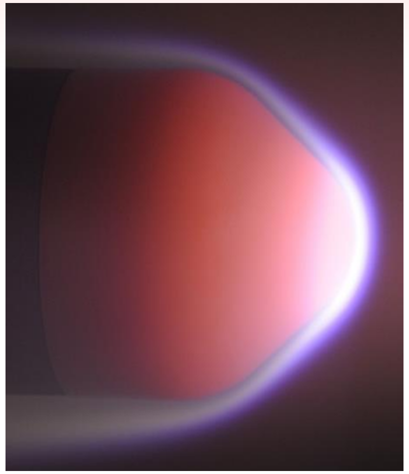
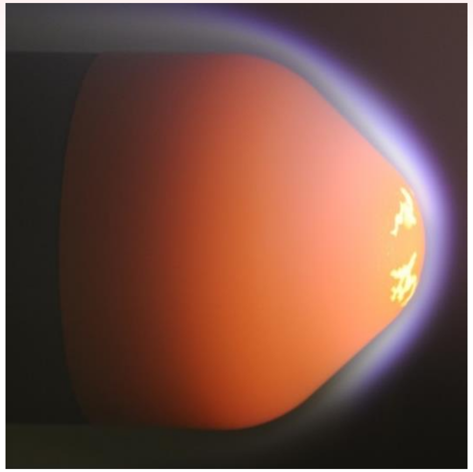
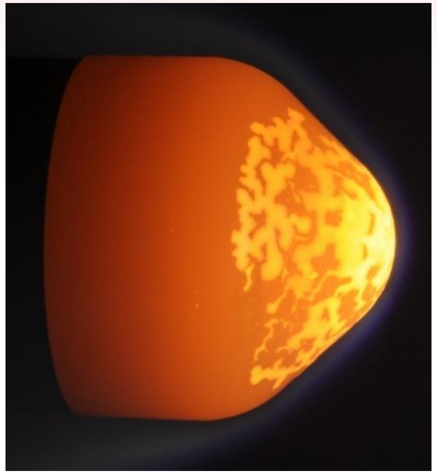
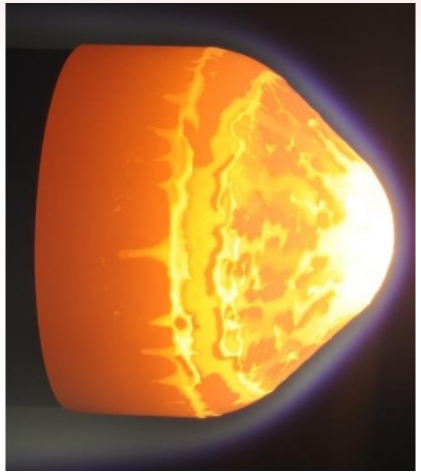




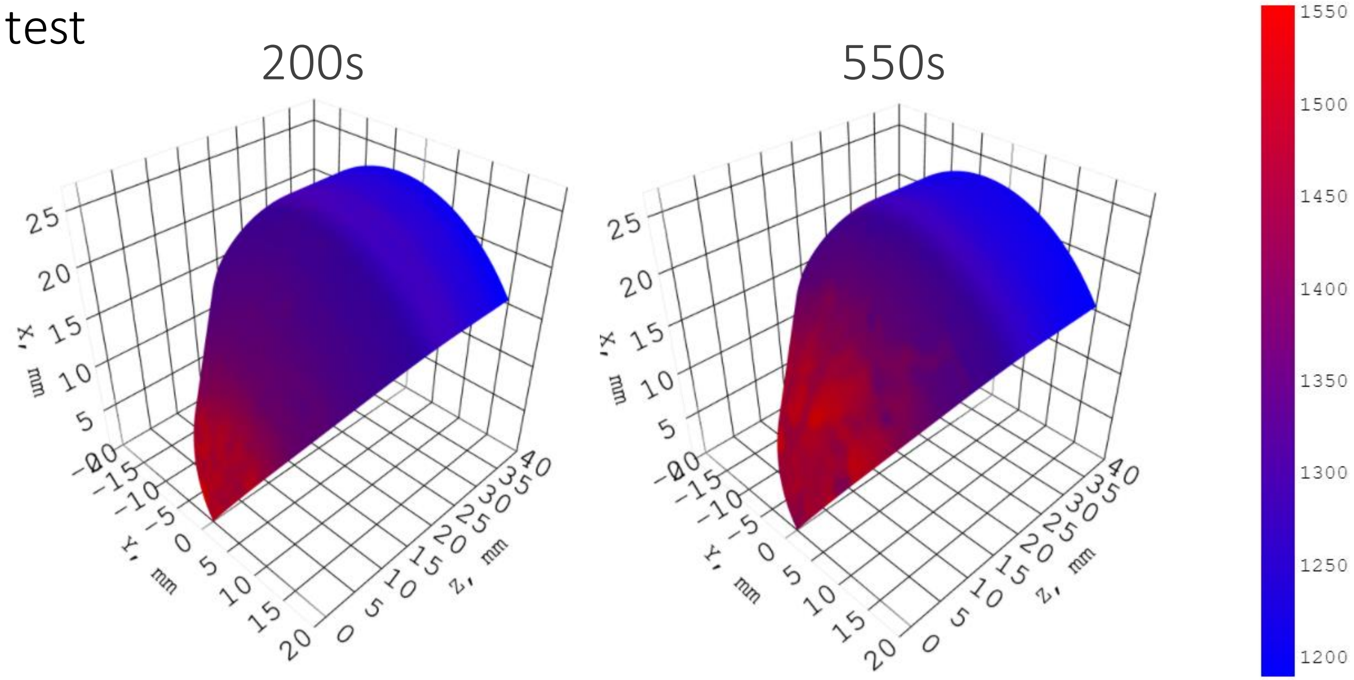
air 16 g/s, 50 mbar, 125kW

Titanium oxidation: difficult to demise and difficult to simulate

injection — oxidation starts — oxidation progresses — test end → time, s

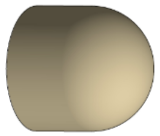
mass gain 0.36 g
No oxide peel-off during test
oxide layer looks brittle



