

Nitric Oxide PLIF Measurements in the Hypersonic Materials Environmental Test System (HYMETs)



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Outline

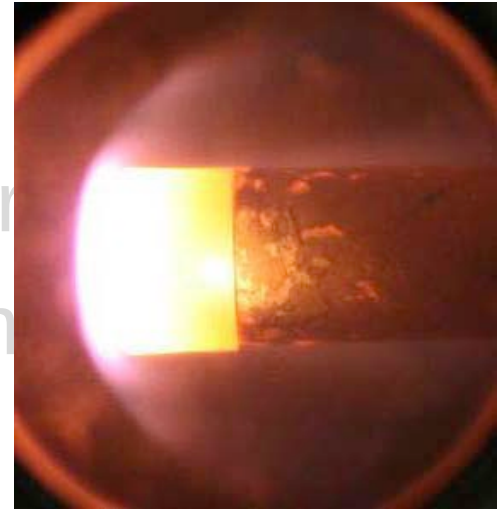
- Motivation
- HYMETs Arcjet Facility
- Planar Laser-Induced Fluorescence (PLIF)
- Molecular Tagging Velocimetry (MTV)
- Doppler Velocimetry
- Concluding remarks

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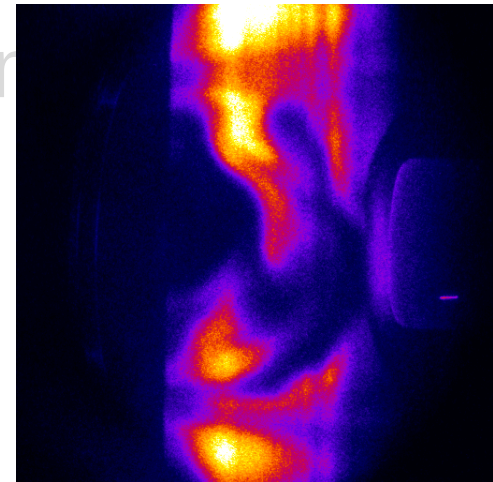
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← Axial →

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↑
Radial
↓

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Motivation

Materials testing in high-enthalpy
reacting flows

Motivation

- To fully understand material response, we must know the environment to which it is exposed and understand interactions with the environment
 - Scaling from ground test facility to flight conditions
- For both Earth ($\text{N}_2/\text{O}_2/\text{Ar}$) and Mars ($\text{CO}_2/\text{N}_2/\text{Ar}$):
 - Characterize free stream arcjet flowfield
 - Characterize post-shock flowfield
- NO PLIF flow vis. & velocity measurements
 - Quantify temporal fluctuations, spatial variations
 - Can use results to monitor/modify flow quality

Hypersonic Materials Environmental Test System (HYMETs)

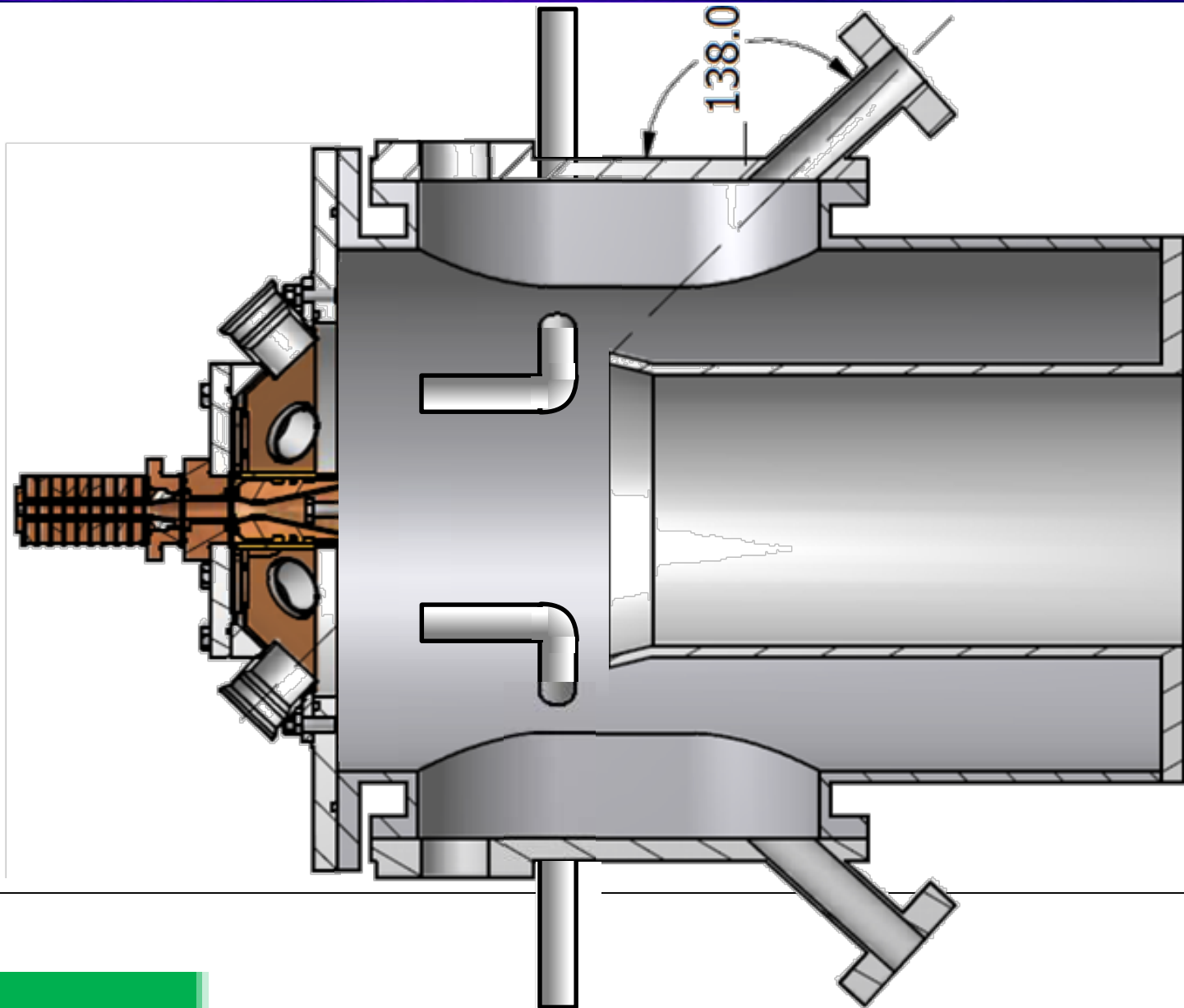
Facility overview

Optical access for laser-based measurements

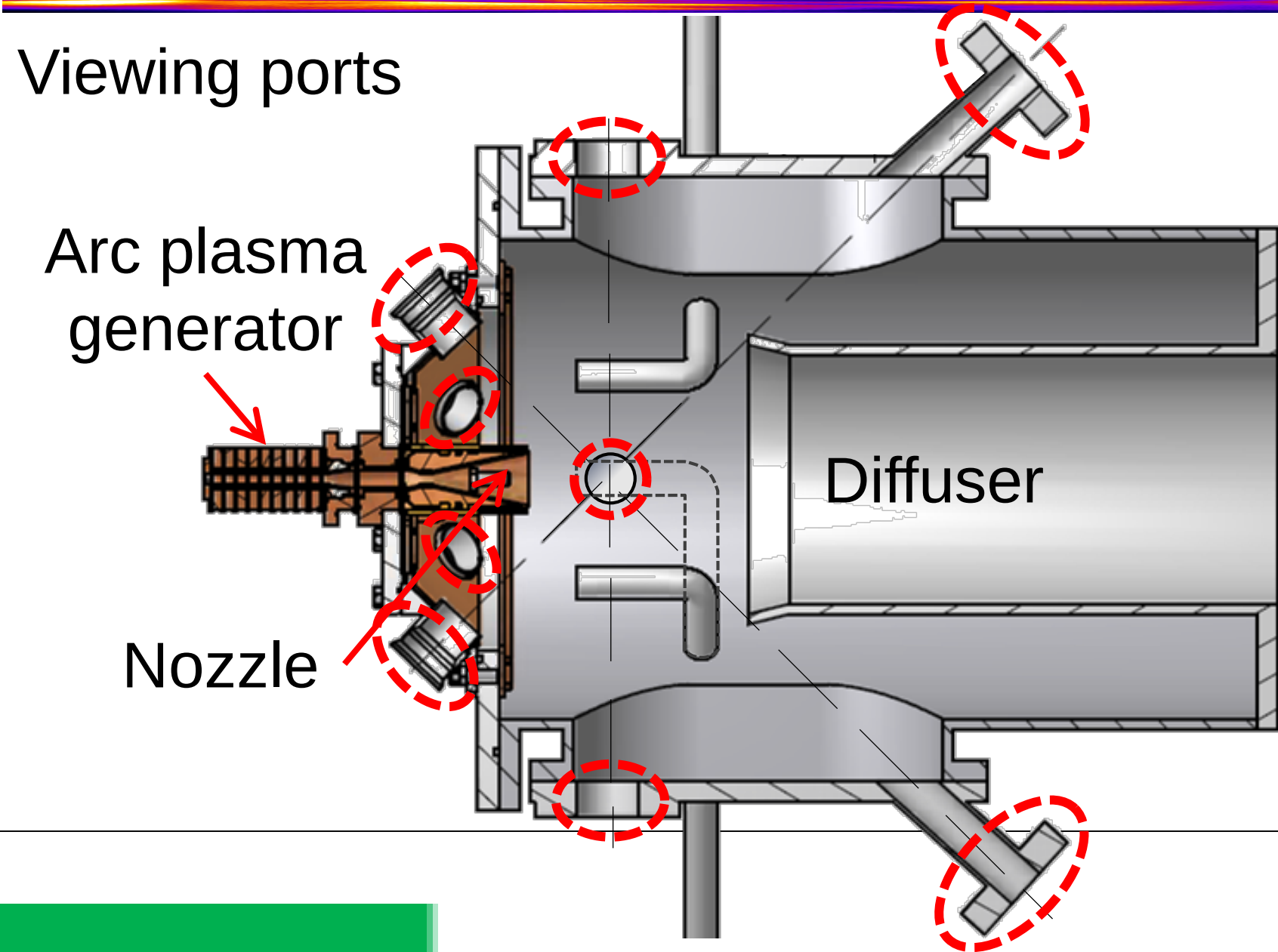
HYMETs: 400 kW Arcjet Facility

- Power Supply: 400 kW
 - Johnson Space Center: 10 MW
 - Ames Research Center: 20 – 60 MW
- Specific bulk enthalpy: 5-28 MJ/kg (2-12 kBTU/lb_m)
- 25 mm (1 inch) diameter sample
- Single operator, fast turnaround between runs
- N₂, O₂, and CO₂ process gases
 - Simulated Earth: 75%N₂, 20%O₂, 5%Ar
 - Actual Earth: 78%N₂, 21%O₂, 1%Ar
 - Simulated Mars: 71%CO₂, 24%N₂, 5%Ar
 - Actual Mars: 95.3%CO₂, 2.7%N₂, 1.6%Ar
- Mach 5 conical copper nozzle (~8 degree half angle)

