



Study of Hypersonic Transition and High-Enthalpy Flows Using NO PLIF

FAP Hypersonics Project

Dr. Paul Danehy
NASA Langley Research Center
Hampton Virginia

2011 Technical Conference
March 15-17, 2011



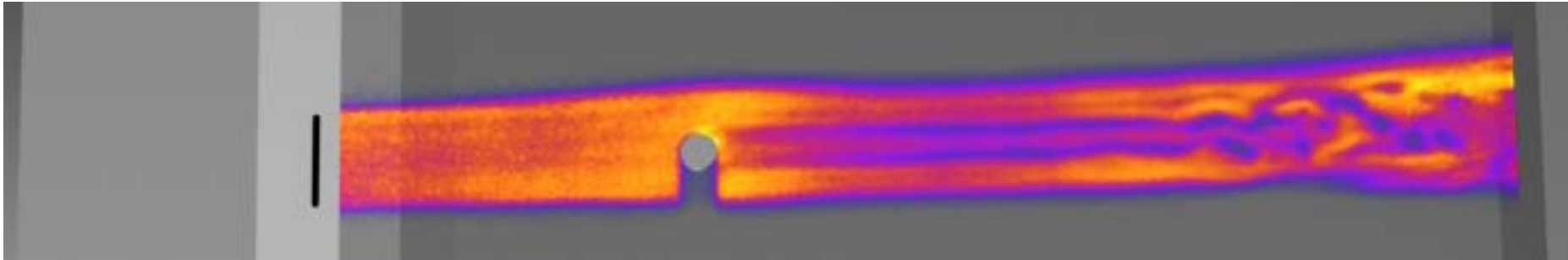
Acknowledgements:



Jennifer Inman, Brett Bathel, Craig Johansen, Stephen Jones, Jeff Gragg, and Scott Splinter
NASA Langley Research Center

Support:

NASA's Fundamental Aeronautics Program, Hypersonics Project, AAP and M&S Disciplines

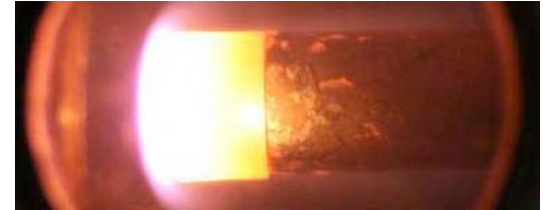


Outline

- Motivation
- Planar Laser-Induced Fluorescence (PLIF)
- HYMETs
 - NO Molecular Tagging Velocimetry (MTV)
 - Doppler Velocimetry
- Laminar-turbulent transition
 - NO MTV in laminar flow: comparison with CFD
 - $\text{NO}_2 \rightarrow \text{NO}$ MTV in transitional flows
- Concluding remarks

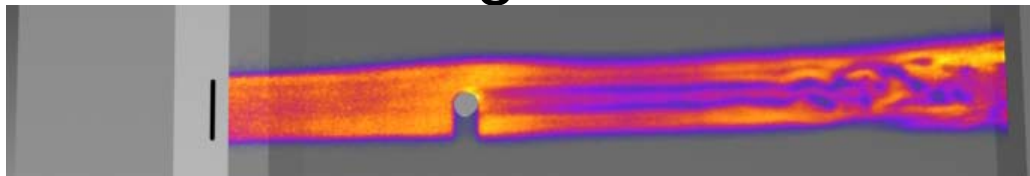
Motivations

- High-enthalpy arcjet flow



- To fully understand material response, we must know the environment to which it is exposed
 - Characterize freestream conditions (enthalpy)
- Measure ablation products to validate physics-based codes

- Transition to turbulence in hypersonic flows can increase vehicle heating & skin friction x3 or more

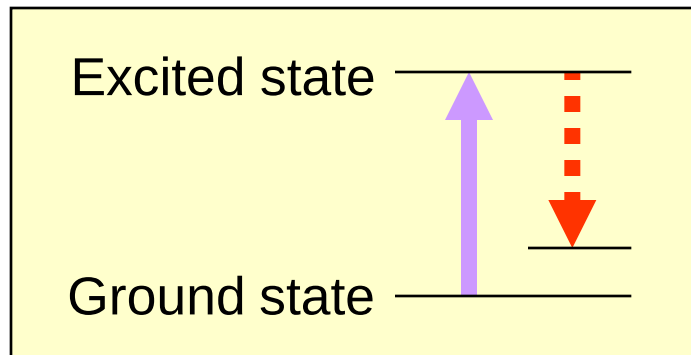


- NO PLIF can provide flow visualization and quantitative measurements (e.g. V , T , c_{NO})

Basic PLIF Concept

Tunable Laser

- NO can be seeded, but is naturally present in arcjet flows over a certain range of low enthalpies (which we determined)



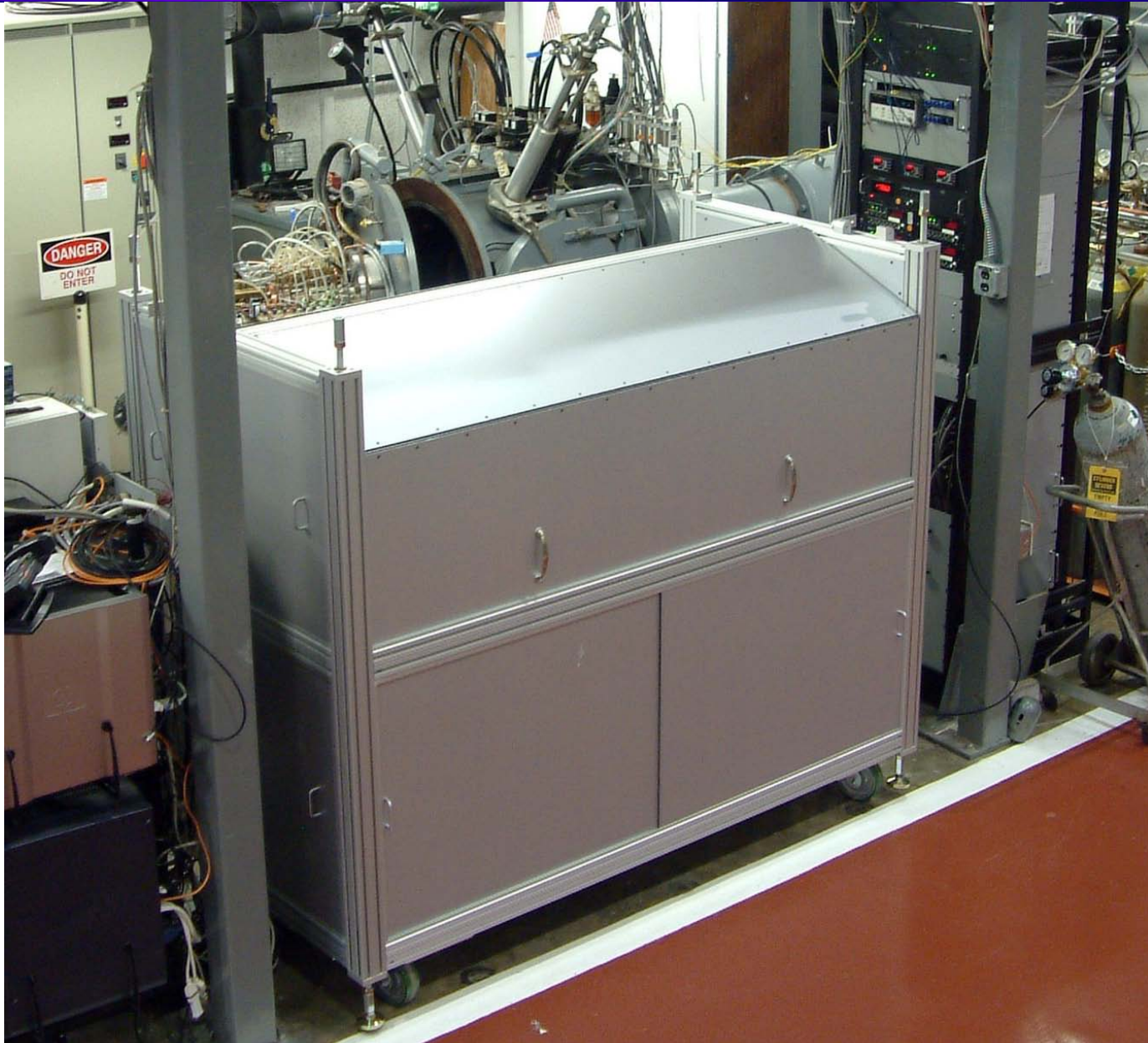
$$\text{LIF} \sim n_{\text{NO}}$$

Pulsed laser sheet
excites molecules

CCD
camera
records
LIF images

n_{NO} = number
density of NO
atoms

Laser system in HYMETs

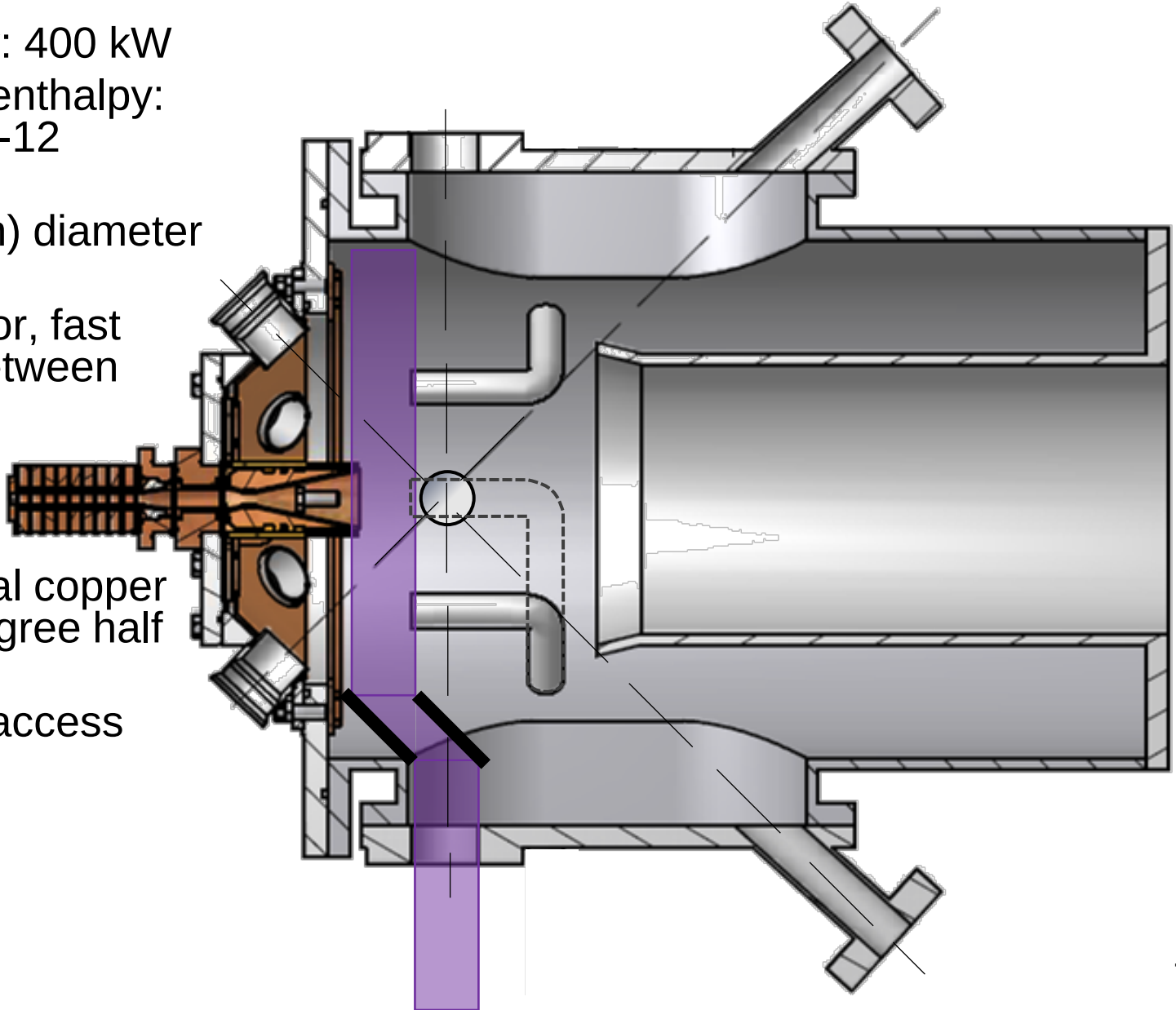


HYMETS (Hypersonic Materials Environmental Test System)

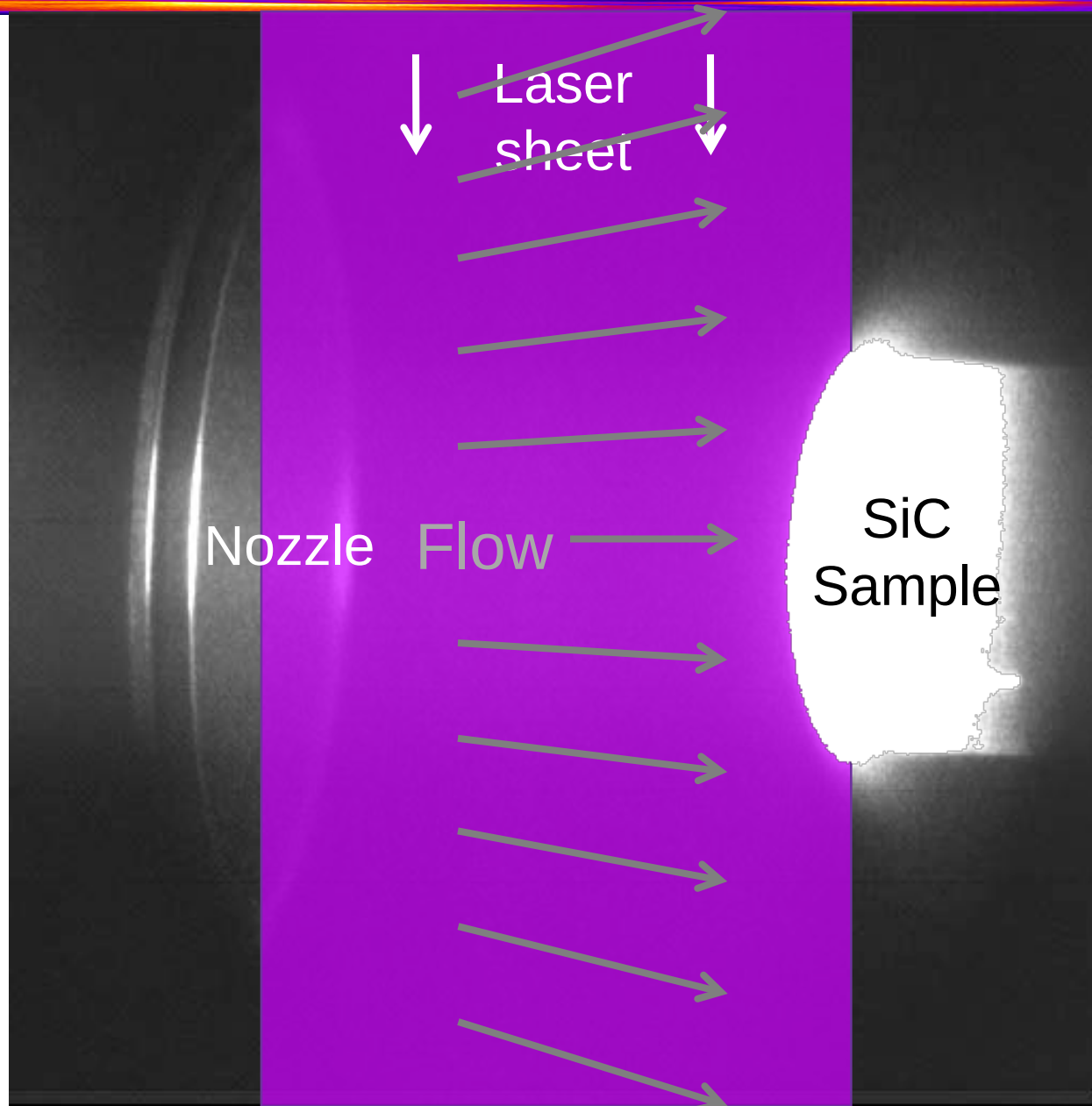
- Power Supply: 400 kW
- Specific bulk enthalpy: 5-28 MJ/kg (2-12 kBTU/lb_m)
- 25 mm (1 inch) diameter sample
- Single operator, fast turnaround between runs

