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Preliminary numerical and experimental analysis of the spallation phenomenon

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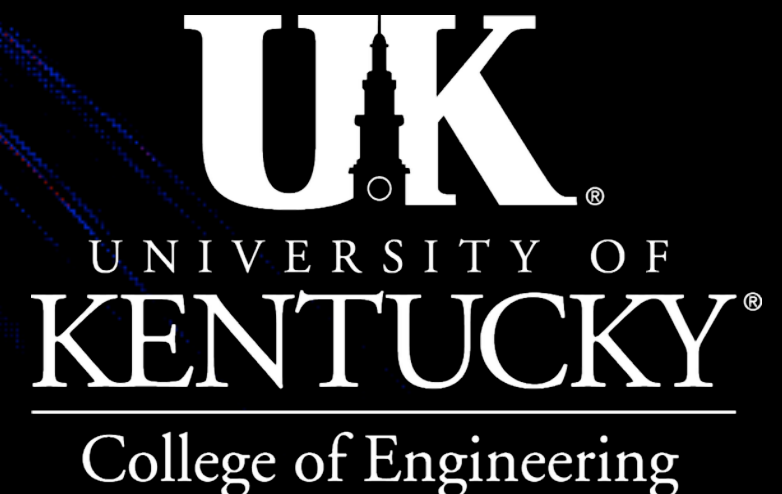
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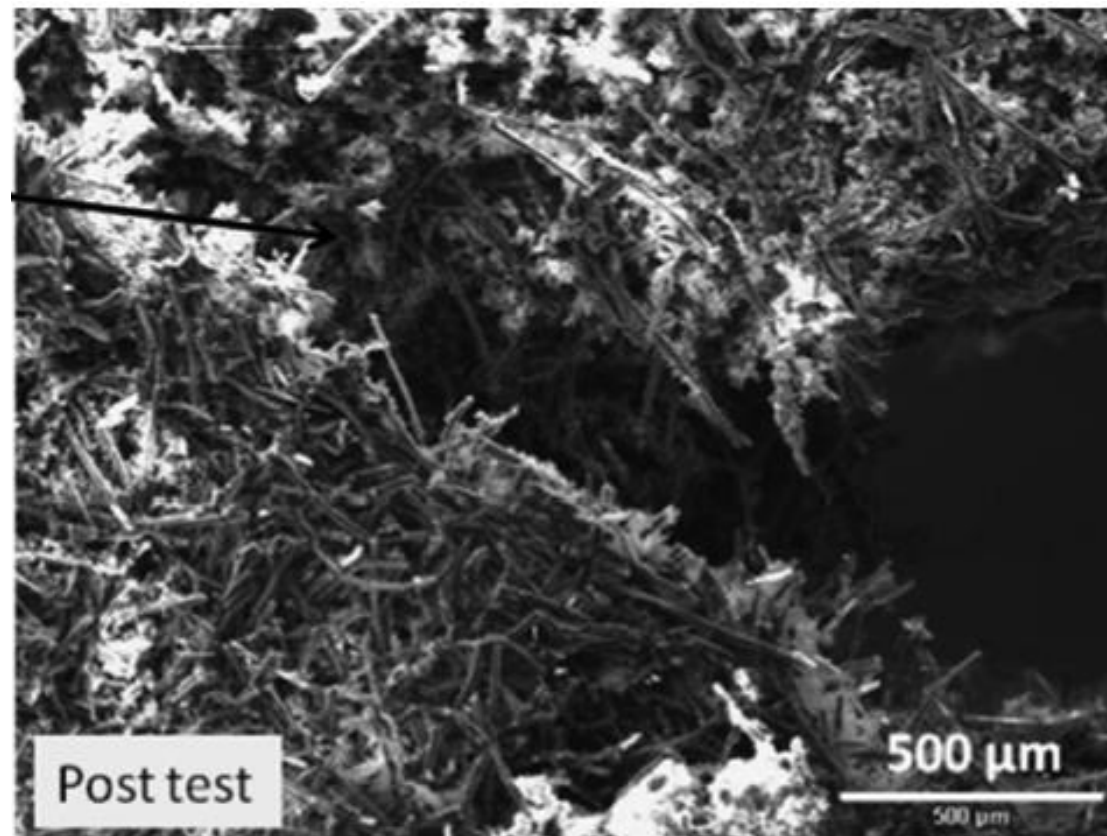


NASA EPSCoR RA
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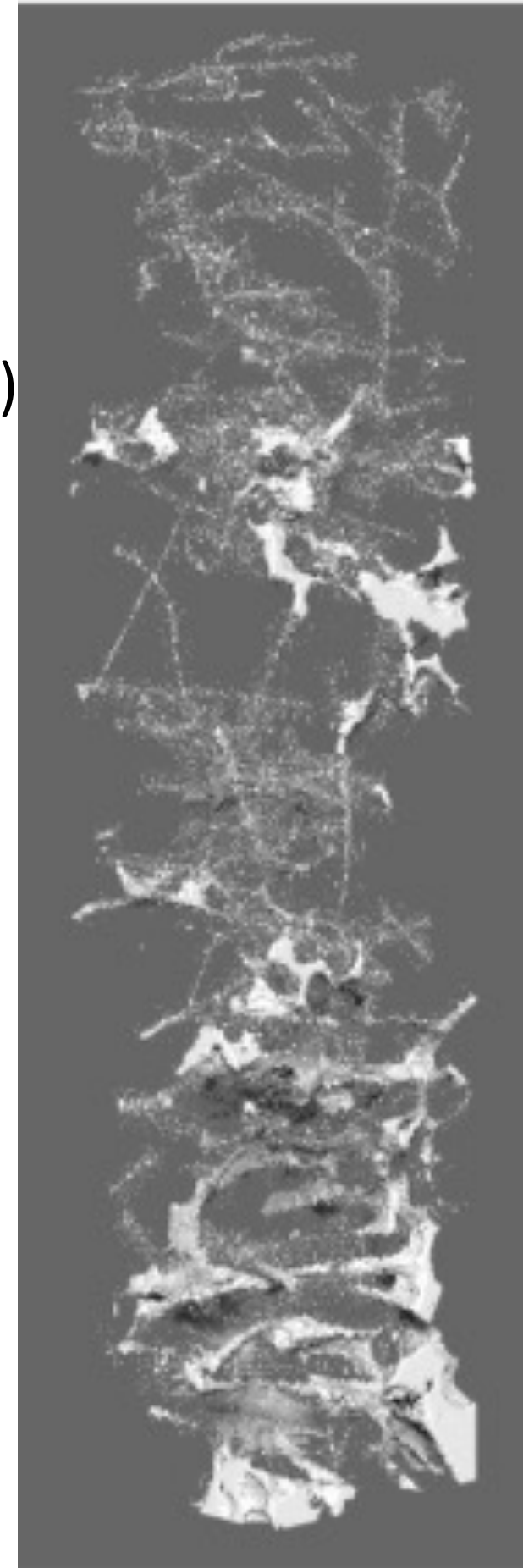


Spallation

- Mechanical erosion of the material
- Accelerates material failure
- (Probably) undesirable because hard to predict (and model...)
- Can be caused by
 - Fracture from high pyrolysis gas pressure
 - Volumetric fiber erosion and detachment
 - Fracture from high thermal stress
 - Shear stress on fibers
 - Soot formation (coking)