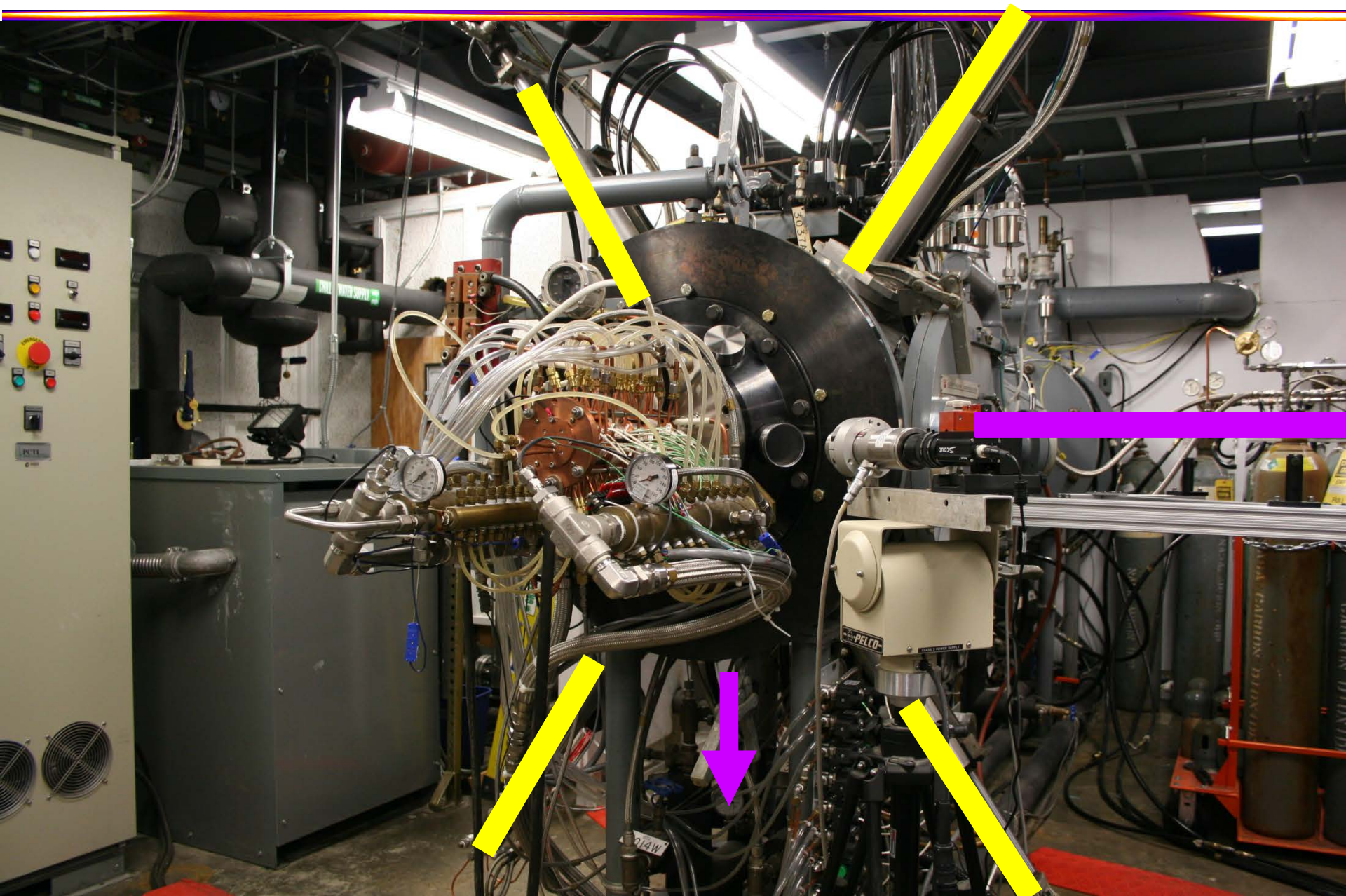
HYMETs: 400 kW Arcjet Facility



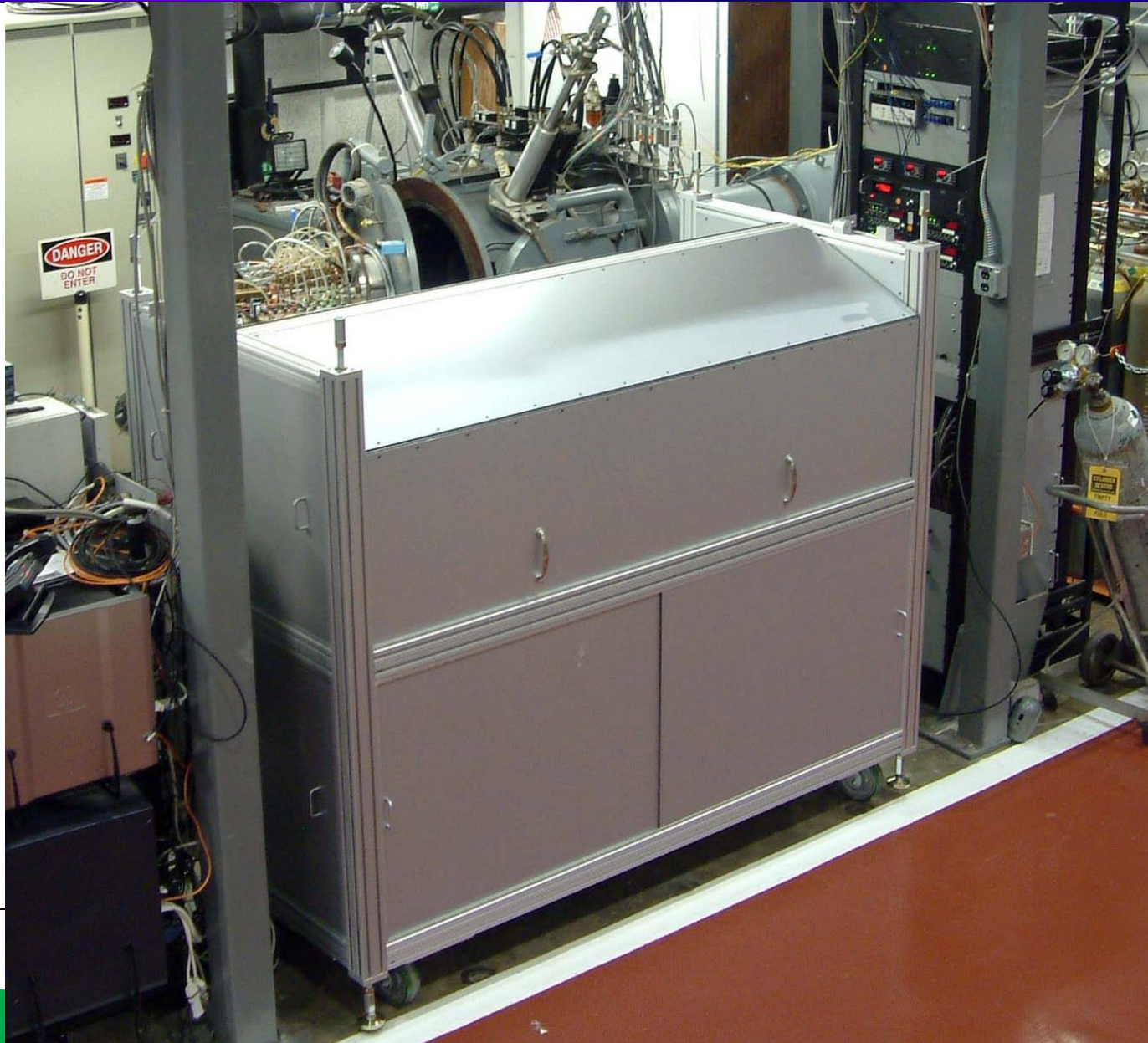
HYMETs: 400 kW Arcjet Facility



HYMETs: 400 kW Arcjet Facility



Laser system in HYMETs



PLIF Measurements

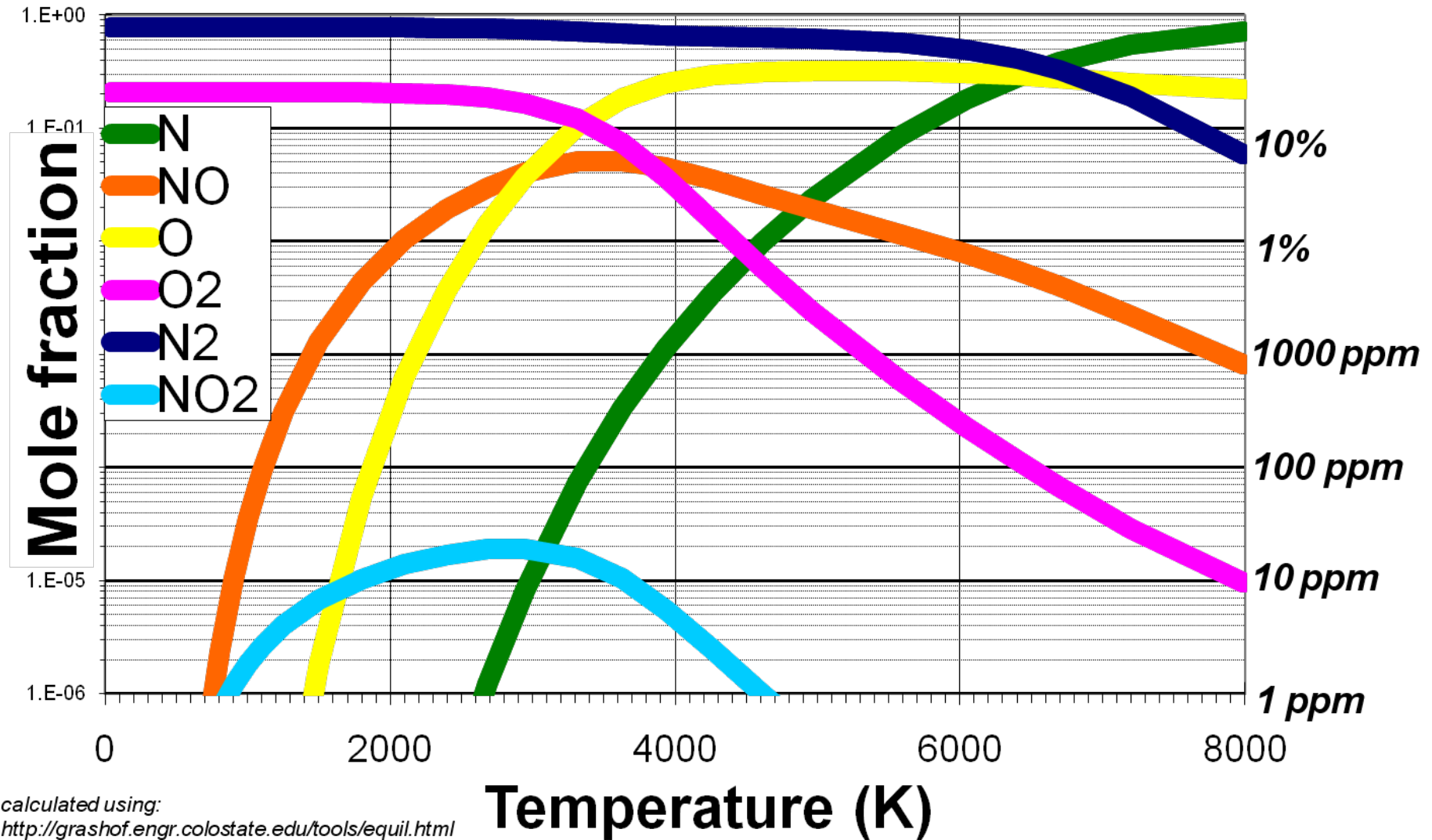
Nitric oxide as probe species

Flow visualization

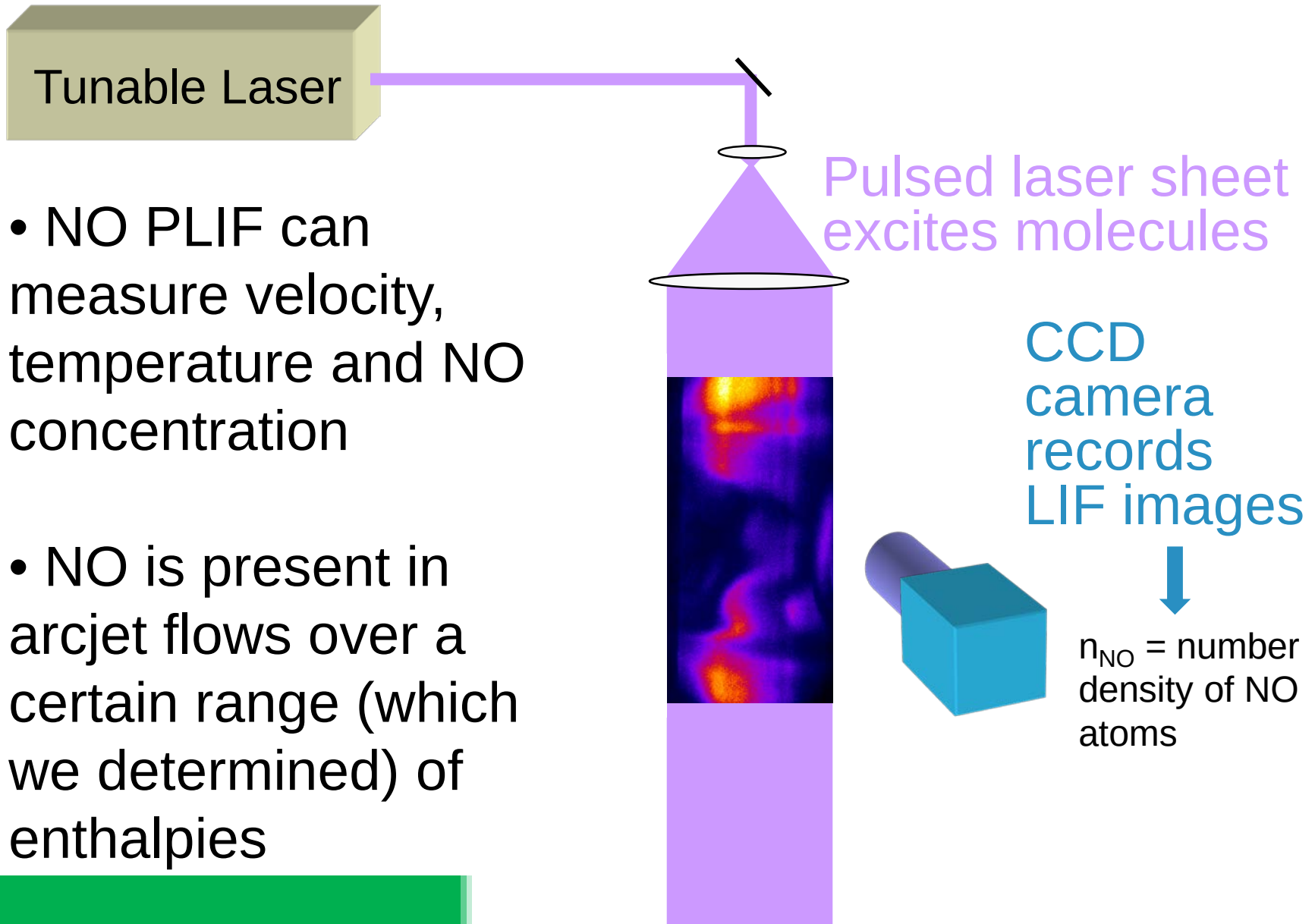
Molecular-tagging (axial) velocimetry

Doppler (radial) velocimetry

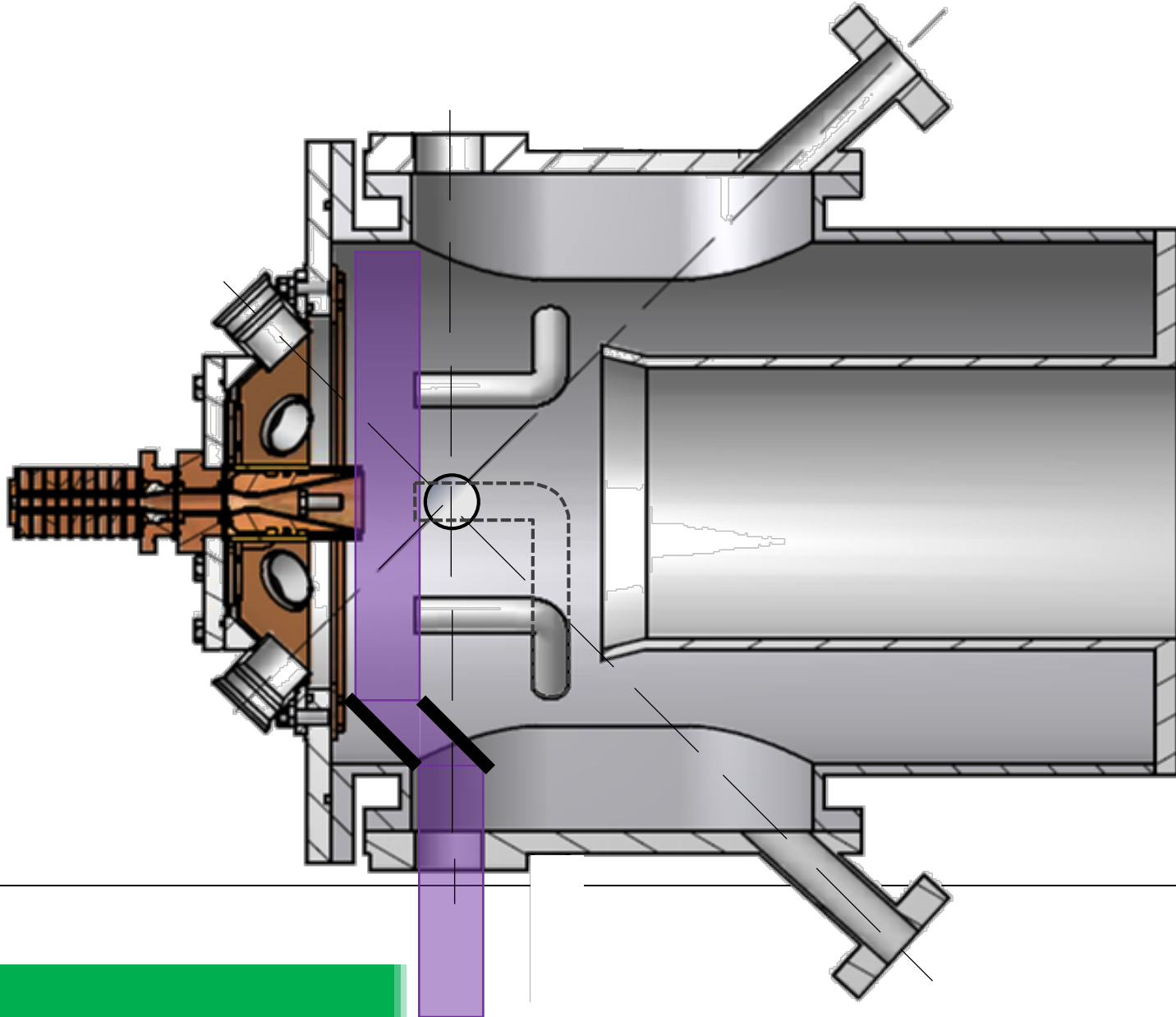
Equilibrium Air Composition, 1atm



Basic PLIF Concept

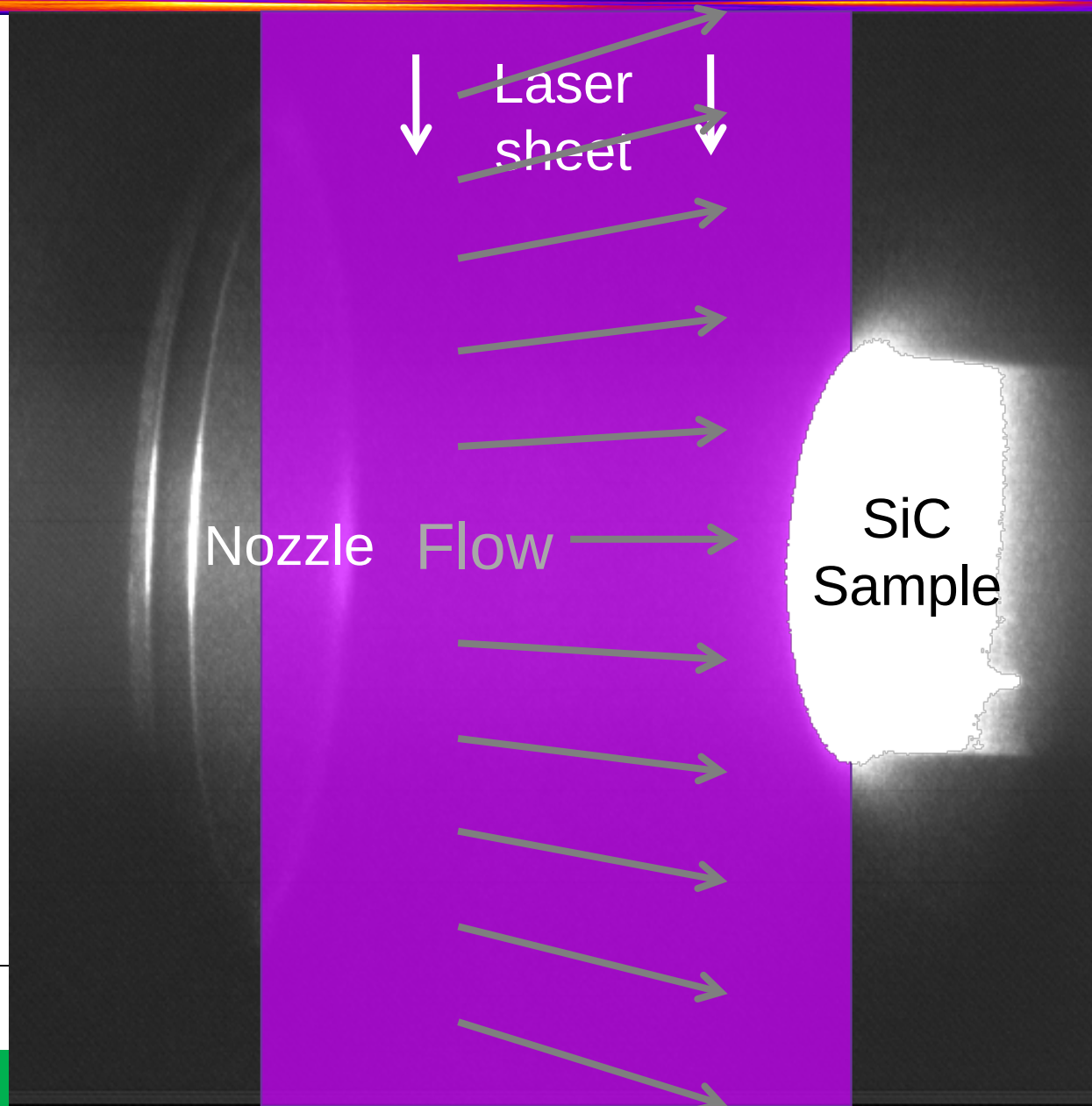


PLIF in HYMETs





Camera View



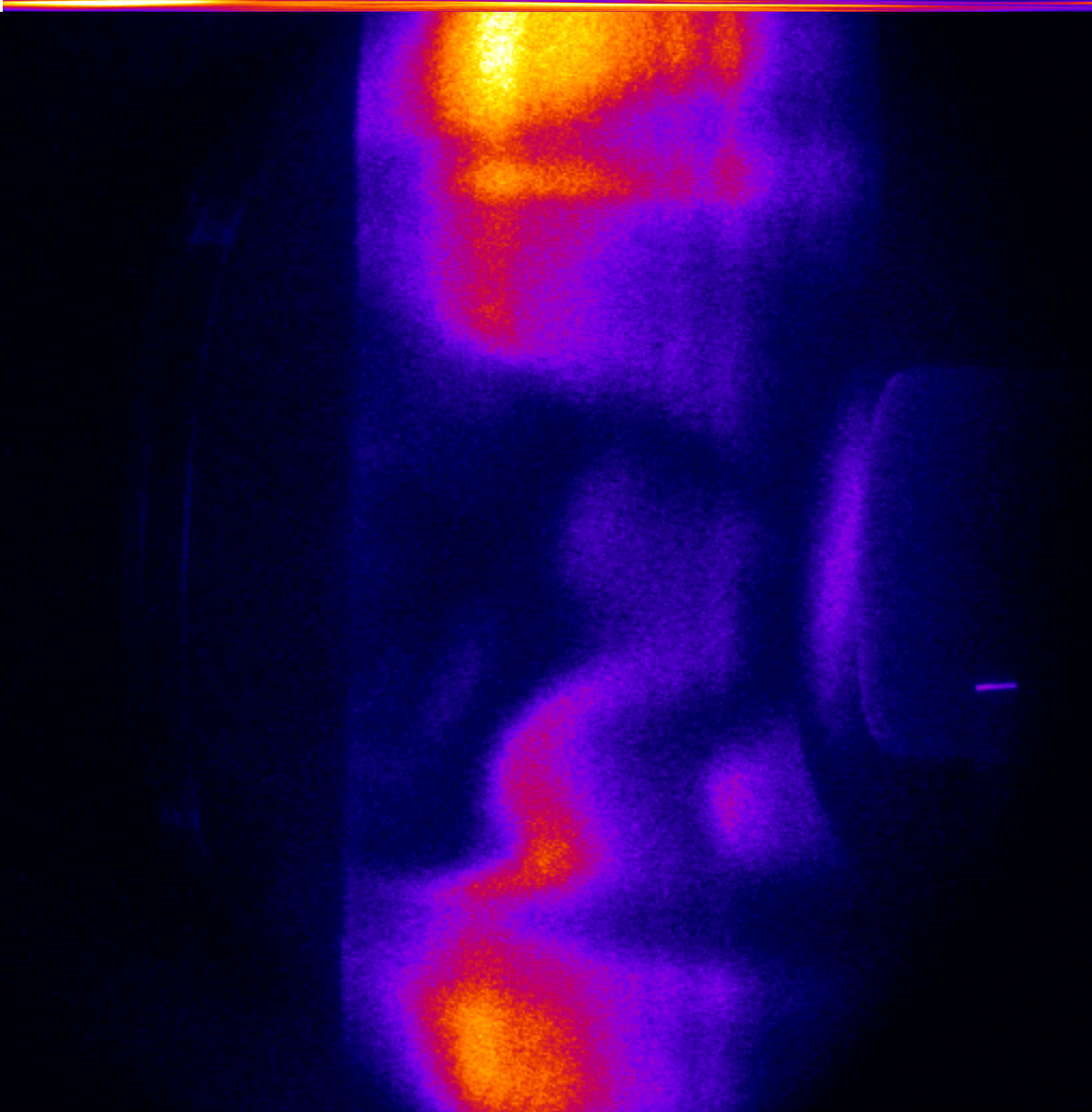
Flow Visualization Results

Flow structures

Intensity vs. Enthalpy

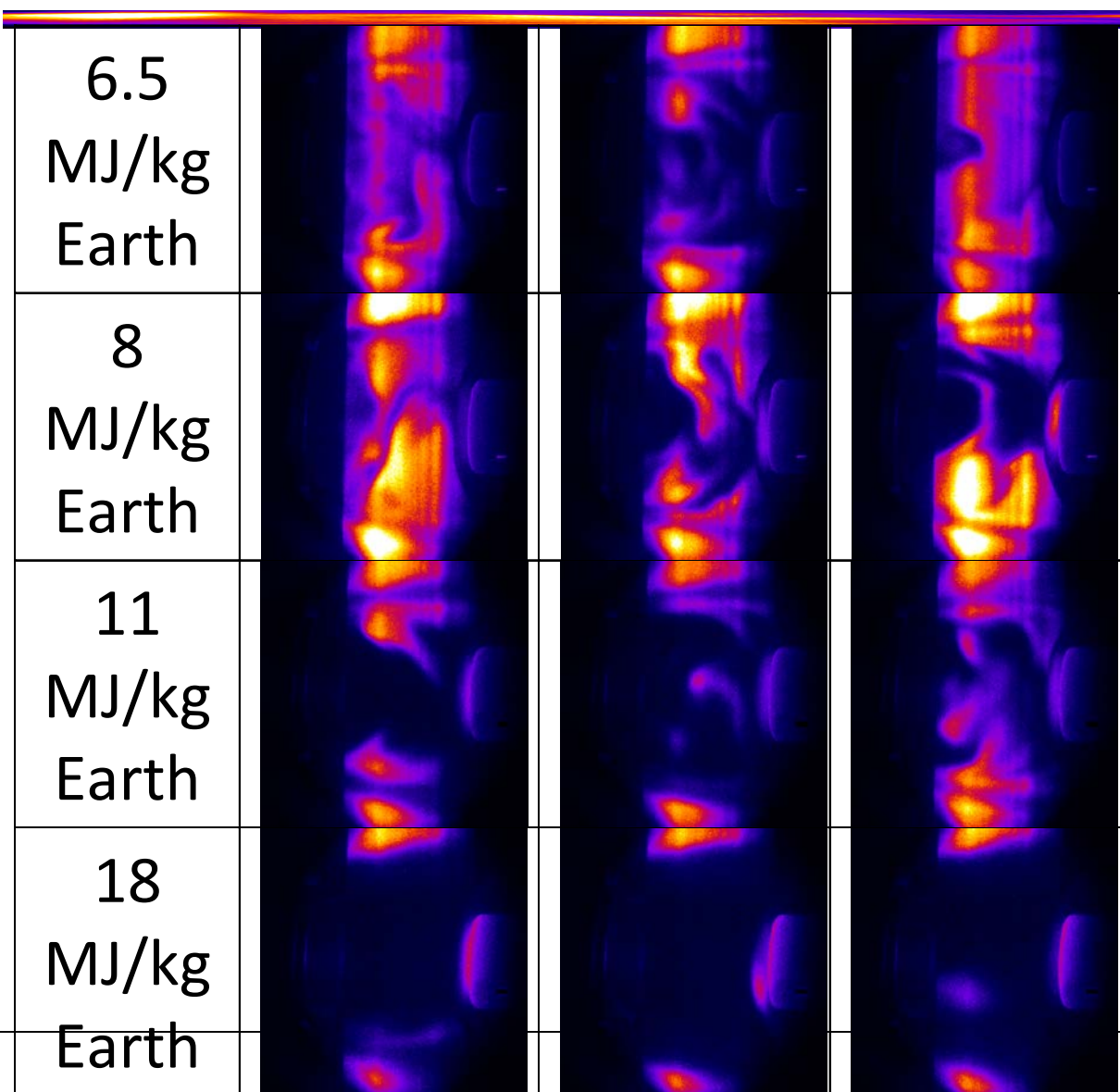
Range of technique applicability

Single-Shot Images

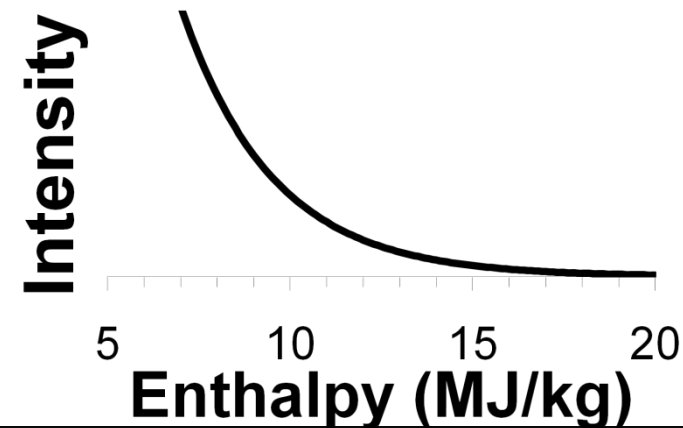


- 1 μs exposure
- Large-scale structures
- Bow shock visible in front of sample
- Can measure shock standoff distance (9.5 ± 1.1 mm)

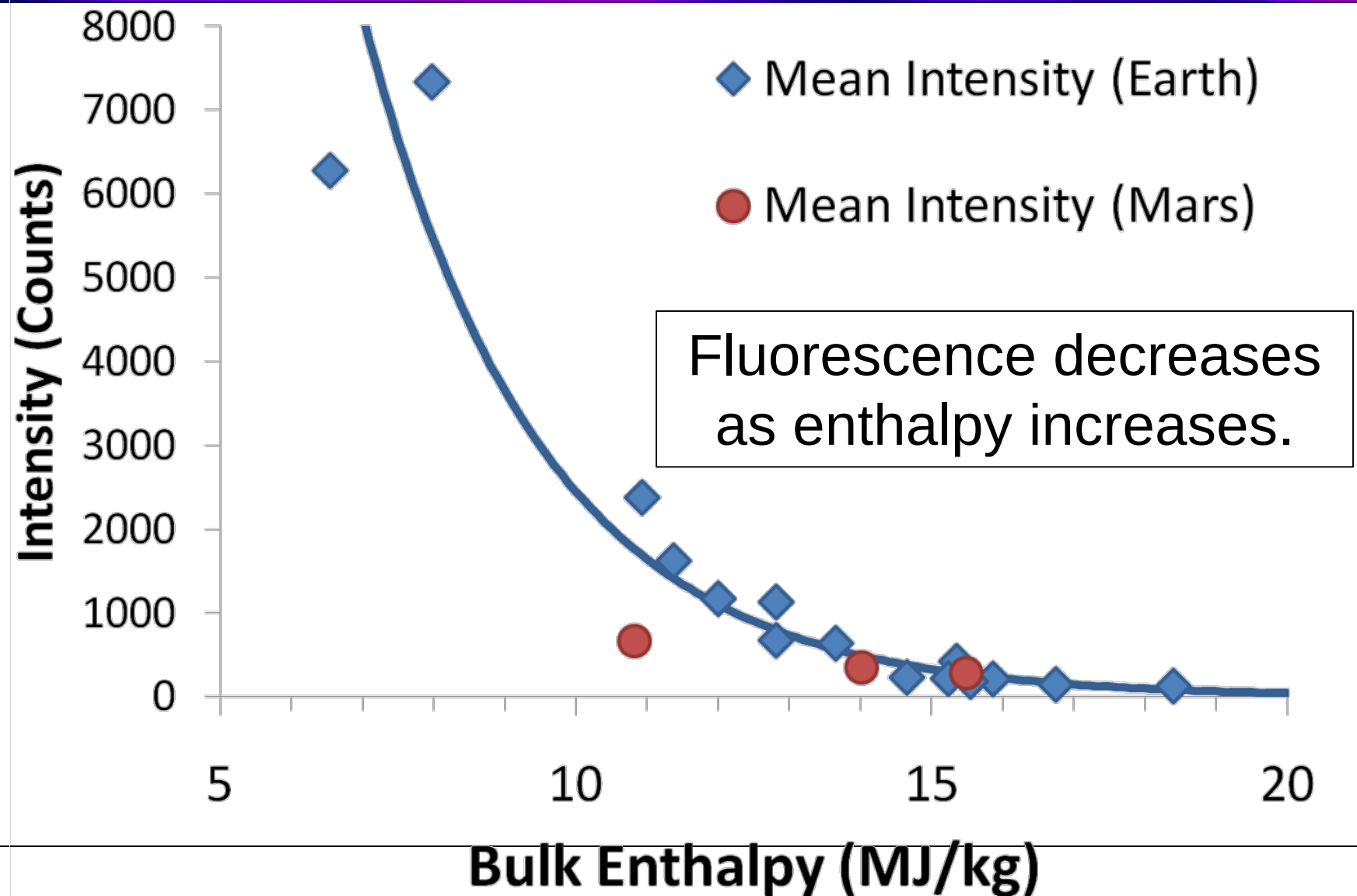
Fluorescence Signal vs. Enthalpy



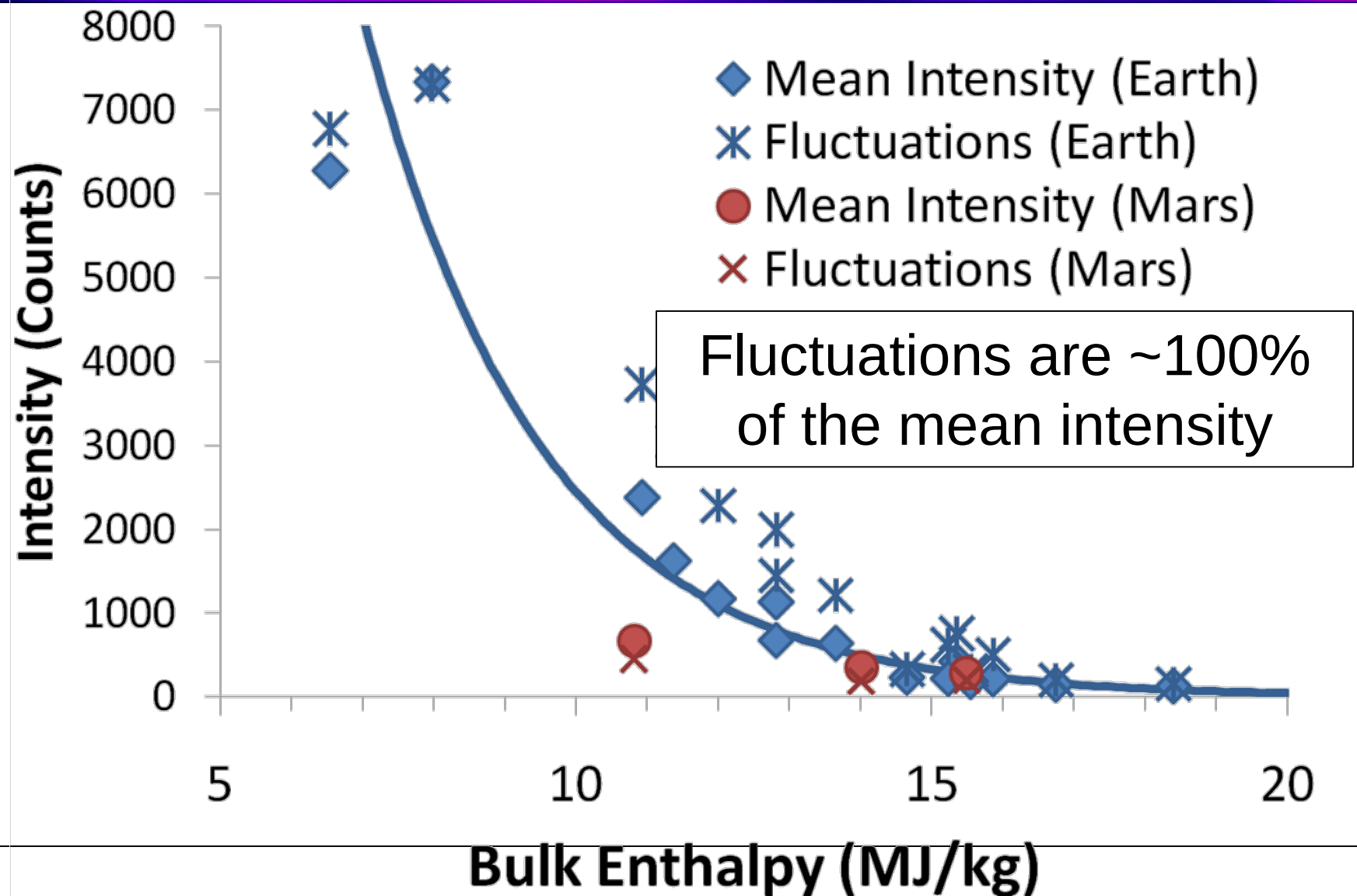
- NO created from dissociated N_2 and O_2 (or N_2 and CO_2)
- NO dissociates at high enough enthalpy



Fluorescence Signal vs. Enthalpy

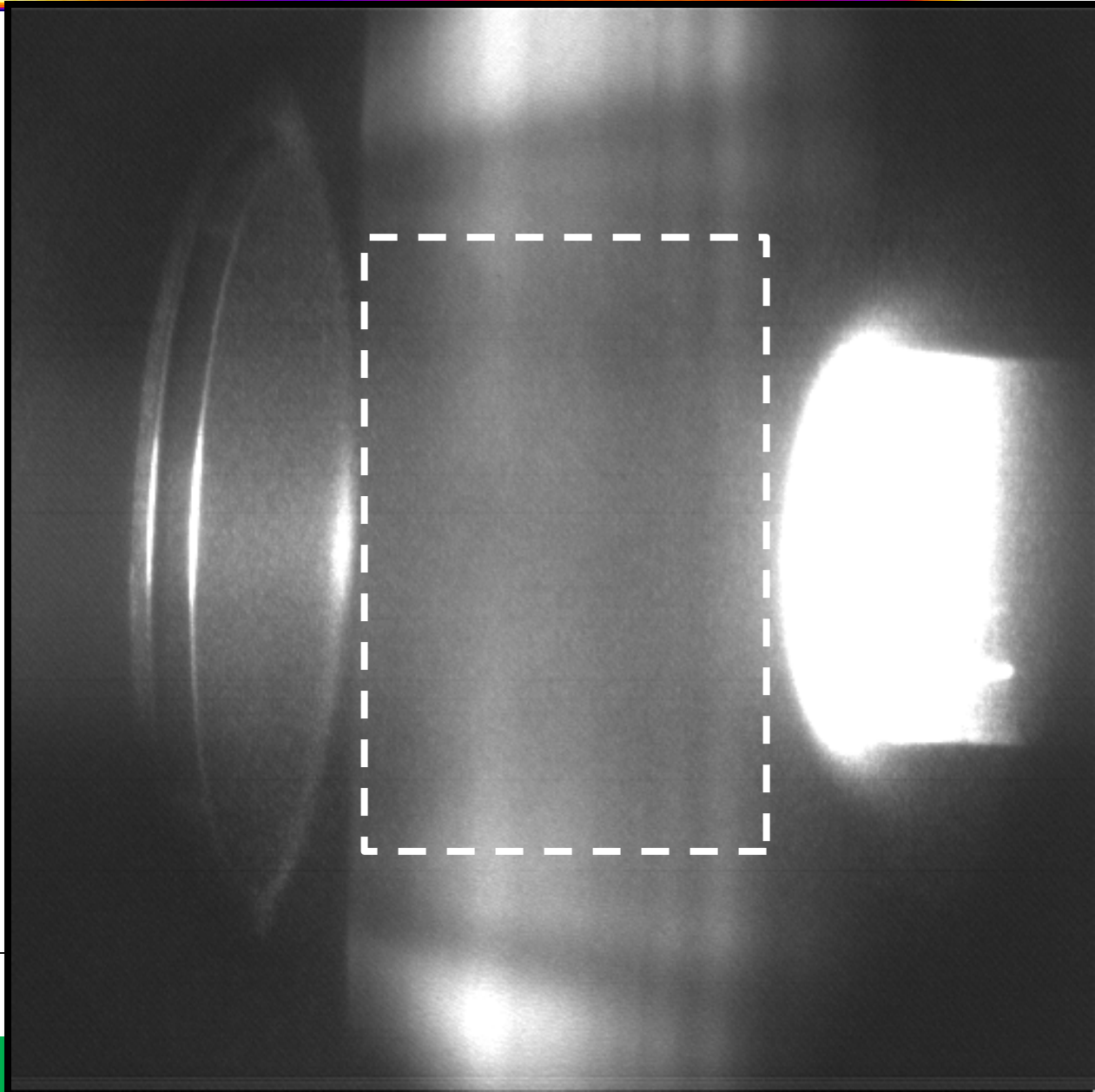


Fluorescence Signal vs. Enthalpy



Core Flow Region of Interest

- At a given enthalpy, what percentage of the core flow has NO present?
- Answer indicates range of conditions where quantitative PLIF techniques are suitable



