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Characterization of a 50kW Inductively Coupled Plasma Torch for Testing of Ablative Thermal Protection Material

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  - Daniel Cha
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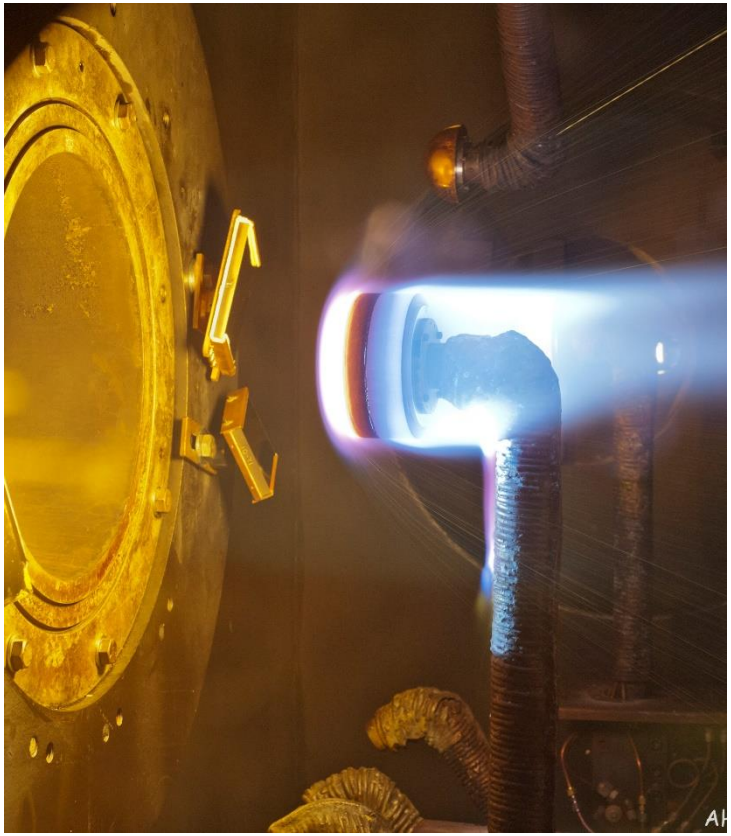
Research Motivation

- Atmospheric entry
  - Typical lunar return reentry velocity: 11 km/s
  - ~10 metric ton reentry vehicle
  - 500 GJ of kinetic energy
  - 15 min from entry to landing
- Thermal protection
  - Ablative heat shields
    - Rely on pyrolysis and mass loss
    - Non-reusable
  - Thermal soak
    - Heat absorbed into TPS material
    - Must be either cooled or ejected

Research Motivation

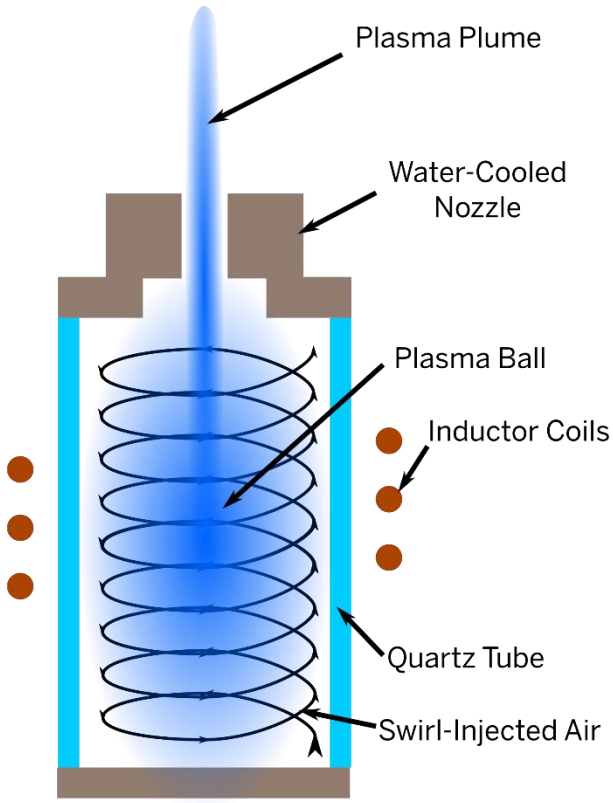


- Ground testing
  - Replicate Mach number, heat flux, pressure, and surface velocity gradient
  - Understand chemistry of pyrolysis
  - Develop computer models of heat shield mass loss and thermal soak
- Difficult to replicate all parameters
- Use different facilities to replicate specific features
- Combine data in computational models

High-Enthalpy Flow Facilities

- Impulse facilities
  - Gun tunnels, shock tubes, expansion tubes, Ludwieg tubes
  - Use unsteady shock motion to generate high-enthalpy, high-velocity flow
  - Run time on order of milliseconds
- Arcjet
  - Use high-voltage discharge to superheat flow
  - Run time virtually unlimited
  - Metal electrodes contaminate flow
- Inductively Coupled Plasma (ICP) Torch
  - Use fluctuating magnetic fields to superheat flow
  - Run time virtually unlimited
  - No metal electrodes in contact with flow
  - Typically run at lower pressures than arcjets

What is an ICP

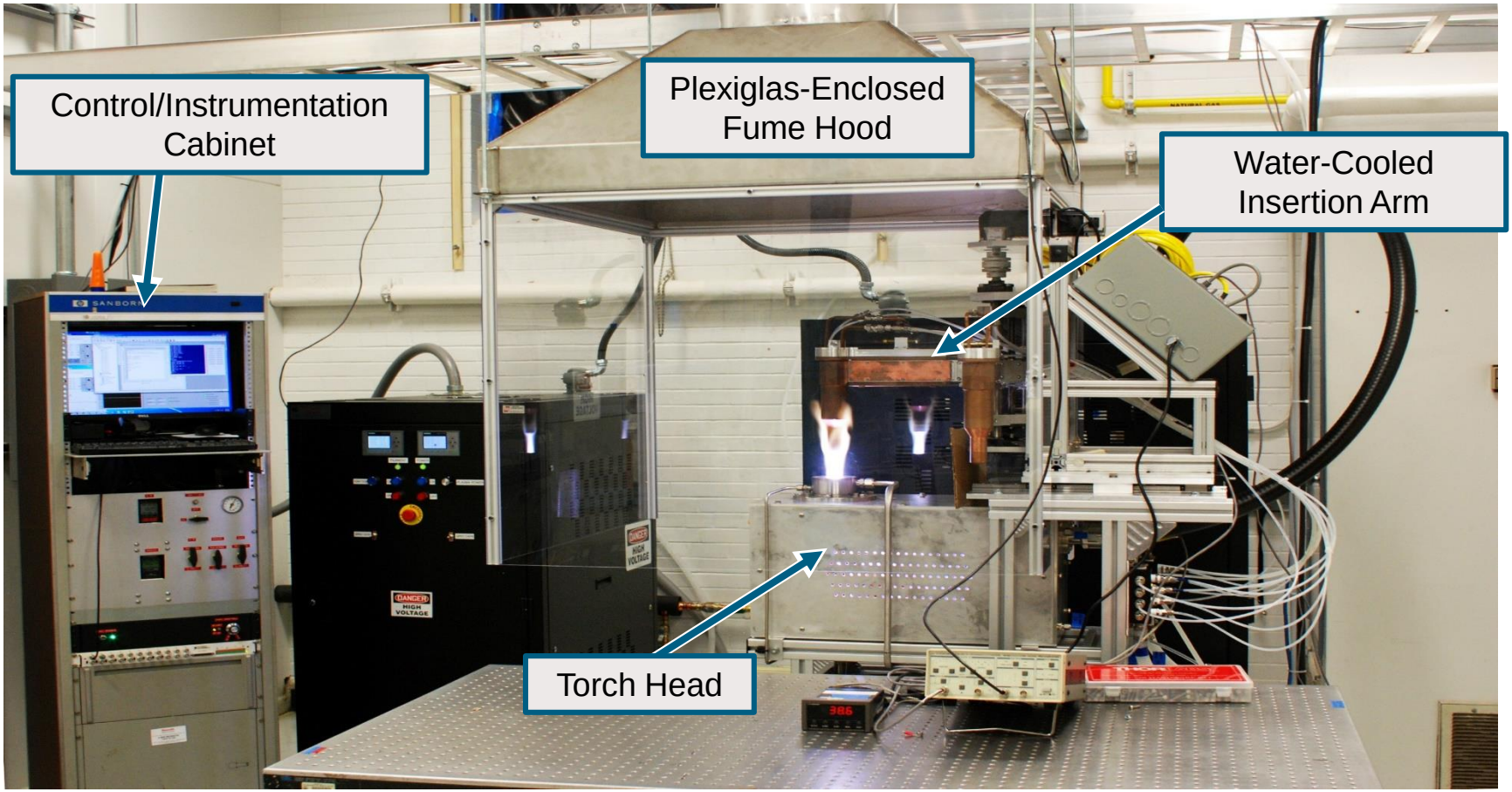


- Induction coils fed with high-voltage MHz AC power
- Fluctuating magnetic field generates electric field necessary for gas breakdown
- Gas injected into cooled quartz tube inside coil
- Swirling motion of air keeps plasma ball away from walls
- Superheated air forced through water cooled nozzle

