

Gas/Surface Interaction Study of Low-Density Ablators in Sub- and Supersonic Plasmas

NASA Applied Modeling & Simulation (AMS) Seminar Series

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based on AIAA 2014-2122

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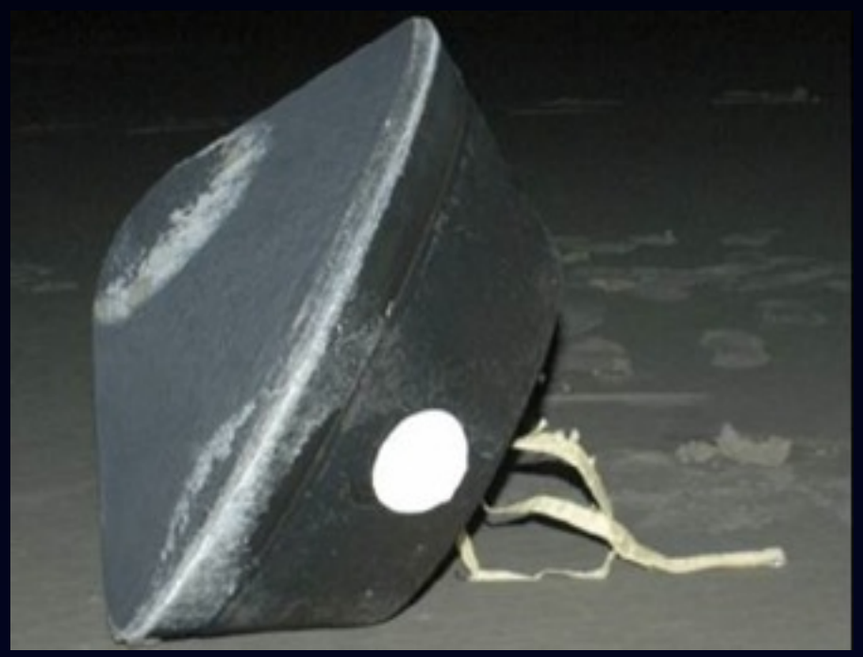
[2] *Research Group Electrochemical and Surface Engineering, Vrije Universiteit Brussel*

TPM for Atmospheric Reentry



Future Missions: Ablative TPM

- Sample return, ISS serving (Dragon, ARV, ...), MPCV
- Atm. reentry speeds $>$ 10km/s
- Mass loss and surface recession
- Prediction of material response required
- High margins decrease payload



NASA Stardust probe, reentry: Jan. 15, 2006 (12.9 km/s) (AIAA 2008-1202)

New materials (1990's)

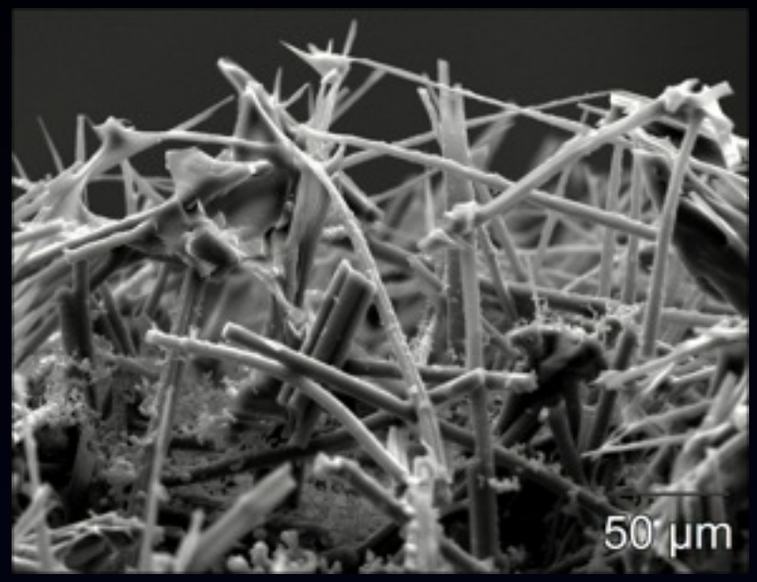
- Phenolic impregnated carbon fiber preform
- Very porous low density ablators

TPM for Atmospheric Reentry

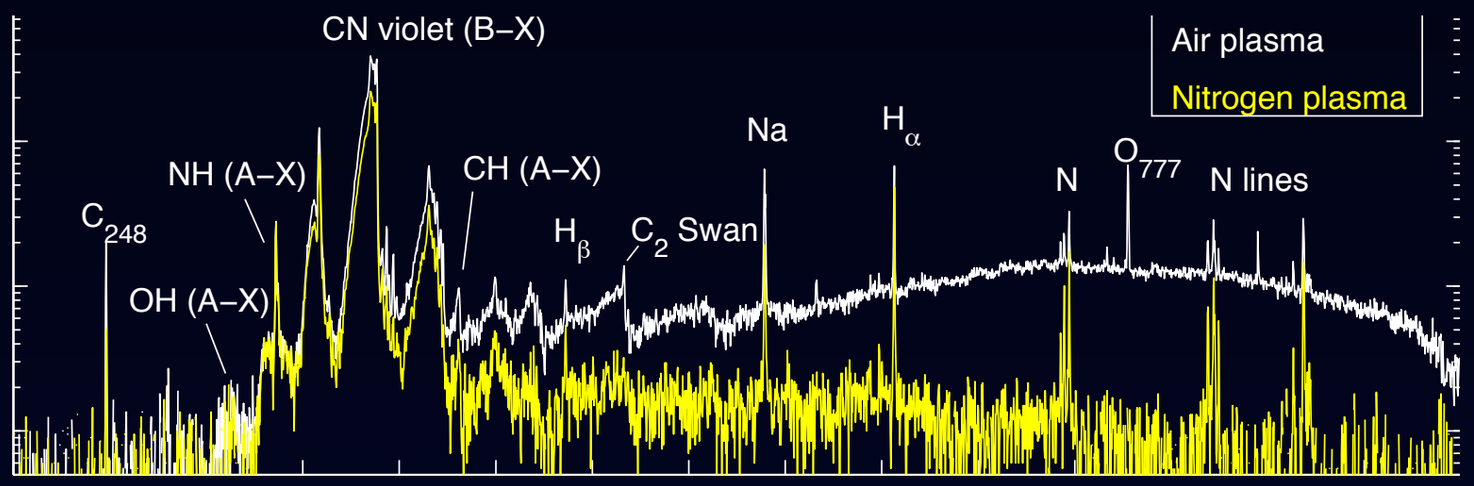
Complex Multiphysics - Multiscale Problem



Gas-Surface Interaction



Material



Radiation

We aim at improvement of

Experimental Methods
(VKI)

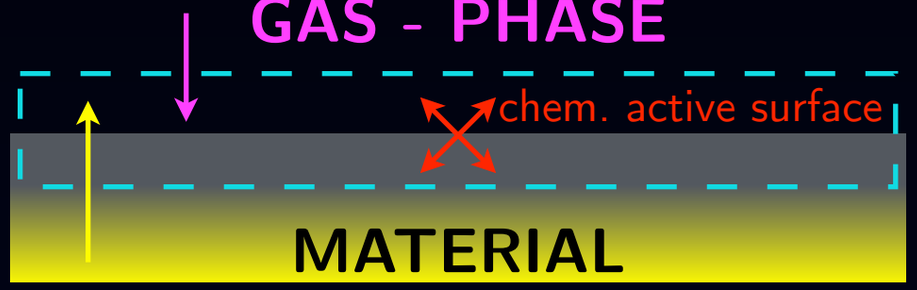


TPS Design / Material
(VUB, Airbus DS, ESA)

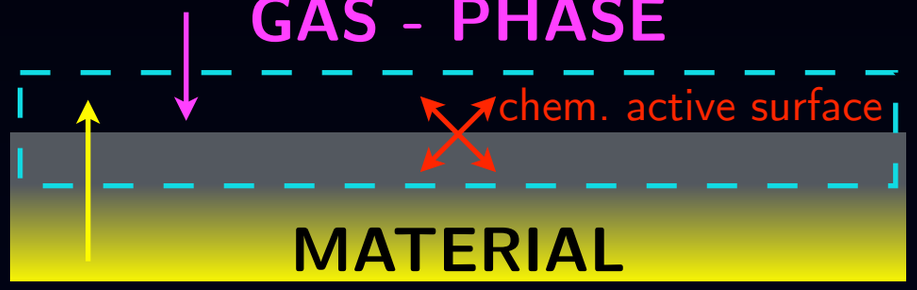


Material Response Modeling & Validation
(VKI, collaborations)

In the following



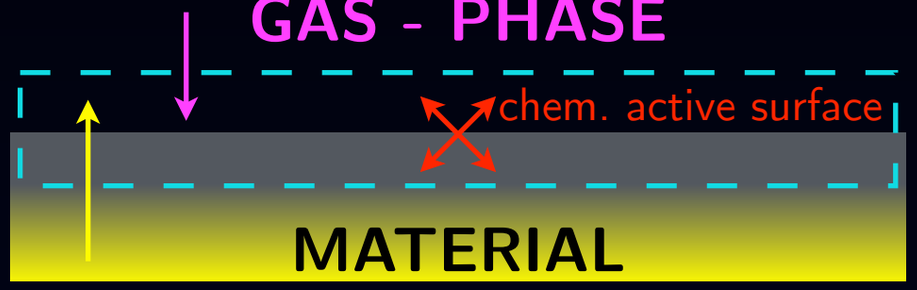
In the following



Reactive Surface

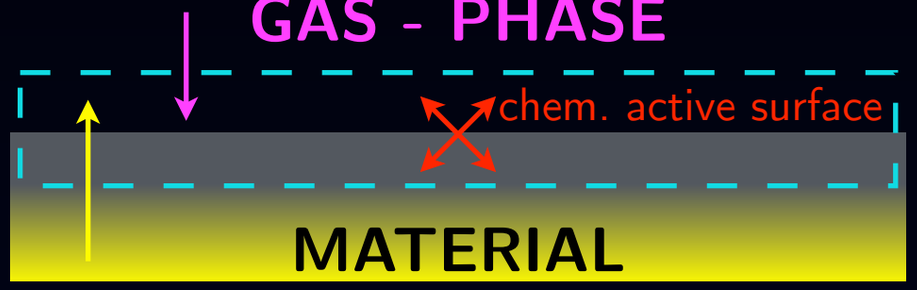
- surface temperature & emissivity
- centerline recession rate
- post-ablation topology (SEM)

In the following



(2) Surface ➪ Temperatures / Recession

In the following

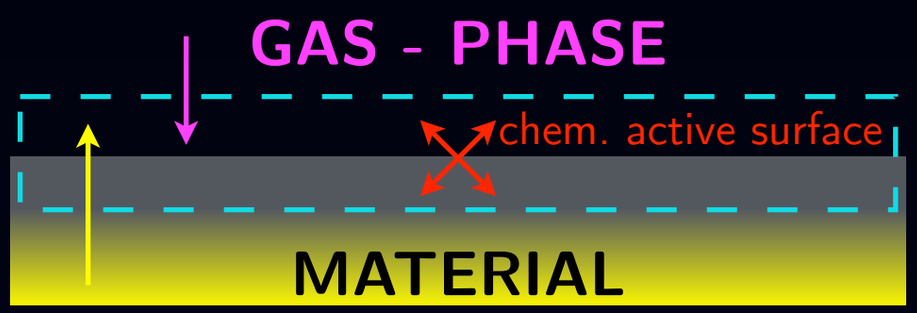


(2) Surface ➪ Temperatures / Recession

Gas-phase

- Ablation species injection
- Strong radiators and boundary layer absorption

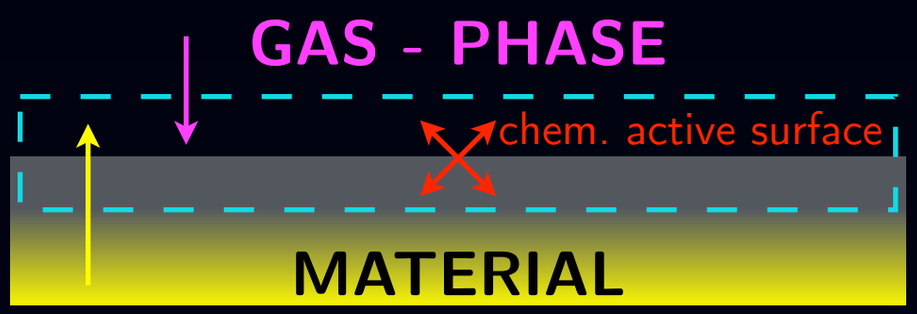
In the following



(2) Surface ➪ Temperatures / Recession

(3) Gas-phase ➪ BL emission & temp

In the following

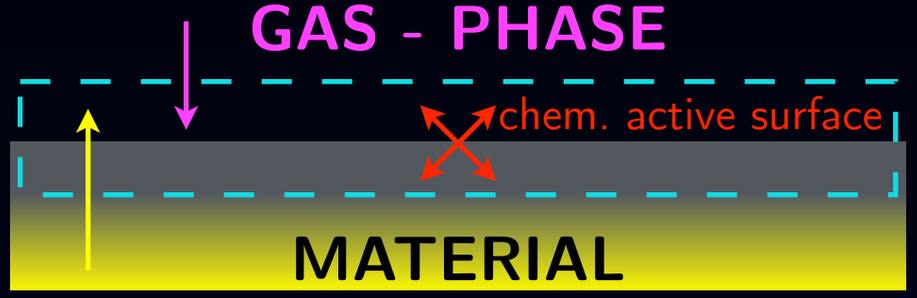


(2) Surface ➪ Temperatures / Recession

(3) Gas-phase ➪ BL emission & temp

(4) Material ➪ Pyrolysis outgassing

In the following



(1) Materials and Methods for Ablation Characterization

(2) Surface ➪ Temperatures / Recession

(3) Gas-phase ➪ BL emission & temp

(4) Material ➪ Pyrolysis outgassing

Materials of Investigation



Carbon fiber preform (Mersen Scotland Holytown Ltd.)

- chopped carbon fibers, fully carbonised
- density: 180-210 kg/m3, porosity: 90%

no phenol



AQ61 (Airbus DS) with phenol

- low density carbon-phenolic
- made of short carbon fibers impregnated
  $\rightarrow$ compacted & pyrolyzed
- low resin content



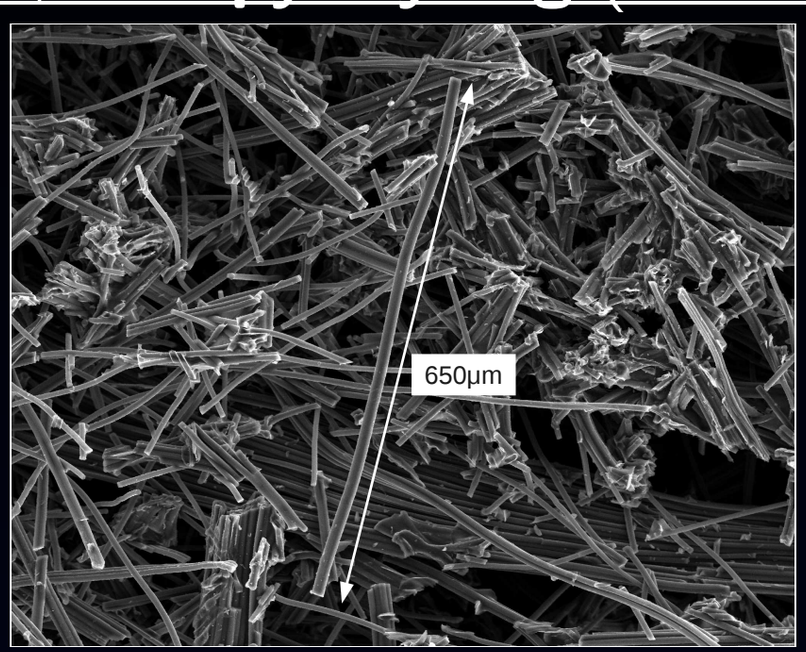
Asterm (Airbus DS) with phenol

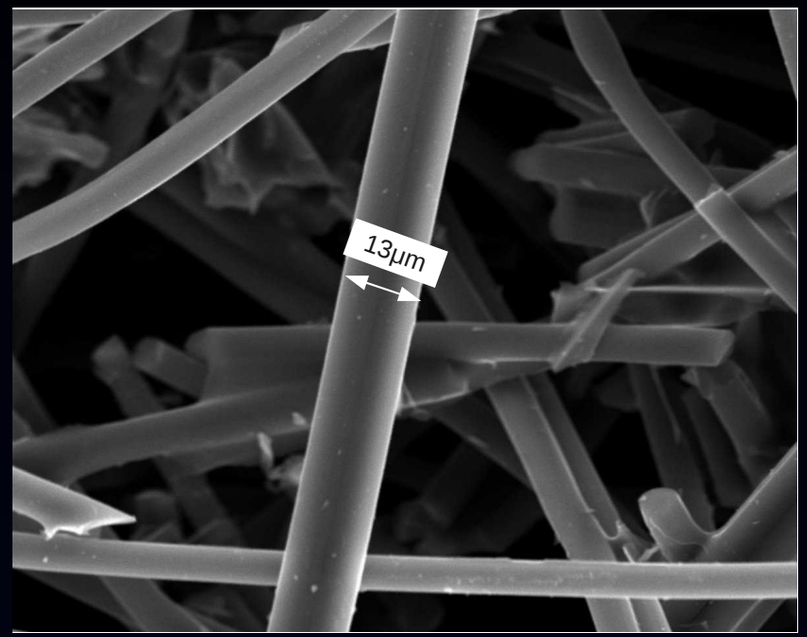
- low density carbon-phenolic
- rigid graphite felt impregnated
  $\rightarrow$ polymerization
- precursor similar to carbon fiber reform

Materials of Investigation

Carbon fiber preform, **non-pyrolyzing** (Mersen Scotland Holytown Ltd.)

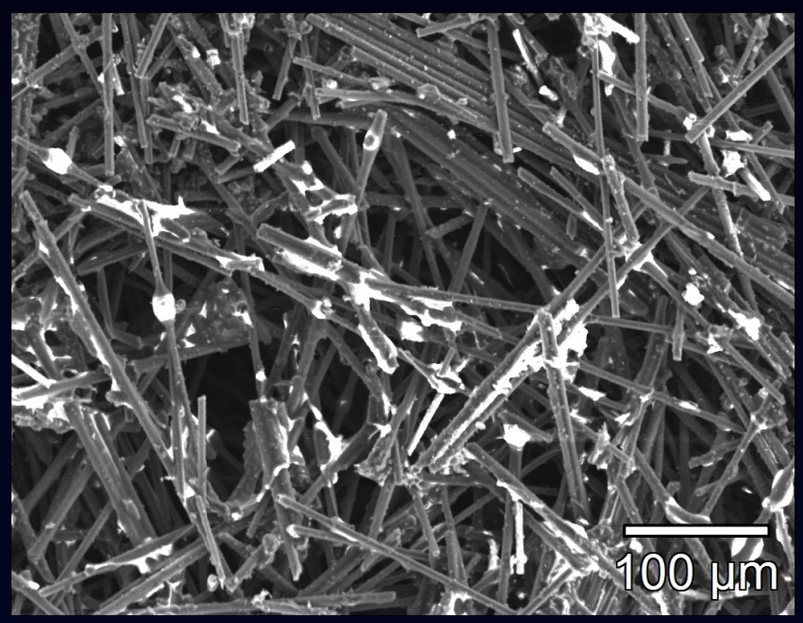


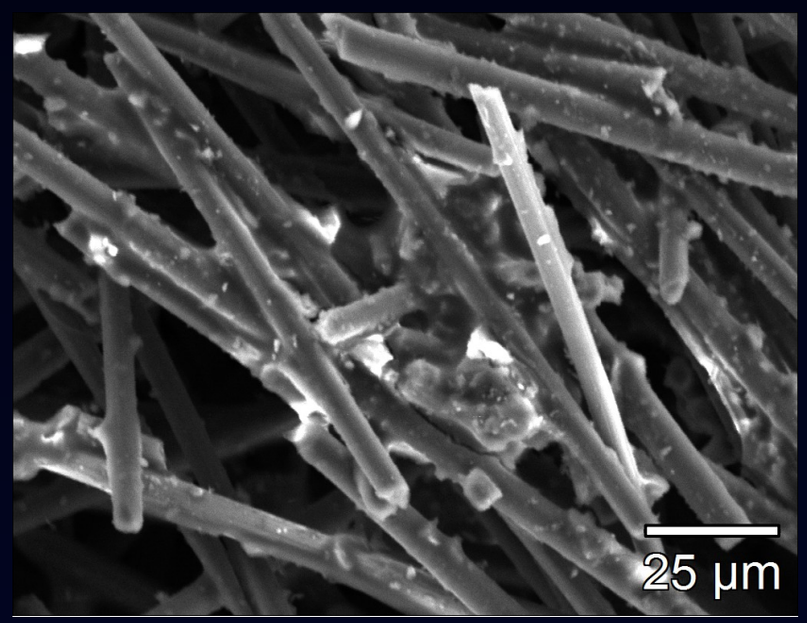




AQ61, **carbon-phenolic** (AIRBUS DS)

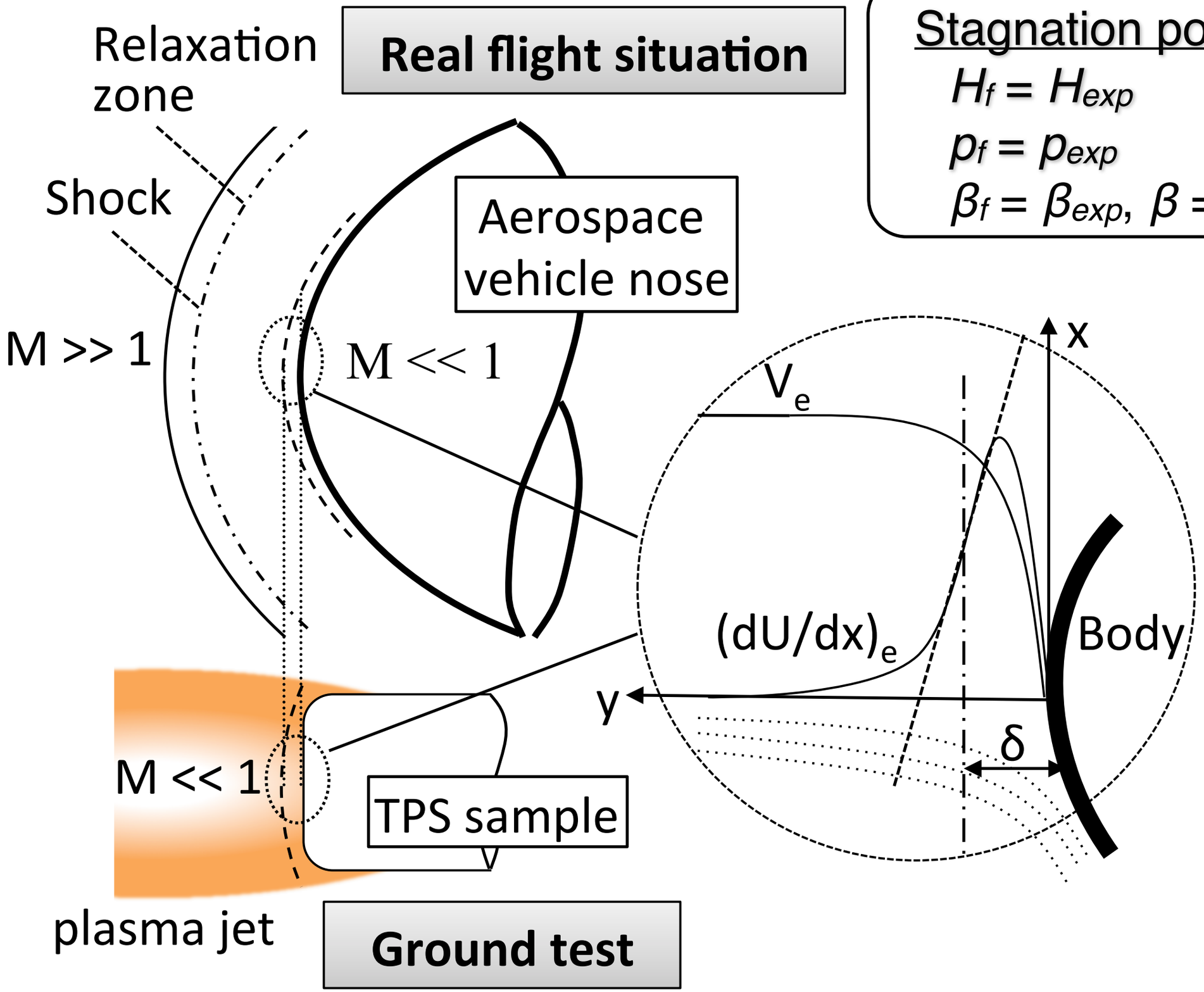






1.2-MW Inductively Coupled Plasmatron: Methodology

Real flight situation



Ground test

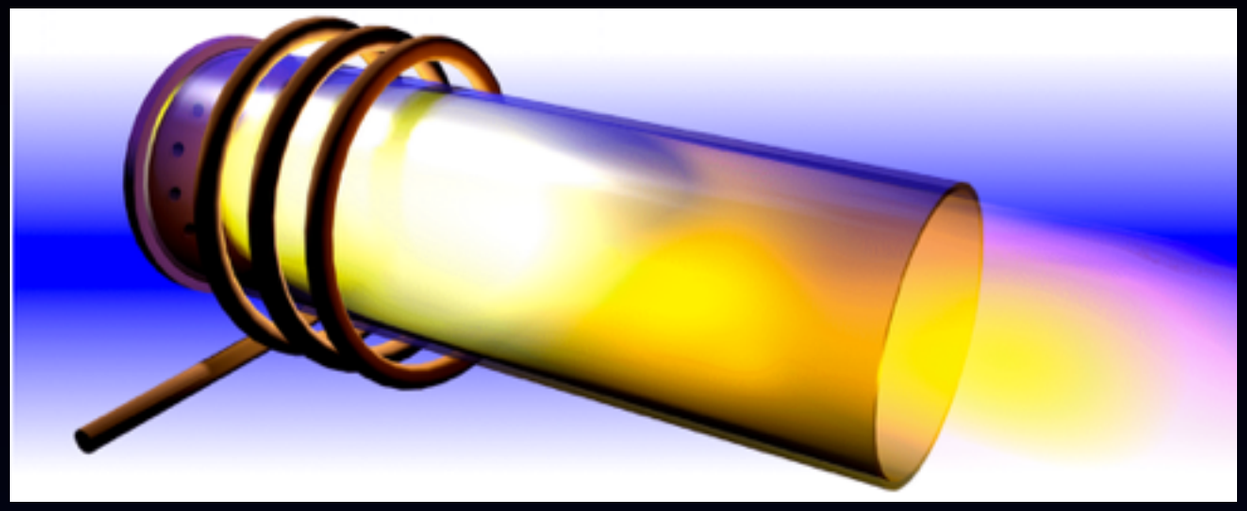
Stagnation point similarity:

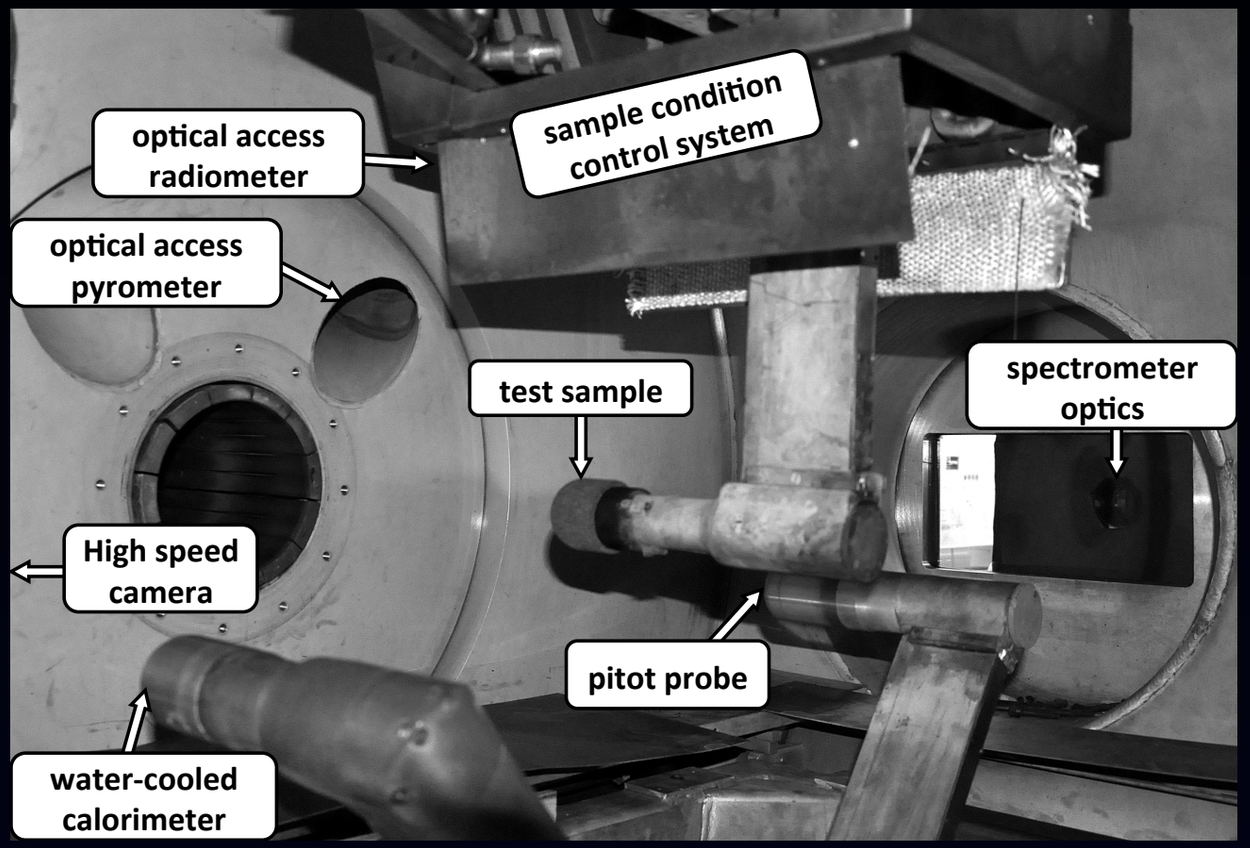
$H_f = H_{exp}$

$p_f = p_{exp}$

$\beta_f = \beta_{exp}$, $\beta = dU/dx|_e$

1.2-MW Inductively Coupled Plasmatron





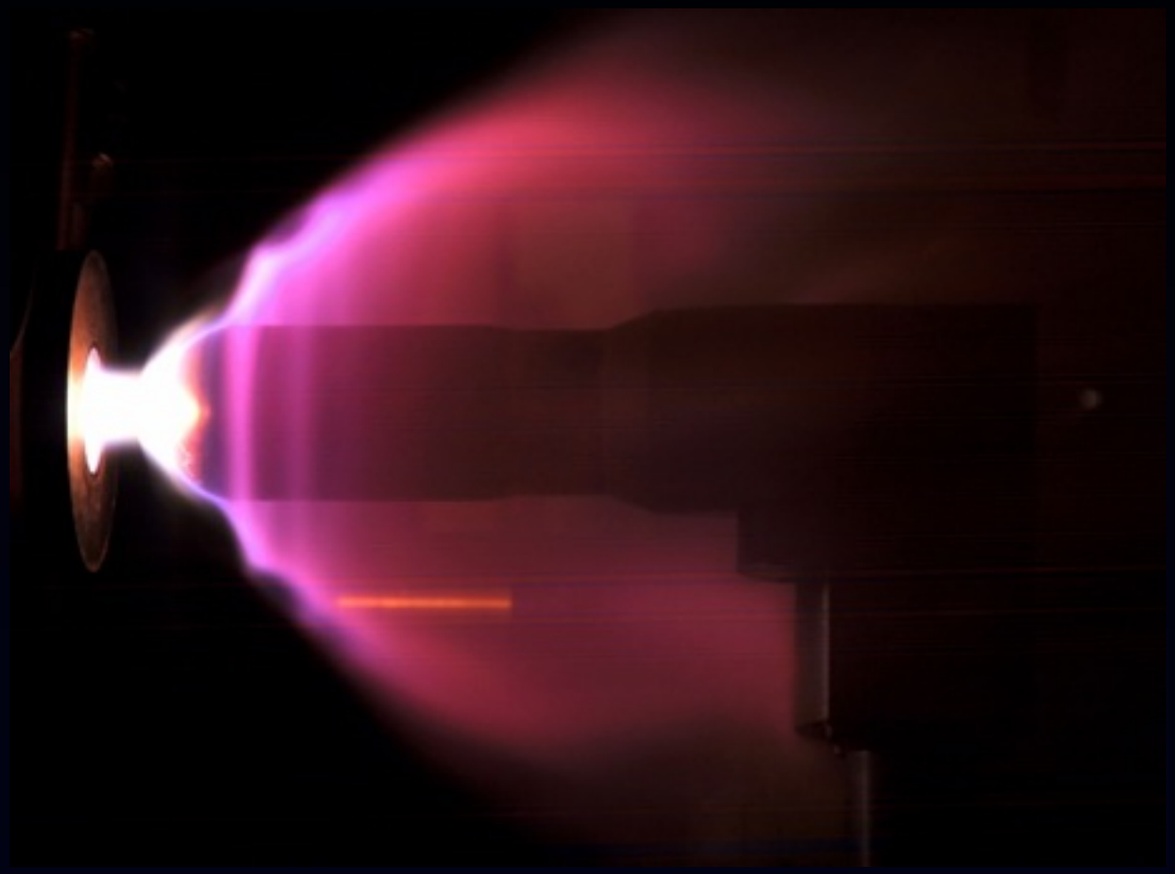
Gas: Air, N_2, CO_2, Ar

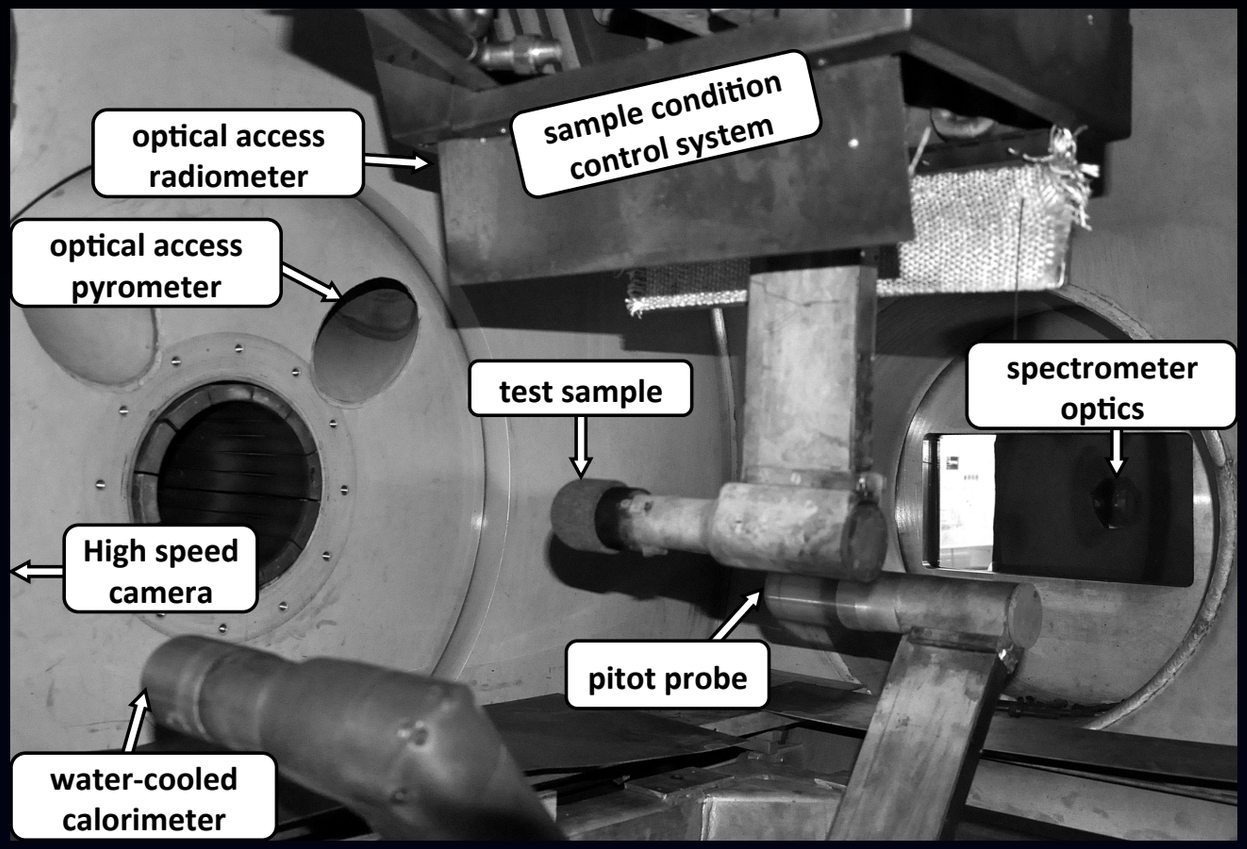
Power: 1.2-MW

Heat Flux: > 12 MW/m^2

Pressure: 10 mbar - 1 atm

1.2-MW Inductively Coupled Plasmatron





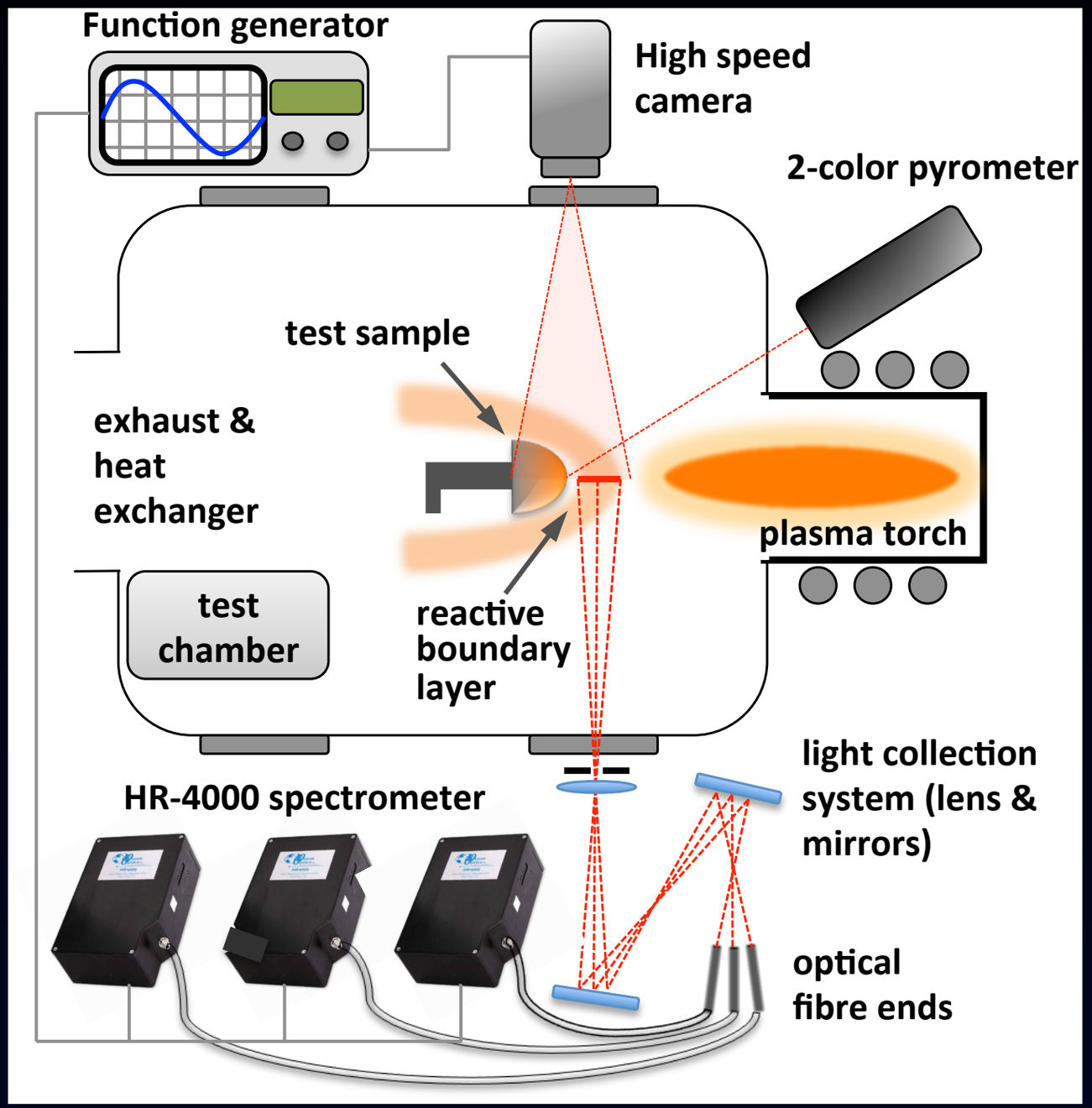
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Techniques for In-Situ Ablation Characterization