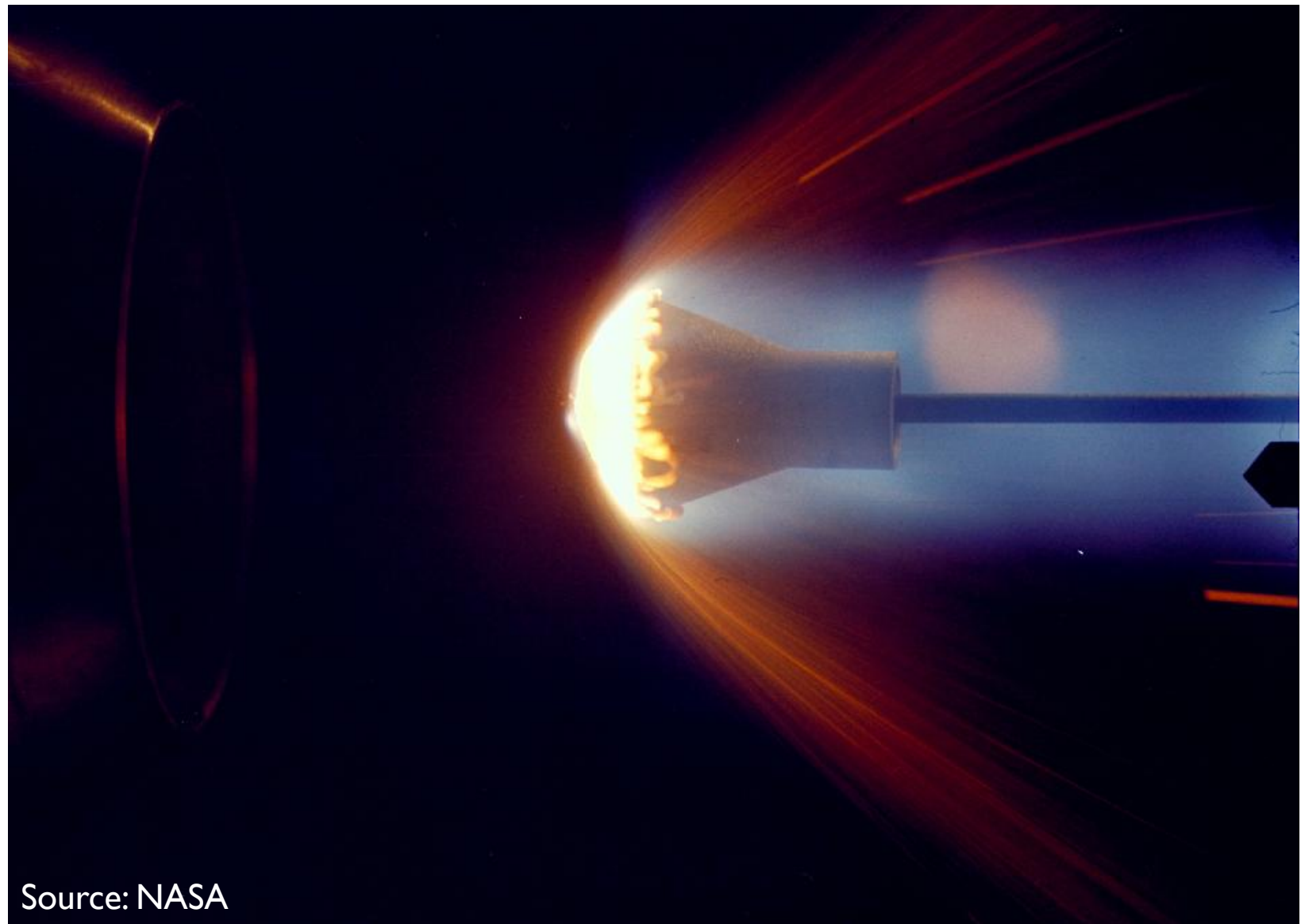
Agrawal et al., 2013



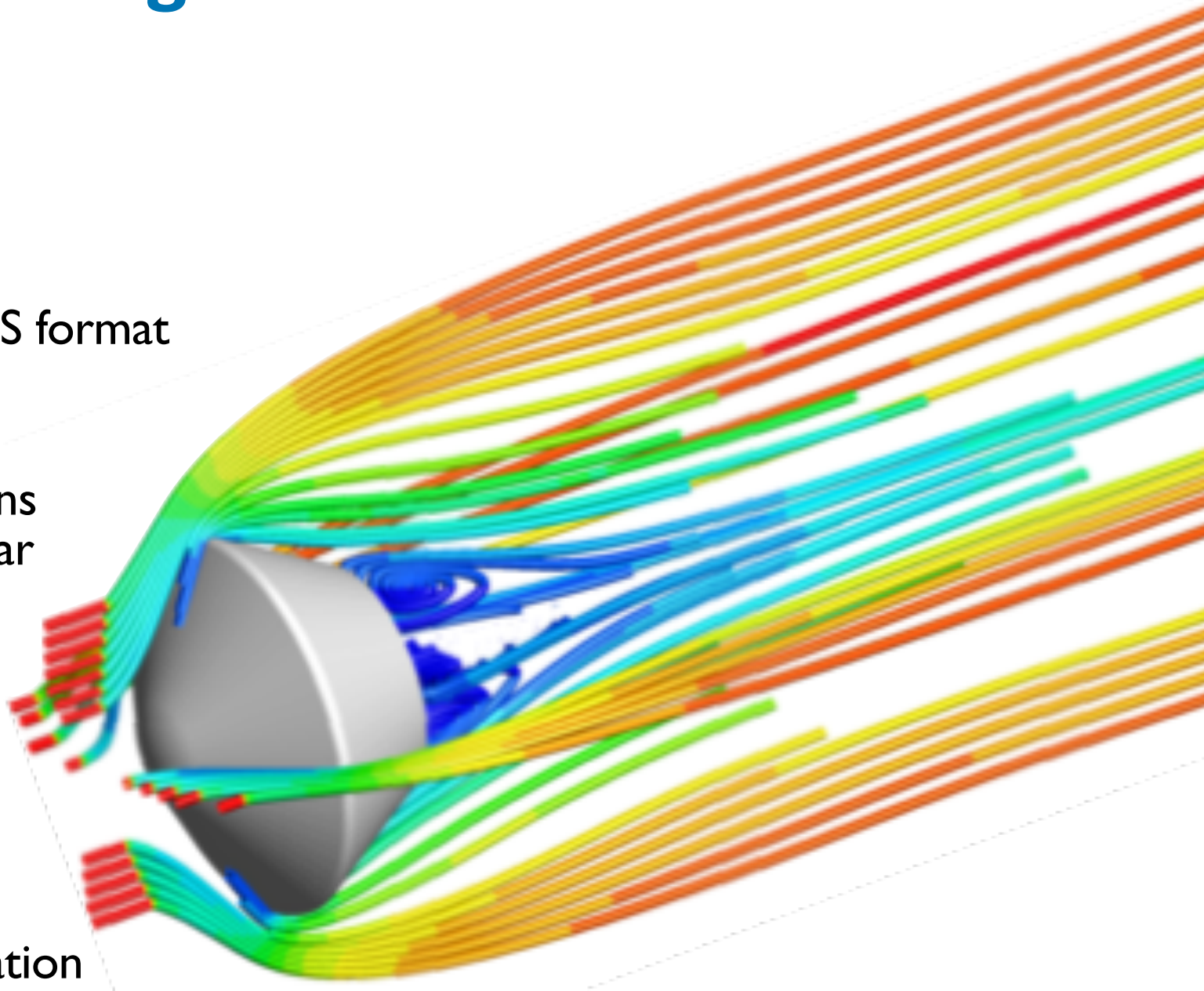
Agrawal et al., 2013

Effects of spallation

- Discrepancies arises between theoretical predictions and experiments performed on ablative material
- Presence of CN emission in the upstream region of the shock was detected in spectroscopic measurements
- Spalled particles vaporize along their path and could alter thermo and chemistry
- Relative dynamics of the particles result in addition of turbulence to the flow.
- However, the significance of the spallation phenomenon is yet to be evaluated



- **General**
 - written in C++
 - reads 3D Unstructured grid in CGNS format
- **Parallelization**
 - ParMETIS for domain decomposition
 - MPI for inter-processors communications
 - PETSC Krylov subspace method as linear solver for iteration
- **Spatial discretization**
 - Cell-centered finite volume method
 - Second-order central differencing
- **Time integration**
 - Fully implicit
 - First-order backward Euler time integration
- **Inviscid fluxes scheme**
 - Steger–Warming flux-vector splitting, AUSM+up, Roe, etc.
- **Numerical flux Jacobian and analytical source Jacobian**
- **Used for**
 - Hypersonic aerothermodynamics
 - Material response
 - Solid mechanics

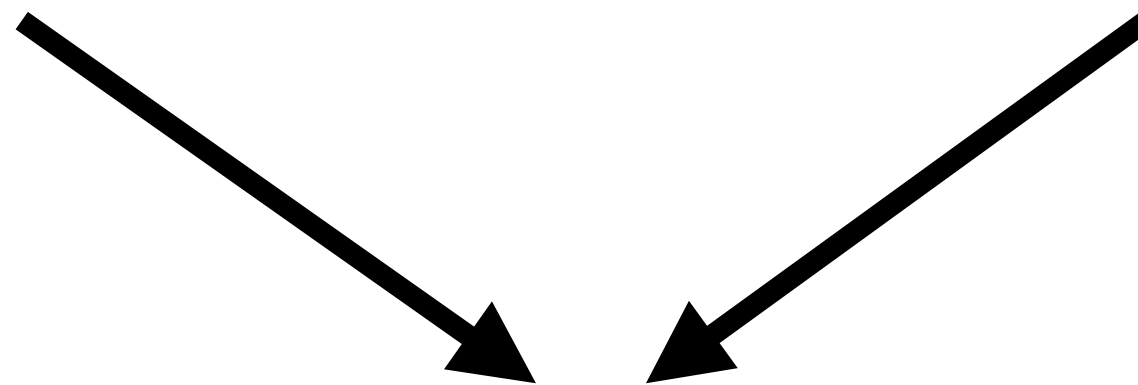


Flow field

- Hypersonic aerothermodynamic CFD code
- Chemical non-equilibrium
- Thermal non-equilibrium (2 temperature model)

Particle

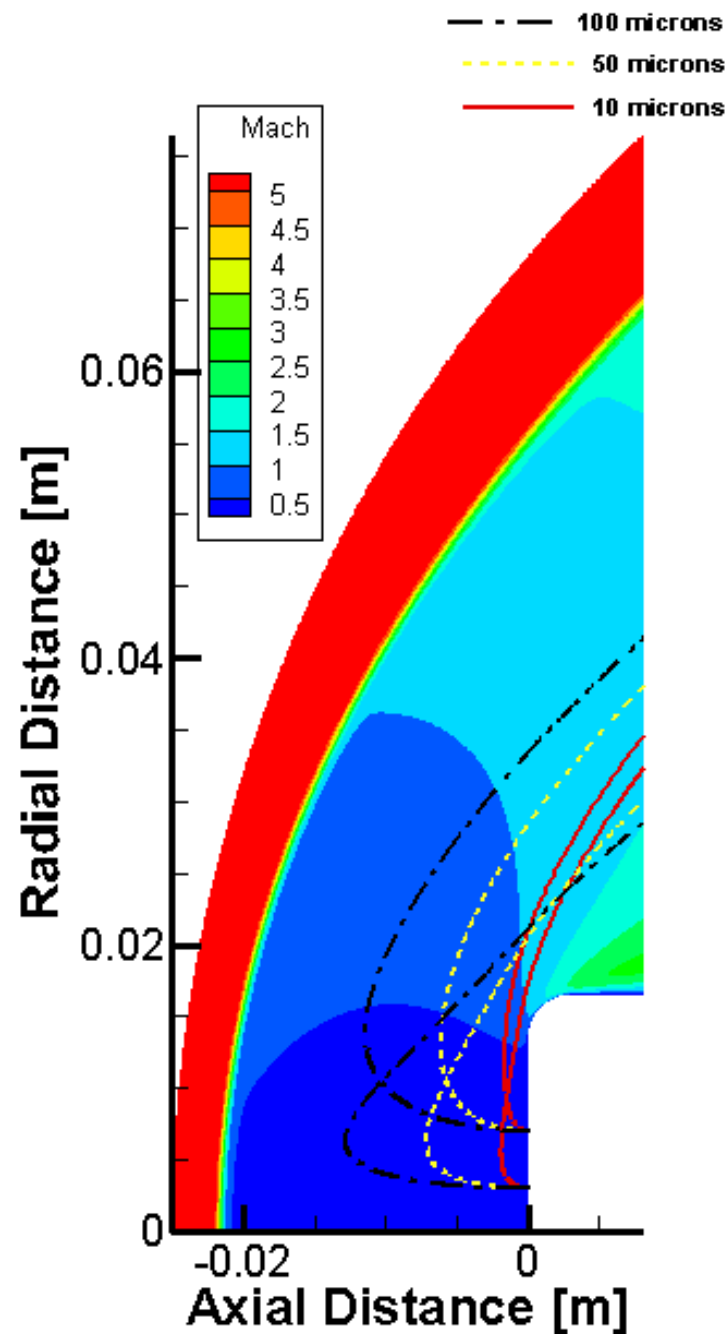
- Lagrangian particle code
- One-way couple using the CFD solution to calculate flight path
- Surface kinetics for particle degradation (oxidation, nitridation, sublimation)