Fraction of Flow with NO

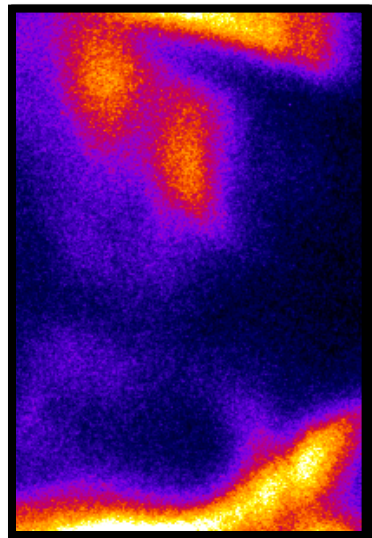
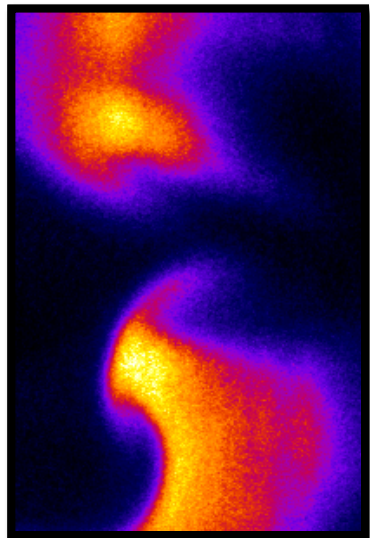
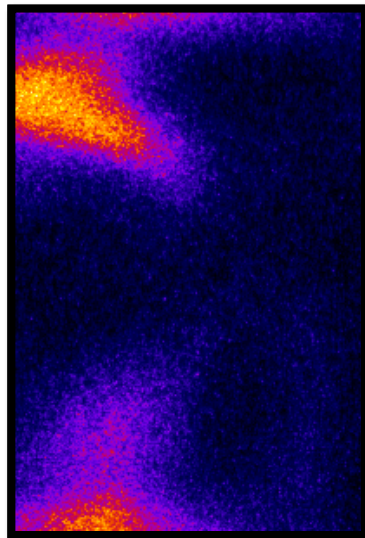
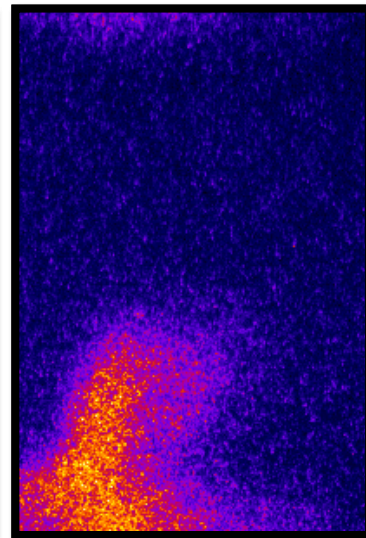
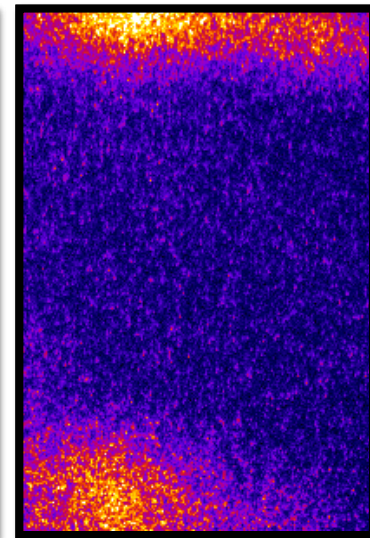
6.5
MJ/kg

8
MJ/kg

13
MJ/kg

15
MJ/kg

18
MJ/kg



97%

97%

41%

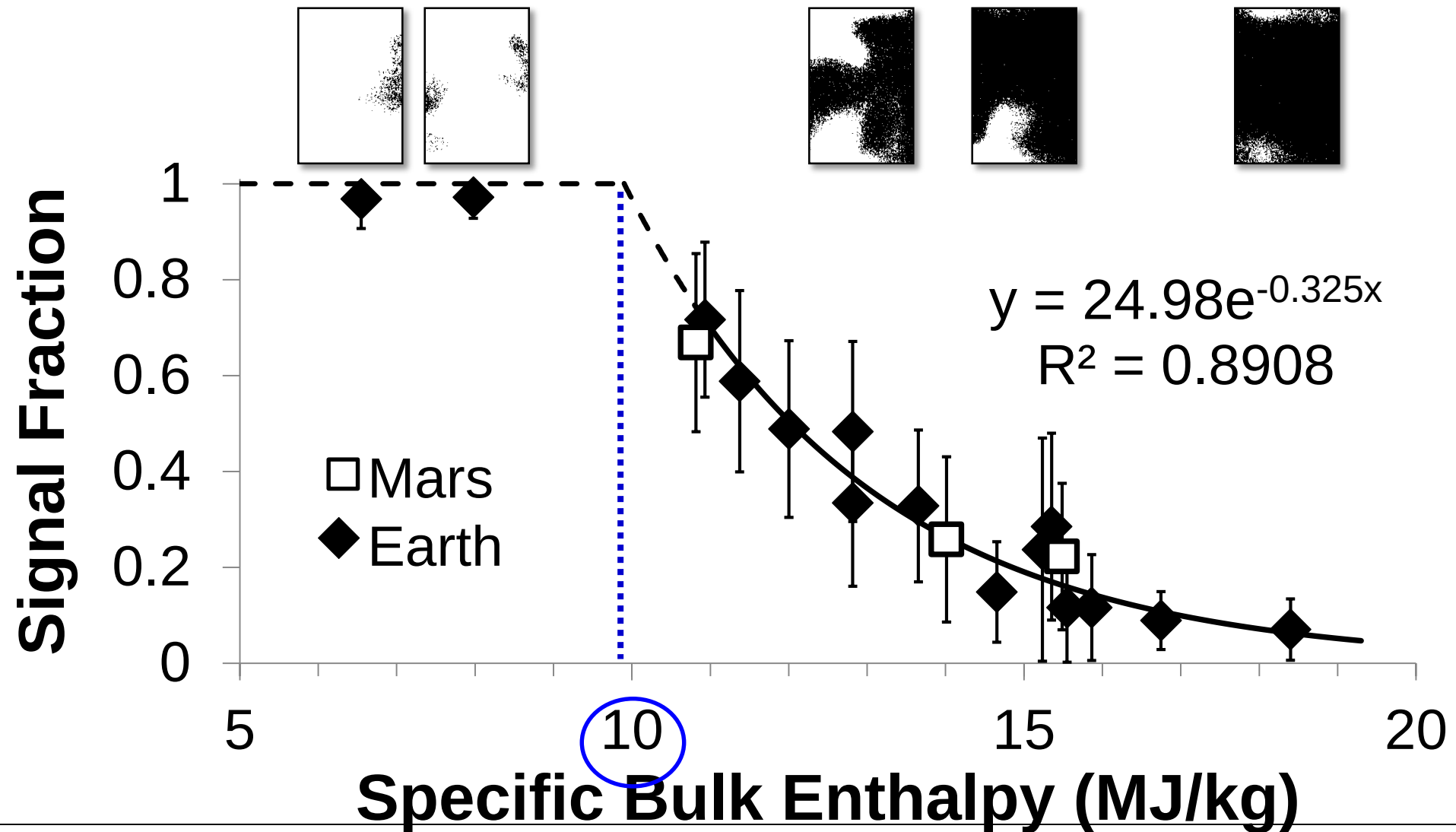
15%

7%

White: signal > 500 counts

Black: signal < 500 counts

Fraction of Flow with NO



Axial Velocimetry

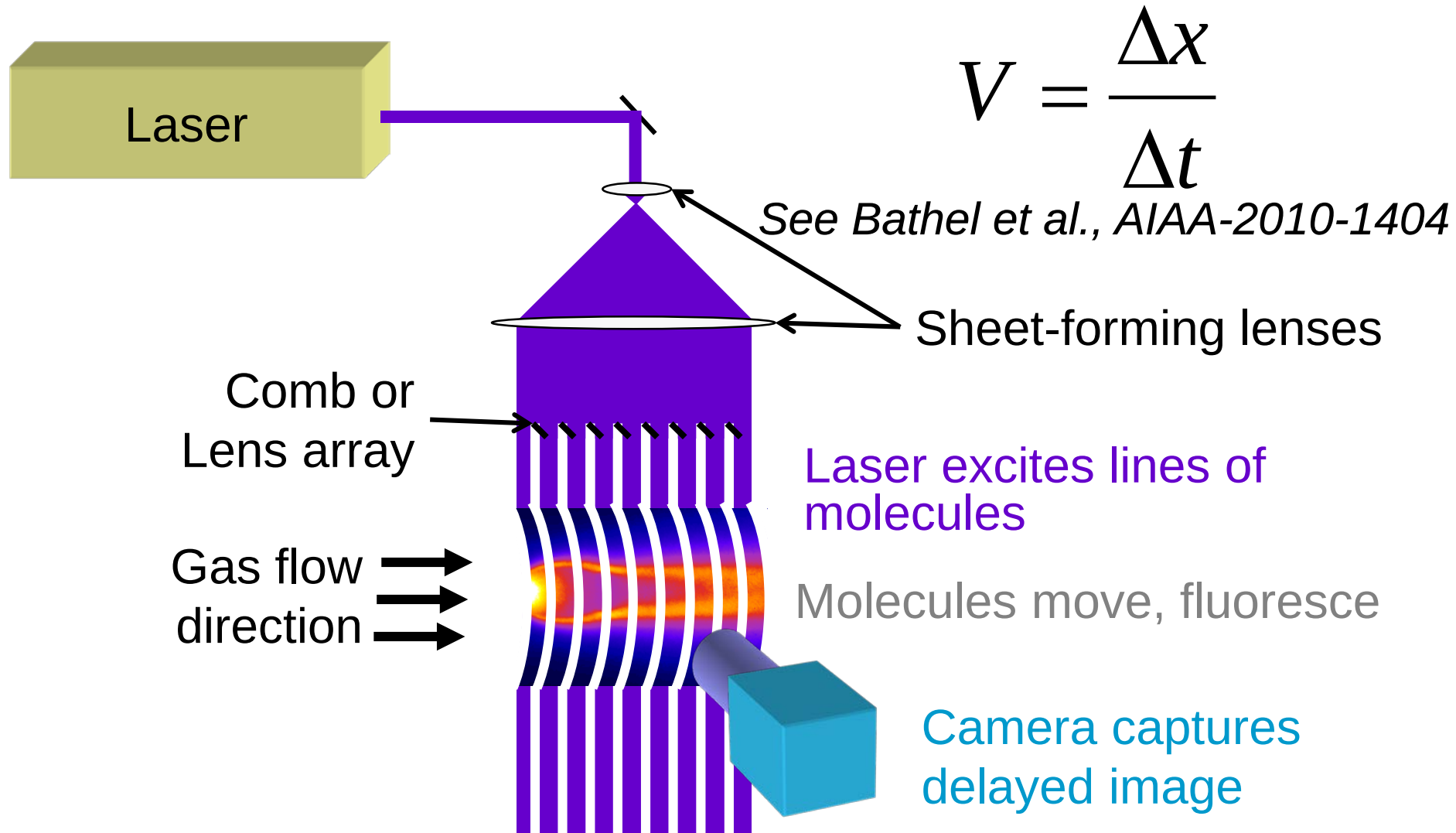
Flow-tagging technique

Time-averaged (mean) results

Single-shot (velocity fluctuation) results

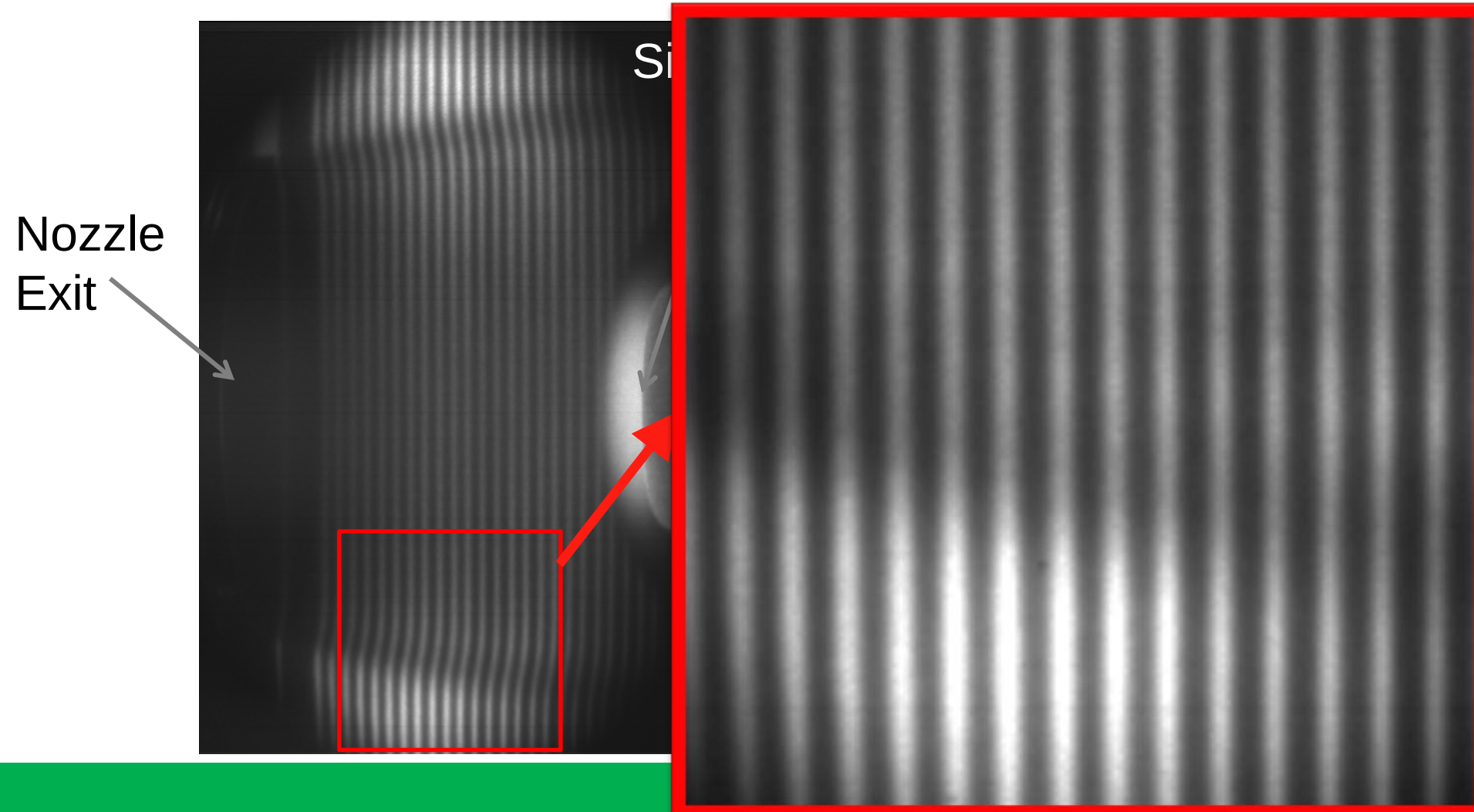
Multi-Line NO PLIF MTV

(Nitric Oxide Planar Laser-Induced Fluorescence Molecular-Tagging Velocimetry)

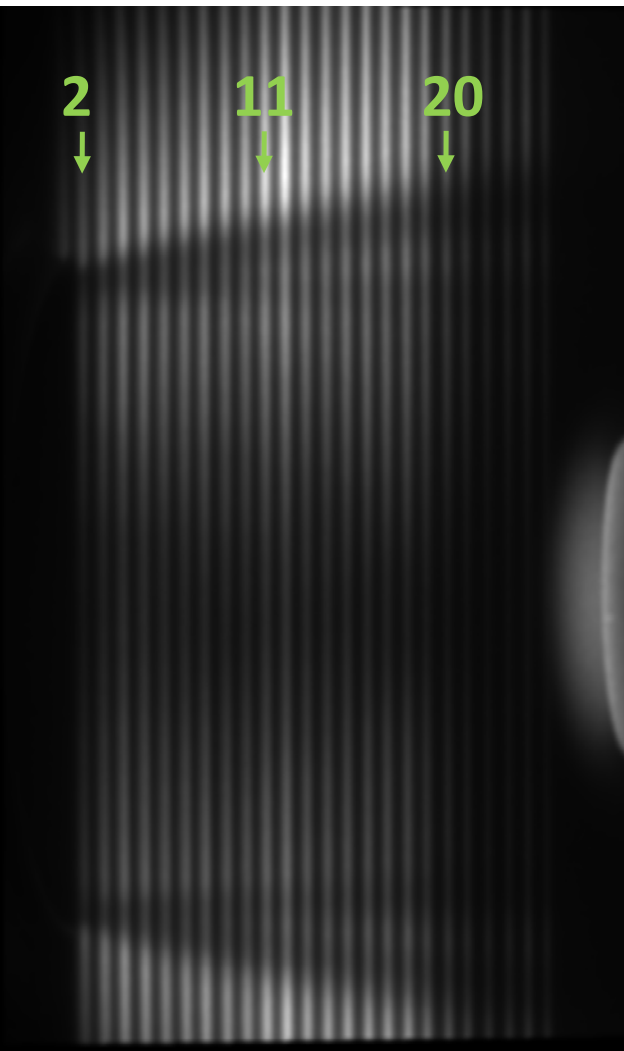
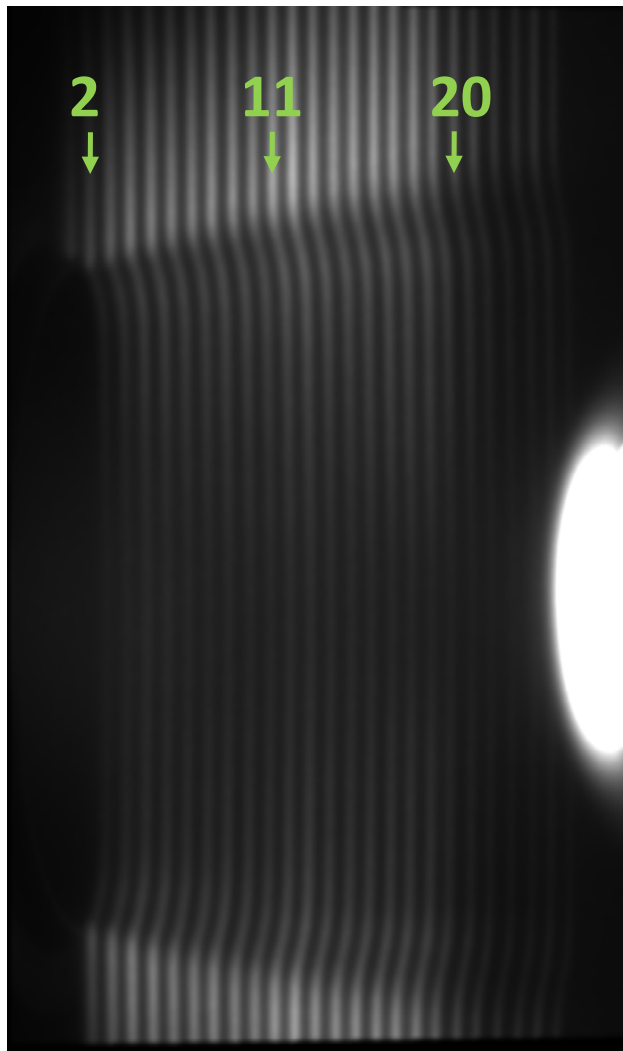


Axial Velocimetry

- Each frame shown here is an average of 100 images
- Shown every 100 ns (from 0 to 500 ns after laser pulse)

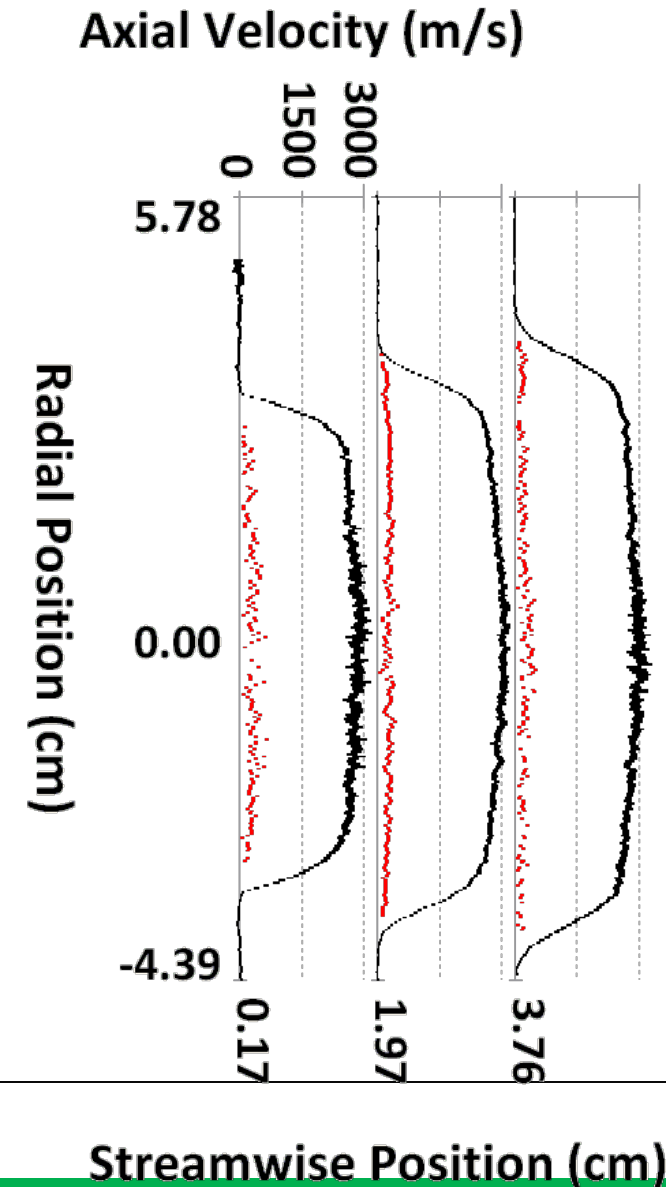
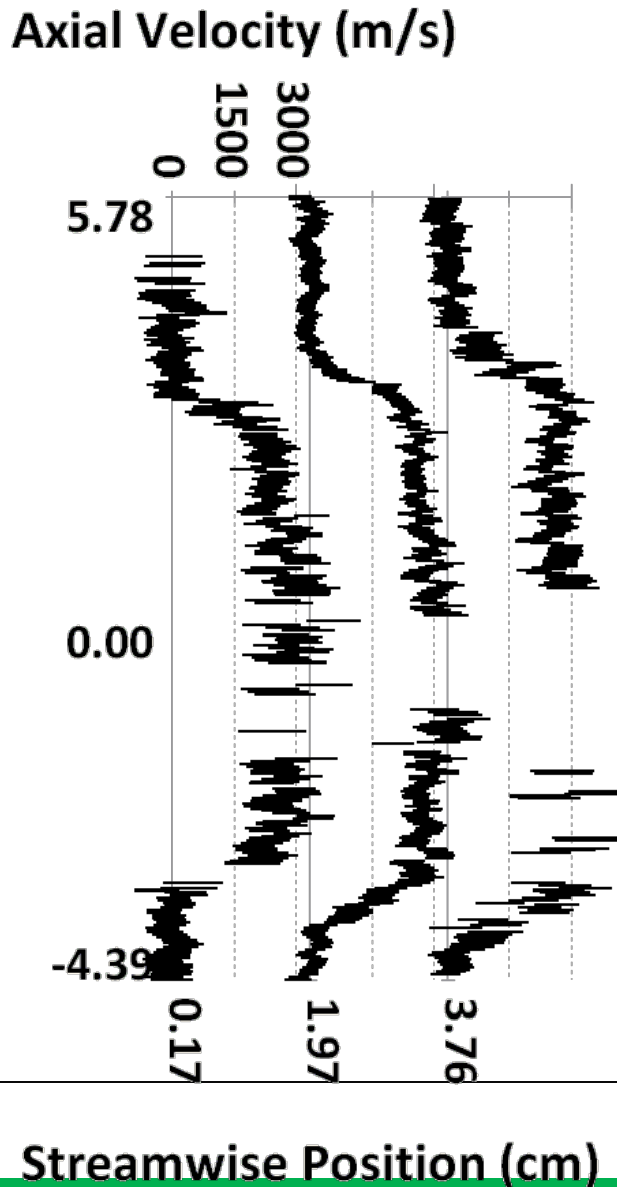


Axial Velocimetry



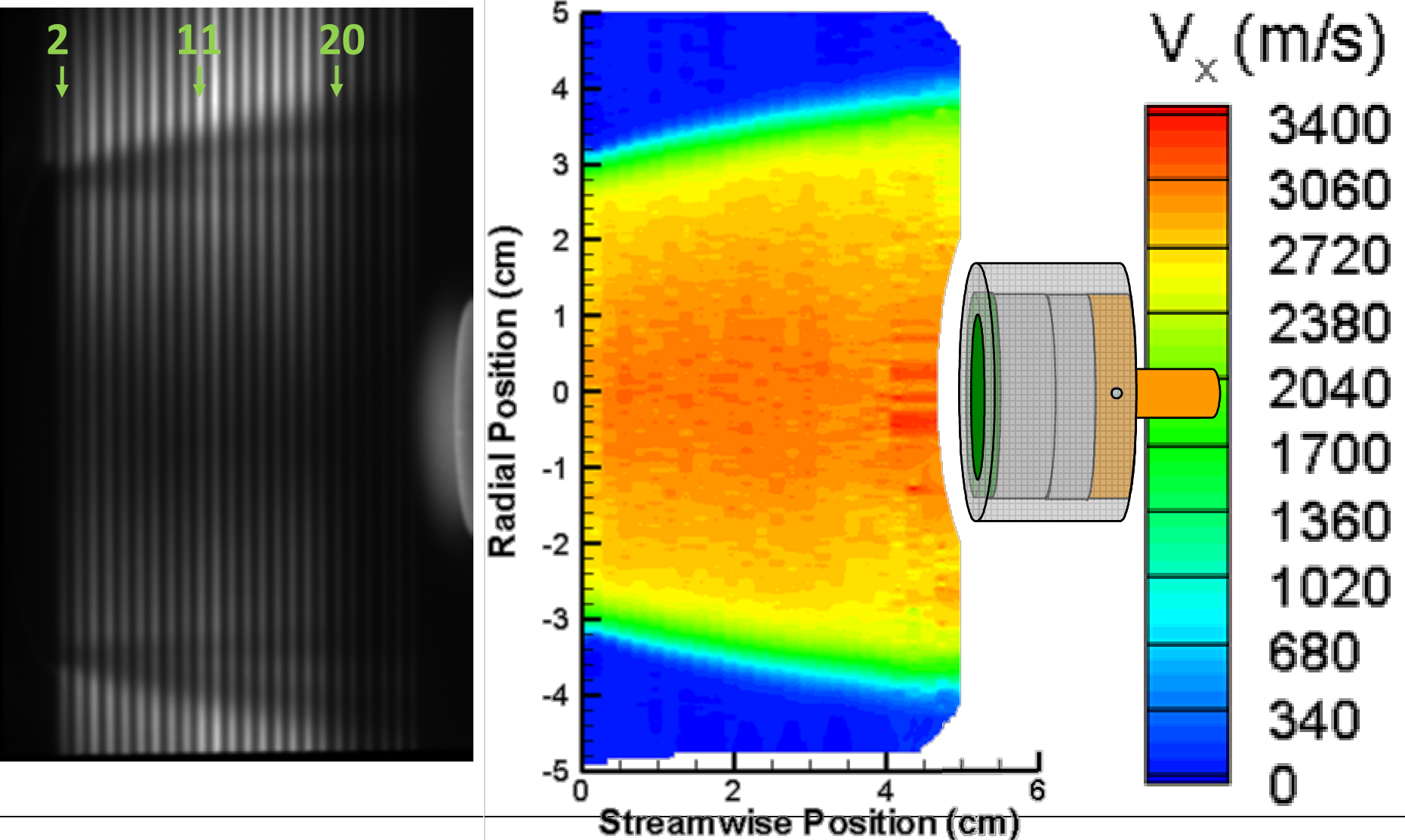
- Dual-frame camera used to acquire single-shot data
- 500 ns inter-frame delay
- Enables measurement of velocity fluctuations

Average and Single-Shot Axial Velocity



- Width of black points corresponds to twice the measured uncertainty
- Red points indicate measured fluctuating velocity component (~6?% of mean)

Mean Axial Velocity Map



Magnitude of velocity, Flow uniformity (spanwise and with distance downstream, cartoon of sample size.