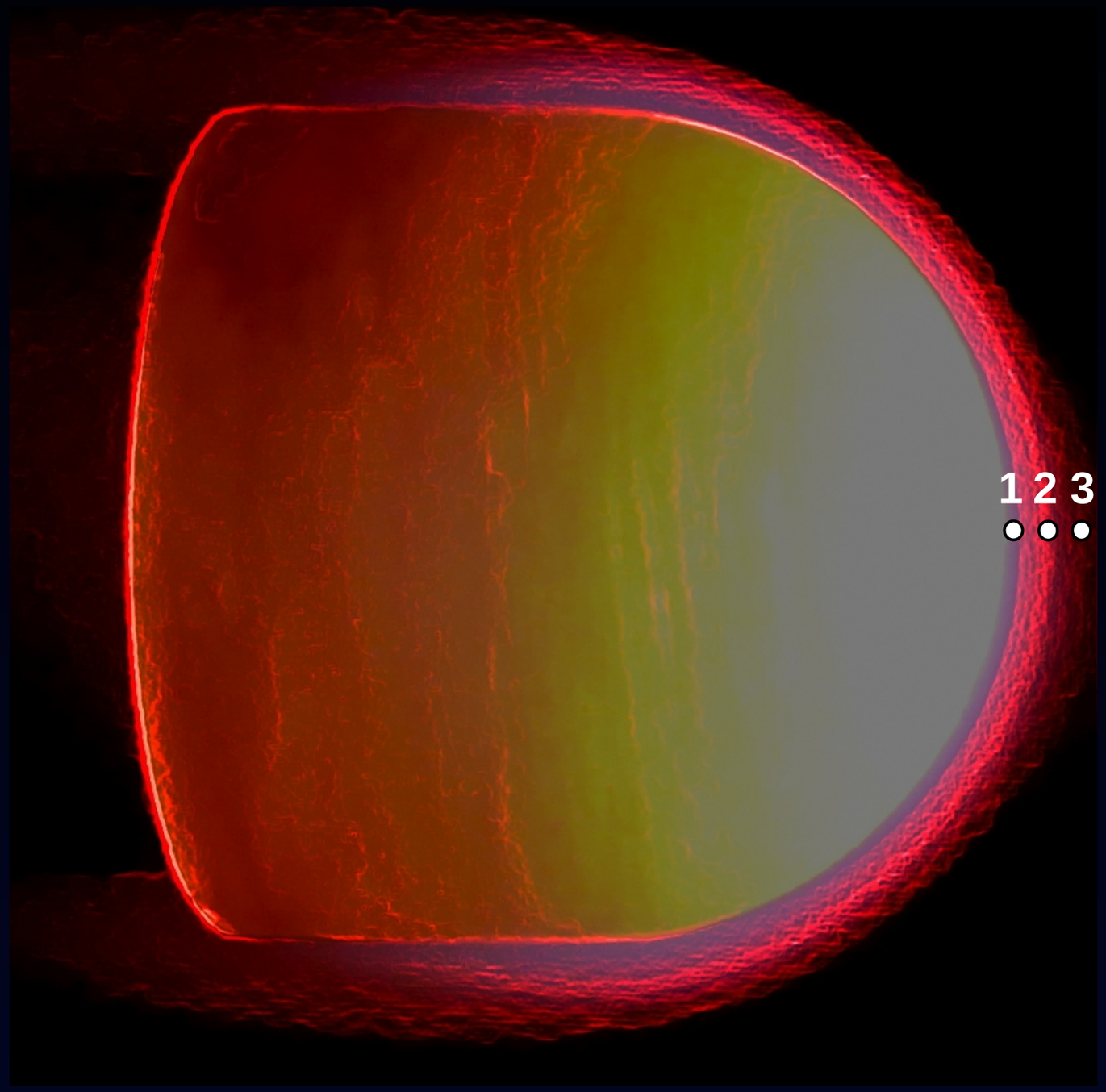


Our interest

Surface temperature
Emissivity
Internal Temperature
In-situ recession analysis
Volumetric recession
Chemical composition
Temperature estimation

(AIAA 2013-2770)

Techniques for In-Situ Ablation Characterization



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Three Dedicated Test Campaigns

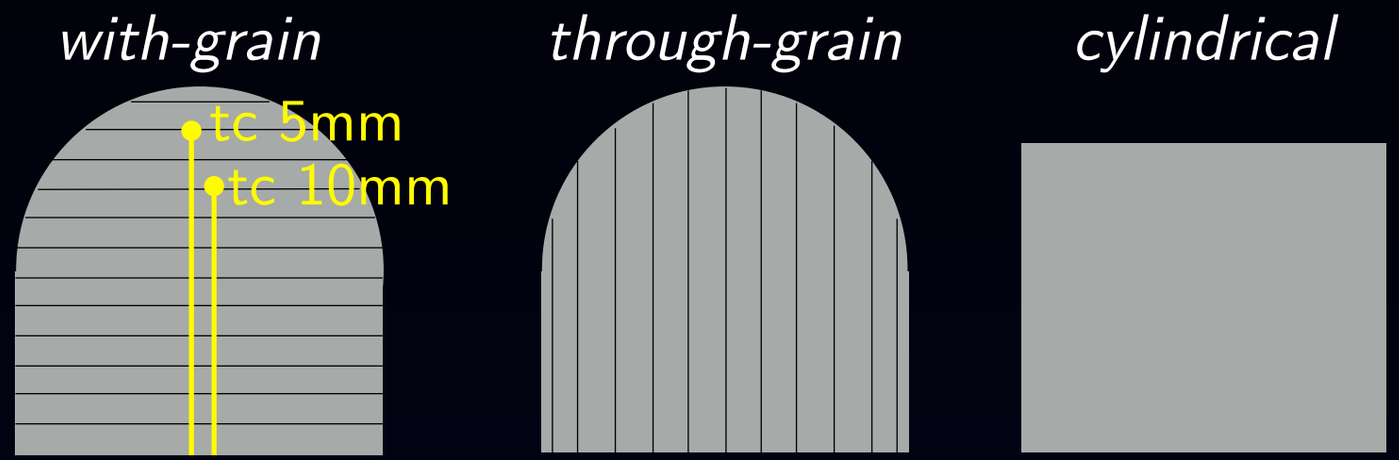
Three Dedicated Test Campaigns

1. <u>General ablation tests</u>:
   - air and nitrogen
   - heat fluxes: 1 - 3 MW/m^2, p_{tot} = 15 - 200 hPa

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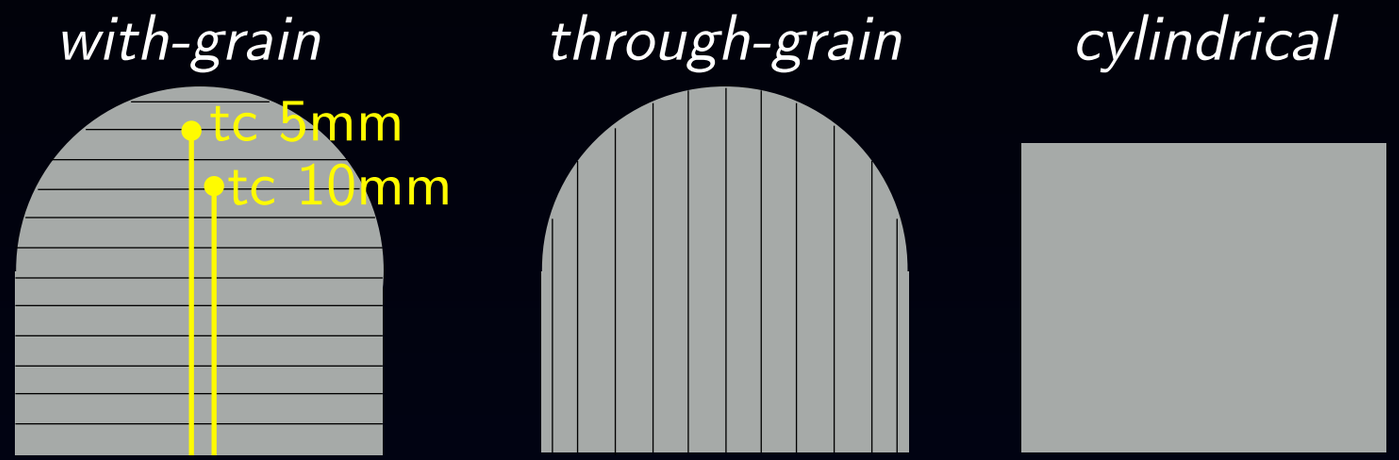
2. <u>Grain study:</u>
   - only air
   - 0.3 - 1 MW/m^2, p = 15hPa



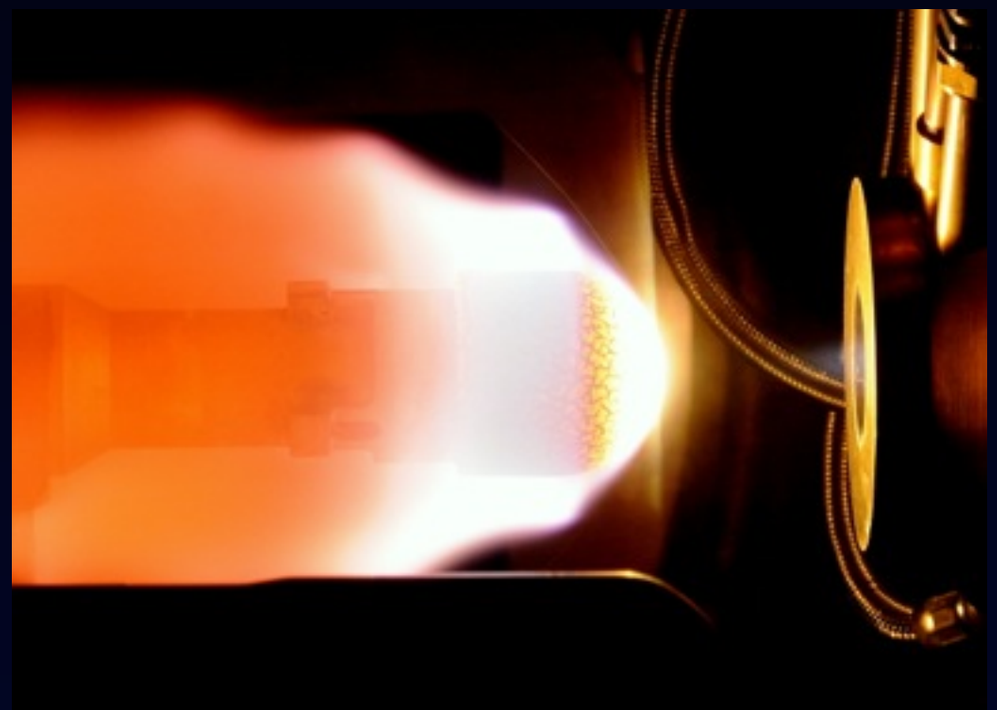
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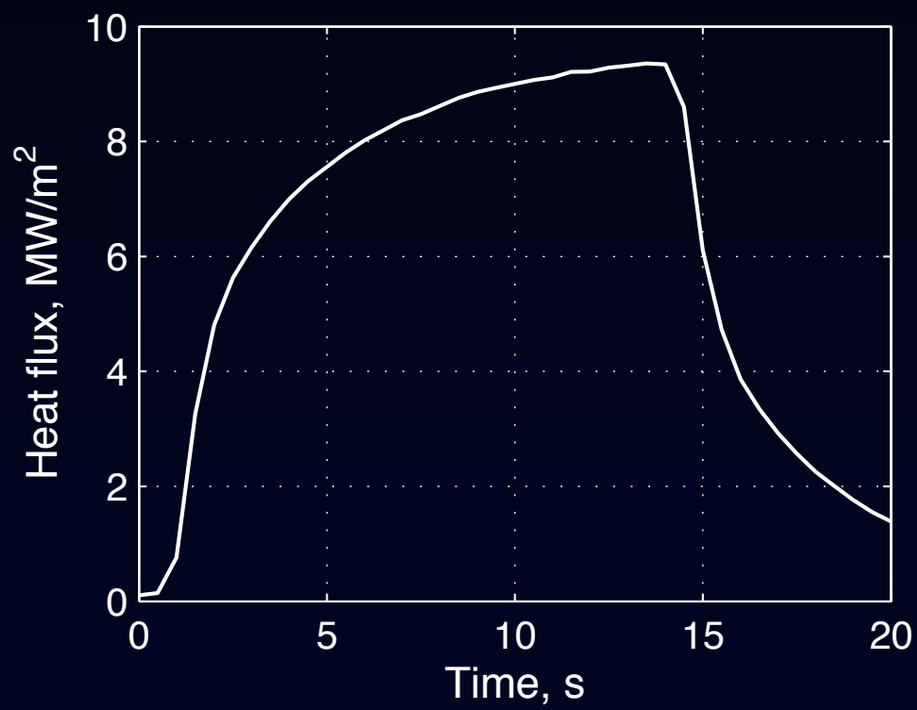
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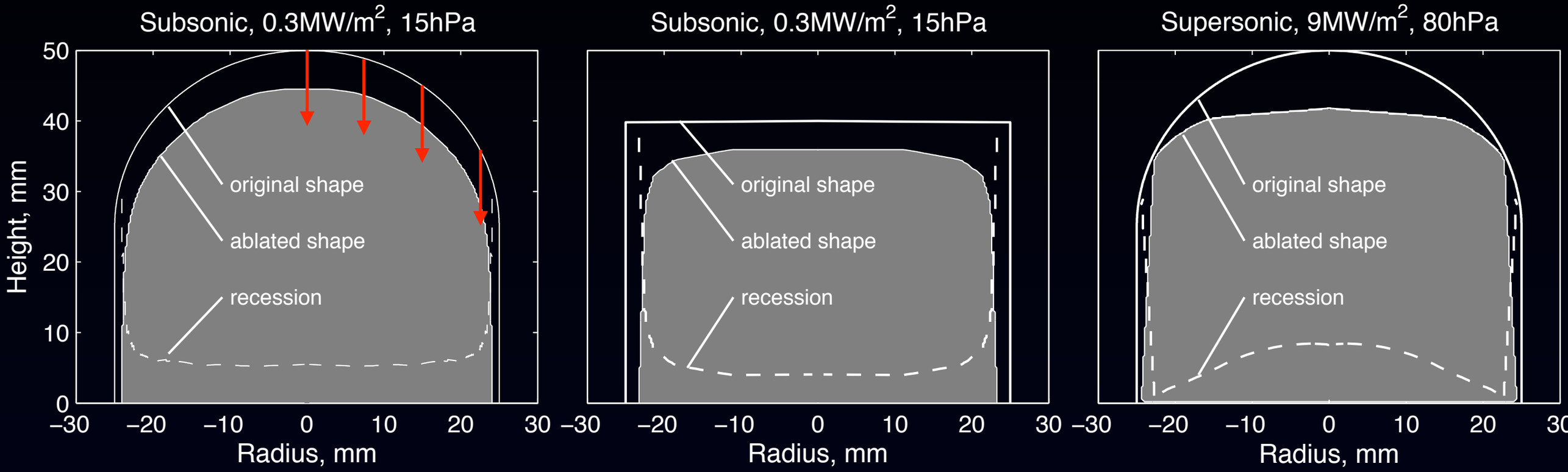
3. <u>High-heat flux tests (supersonic)</u>





Volumetric Ablation (shape change)

Non-pyrolyzing carbon-preform



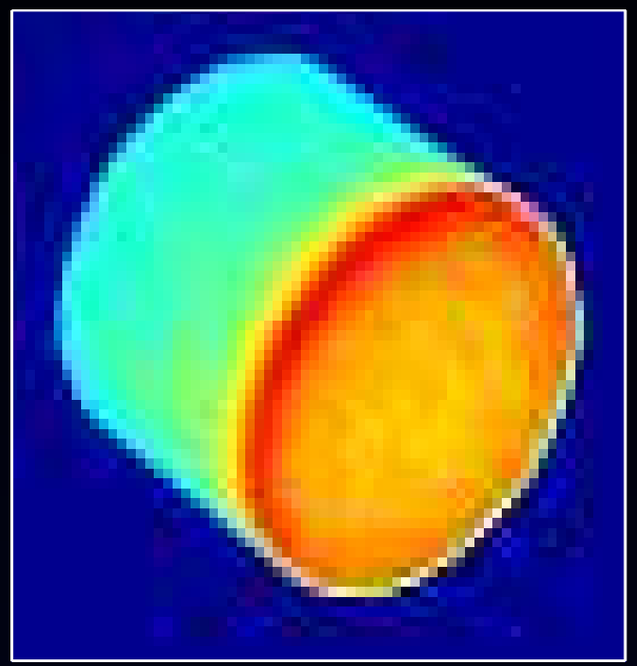
- linear (axial) recession up to r = 20mm
- small shape change
  ➟ constant boundary conditions

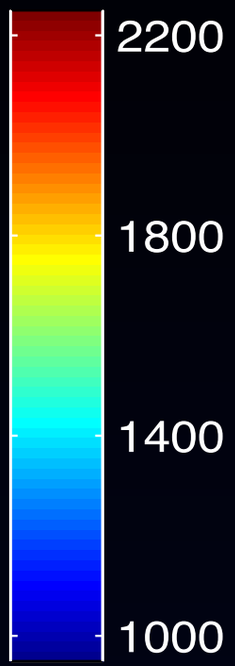
- edge ablation (shoulder) due to peak heating
- shape change
  ➟ increase of surface temperature

- high centreline ablation
- iso-q shape
  ➟ caused by shock or nozzle (35mm)

Surface Temperature Distribution by IR-imaging

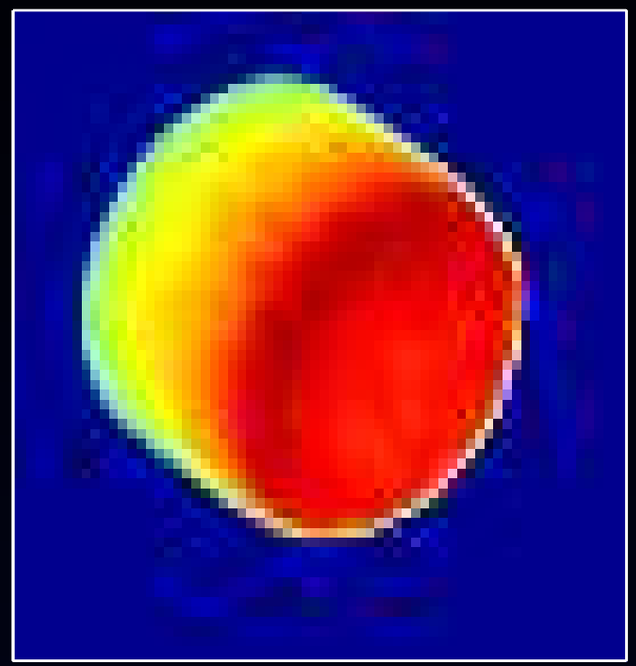
$q_{cw} = 1\mathrm{MW/m^2}$, $p_s = 15\mathrm{hPa}$