Loosely coupled through the source terms

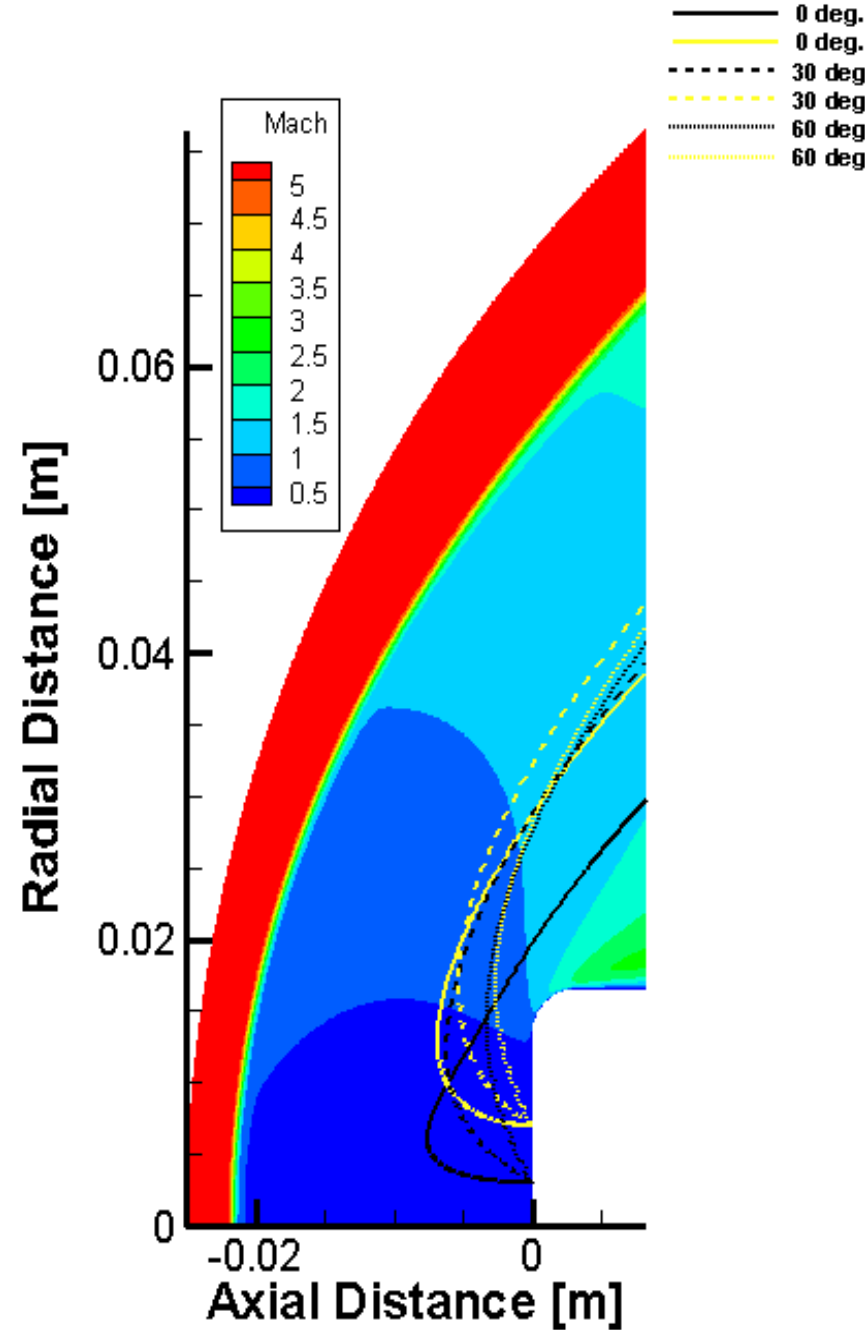
Mach 5 High-enthalpy Argon flow

Radius effect



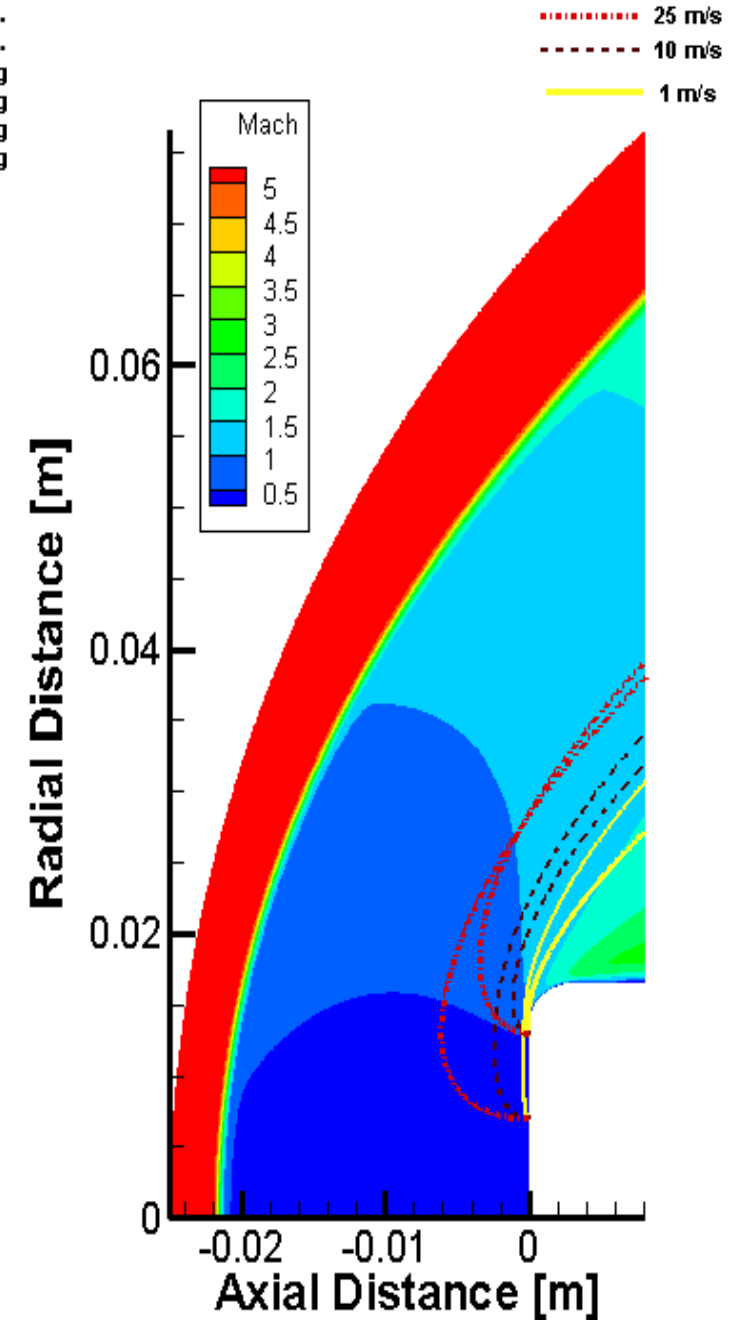
Velocity = 25 m/s
Angle = 0 deg

Angle effect

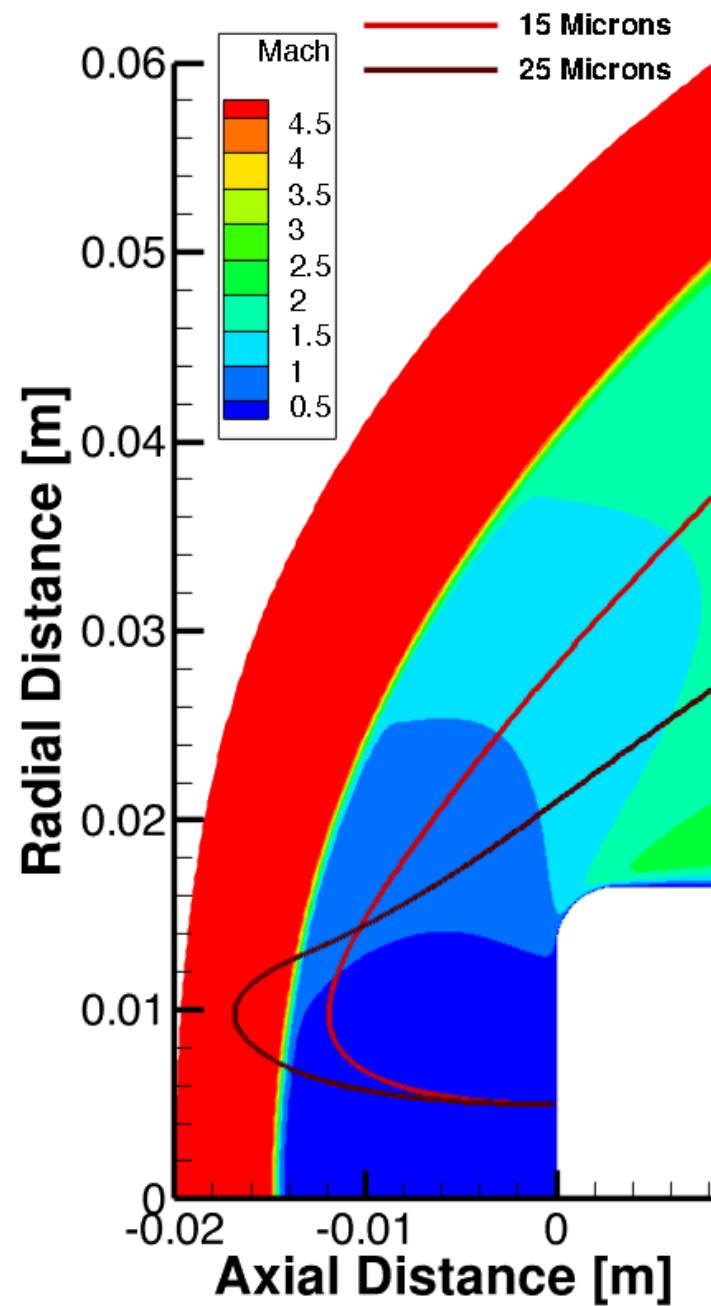


Radius = 10 microns
Velocity = 100 m/s

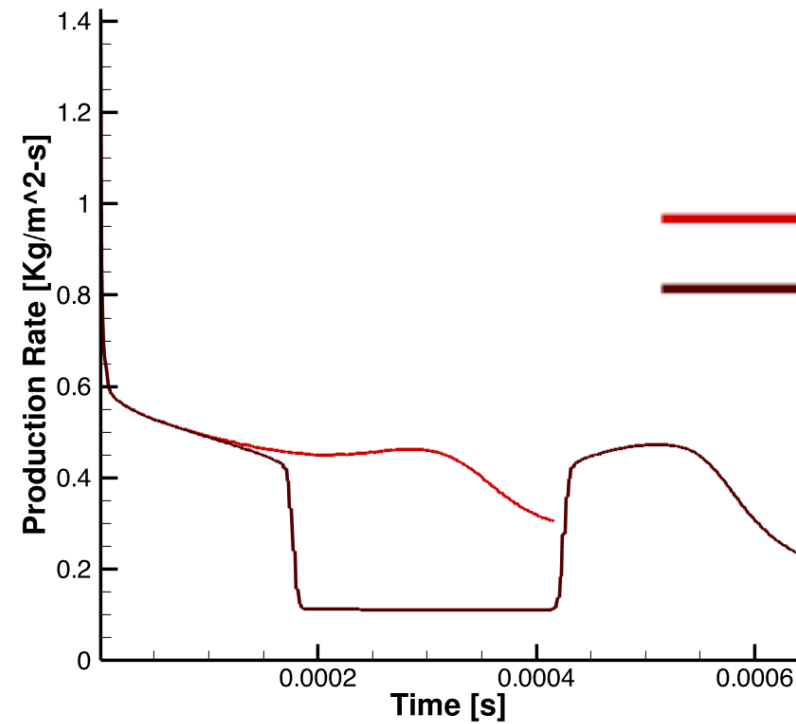
Velocity effect



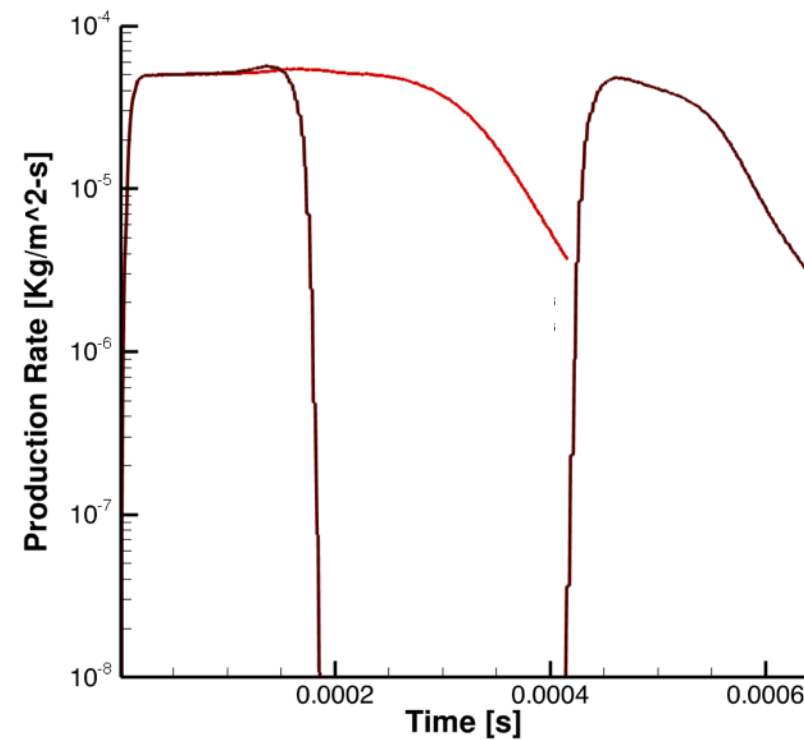
Radius = 50 microns
Ejection angle = 0 deg



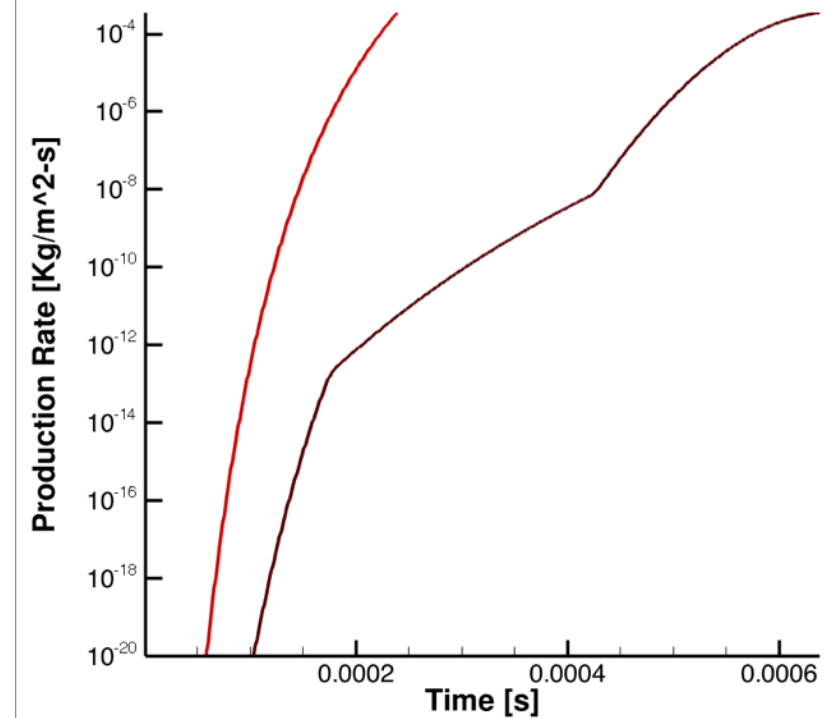
Ejection velocity = 100 m/s
Ejection position = 5 mm