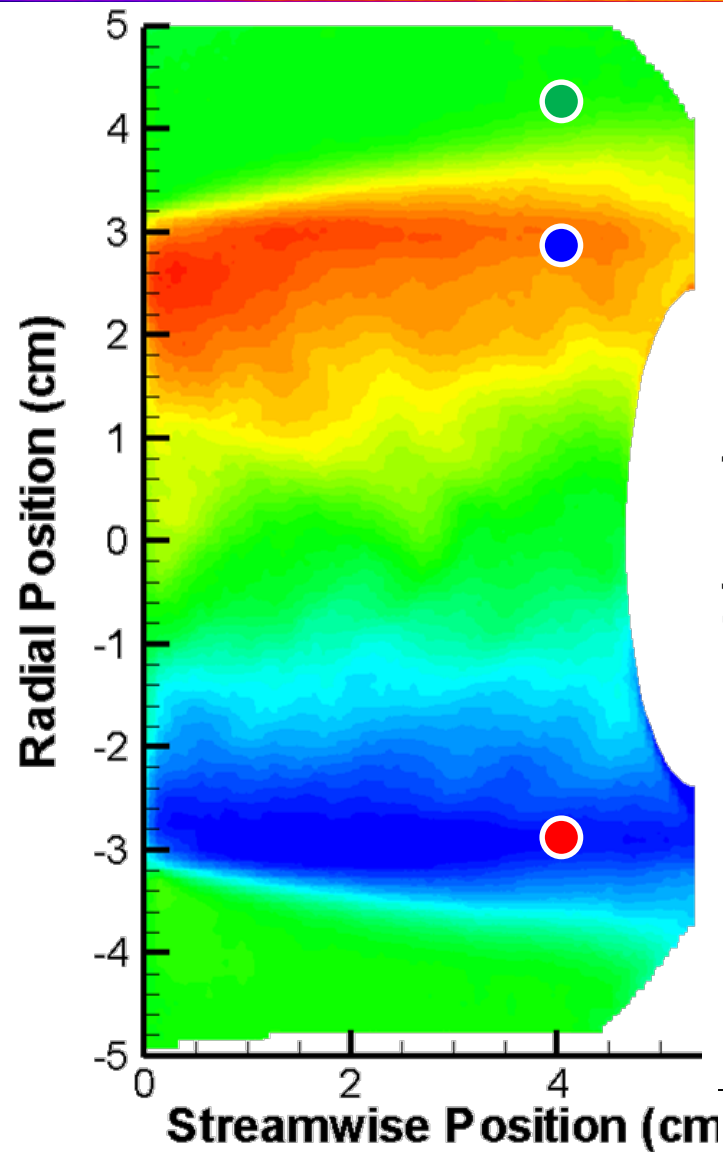
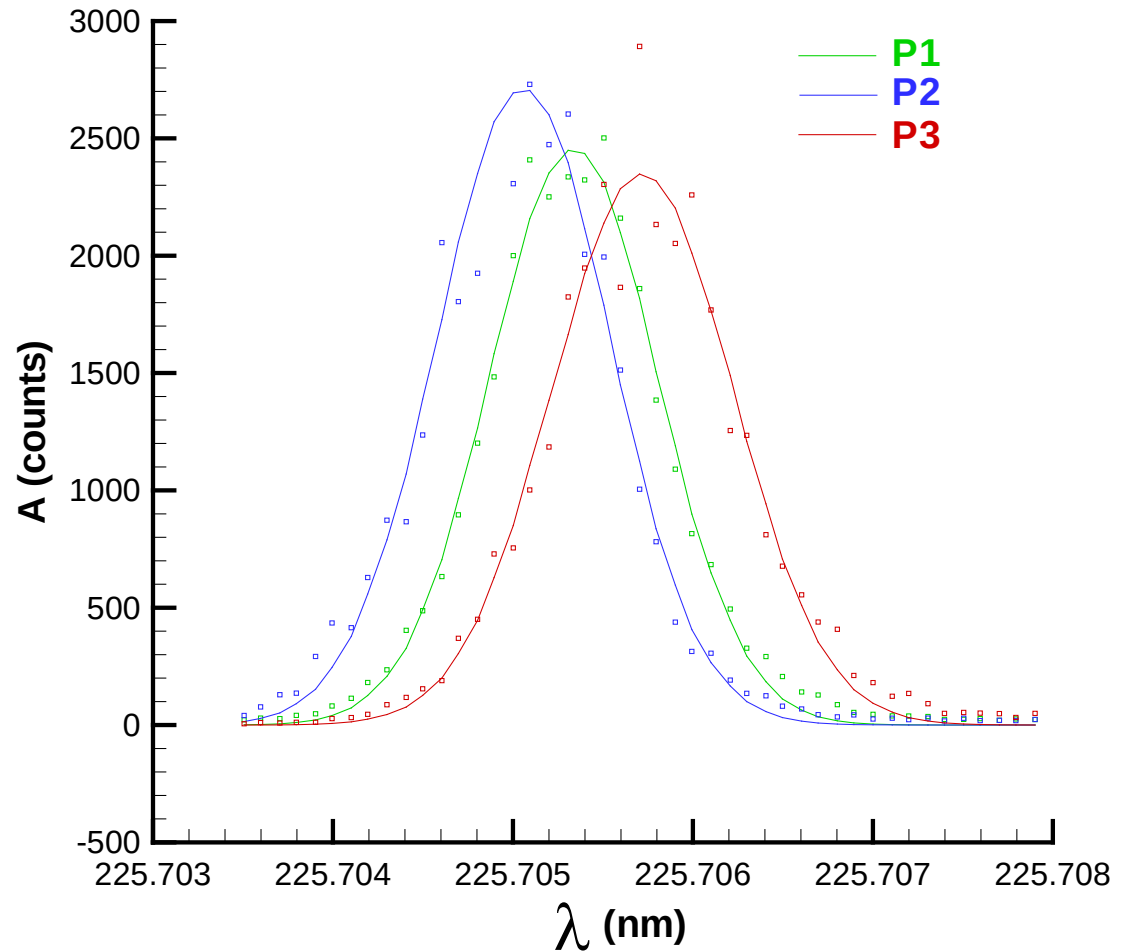
Radial Velocimetry

Measuring Doppler shift

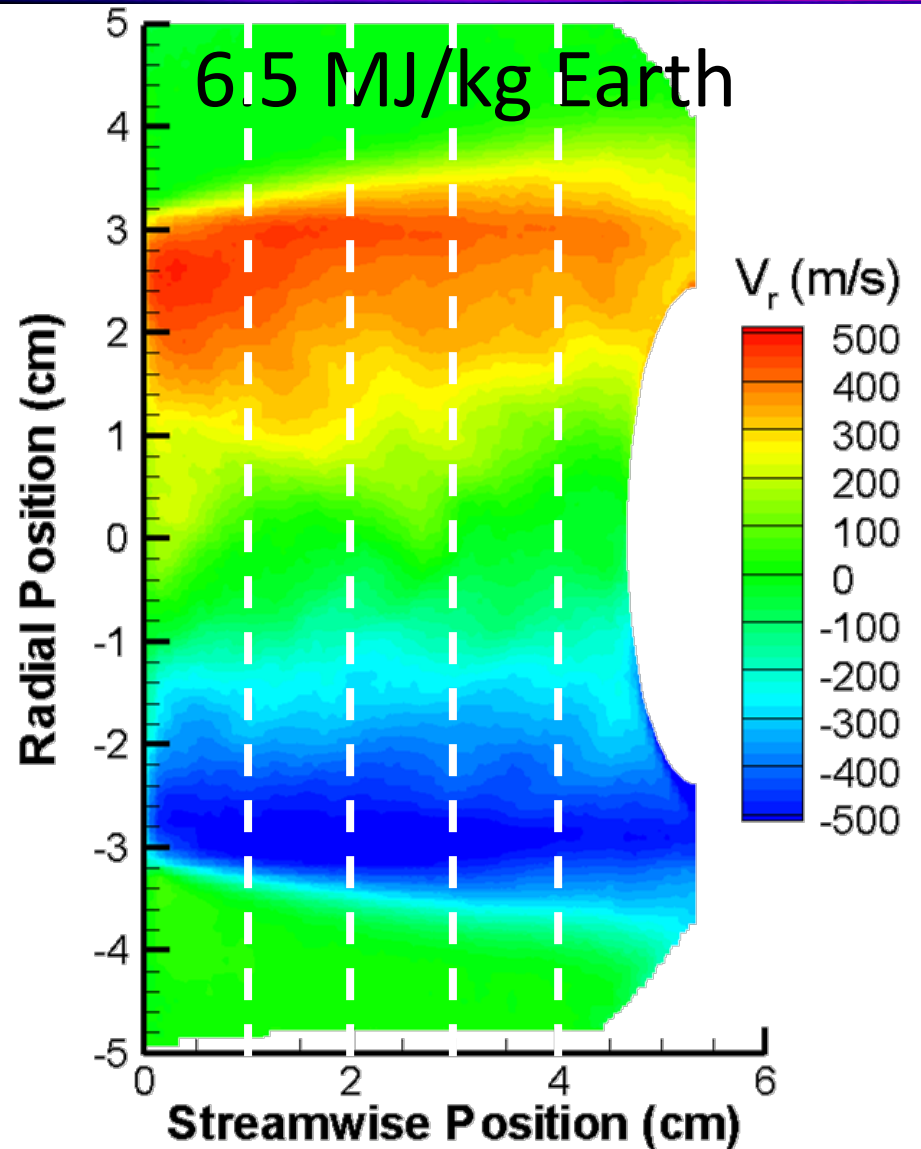
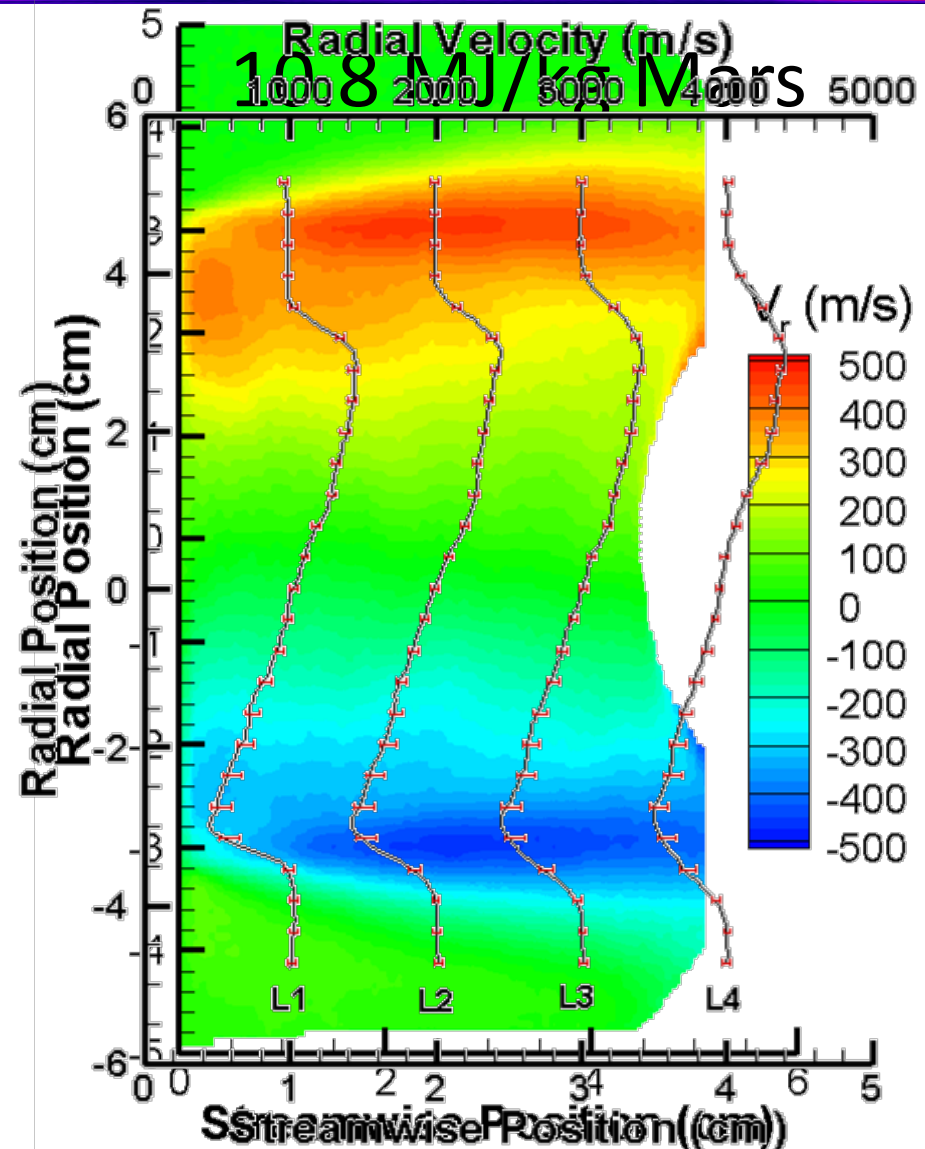
Radial velocity maps

Combined axial/radial results

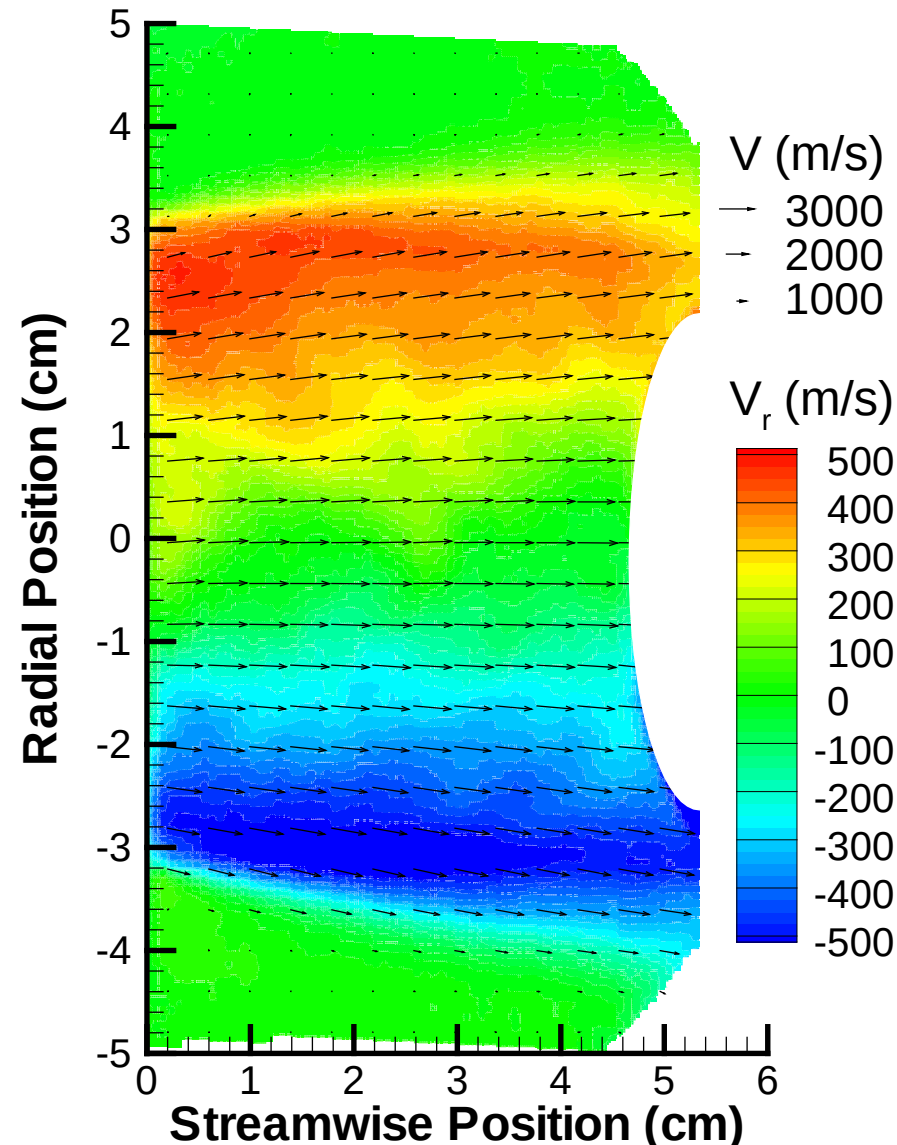
Doppler Radial Velocimetry



Radial Velocity Maps



Combined Axial and Radial Velocity



- Axial
 - Magnitude: 3,000 m/s
 - Fluctuations: 207 m/s (7%)
 - Uncertainty
 - Mean: 182 m/s
 - Single-shot: 760 m/s
- Radial
 - Magnitude: ± 500 m/s
 - Uncertainty: 62 m/s
 - Upper temperature bound
 - 1,300 K (6.5 MJ/kg Earth)
 - 1,600 K (10.8 MJ/kg Mars)

Concluding Remarks

Summary of major results

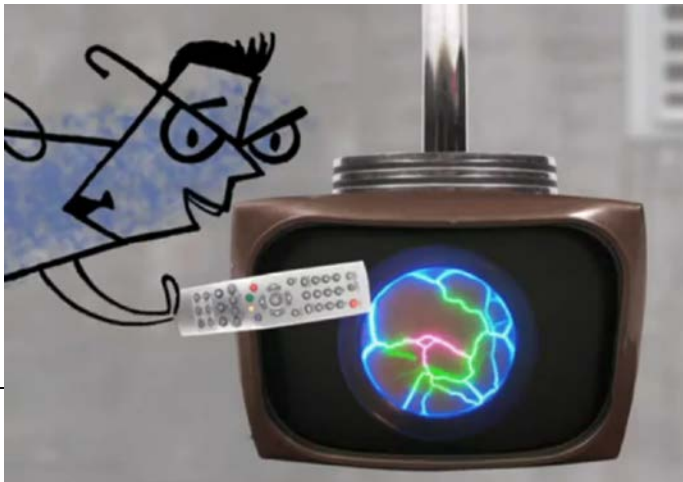
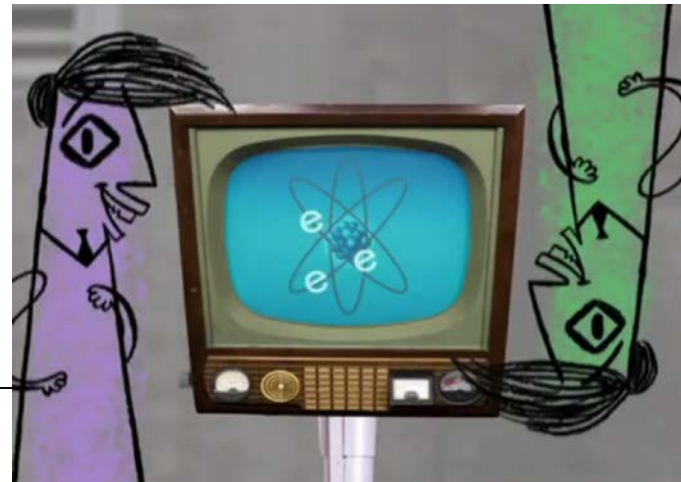
Acknowledgements

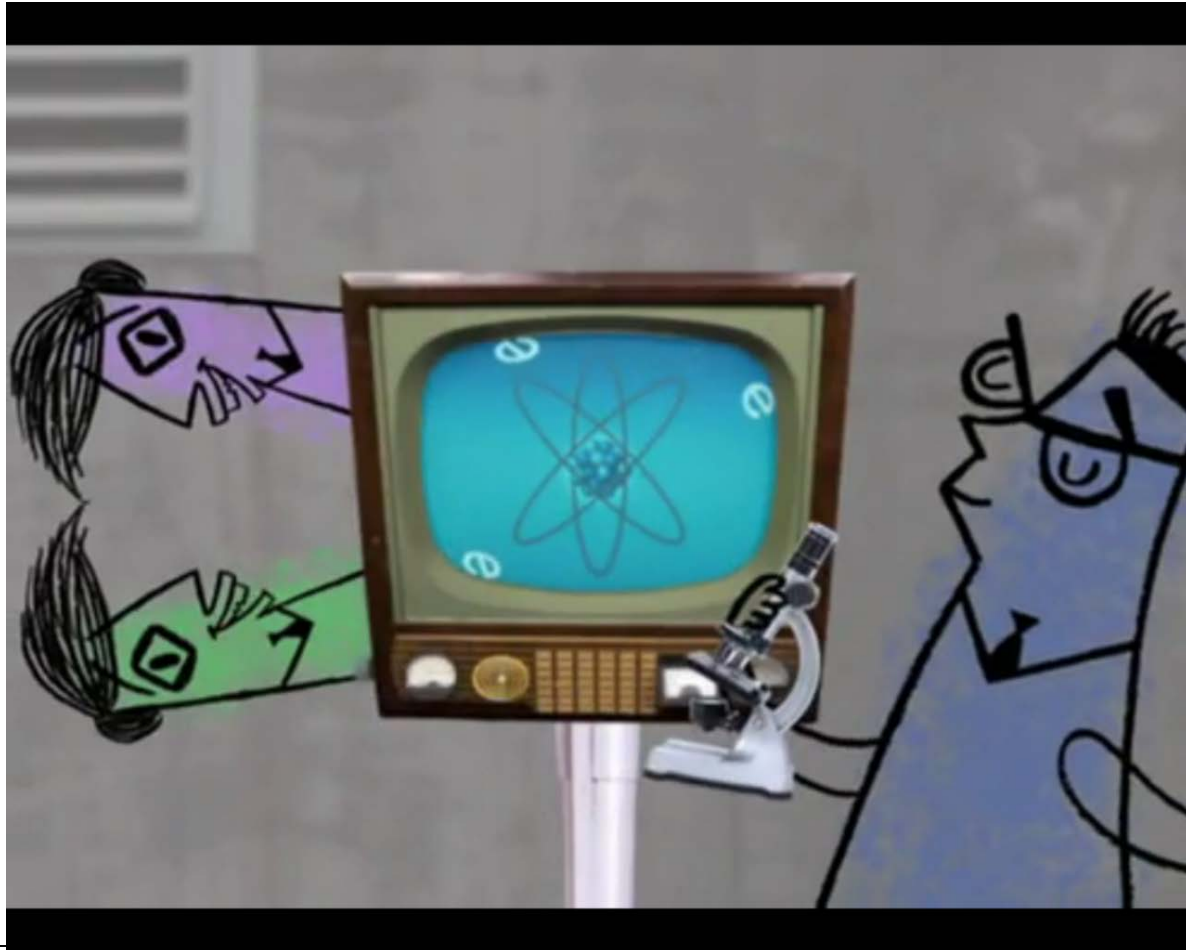
Summary of Major Results

- Flow visualization has furthered understanding of the flow
 - Identified presence of large, unsteady flow features
 - Provides an indication of nozzle performance
 - Shock standoff distance (9.5 ± 1.1 mm)
- Velocity measurements have been demonstrated in a high-enthalpy, low-pressure, unsteady, supersonic arcjet flow for simulated Earth and Mars atmospheres
 - Mean axial velocity along centerline: 3 km/s
 - Centerline axial fluctuations: 0.2 km/s (7% of mean)
 - Maximum mean radial velocity: ± 0.5 km/s