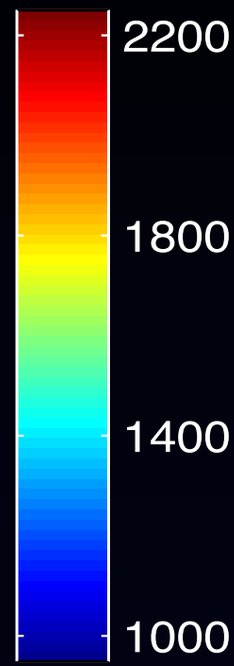




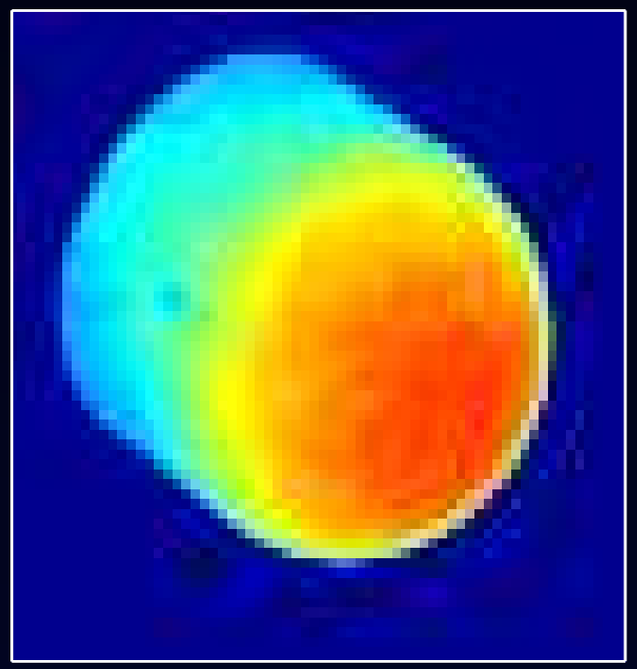
cylindrical

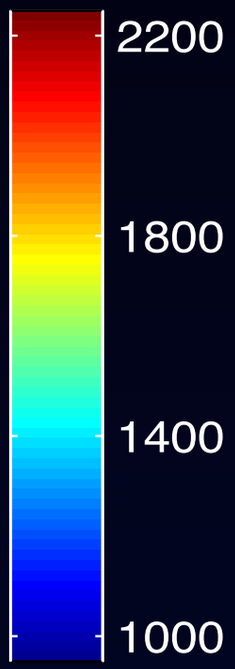
T_{stag} increase





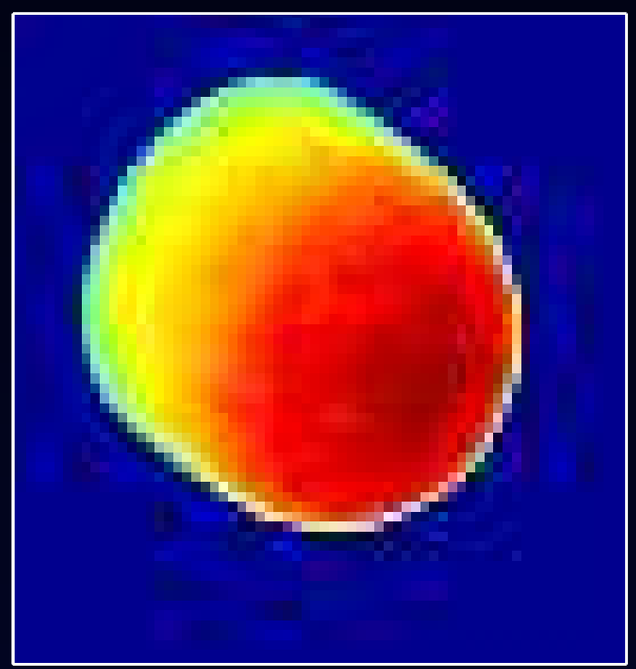
Test start

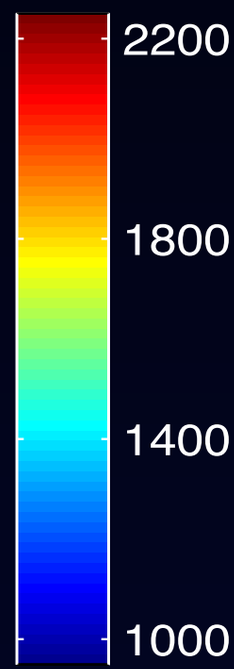




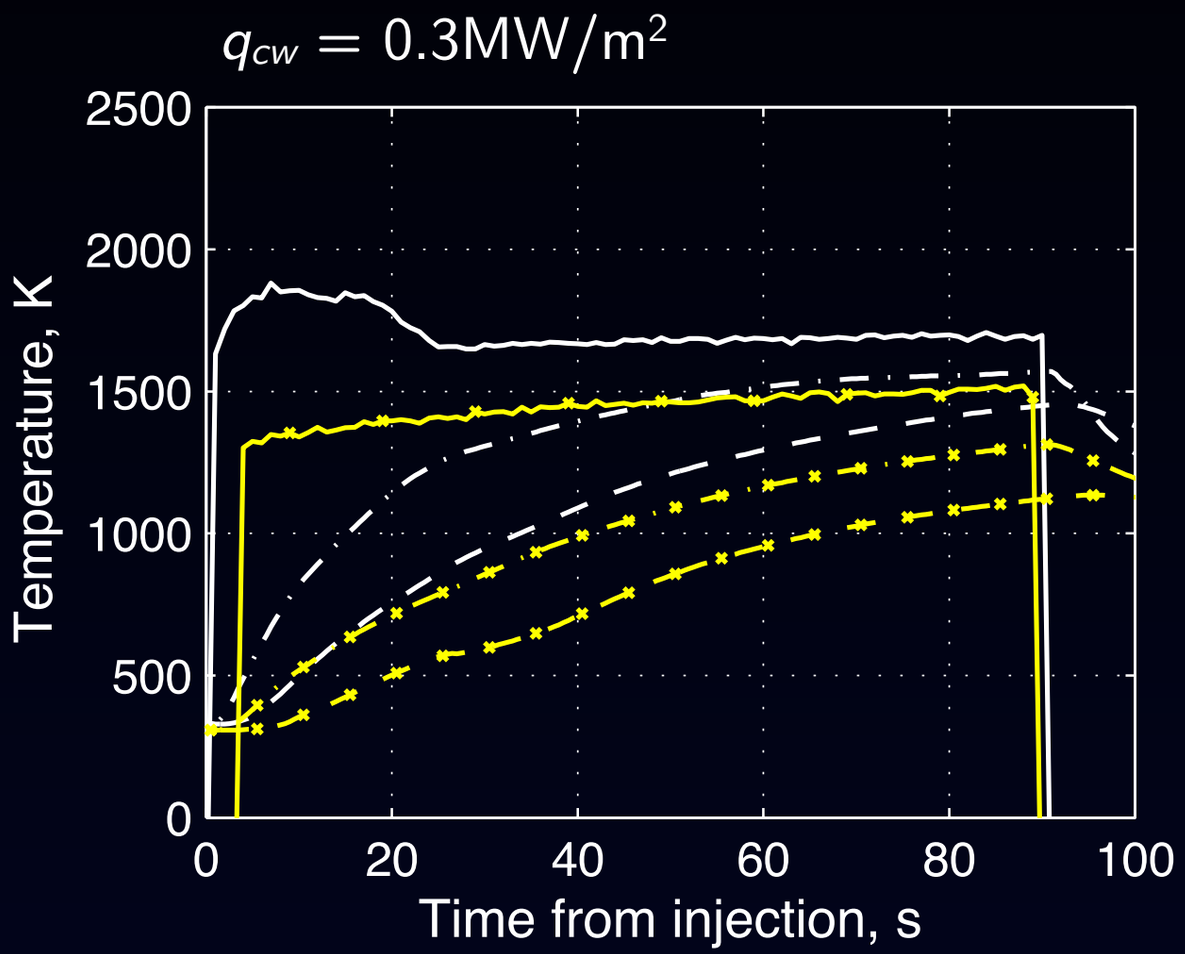
hemispherical

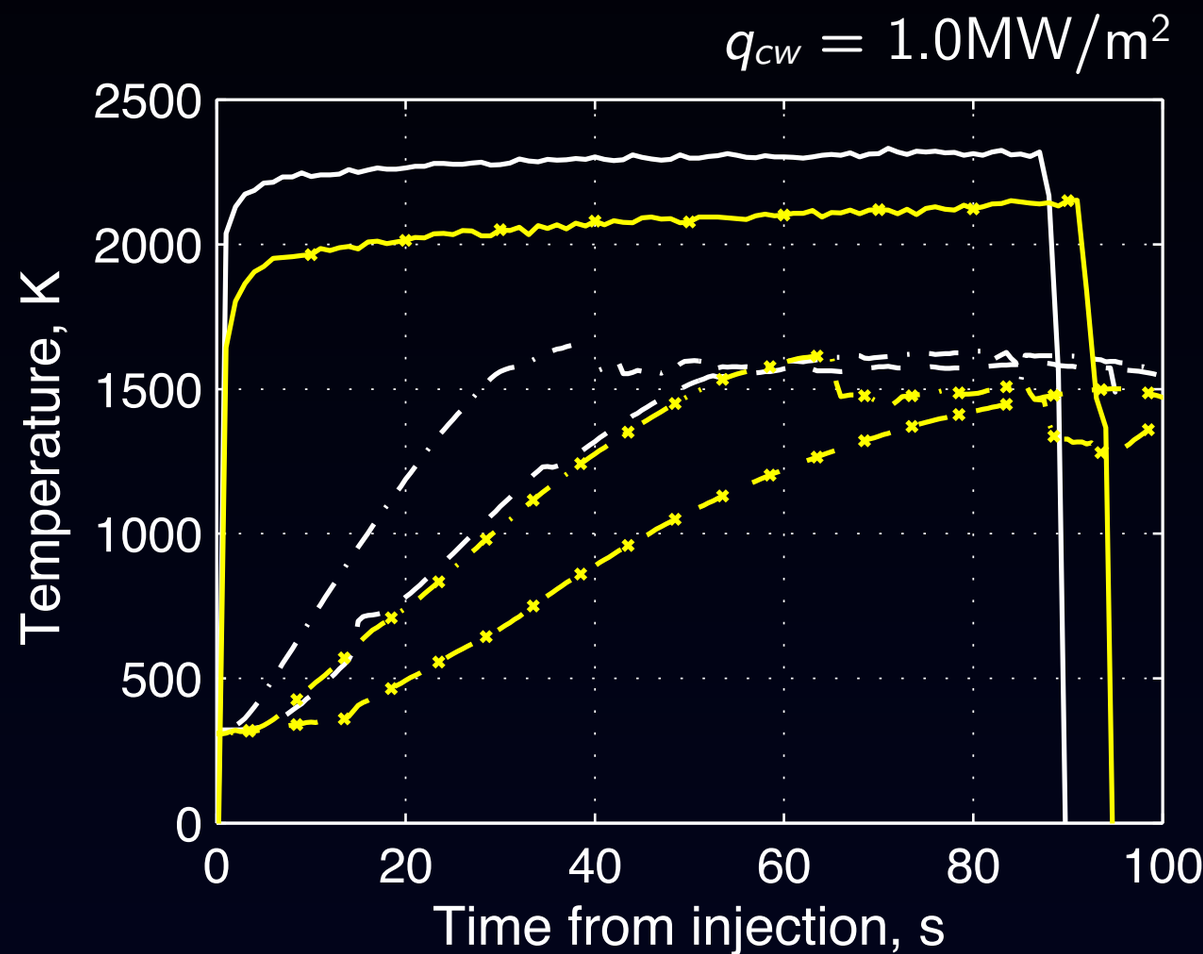
Test end





Test Sample Shape Affects Temperatures

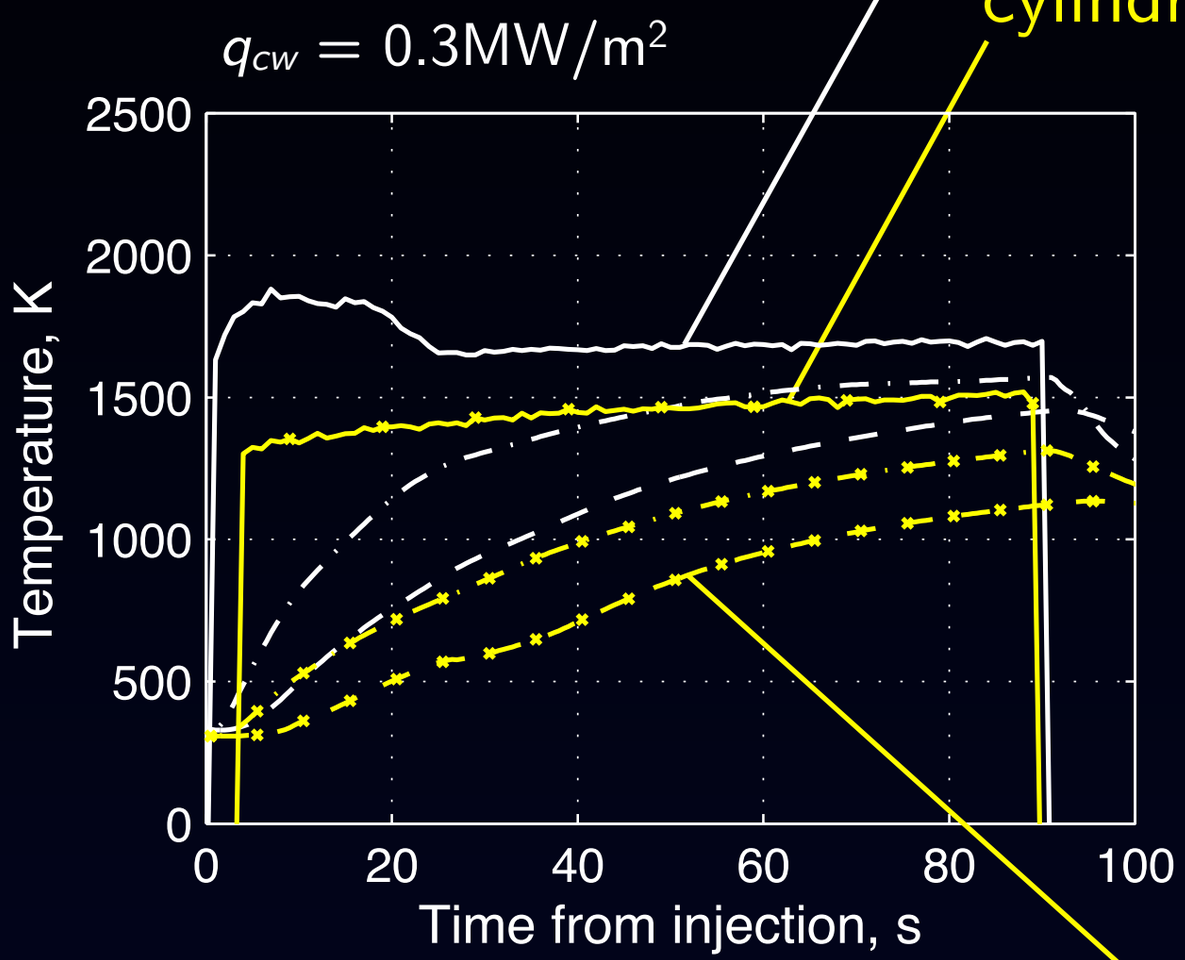


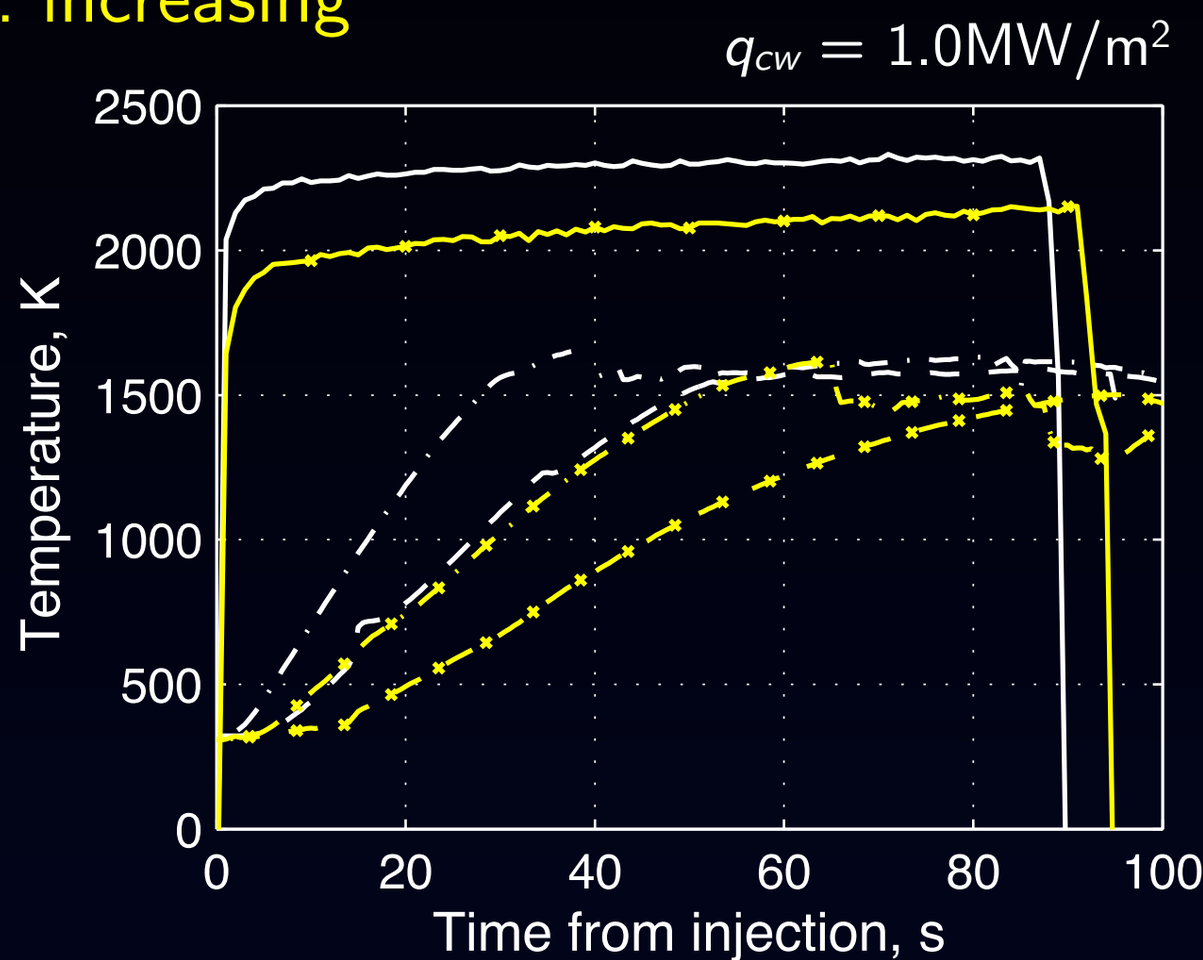


Test Sample Shape Affects Temperatures

hemispherical: quasi-steady

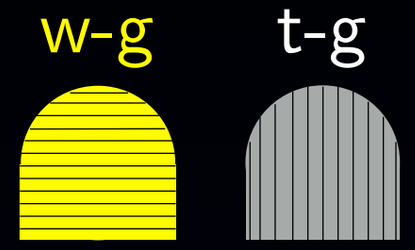
cylindrical: increasing

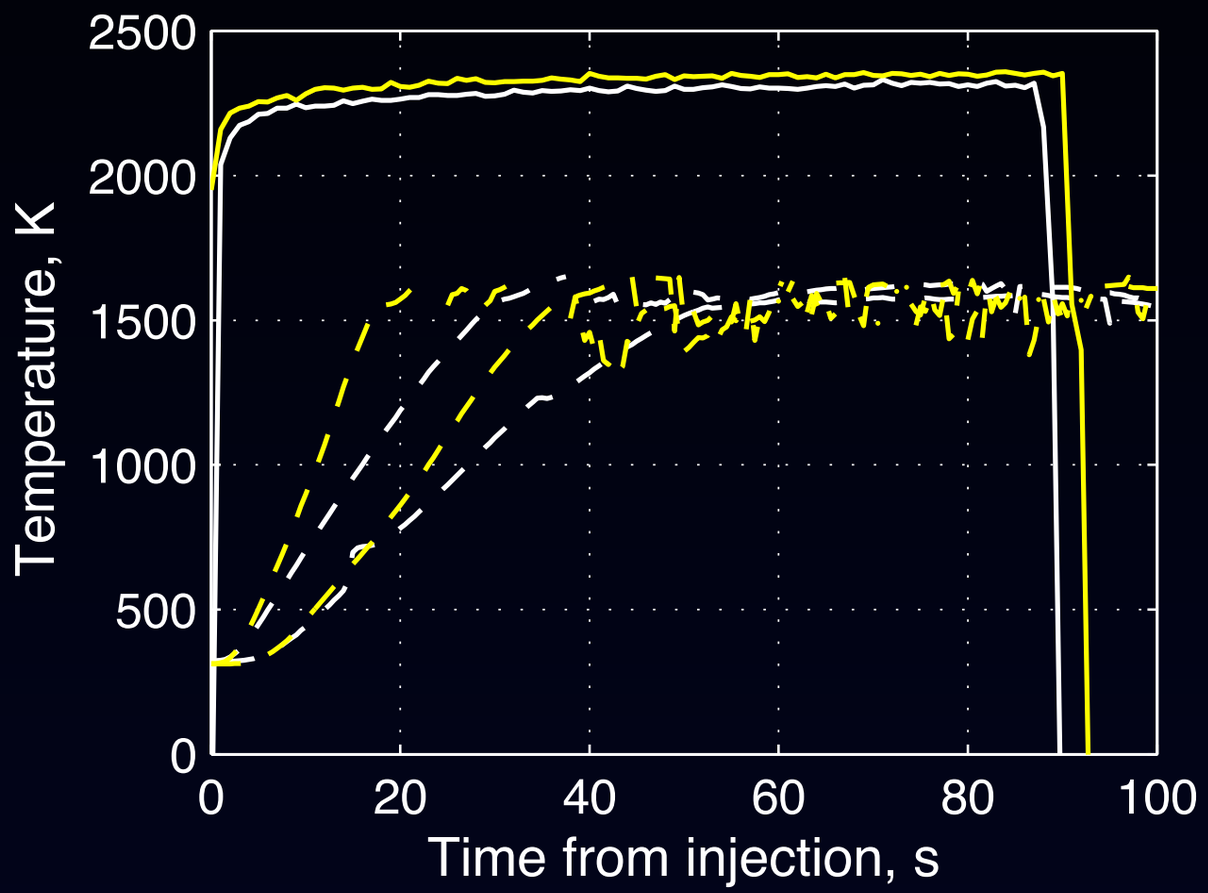


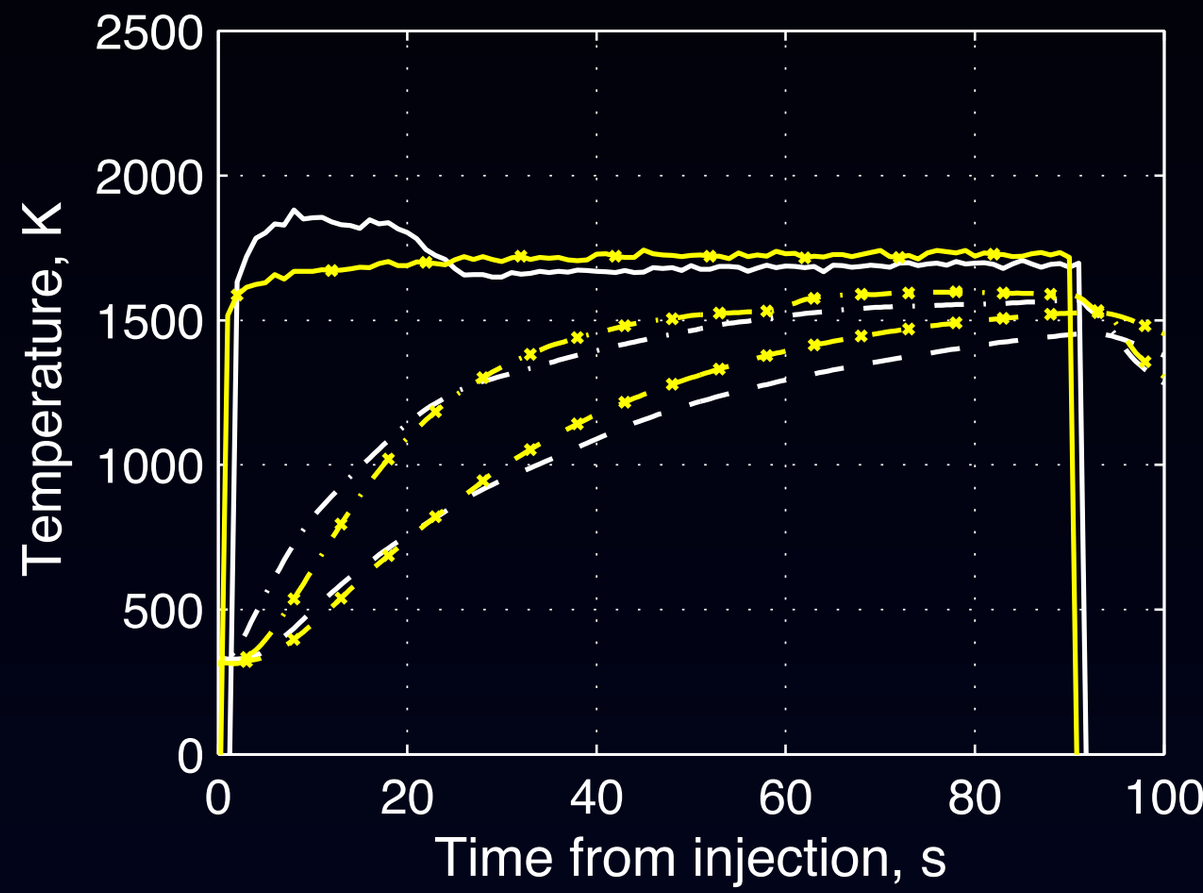


cylindrical: lower internal heating

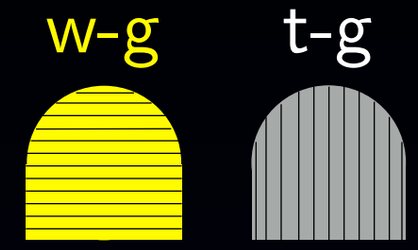
Fiber Direction Slightly Affects Temperatures





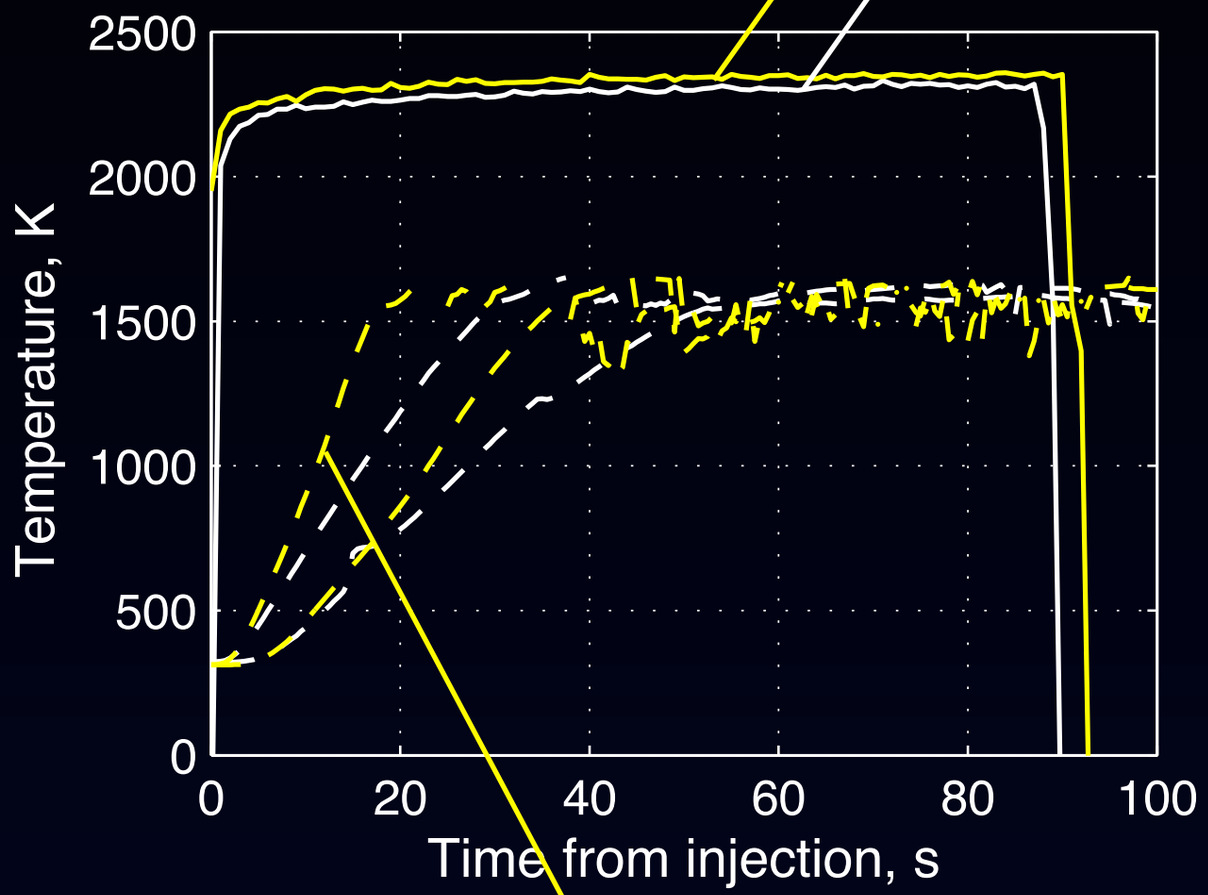


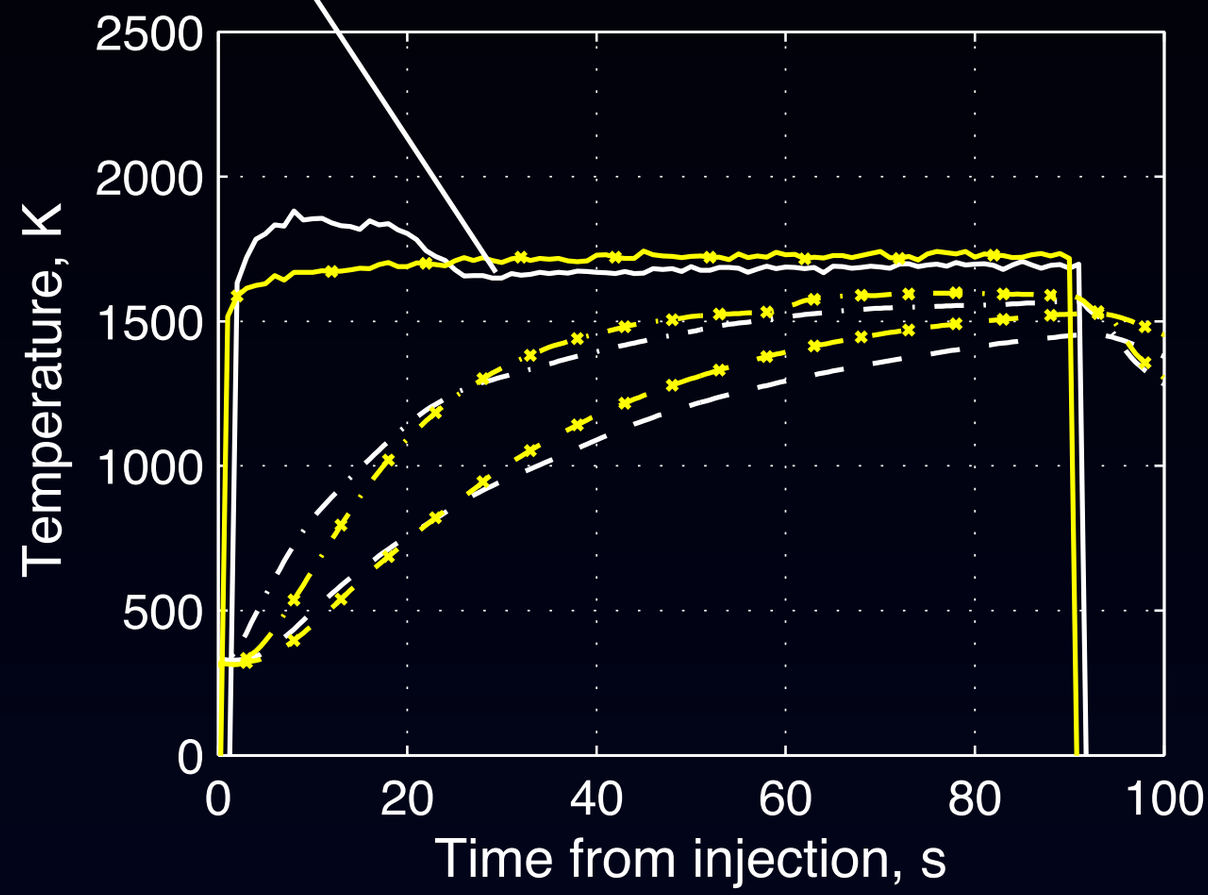
Fiber Direction Slightly Affects Temperatures



with-grain: higher Ts

through-grain: lower Ts





with-grain: higher internal temperature

- unexpected (lower conduction in axis direction)
- but: higher conduction in radial direction

  $\Longrightarrow$ stronger sidewall heating

Emissivity: 0.86 - 0.97

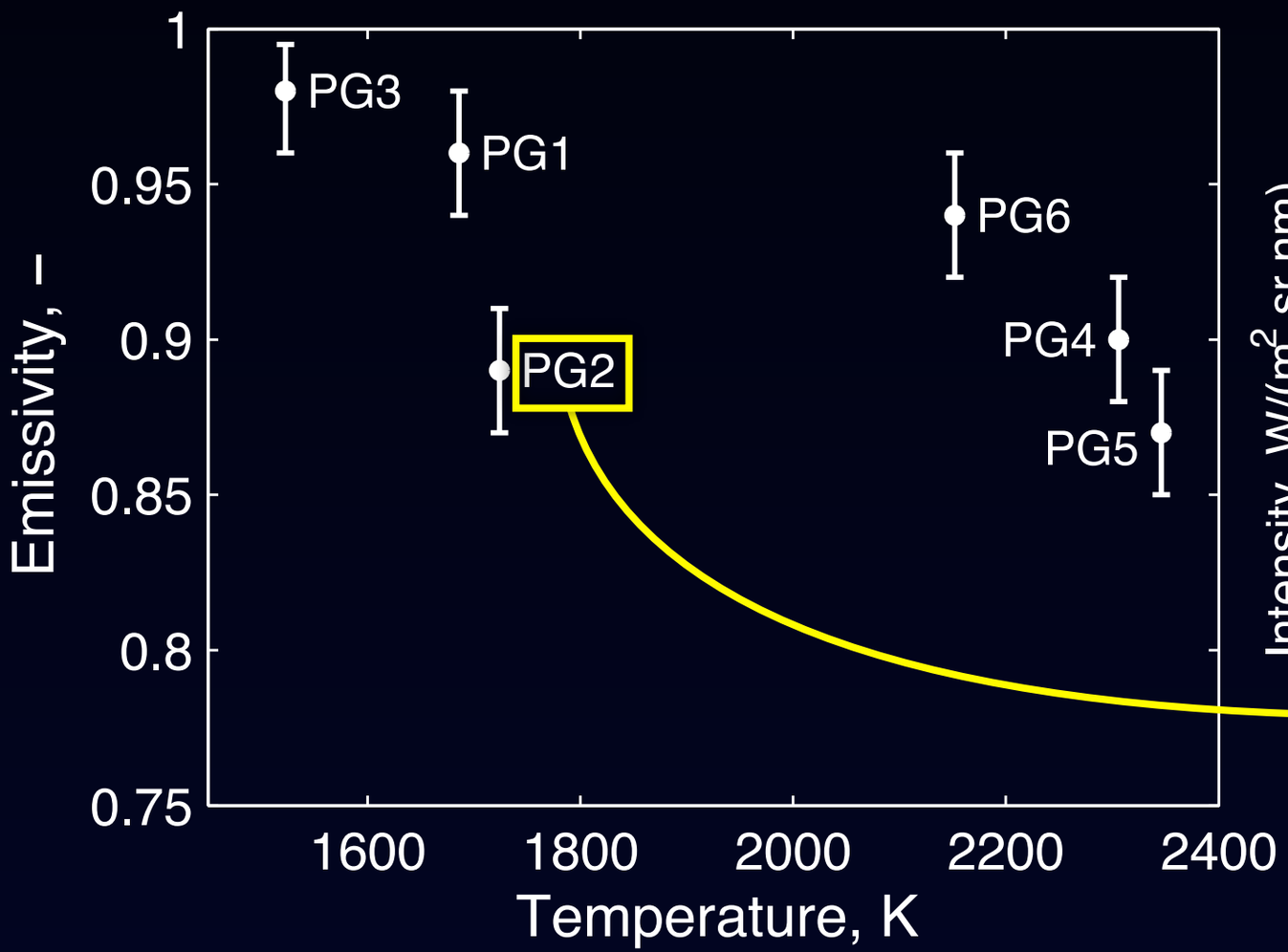
Gray body emissivity ($8-9\mu m$, T):

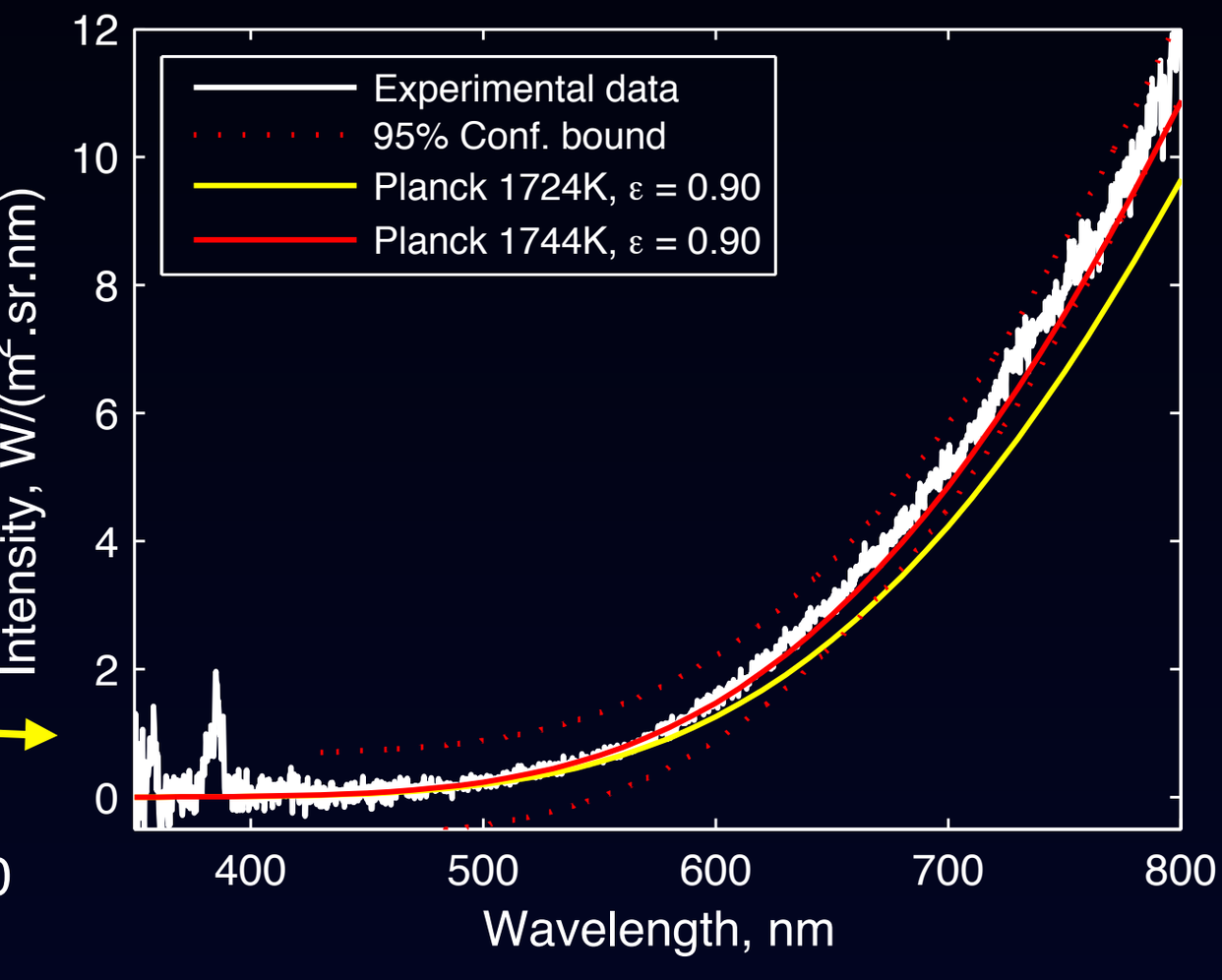
$$\varepsilon_{8-9\mu m,T} = \frac{B(IR)}{B^{bb}(Pyrometer)}$$

Planck's law (spectral radiance):

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} [\frac{W}{m^2.sr.nm}]$$

Measured: T = 1724K, p_s = 15mbar





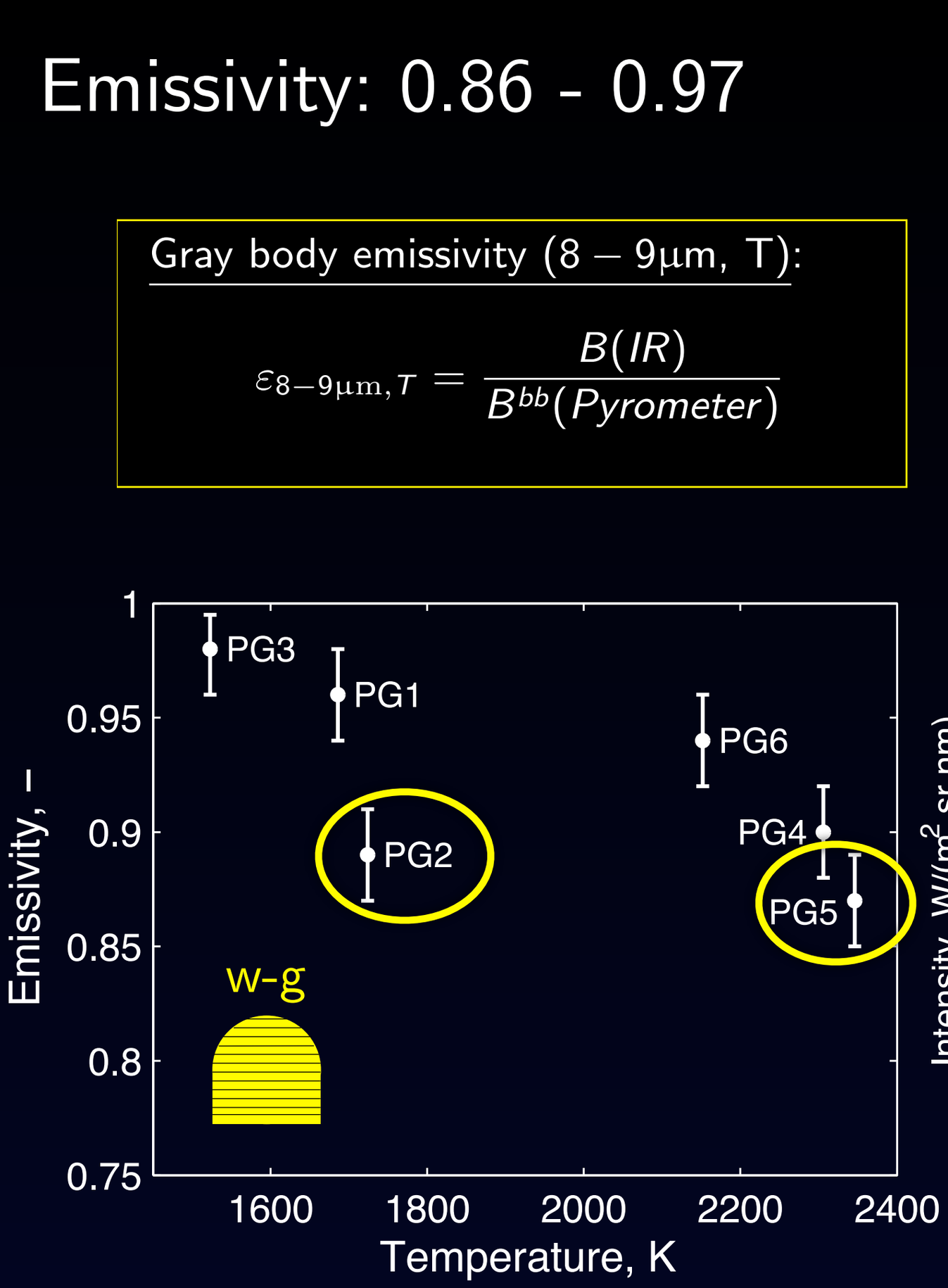
Emissivity: 0.86 - 0.97

Gray body emissivity ($8-9\mu m$, T):

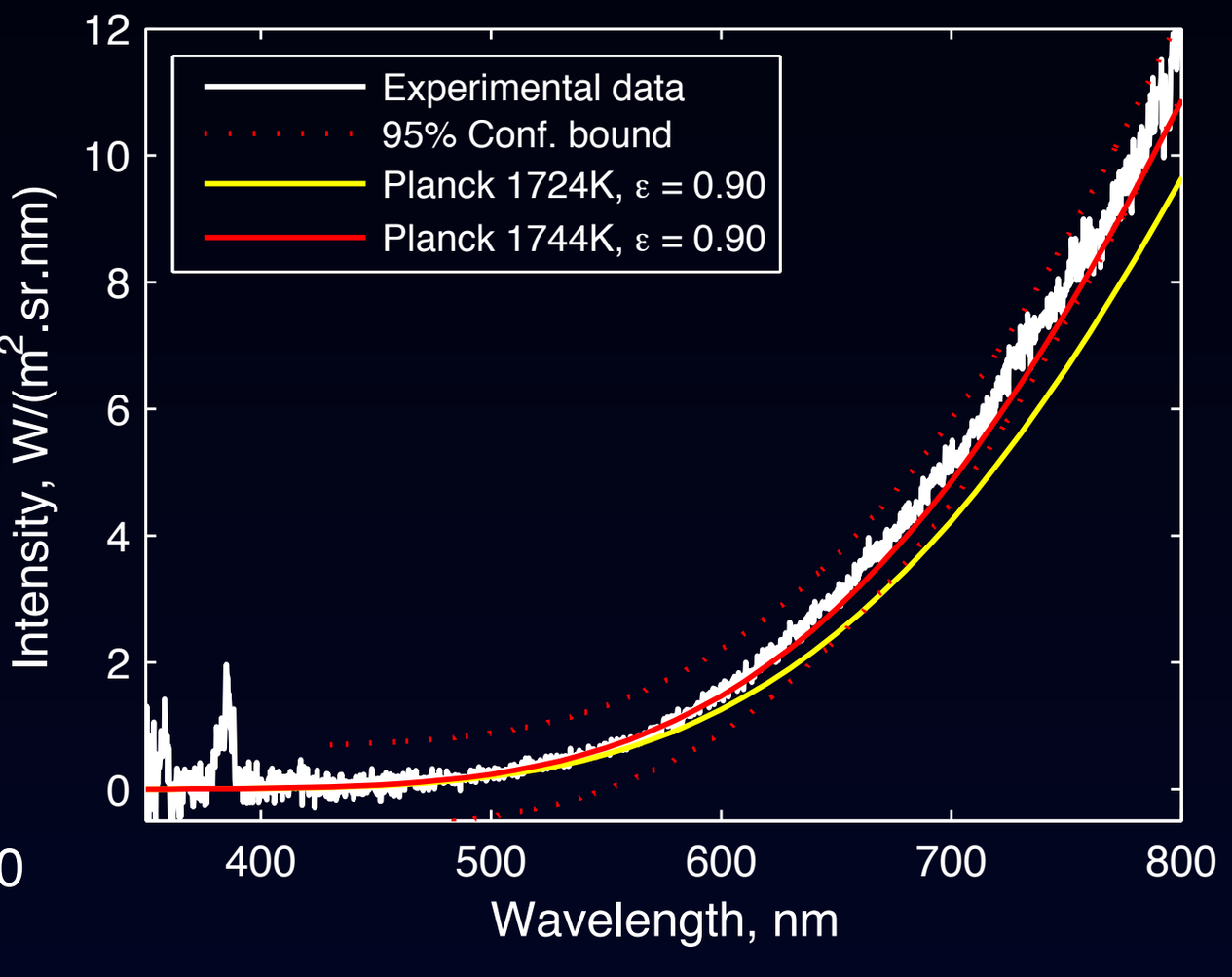
$$\varepsilon_{8-9\mu m,T} = \frac{B(IR)}{B^{bb}(Pyrometer)}$$

Planck's law (spectral radiance):