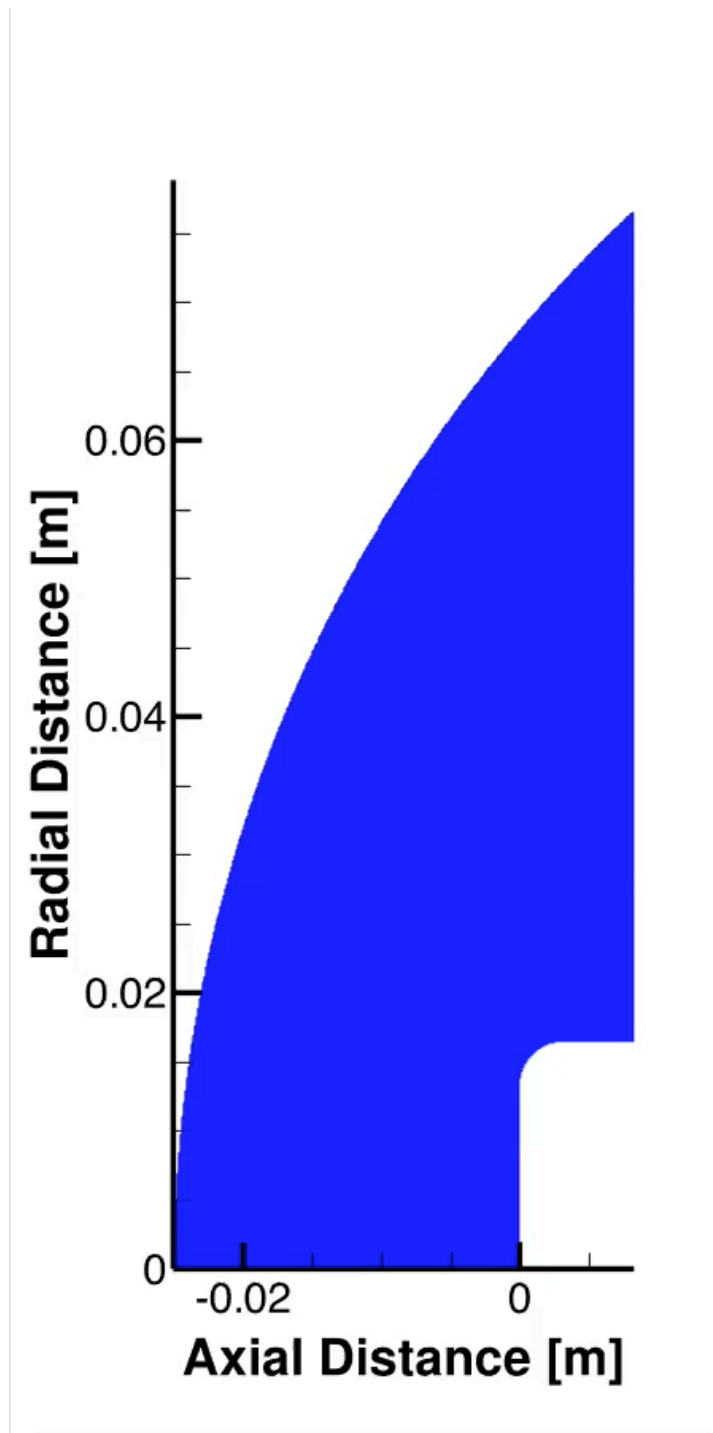
Oxidation



Nitridation

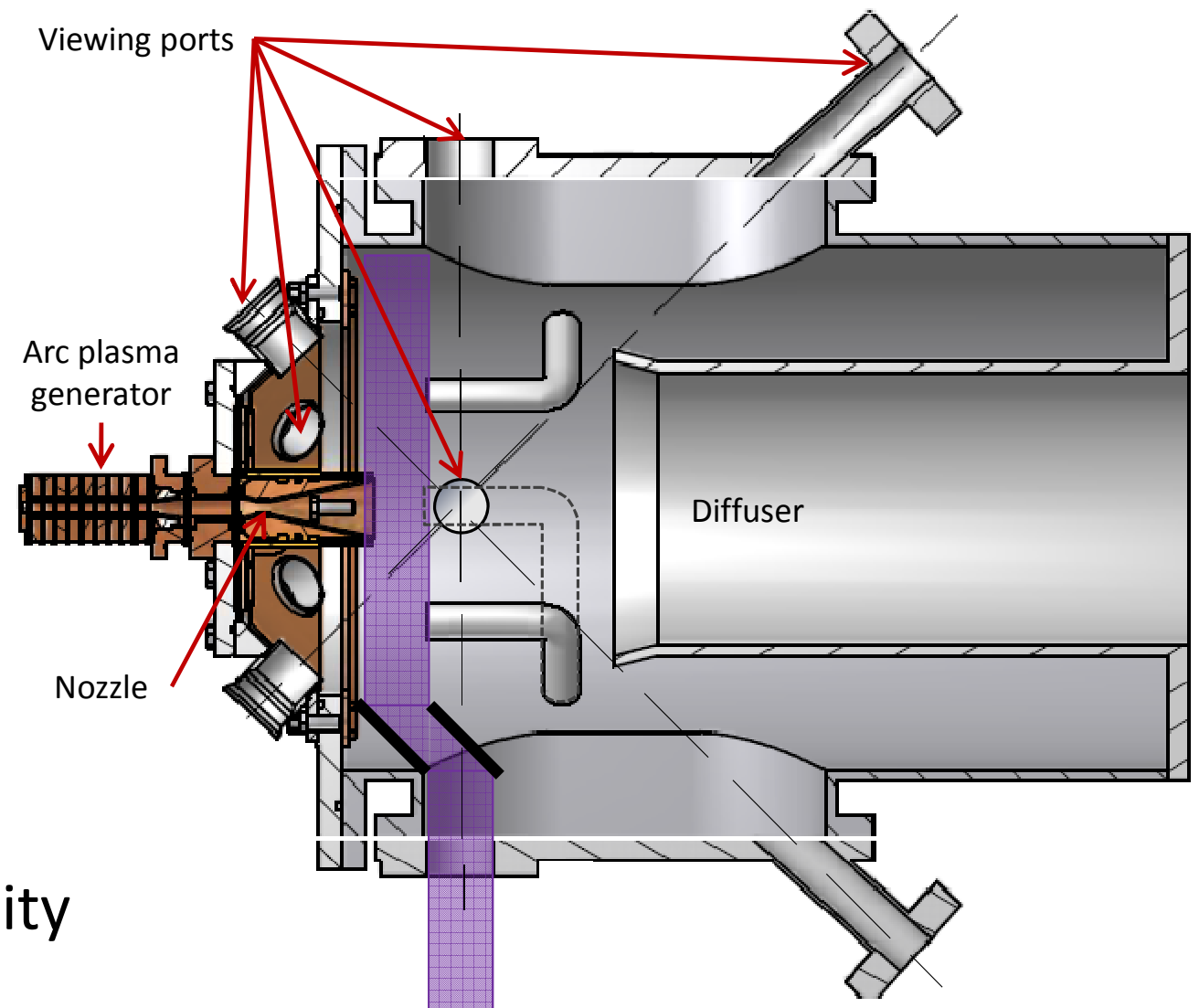


Sublimation



CO mass fraction

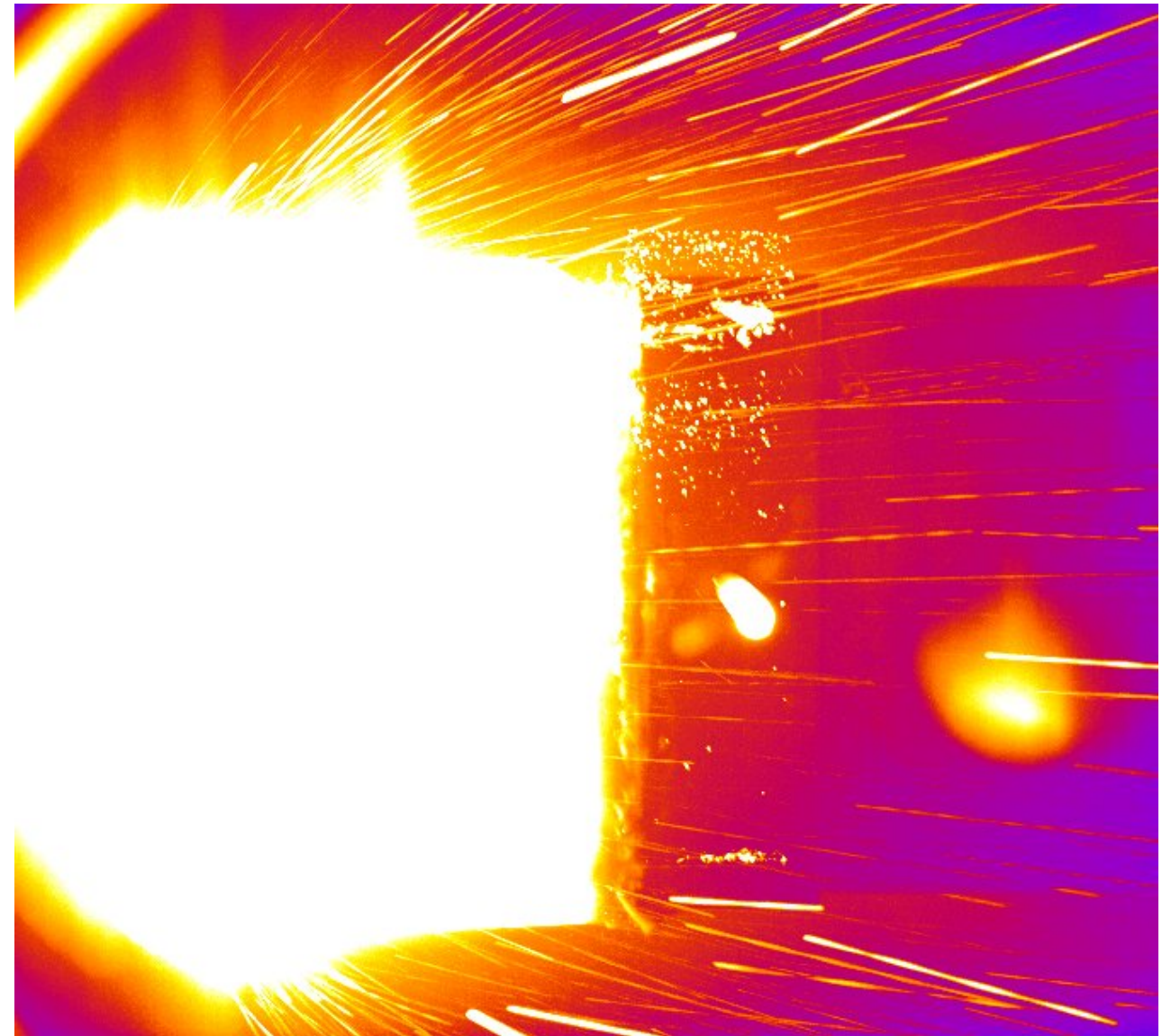
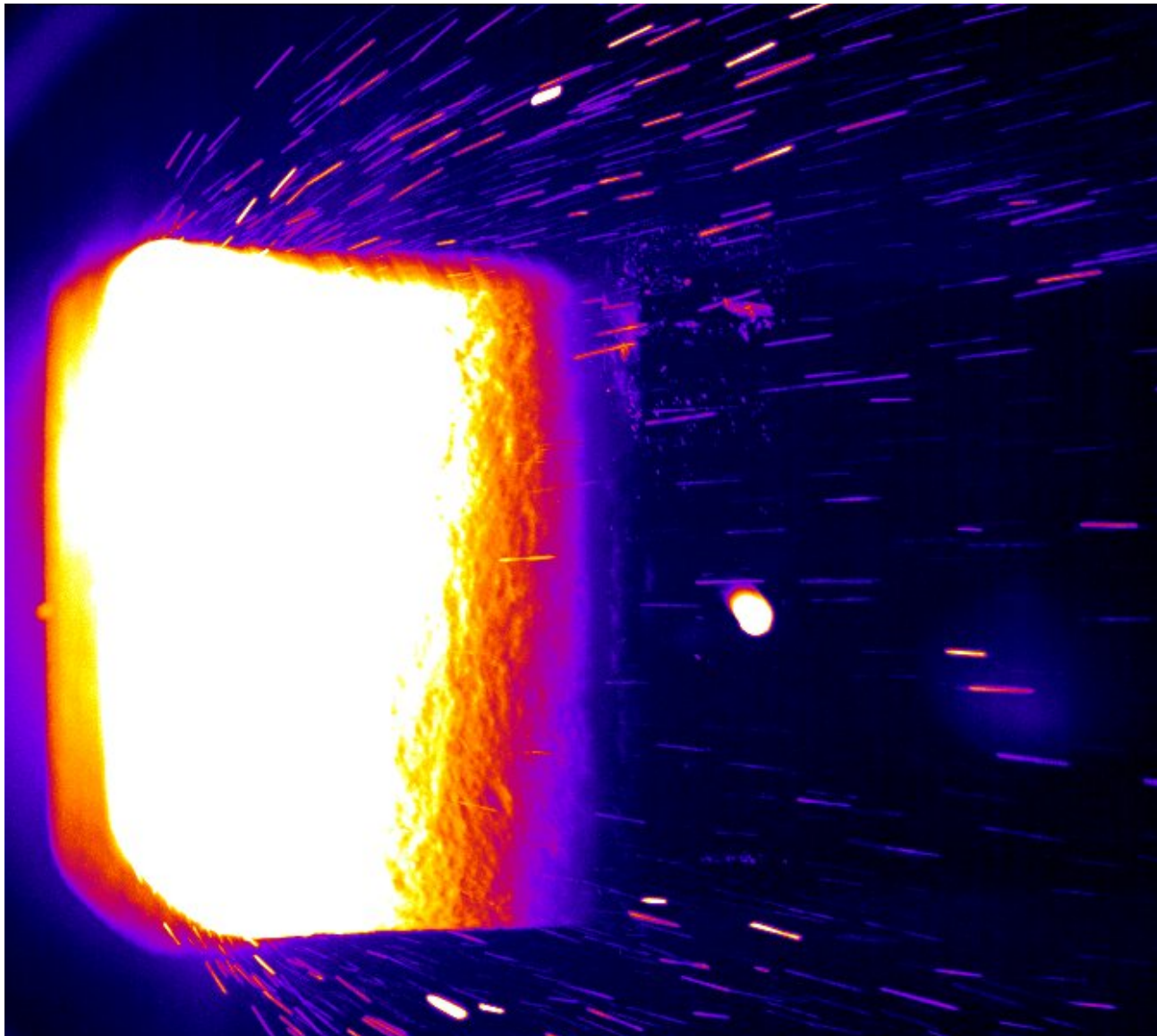
- The Hypersonic Materials Environmental Test System (HYMETs) facility at NASA Langley Research Center.
- Arc-jet wind tunnel with a 400 kW power supply
- Advantage
 - small workforce to operate the facility