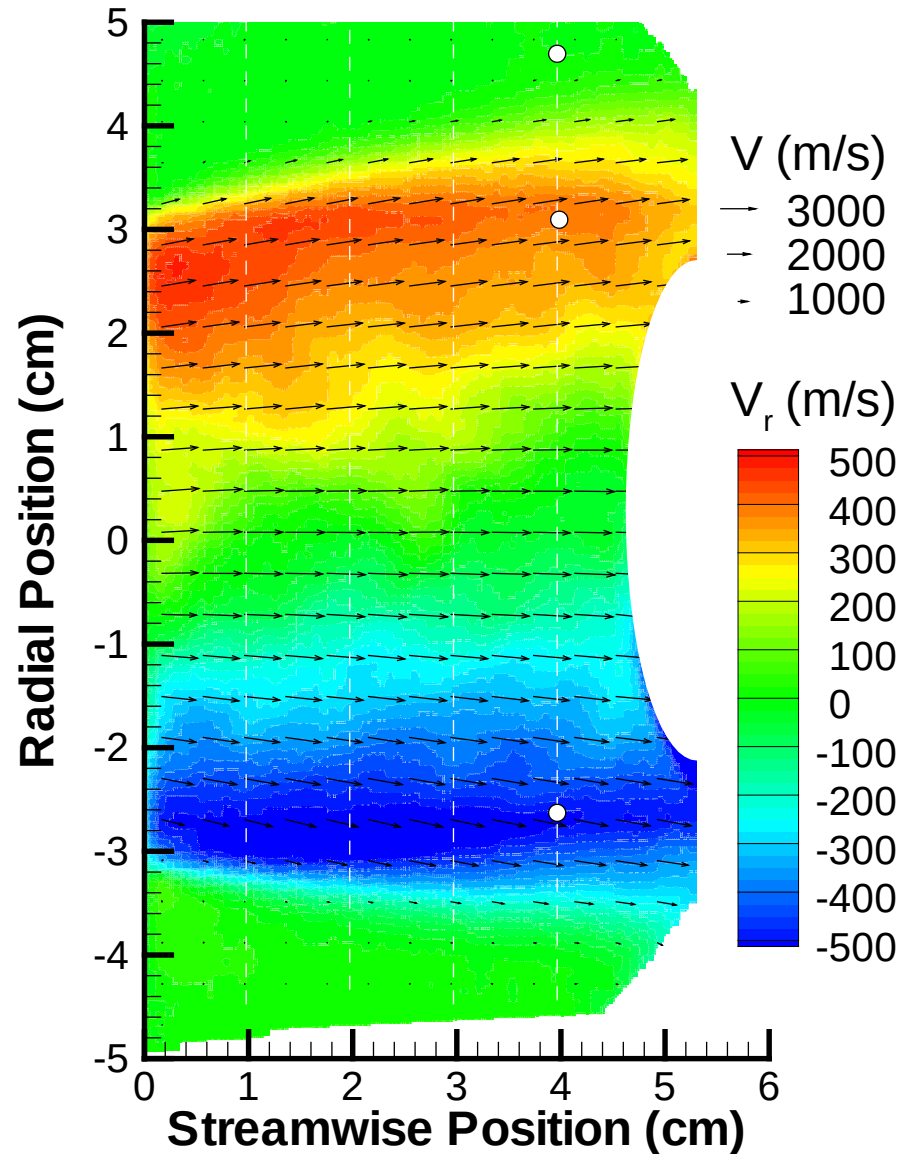
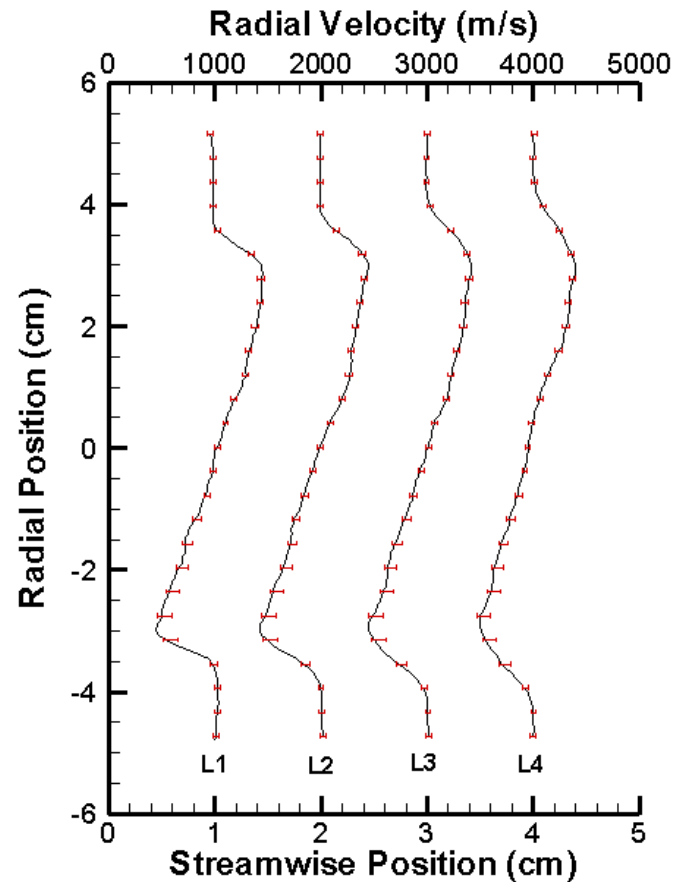
Acknowledgements

- Amy Brewer
- Jeff Wheeler (Whitworth University)
- Ethan Brewer (Ohio State)
- Natural Sciences and Engineering Research Council of Canada (NSERC)
- NASA's Fundamental Aeronautics Program, Hypersonics Project

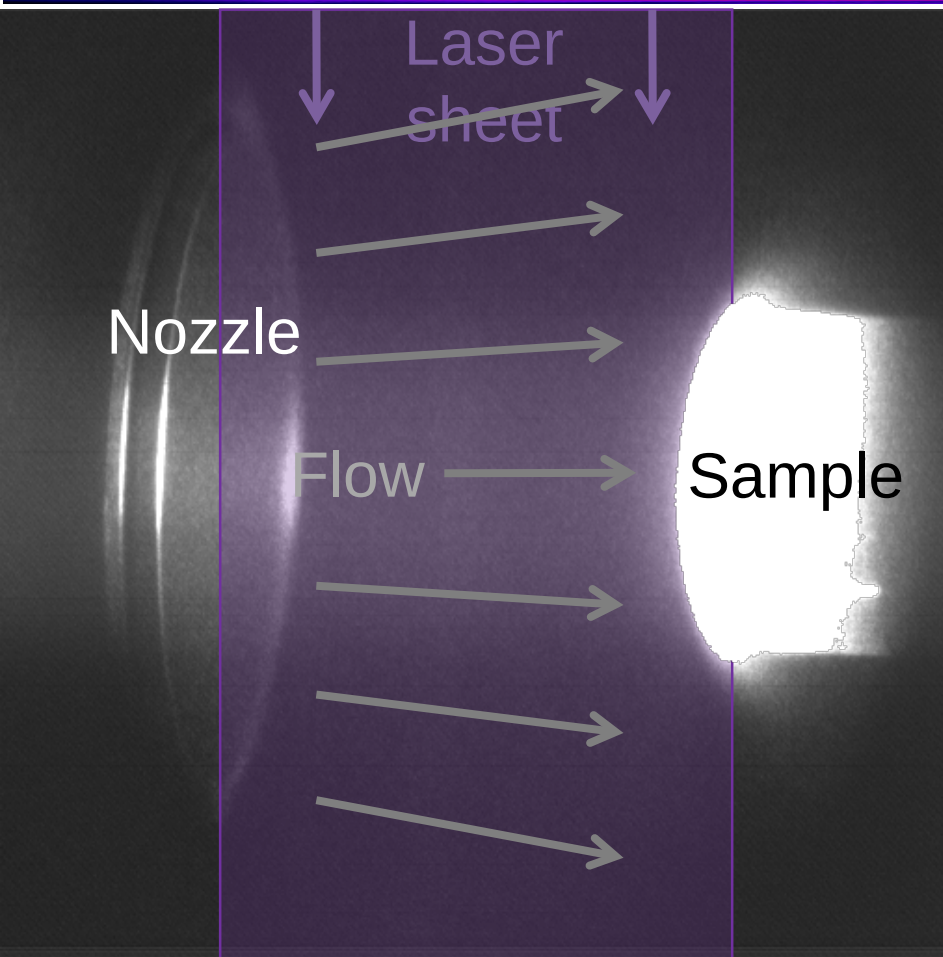
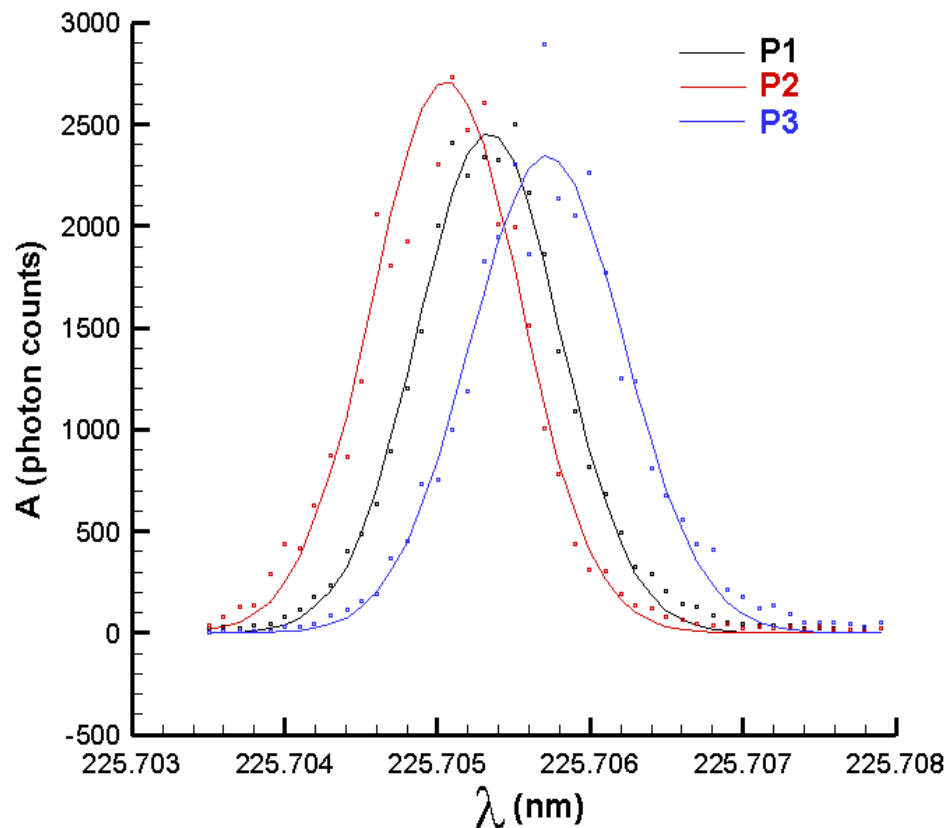




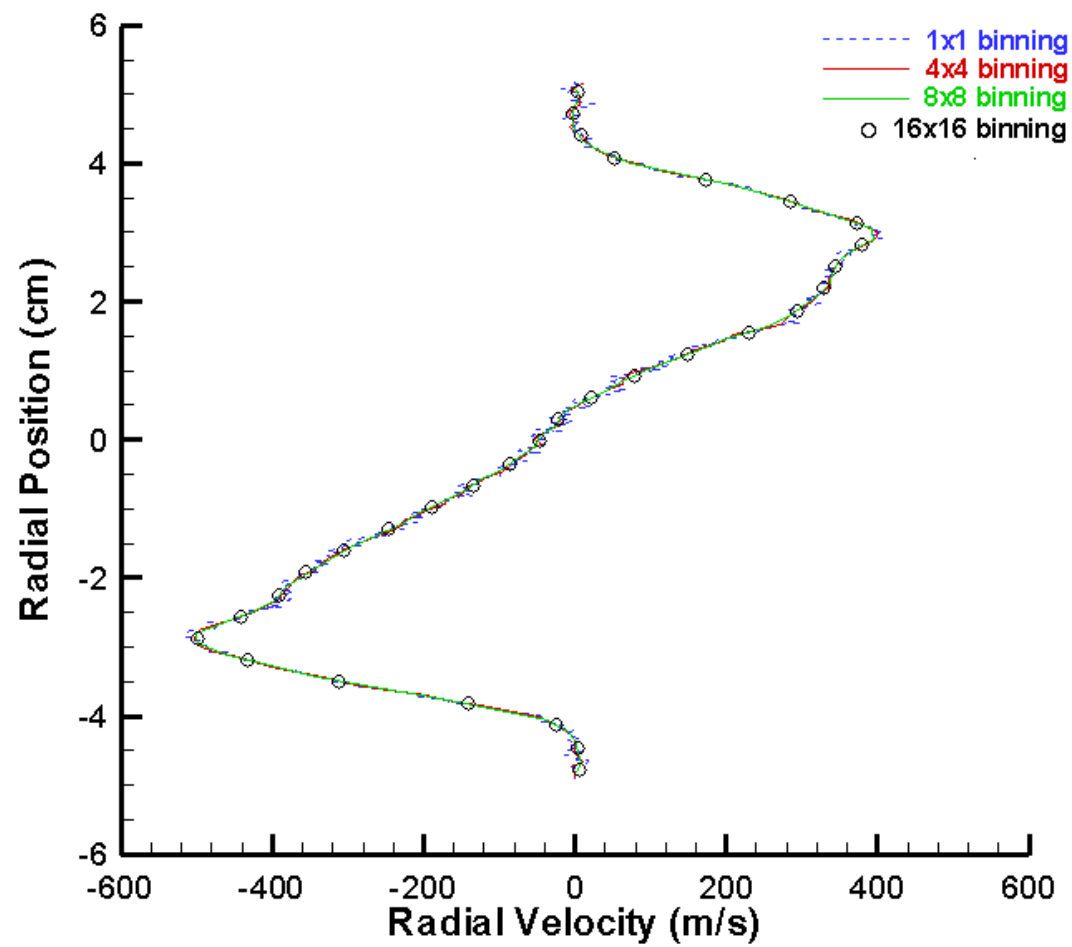
Combined Axial and Radial Velocity

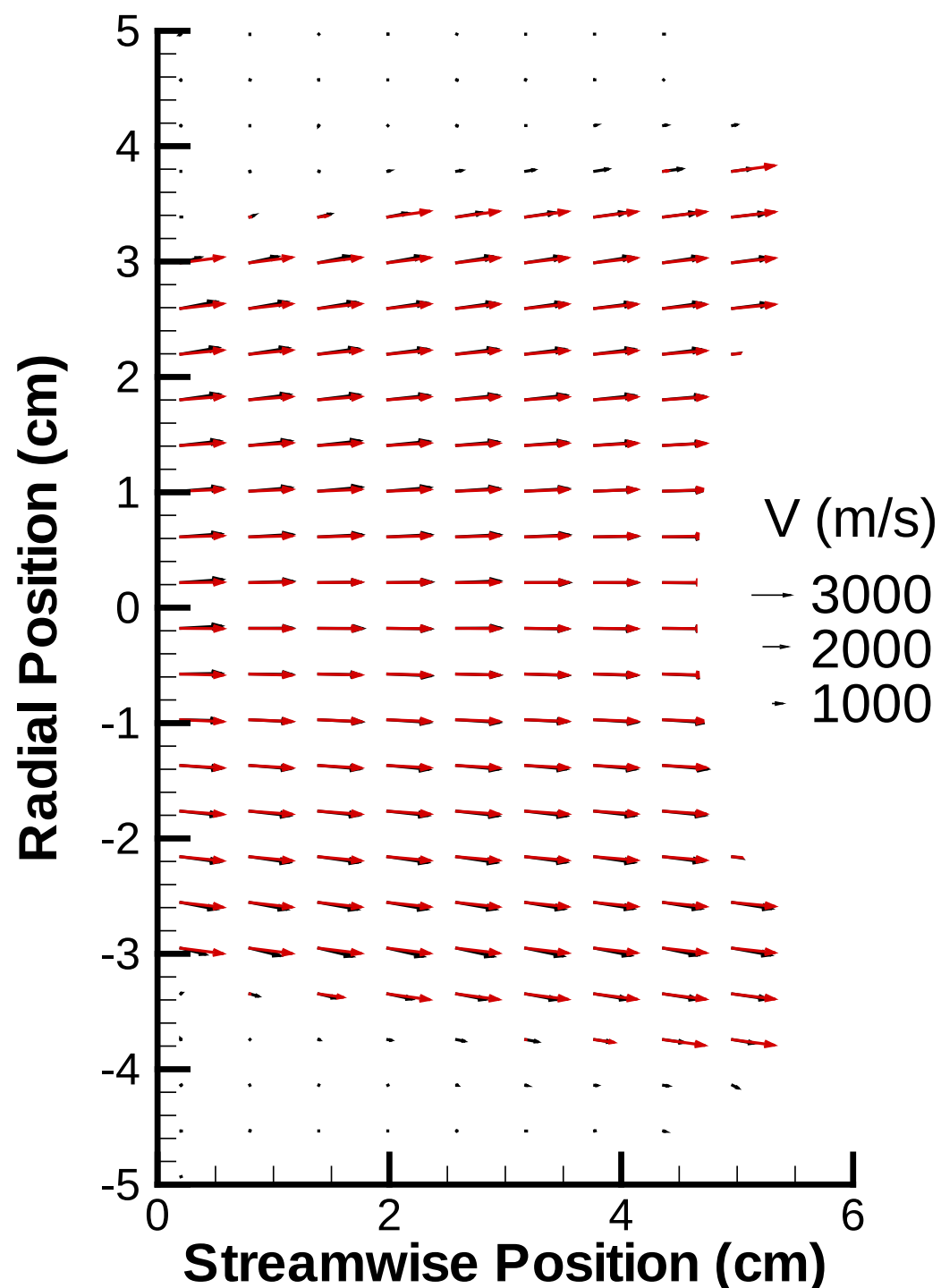


Doppler Radial Velocimetry



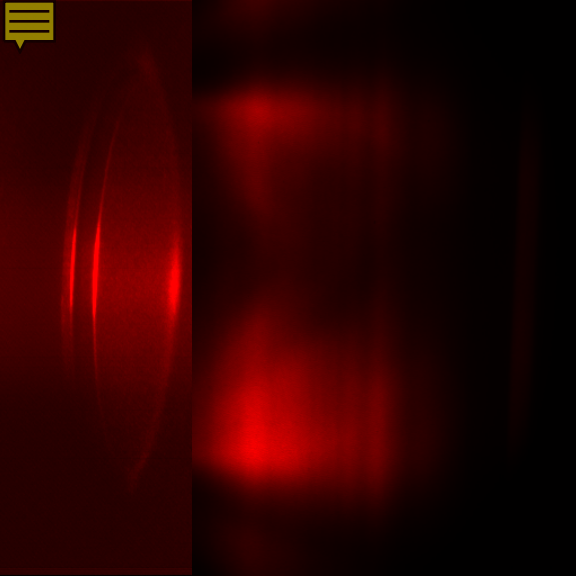
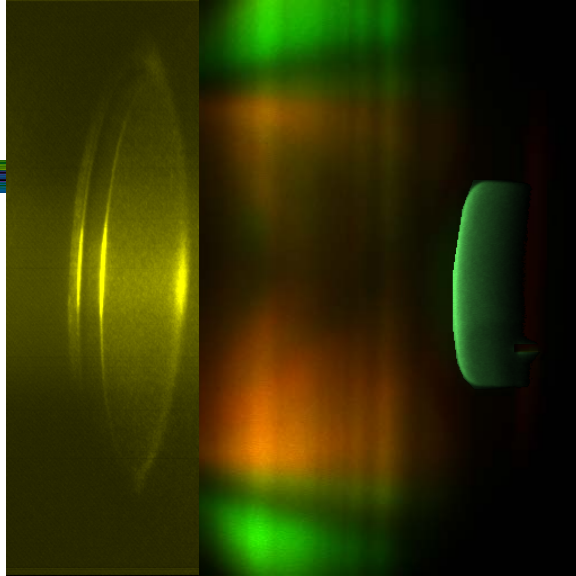
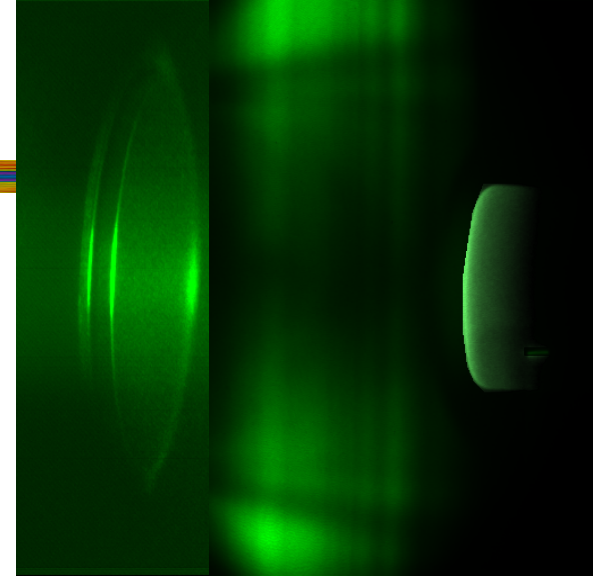
Obtain spectra by scanning laser wavelength. Cartoon, then replace by data. Pressure low enough to neglect pressure shift (quote error in m/s or %).







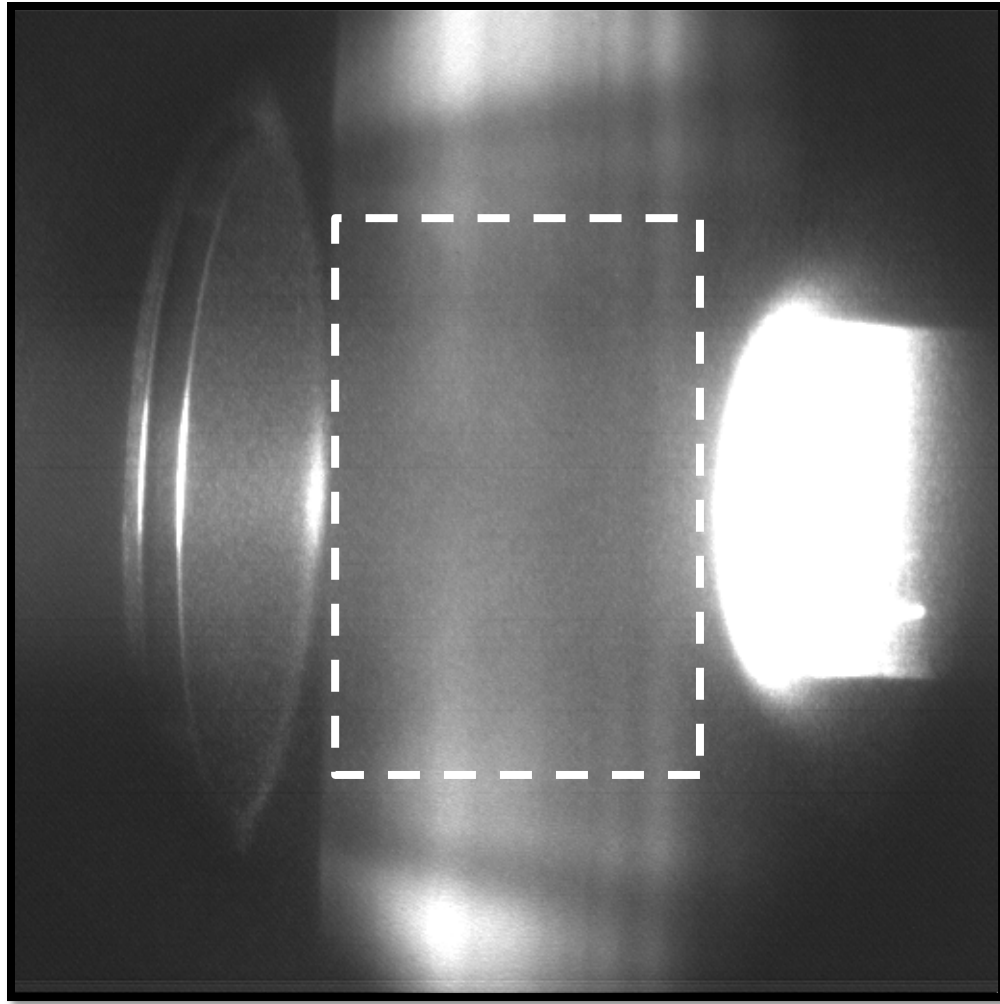
Uncertainty Type	P1 ($y = 4.4$ cm)	P2 ($y = 2.8$ cm)	P3 ($y = -2.8$ cm)
Random Noise (m/s)	25.9	25.9	25.9
Laser Beam Attenuation (m/s)	0.1	14.6	55.9
Laser Non-Linearity (m/s)	0.0	3.0	4.5
Collisional Shift (m/s)	1.1	1.1	1.1
Total Uncertainty (m/s)	25.9	29.9	61.8



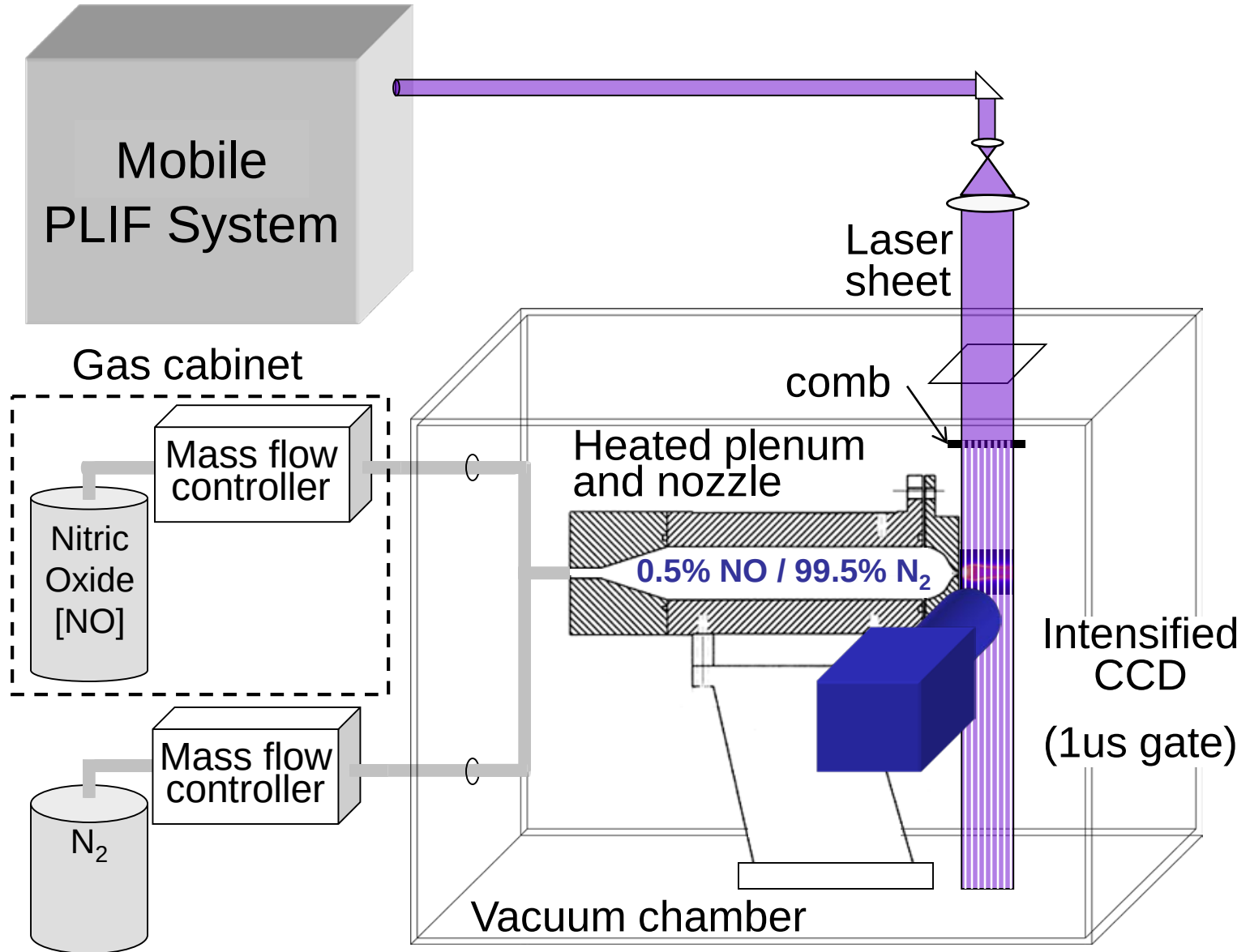
Core Flow 4/7/2010, Run
39, Frames 15-56