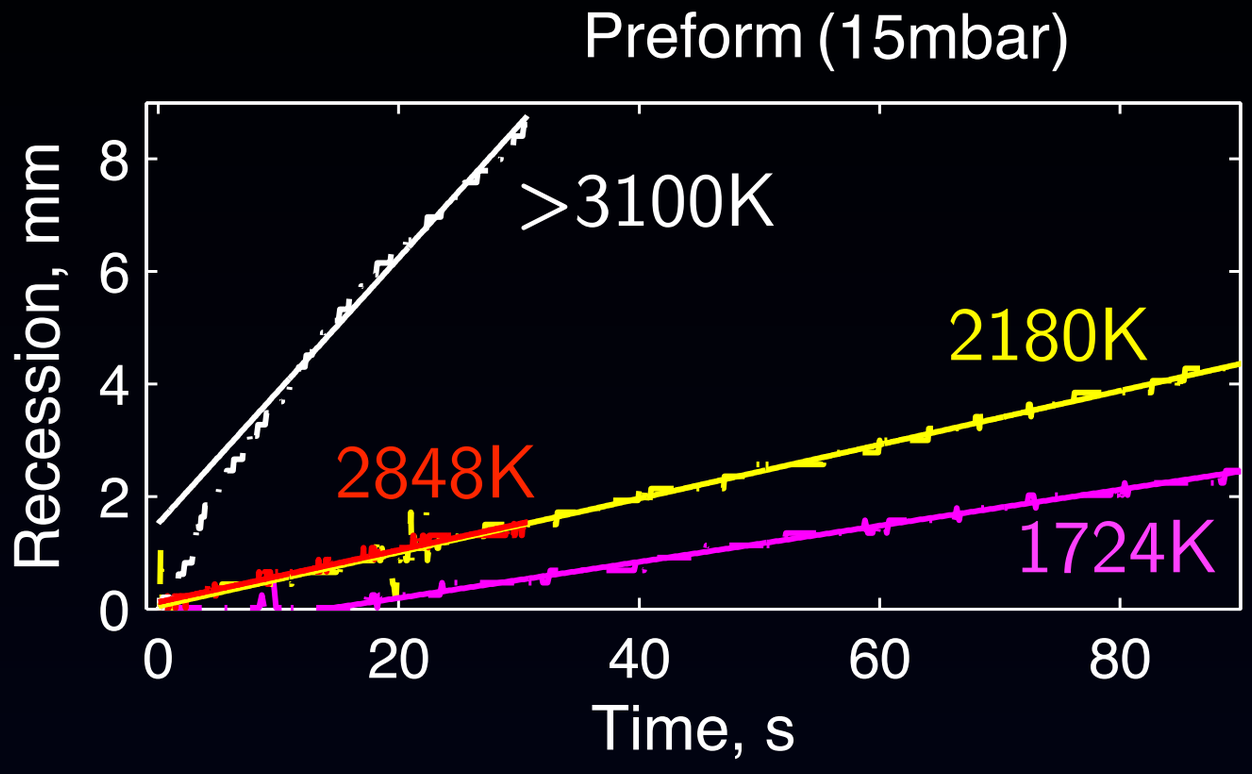
$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}}-1}[\frac{W}{m^2.sr.nm}]$$

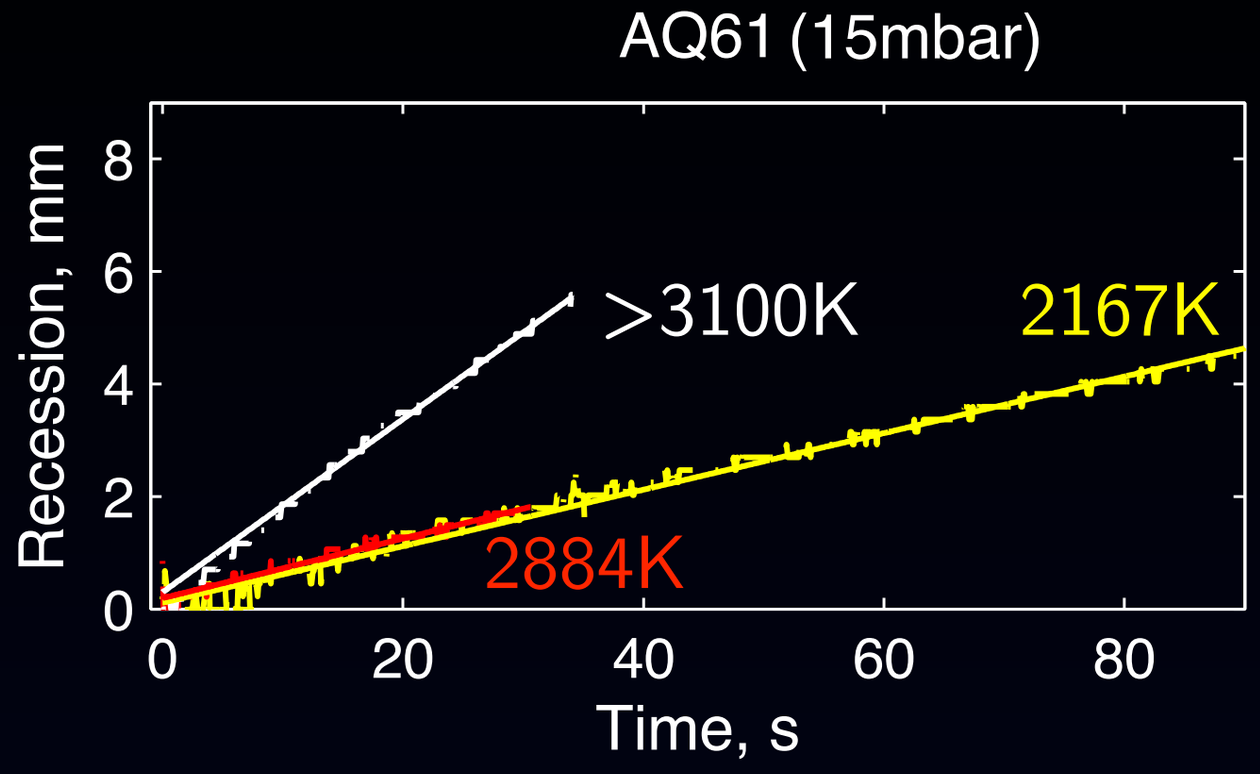


Measured: T = 1724K, p_s = 15mbar



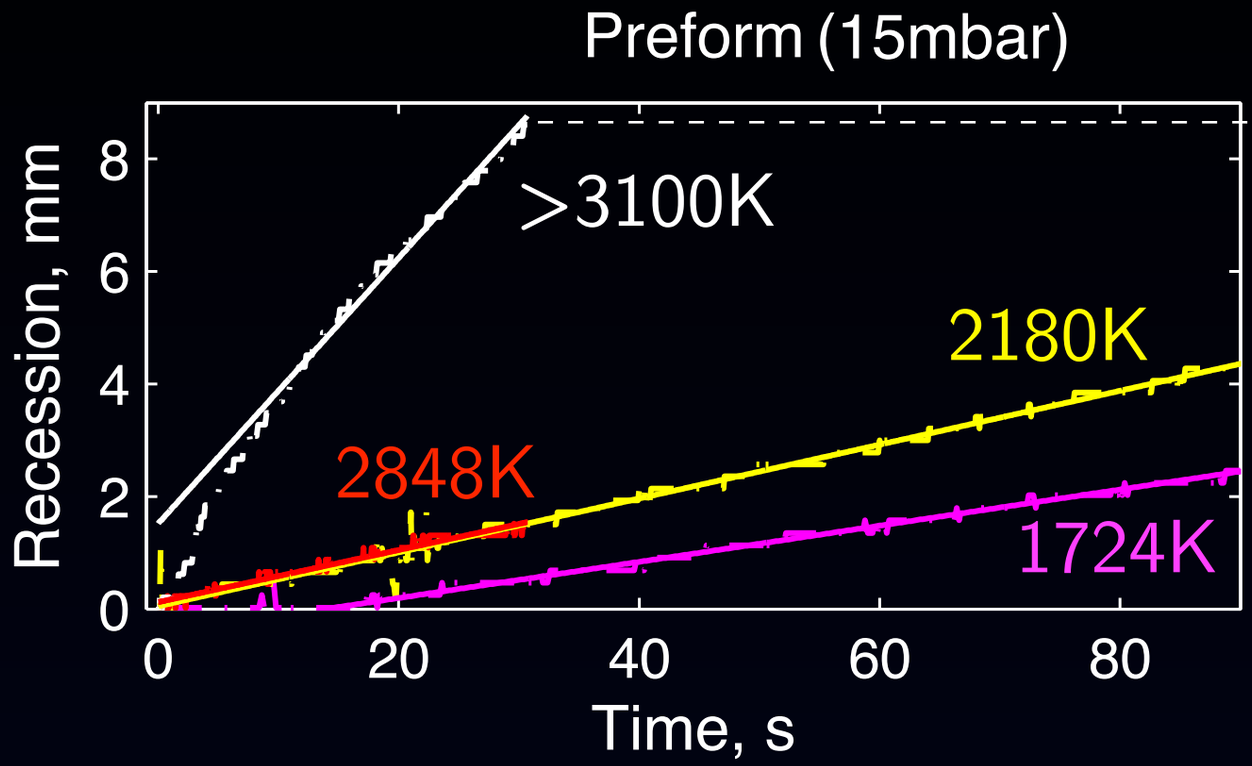
In-situ Recession Analysis (HSC)

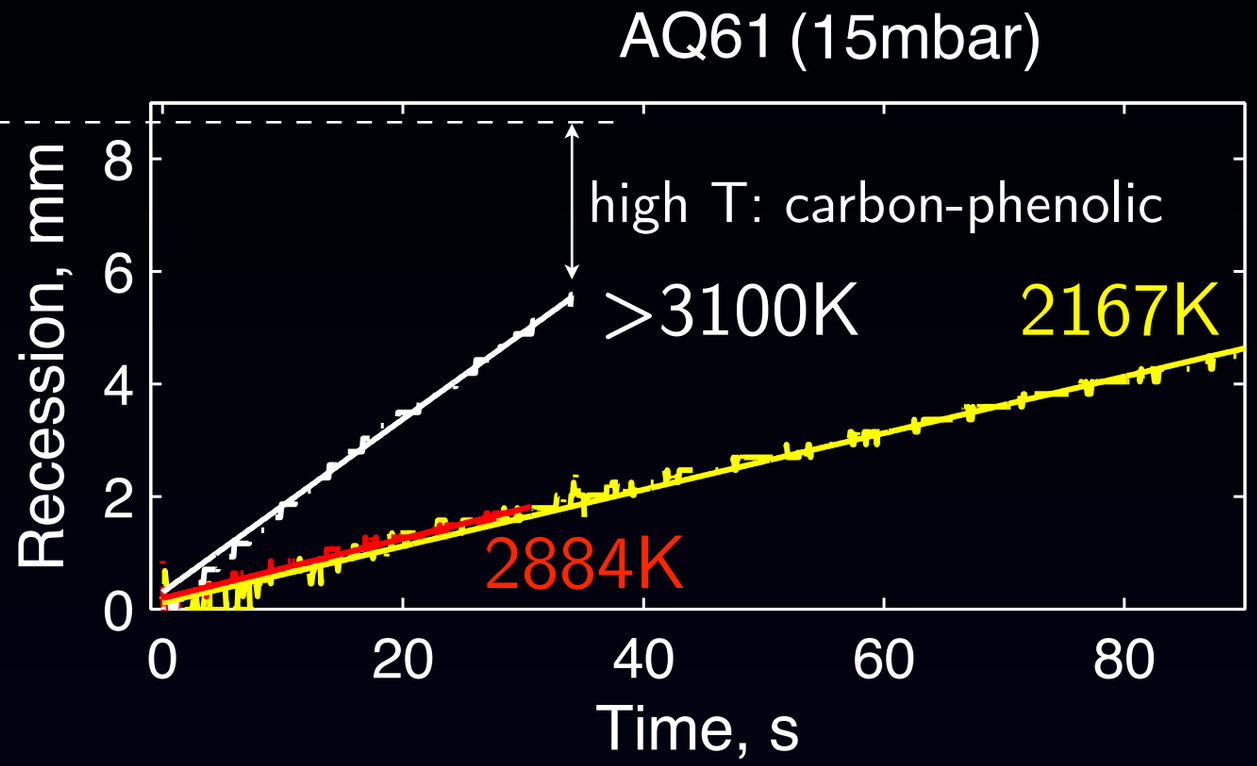




➠ diffusion limited at 15mbar between 2000K and 3000K

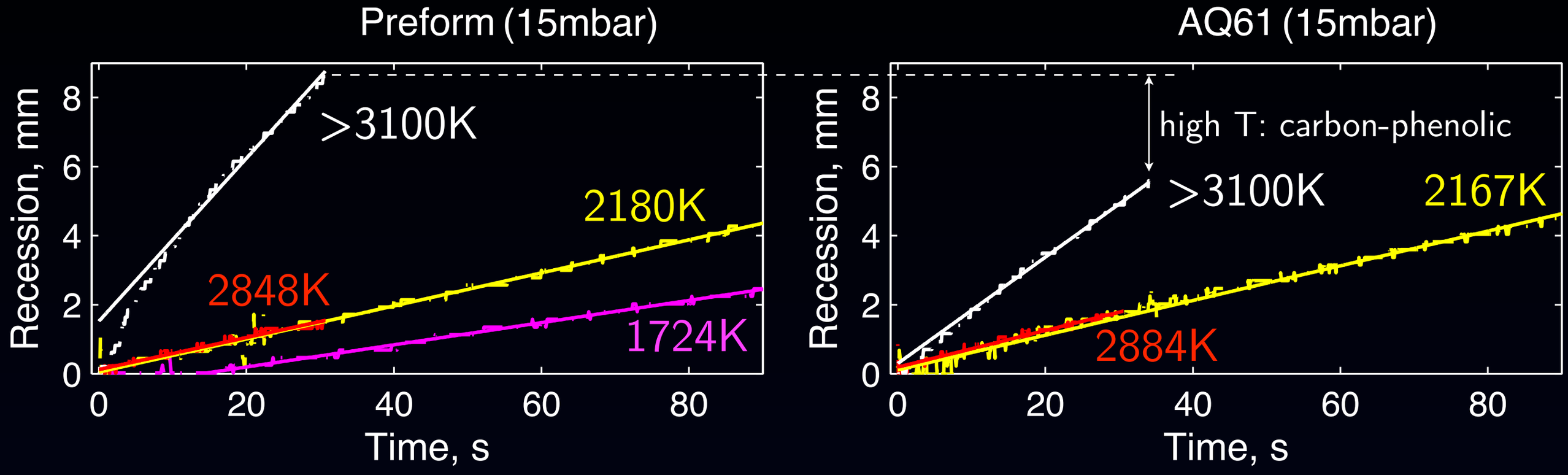
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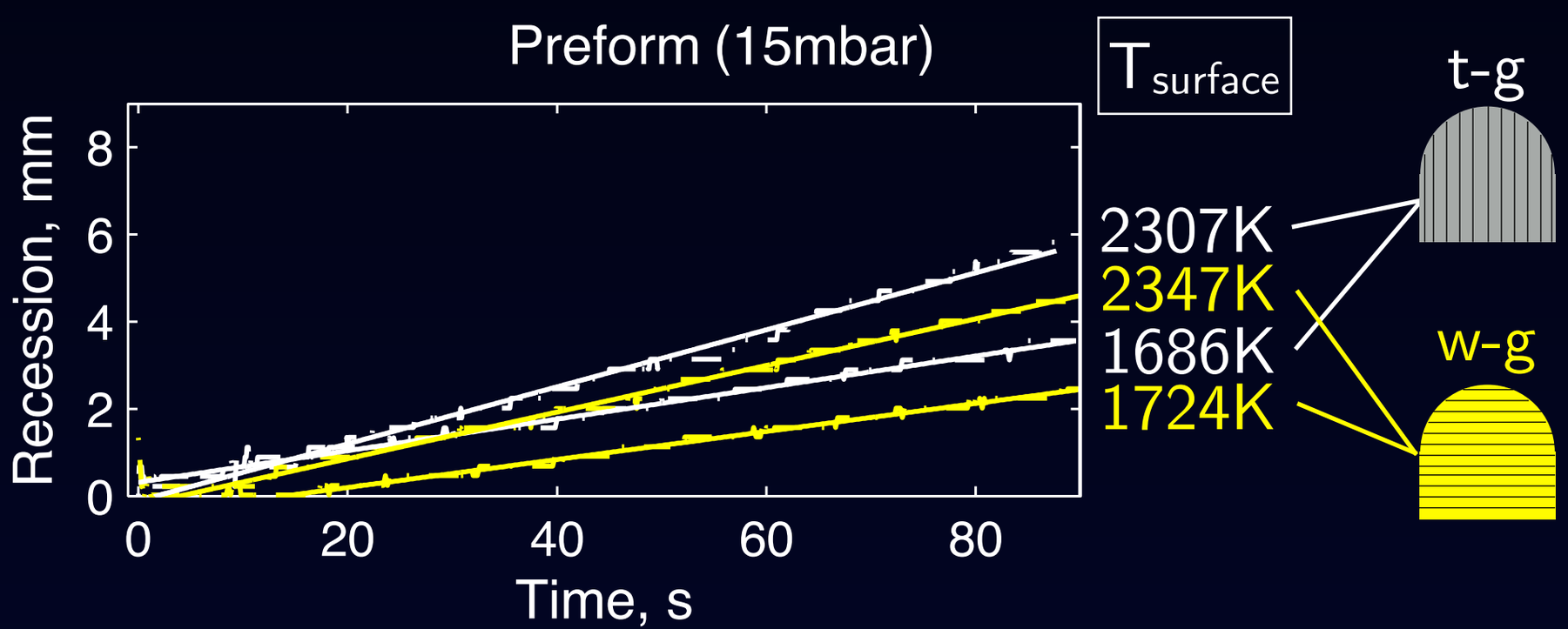


➠ diffusion limited at 15mbar between 2000K and 3000K

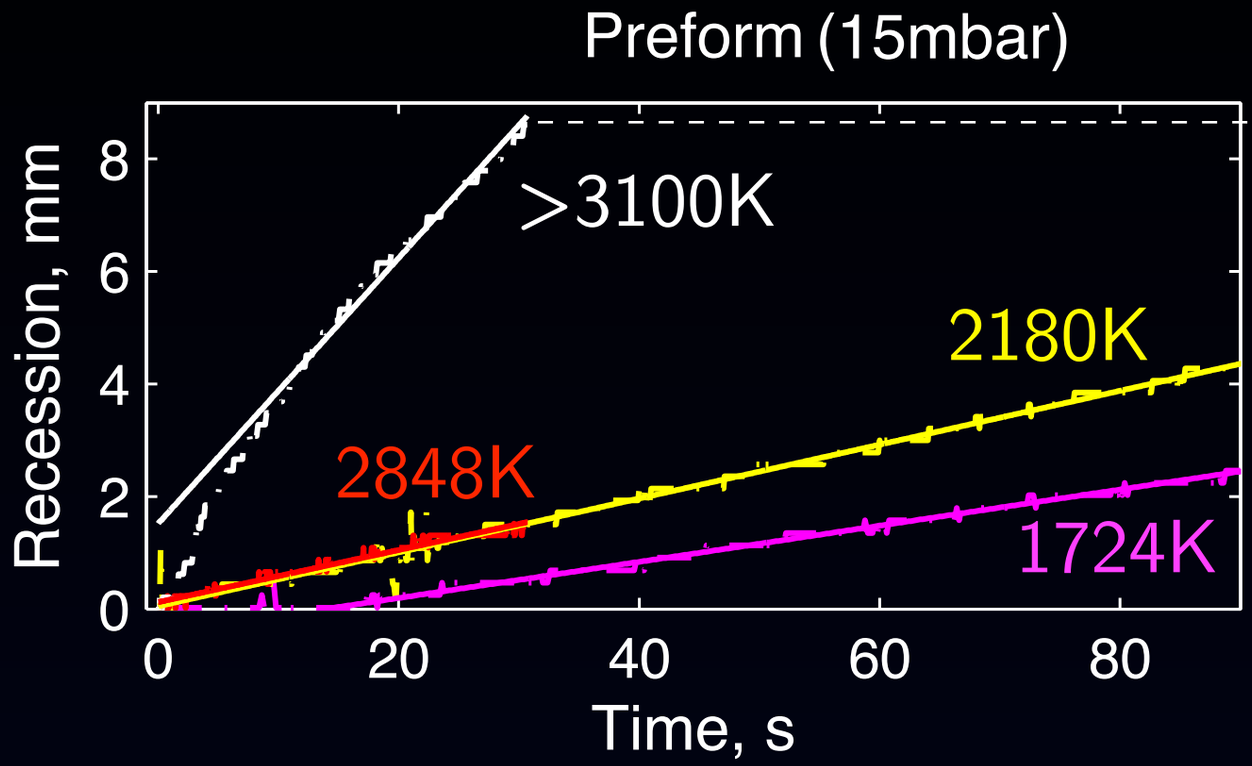
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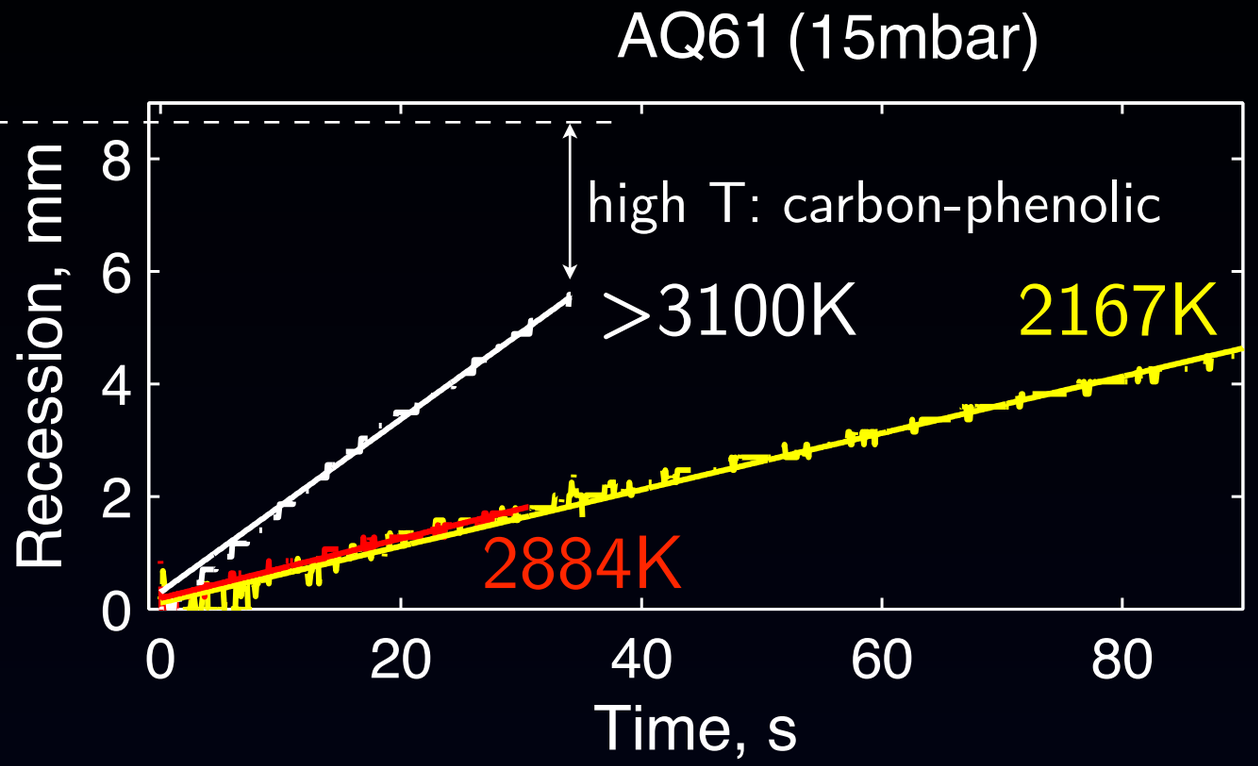


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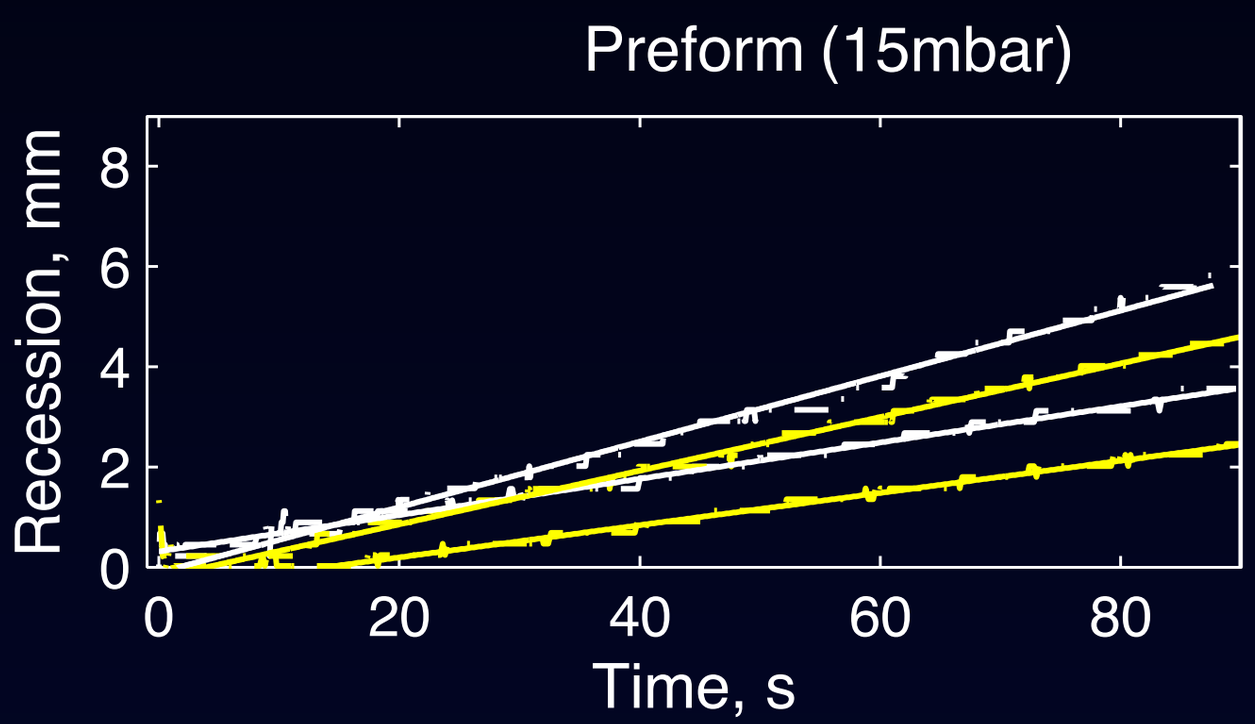


In-situ Recession Analysis (HSC)



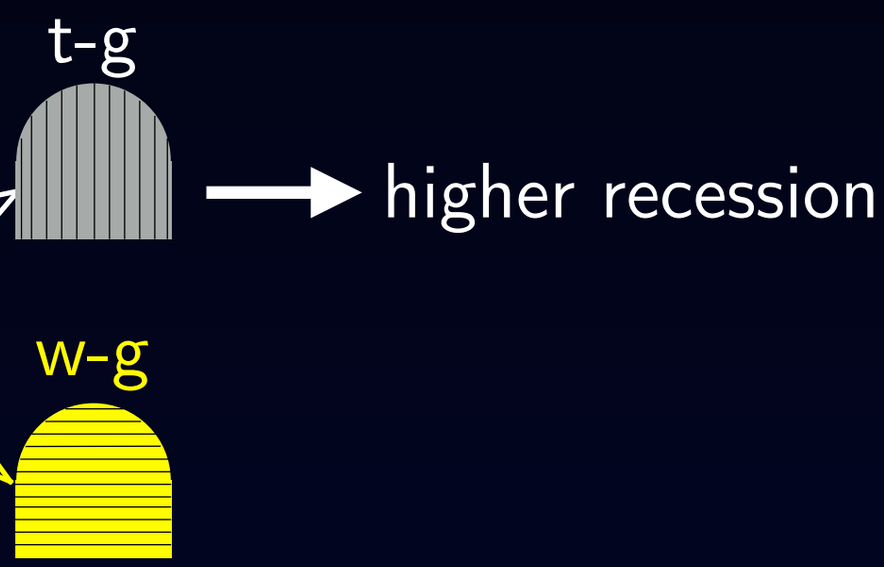


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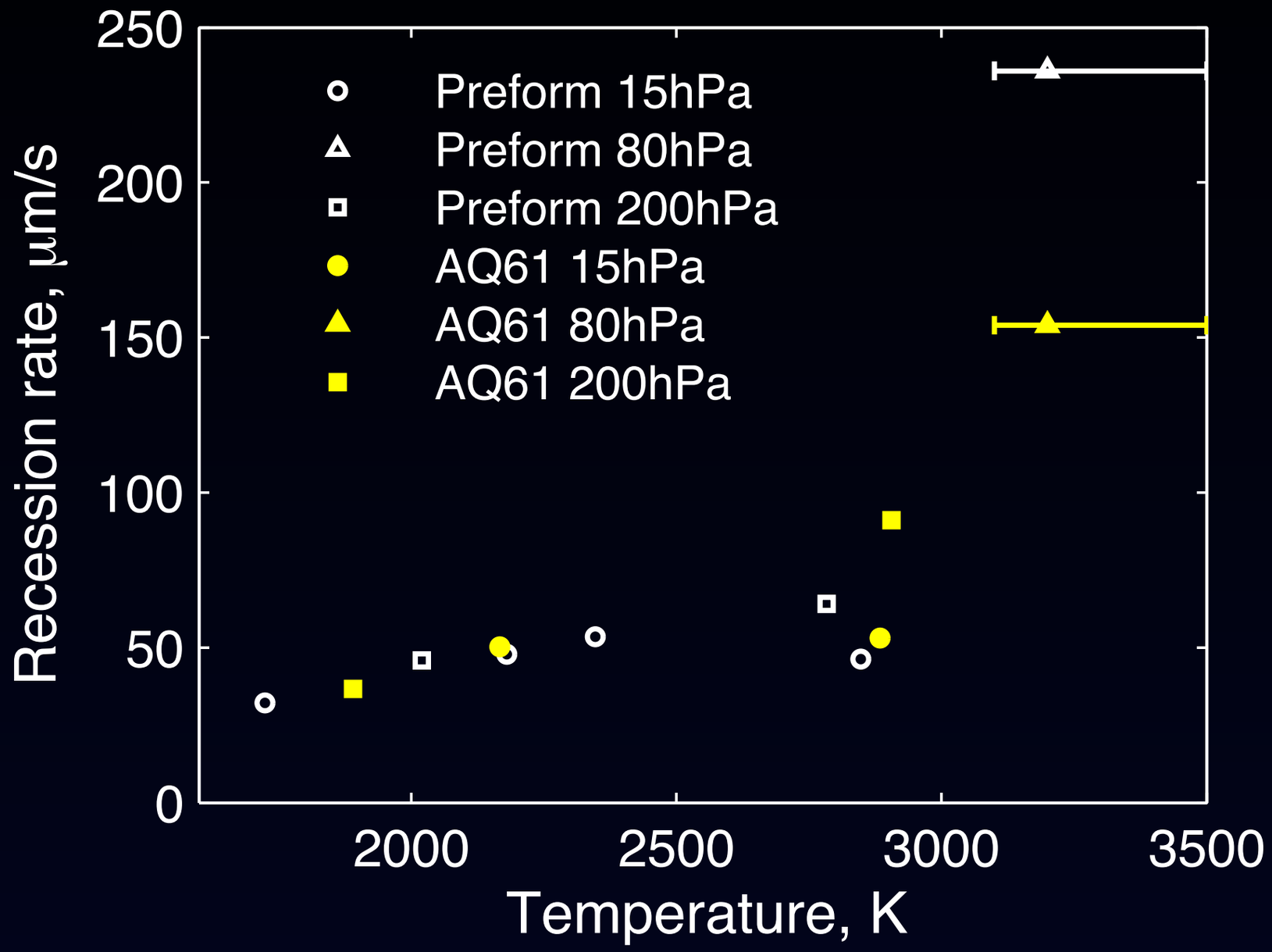


$T_{surface}$

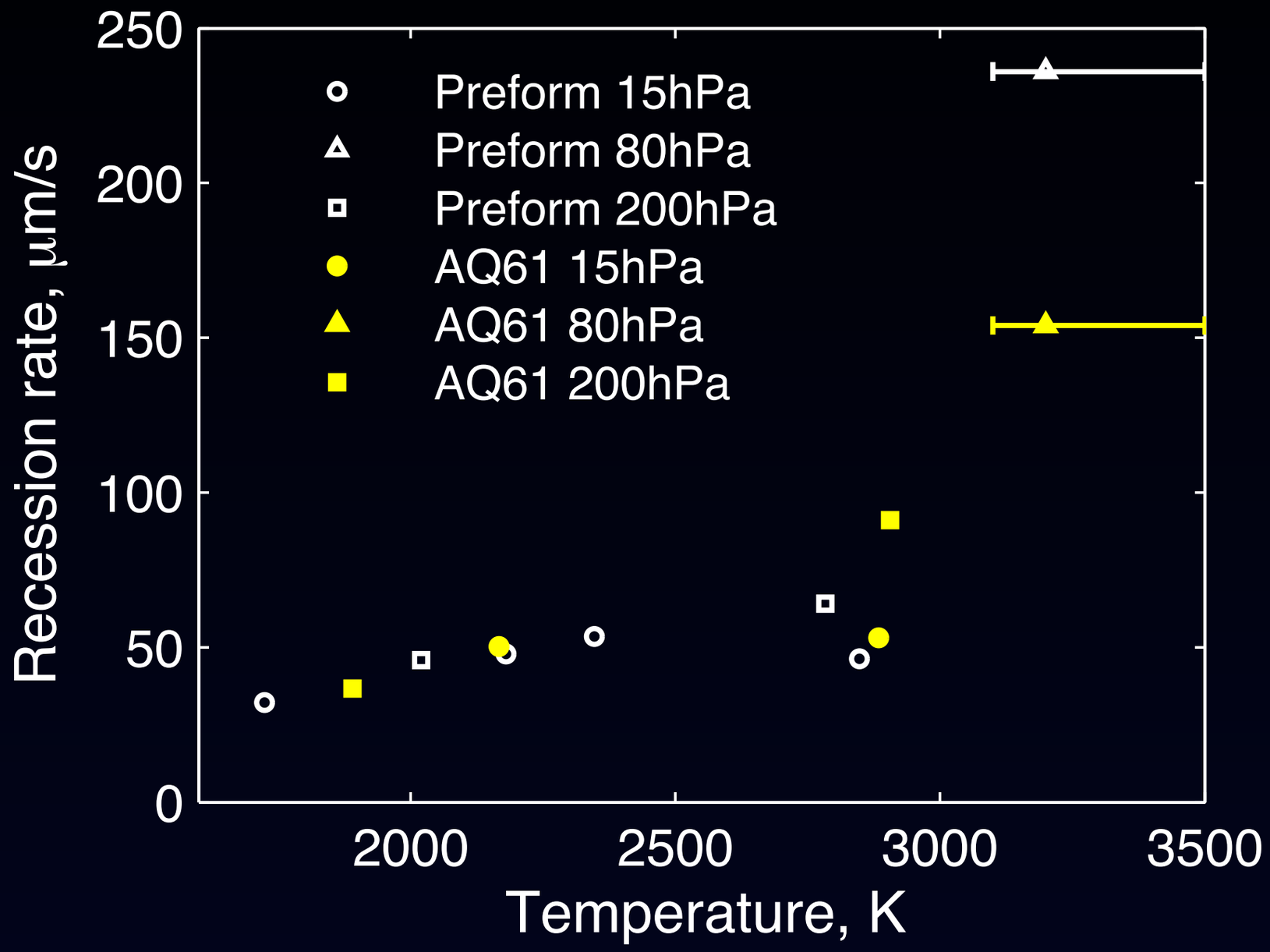
2307K
2347K
1686K
1724K



Ablation Regimes of Preform and AQ61



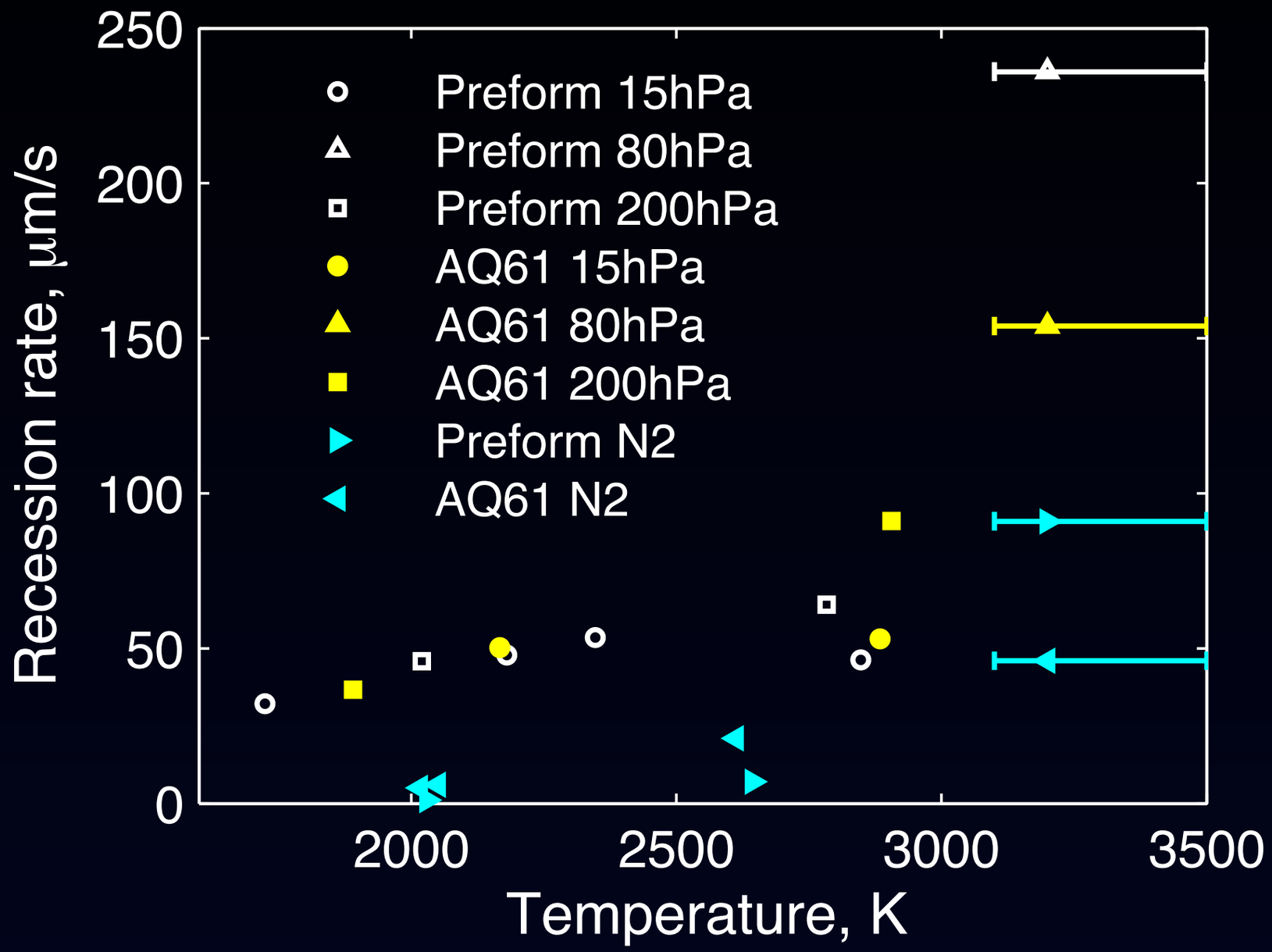
Ablation Regimes of Preform and AQ61



➠ diffusion limited ablation and sublimation regime

➠ recession not much influenced by pressure! (*AIAA 2012-2876*)