Demise material testing overview

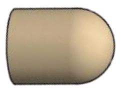
	Run	Gas	p_{static} [hPa]	P_{el} [kW]
Quartz	Qz-HS50-A	Air	100	290
	Qz-SC50-A	Air	50	290
	QZ-HS30-A	Air	50	150
	QZ-SC40-A-SS	Air	5	500
Zerodur	Ze-HS30-A	air	50	150
	Ze-HS50-A	air	100	392
Titanium	TiG2-HS30-A	Air	100	160
	TiG2-HS50-N	N_2	50	?
	TiG5-HS30-A	Air	50	125
	TiG5-Sc50-A	Air	50	125

HS50: 50 mm hemisphere-cylinder



Non-equilibrium gas chemistry
Low shear

HS30: 30 mm hemisphere-cylinder



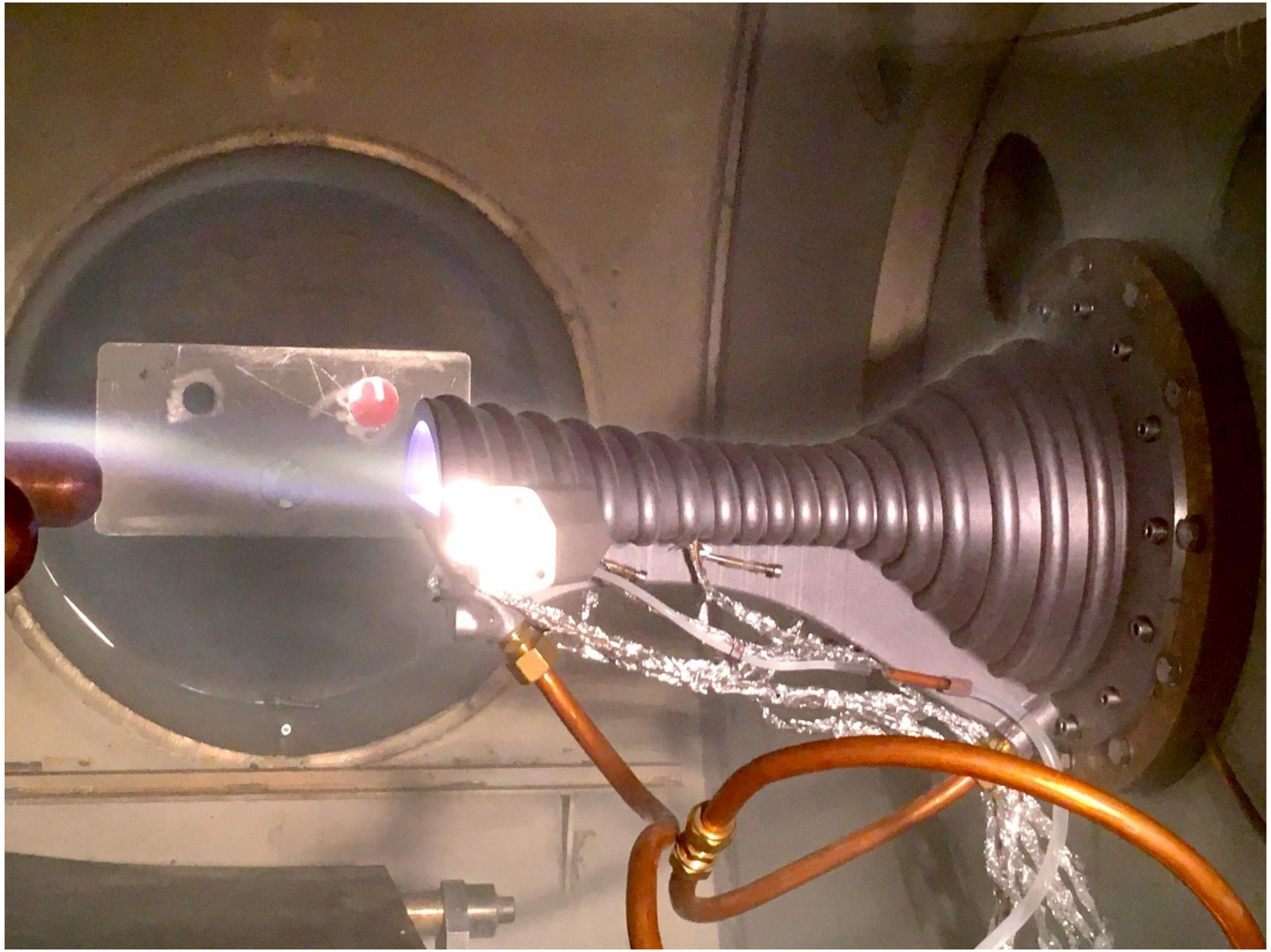
Frozen gas chemistry
High shear

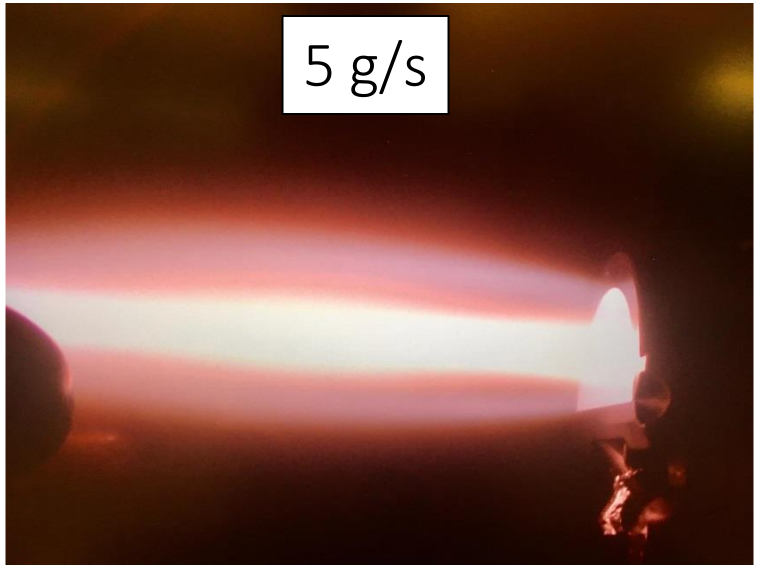
SC50: 50 mm sphere-cone

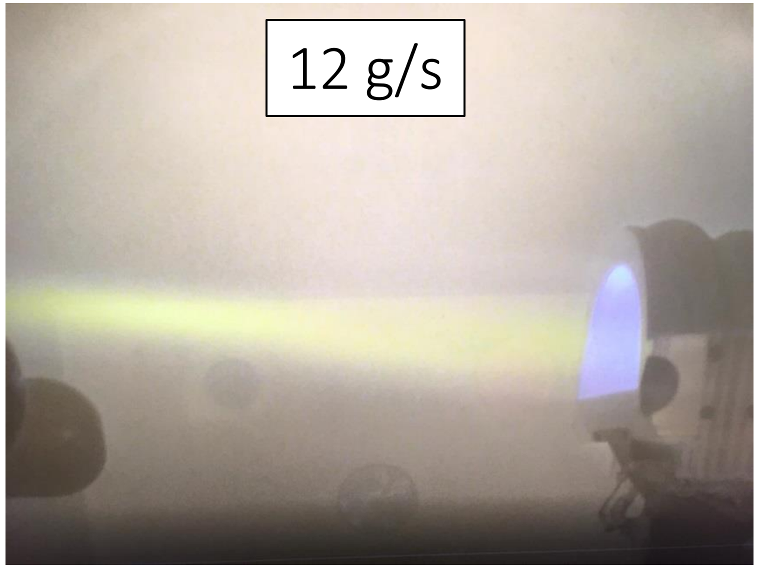
Non-equilibrium gas chemistry
Uniform melt thickness