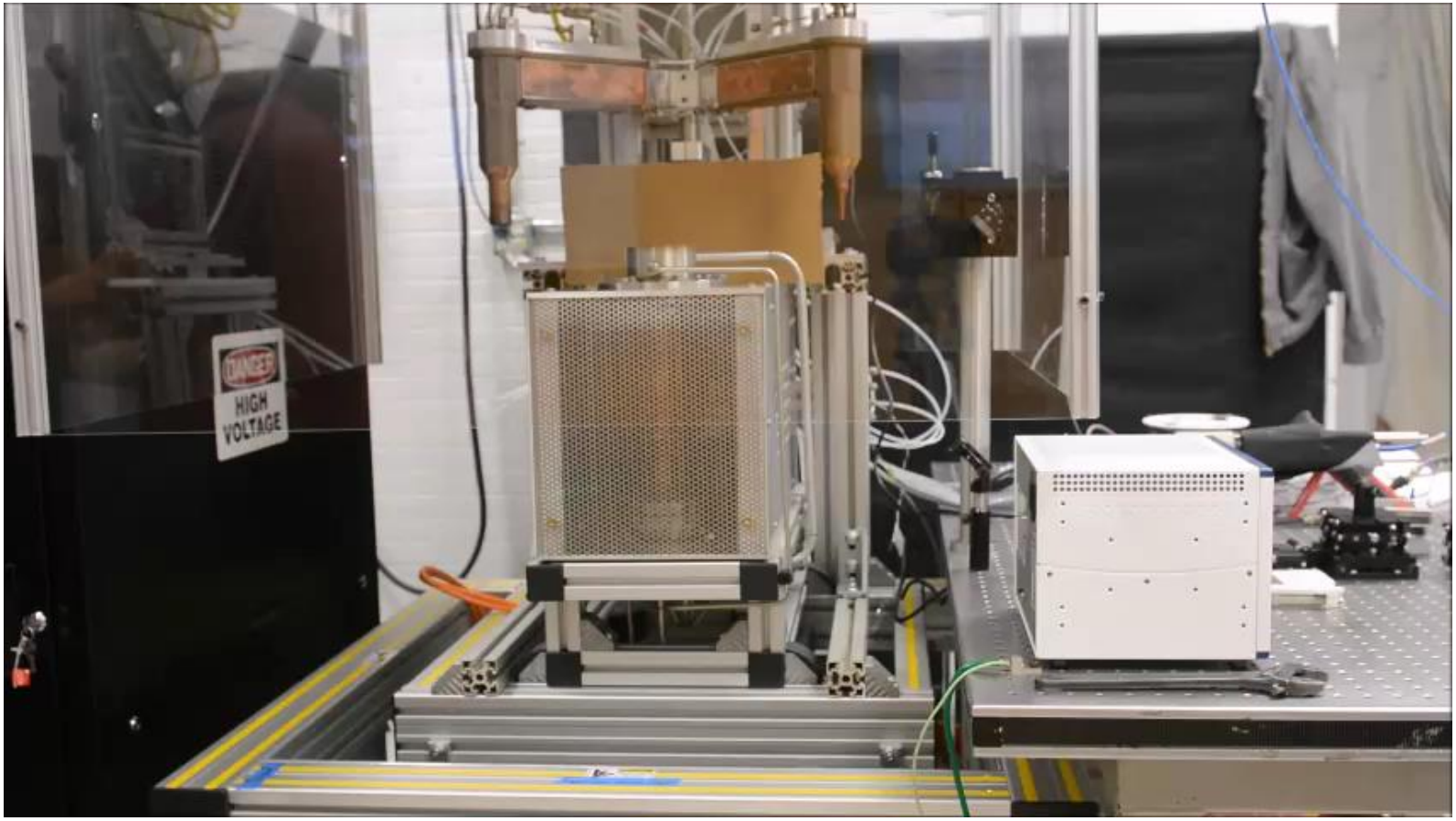
Current Facility

COMPONENTS AND CAPABILITIES

Current Facility

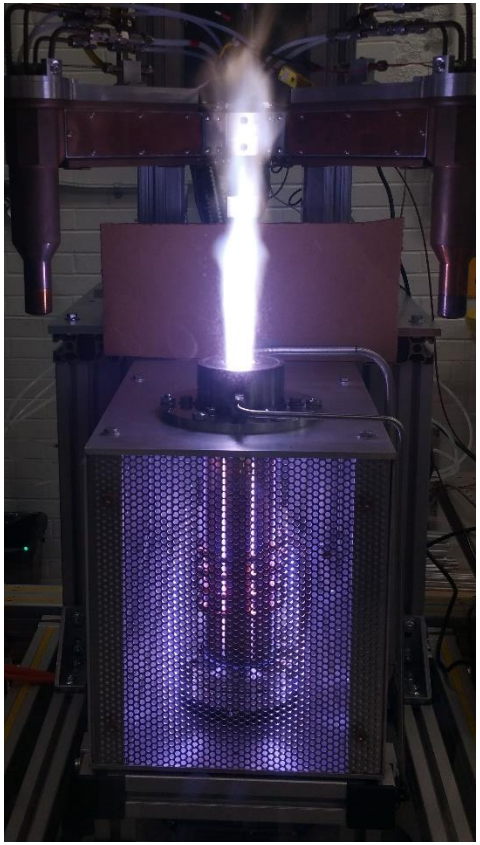


Video of Startup



Torch

- Developed by Applied Plasma Technologies
- Up to 50kW inductively coupled plasma
- Coil voltage between 9 kV and 12 kV at 6 MHz
- Plasma chamber
  - Water-cooled quartz tube
  - 250 mm in length
  - 30 mm exit nozzle
- Torch head tethered to power supply with flexible cable



Traverse Table

- 3-Axis translation with 1 ton capacity
- Move torch with respect to a fixed optical diagnostic setup
  - Resolution: 0.5 mm
  - Travel: 150 mm
- Allows optical diagnostics to probe arbitrary locations in plume with no readjustment of optics

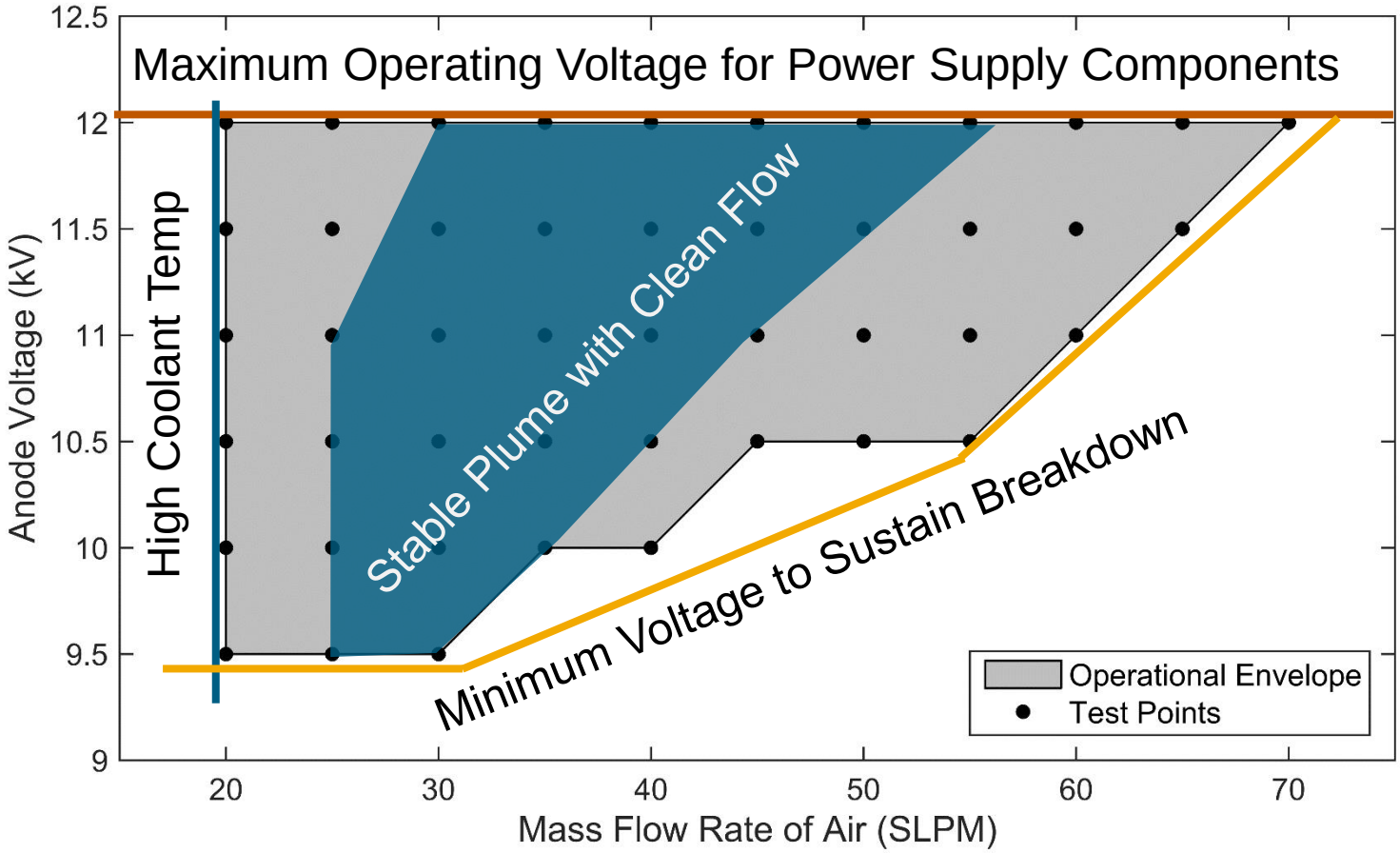
Insertion Mechanism

- Developed by NASA collaborators
- Two water-cooled arms
- Adjustable height above torch
  - 0 to 150 mm
- Motorized insertion
  - Fast: 45° per second
  - Slow scan: 1 mm resolution through plume diameter
- Adapters for mounting instruments and test articles