 - long run overall time
 - short downtime between runs (sample change)
 - Numerous optical ports for diagnostics and image capturing



Inman, et al., AIAA Paper 2011-1090

Test campaign at HYMETs

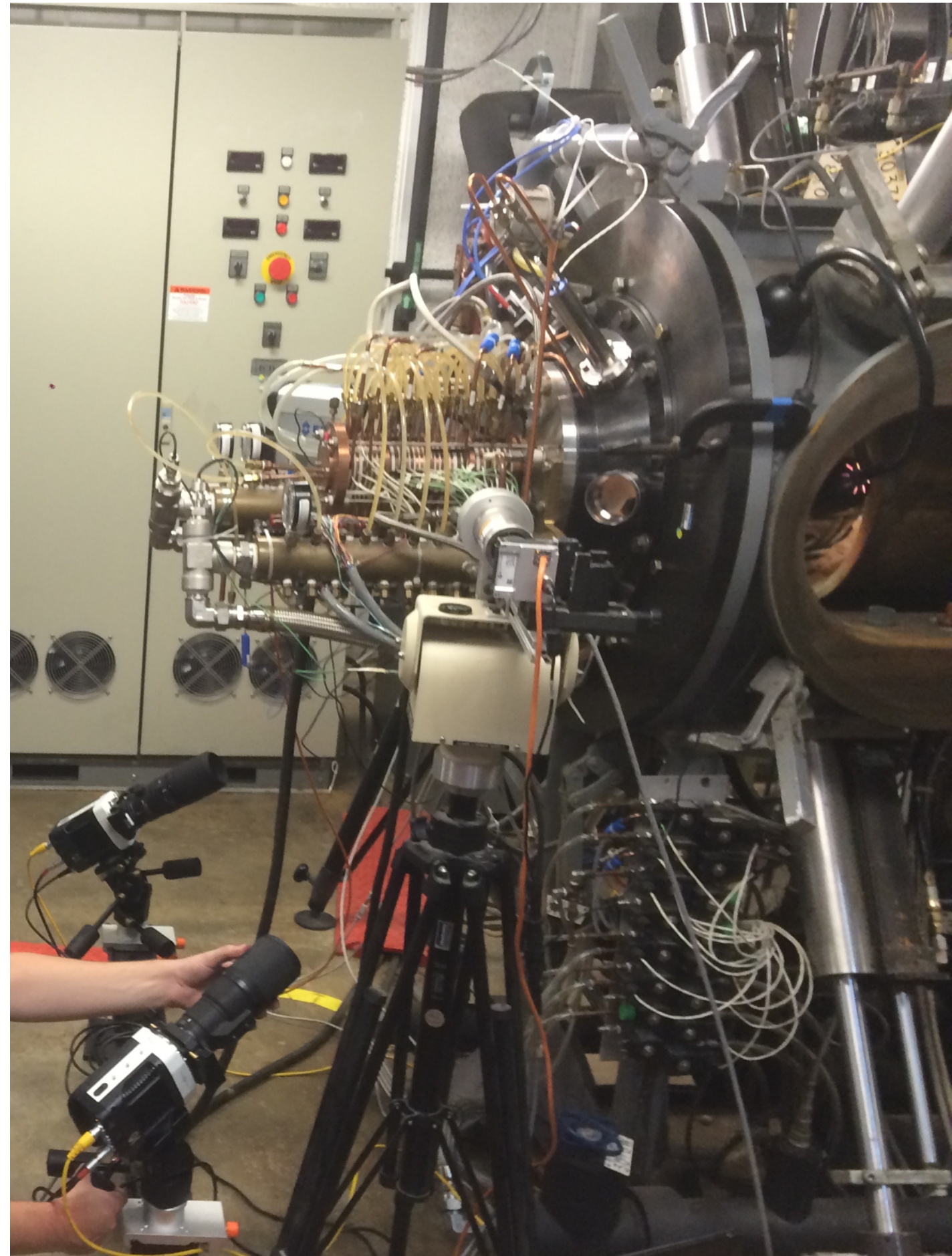
- Preliminary tests to confirm the presence of particles
- A total of 10 samples (PICA and FiberForm) were tested in air plasma using 3 heat flux (100, 200 and 400 W/cm²)