Supersonic nozzle commissioning and characterization

Semi-elliptical nozzle for flat plate testing

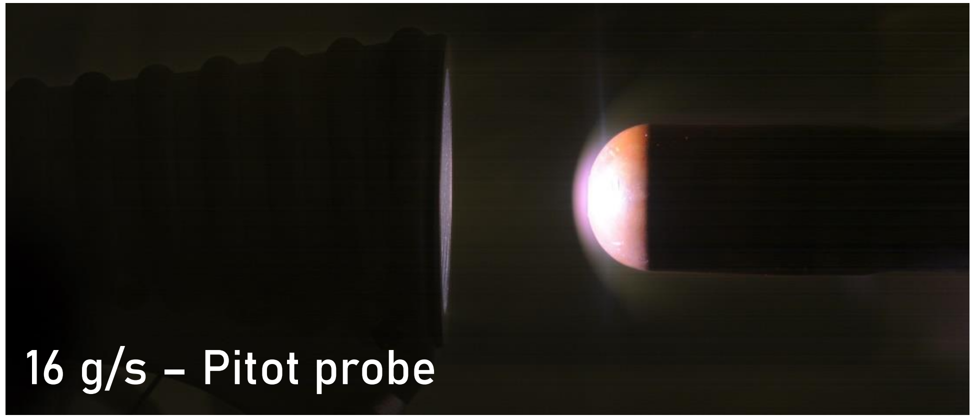


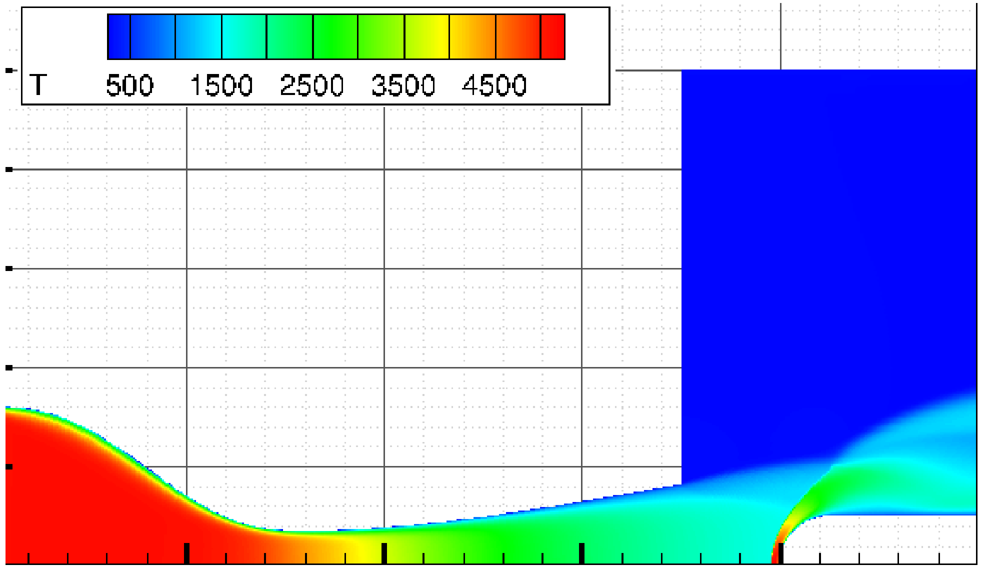


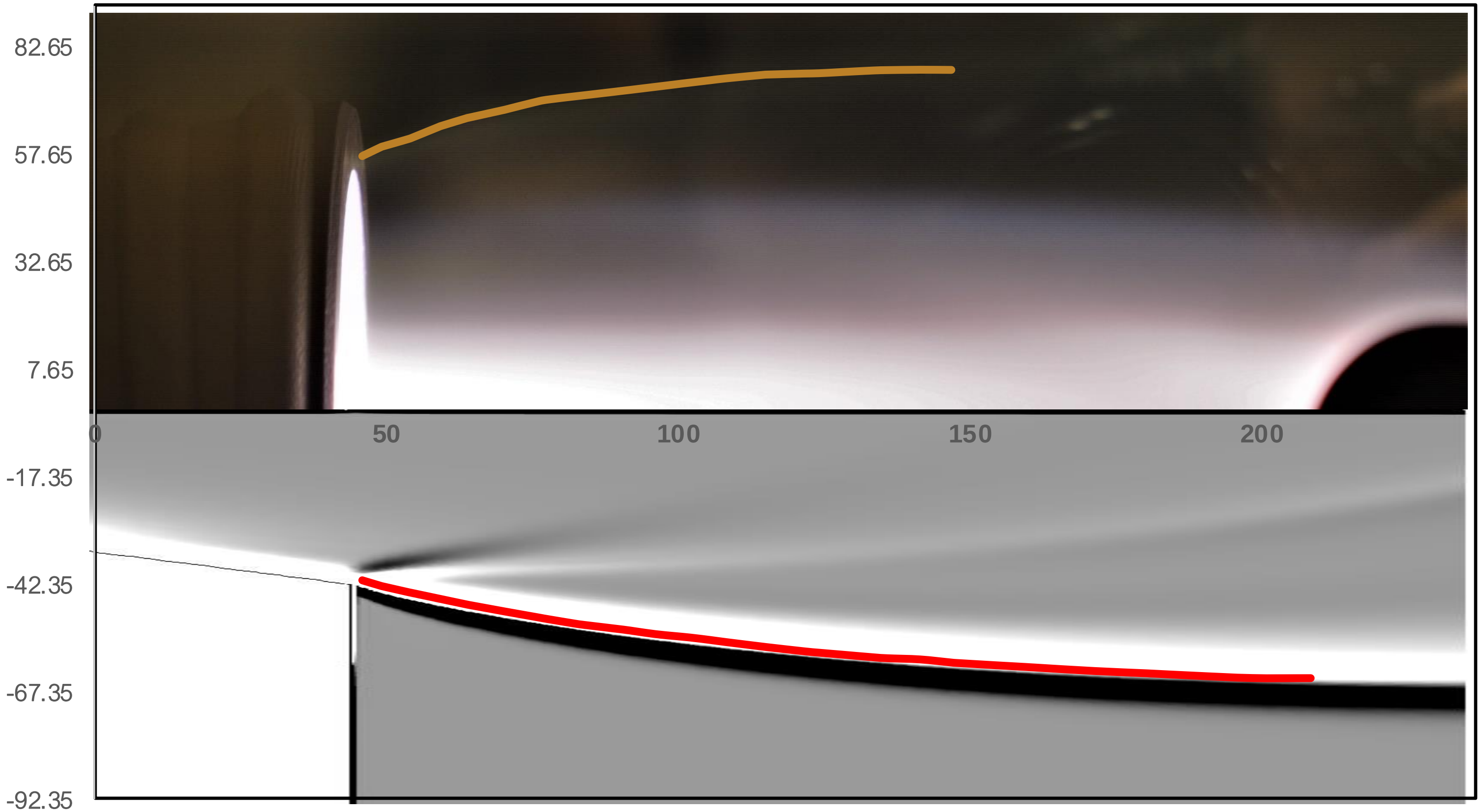


Supersonic nozzle commissioning and characterization