Testing Results

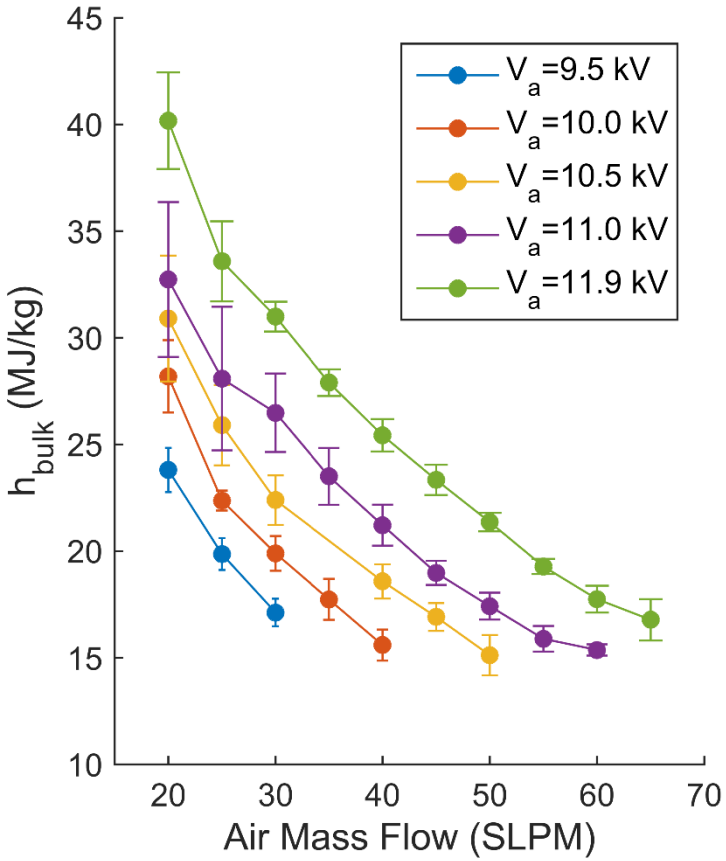
FLOW CHARACTERIZATION

Operational Envelope



Bulk Enthalpy

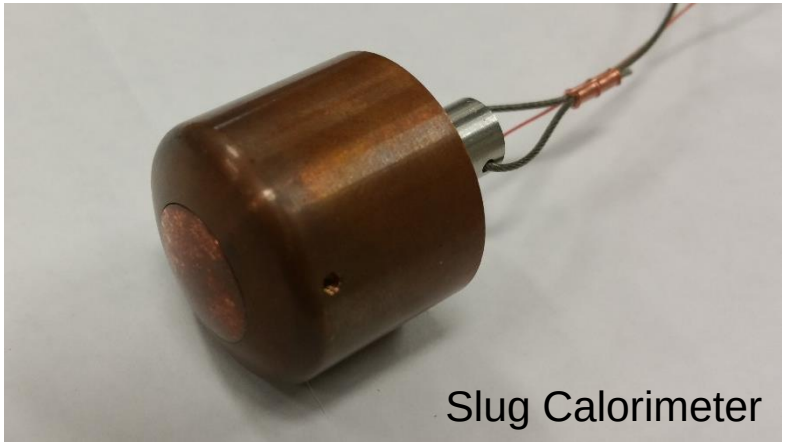
- $P_{plasma} = V_a I_a - \dot{m}_{H_2O} c_p \Delta T$
- Use P_{plasma} to calculate bulk enthalpy of gas
- $P_{plasma} \approx constant$ for given voltage
  - Increased flow rate for given voltage decreases bulk enthalpy of gas



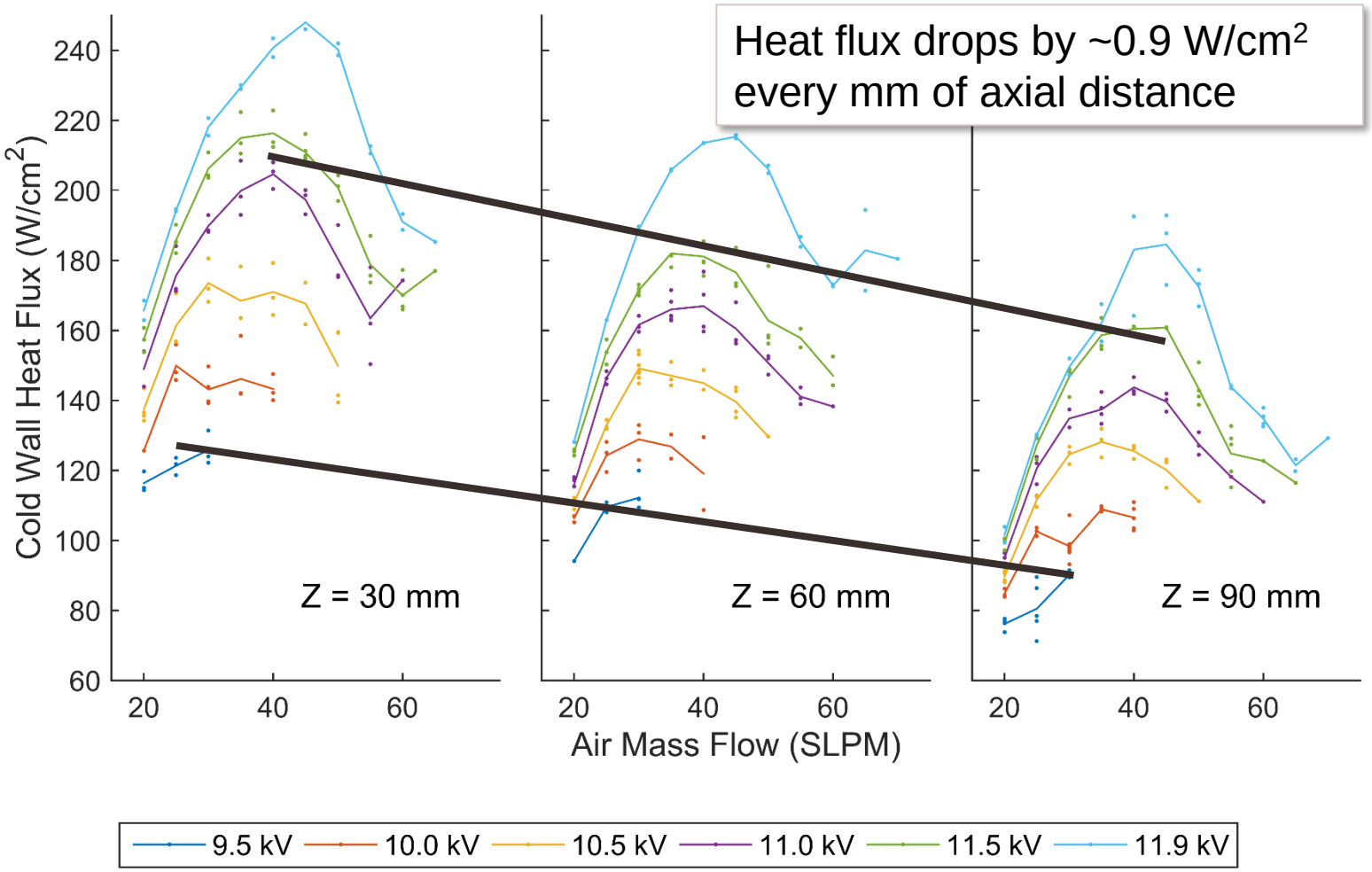
Heat Flux

- Medtherm gardon gauge heat flux sensor
  - Consists of a constantan foil thermocouple junction
  - Water cooled
  - Outputs a voltage proportional to the incident heat flux
- Slug calorimeter heat flux sensor
  - Type K thermocouple embedded in copper slug
  - One face of copper slug exposed to flow
  - Heat flux related to slope of temperature rise
    - $q = \frac{mc_p}{A}\dot{T}$