Ablation Regimes of Preform and AQ61



➠ diffusion limited ablation and sublimation regime

➠ recession not much influenced by pressure! (*AIAA 2012-2876*)

➠ strong recession in N_2 for T>3000K ➠ sublimation

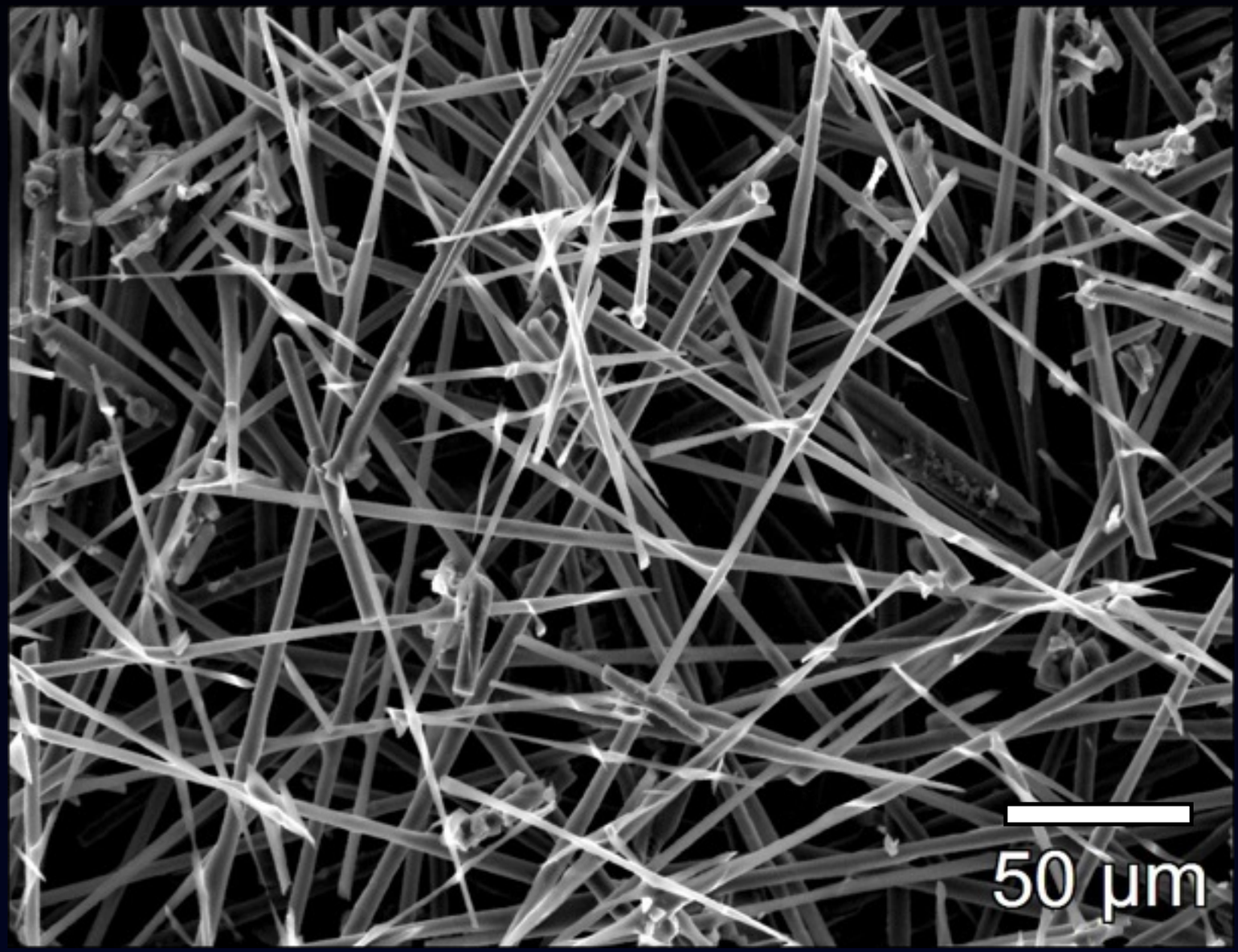
comparison num. model: talk A. Turchi

Post-Oxidation Micrographs

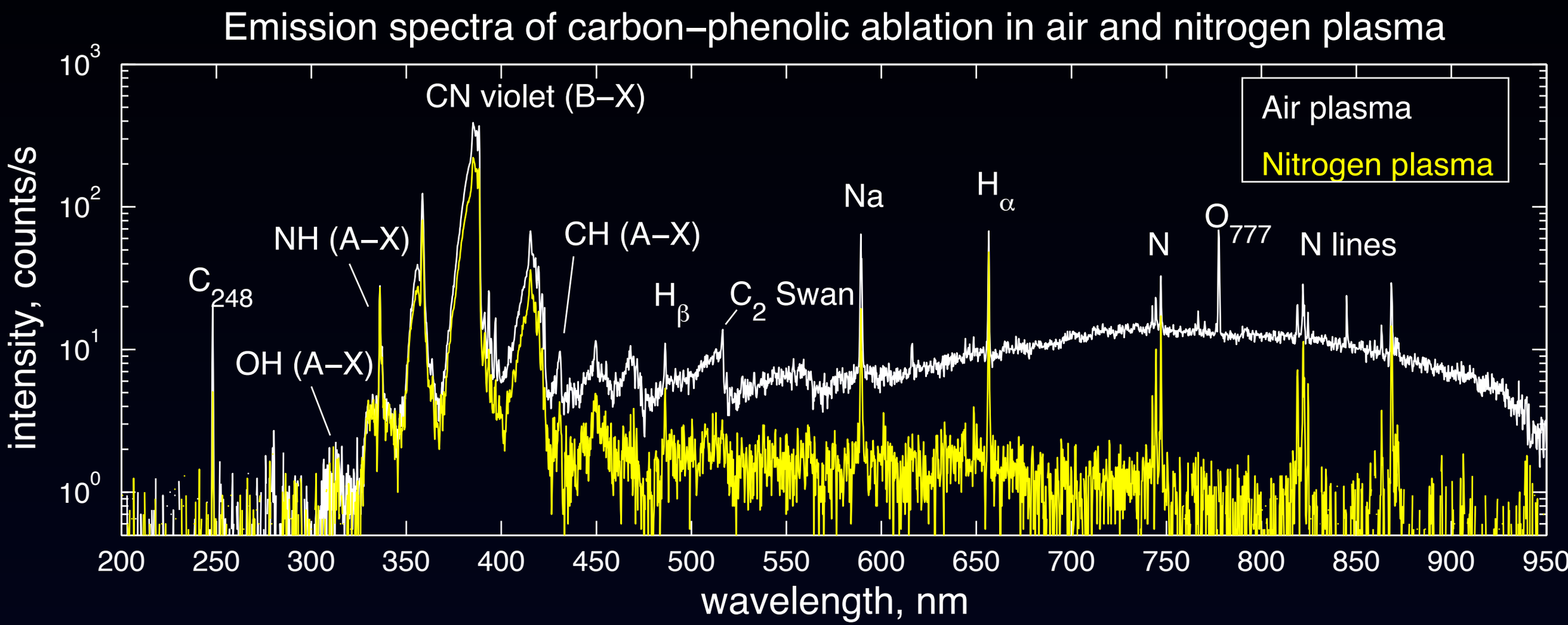
Carbon preform oxidation



AQ61 oxidation



Ablation / Pyrolysis Product Contaminated BL

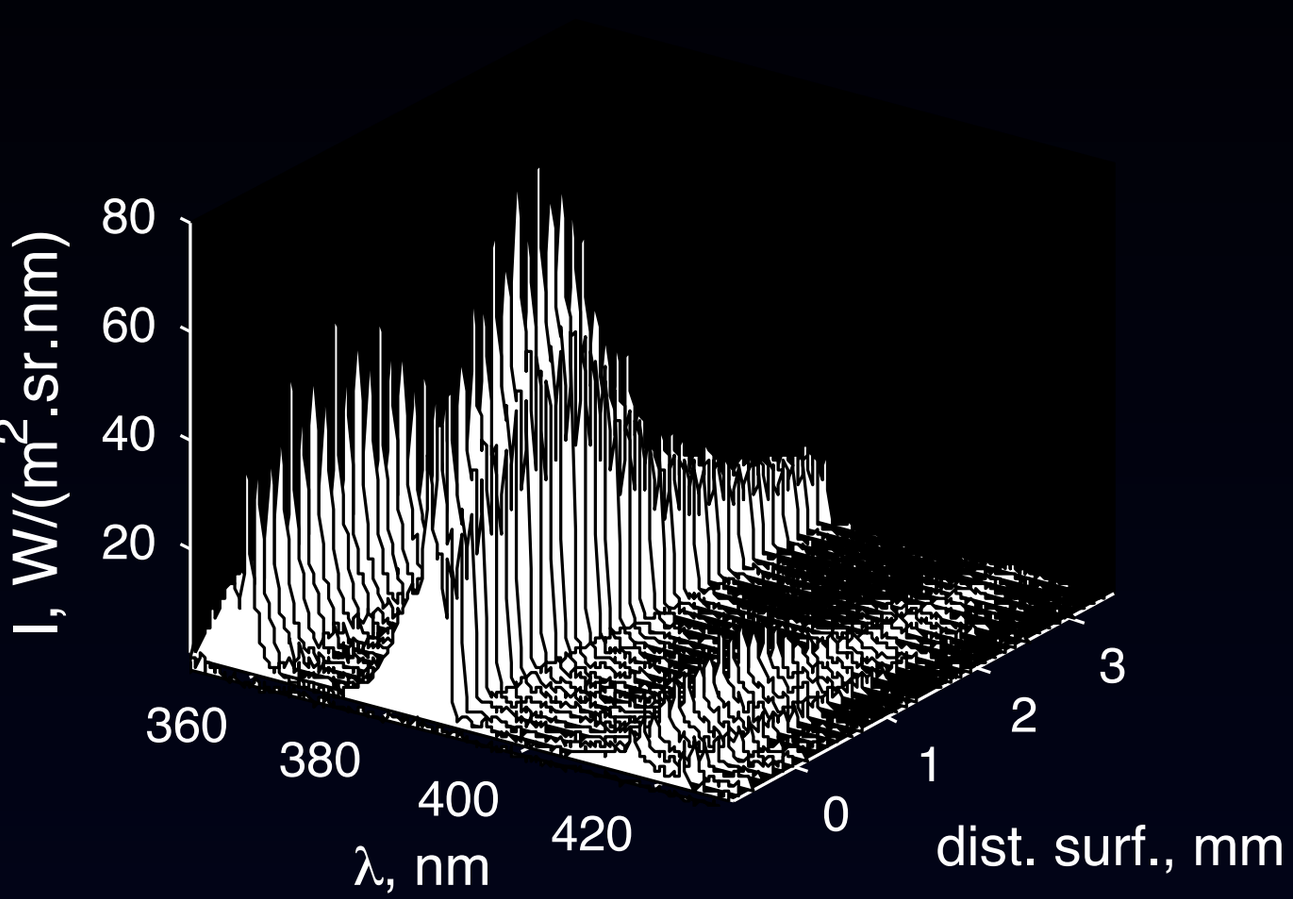


Detection of contamination products originating from phenol

1. pyrolysis ➟ C_2, CH, H, NH, OH
2. ablation ➟ C, CN

Boundary Layer Radiation Profiles

Experimental: Spatial CN violet emission (*AIAA 2013-2770*)

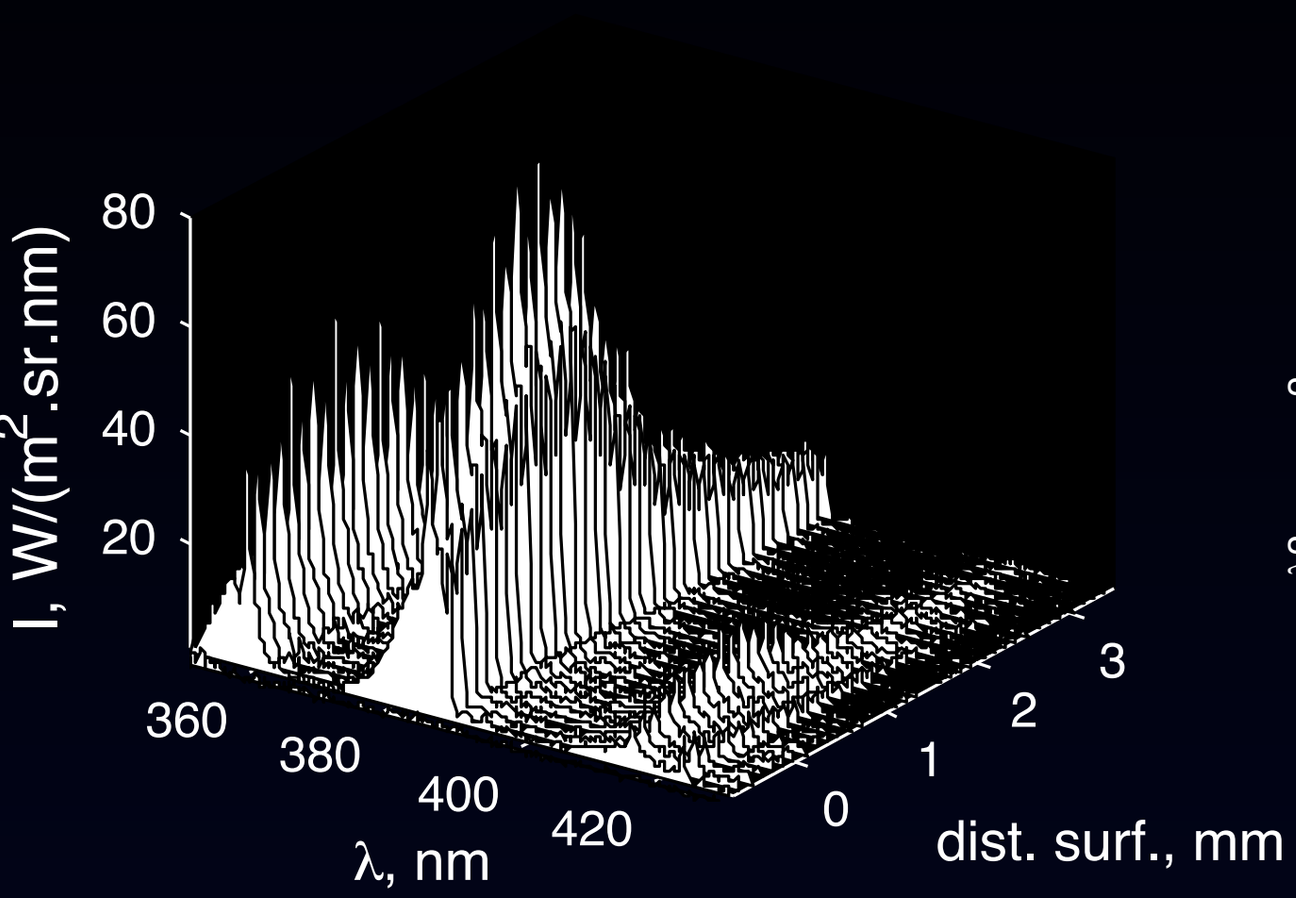


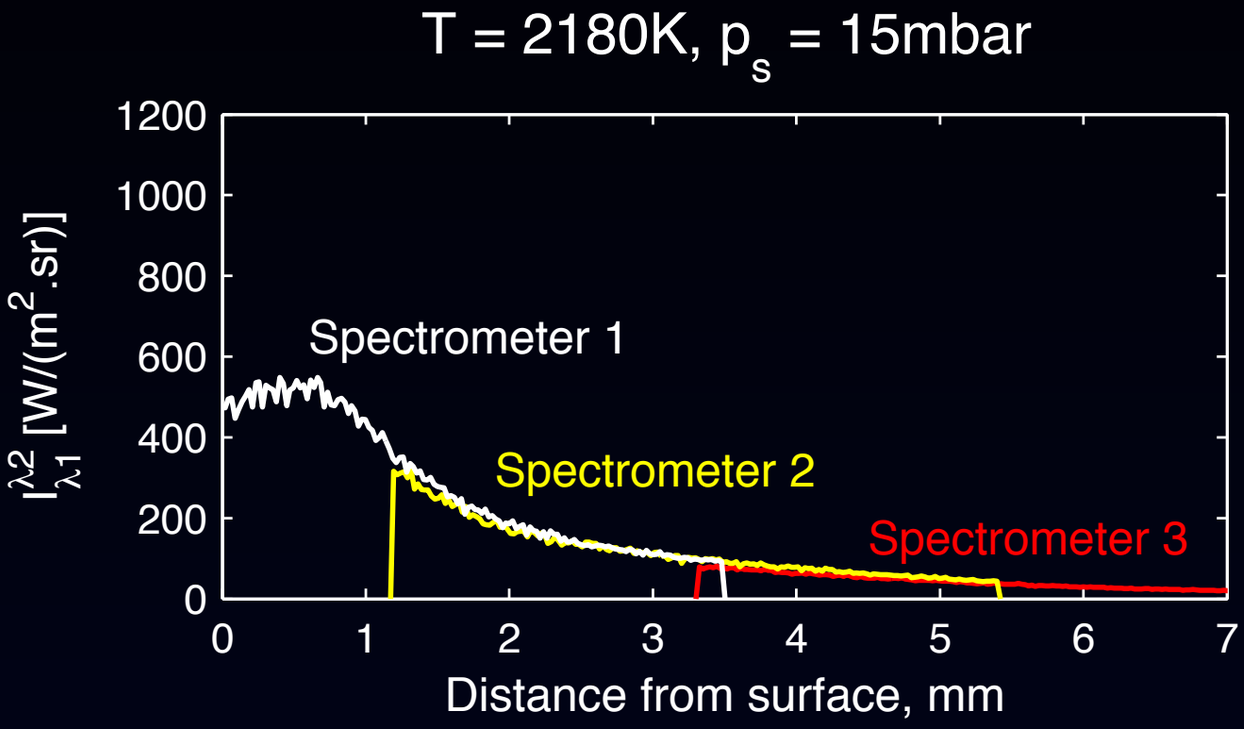
CN Production:

- gas phase: $CO + N \rightleftharpoons CN + O$
- wall: $C_w + N_w \longrightarrow CN$

Boundary Layer Radiation Profiles

Experimental: Spatial CN violet emission (*AIAA 2013-2770*)



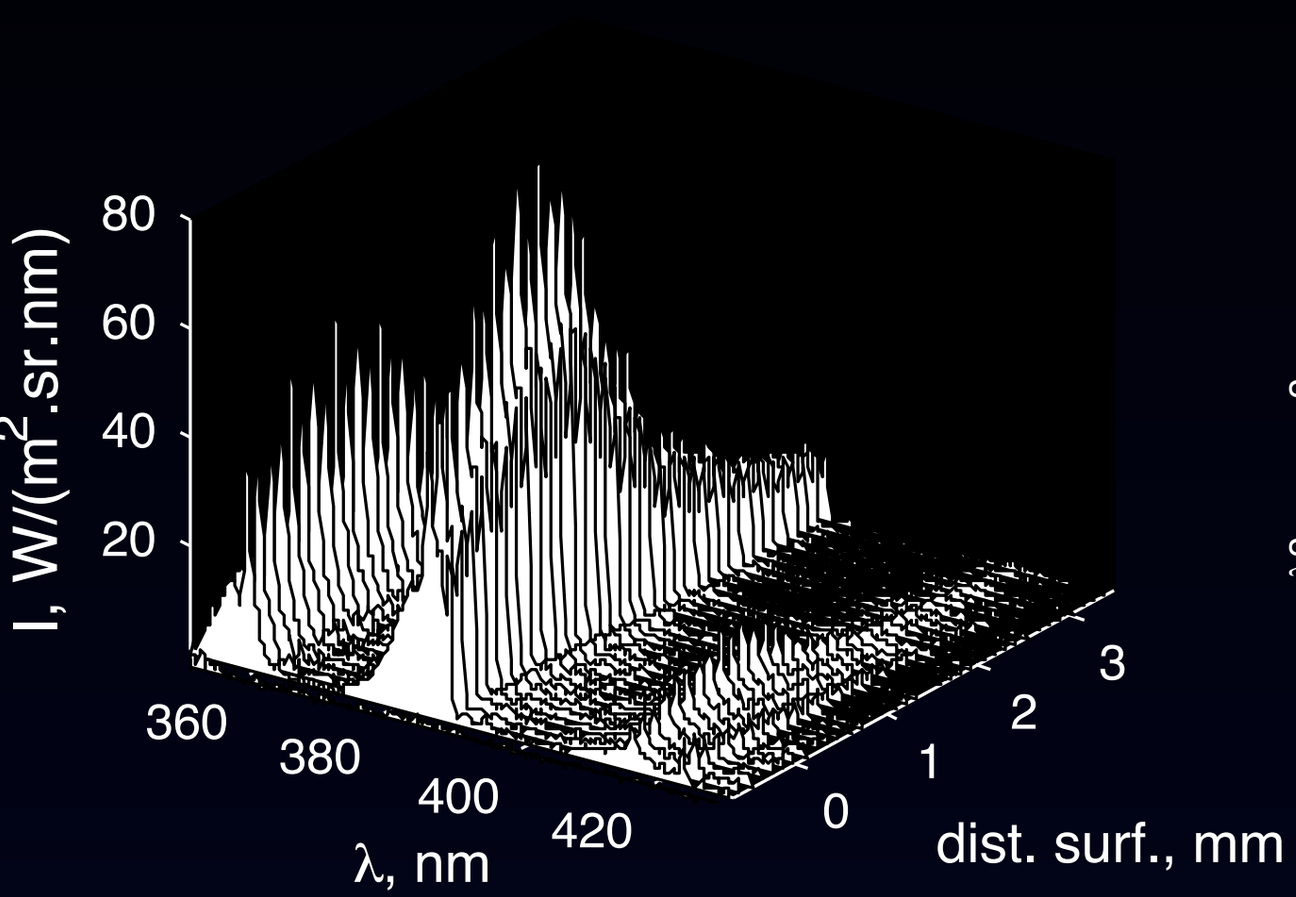


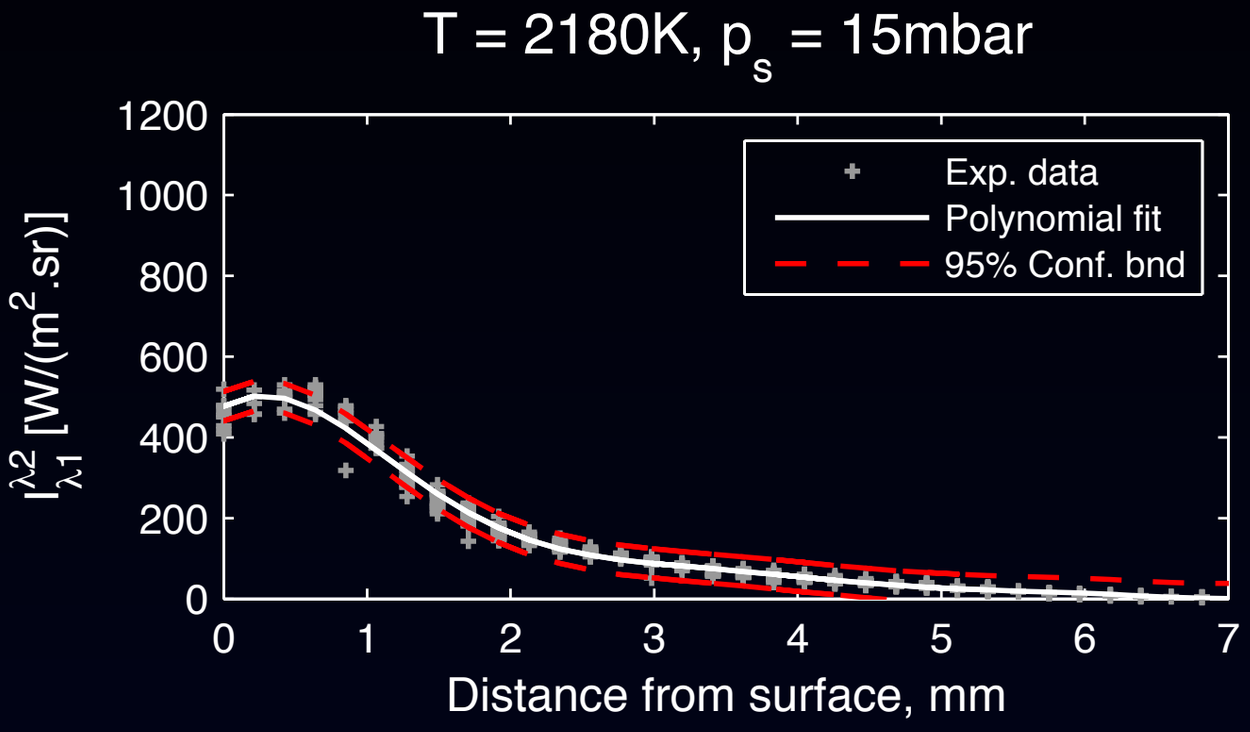
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Boundary Layer Radiation Profiles

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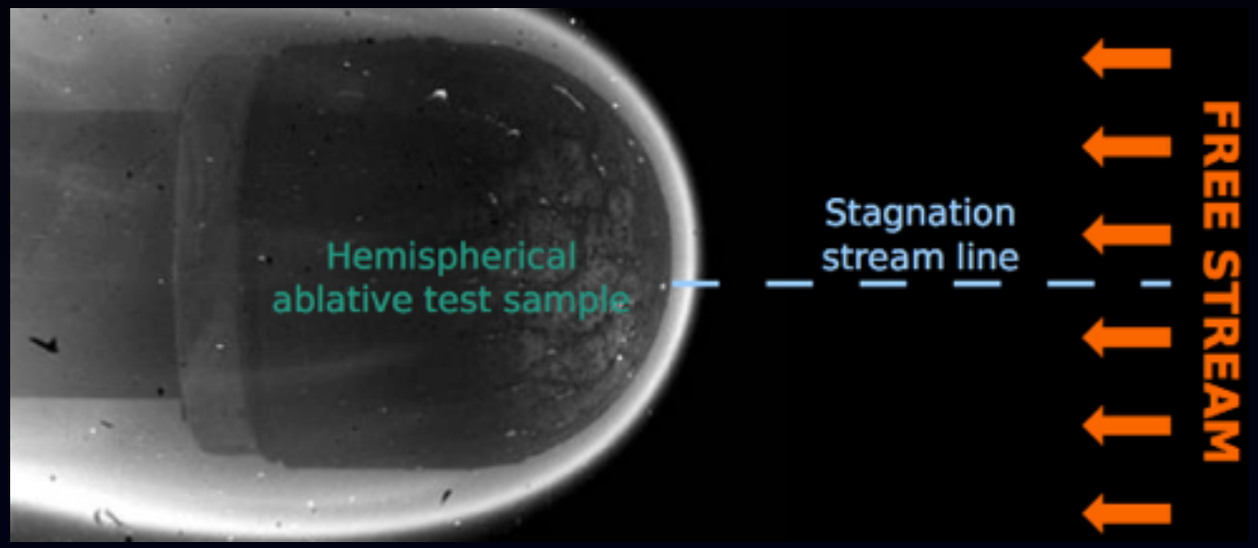
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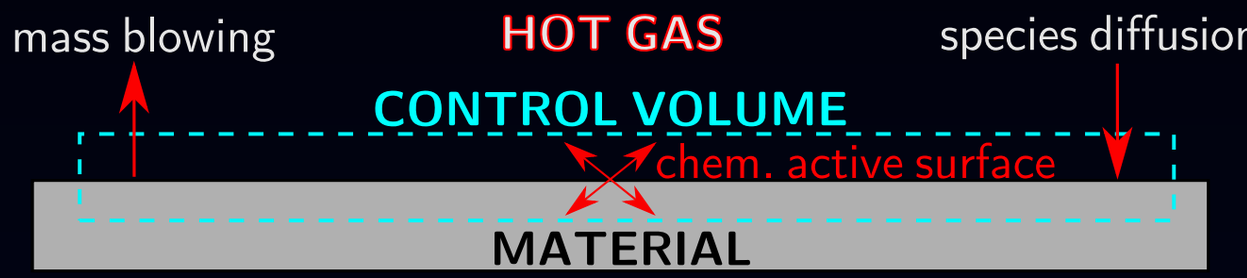
Approach for ablation modelling (Kendall et al.[1])

VKI: 1D Stagnation line description w/ surface ablation

(A. Turchi AIAA 2014-2125)



Surface Mass Balance (SMB)



[1] Kendall et al., NASA CR 1060 (1968)

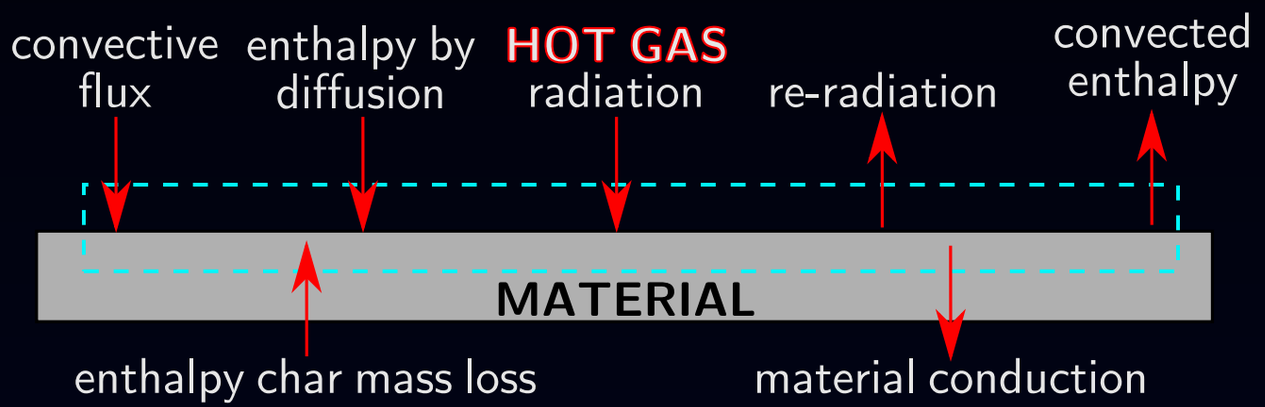
[2] A. Munafò, PhD Thesis, Ecole Central Paris, 2014

Approach for ablation modelling (Kendall et al.[1])

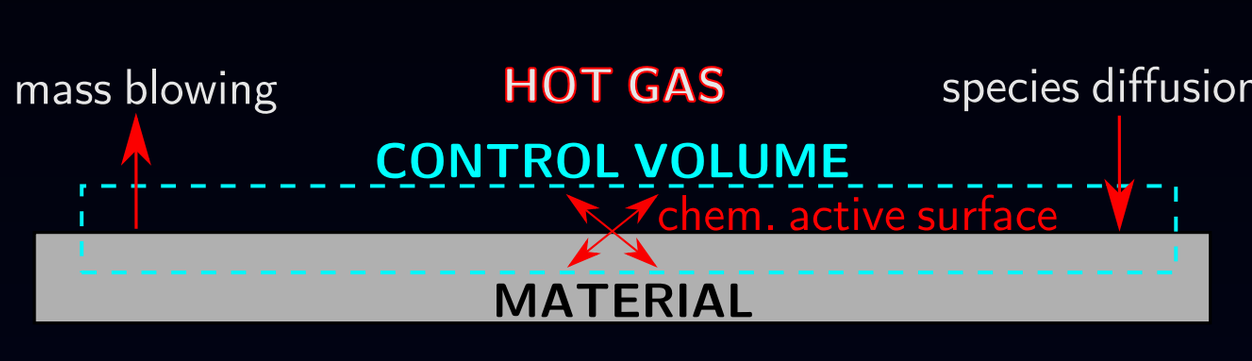
VKI: 1D Stagnation line description w/ surface ablation

(A. Turchi AIAA 2014-2125)

Surface Energy Balance (SEB)



Surface Mass Balance (SMB)



[1] Kendall et al., NASA CR 1060 (1968)

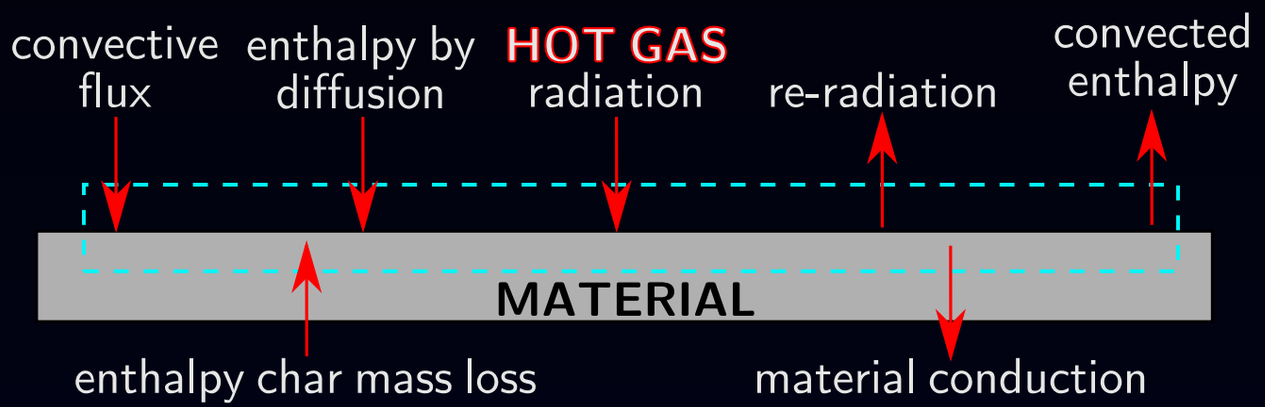
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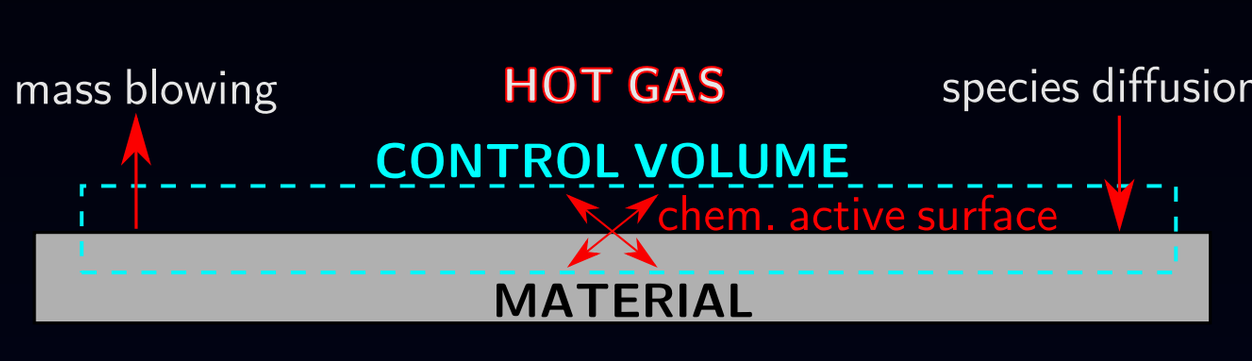
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Surface Energy Balance (SEB)



Surface Mass Balance (SMB)



[1] Kendall et al., NASA CR 1060 (1968)