Conical nozzles for stagnation point testing







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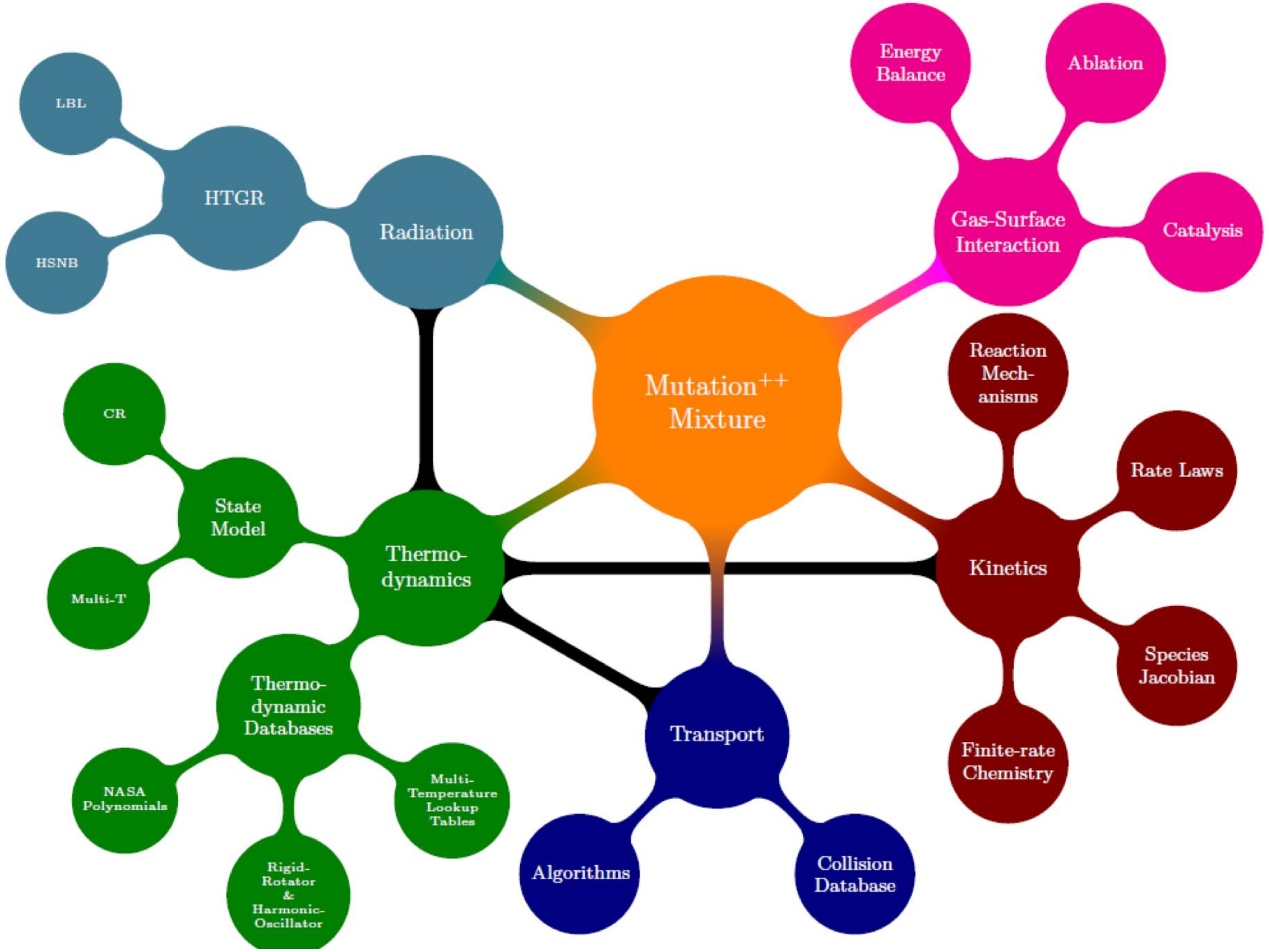
- High-fidelity *ARGO* simulations

Mutation++
MUlticomponent Thermodynamic And Transport properties/chemistry for IONized gases