Gardon Gauge


Slug Calorimeter

Heat Flux (Gardon Gauge)



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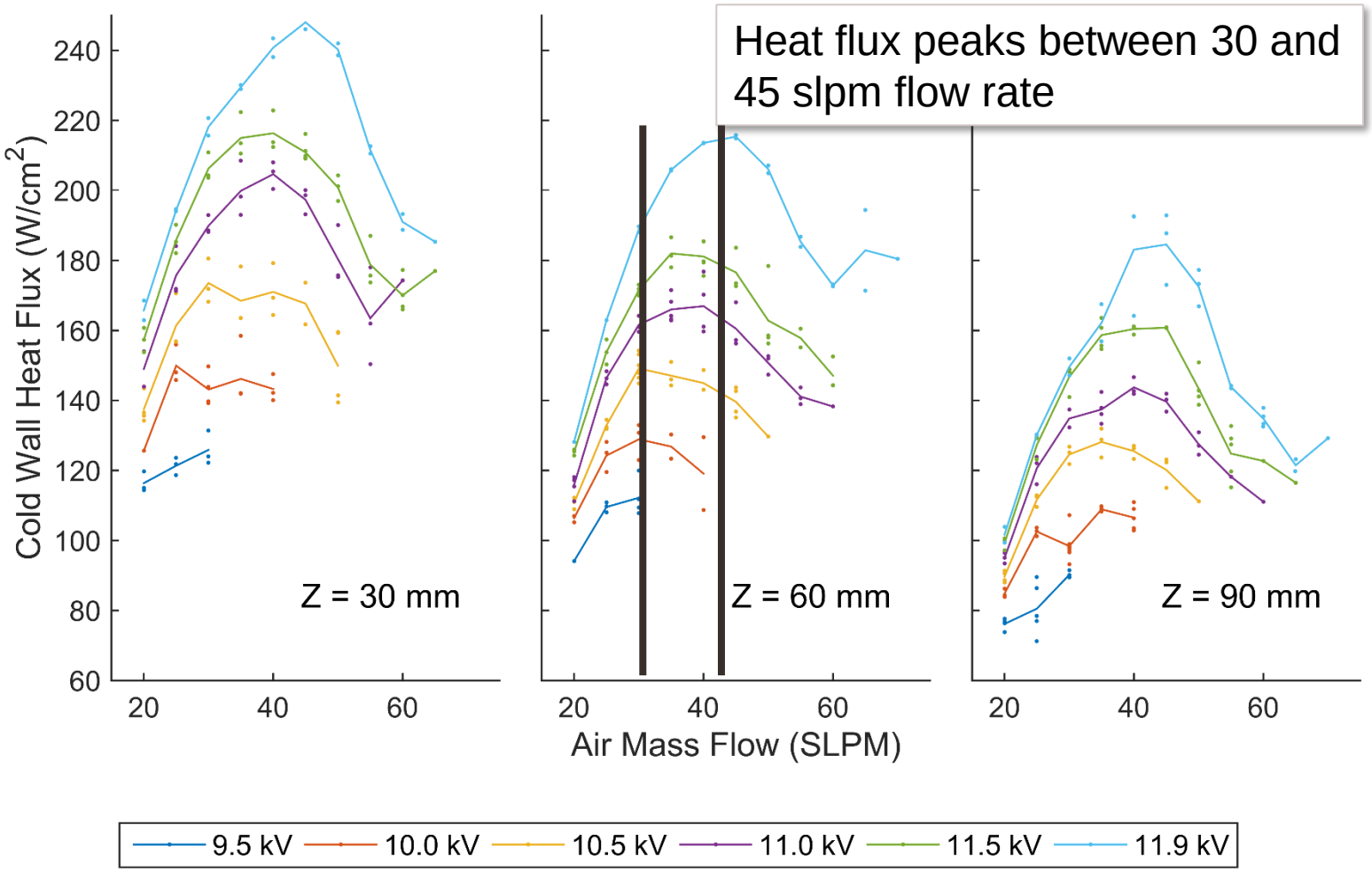
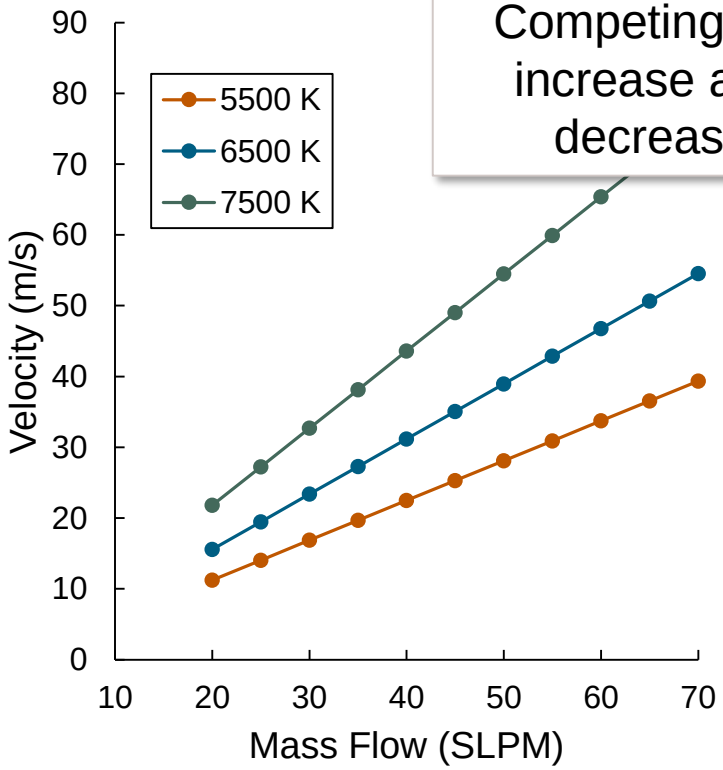
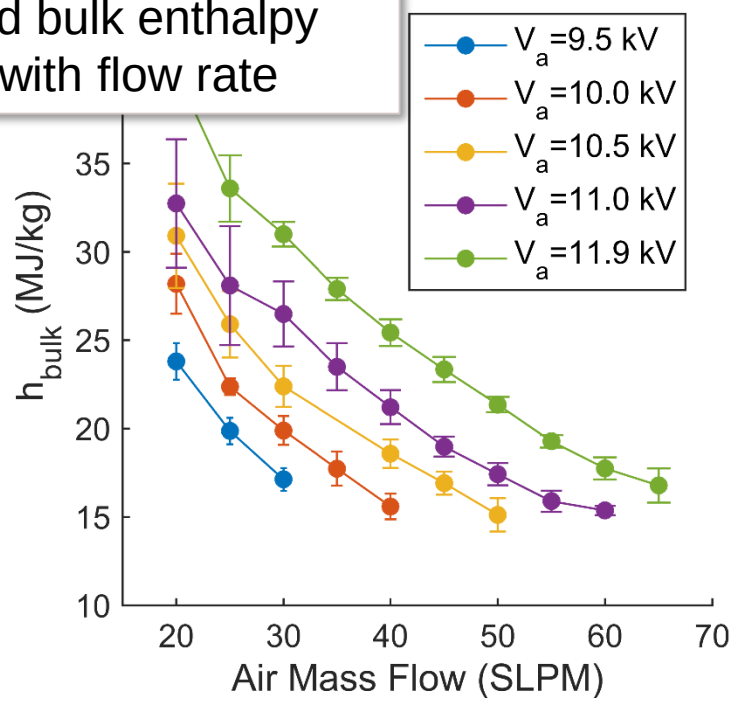