Combined

With Probe 4/7/2010, Run
39, Frames 1-12, 59-100 50

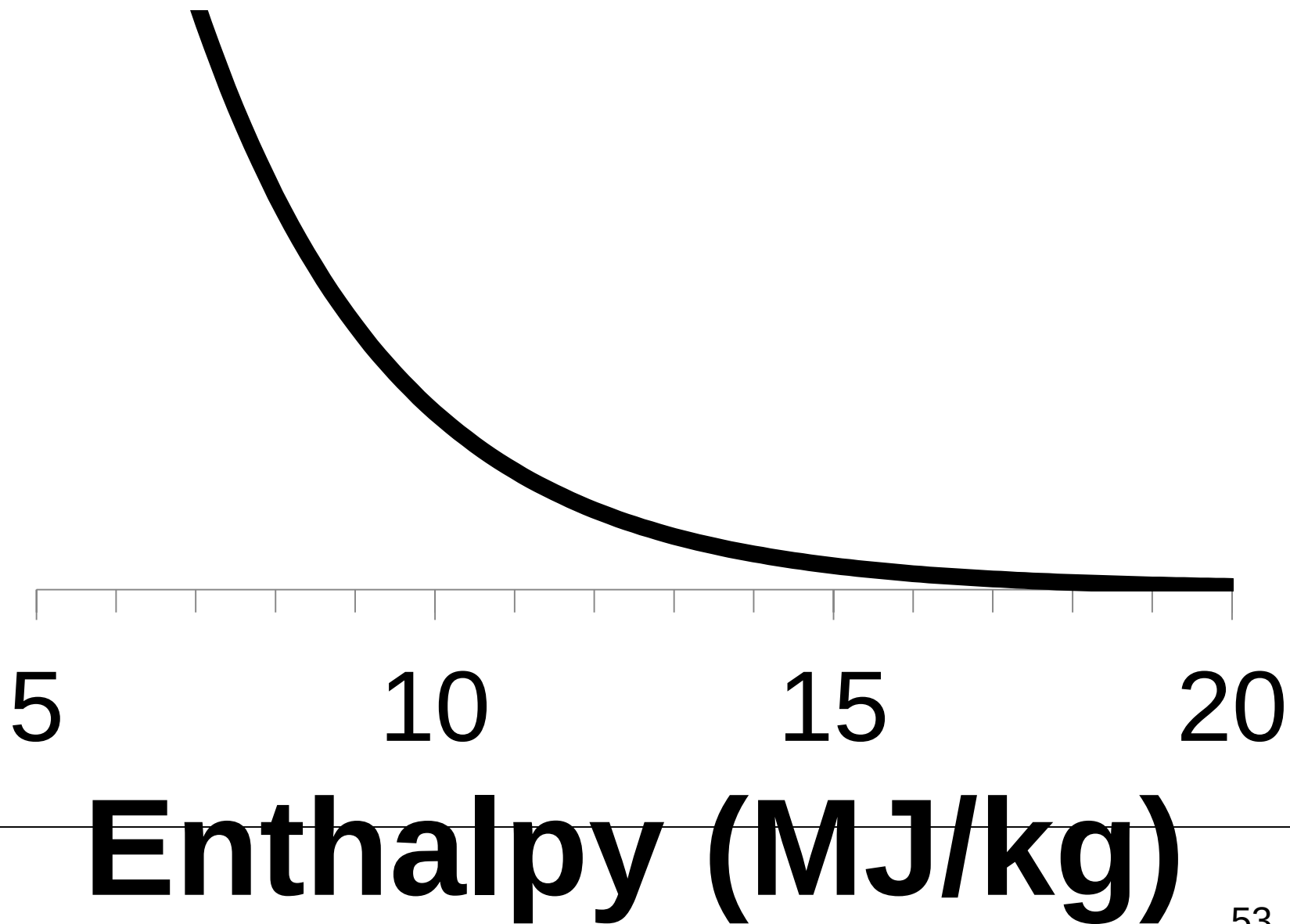


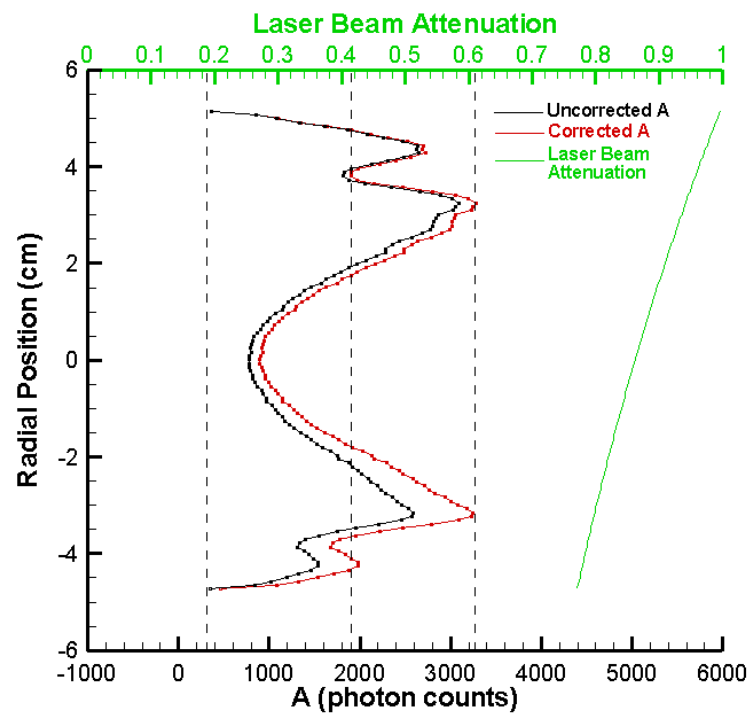
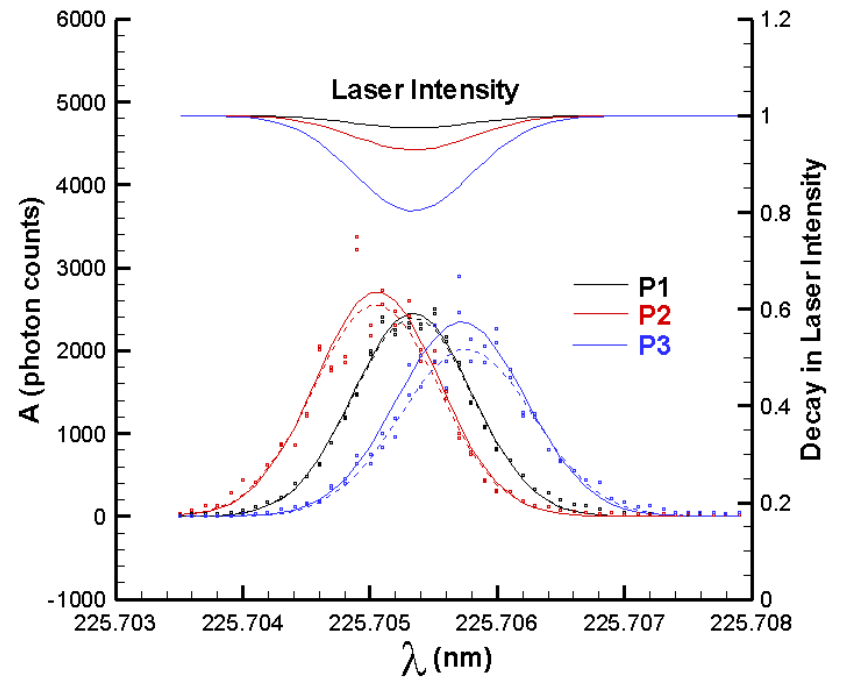
Experimental Setup