[2] A. Munafò, PhD Thesis, Ecole Central Paris, 2014

Boundary condition from experiments & plasma free-stream

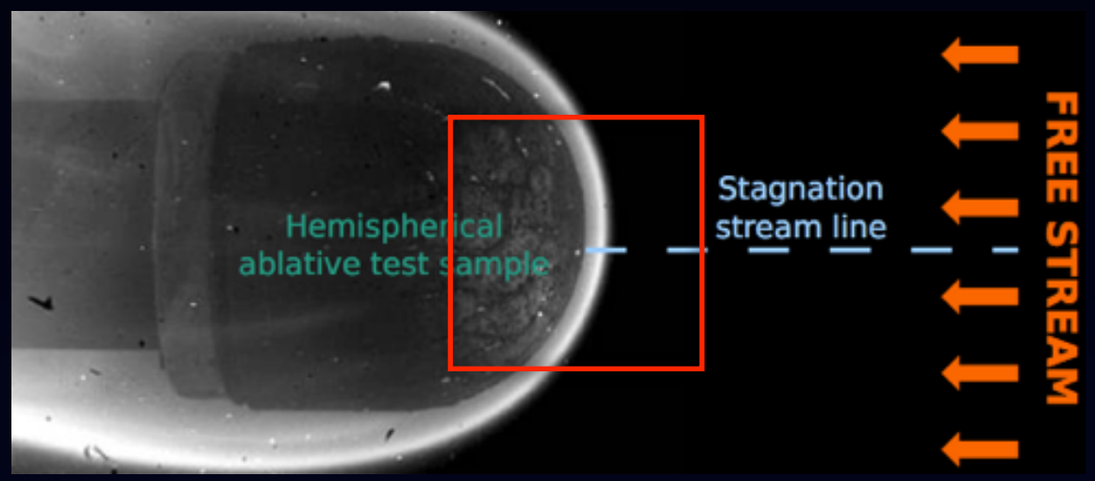
Experimental data for validation

GOAL: Coupling 1-D SL-code & material code

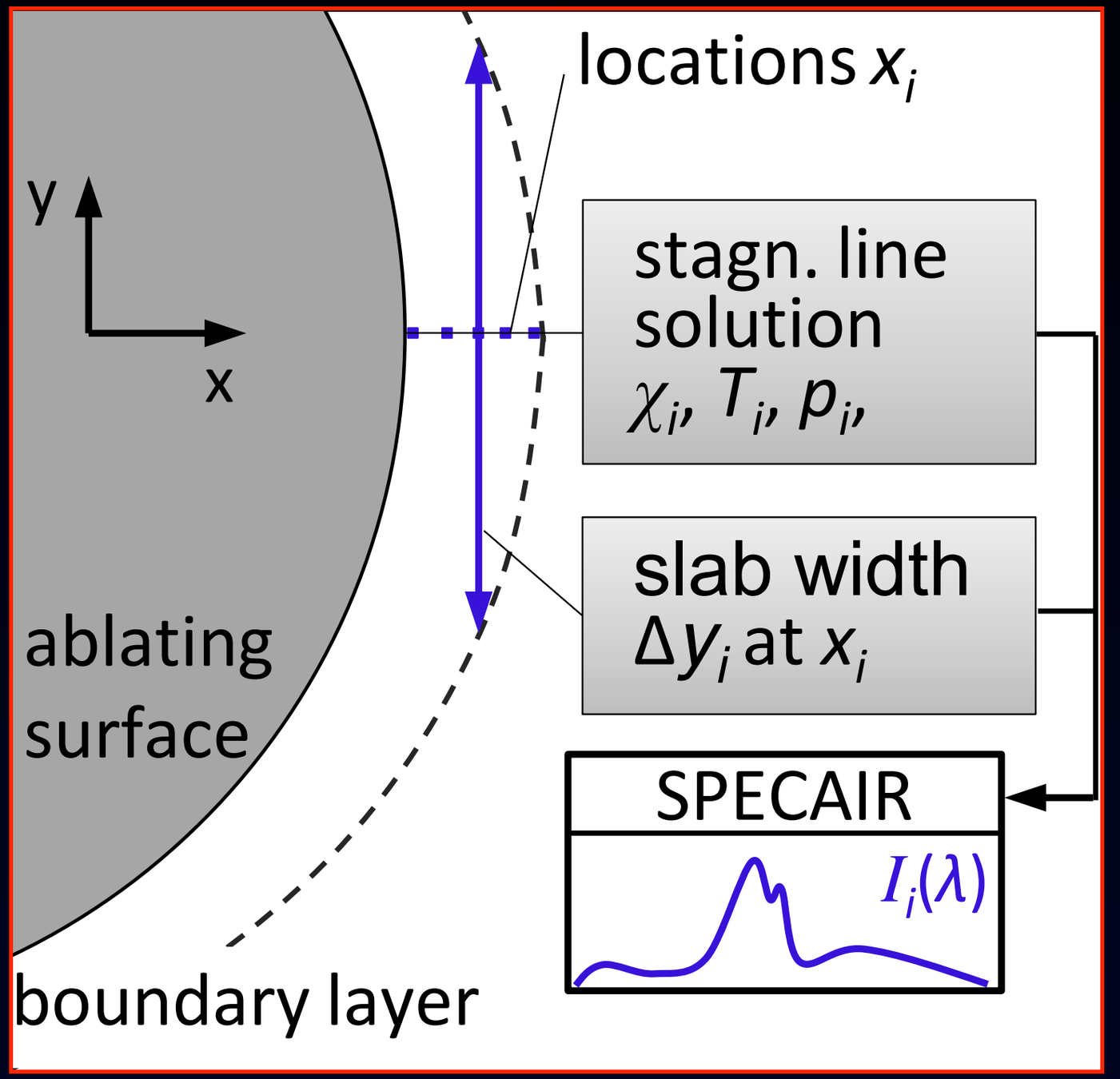
(PhD Candidate P. Schrooyen)

Boundary Layer Radiation Profiles

Numerical: Simplified approach using Specair slab

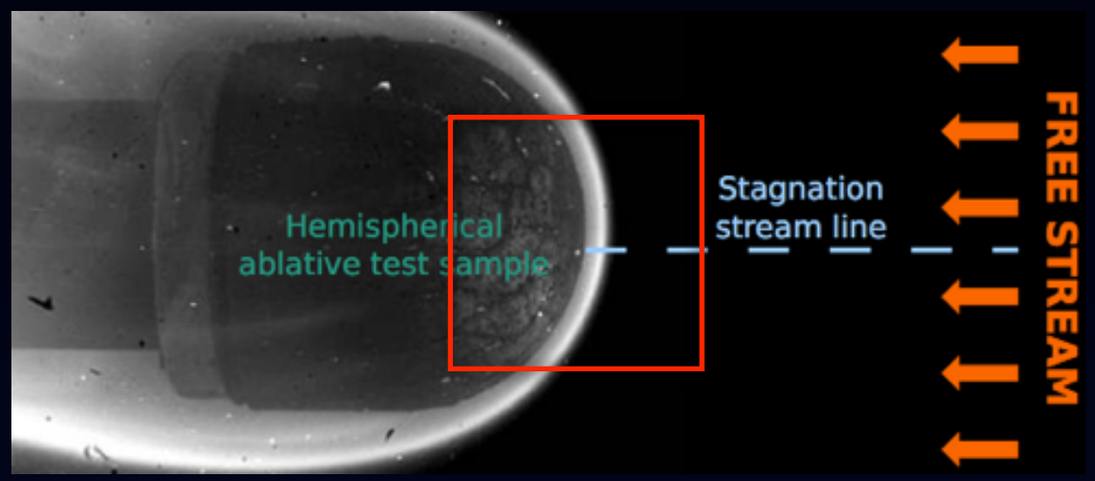


Simulate line-of-sight measurement

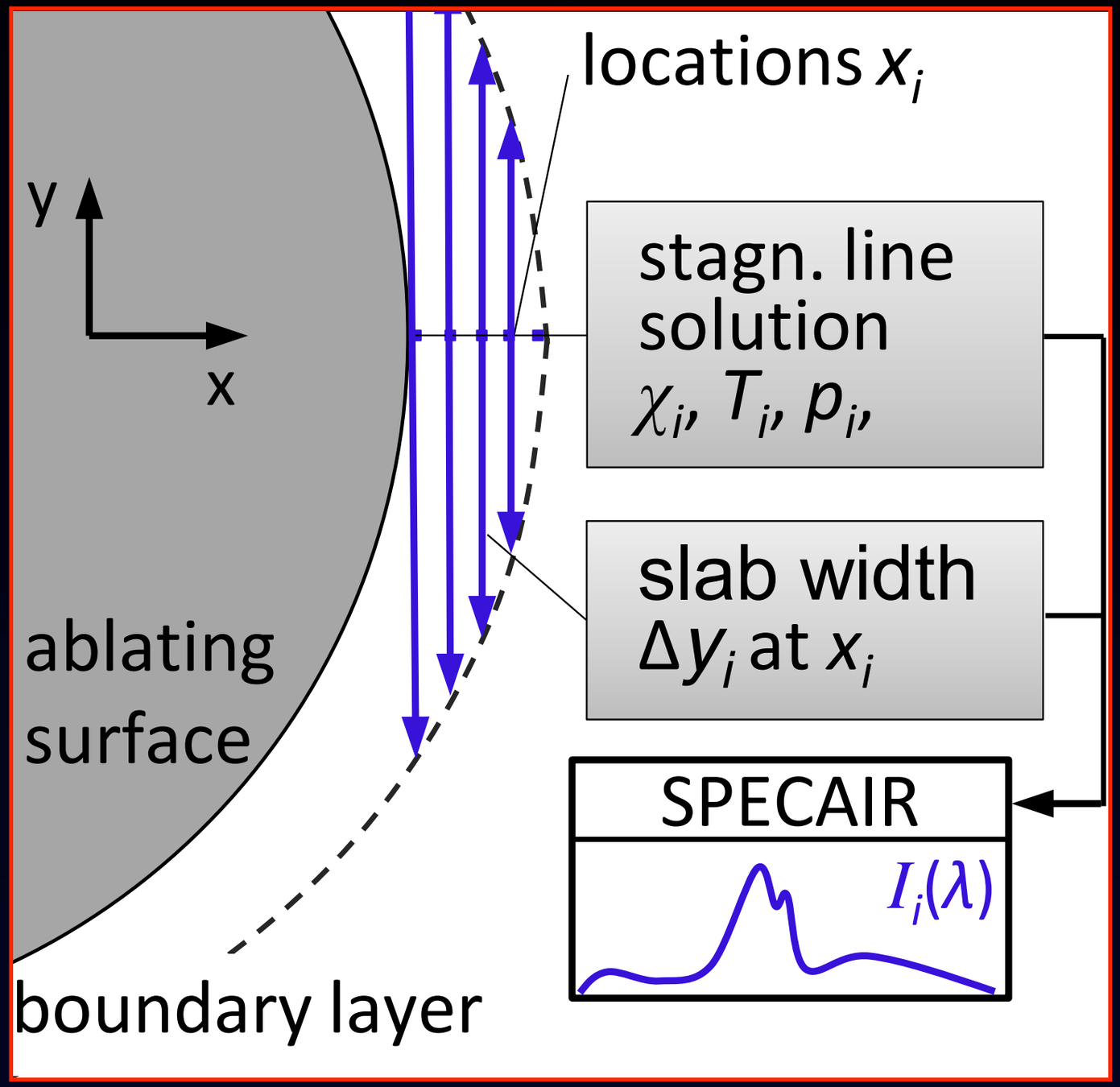


Boundary Layer Radiation Profiles

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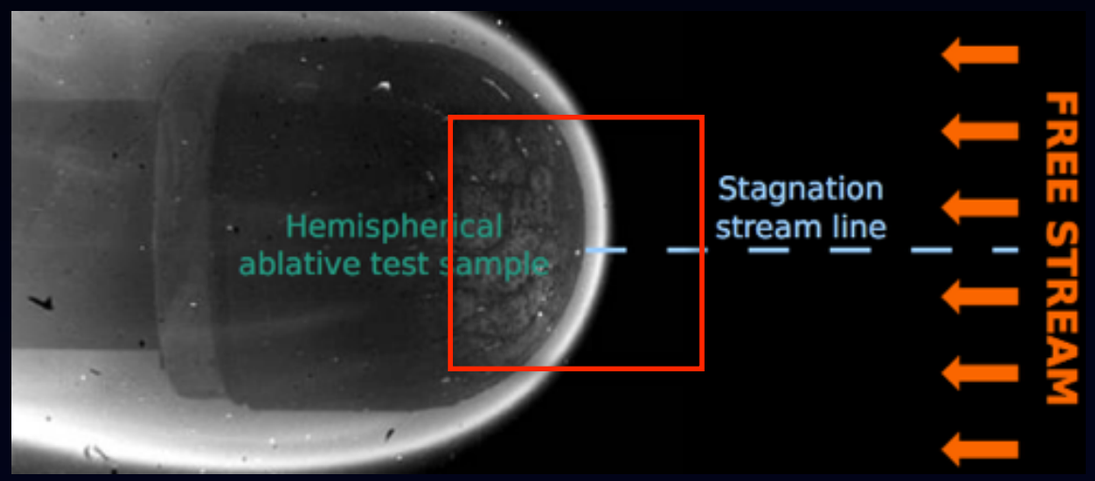


Simulate line-of-sight measurement

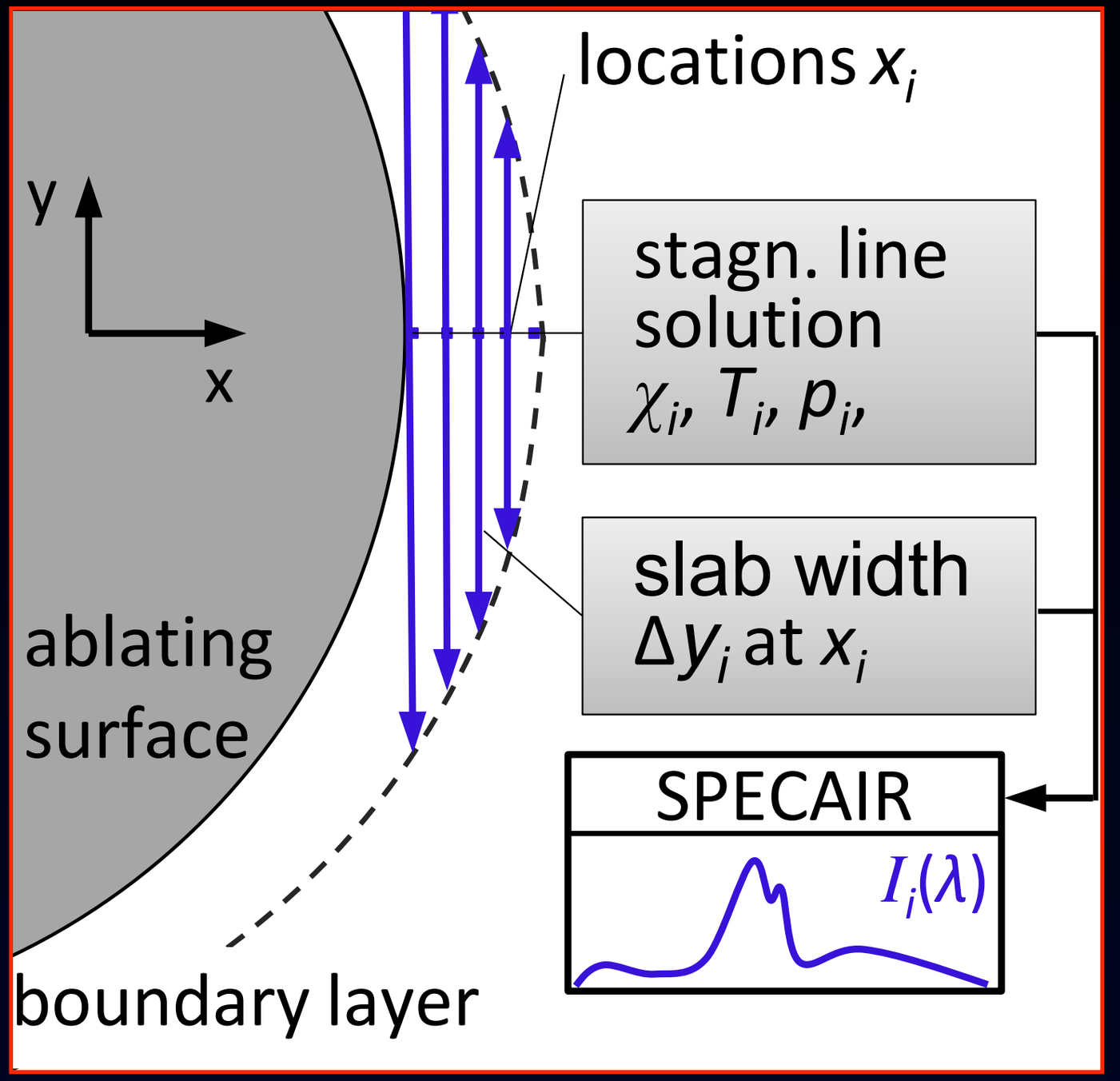


Boundary Layer Radiation Profiles

Numerical: Simplified approach using Specair slab



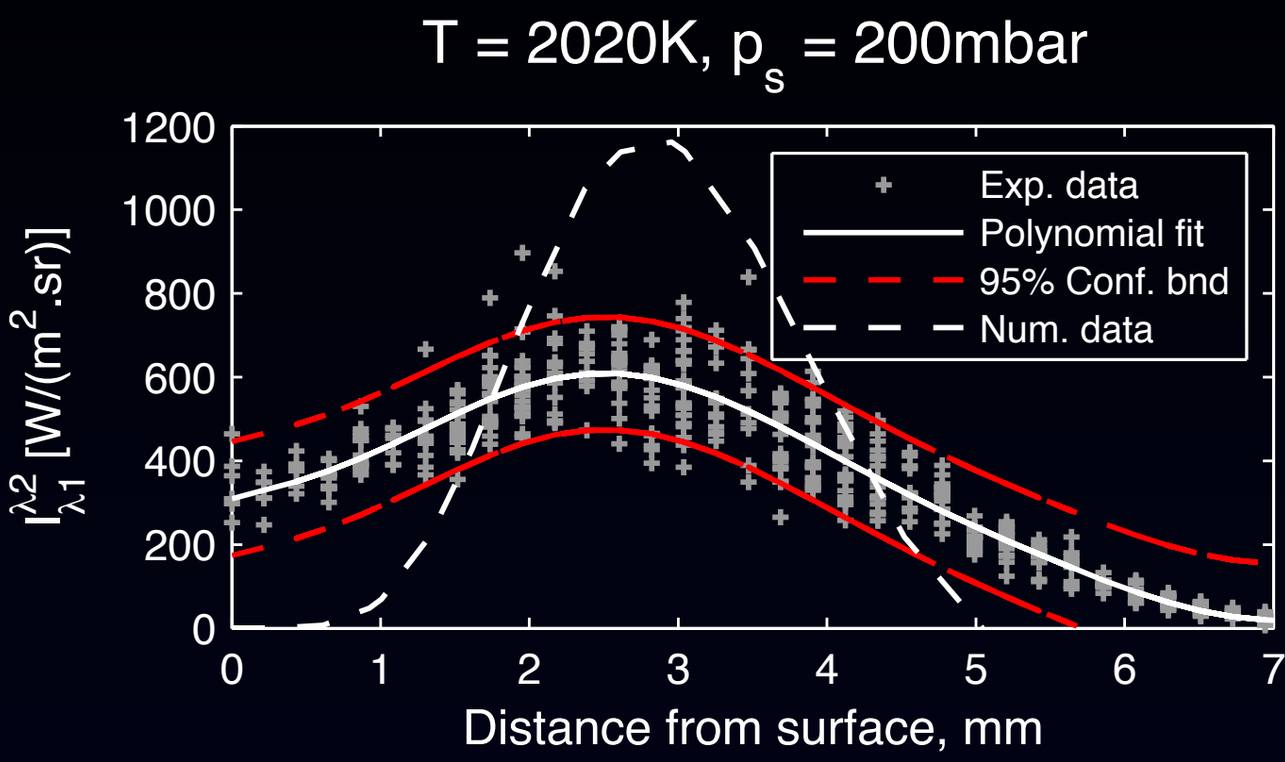
Simulate line-of-sight measurement



Perspective:
Radiation Coupling
(PhD Candidate J.B. Scoggins)

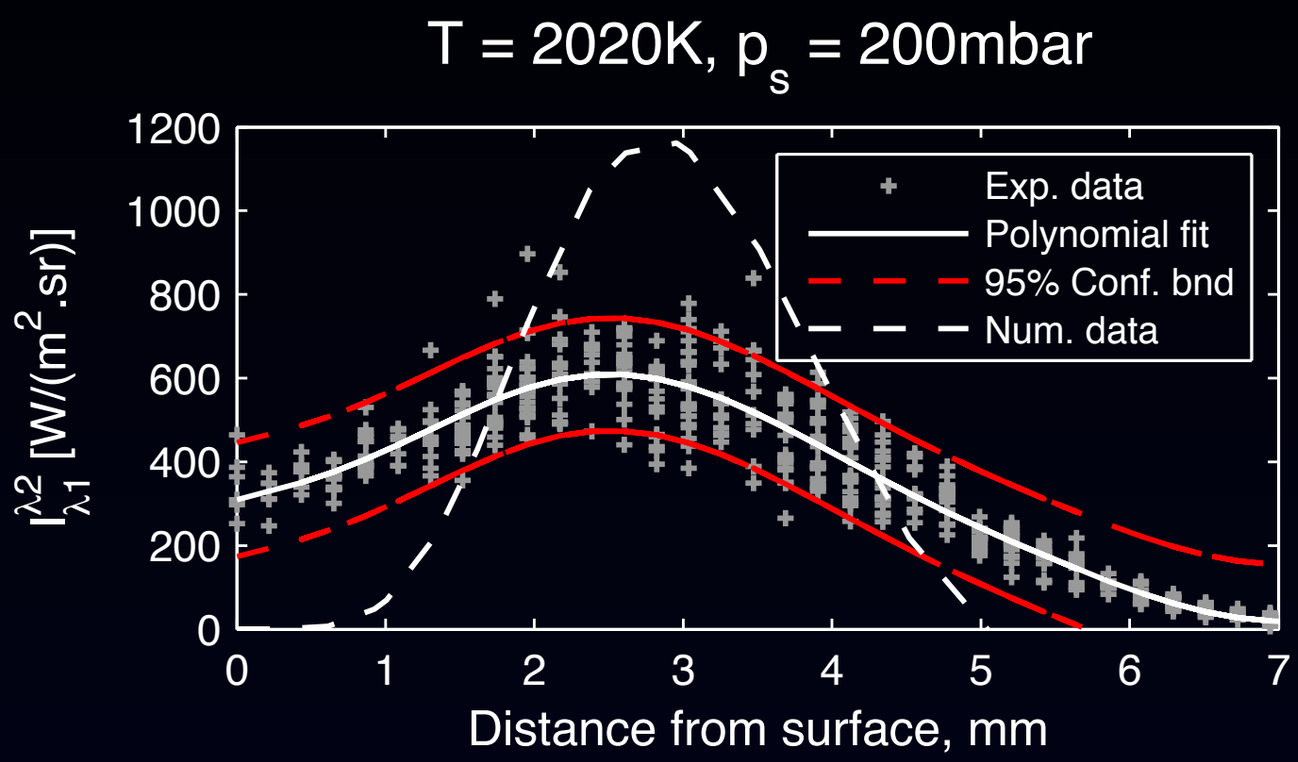
Comparison of Boundary Layer Radiation Profiles

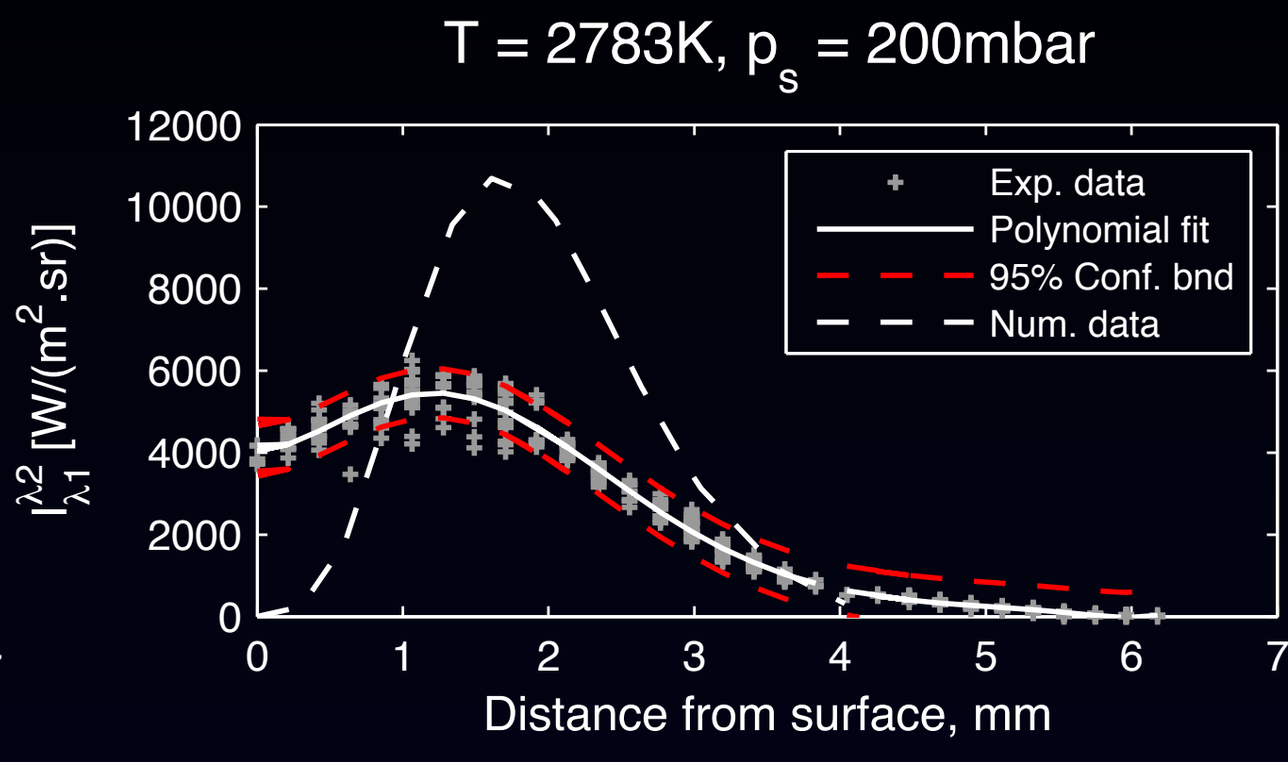
Experimental - Numerical



Comparison of Boundary Layer Radiation Profiles

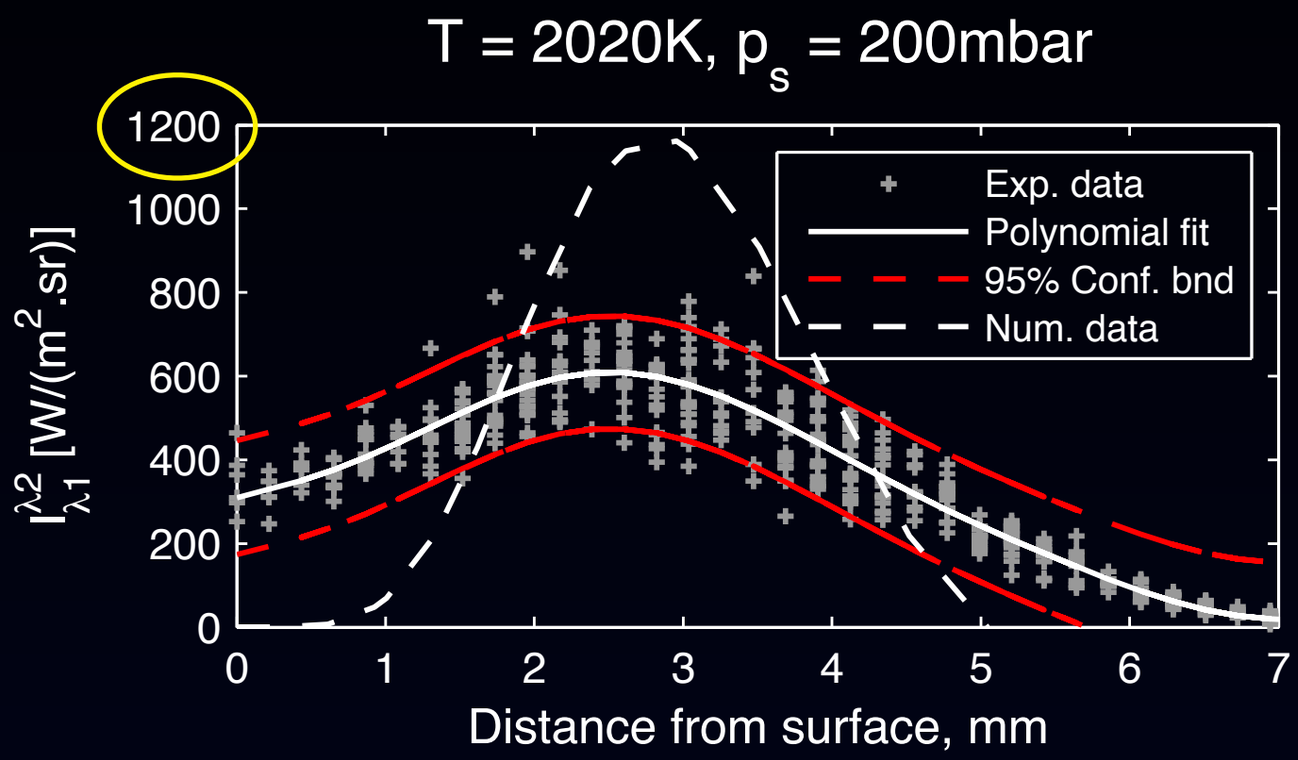
Experimental - Numerical

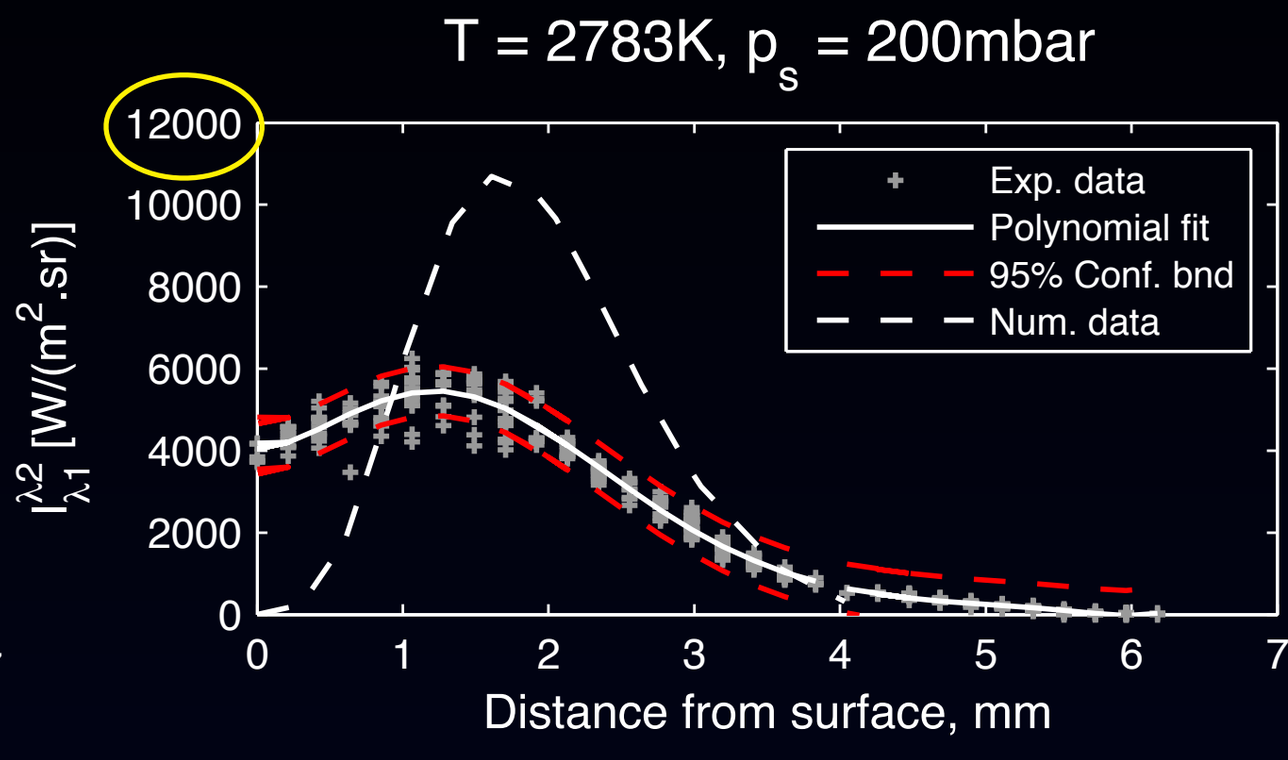




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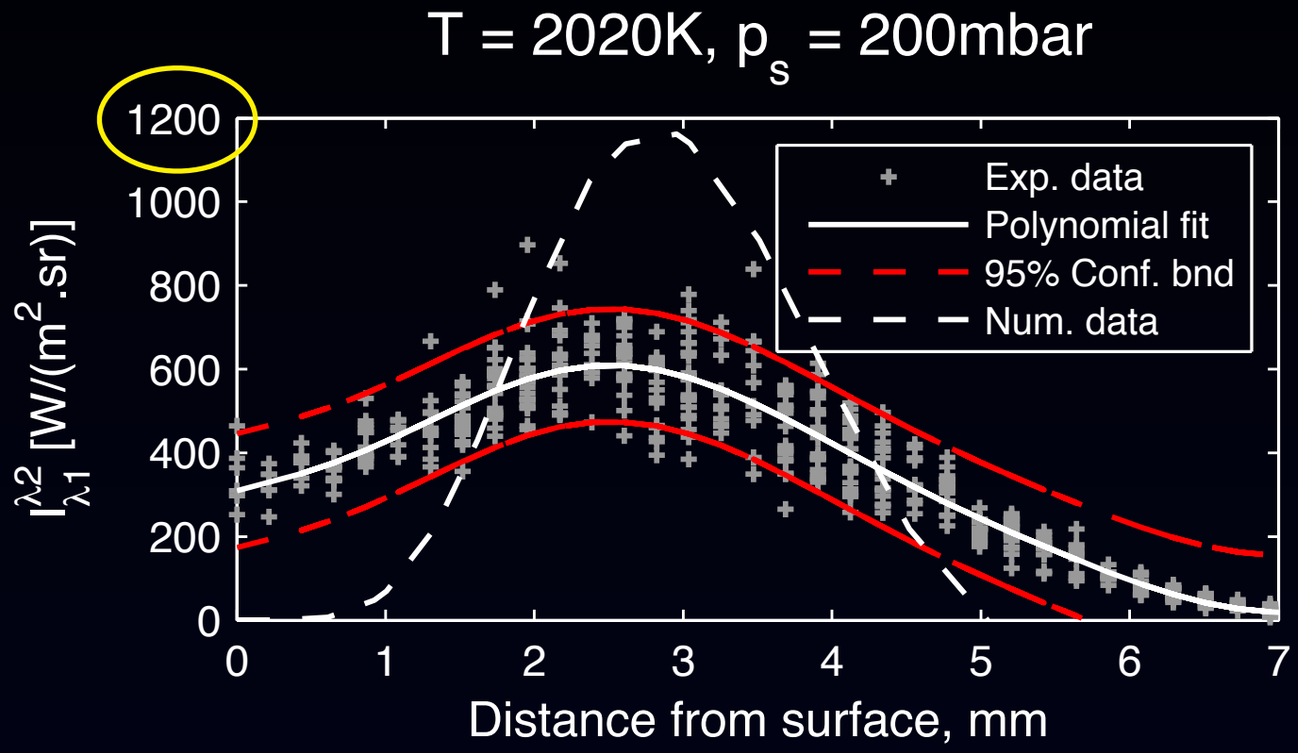
Experimental - Numerical