Arc plasma generator →

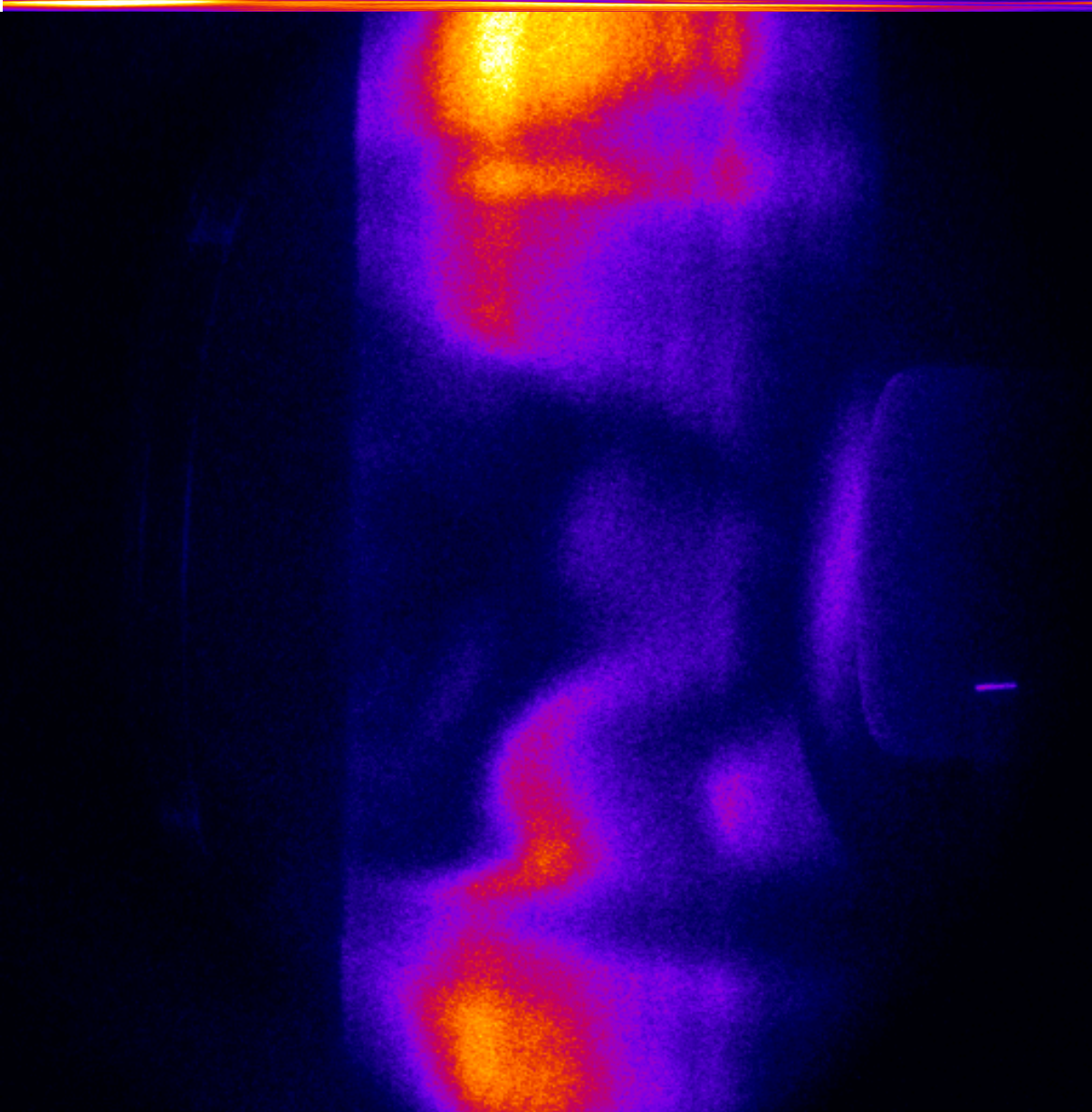
- Mach 5 conical copper nozzle (~8 degree half angle)
- Good optical access



Camera View

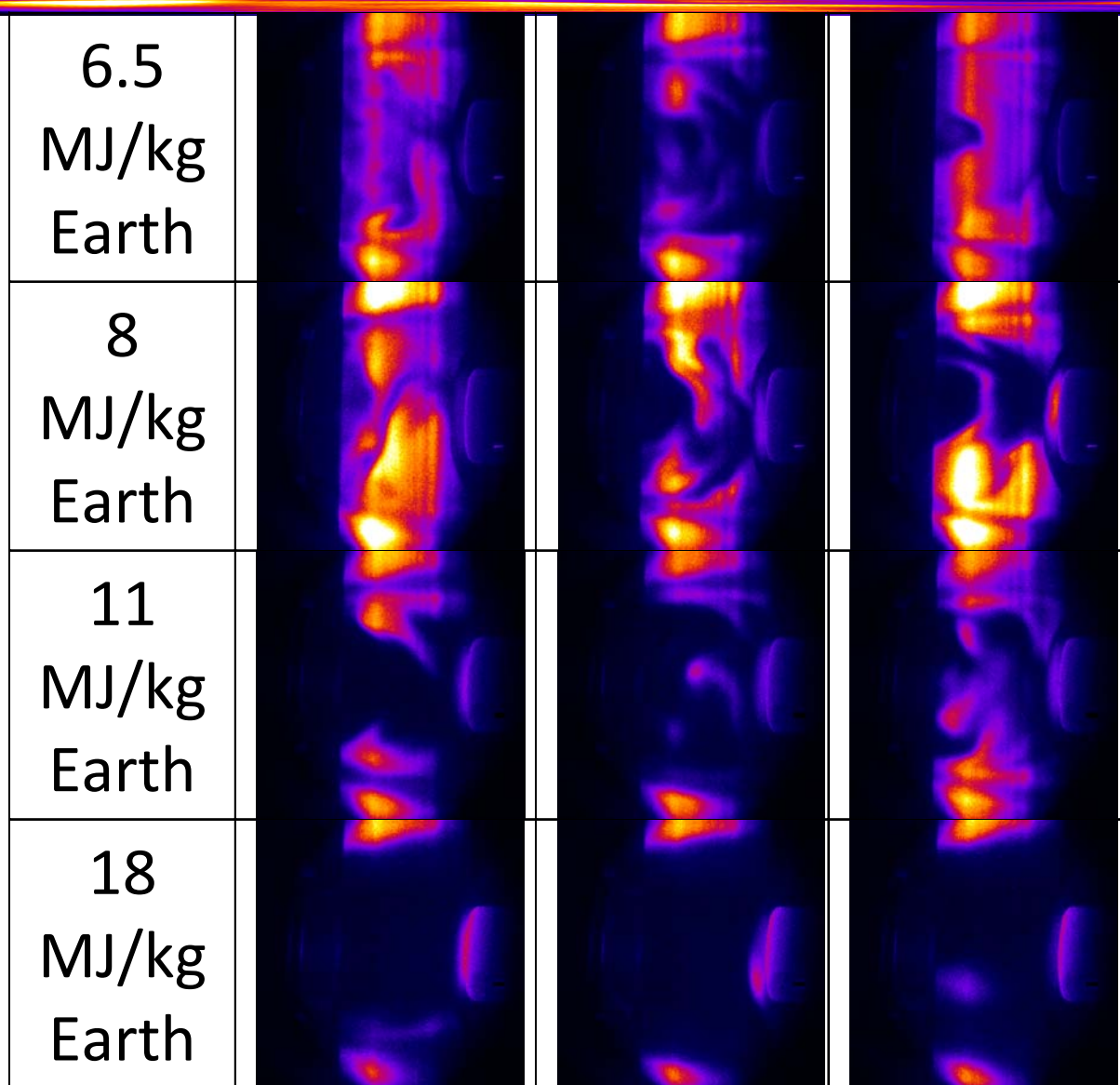


Single-Shot Images

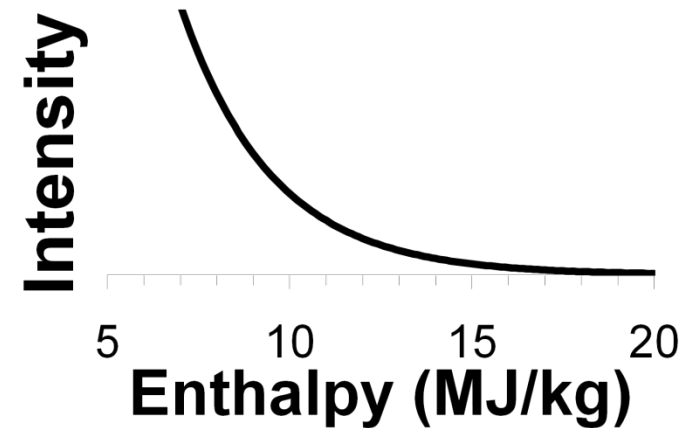


- 1 μs exposure
- Large-scale structures
- Bow shock visible in front of sample
- Can measure shock standoff distance (9.5 ± 1.1 mm)

Fluorescence Signal vs. Enthalpy

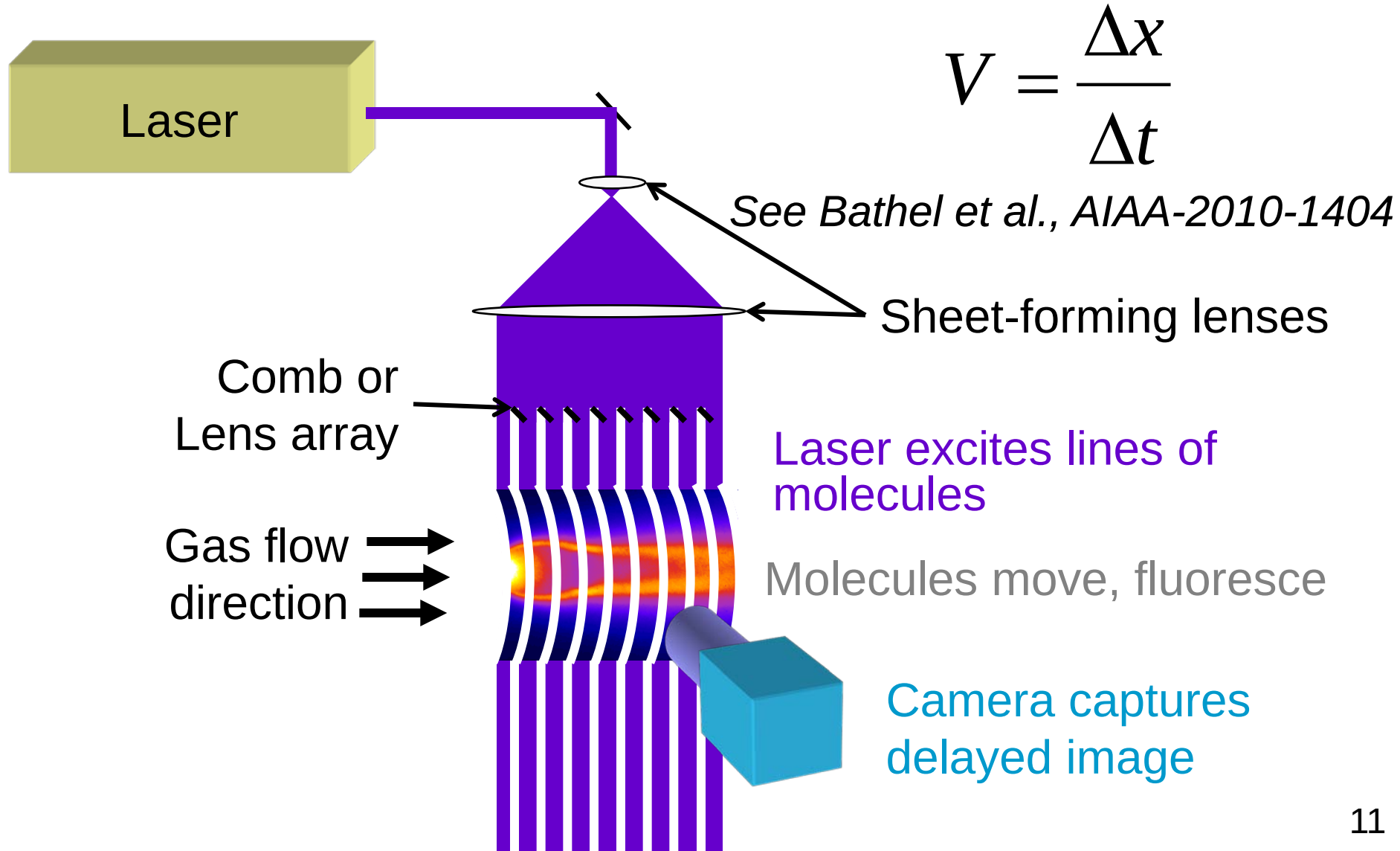


- NO created from dissociated N_2 and O_2 (or N_2 and CO_2)
- NO dissociates at high enough enthalpy