Intensity

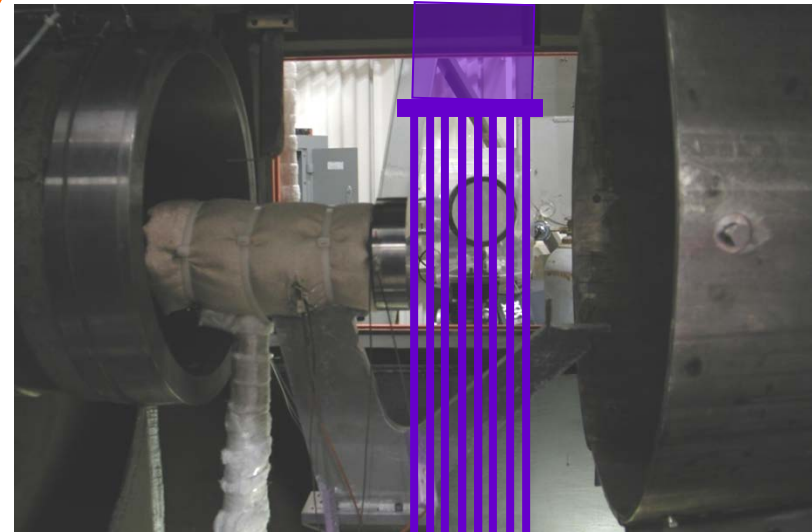




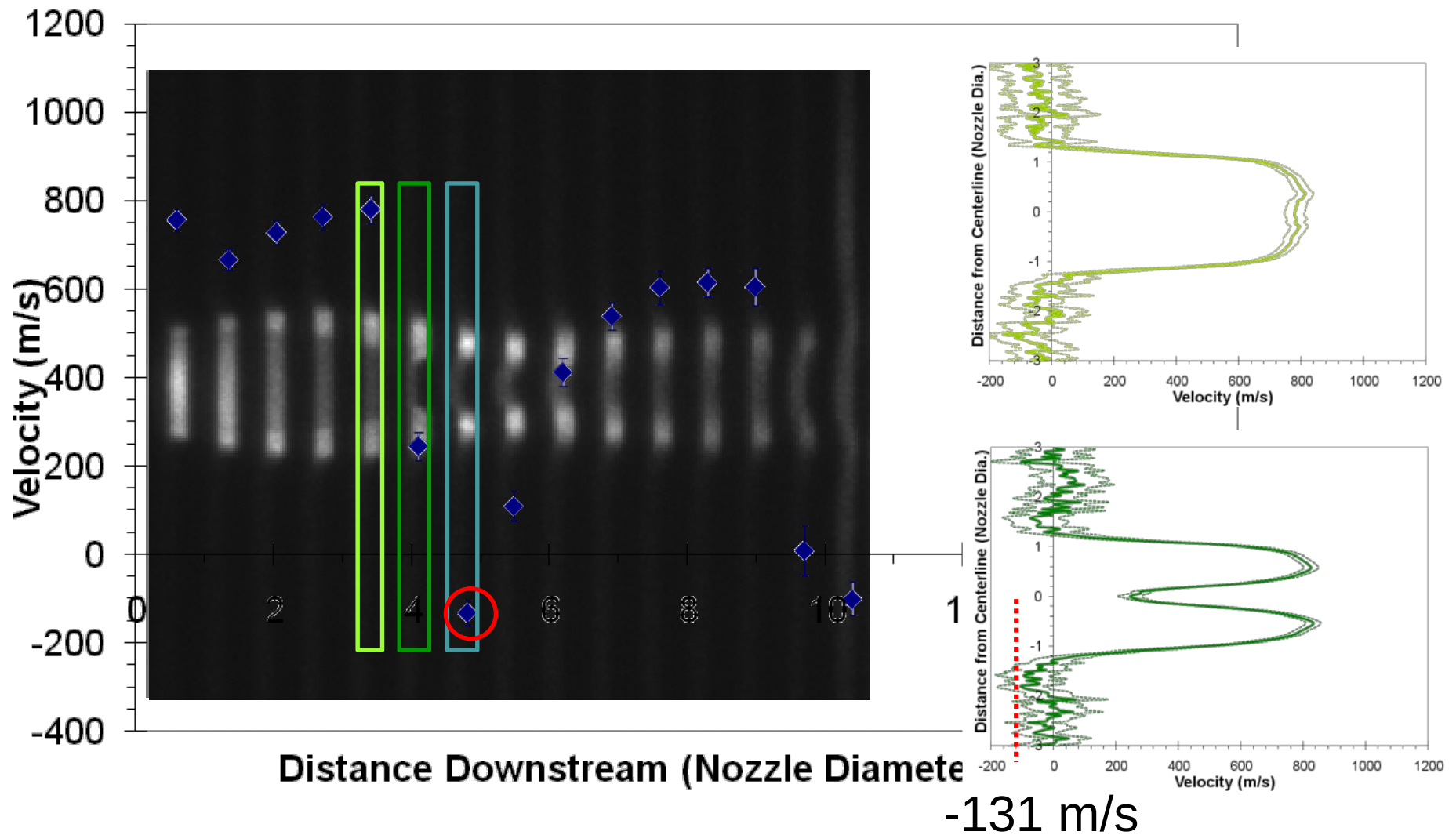
Vacuum Chamber



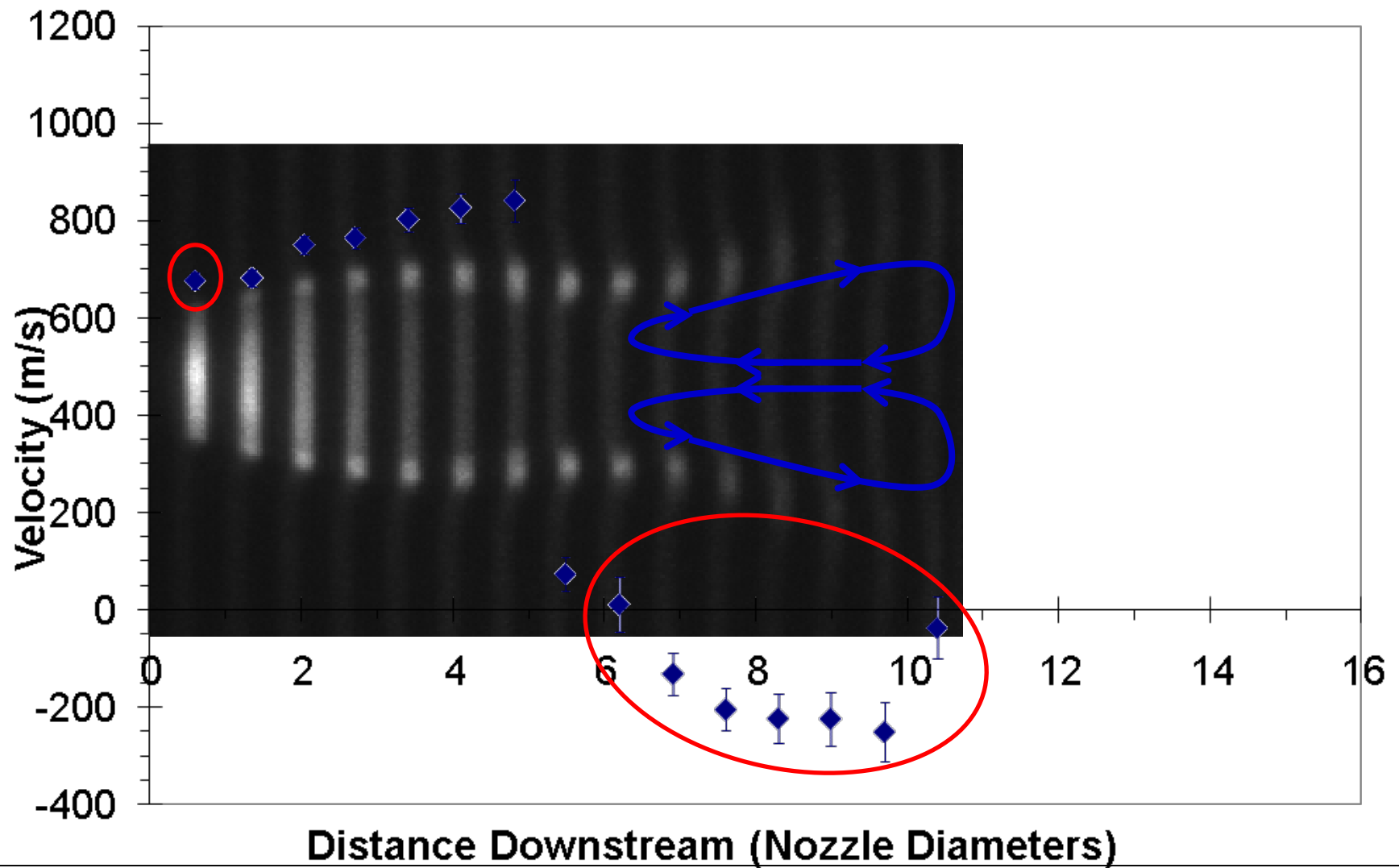
Laser sheet enters
top of test section



Run 435

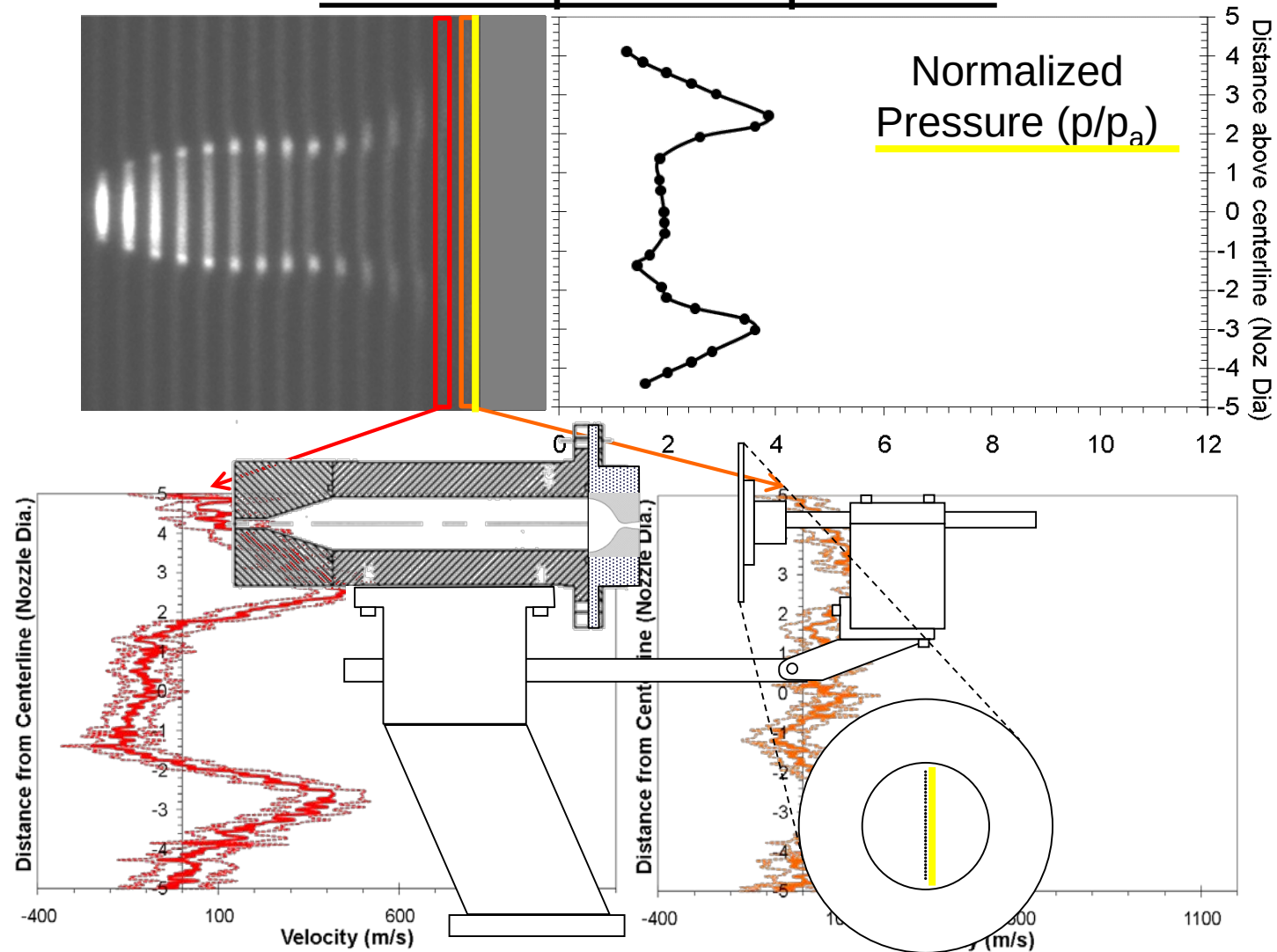


Recirculation



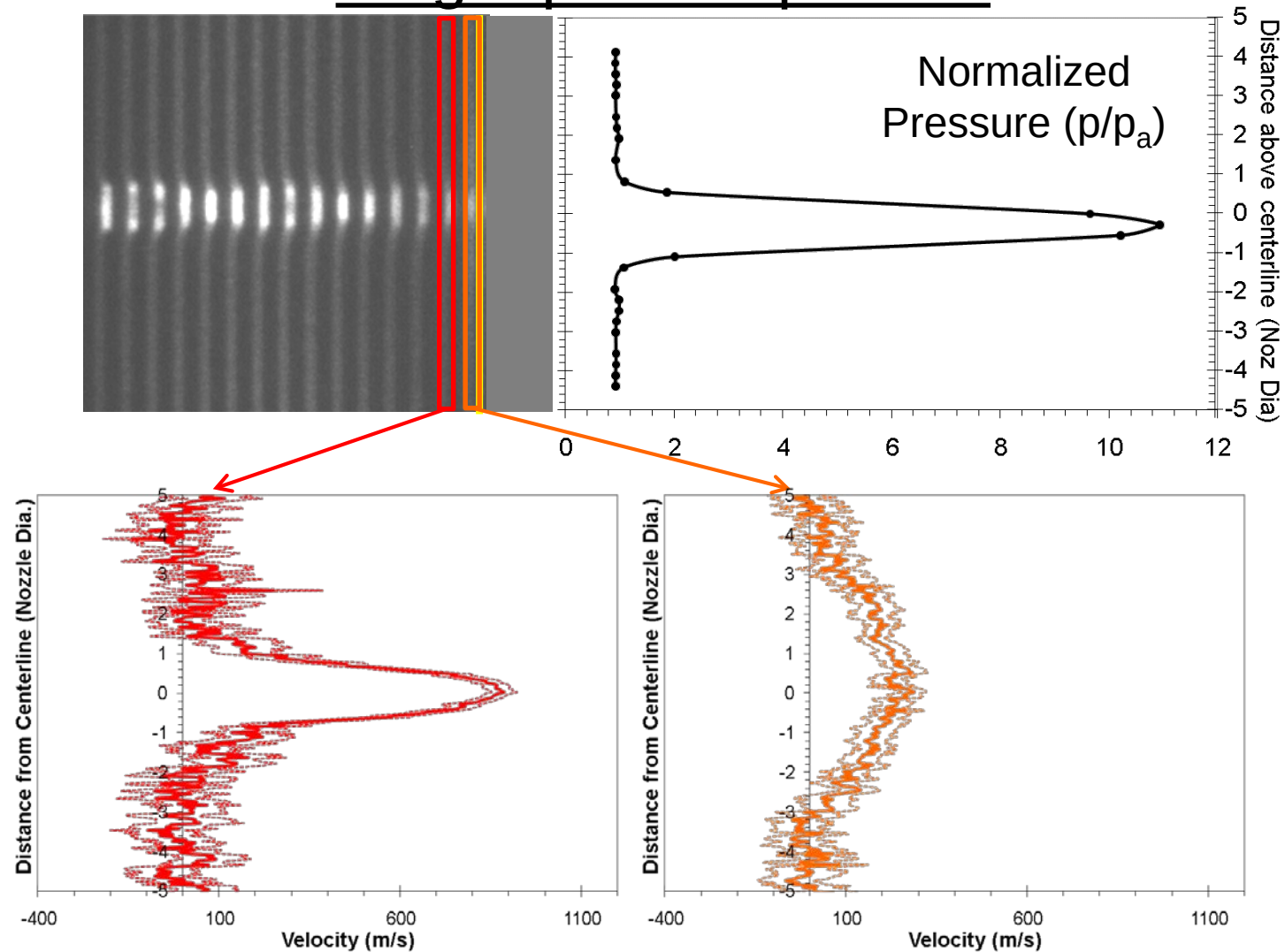
Comparison With Pressure

Double-peaked profiles



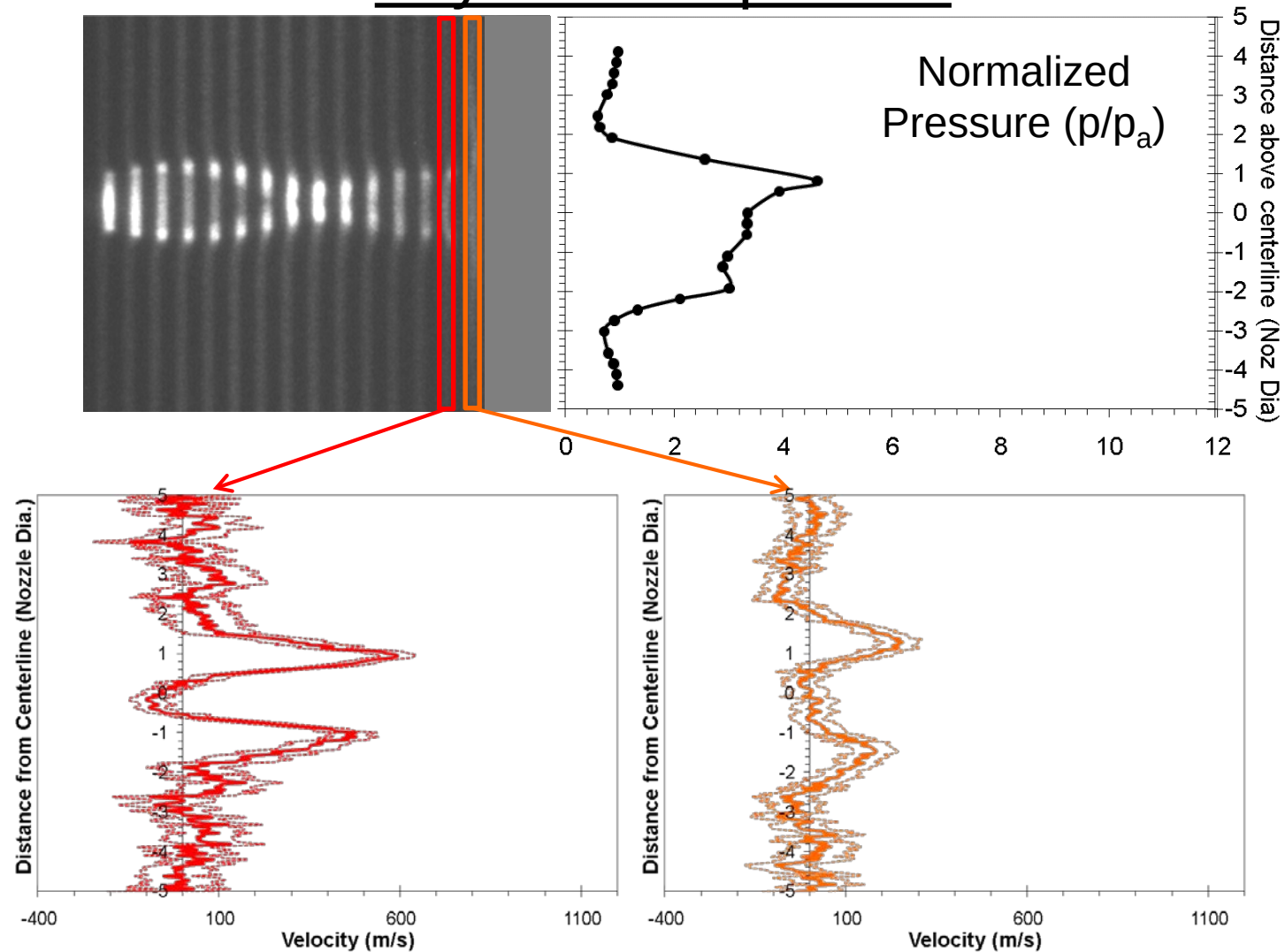
Comparison With Pressure

Single-peaked profiles

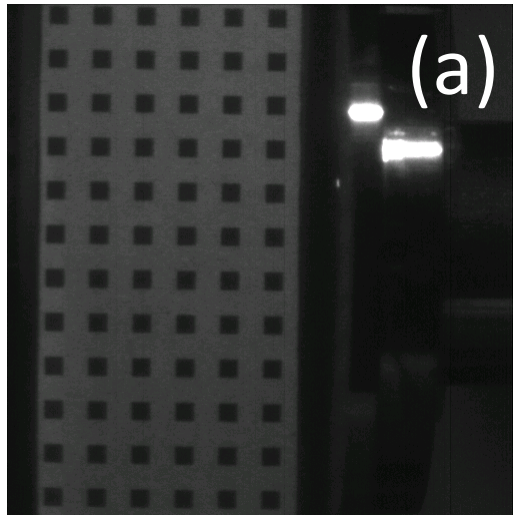
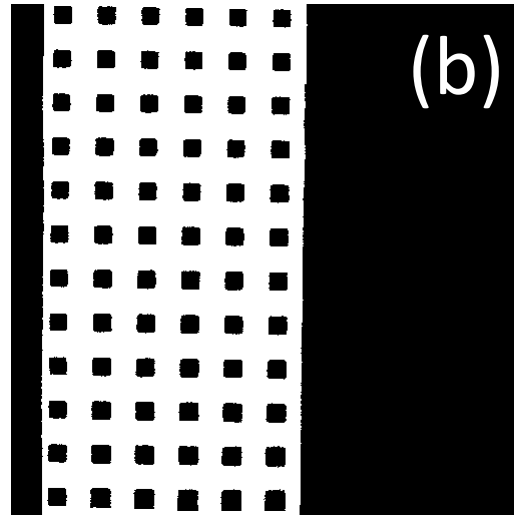
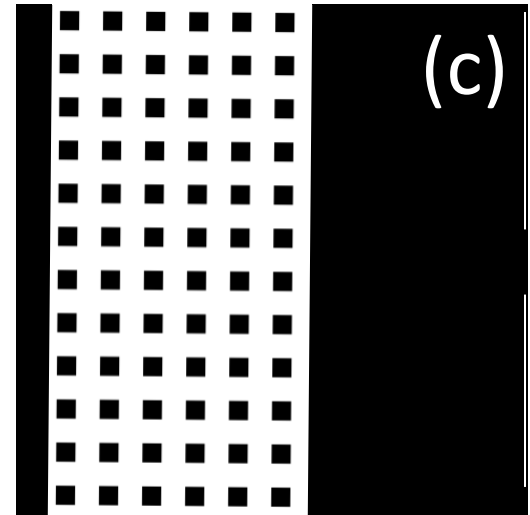
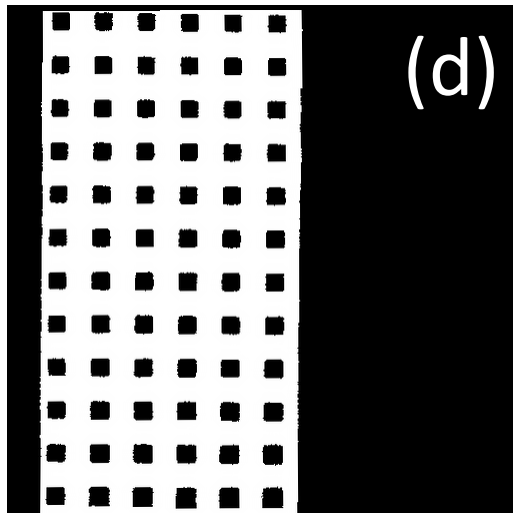
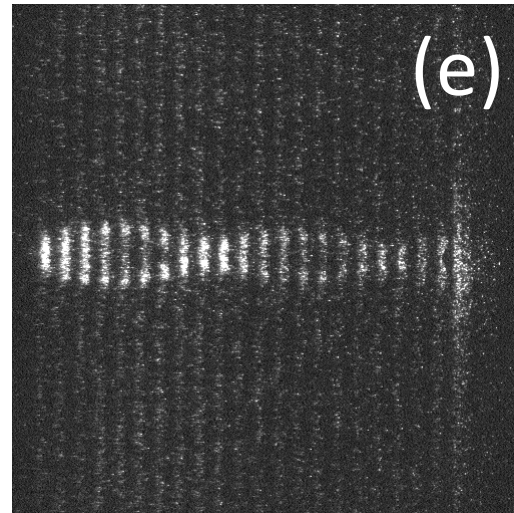
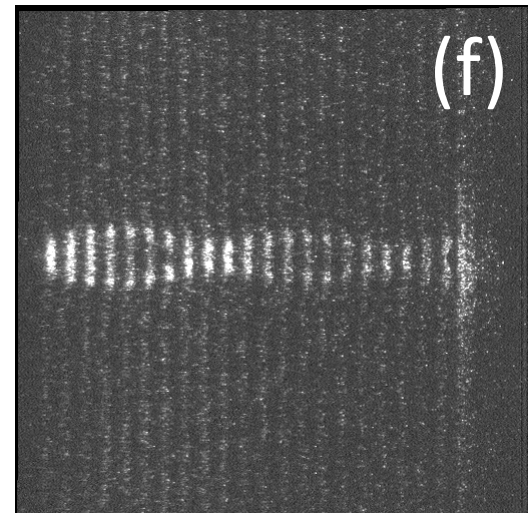


Comparison With Pressure

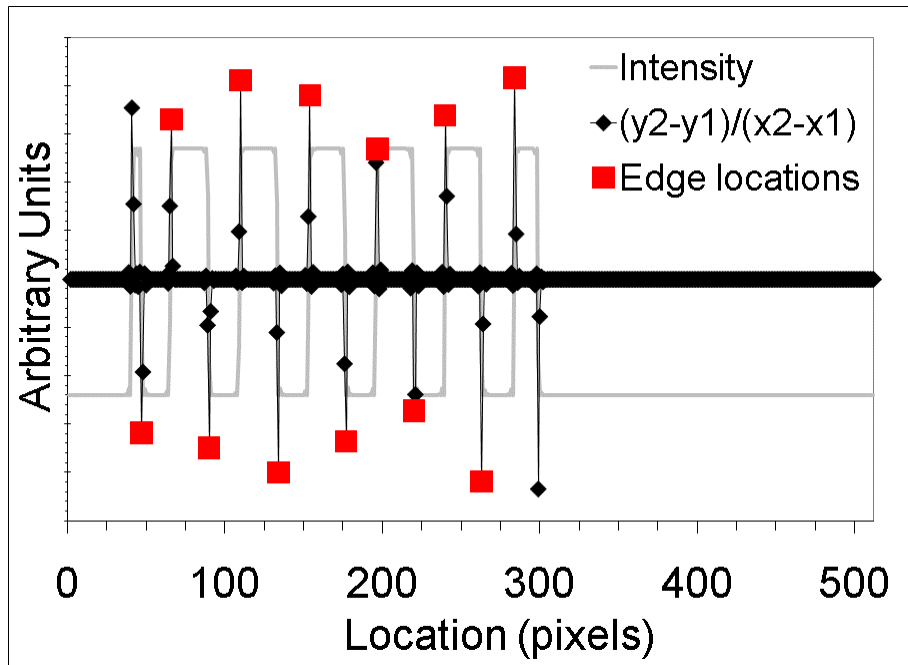
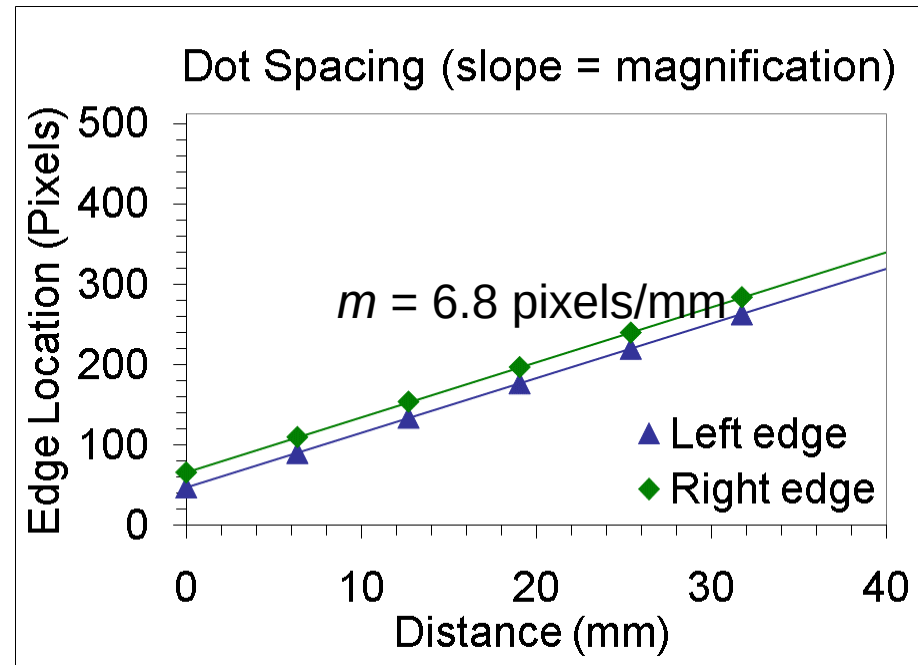
Asymmetric profiles



Dotcards and Unwarping

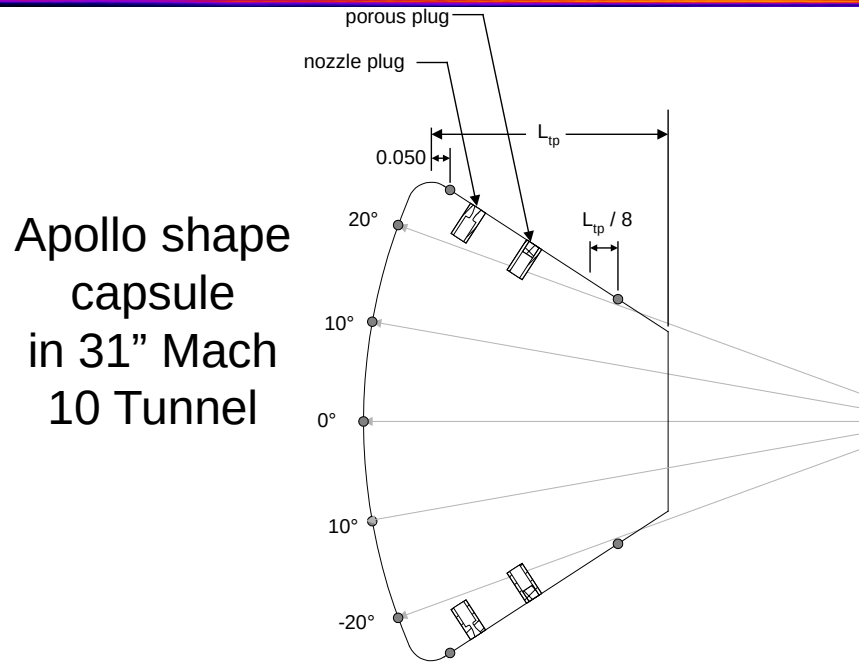


Determining Magnification

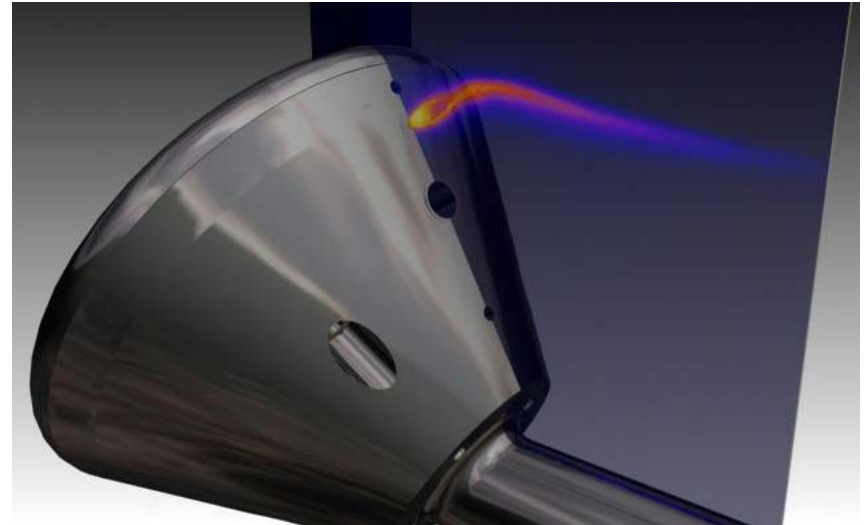


- Find dot locations (pixel number) using discrete derivative of dotcard image intensity
- Calculate magnification using known dot spacing (0.25")

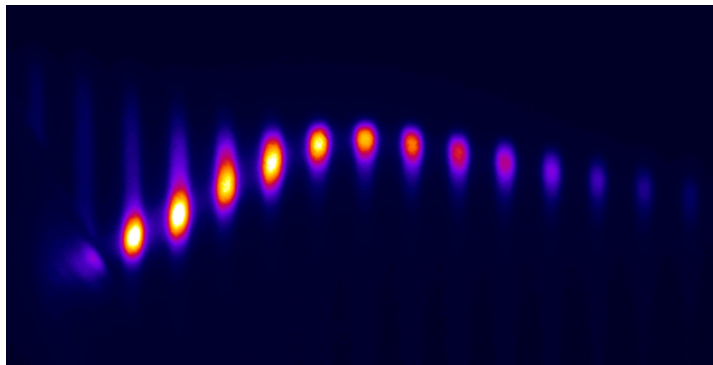
PLIF Measurement of RCS Jet



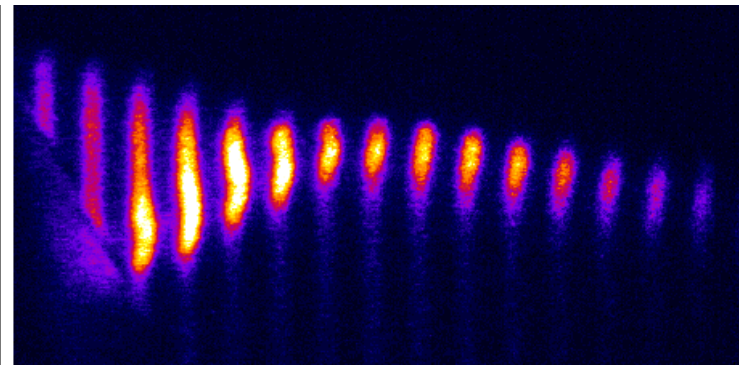
Mach 3 RCS jet
 N_2 seeded with 5% NO



Flow Visualization



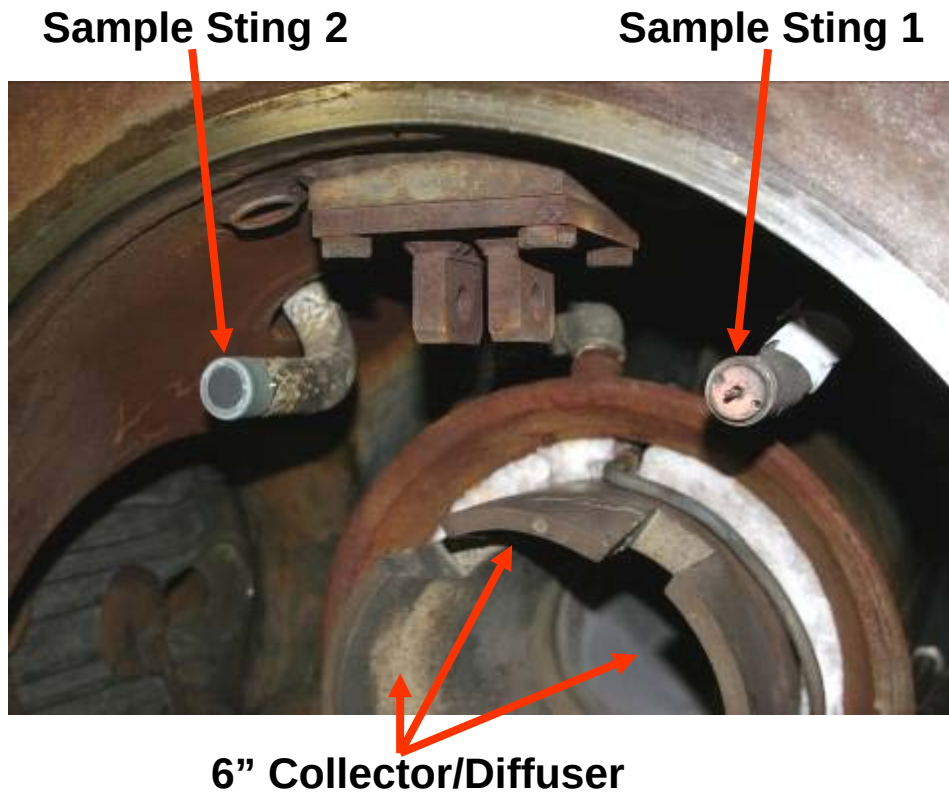
No delay



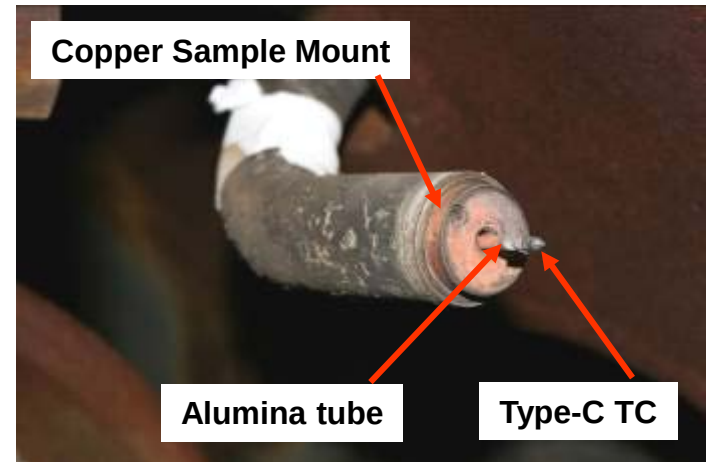
500 ns delay

Velocimetry

HyMETS Facility



Sample Sting 1

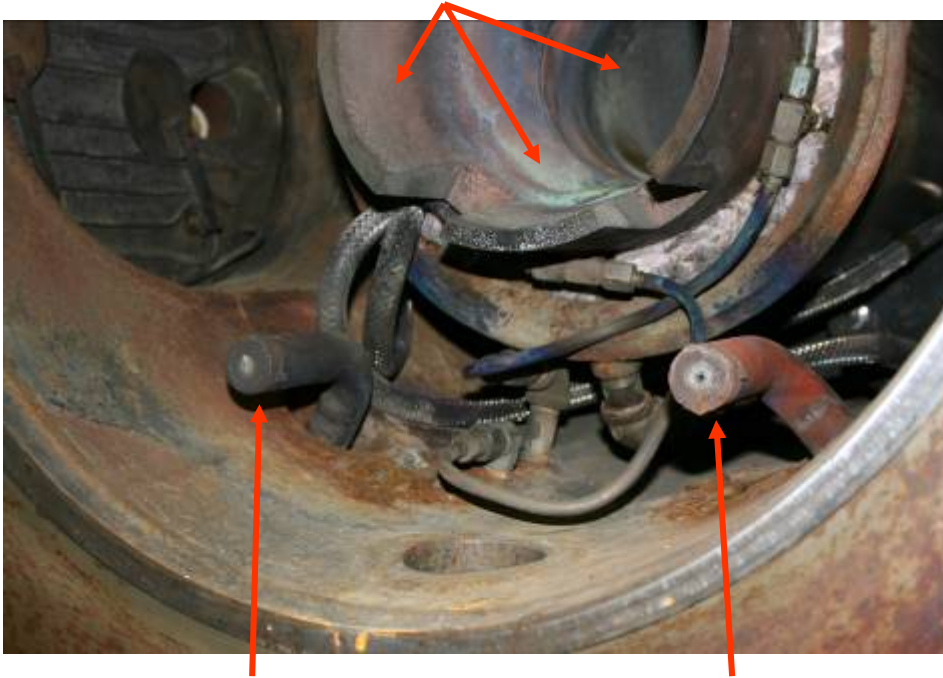


Sample Sting 2



HyMETS Facility

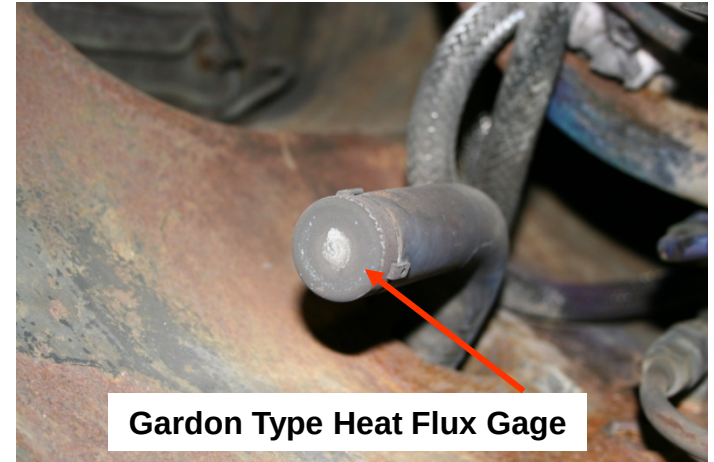
6" Collector/Diffuser



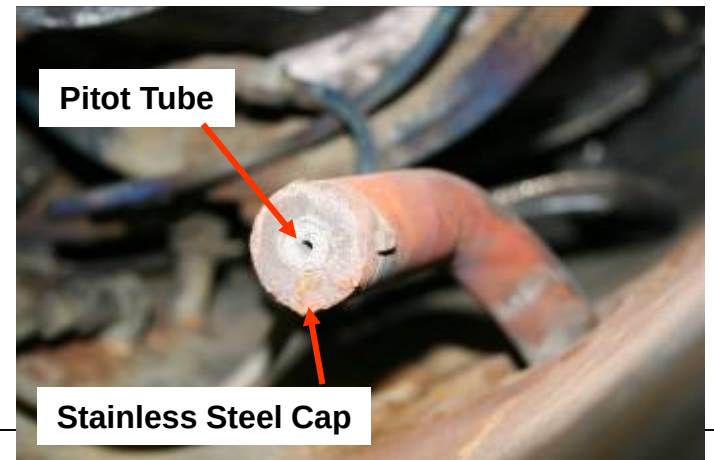
Gardon Gage
Sting 3

Pitot Tube Sting 4

Gardon Gage Sting 3

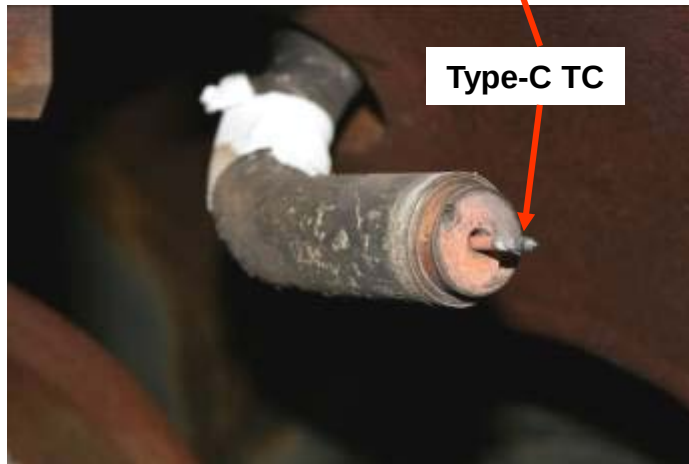


Pitot Tube Sting 4



HyMETS Facility

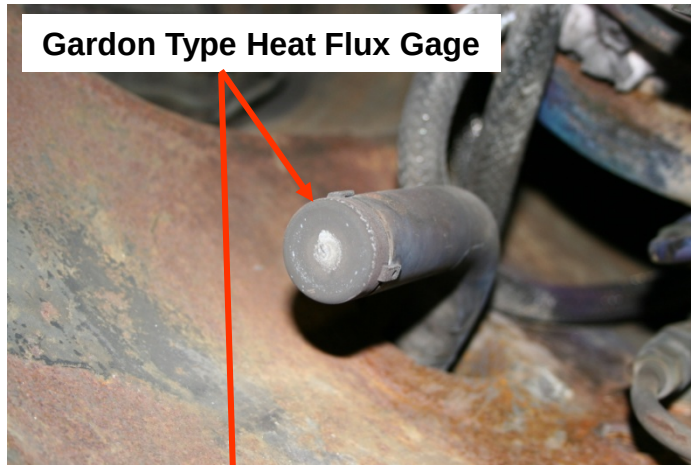
◆ Surface Temperature Measurement



- ◆ **Thermocouples:**
 - Two Type-C:
-32°F to 4208°F
- ◆ **IRCON Modline 5R Ratio (2-Color) Pyrometers (0.75-1.05 μ m, 1.0-1.1 μ m)**
 - 5R-1810:
1292°F to 3272°F
 - 5R-3015:
1832°F to 5432°F

HyMETS Facility

◆ Cold Wall Heat Flux Measurement

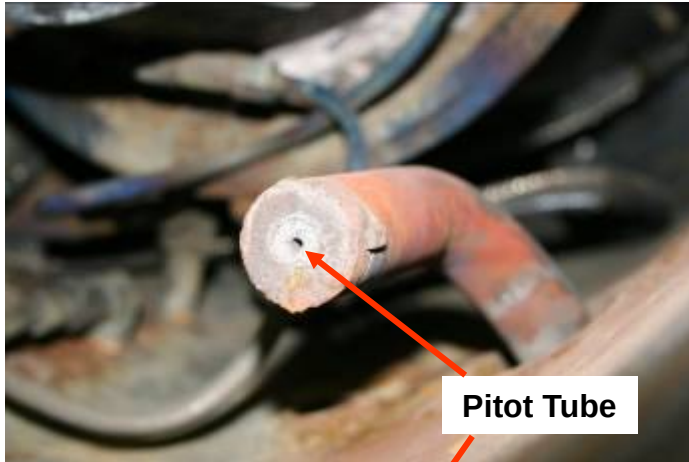


◆ Vatell Corporation TG 1000-65 Thermogage Circular Foil Heat Flux Transducers (Gardon Gage)

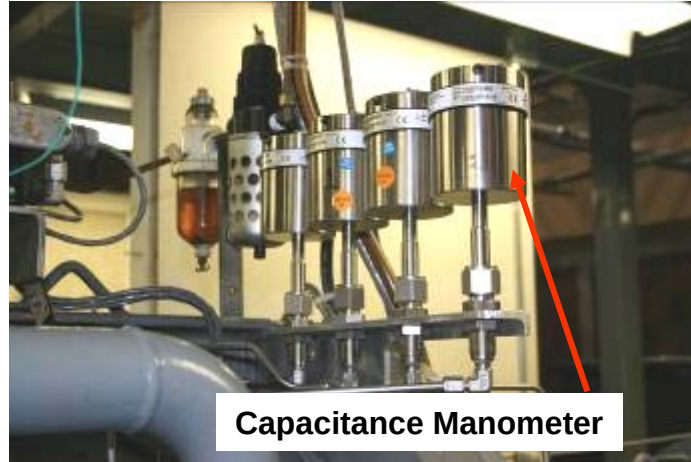
- 0 to 752 BTU / ft² - sec
- 0 to 1166 BTU / ft² - sec