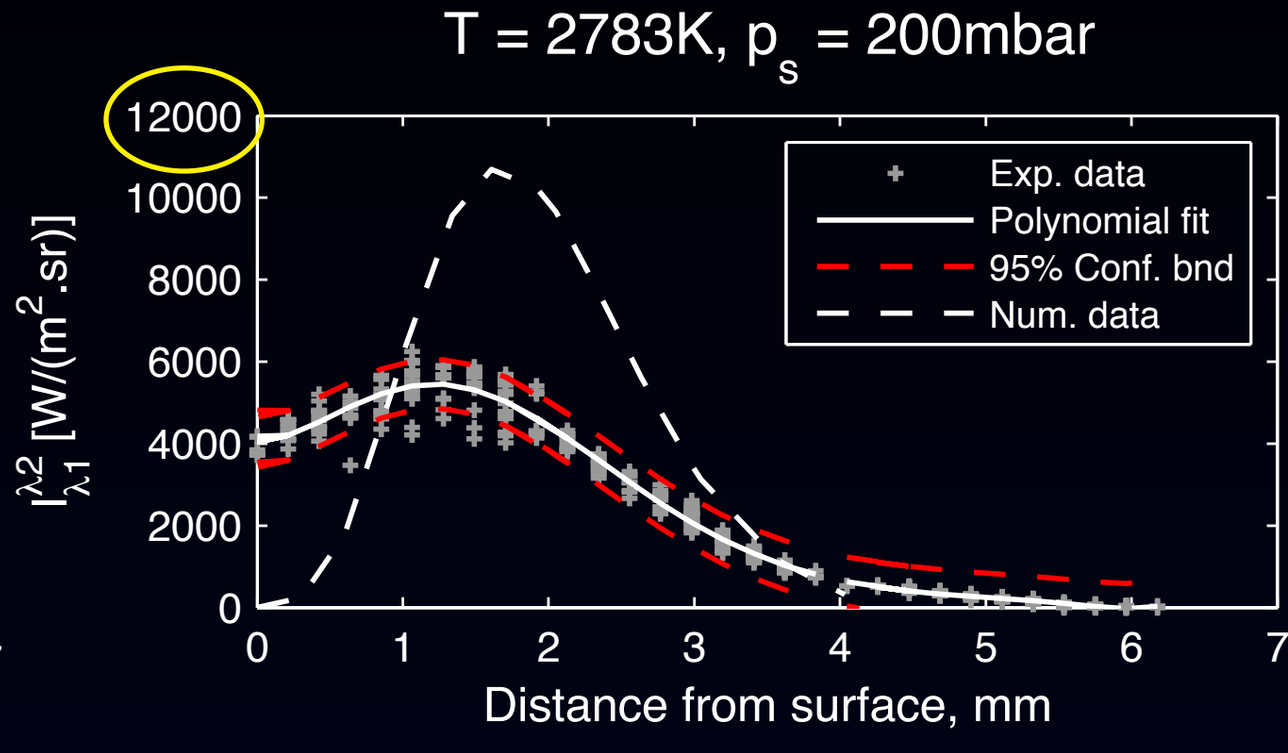




Comparison of Boundary Layer Radiation Profiles

Experimental - Numerical



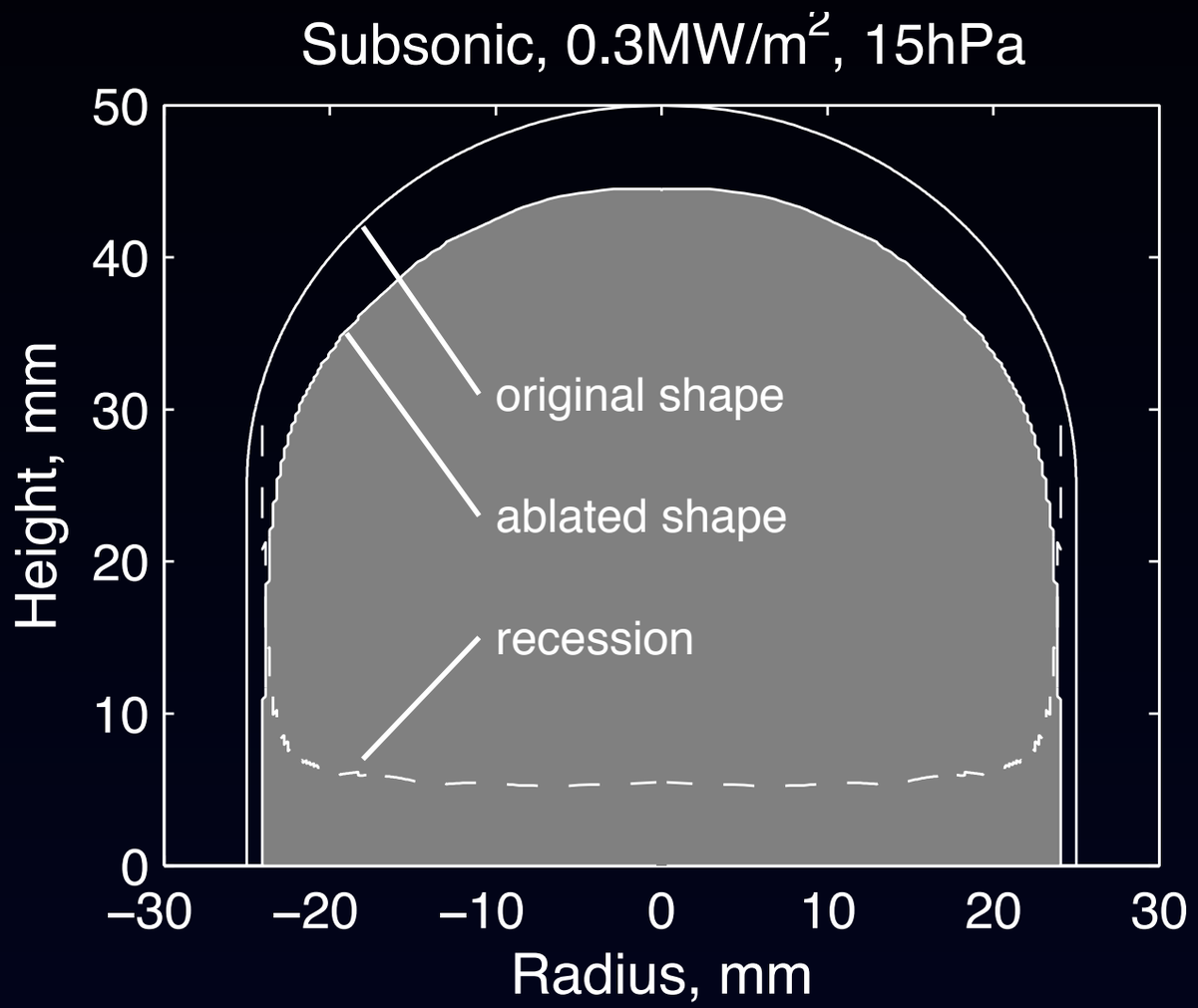


- ✓ Locations of maxima
- ✓ BL thickness
- ✓ Order of magnitude

- no nitridation in model
- strong assumption of constant properties over slab

Pyrolysis-Gas Blowing Rate Determination

Non-pyrolyzing carbon-preform



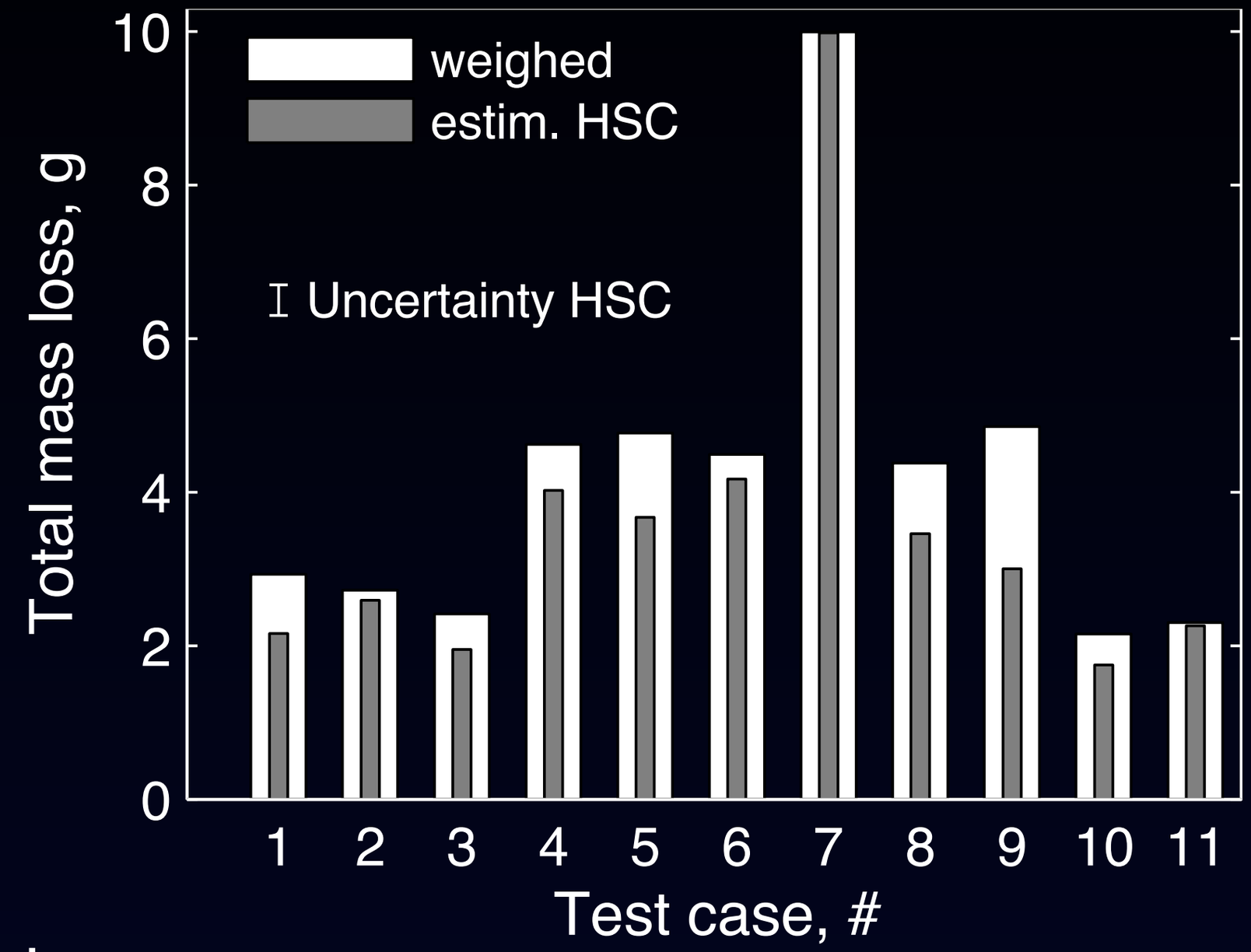
$$m_{pg} + m_c = (\rho V)_w$$

$$m_{pg} = m_{tot} - (V_{abl} \cdot \rho_c)$$

Carbon Preform (non-pyrol.):

➠ $m_c = m_{tot} = V_{abl} \cdot \rho_c$

Mass Loss Carbon Preform: Weighed vs HSC

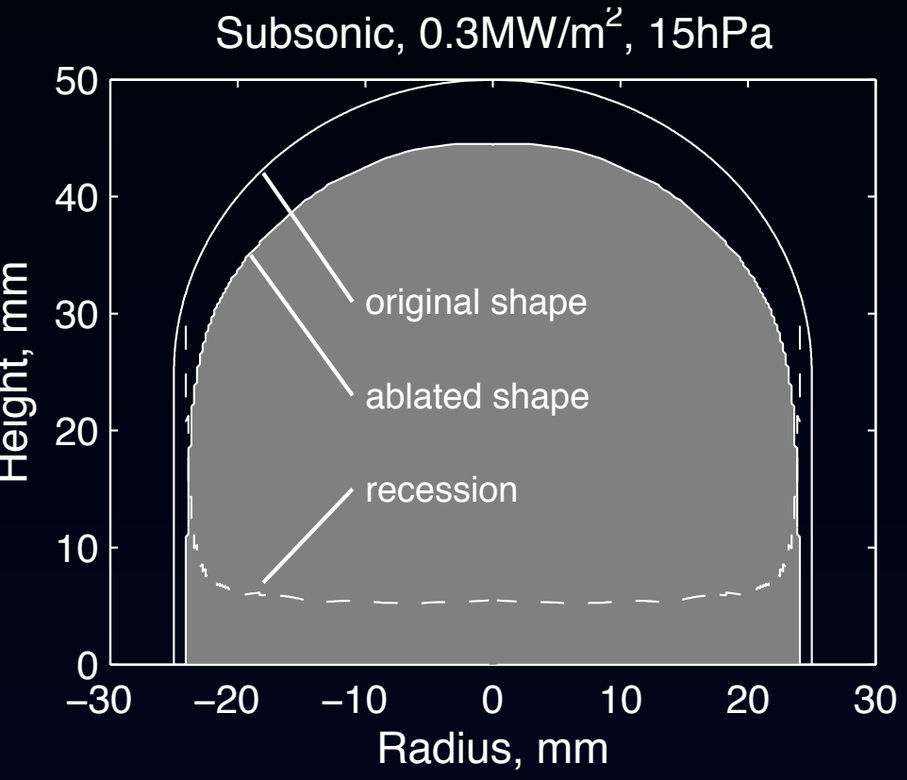


discrepancy:

- water
- initial density
- damage by deinstallation

AQ61 Pyrolysis-Gas Blowing Rates

STA (Simultaneous Thermal Analysis, VKI):
charred AQ61: $\rho_c = 80\text{-}85\%\ \rho_v$



	T	p	m	%
AQ1	2167	15	1.12	23
AQ6	2884	15	1.77	44
AQ7	2906	200	2.26	60

➠ compare to num. model

<u>Main challenges</u>:
Side-wall outgassing, non-1D effects, too-long test times

Conclusions

(1) Materials and Methods
- hemispherical samples
- HSC imaging → volume recession → (4)
- IR-camera: emissivity

(2) Char blowing rates
- higher recession for fibers through-grain
- diffusion limited ablation & sublimation (P+AQ61)
- Nitrogen: sublimation and nitridation of surface (SEM)

(3) BL emission
- steady ablation process
- num. estimation: order of magn., location of maxima, BL thickness

(4) Pyrolysis outgassing
- Vol. ablation + TGA → $\dot{m}_{pg}$

Future Work

Material:

- simultaneous TGA/DSC at VKI of resin, AQ61, Asterm (ongoing)
- additional SEM (fiber direction study)

Modeling:

- rebuild experiments with thermal response model (e.g. SAMCEF Amaryllis, or PATO)
- rebuild boundary layer emission with updated model (nitridation, recombination → talk A. Turchi)
- compare experimental pyrolysis outgassing rates to model

Acknowledgements

Funding and materials supply:







In particular:

- N.N. Mansour (NASA ARC),
  J. Lachaud (UC Santa Cruz),
  F. Panerai (University of Kentucky) for informative support
- Jean-Marc Bouilly & Gregory Pinaud (Airbus Defence & Space)
- VKI Plasmatron & Ablation Team
- VUB SURF research team