Integrated image of the two FiberForm samples (100 and 400 W/cm²). The image shows the brightest pixel of all the image taken during the whole 30 second run (Phantom Camera)

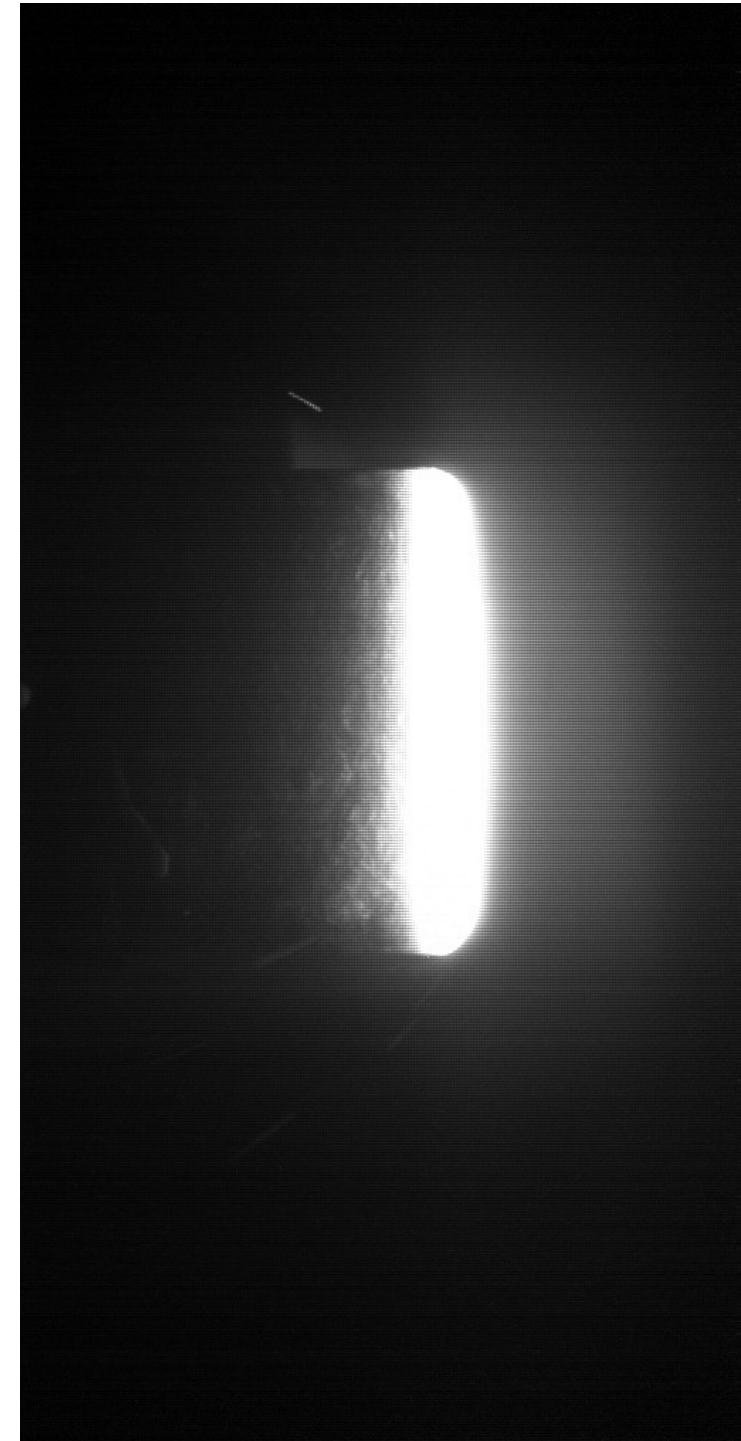
Instrumentation

- 4 different high speed cameras for particle detection at different view angles
- 2 spectrometers (VUV and N-IR)
- 1 infrared camera
- a two color pyrometer for temperature measurements
- intrusive probes for flow calibration
- thermocouples at the back-face of the sample



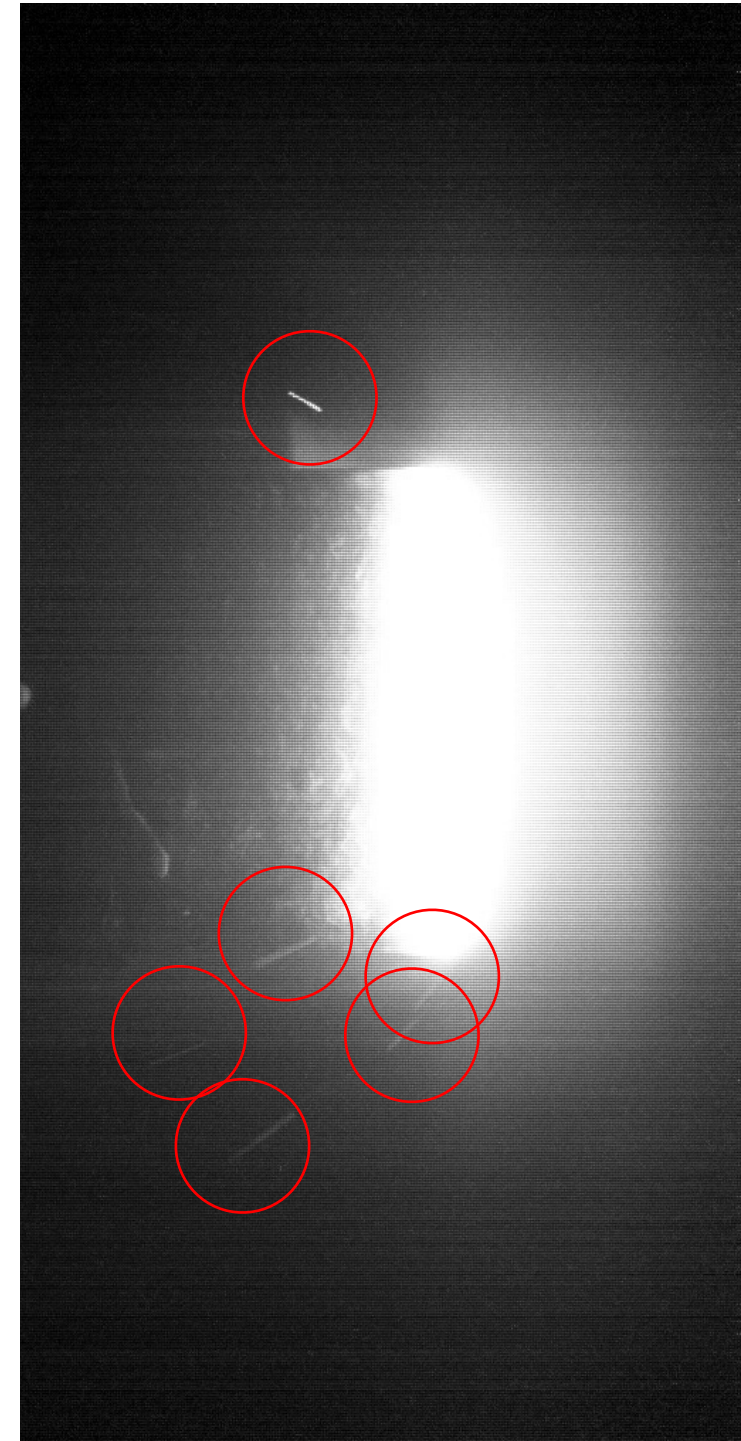
Original image

- FiberForm sample subjected to a 200 W/cm^2 heat flux for 30 s
- Images were acquired using 30 microsecond exposure
- over 800 images were acquired



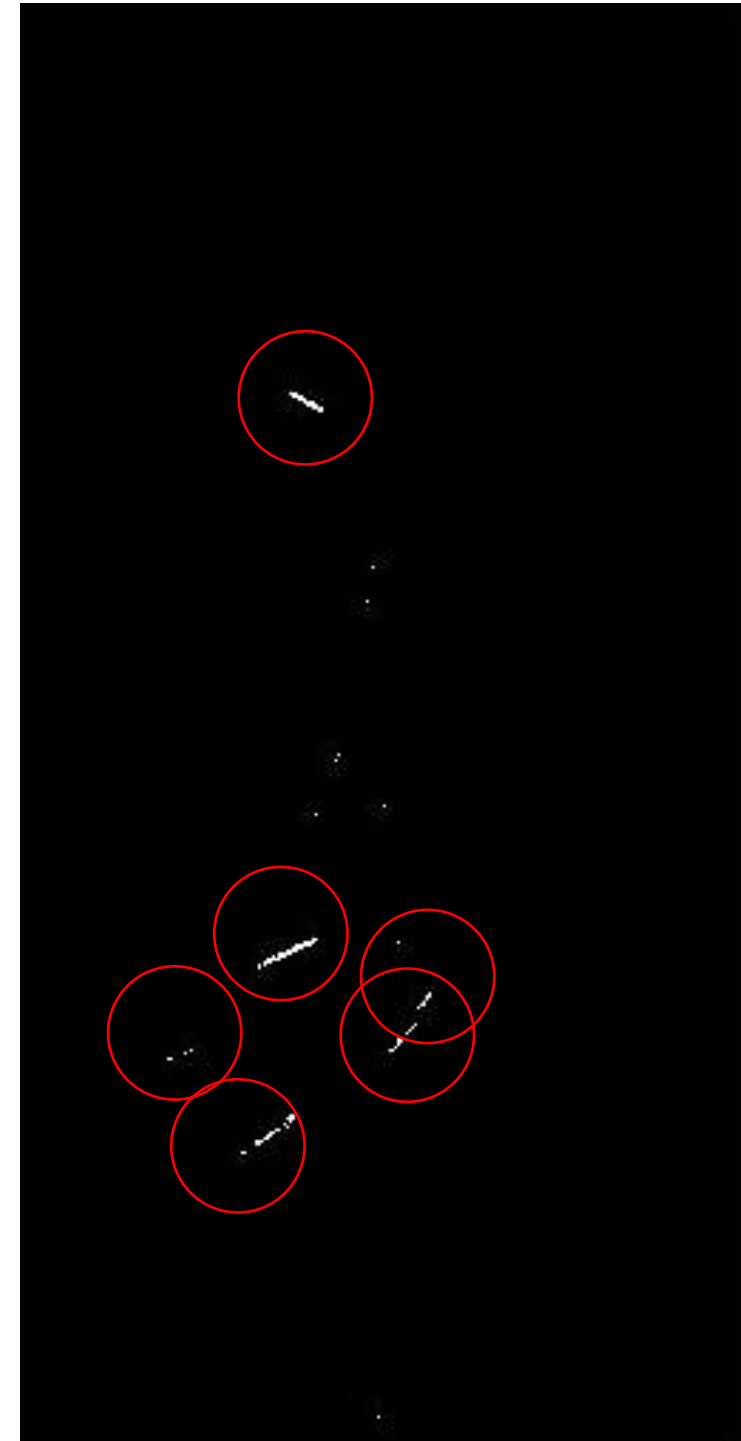
Enhanced image

- Image enhanced using photo editing software
- Multiple spalled particles are seen being ejected from the surface