HyMETS Facility

◆ Stagnation Pressure Measurement



Pitot Tube



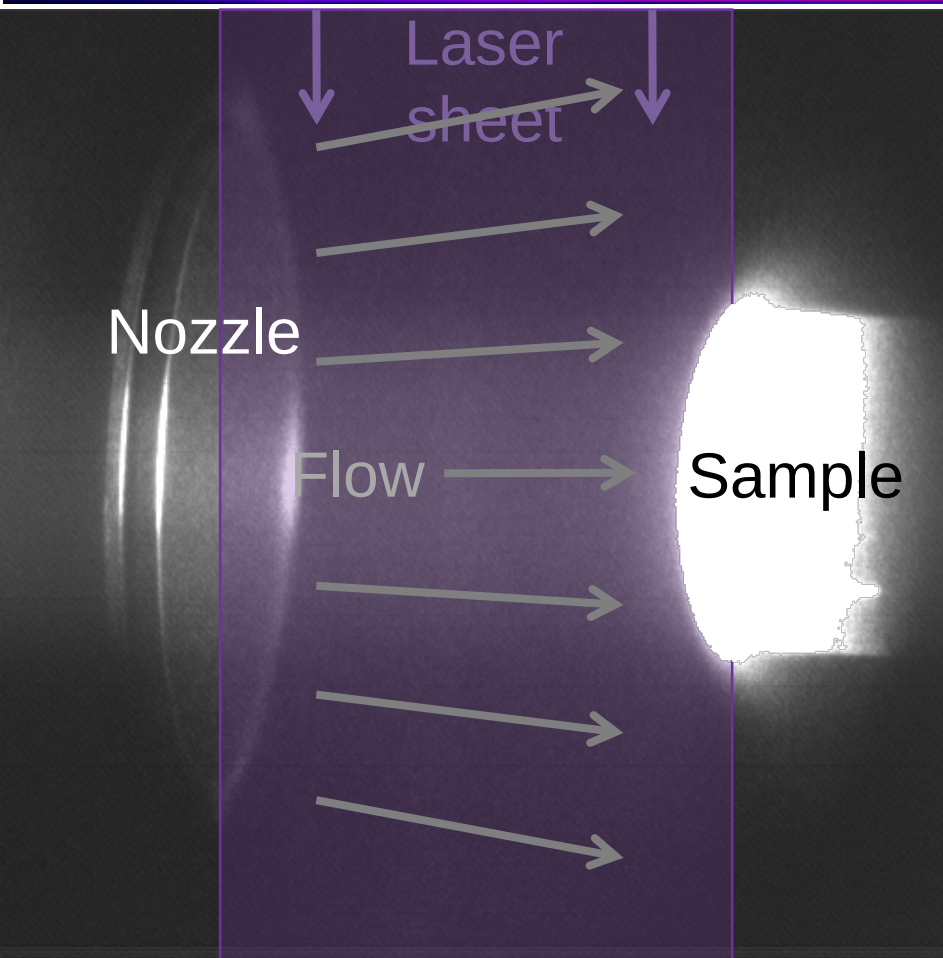
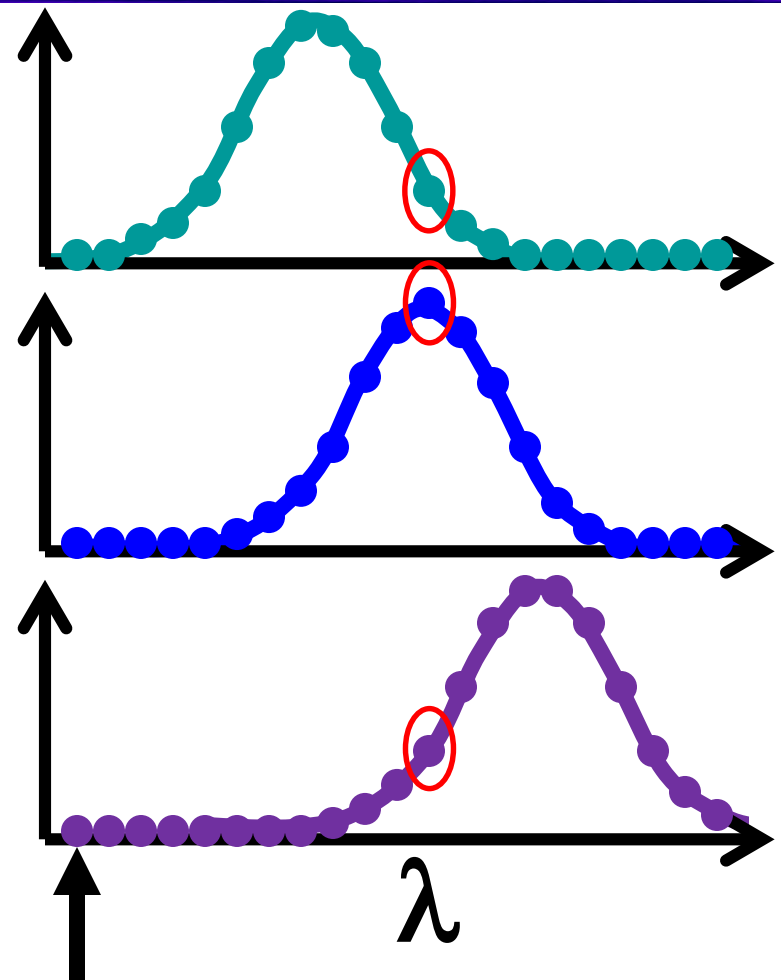
Capacitance Manometer



◆ MKS 627B Baratron® Absolute Capacitance Manometer, High Performance

- 6.6E-5 atm to 0.13 atm
(0.05 torr to 100 torr)

Doppler Radial Velocimetry



Obtain spectra by scanning laser wavelength. Cartoon, then replace by data. Pressure low enough to neglect pressure shift (quote error in m/s or %).

HyMETs Facility

◆ Enthalpy Calculations

Stagnation Enthalpy

$$H_o = \frac{q}{K} \sqrt{\frac{R}{P_{t2}}} + H_w$$

H_o = Stagnation enthalpy, BTU / lb_m

q = Stagnation heat flux, BTU / ft²-sec

K = 0.0461 lb_m / (ft^{3/2}-sec-atm^{1/2})

R = Hemispherical nose radius, ft

P_{t2} = Stagnation pressure, atm

H_w = Wall enthalpy, 120 BTU / lb_m

Sonic Enthalpy

$$H_o = \left(\frac{281 * A_{star} * P_t}{M_{Total}} \right)^{2.513}$$

H_o = Total sonic enthalpy, BTU / lb_m

A_{star} = Area of nozzle throat, ft²

P_t = Arc heater total pressure, atm

M_{Total} = Total gas mass flow, lb_m / sec

Bulk Enthalpy

$$H_o = \frac{E * I * C_1 - C_2 * CW * C_p * \rho * \Delta T}{M_{Total}}$$

H_o = Total bulk enthalpy, BTU / lb_m

E = Arc heater voltage, volts

I = Arc heater current, amps

C_1 = 9.48 E-4 BTU / sec-Watt

C_2 = 2.23 E-3 min ft³ / sec gal

CW = Cooling water flow, GPM

C_p = Specific heat of water, 1 BTU / lb_m-°F

ρ = Water density, 62.4 lb / ft³

ΔT = Cooling water temp. difference, °F

M_{Total} = Total gas mass flow, lb_m / sec

◆ Range:

- Bulk Enthalpy:
0 to 15,000 BTU / lb_m
- Sonic Enthalpy:
0 to 7,000 BTU / lb_m
- Stagnation Enthalpy:
0 to 30,000 BTU / lb_m

HyMETs Facility

◆ Actual Operational Conditions

◆ Surface Temperature:

- ~1800°F to ~3500°F

◆ Cold Wall Heat Flux:

- ~166 to ~736 BTU / ft²-sec

◆ Stagnation Pressure:

- ~0.009 atm to ~0.053 atm
- (~7.00 torr to ~40.42 torr)

◆ Enthalpy:

- Bulk: ~2400 to ~11,125 BTU / lb_m
- Sonic: ~1620 to ~6855 BTU / lb_m
- Stag.: ~7200 to ~27,830 BTU / lb_m

◆ Current Range:

- ~70 amps to ~400 amps

◆ Voltage Range:

- ~350 volts to ~800 volts

◆ Mass Flow Rates:

- ~35 SLPM to ~300 SLPM

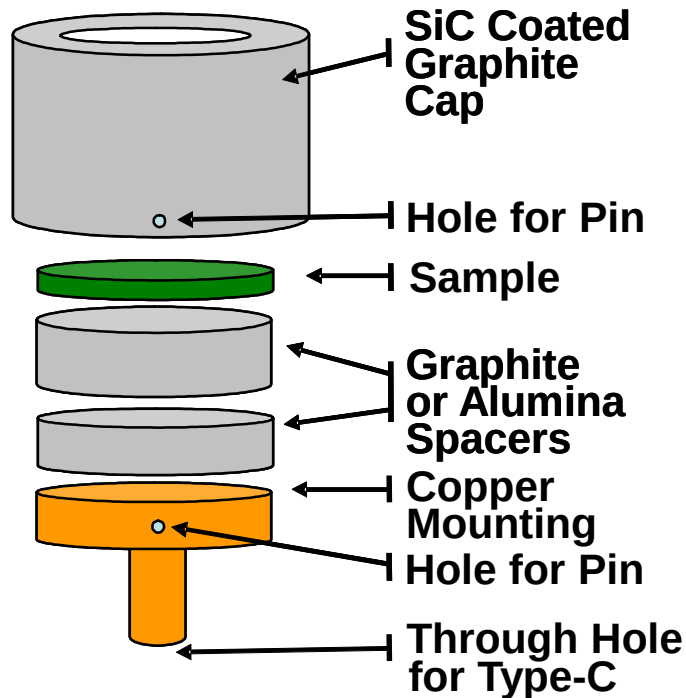
◆ Arc Pressure:

- ~0.13 atm to ~1.29 atm
- (~100 torr to ~980 torr)

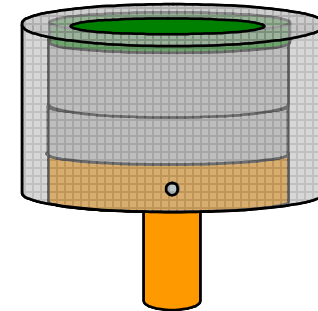
◆ Chamber Pressure:

- ~1.3E-4 atm to ~2.6E-3 atm
- (~0.1 torr to ~2.0 torr)

HyMETs Facility



- ◆ Exploded View of Stagnation Holder



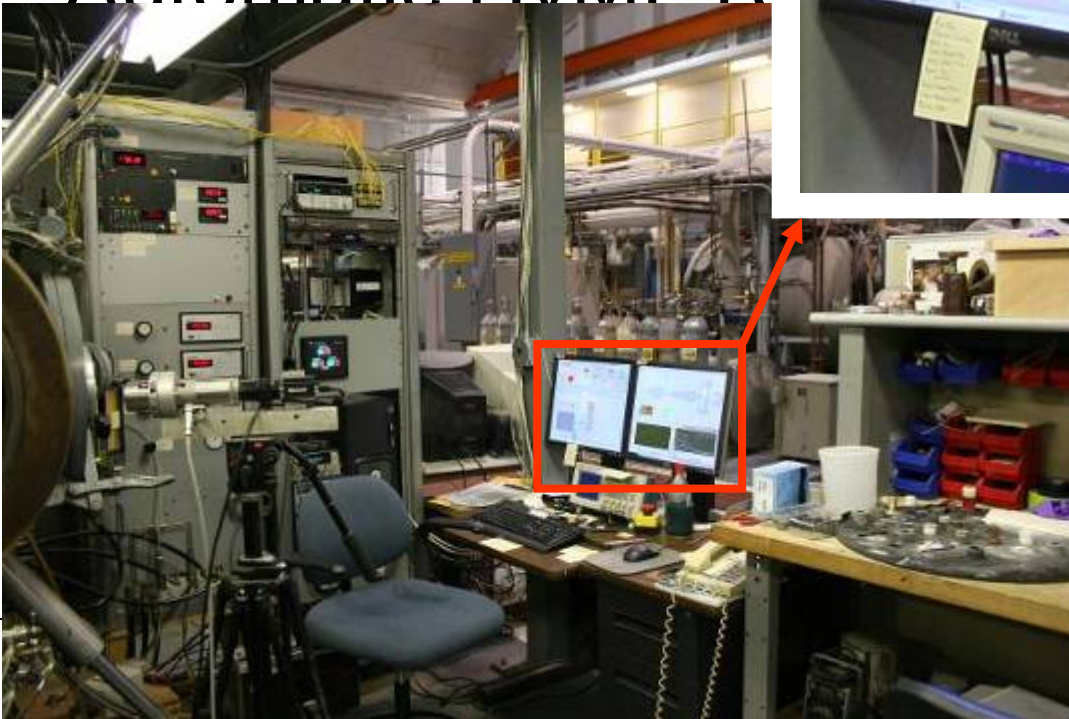
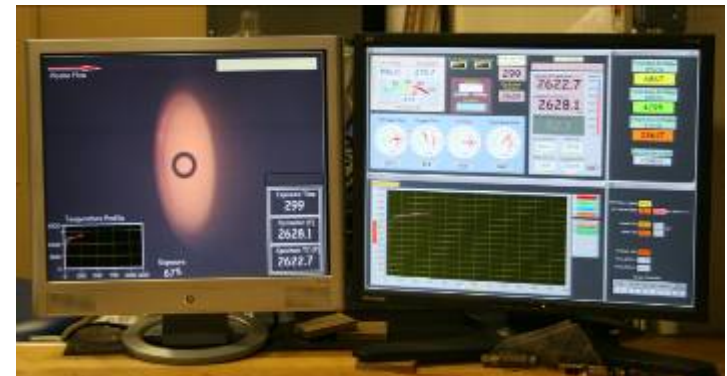
- ◆ Assembled View of Stagnation Holder

- ◆ Copper Wedge Holder



HyMETS Facility

- LabView Control System
 - 400 kW Power Supply
 - Mass Flow Control
- Automatic HyMETS



◆ Viewing Gallery

HyMETS Facility

◆ Gas Handling and Cooling Systems

◆ Mass Flow Controllers:

- One each for N₂, O₂, Ar, and “Air”
- Fed from gas cylinders
- Adjustable quantity of mass flow controllers
- Adjustable quantity and type of gas cylinders

◆ Vacuum Pumps:

- 1st Stage - Two Roots type blowers operating in parallel
- 2nd Stage - Rotary piston backing pump

◆ Cooling Water System:

- 40 Ton Chiller for the arc column
- Lab cooling tower for the remainder of the system
- Eventual upgrade to 150 ton chiller for the whole system



HyMETS Facility

Then (~2000)

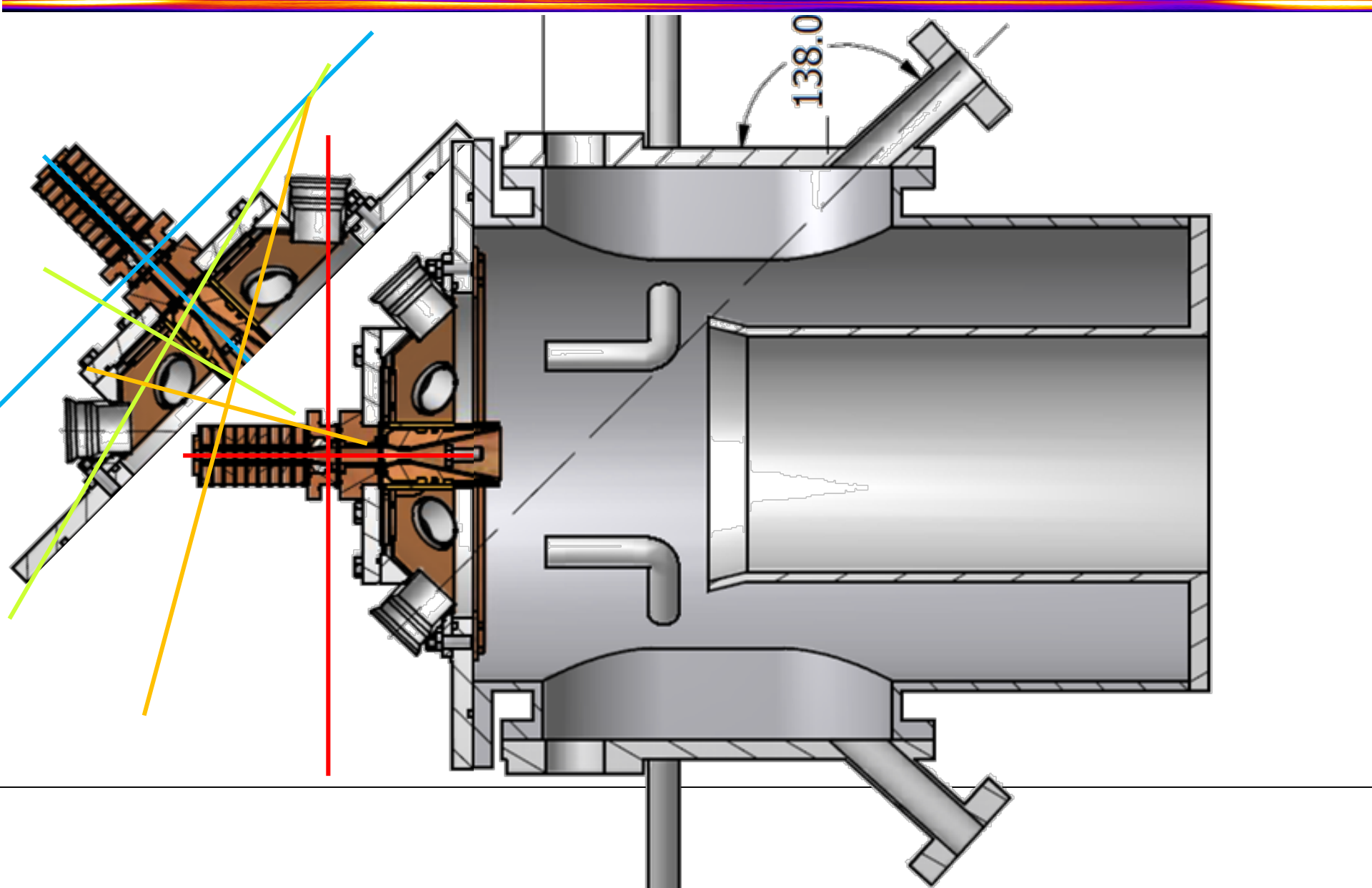
- ◆ Installed in the 1960's
- ◆ Originally 100 kW, but only operational at 50 kW
- ◆ Used primarily for testing metals and coatings for hypersonic vehicles
- ◆ Facility was in need of restoration

Now

- ◆ General repairs and restorations completed
- ◆ New water cooling system with separated high and low pressure systems and new chiller
- ◆ Arc-segments overhauled and plenum section added
- ◆ Thermopile installed to measure temperature drop across arc-segments
- ◆ Increased volume of gas
- ◆ Data acquisition system with digital camera
- ◆ New power supply (400 kW 12 Pulse DC)

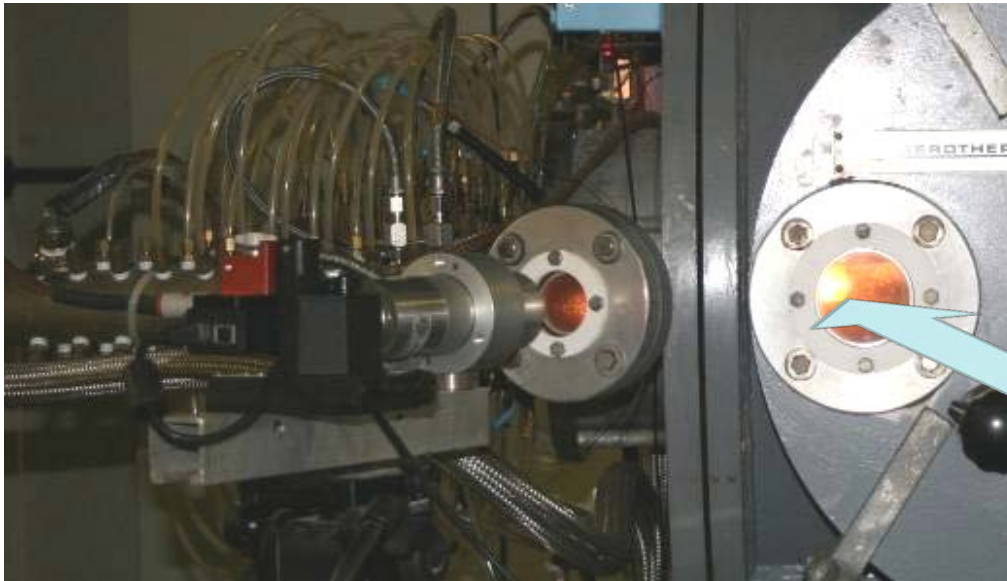
More still coming

- ◆ New nozzle and collector / diffuser design
- ◆ New arc and air injection segment design to extend the arc operating pressure
- ◆ New heat exchanger and chiller to increase cooling capacity
- ◆ Mirror system to provide a better viewing angle on the sample
- ◆ Infrared camera / imaging system
- ◆ **Modifications to run CO₂ for Martian atmosphere study and correlation**



Setup / Imaging Region

- Laser sheet enters test section from side
- Camera mounted under tunnel, looking up via mirror.

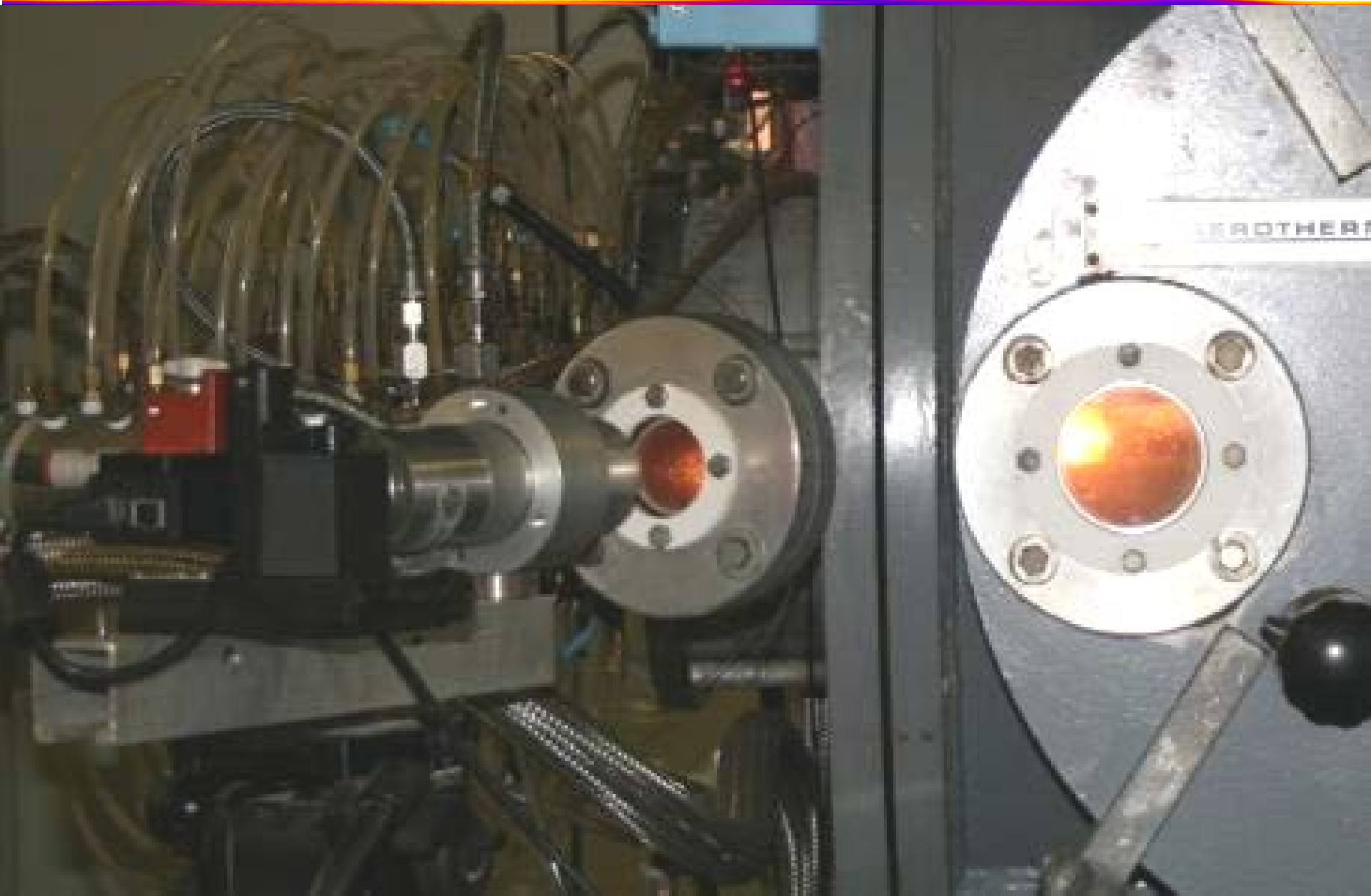


Laser sheet in through side window

Camera

mirror

HYMETs: 400 kW Arcjet Facility



HYMETs: 400 kW Arcjet Facility

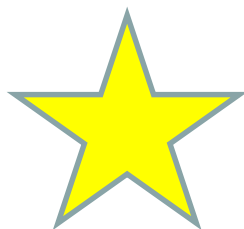
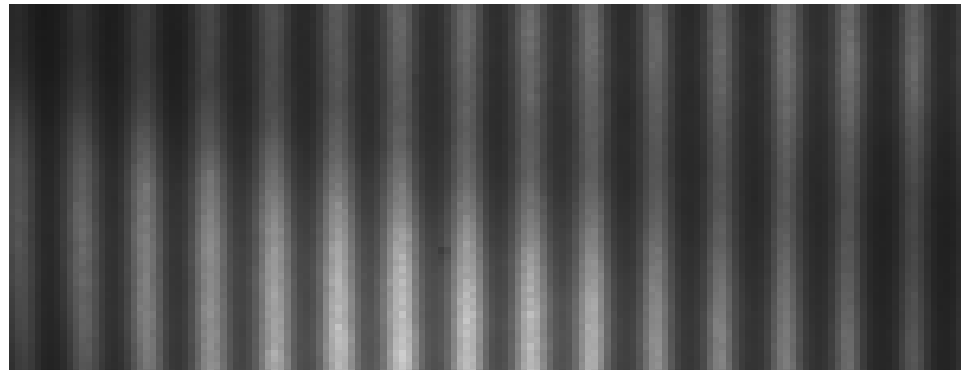
- Power Supply: 400 kW (Johnson Space Center: 10 MW; Ames Research Center: 20 – 60 MW)
- Mach 5 copper nozzle with 13 mm diameter throat and 64 mm diameter exit (~8 degree half angle)
- N_2 , O_2 , and CO_2 process gases, mixed as required; argon shield gas, 5% by mass (injected at anode)
- Segmented arc heater with 0.5 inch core
- Cathode - Copper puck with Tungsten button;
Anode - Sterling Silver
- Multiple (~30) 3 inch dia. 0.25 inch thick arc/gas injection segments with boron nitride and Delrin® isolators

Suitability of NO PLIF MTV

Nitric Oxide Molecular-Tagging Velocimetry

Advantages

- Good in low-pressure, low-density environments
- Non-intrusive
- Spatially resolved
- Many measurement locations
- Naturally present over a range of high-enthalpy conditions
- Simultaneous flow visualization



Drawbacks

- Requires laser system, good UV optical access
- NO dissociates above about 10 MJ/kg specific bulk enthalpy
- Single component (more are possible)
- Quenching at higher pressures