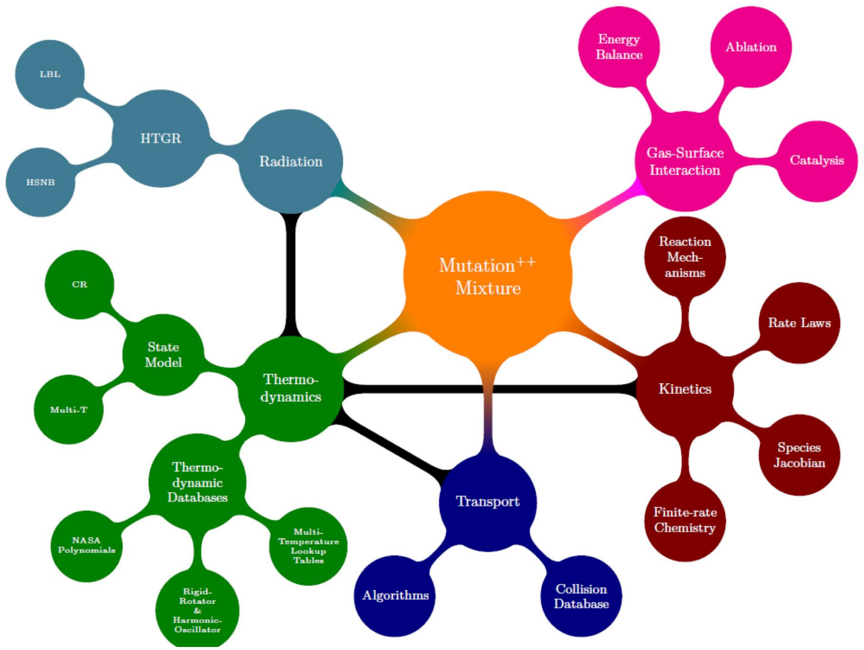


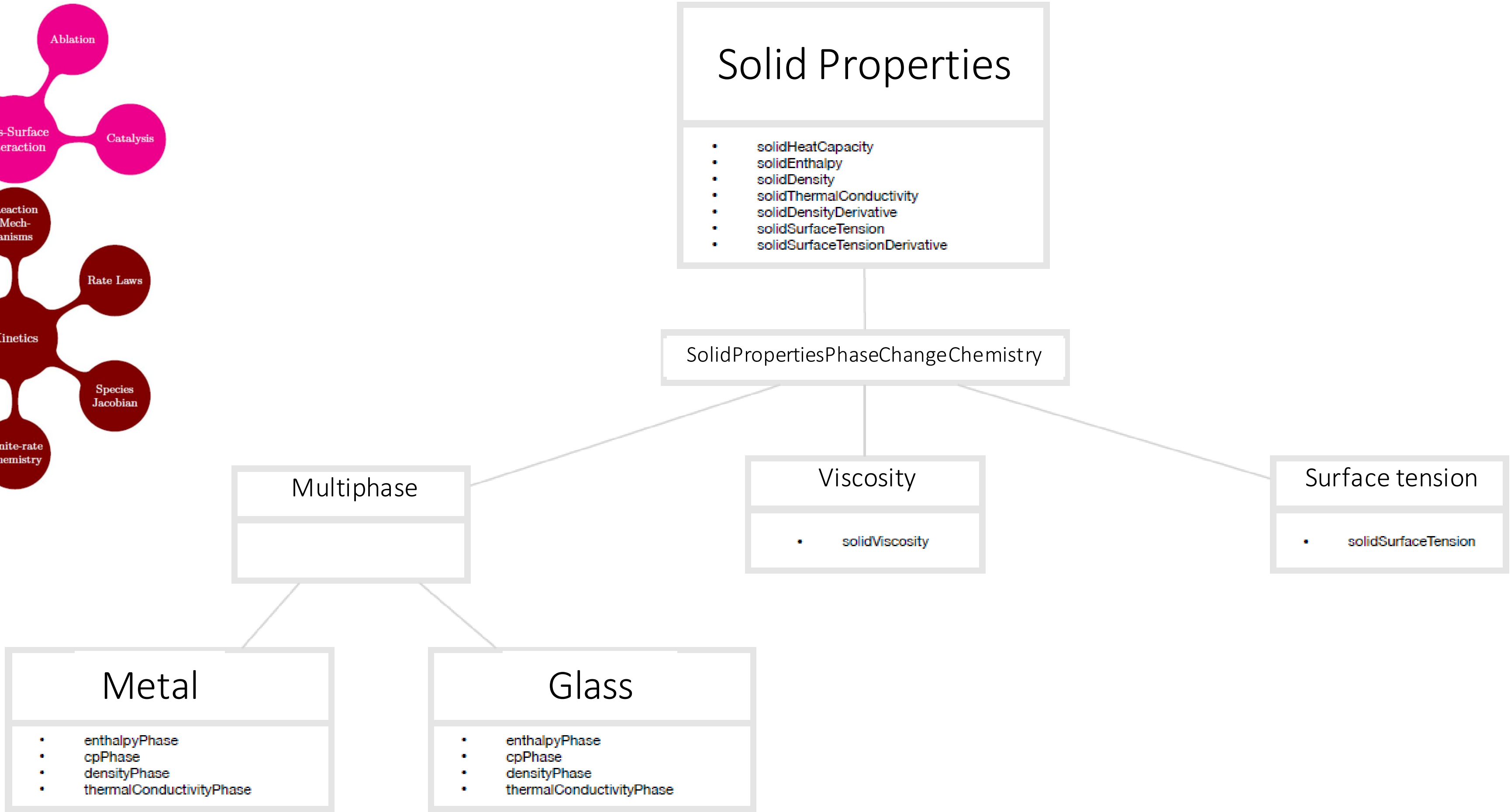
Include Phase-change material properties
- Zinc (test case)
- silica

Coupling with any material solver (*ARGO*)

Mutation^{++}

MUlticomponent Thermodynamic And Transport properties/chemistry for IONized gases





Mutation++
Multicomponent Thermodynamic And Transport properties for IONized gases in C++