Heat Flux

ESTIMATED EXIT VELOCITY

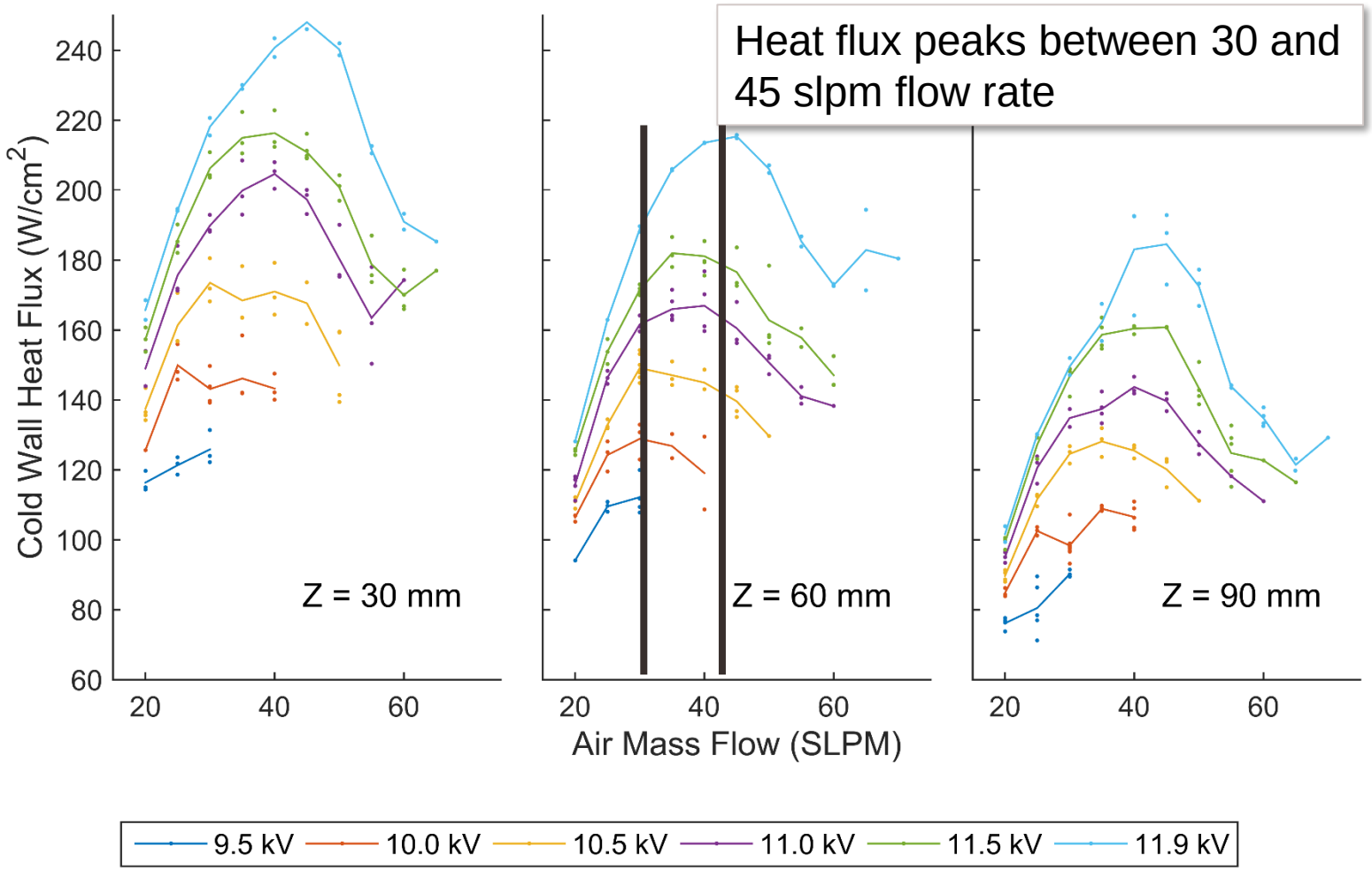


BULK ENTHALPY



Competing effects of velocity increase and bulk enthalpy decrease with flow rate

Heat Flux (Gardon Gauge)



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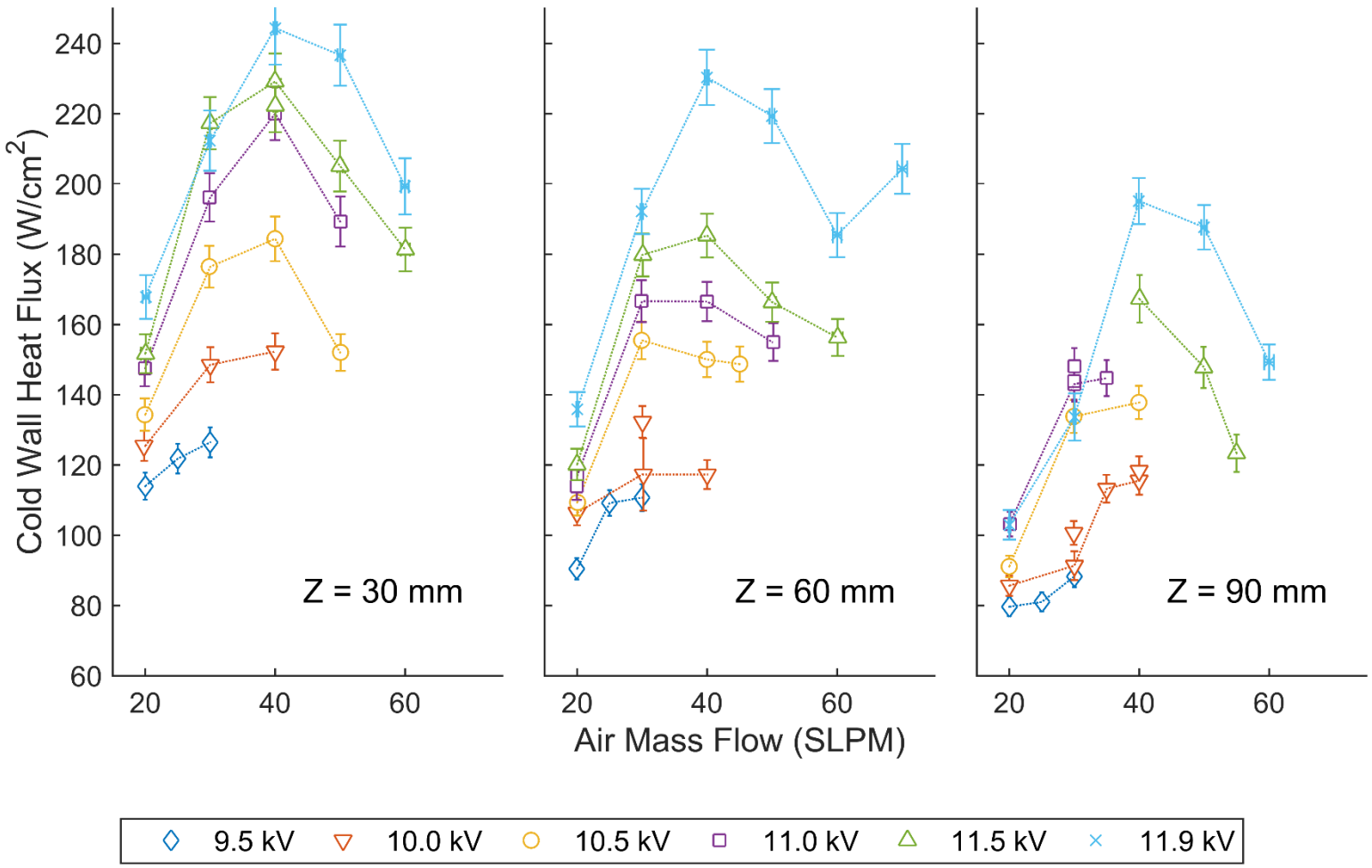
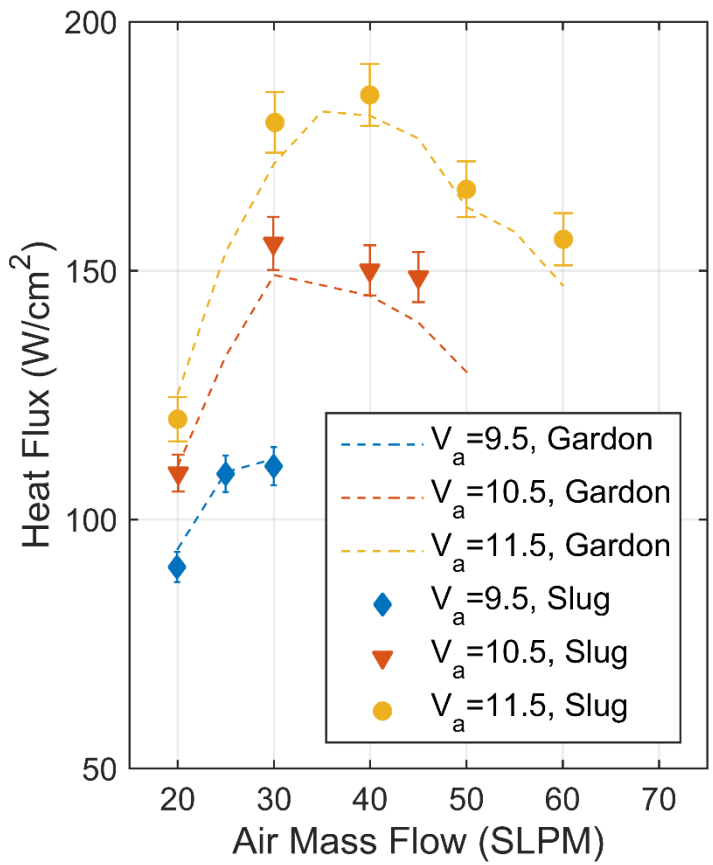
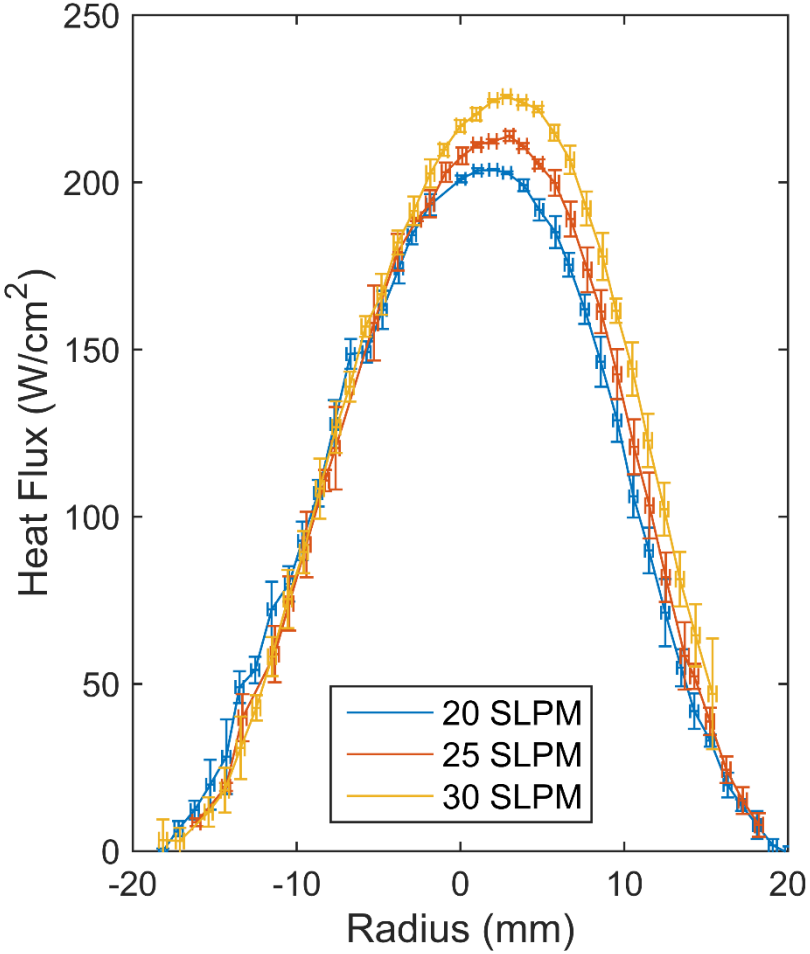