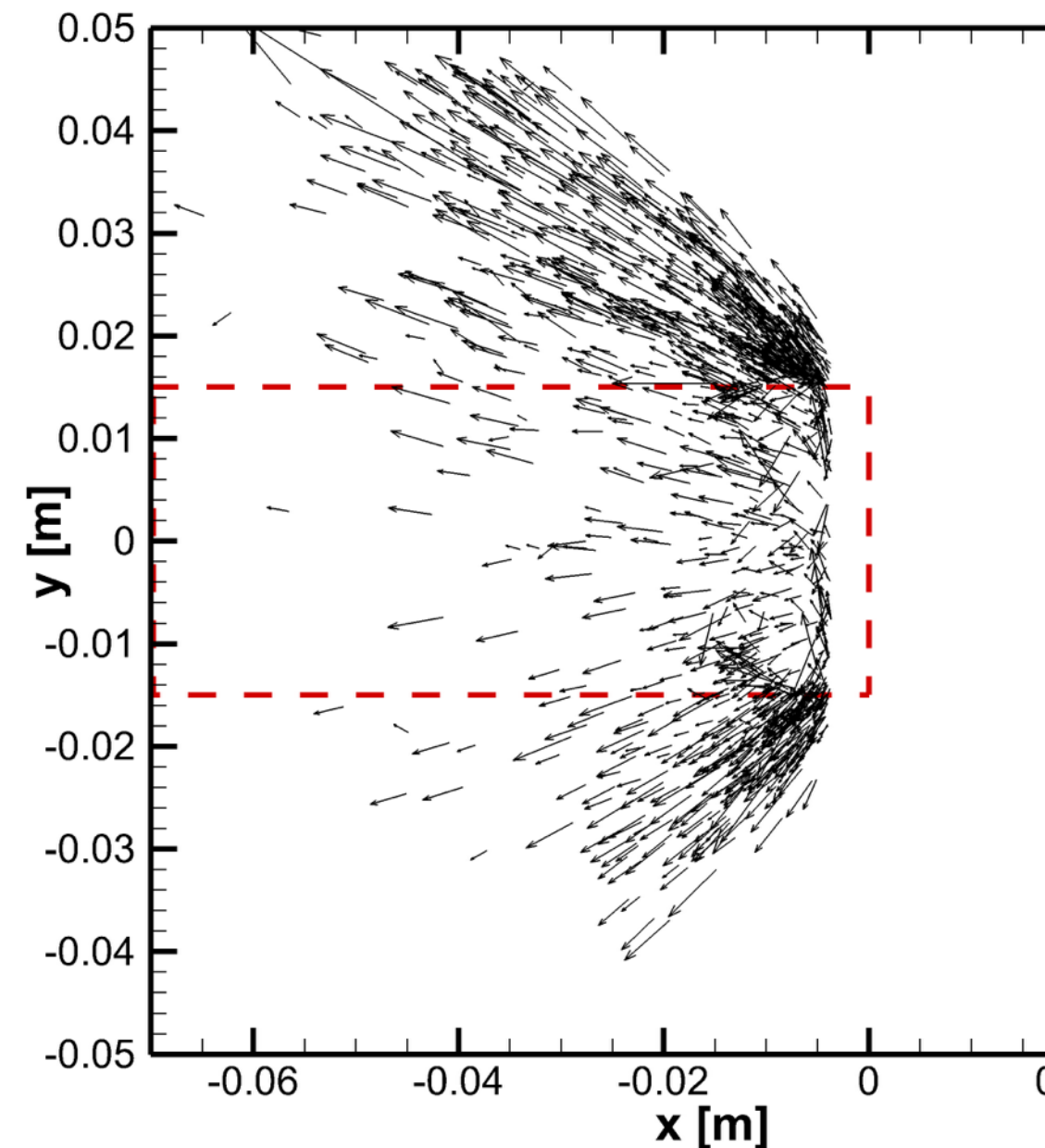
Processed image

- Background subtraction
- Region around leading edge discarded to remove radiated light from leading edge
- Pixel intensity threshold
- Groups of pixels identified as “particles”
- Particles with fewer than 5 pixels discarded



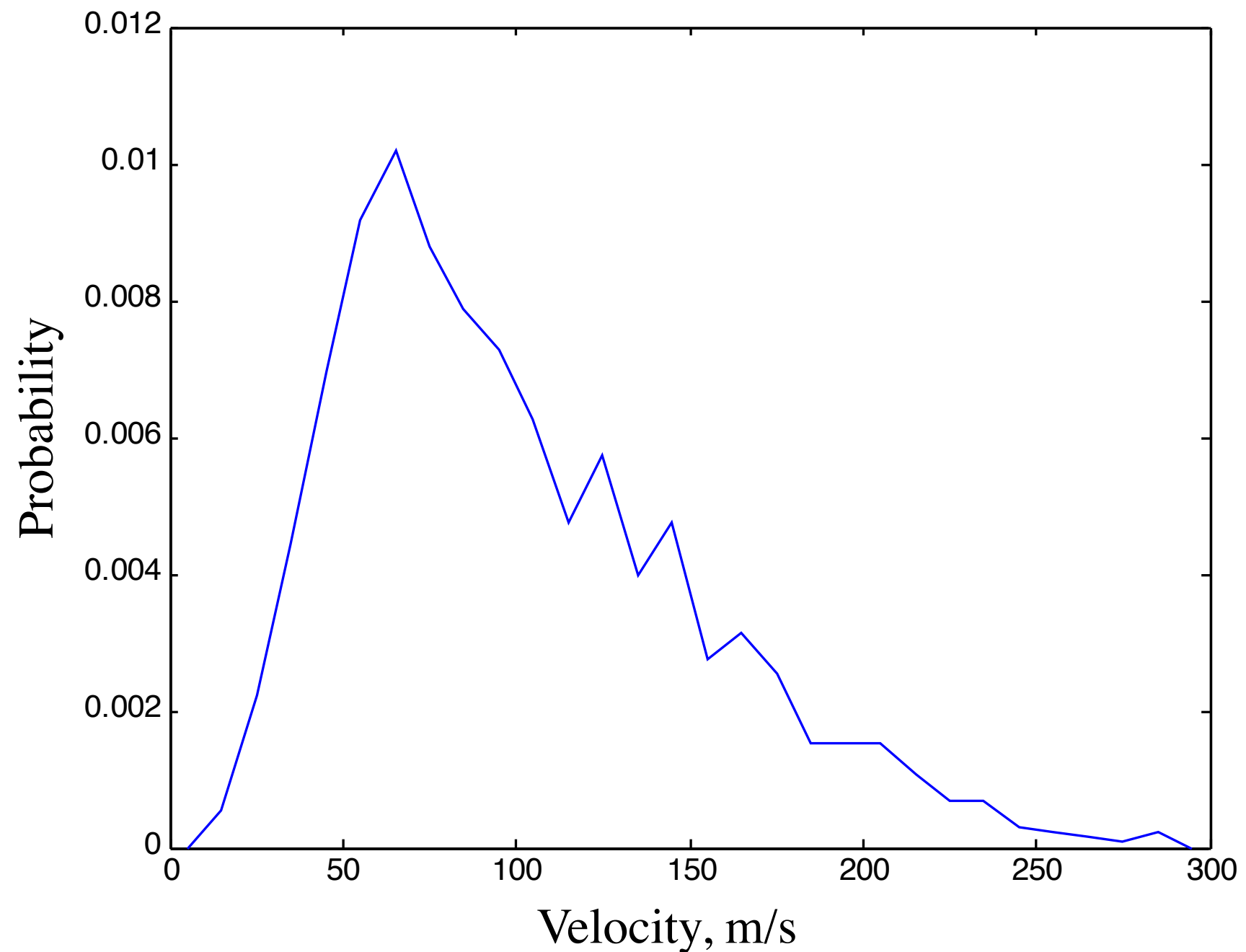
Data

- 1300 particles identified
- Velocity vectors estimated by exposure length and pixel grouping geometry