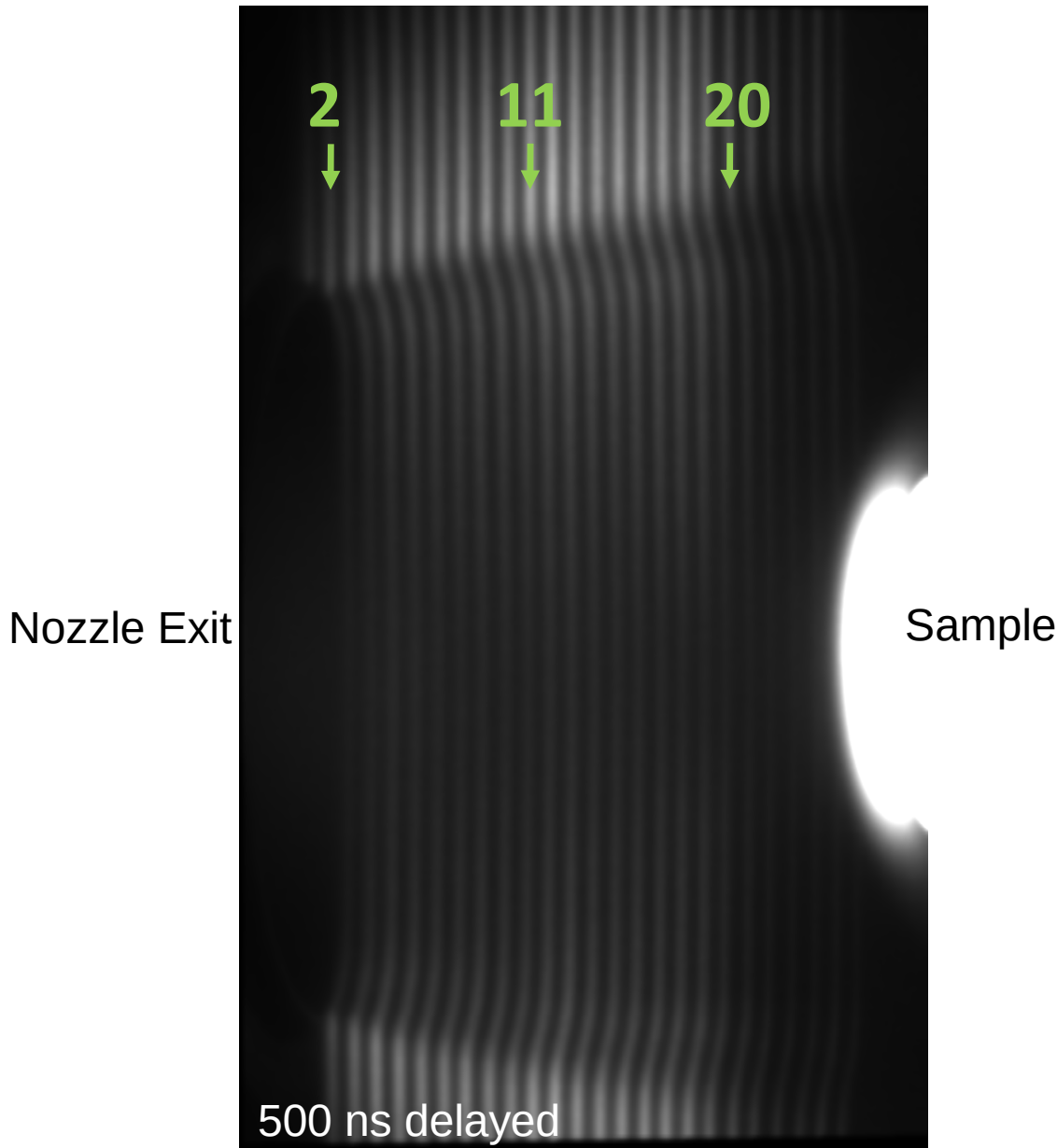


Multi-Line NO PLIF MTV

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

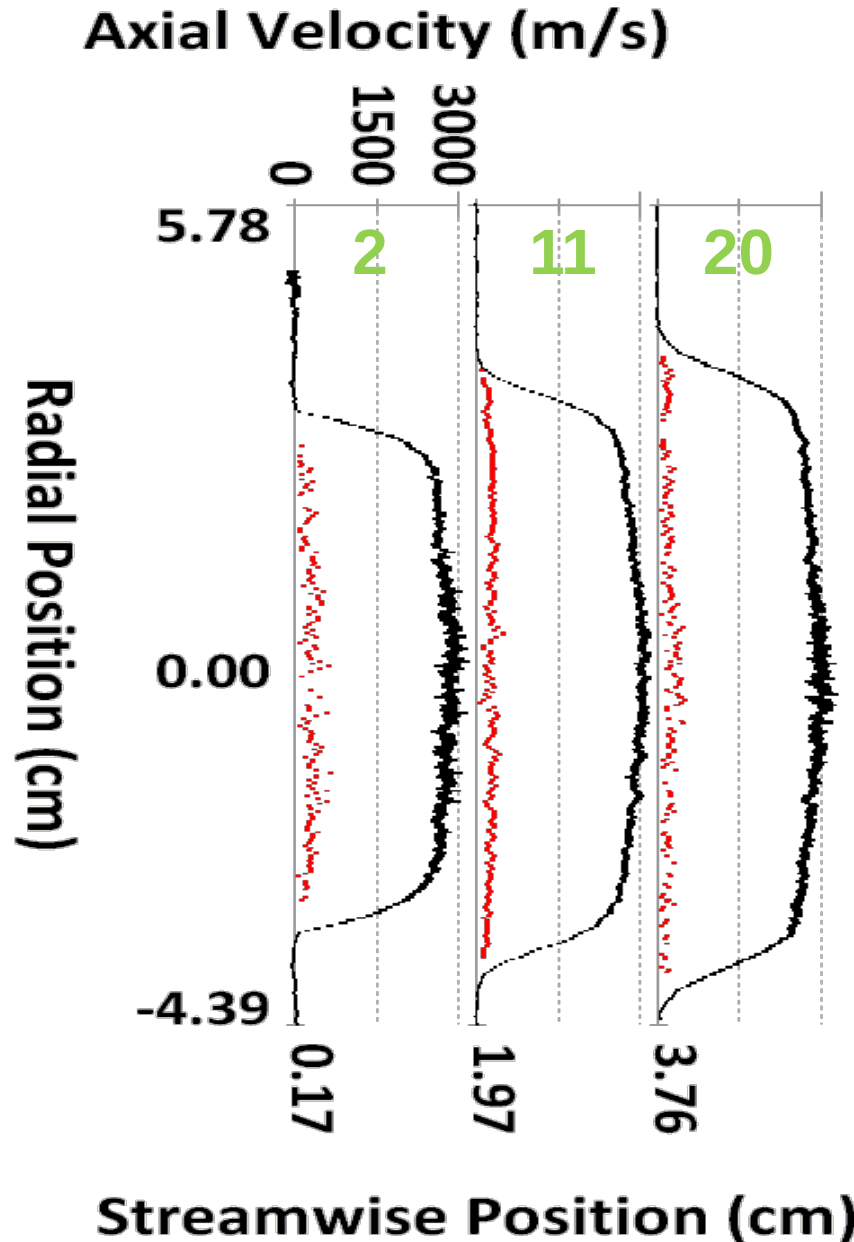


Axial Velocimetry



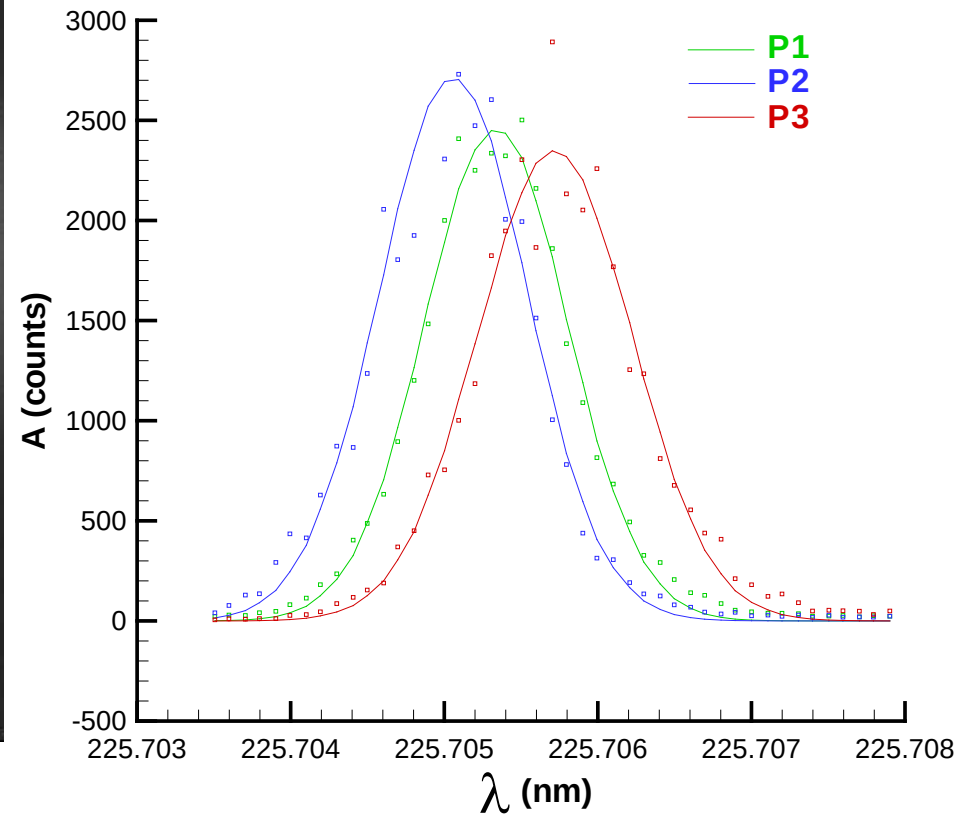
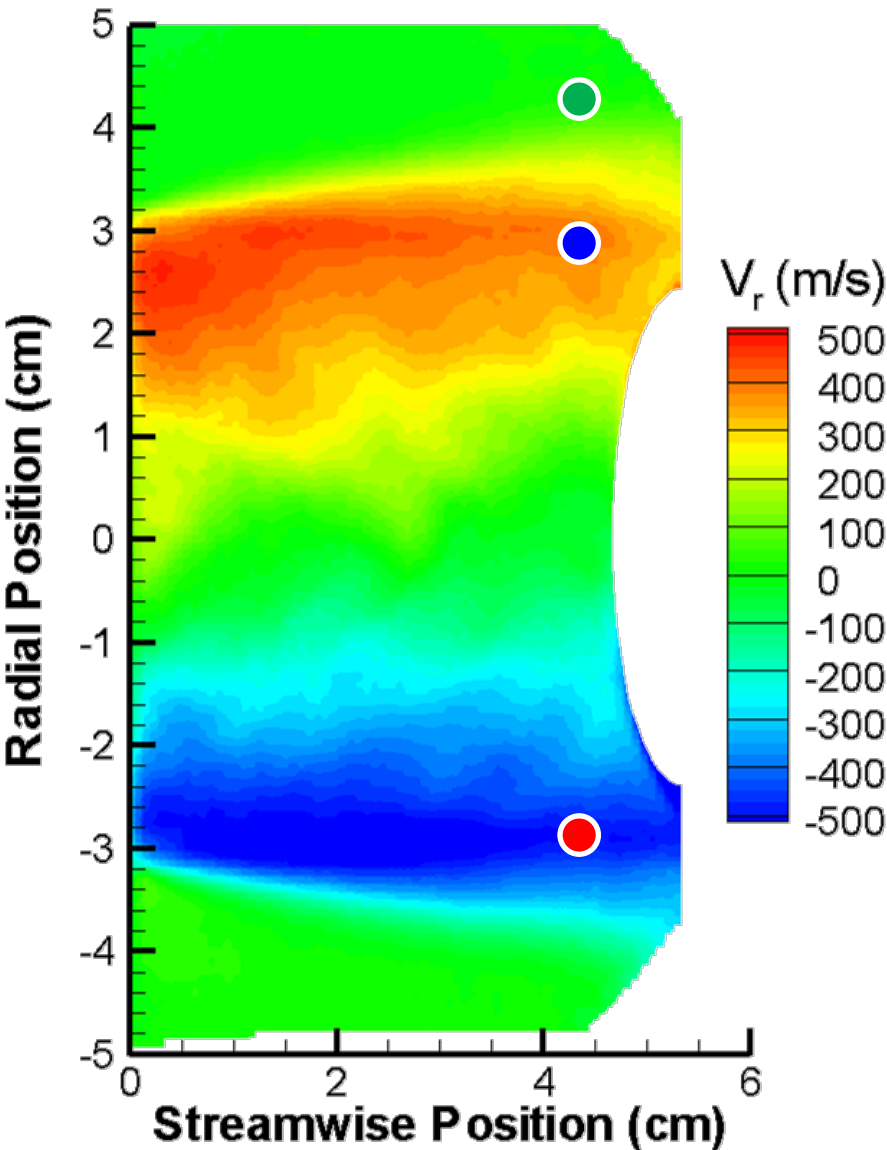
- Dual-frame camera used to acquire single-shot data
- 500 ns inter-frame delay $V = \frac{\Delta x}{\Delta t}$
- Enables measurement of velocity fluctuations as well as means
- These images are:
 - averages of ~100 shots
 - normalized

Axial Velocity Measurement

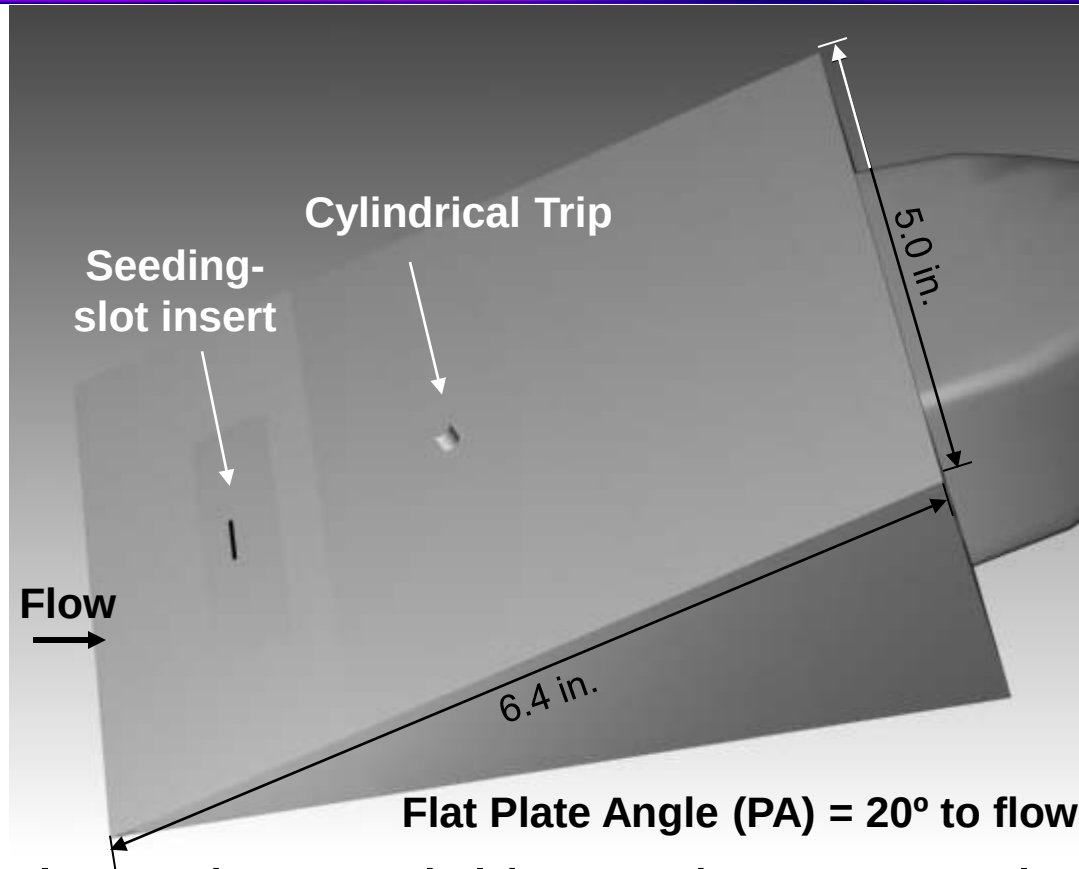


- Measured mean velocity is about 3 km/s.
 - Fairly uniform in cross-stream *and* streamwise directions
- Width of black points corresponds to twice the measured uncertainty
- Red points indicate measured fluctuating velocity component (~7% of mean)

Doppler Radial Velocimetry



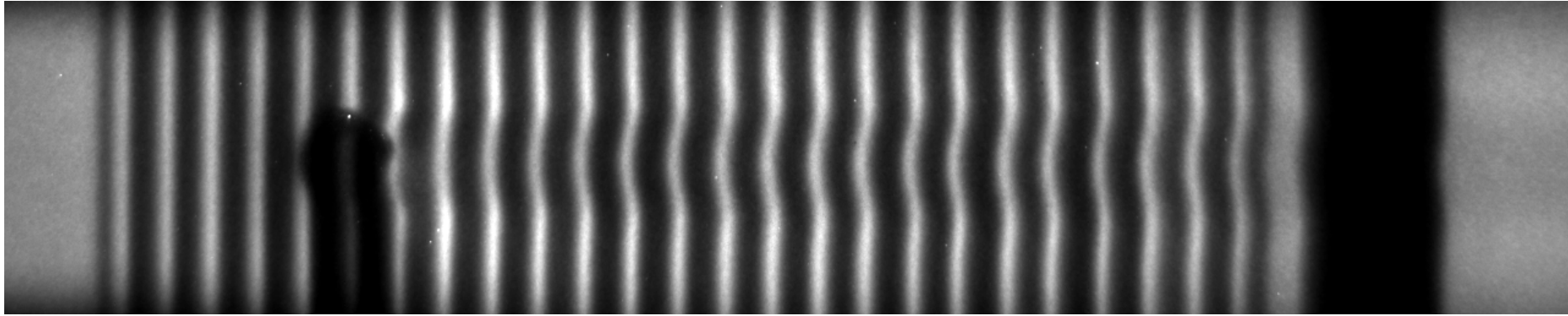
Transition Studies: Model and Protuberances



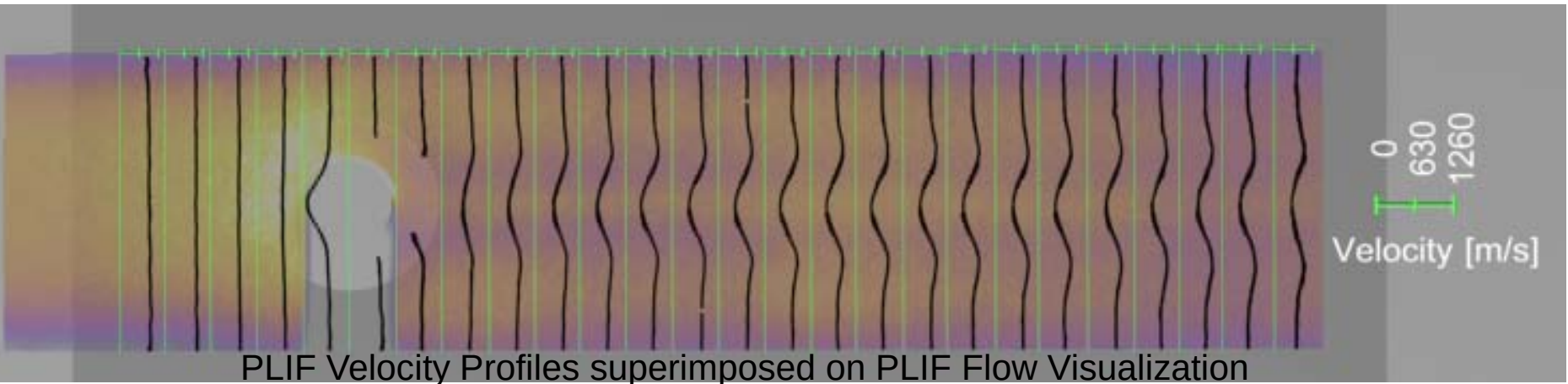
- 20° full angle wedge model in Mach 10 Tunnel
 - Top surface: 20° wrt oncoming flow ($M_e \sim 4$) for most runs
 - Varied between 5° and 25° for 2 runs
- Interchangeable inserts for NO seeding and trips
- 1-, 2-, 4-mm tall x 4-mm diameter trips as well as “DTO”