Heat Flux



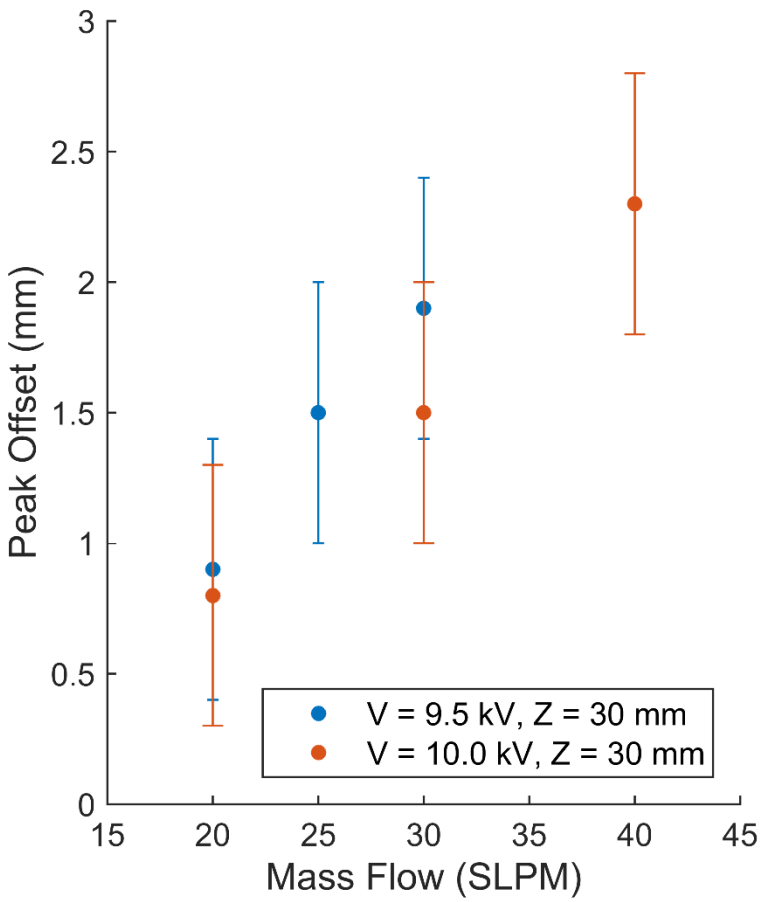
- Calorimeter error based on temperature slope goodness of fit
- Measurements match within experimental error
- Calorimeter reads slightly higher than Gardon gauge

Heat Flux (Radial Variation)



- Radial profiles taken at $V_a = 9.5$ kV and various flow rates
- Peak heat flux much higher than that measured by calorimeter due to difference in probe shape

Heat Flux (Radial Variation)



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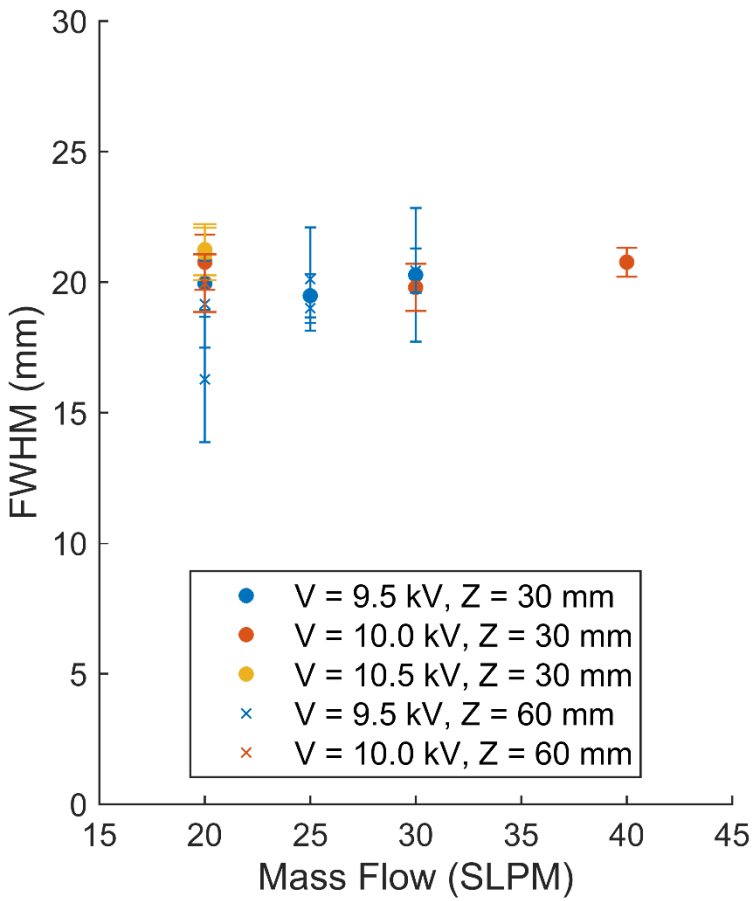
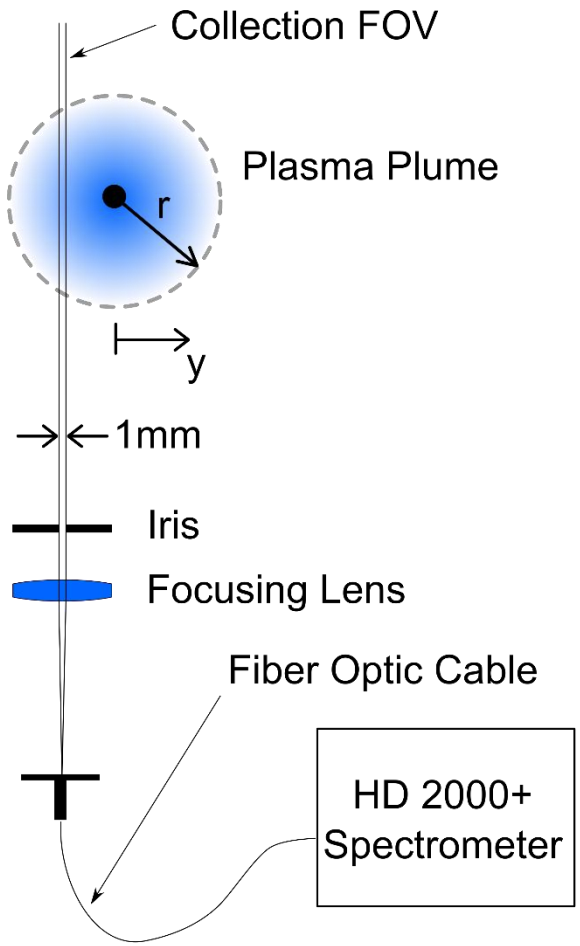
- Slight drift in central peak with flow rate
  - Consistent trend for both voltages

Heat Flux (Radial Variation)