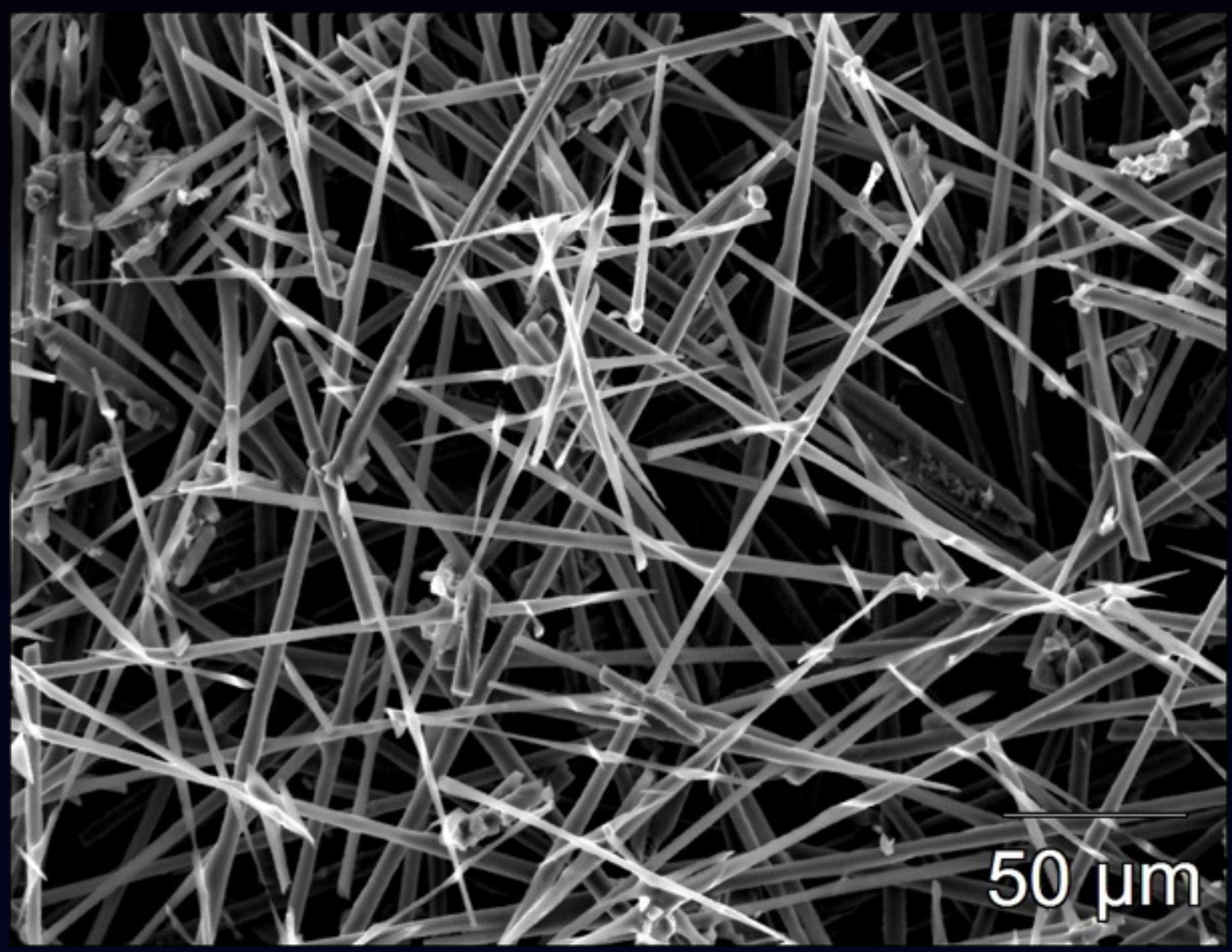
Oxidation of Preform & AQ61 in air

Oxidation of Preform and AQ61

Carbon preform oxidation

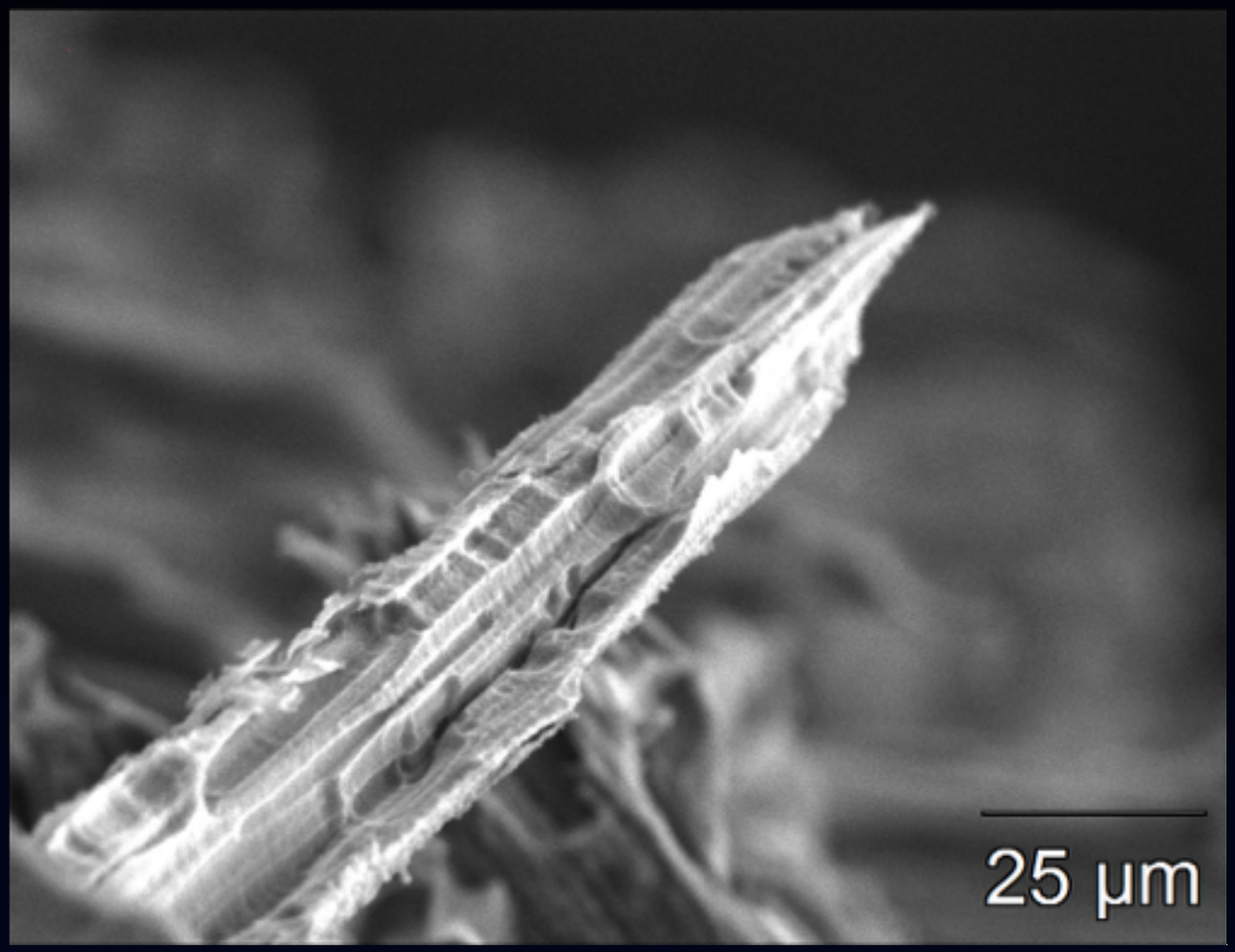


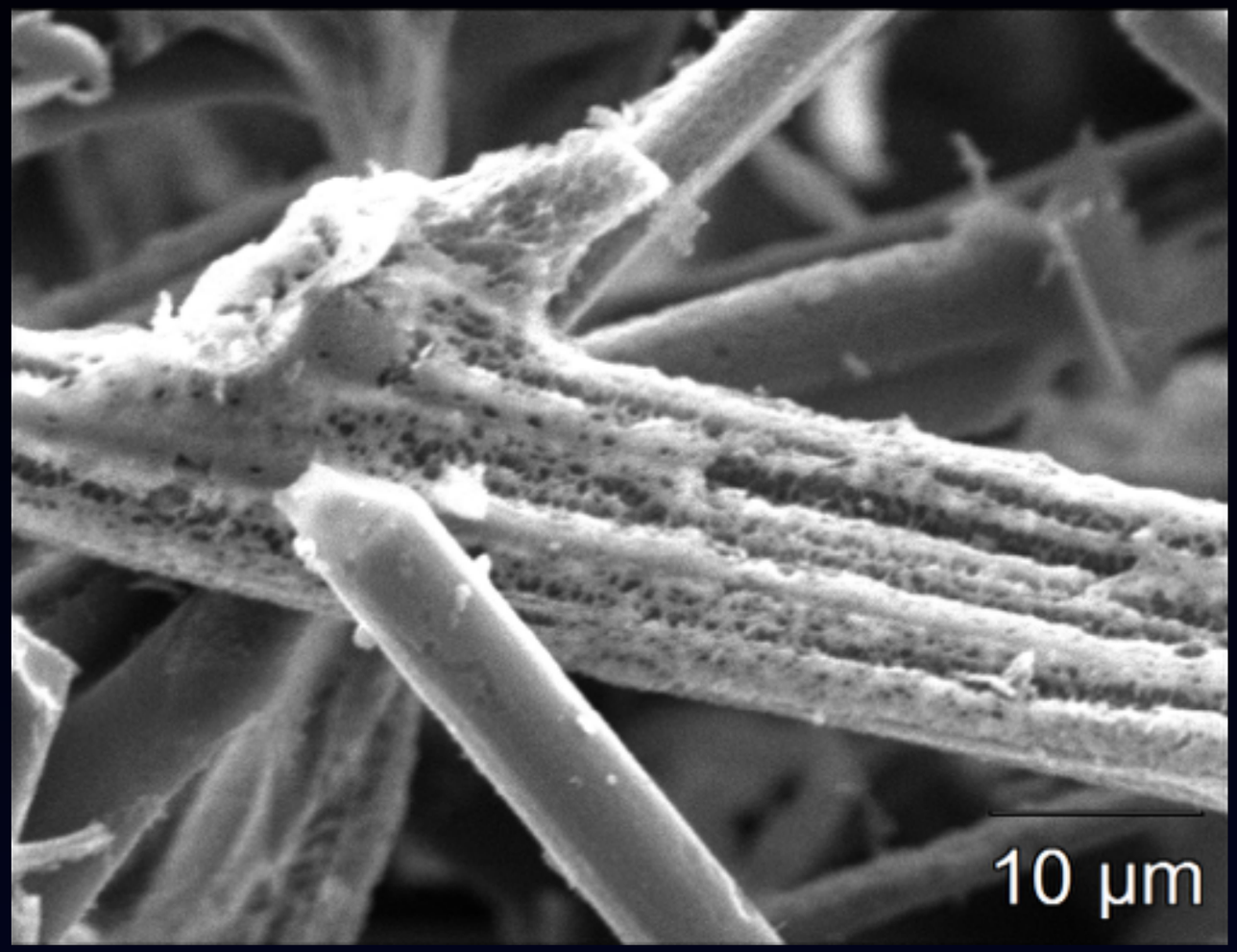
AQ61 oxidation



Preform & AQ61 in nitrogen

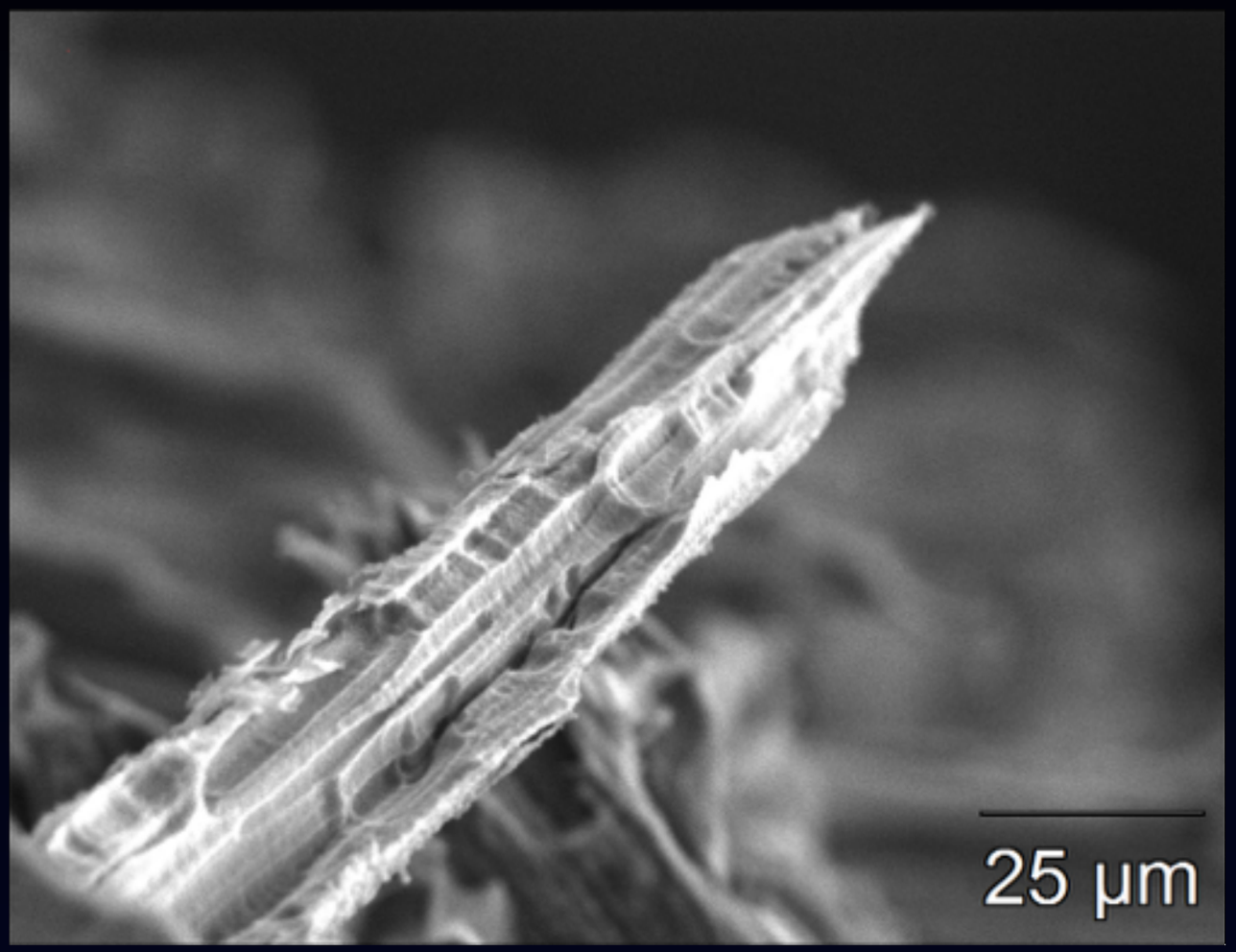
Nitridation Preform

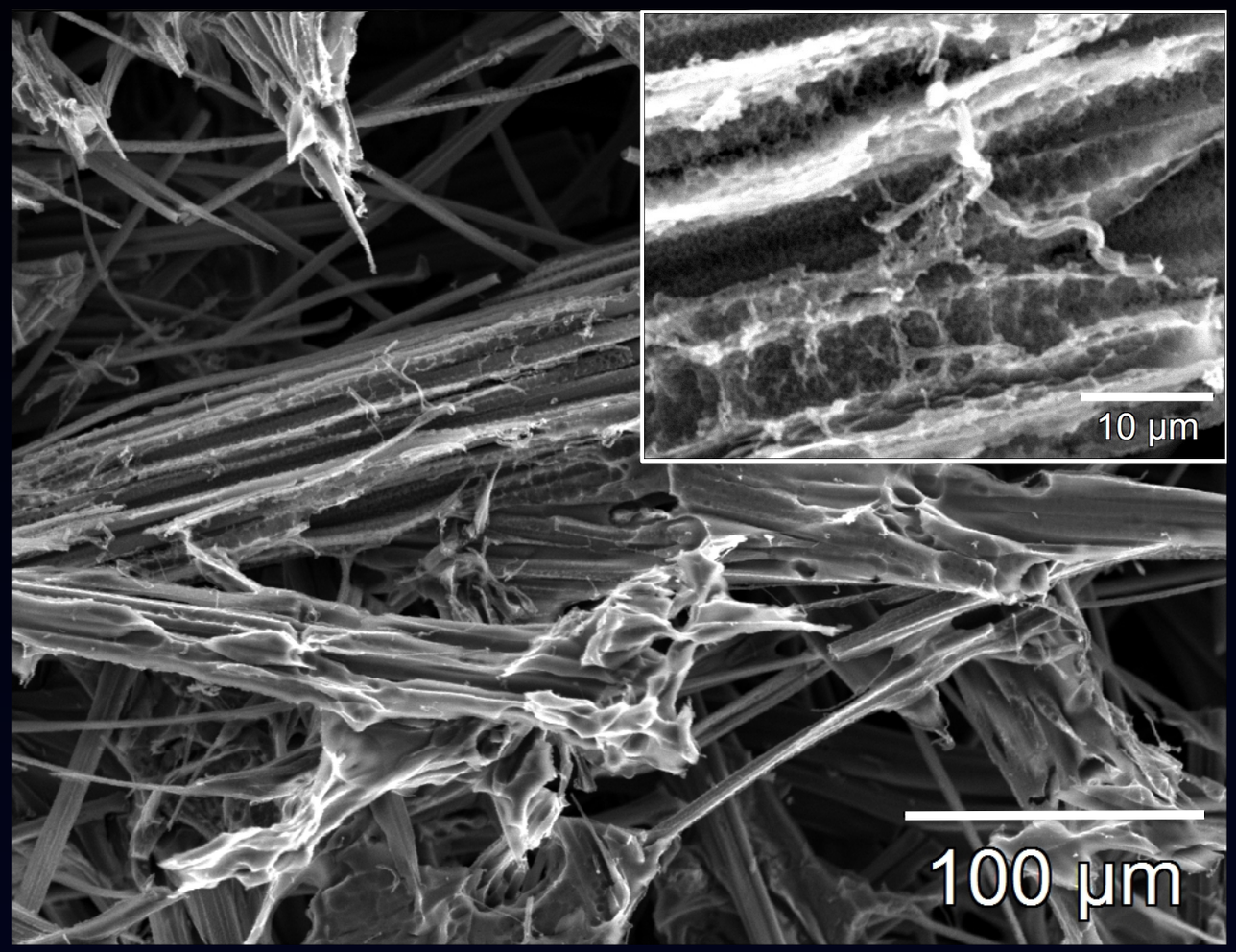




Preform & AQ61 in nitrogen

Nitridation Preform

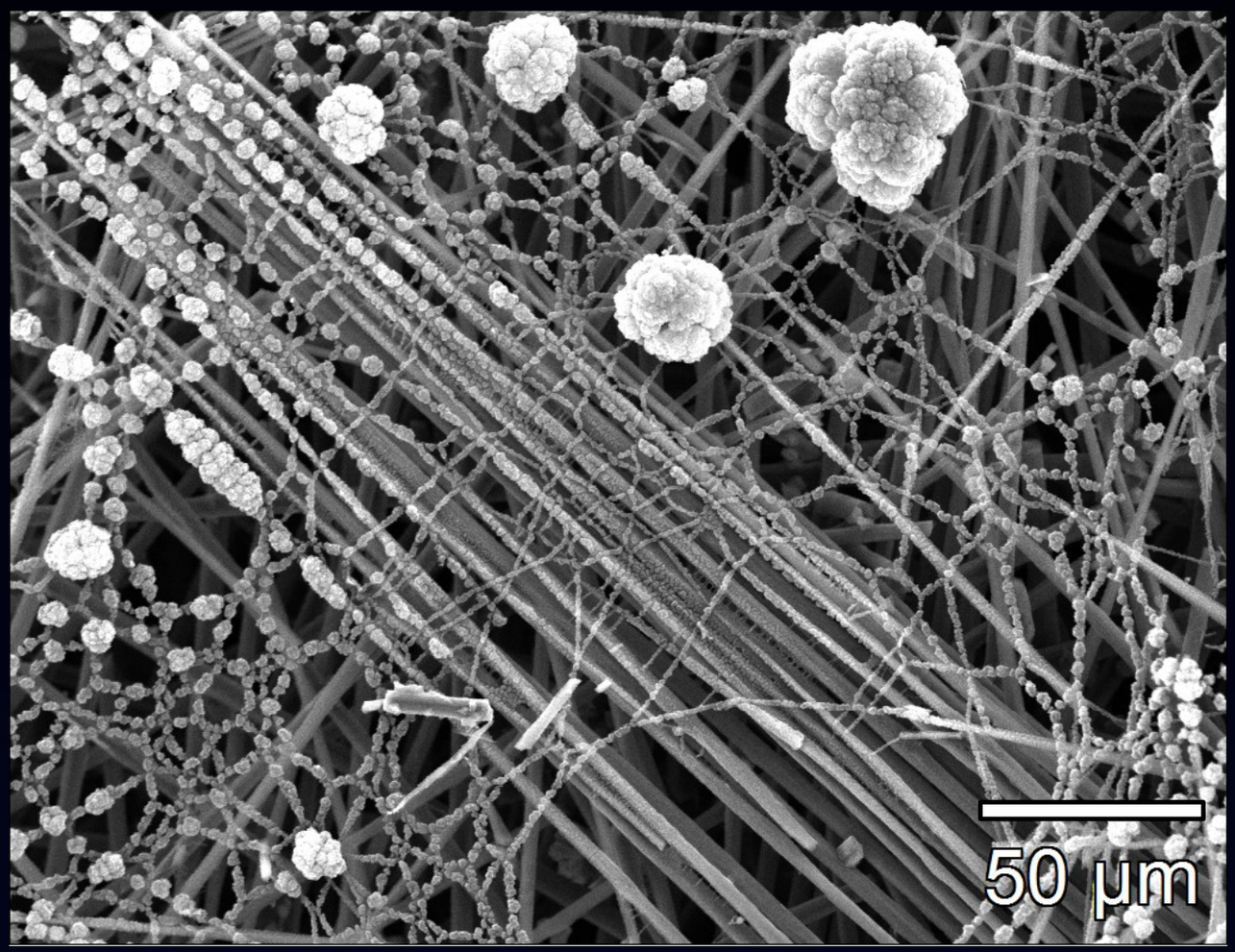




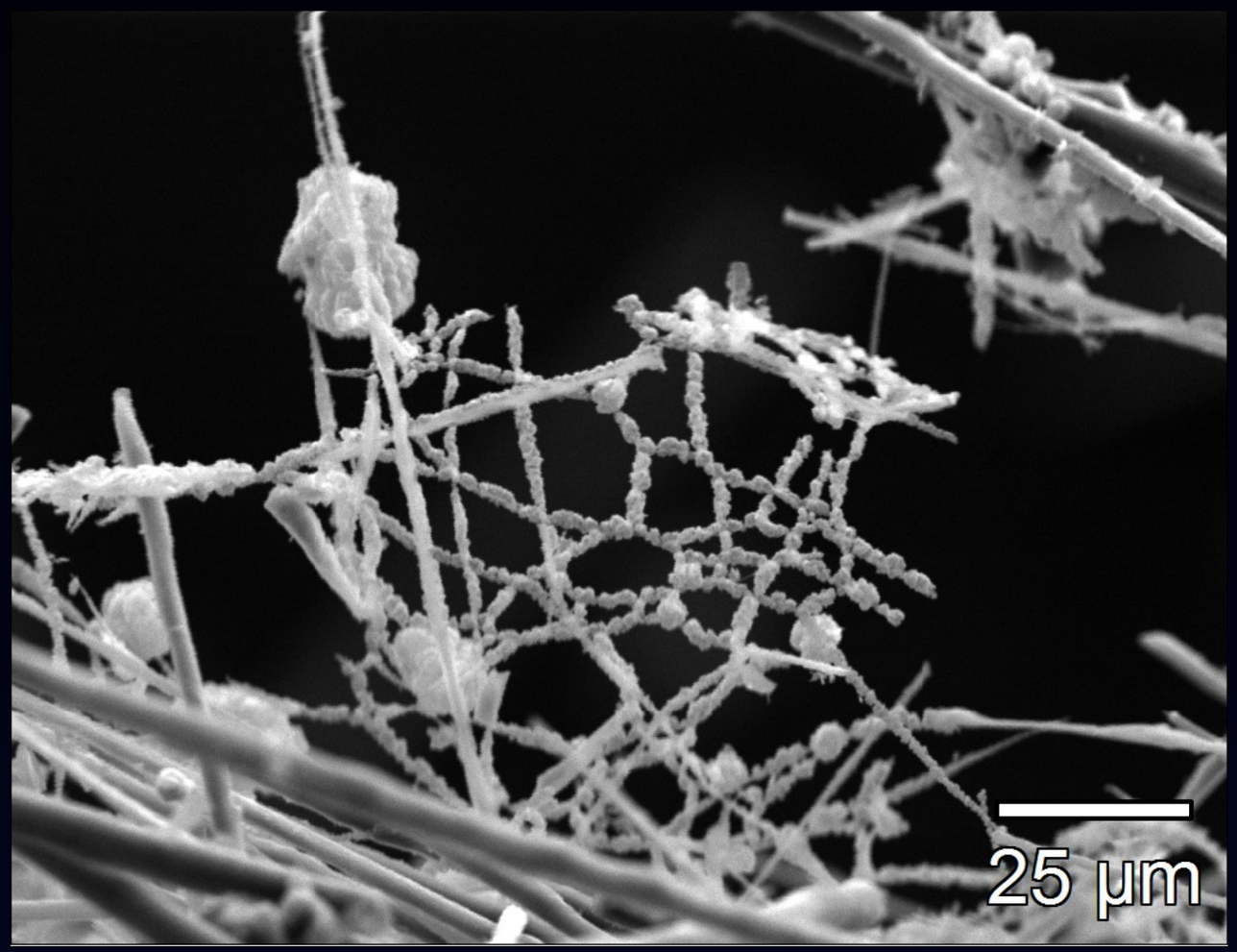
Preform & AQ61 in nitrogen

Nitridation AQ61

AQ61 nitrogen



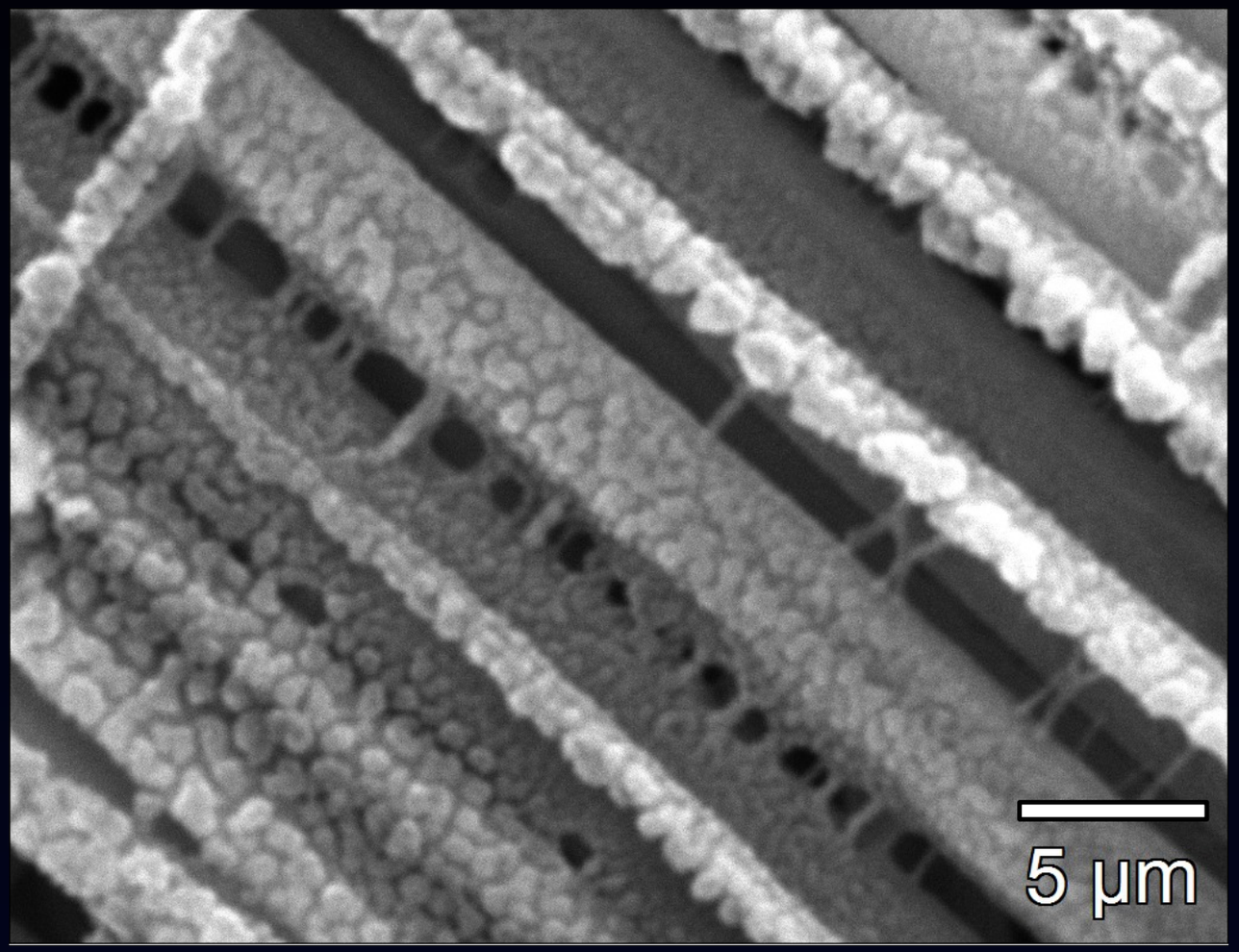
AQ61 nitrogen



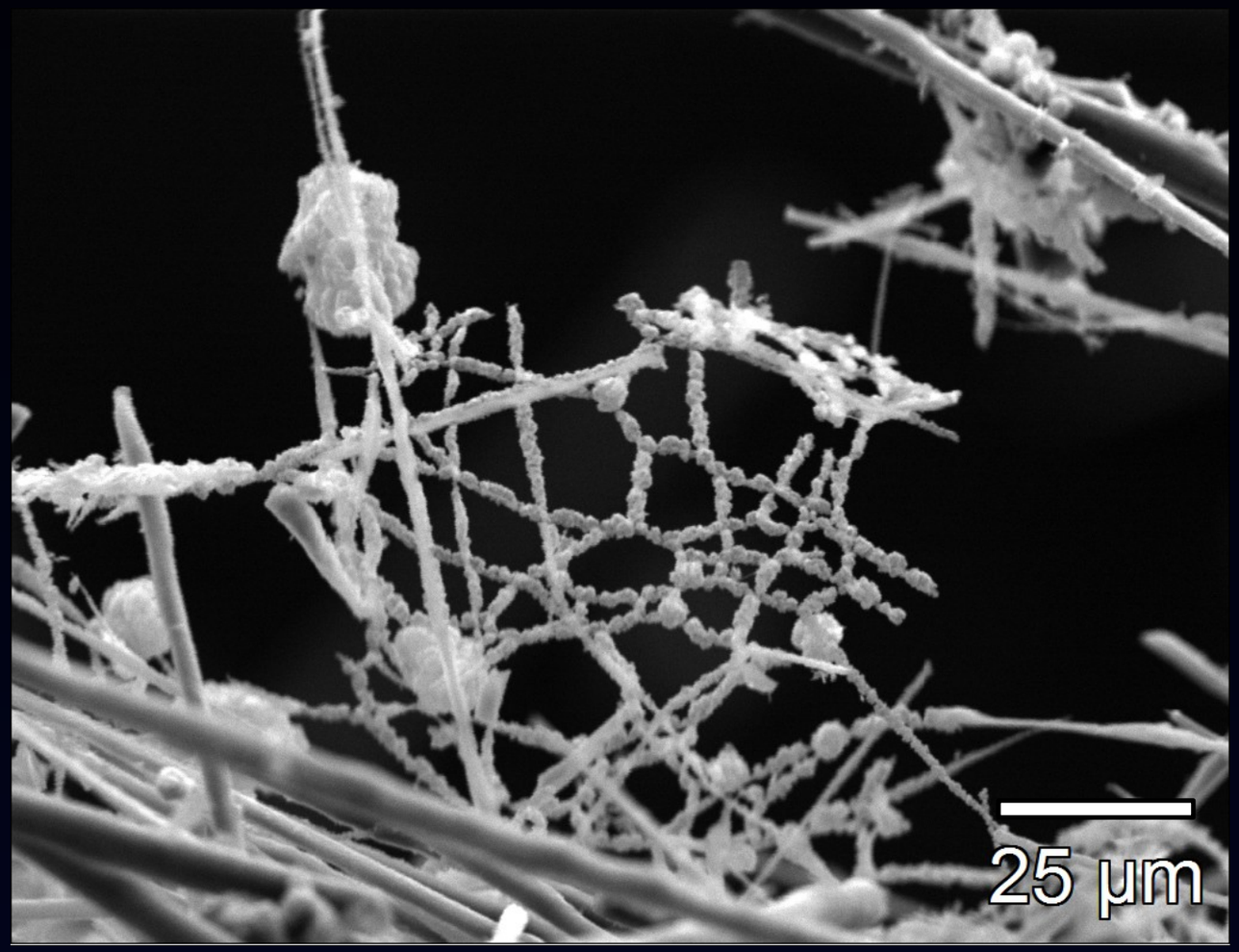
Preform & AQ61 in nitrogen

Nitridation AQ61

AQ61 nitrogen



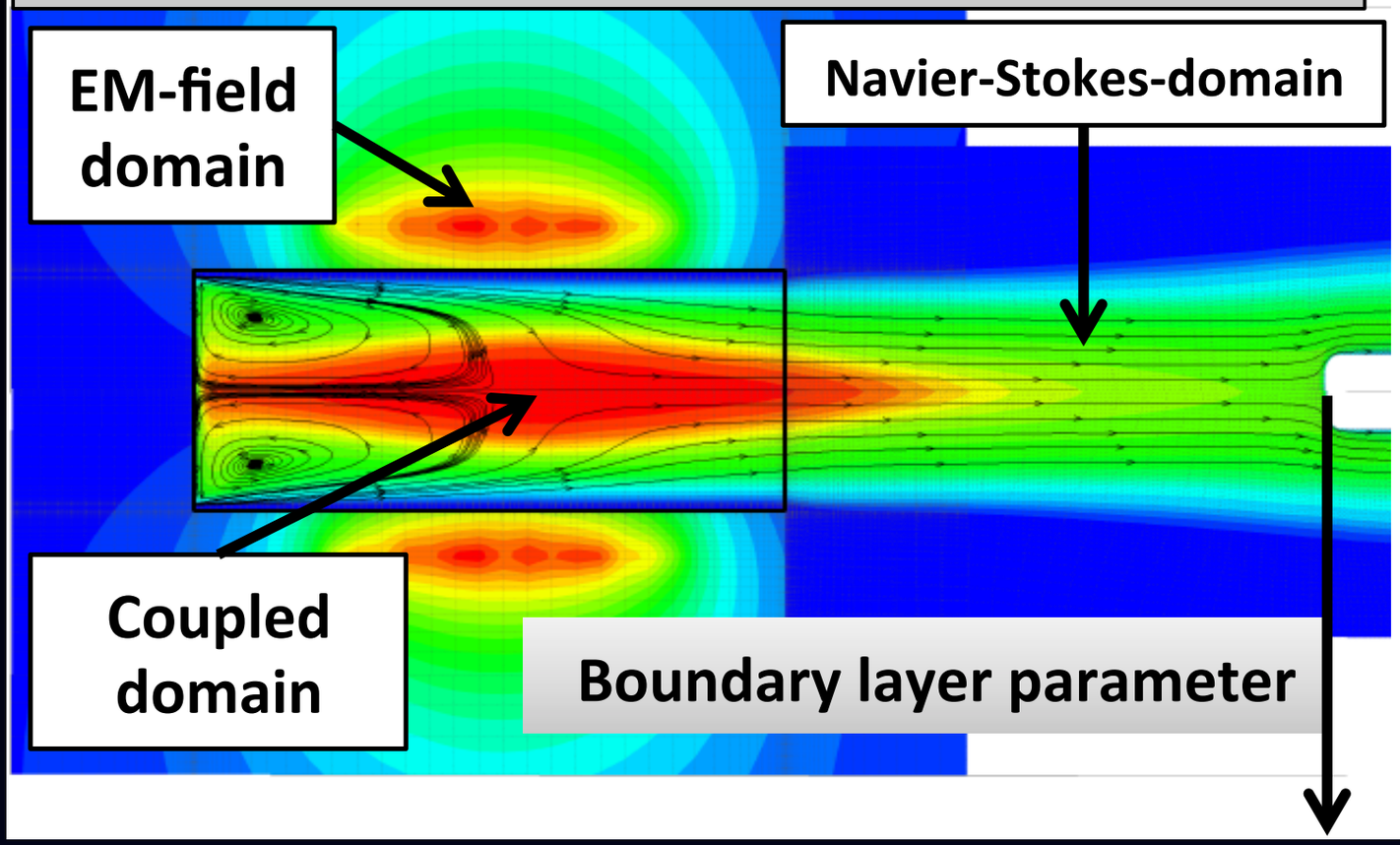
AQ61 nitrogen



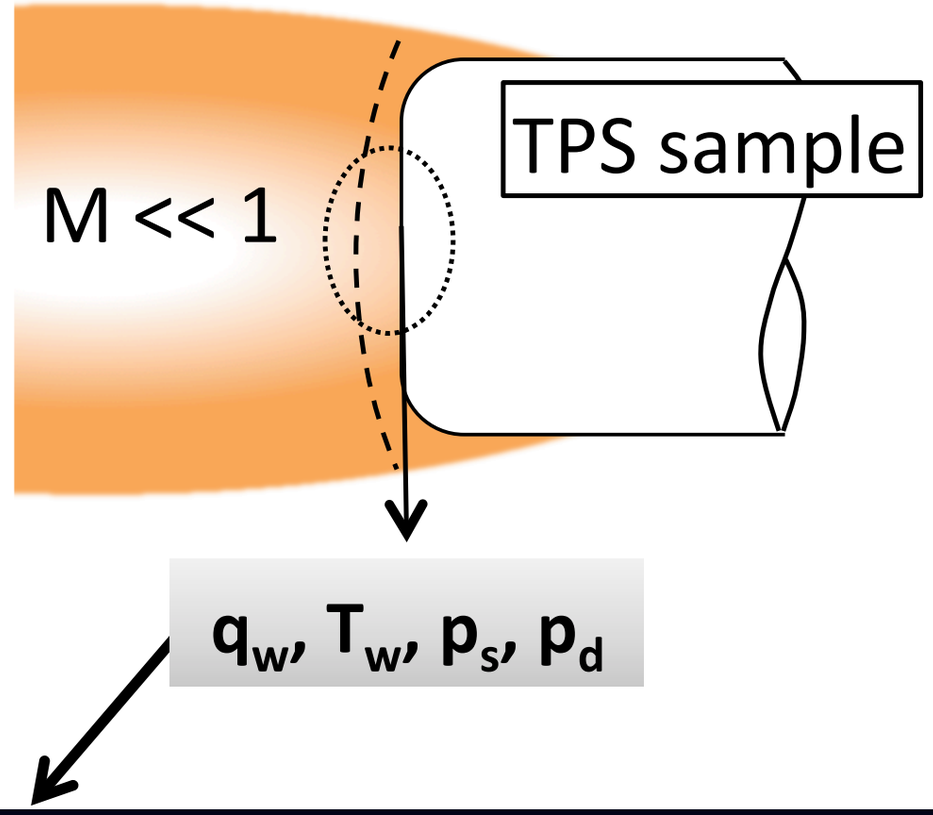
APPENDIX: Combined Rebuilding Procedure

Boundary Layer Solver

VKI ICP code (LTE assumption)



Ground test measurements



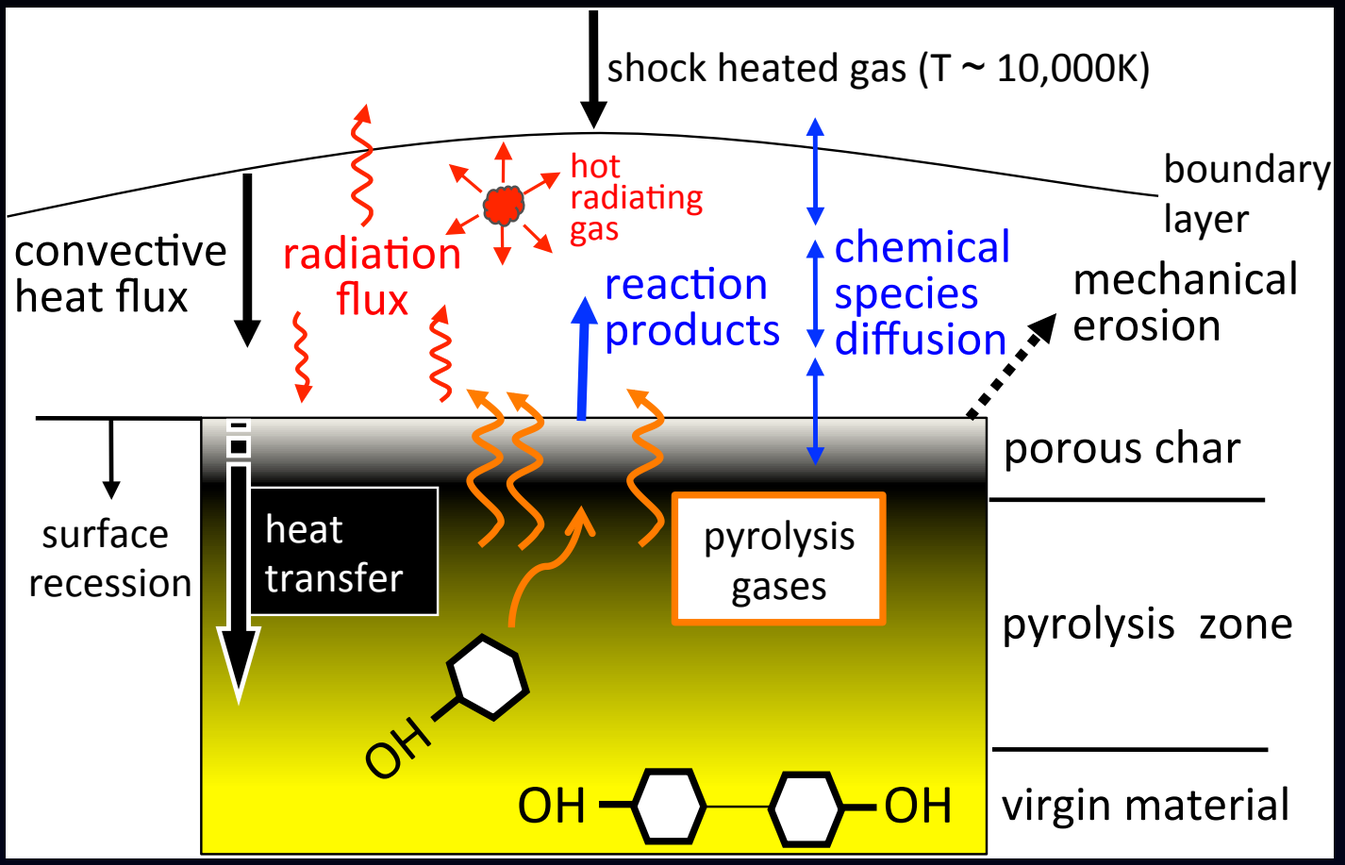
- **Input**: Boundary layer parameter (LTE CFD computation) & measurements from experiments
- **Procedure**: Iteration on boundary layer edge temperature T_e:

$$\Rightarrow q_w^{\,n} = q_w^{\,exp} = q_w(\gamma,\ T_w,\ p_e,\ h_e,\ \beta)$$

- **Output**: Edge enthalpy He, boundary layer chemistry, (catalycity)

Complex Multiphysics - Multiscale problem

Coupled phenomena



<u>Gas-phase</u>

- Ablation species injection
- Strong radiators and boundary layer absorption

<u>Gas-surface interaction</u>

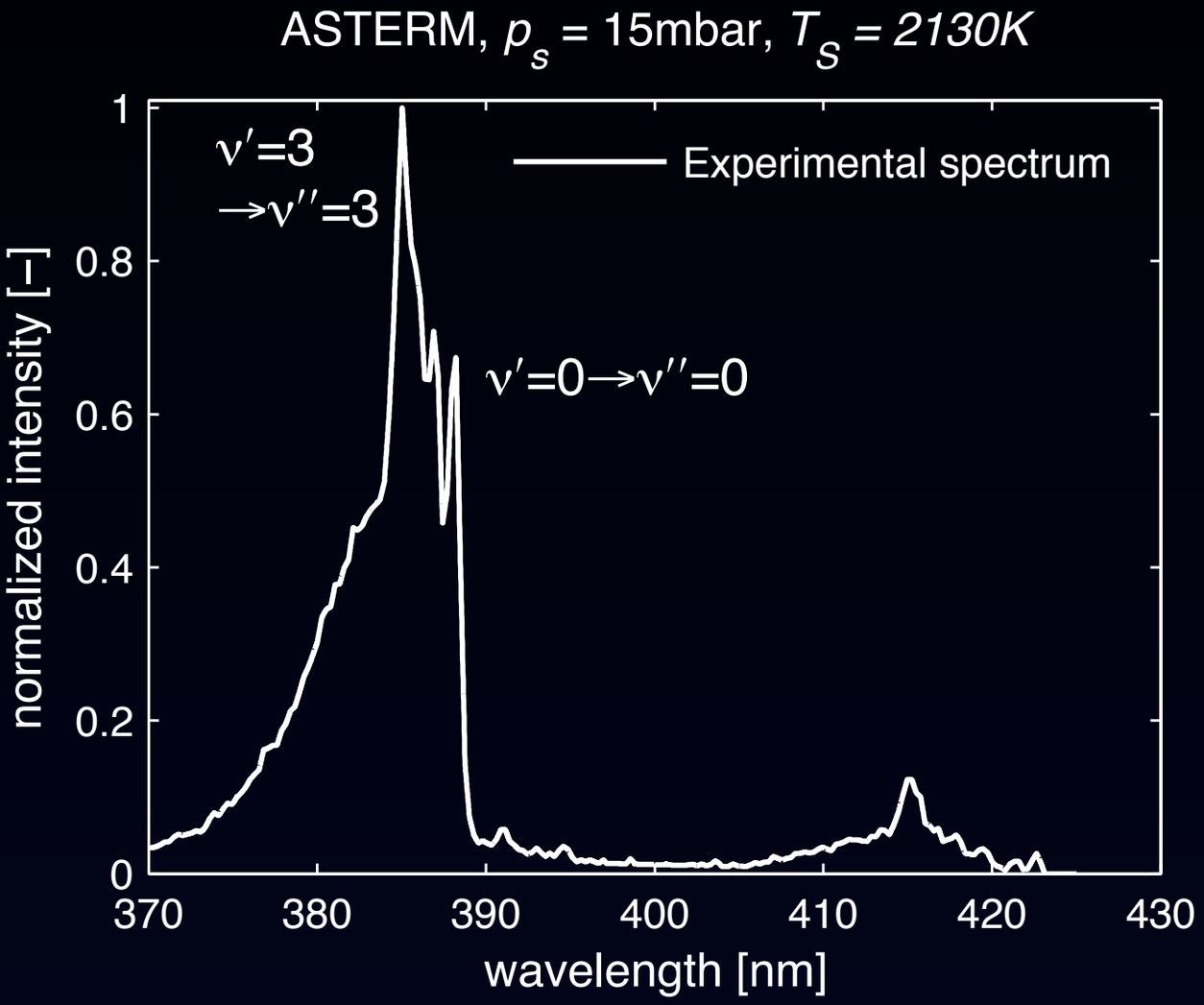
- Surface reactions & recombination
- Recession rate

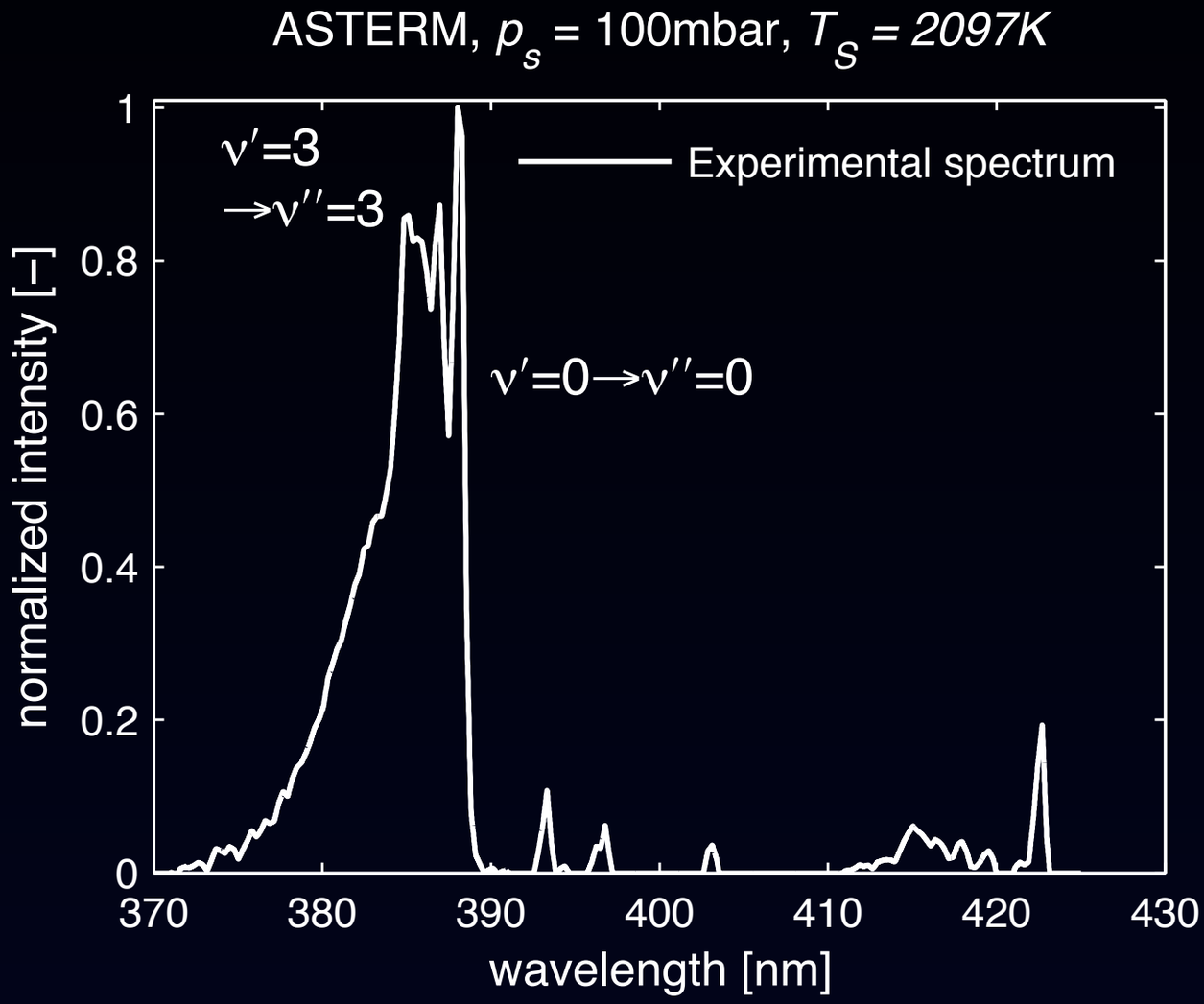
<u>Material</u>

- Pyrolysis gases production and outgassing

CN Radiation Simulation for Temperature Estimation

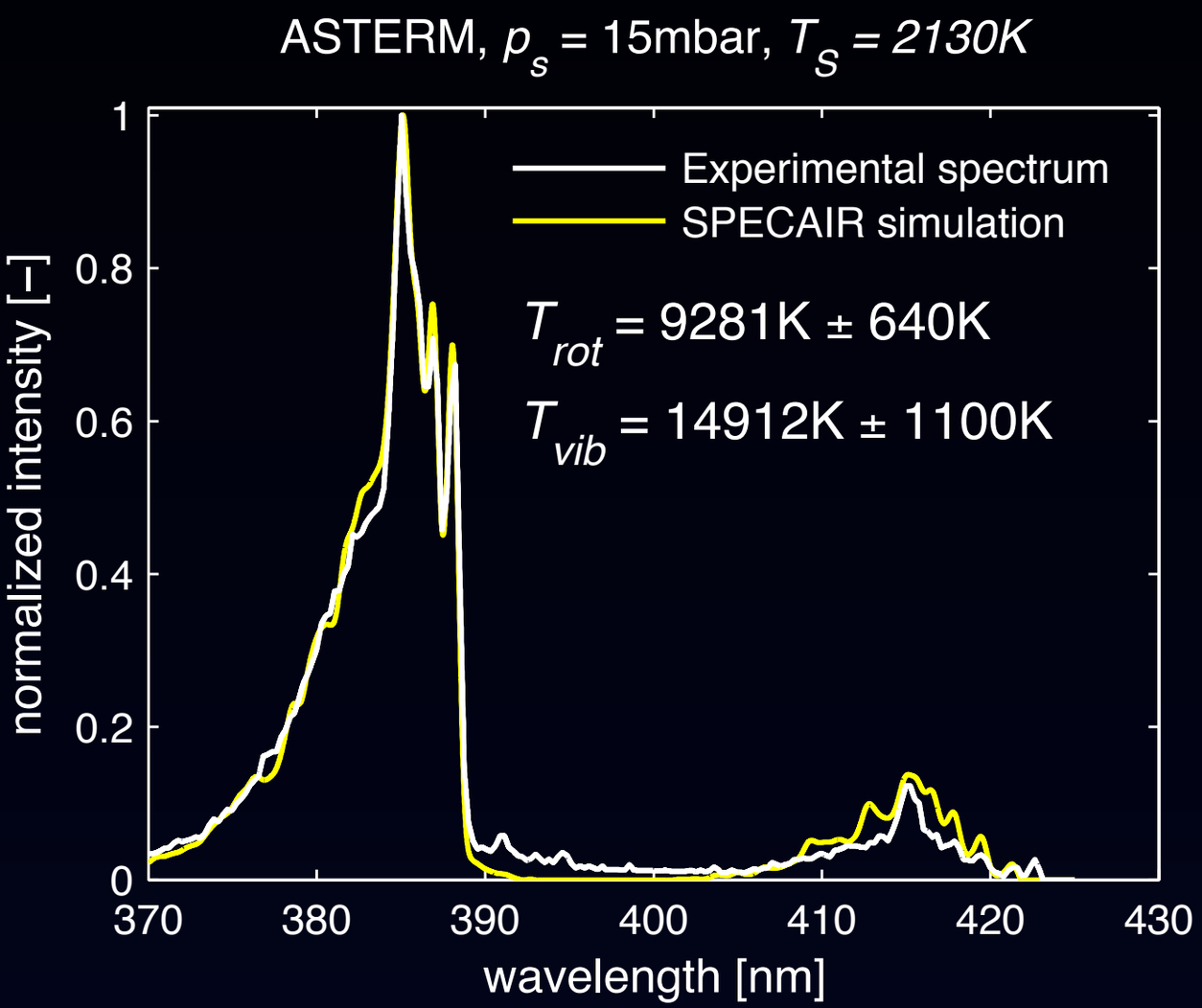
Non-equilibrium?

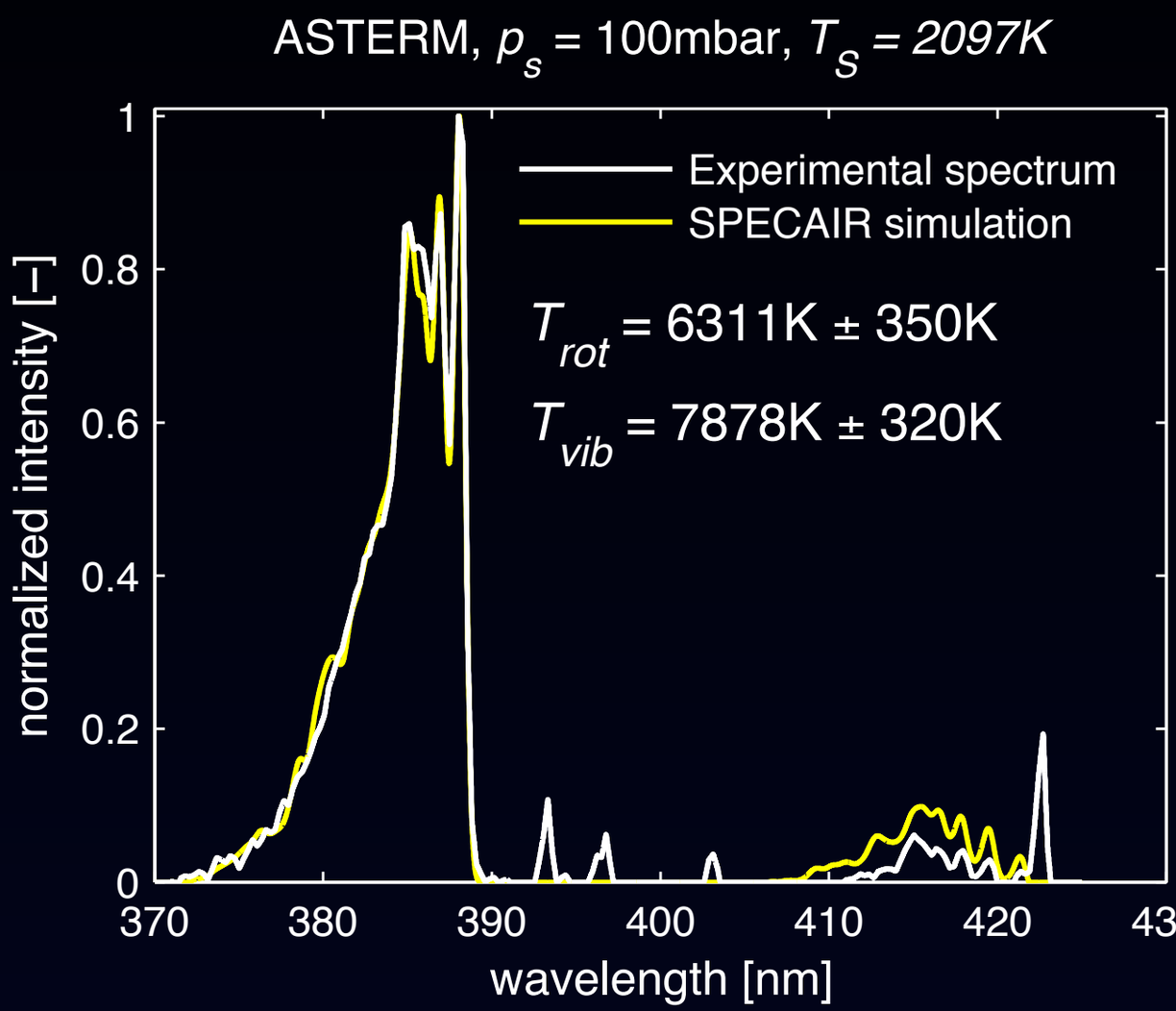




CN Radiation Simulation for Temperature Estimation

Non-equilibrium?





Non-thermal vibrational level distribution at low pressure (AIAA 2013-2770)

- ➠ Thermal non-equilibrium?
- ➠ Deviation from Boltzmann distribution?

Boundary Layer Temperature Profile

Non-equilibrium at the wall?