NO PLIF MTV: Flow over Cyl. Trip

Run 25, Averaged (2 mm above surface, Frames 170-210):



500 ns Delay Image



PLIF Velocity Profiles superimposed on PLIF Flow Visualization

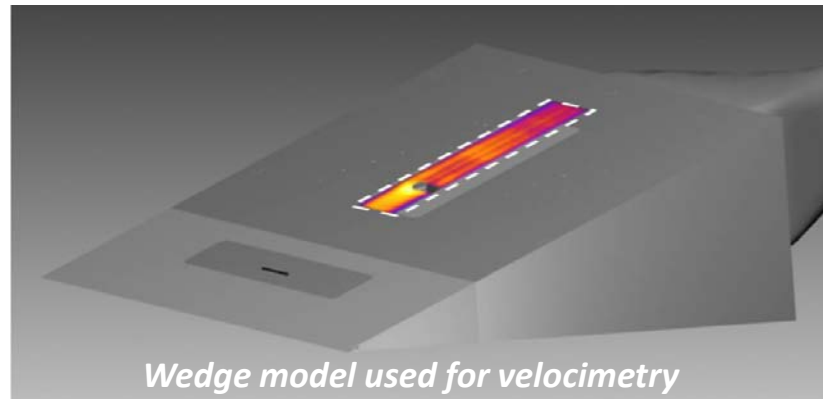
2 mm tall x 4 mm wide Cylinder Trip, $P_0 \sim 350$ psi, $T_0 = 1350$ °F, $\dot{m} = 150$ sccm, AoA = 5°

$$M_e \approx 8$$

$$k/\delta = 0.7$$

- Uncertainty ~ 30 m/s for averaged measurements, ~ 130 m/s for s.s.
- Bathel et al, AIAA-2010-1404 and AIAA-2010-4998

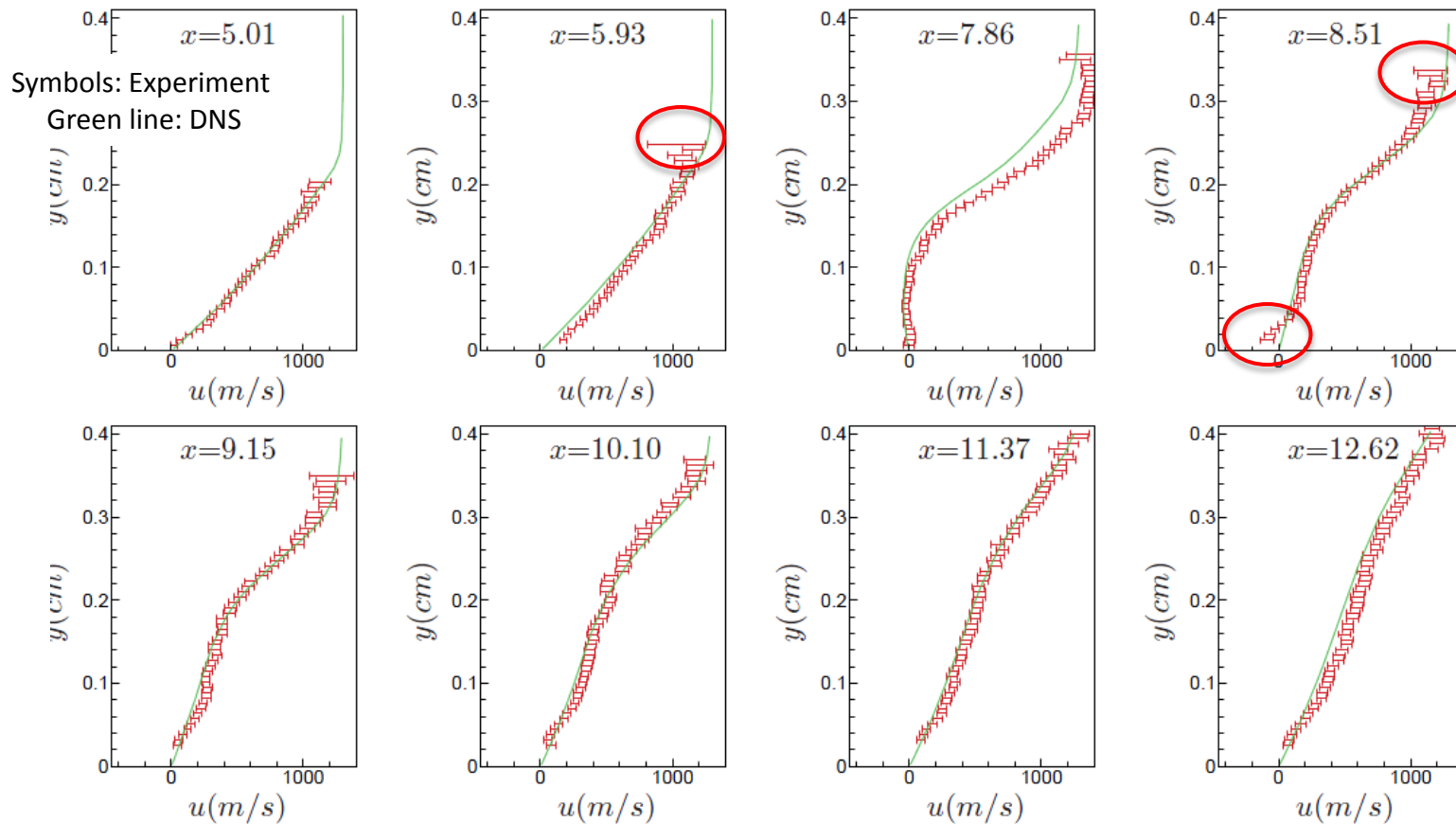
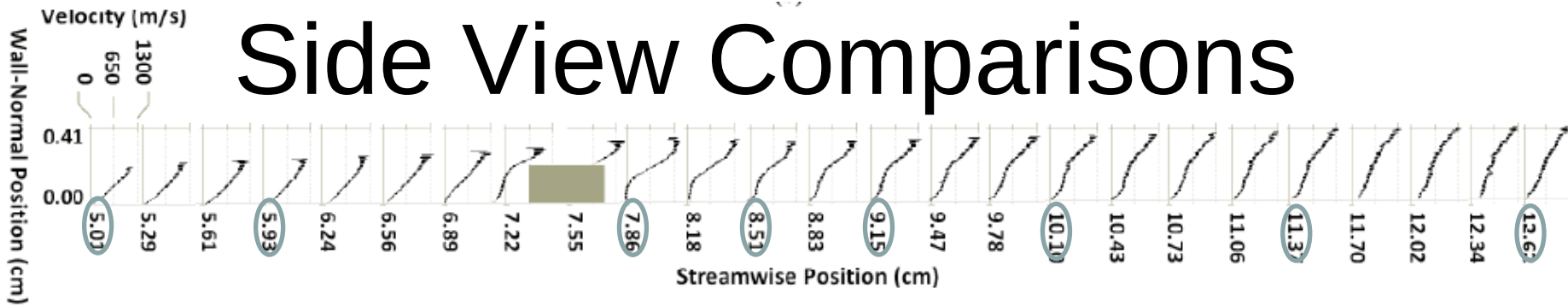
Comparison between DNS and NO PLIF molecular tagging velocimetry (MTV) in a laminar boundary layer flow over a cylindrical trip on a flat plate



NO PLIF Results from **Bathel et al, Chicago**
AIAA Paper AIAA-2010-4998

Computations are DNS by K. Mahesh, U. Minnesota,
Graduate student and research associate: Mr. Prahladh
Iyer, Dr. Suman Muppidi,
Iyer et al, Paper AIAA-2011-566

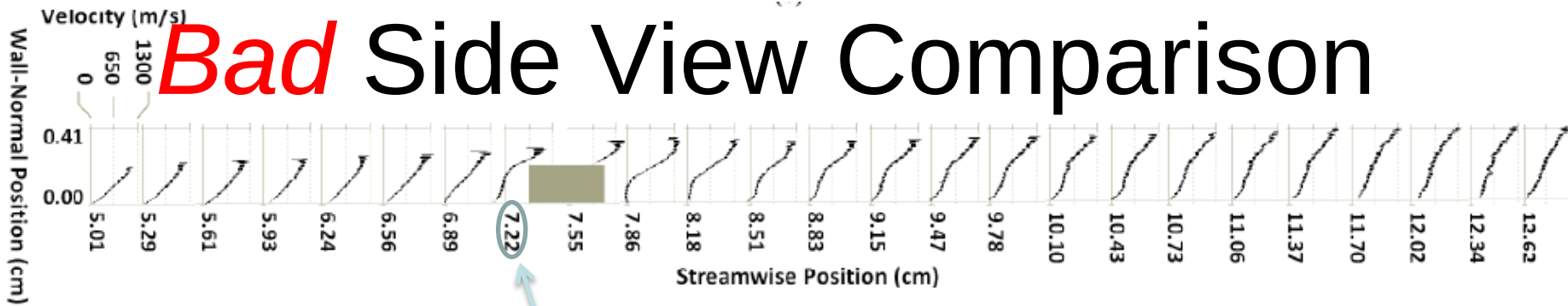
Side View Comparisons



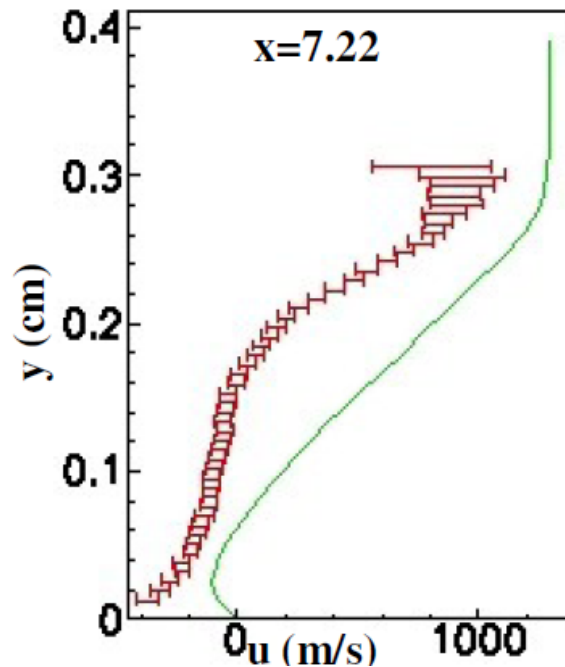
Iyer et al,
Paper AIAA-
2011-566

- Conditions were laminar flow: $Po = 350$ psi (0.5 million/ft), Mach 10, $AoA_{flat\ plate} = 5^\circ$
- Trip is 2 mm tall and 4 mm diameter, 75.4 mm downstream of sharp leading edge (LE)
- NO seeded at low rate from a slot 29.4 mm downstream of LE (neglected in DNS)

Bad Side View Comparison



We reported the starting (wrong!) measurement location



Breaks a fundamental assumption: There are velocity gradients in measurement region

$$V = \frac{\Delta x}{\Delta t}$$

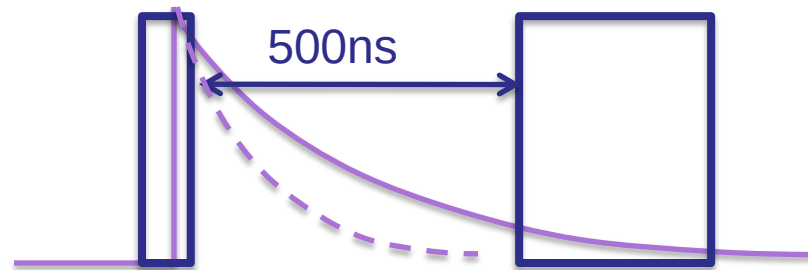
Not in:
Iyer et al,
Paper AIAA-
2011-566

- Could compute displacement with CFD and compare with experiment to validate CFD
 - CFD is helping us understand our data better

NO MTV versus $\text{NO}_2 \rightarrow \text{NO}$ MTV

- NO PLIF MTV has limitations

- Delay between camera images is limited by camera ($>500\text{ns}$) and by fluorescence $1/e$ lifetime (200 ns)



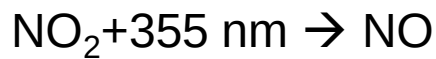
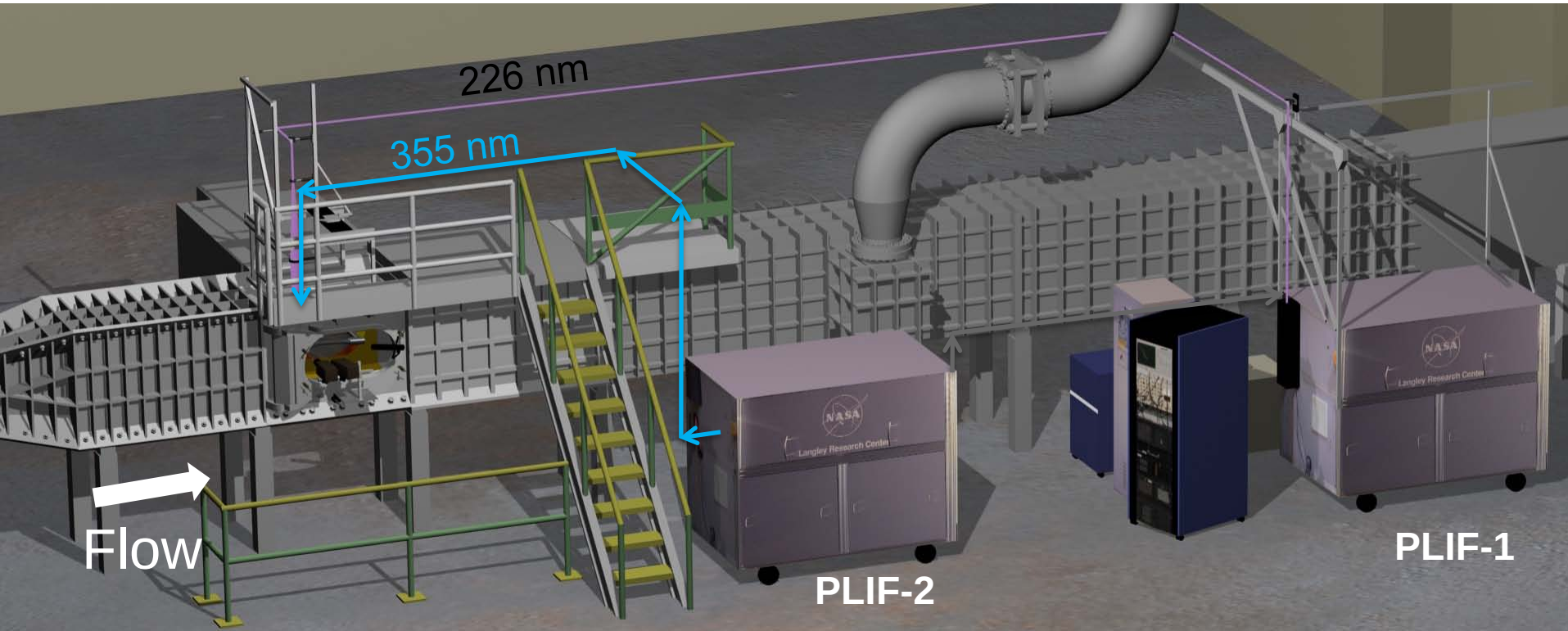
- Lifetime gets shorter at higher pressures, (higher Re) where transition is more likely

- $\text{NO}_2 \rightarrow \text{NO}$ MTV is much harder to do...