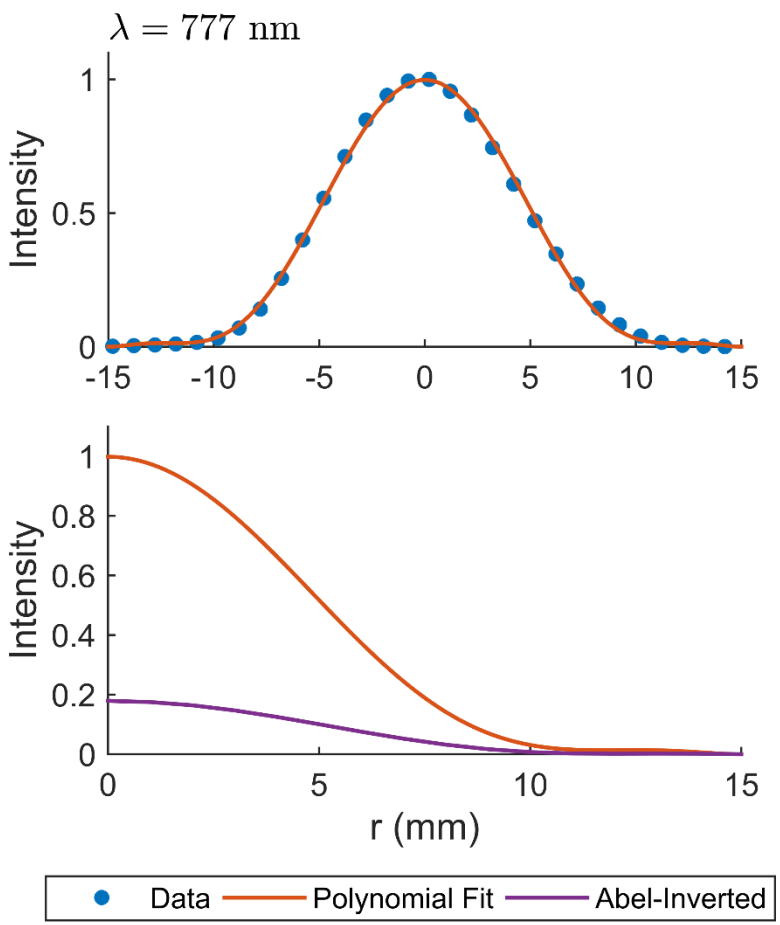
- Radial profiles taken at $V_a = 9.5$ kV and various flow rates
- Peak heat flux much higher than that measured by calorimeter due to difference in probe shape
- Slight drift in central peak with flow rate
  - Consistent trend for both voltages
- Width of peak does not change with flow rate

Emission Spectroscopy



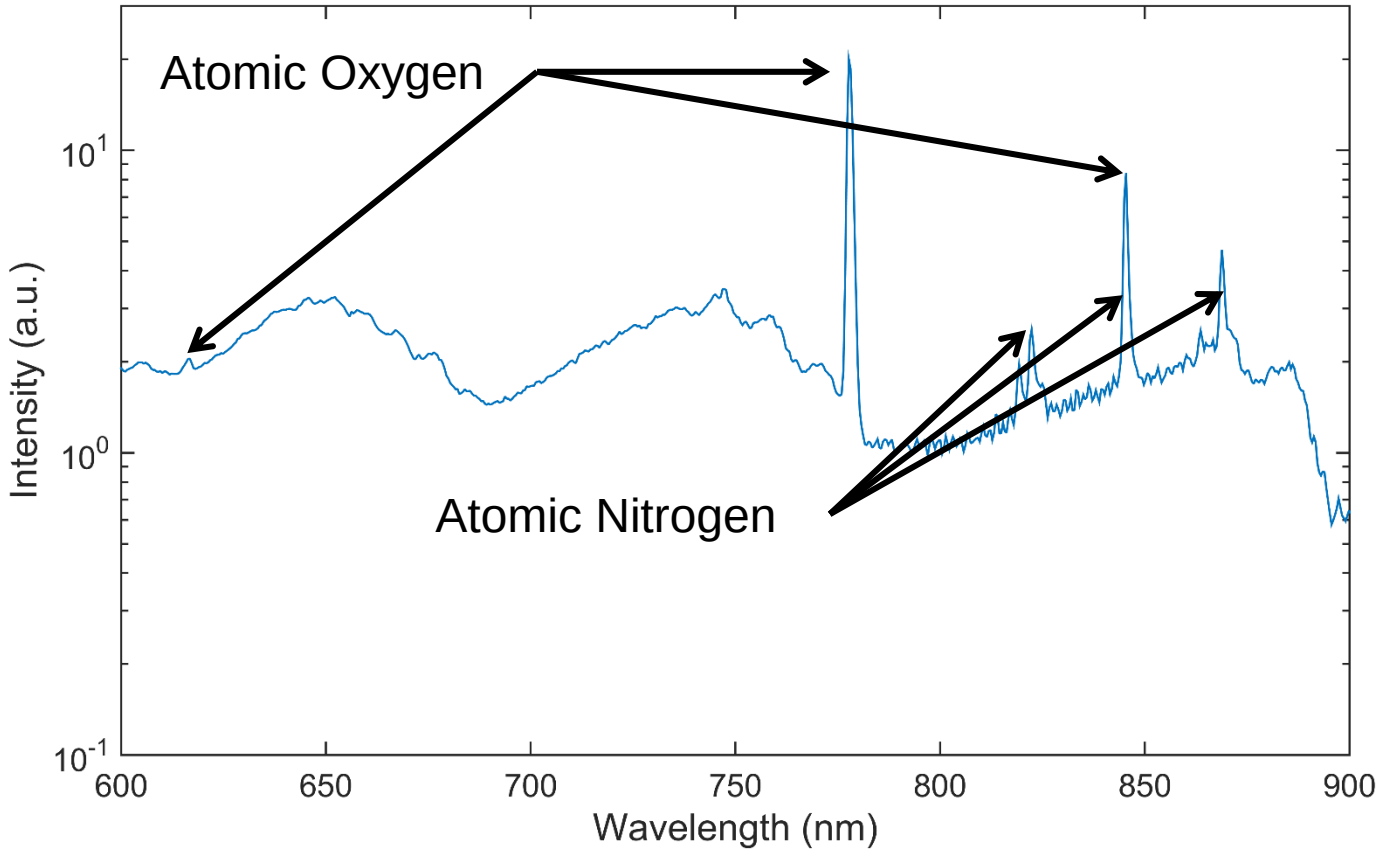
- OceanOptics HD2000+ USB Spectrometer
  - 200nm - 1200nm
  - Calibrated with OceanOptics LS1-CAL tungsten calibration lamp
- 1mm diameter field of view
- Emission spectra taken at 2mm intervals through plume diameter
- Spectra are Abel inverted to obtain $I(\lambda; r)$

Emission Spectroscopy



- Capture spectrum from narrow beam through plume at multiple radial locations
- Fit symmetric polynomial in x to intensity measurements, $I(x;\lambda)$, for every λ
- Abel invert polynomial fit to get $I(r;\lambda)$ and therefore $I(\lambda;r)$

Emission Spectroscopy

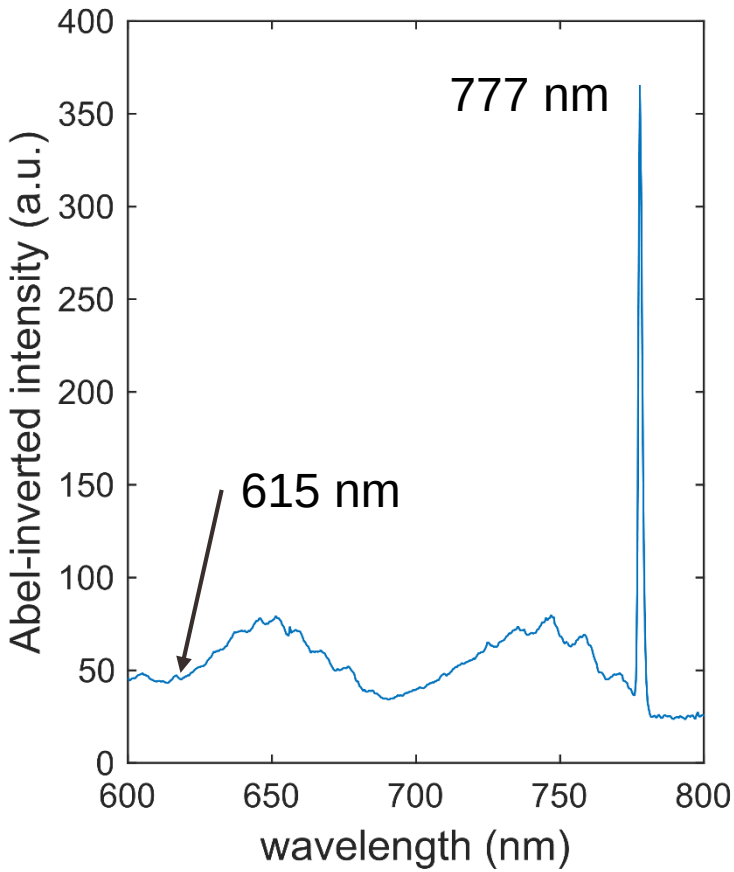


Emission Thermometry

- Use oxygen emission
- Only 777nm and 615nm lines visible and non-overlapping with N emission
- Fit line to Gaussian profile to determine intensity
- Use intensity ratio of two lines to get temperature

$$T = \frac{\varepsilon_{u2} - \varepsilon_{u1}}{k \ln\left(\frac{I_1}{I_2}\frac{A_2}{A_1}\frac{\Delta\varepsilon_2}{\Delta\varepsilon_1}\frac{g_{u1}}{g_{u2}}\right)}$$