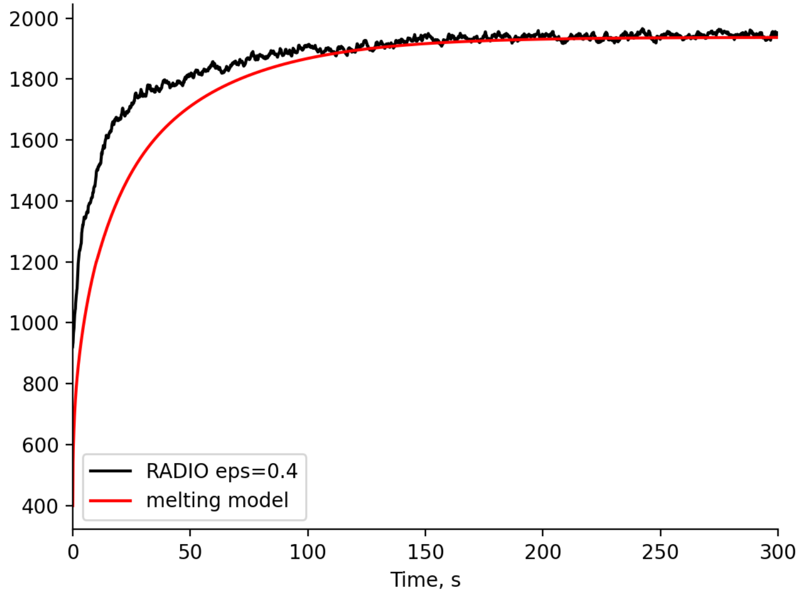
von Karman Institute for Fluid Dynamics

https://github.com/mutationpp/Mutationpp

Numerical 1D approach:
Design of experiments and post-test comparison

Quartz, 50 hPa, 150 kW

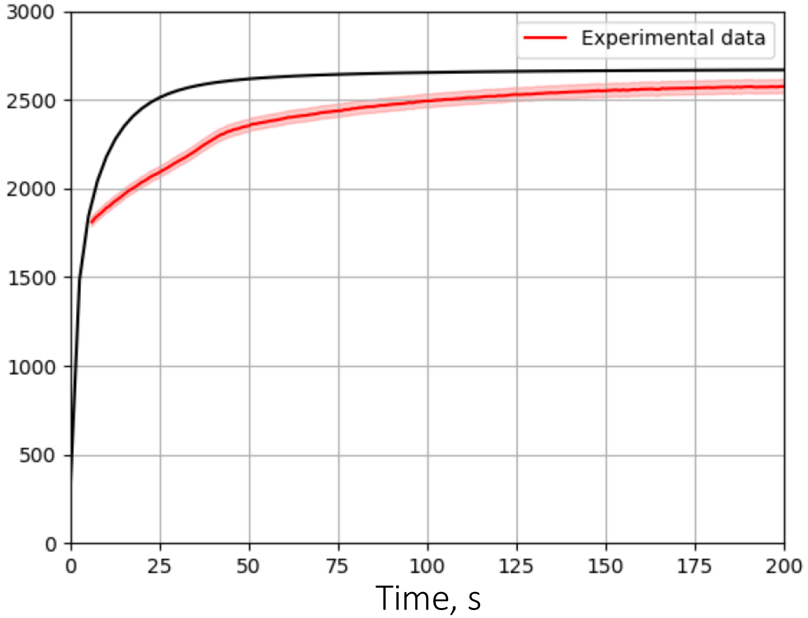
Temperature, K



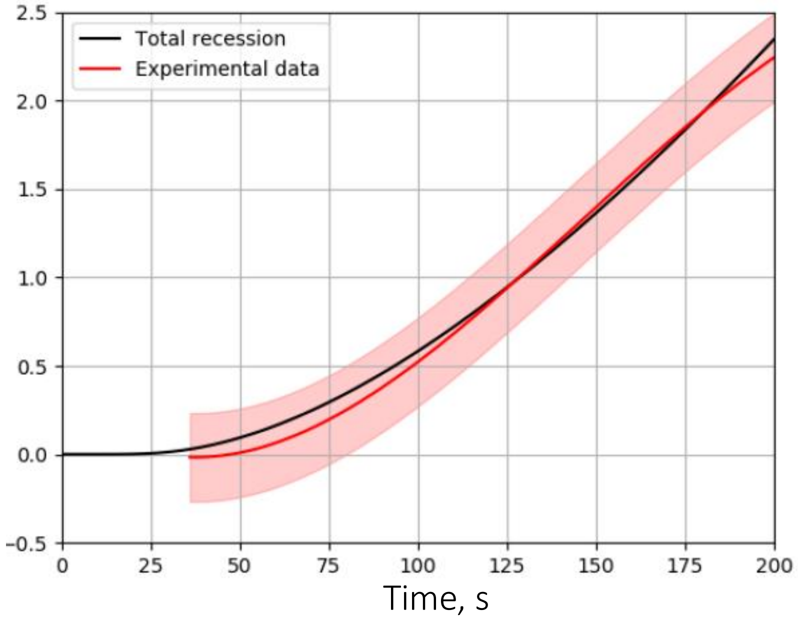
Focus on surface energy balance

Quartz, 100 hPa, 290 kW

Temperature, K



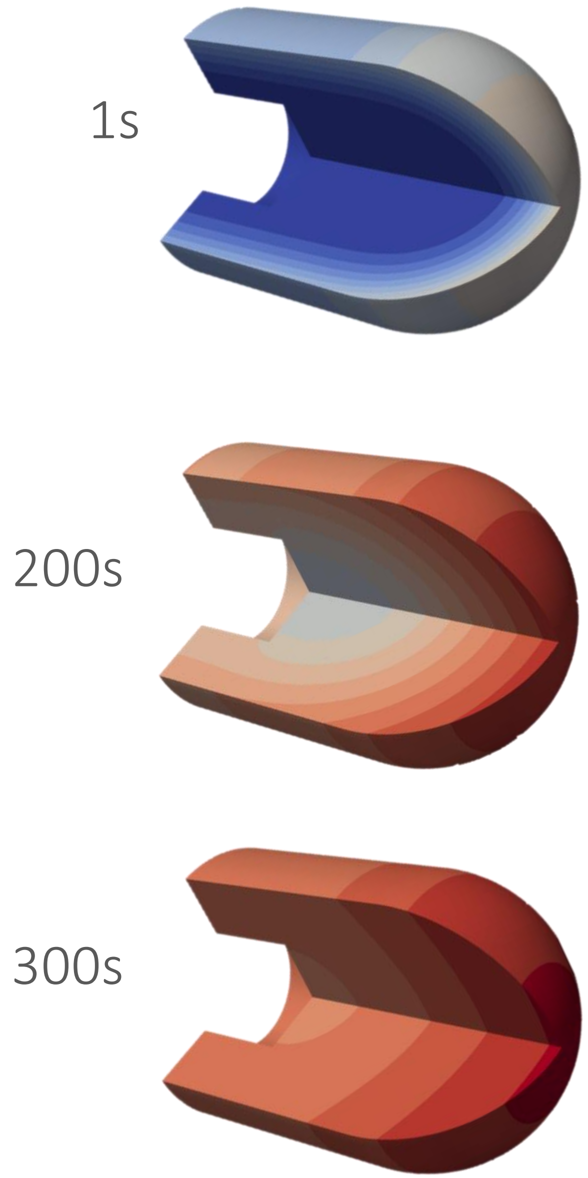
Recession, mm

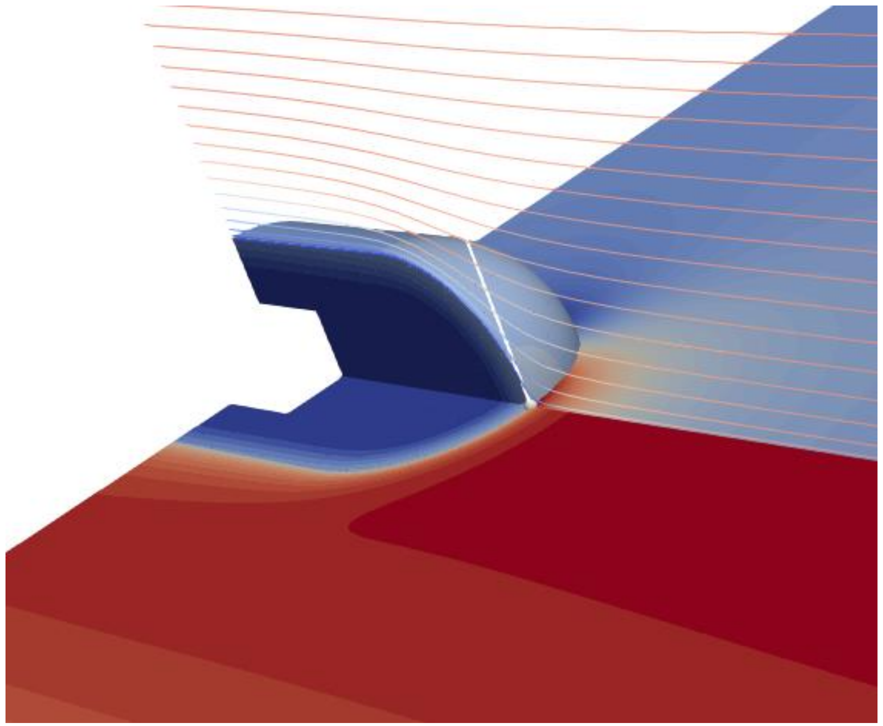