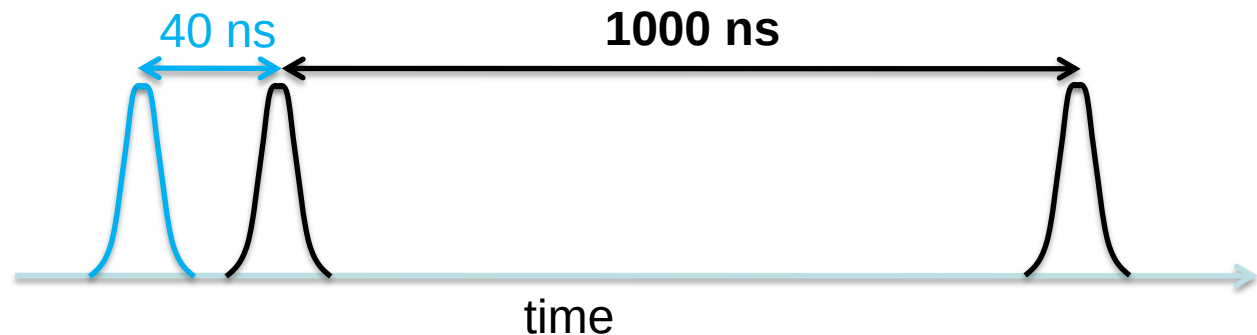
- Use a UV laser to photodissociate seeded NO_2 into NO
- NO survives and can be probed with $>2\times$ longer delay
 - Works at high P *and* is $>2\times$ more accurate single shot than NO MTV
- Previously developed and used by the University of Heidelberg, Japan, Texas A&M and Ohio State

Dual-laser setup for $\text{NO}_2 \rightarrow \text{NO}$ velocimetry

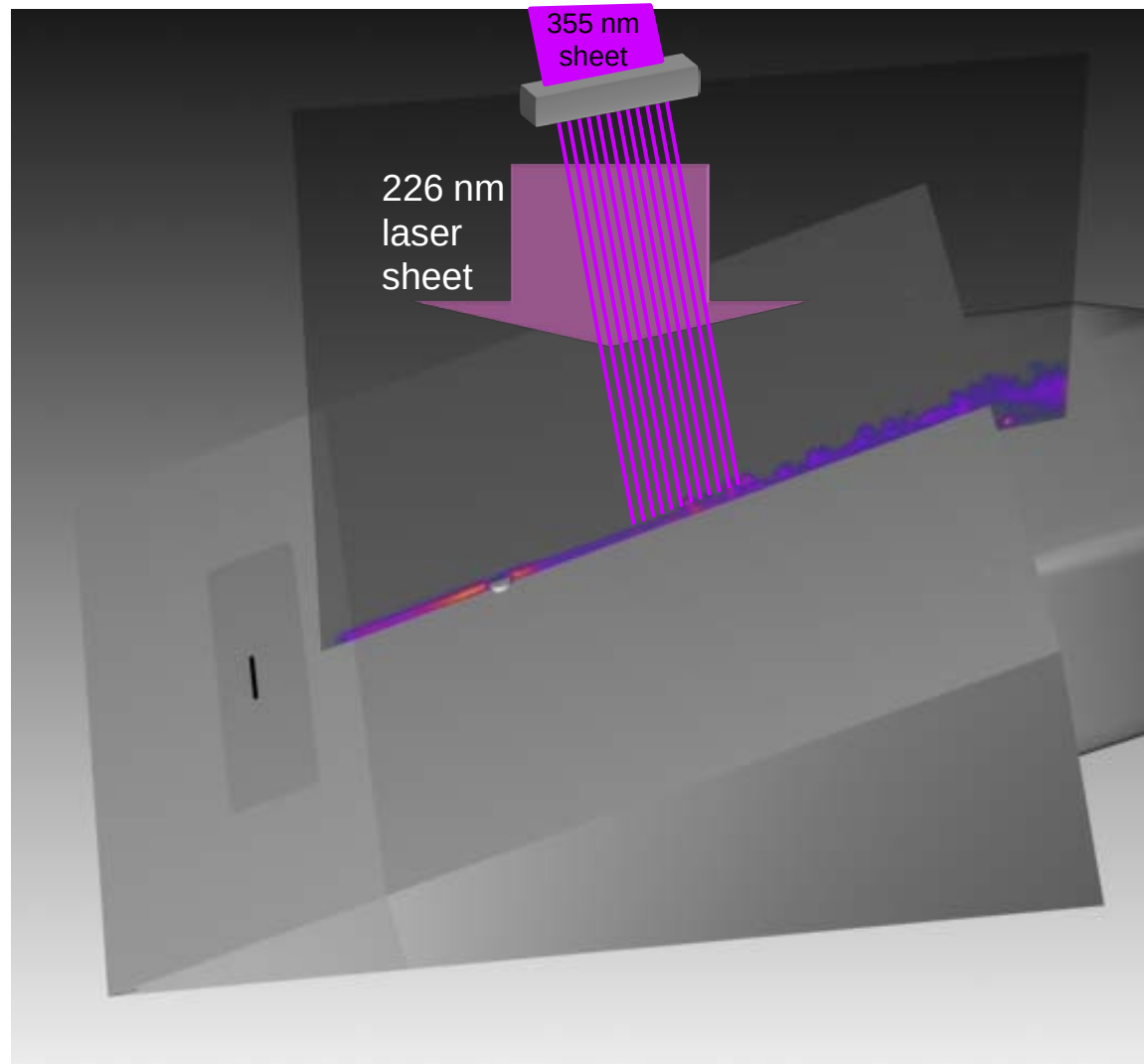
31 Inch Mach 10 Wind Tunnel (only 5 days to do expt)



Write lines of NO into
 NO_2 seeded in the flow

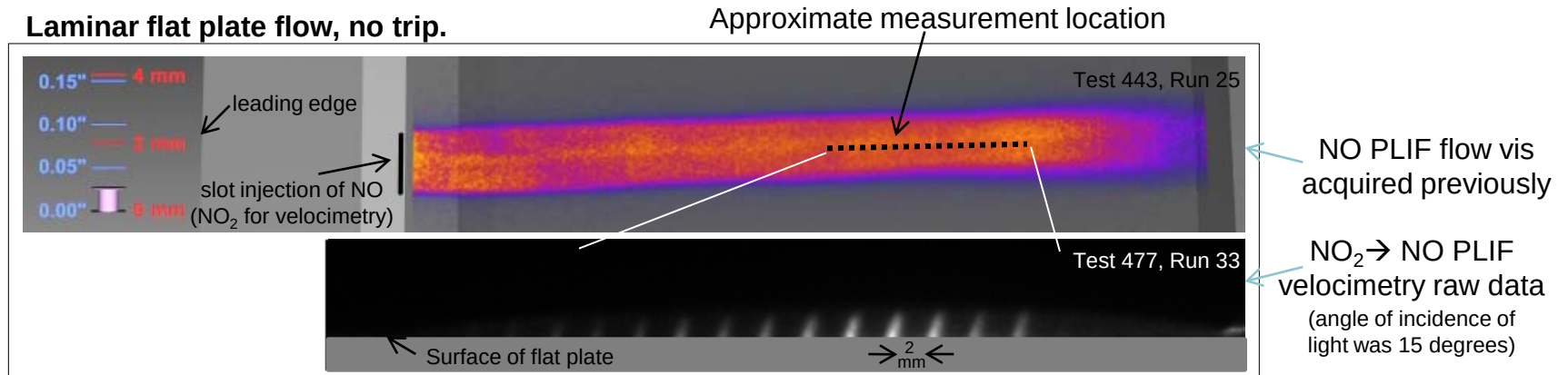


$\text{NO}_2 \rightarrow \text{NO}$ MTV Time Sequence



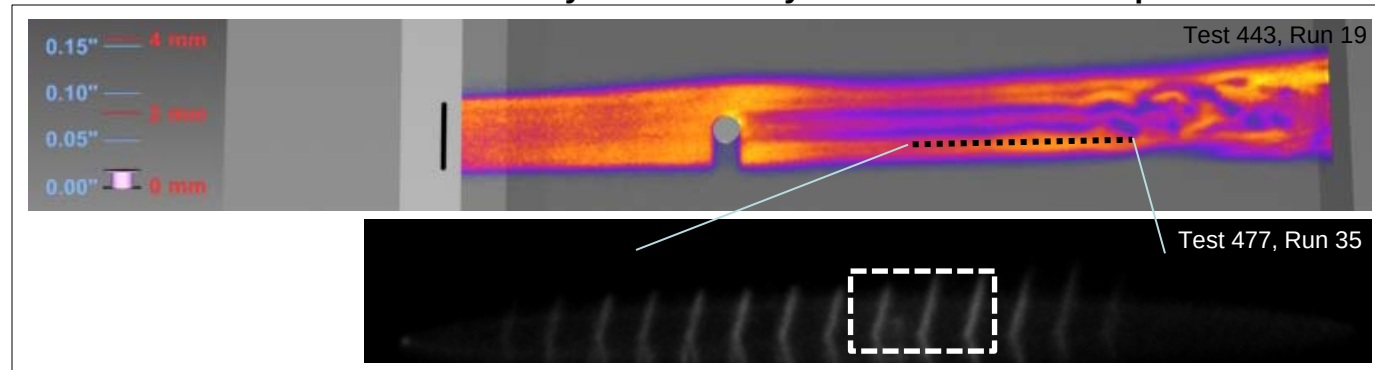
- Acquired using side views
 - Less sensitive to laser sheet movement from tunnel vibrations

$\text{NO}_2 \rightarrow \text{NO}$ PLIF Velocimetry Demonstration

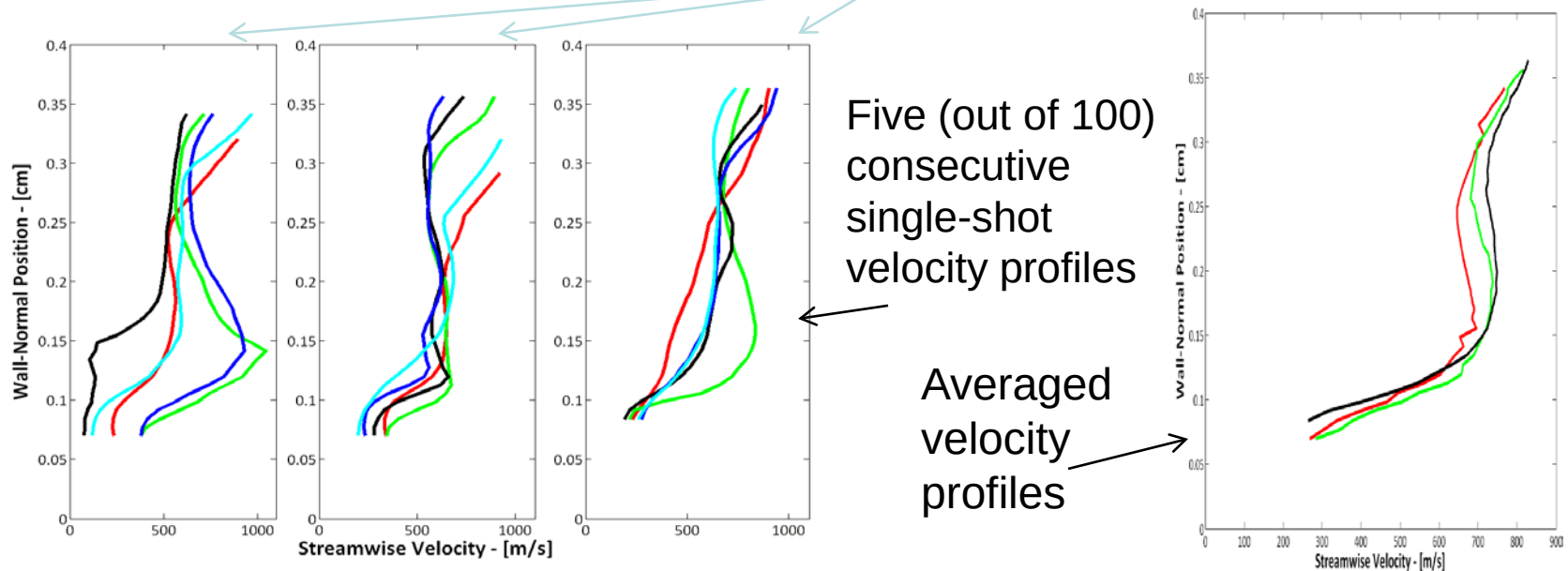


Progress on $\text{NO}_2 \rightarrow \text{NO}$ PLIF Velocimetry

Transitional flow over a 1-mm tall by 4-mm wide cylinder attached to flat plate.



First frame is a 'reference' image, acquired at zero time; all other images are delayed from first image by 1 usec.

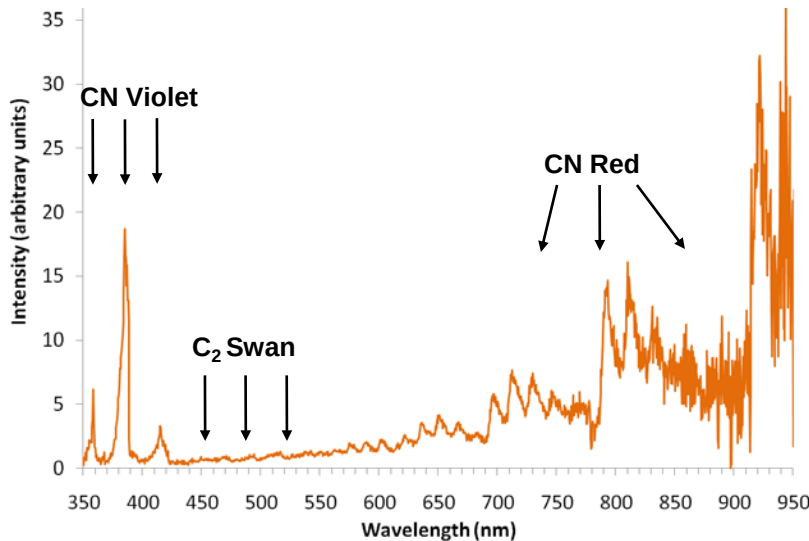


- Very preliminary result. Just starting analysis, but wanted to check S/N for data quality.
 - Will get data much closer to wall in final analysis; have hundreds of images at different locations.
- Paper submitted by Bathel et al, to Hawaii AIAA Fluids Conference

Conclusions

- HYMETs High Enthalpy Arc Jet
 - NO PLIF provided 2D flow visualization: unsteady flow
 - PLIF axial and radial velocity measurements at lower enthalpy range of operation
- Laminar-Turbulent Transition
 - NO MTV provided data on laminar flow over trips
 - Compared favorably with CFD
 - $\text{NO}_2 \rightarrow \text{NO}$ MTV data acquired in transitional hypersonic flow for first time

Future Work: FY11+

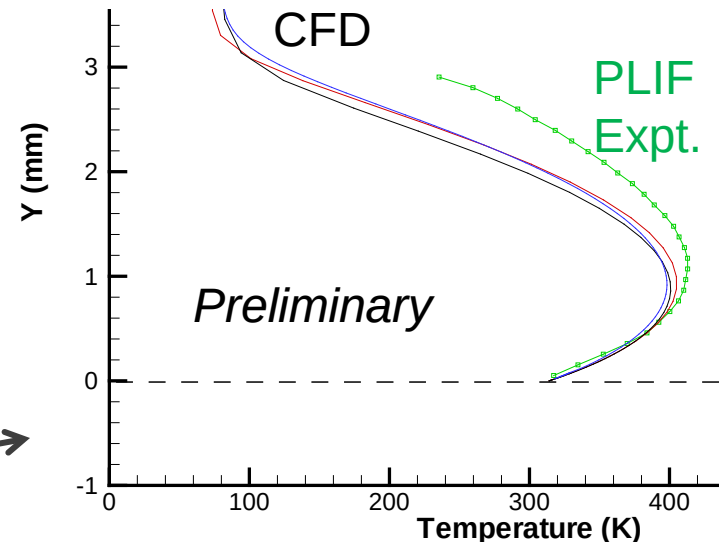


- HYMETs Arc Jet

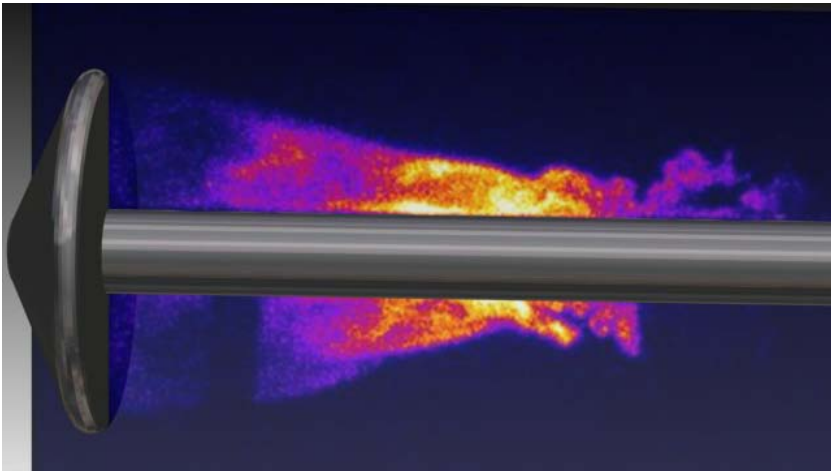
- O-atom LIF for higher enthalpy Earth and Mars simulation flowfields
- Visible and infra-red spectroscopies for ablation gas species measurement

- Laminar-Turbulent Transition

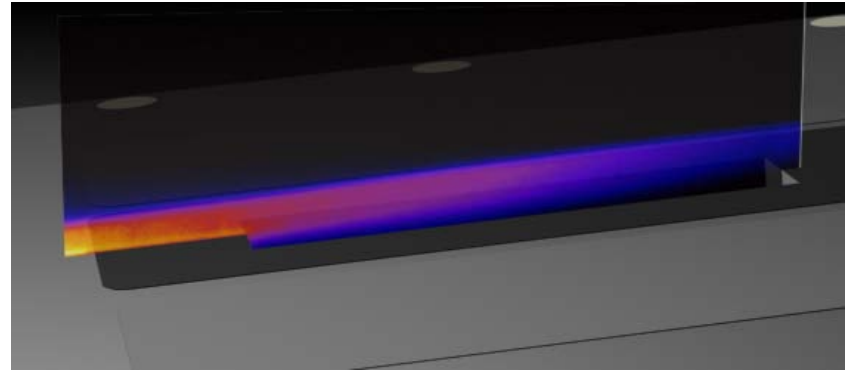
- NO₂ → NO MTV data
 - In preparation for AIAA Fluids Meeting in Hawaii
 - Implement improved velocimetry (eg. accuracy, 2D velocity)
- Developing Thermometry



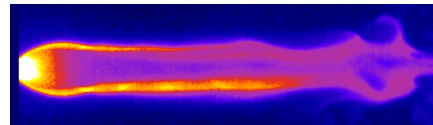
Thanks!