- Eliminates need for absolute intensity



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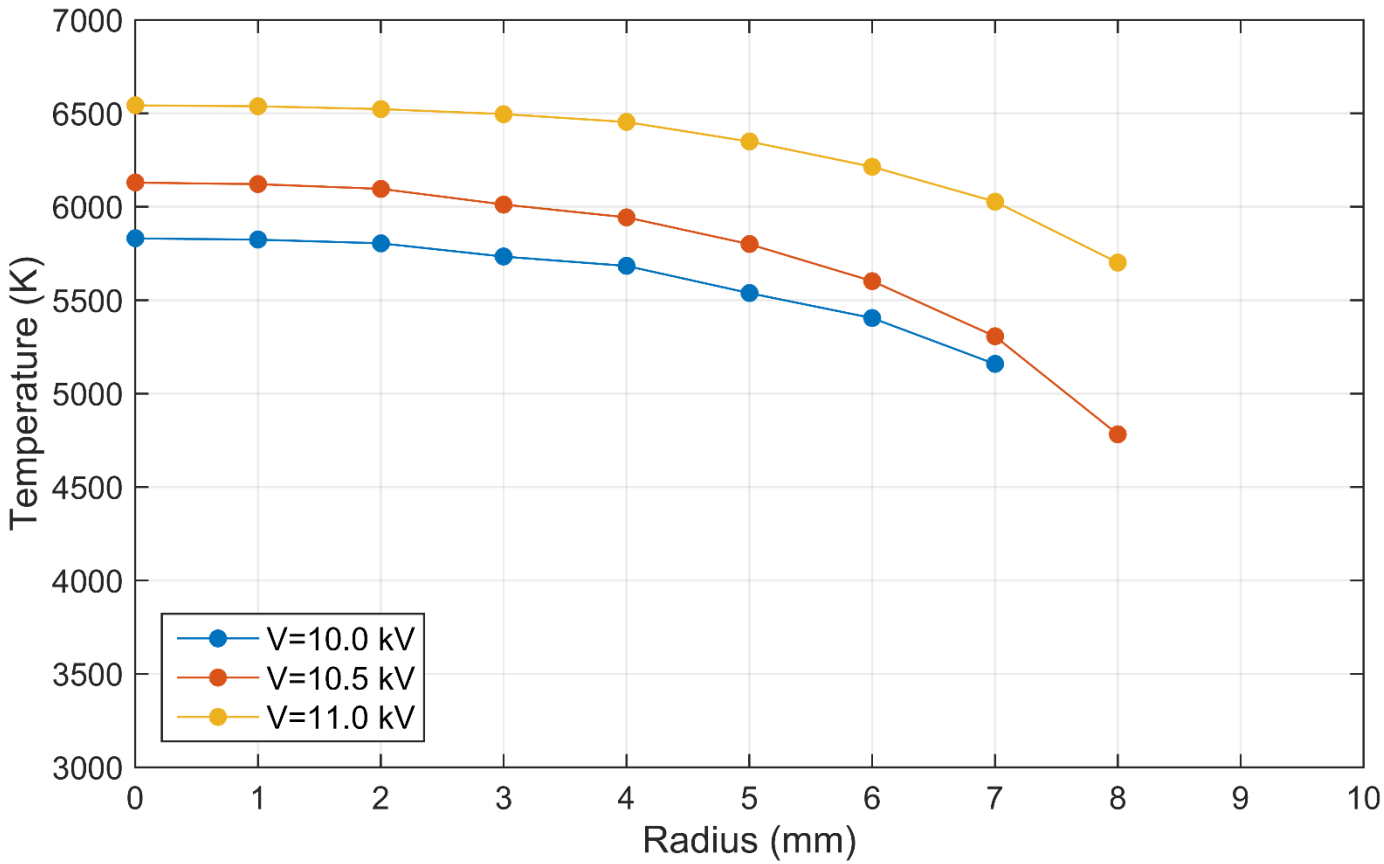

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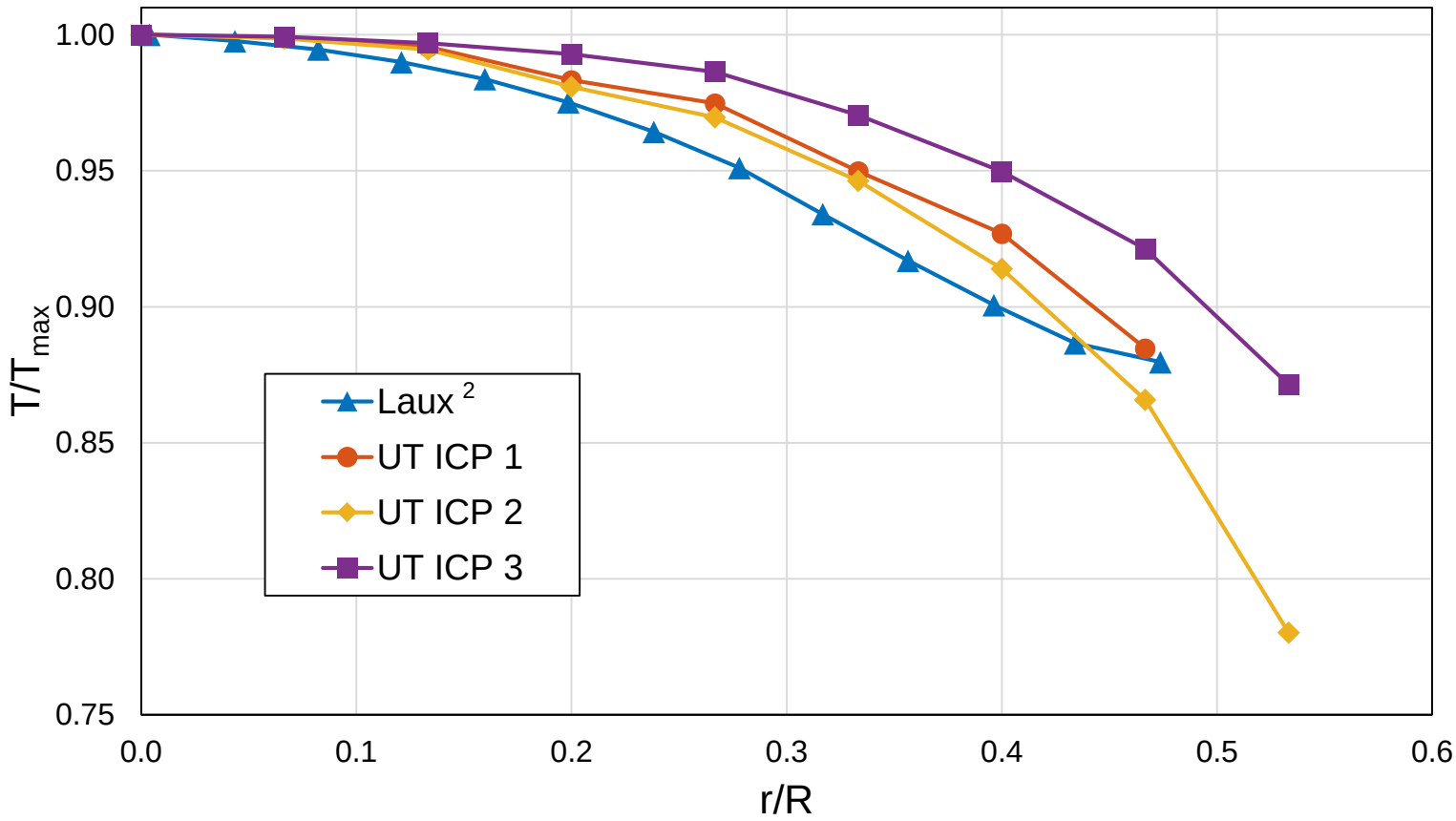

Comparison to Other Facilities

	UT-Austin	UVM[4]	VKI Plasmatron[6]	Ecole Centrale, Paris[3,5]
Run time	1.5 hr	6 min		>10 min
Max Heat Flux	225 W/cm2	85 W/cm2	350 W/cm2	
Operating Pressure	500 kPa	10 kPa	1.5 kPa - 20 kPa	100 kPa
Flow Regime	Subsonic	Subsonic	Subsonic/Supersonic	Subsonic
Gas Composition	Air, Ar	Ar, Air, N_2, CO_2	Air, Ar	Ar, Air
Flow Rate	20-75 slpm	0 to 50 slpm	800 slpm	70 slpm
Operating Frequency	6 MHz	2.7 MHz	400 kHz	4MHz
Operating Power	50 kW	30 kW	1.2 MW	50 kW

Future Work

- Graphite and Teflon test articles
  - Pyrometry to measure model surface temperature
  - LIF to measure species concentration near model surface
  - Raman scattering to measure temperature and species concentration
- Measure recession rates over a simulated heating cycle

Questions?

References

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