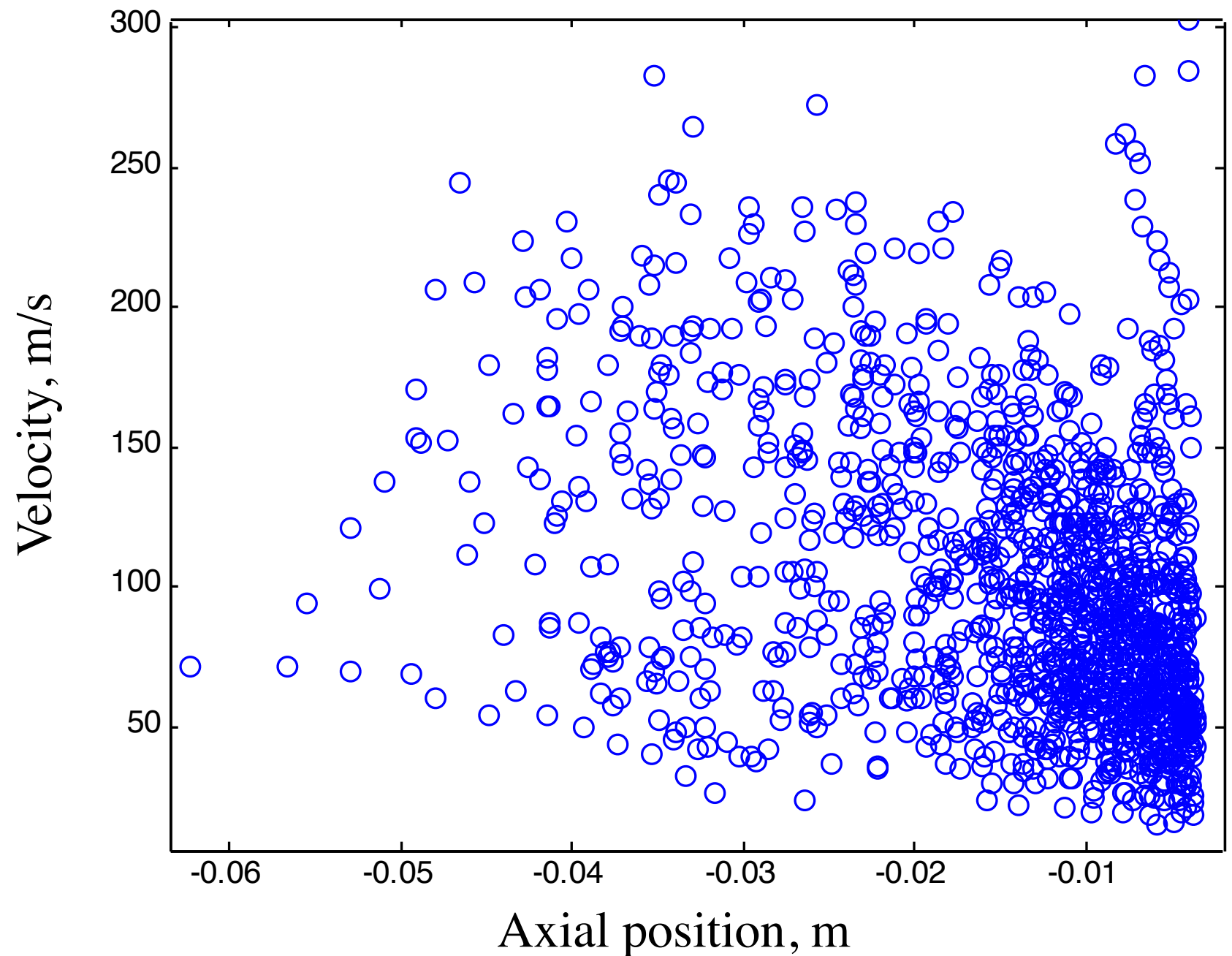
Velocity probability

- Mean velocity of particles 102 m/s
- Skewed distribution
- Most probable velocity: 60 m/s



Velocity correlation

- No obvious correlation between velocity and position
- Acceleration difficult to extract
- More processing required



Post-test characterization of the samples

- High resolution tomography to look at the integrity of individual fibers
- Low resolution tomography to extract density profiles

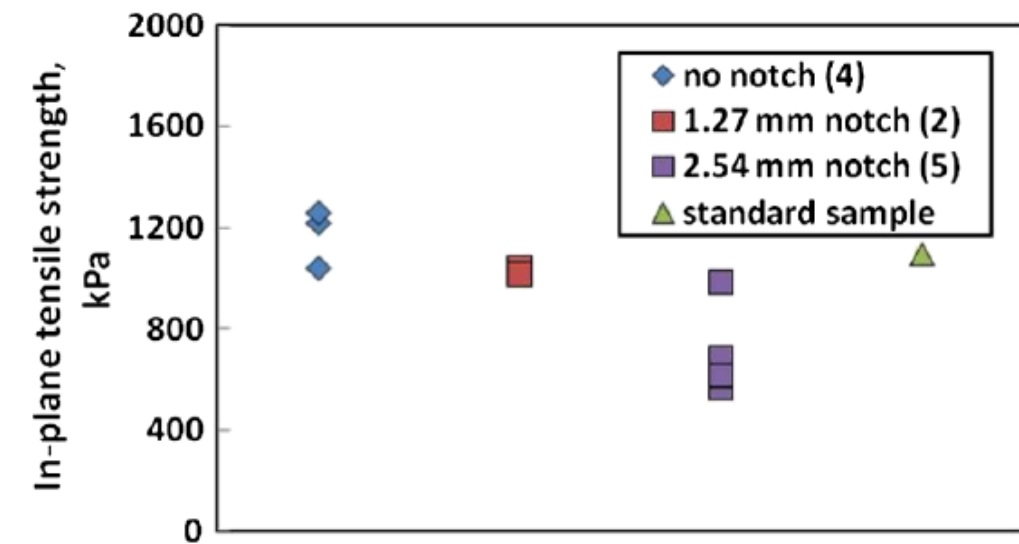
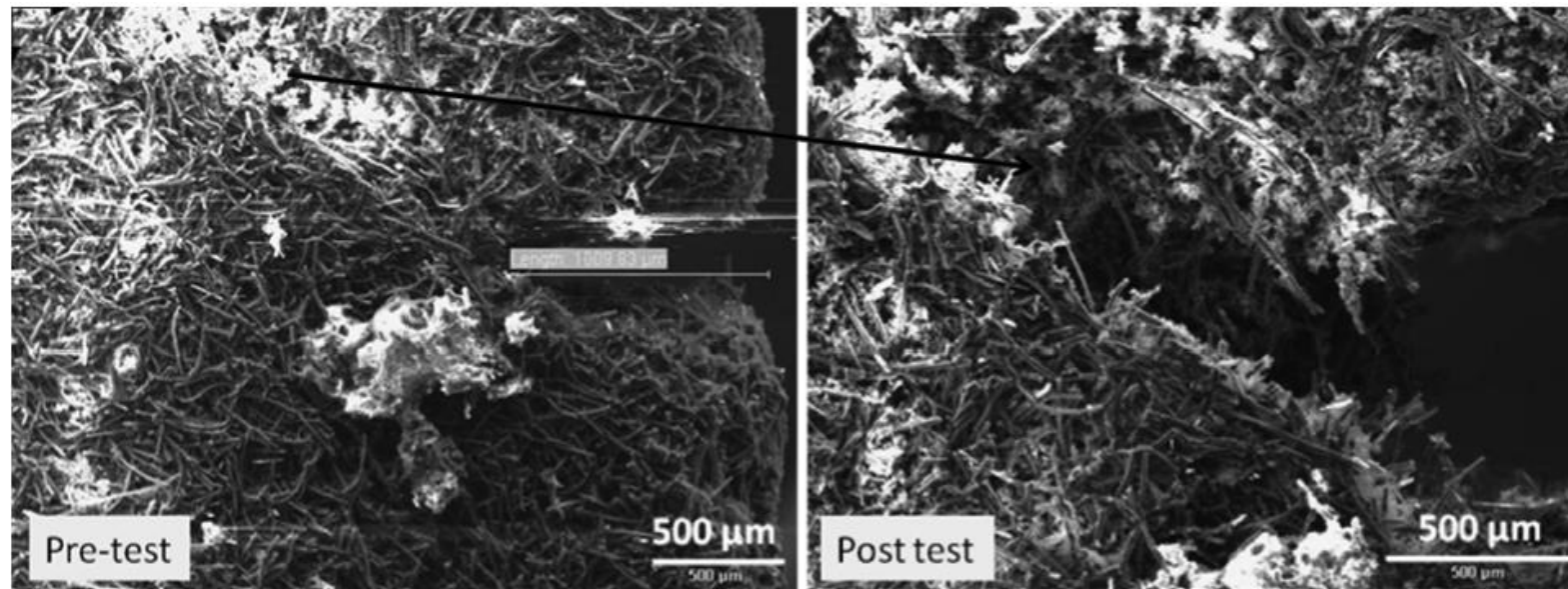
3D stereo reconstruction of particle trajectory

Ejection parameters from particle

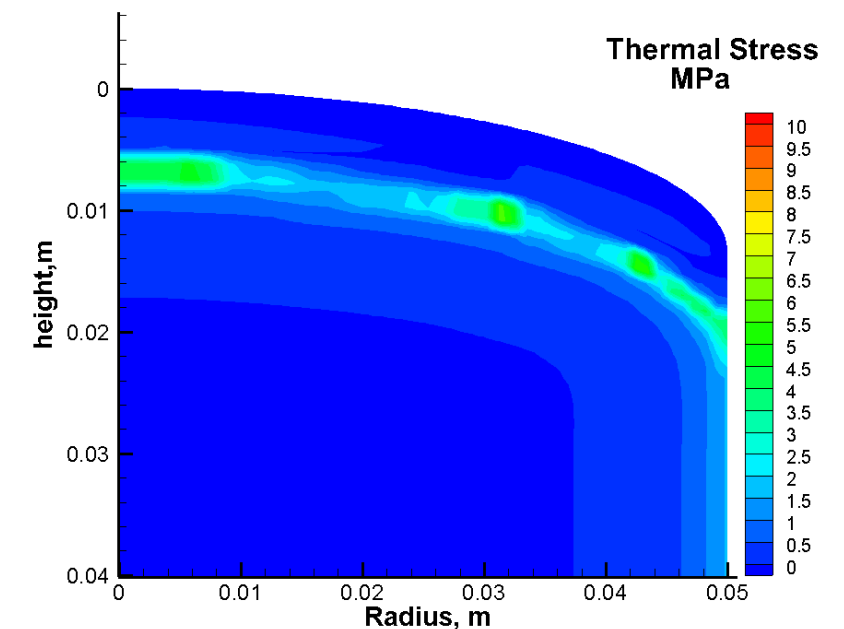
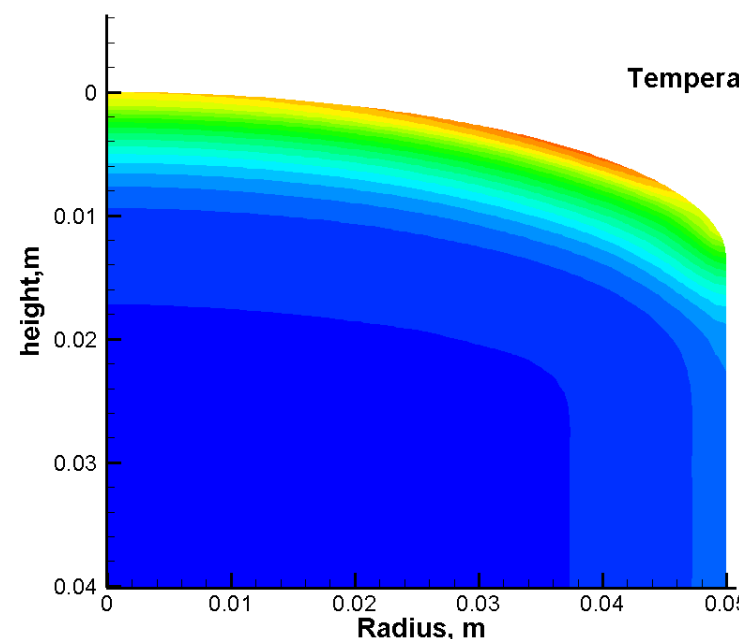
- Model the HYMETs flow field
- Fit the trajectory code to the experimental data using an inverse approach

Thermo-Mechanical Response

- Most specimens failed between 600 and 900 kPa
- The charred PICA samples made from arc-jet articles showed similar behavior and tensile strength as the furnace char



- 10 sec of constant heat flux
- High stress region does not correspond to high temperature region
- When combine with volumetric fiber ablation, could results in mechanical erosion



Questions?