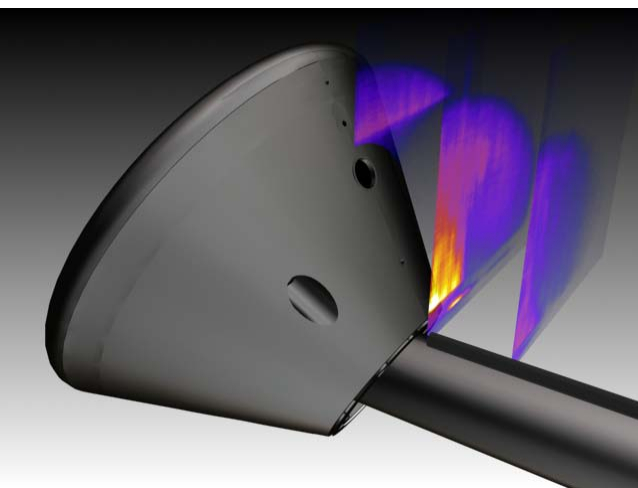
Capsule Wake Flow



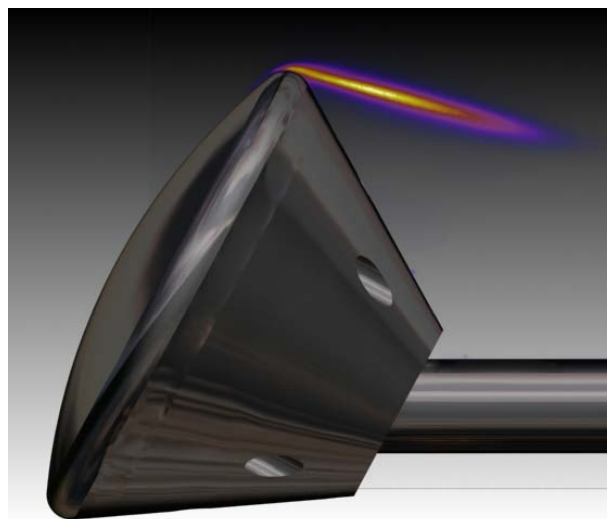
Flow Over a Cavity



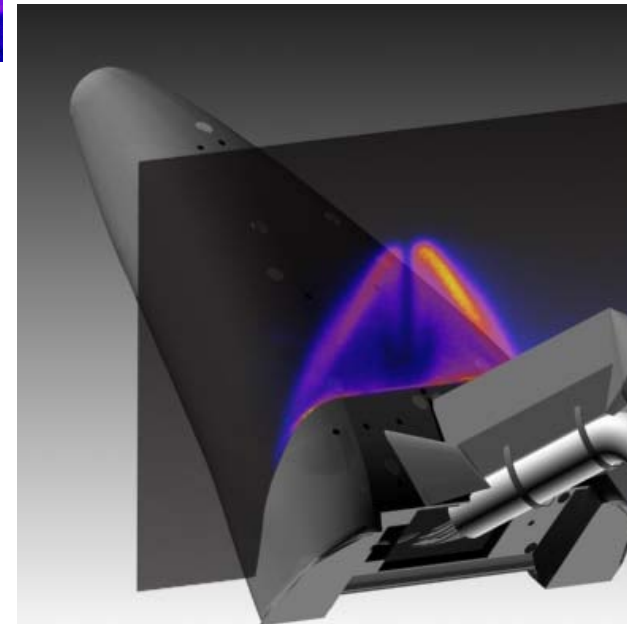
Shuttle Wing Breach



CEV Wake Flow

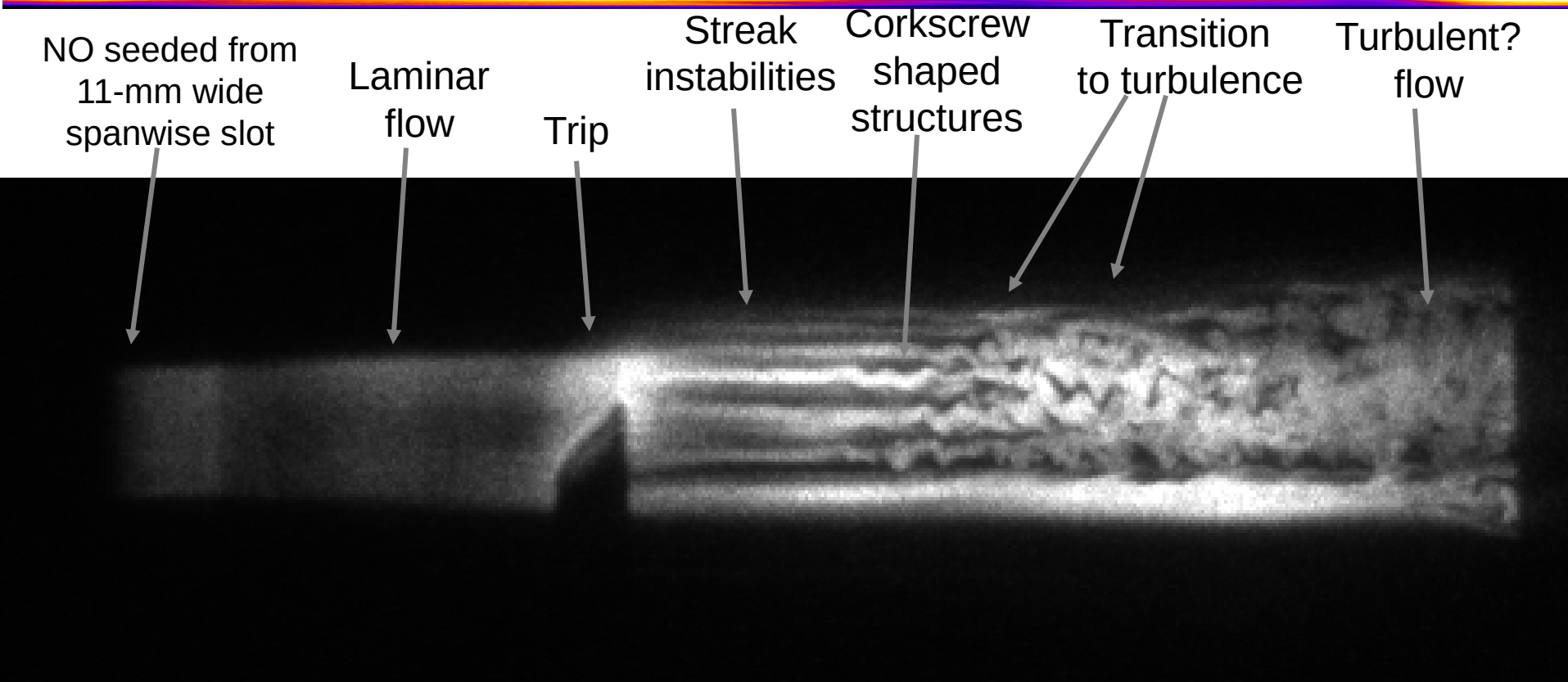


CEV Shear Layer



X-33 Leaside Flow

NO PLIF Visualization of DTO Trip



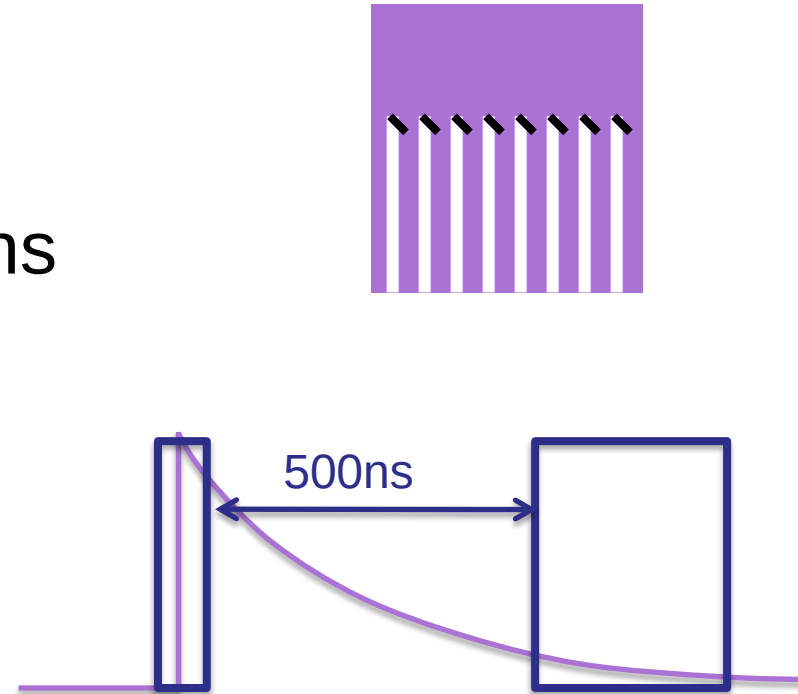
Run 5, high-Re, DTO Trip

- Flow is from left to right, $M_e \sim 4$ (flat plate at 20 deg to Mach 10 flow)
- Laser sheet enters flow parallel to the flat plate, from the top of this image (note shadow)

$$\begin{aligned} k/\delta &= 1.3 \\ M_e &\approx 4 \end{aligned} \quad Re_k = 5,600$$

NO PLIF Molecular Tagging Velocimetry

- Flow tagging of NO molecules
 - One laser pulse: take two images separated by 500 ns on same CCD camera
 - Velocity = $\frac{\text{displacement}}{\text{time}}$
- Previously (AIAAJ 2001) implemented along 1 line with uncertainty of ~100 m/s
- We extended to 25 lines



Seeking Suggestions and Collaborations

- Need close collaboration with modelers to guide experiments
- Need advice on prioritizing measurement development
 - Compromise between importance of measurement, difficulty, safety, etc.
 - Potential for many options, need to focus on a few
 - Complement (not duplicate) work being done at NASA Ames, UVM, VKI, DLR
 - Collaborate with these organizations

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)