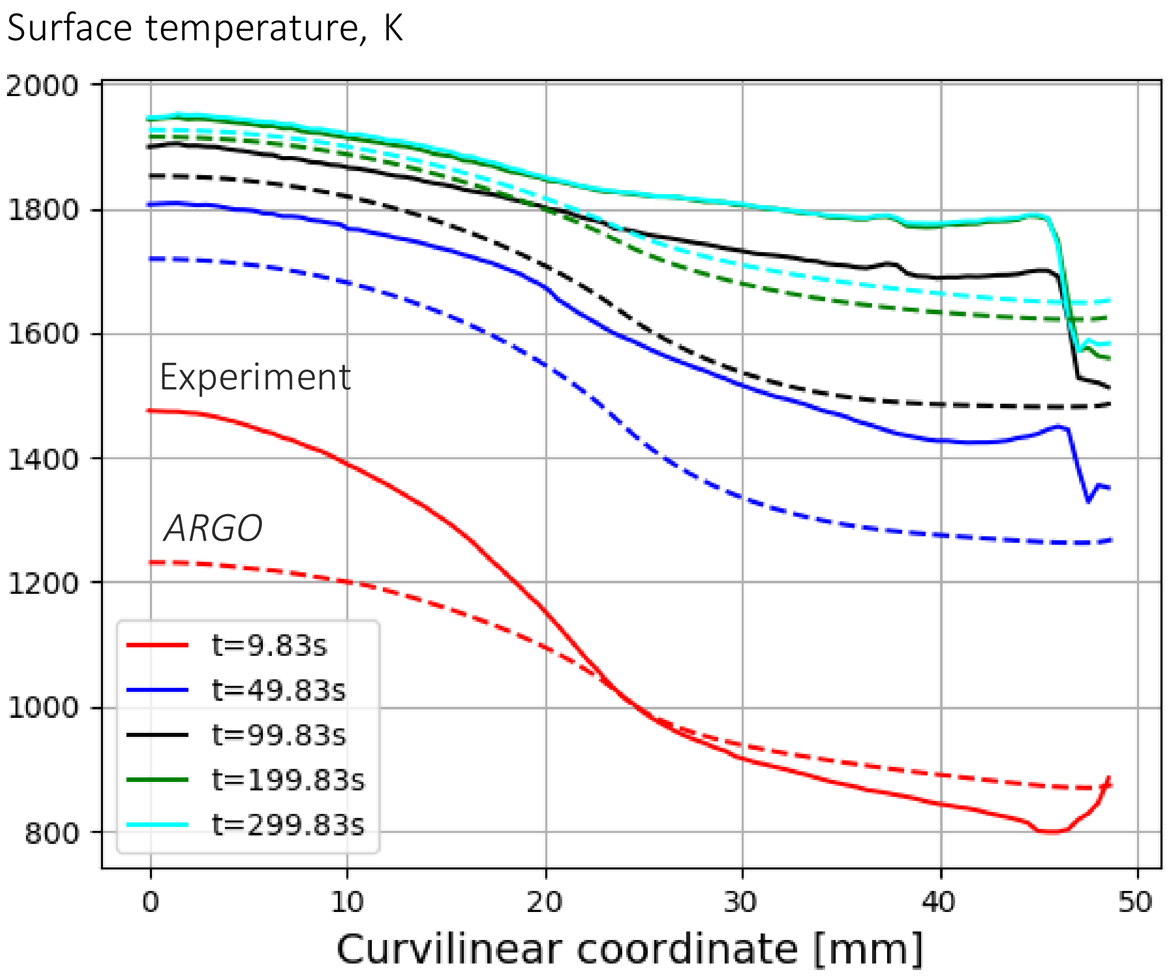
Adding evaporation and shear ablation

Fagnani, Dias, Schrooyen, Helber, Magin, Chazot, AIAA 2021-3137

High-fidelity simulations with *ARGO* (coupled material-flow solver)







Summary and Outlook

Subsonic experiments on quartz, ZERODUR®, Titanium finalized

→	from basic to more complicated test cases, high-quality data for model validation
→	in-band emissivities determined with detailed instrument error analysis
ongoing	1D-modelling by VKI
ongoing	high-fidelity modelling with *ARGO* (extended to melting materials)
ongoing	surface analysis for oxidation (varying with test condition)
future	detailed oxidation study (?)

Semi-elliptical and conical nozzles commissioned

→	characterization for conical nozzles completed
→	first stagnation point experiment finalized (quartz)
ongoing	SE-nozzle flat plate characterization early 2022 (dummy sample + calorimeter)
ongoing	simulation with *ARGO* (extended to treat supersonic flow)
future	SE-nozzle flat plate experiments, including GSTP R.TECH