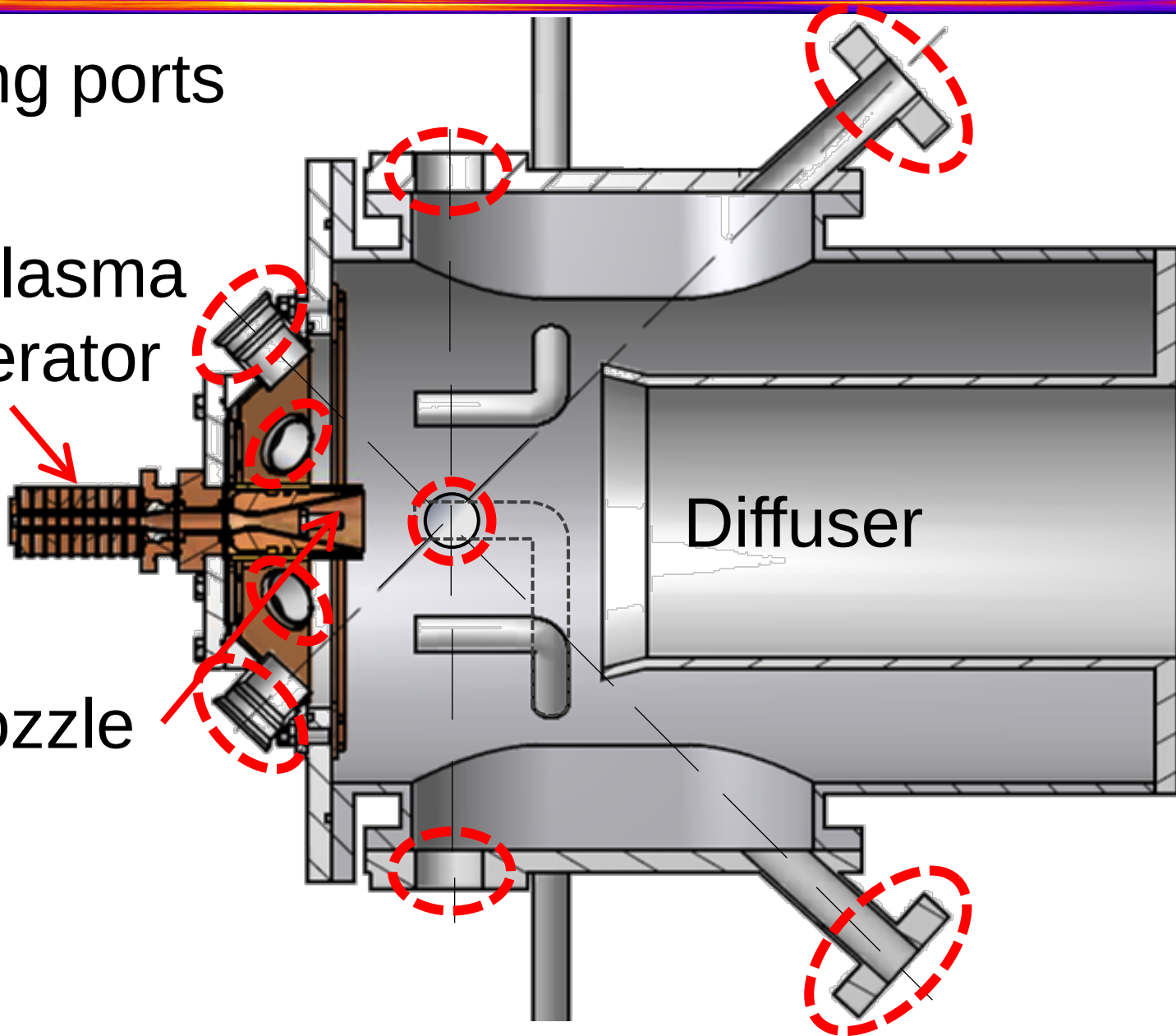
HYMETs: 400 kW Arcjet Facility

Viewing ports

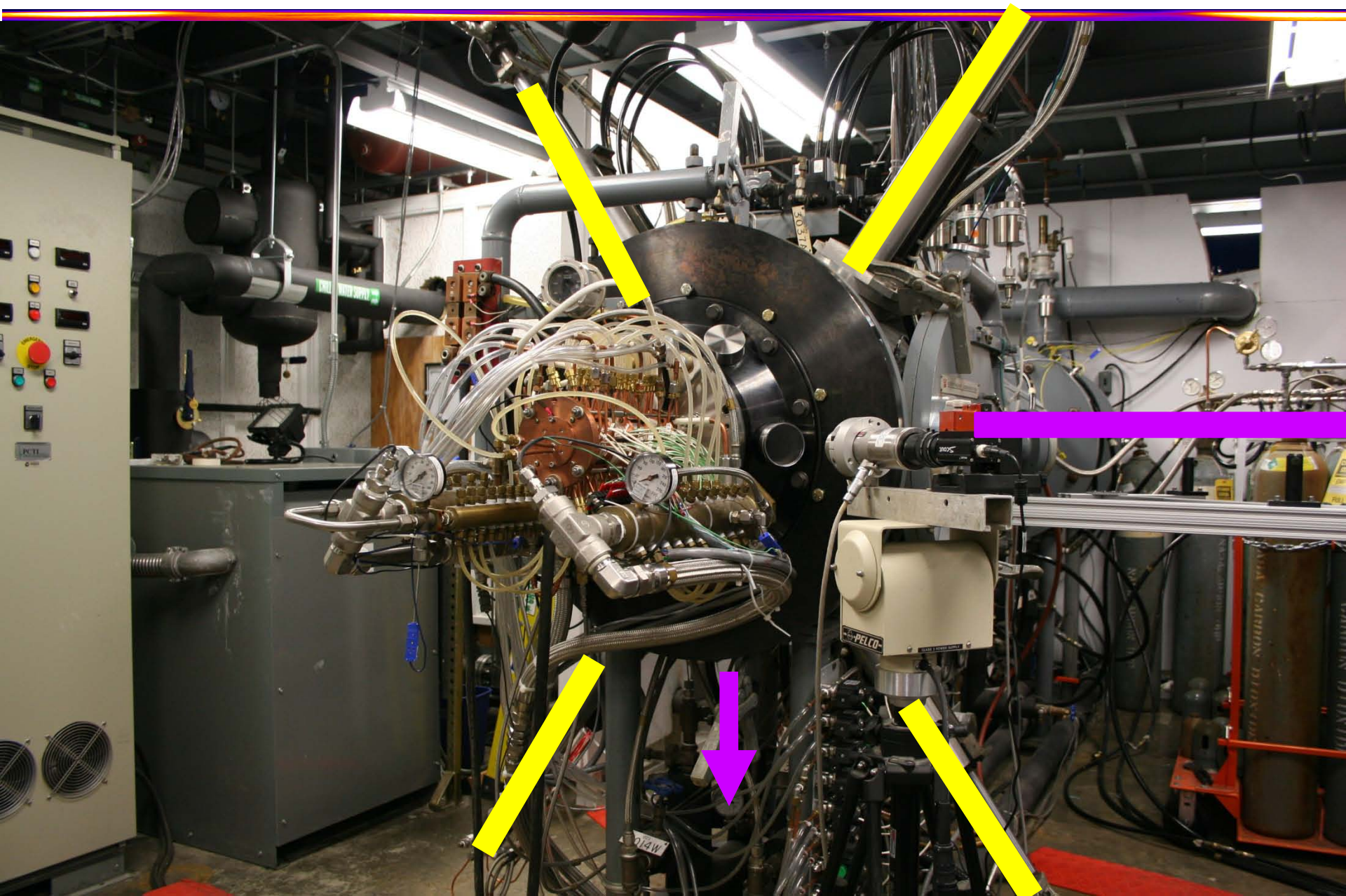
Arc plasma
generator

Nozzle

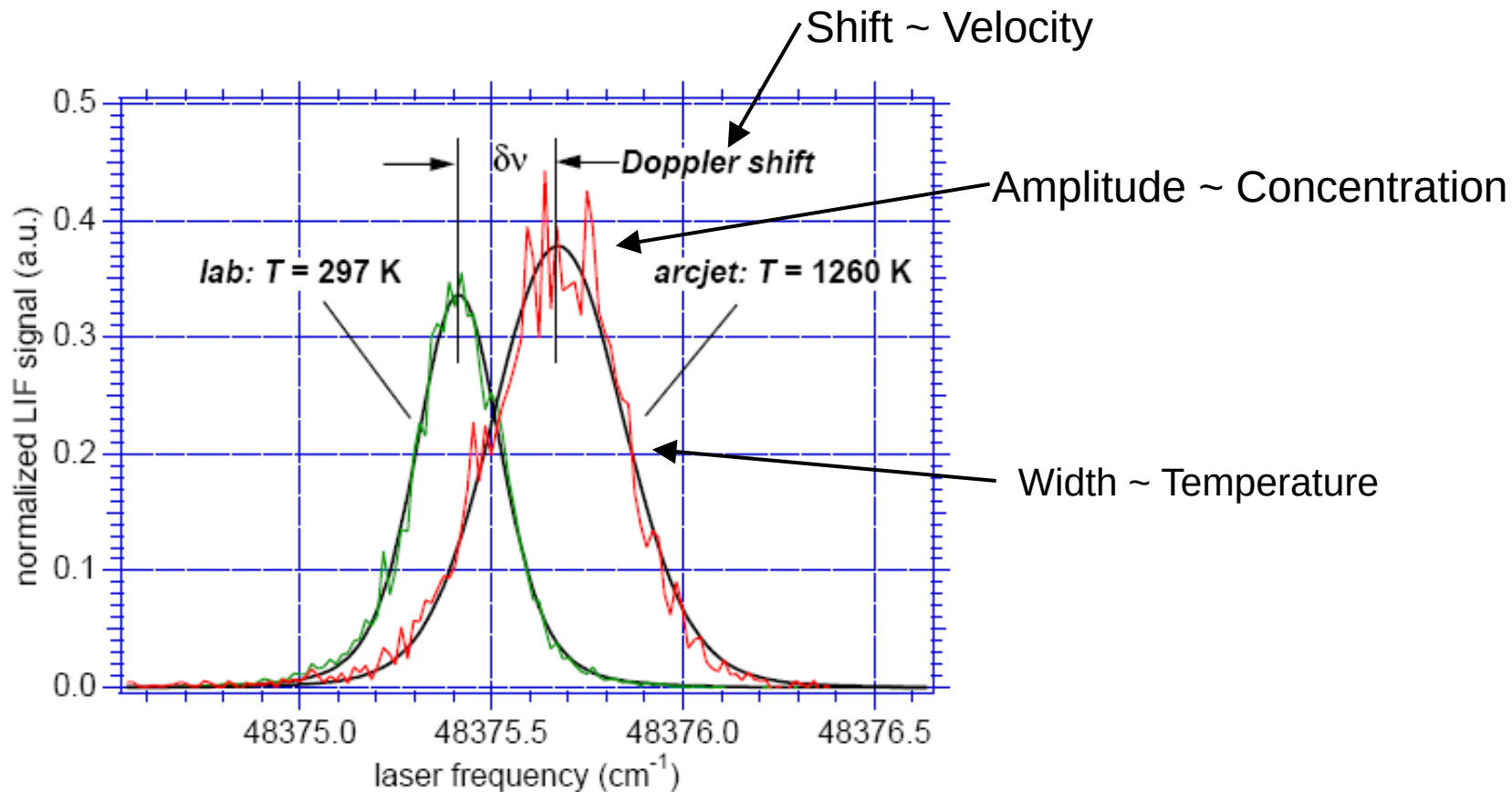
Diffuser



HYMETs: 400 kW Arcjet Facility



O-atom LIF Spectroscopy (NASA Ames and JSC)



Grinstead et al, AIAA 2003-400

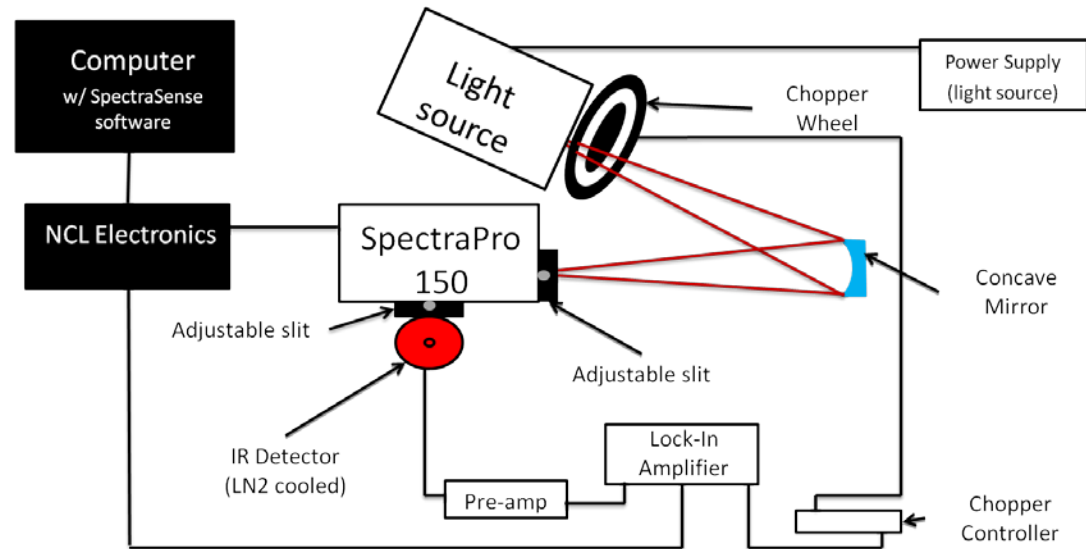
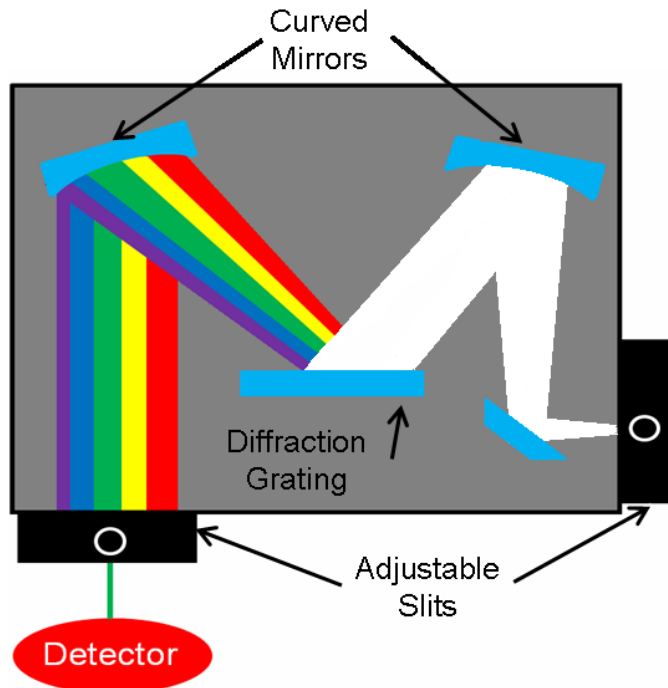
- We performed proof of concept O-atom LIF in HYMETs (FY10)
- Status: will measure velocity and temperature in FY11

IR absorption spectroscopy

IR spectroscopy has potential to measure species relevant to ablation physics:

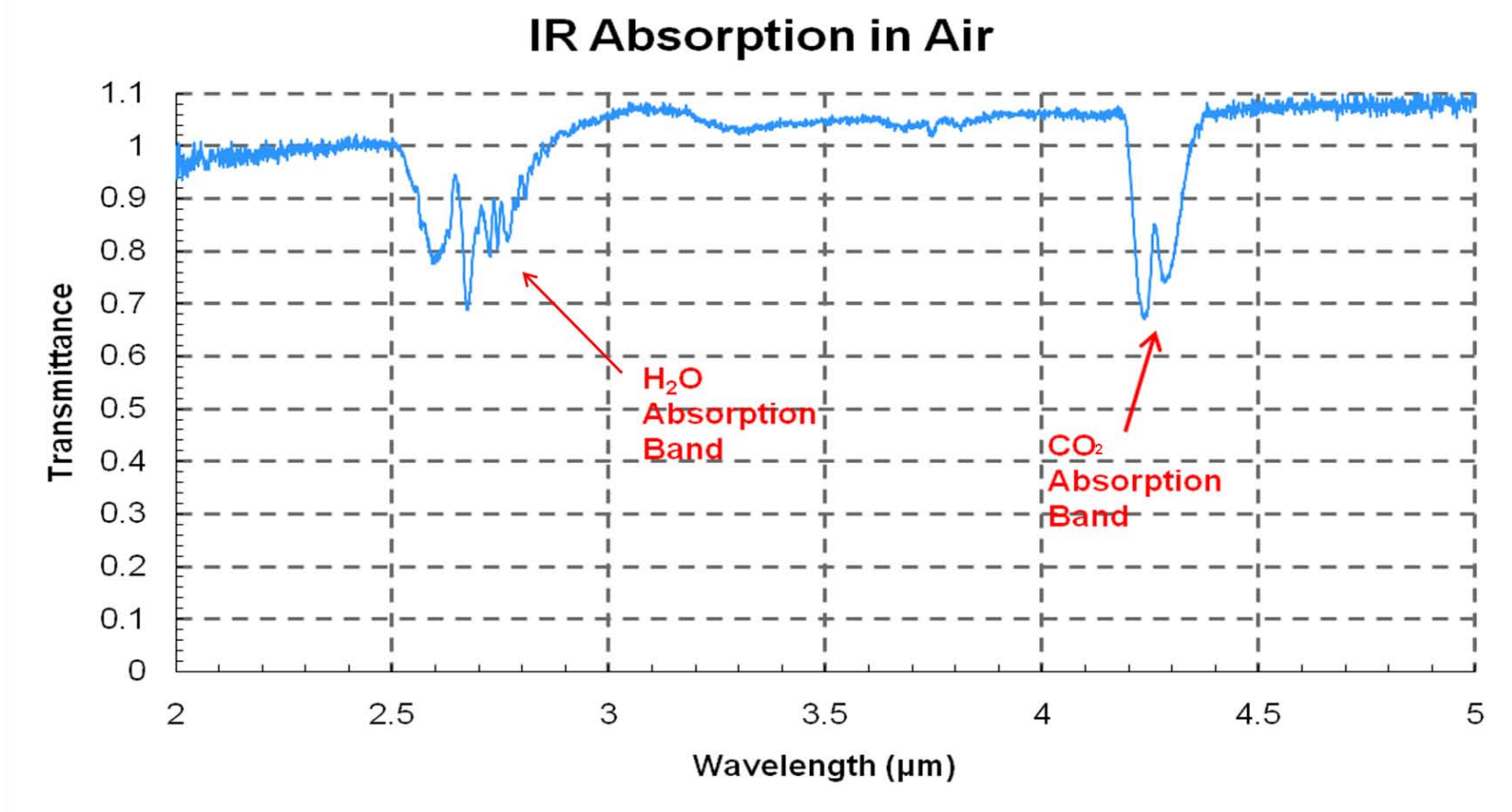
- CO_2 , H_2O , C_2H , C_2H_2 , C_3 , CH_3 , CH_4 , H , H_2 , HCN , NO , CN , CH , CH_2 , C , and C_2

Same instrument potentially can measure several simultaneously



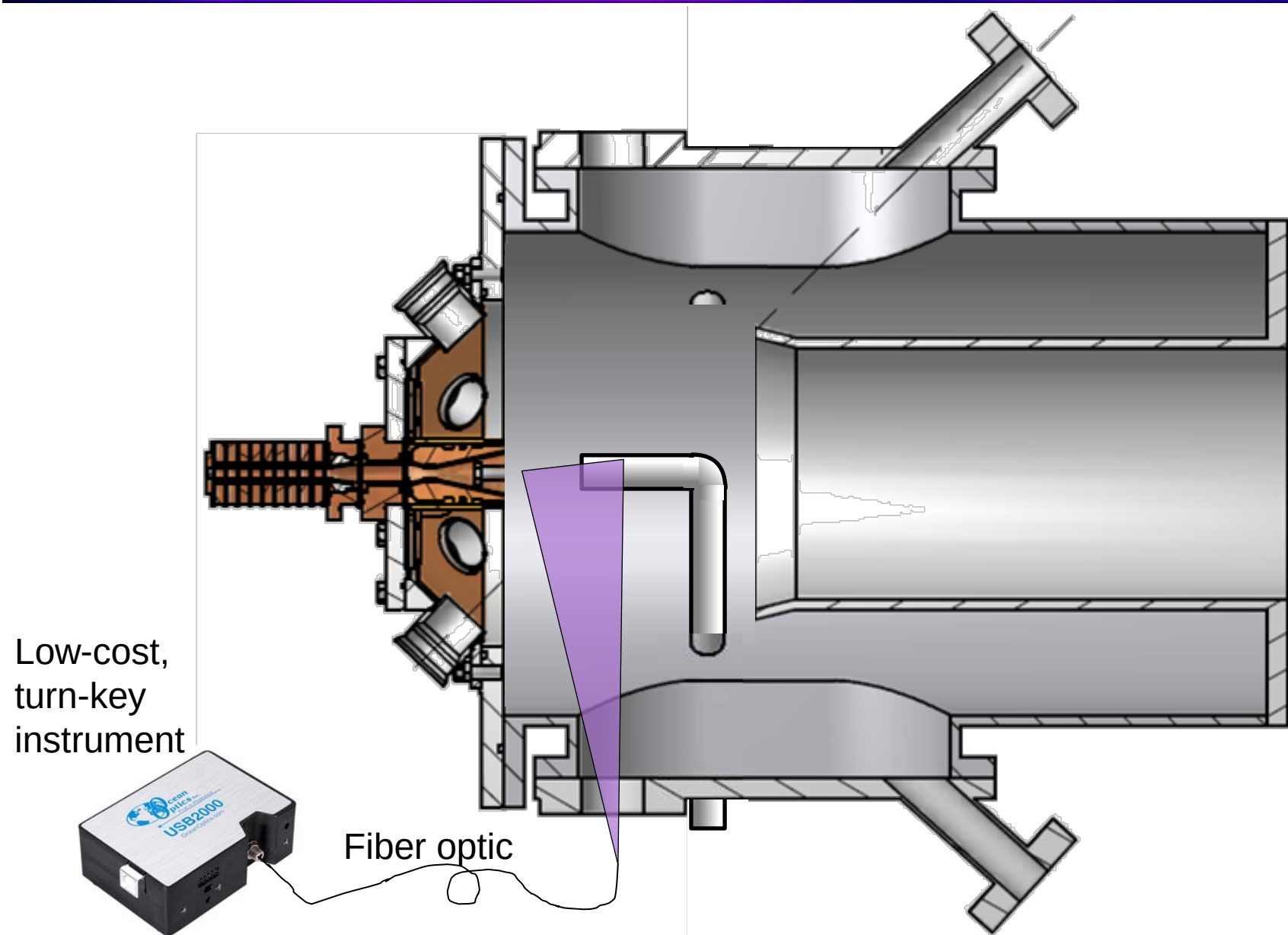
- Would need to develop calibration procedures to quantify species

Preliminary IR Absorption Measurement in Lab

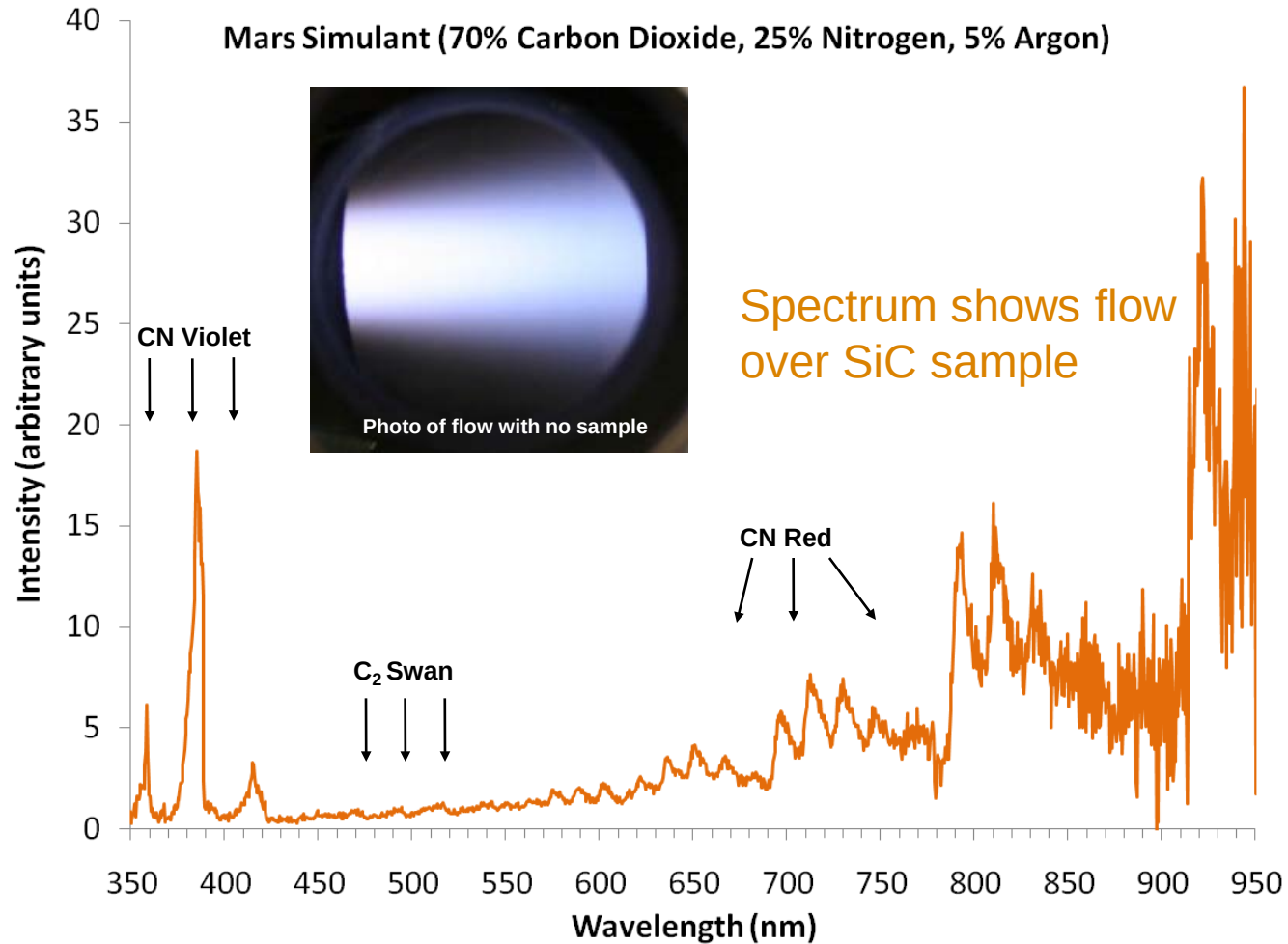


- Measured ambient H_2O and CO_2 (400 ppm)
- *Low cost*: instrument is turn-key and easy to use
- *High risk*: emission may dominate absorption
- Status: Have ordered IR-transparent windows for HYMETs 36

Visible Emission Spectroscopy in HYMETs

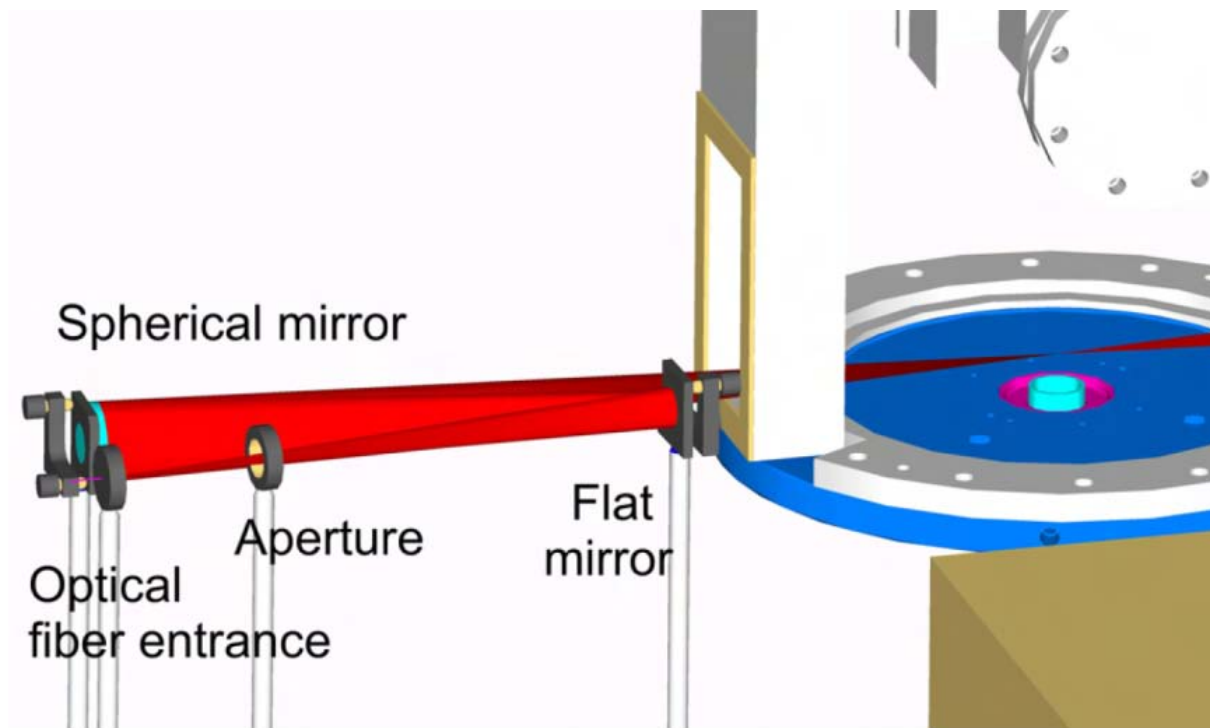


Visible Spectroscopy: Mars Simulant



- Spectrum is dominated by CN emission
 - Previously Studied and modeled in detail by Playez et al., VKI

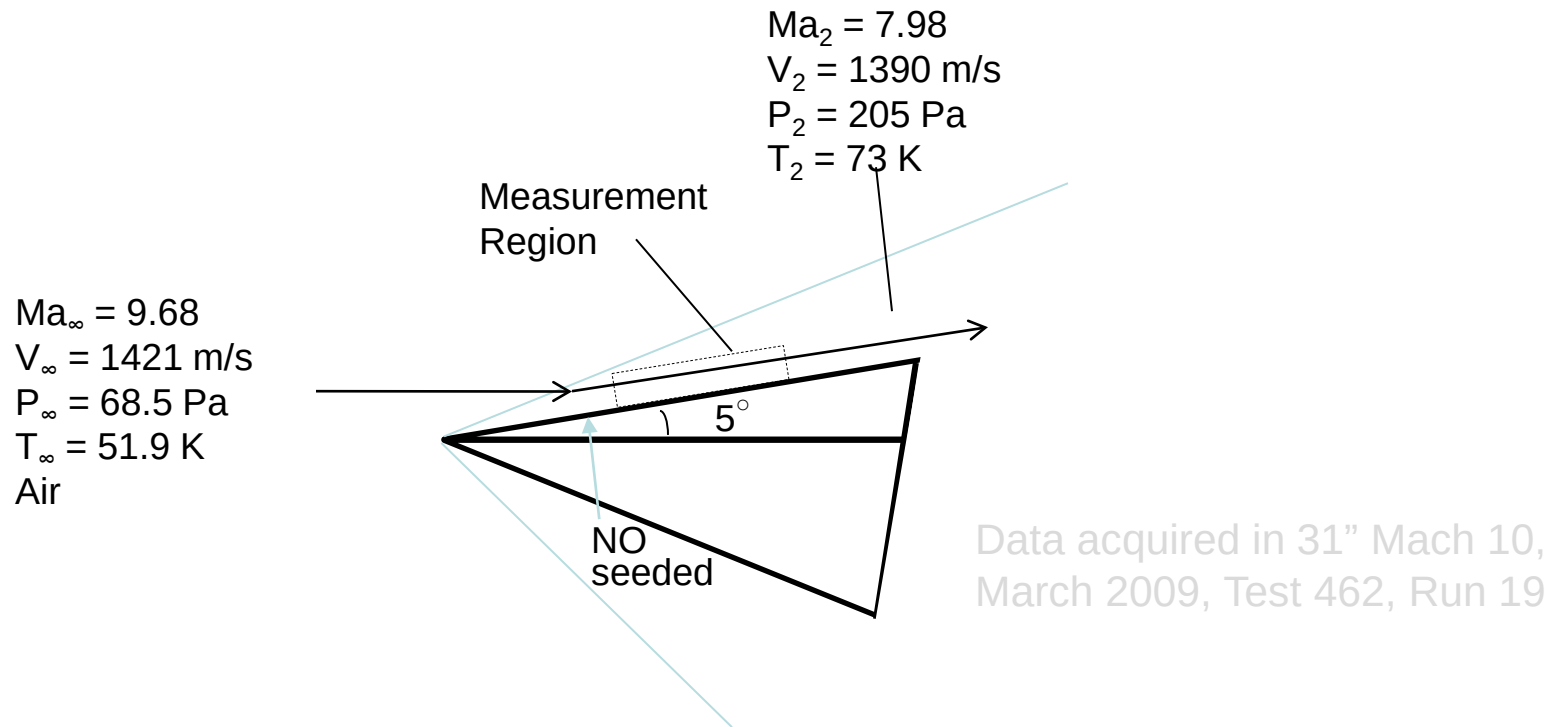
Future Visible Spectroscopy in HYMETs



Mickael Playez, VKI

- Could quantify radiative emission
 - Could determine T_{rot} , T_{vib}
- Status: Improving spatial resolution by using appropriate optics; rerun soon

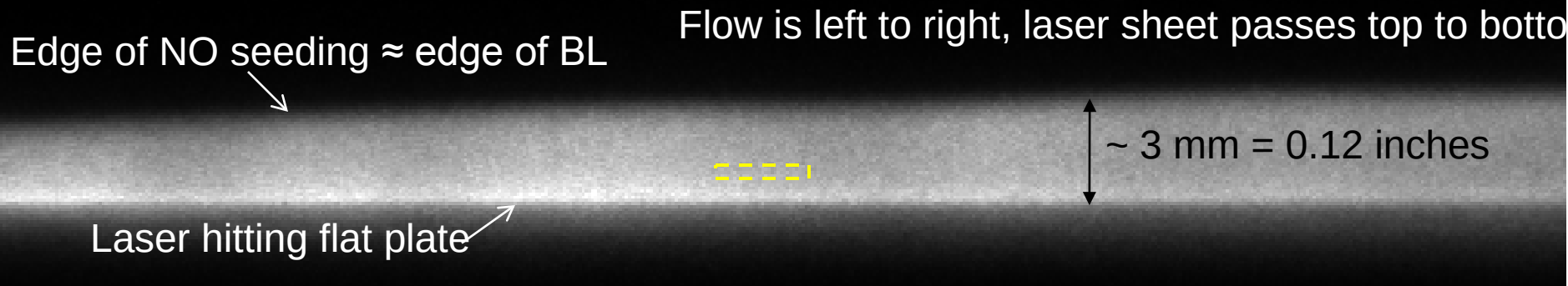
NO PLIF Thermometry: Fluids Setup



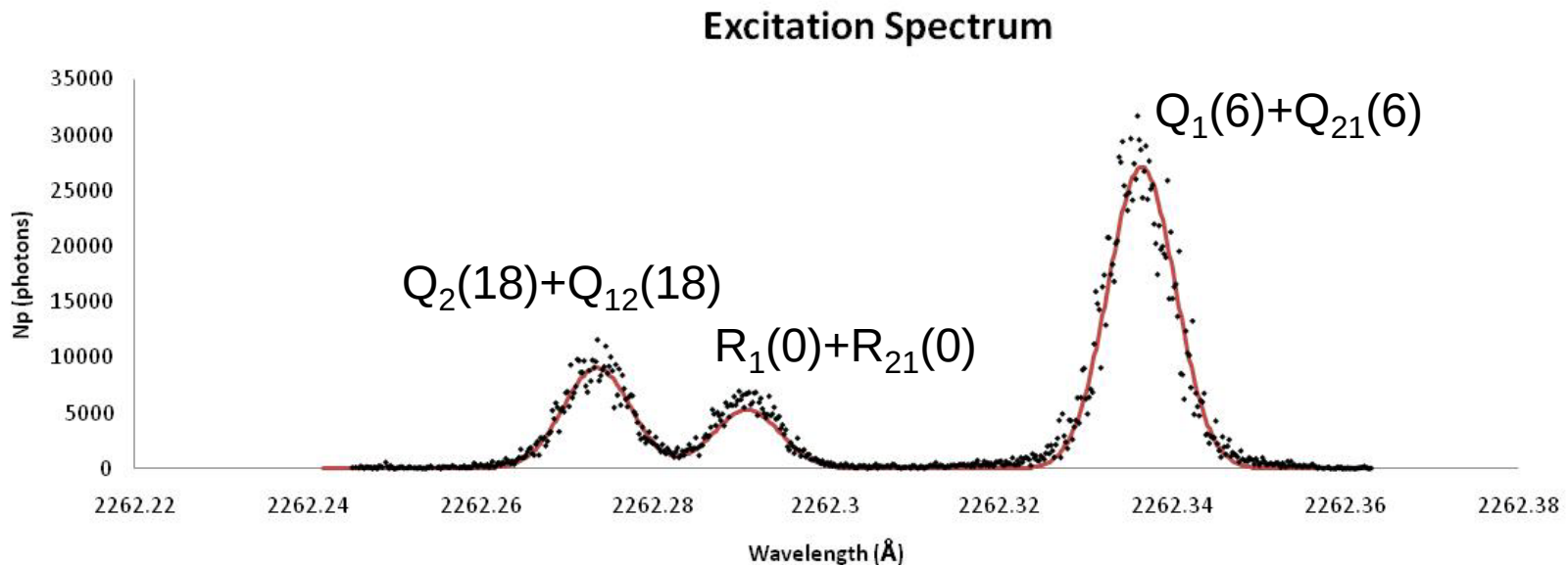
NO PLIF thermometry (frequency scanning method for laminar flows)

- Seed nitric oxide (NO) into the flow at a low flowrate
- Use NO planar laser-induced fluorescence (NO PLIF) to interrogate region downstream of seed location.
- Scan laser frequency while acquiring images: spectrum determines temperature

Processing of PLIF thermometry images



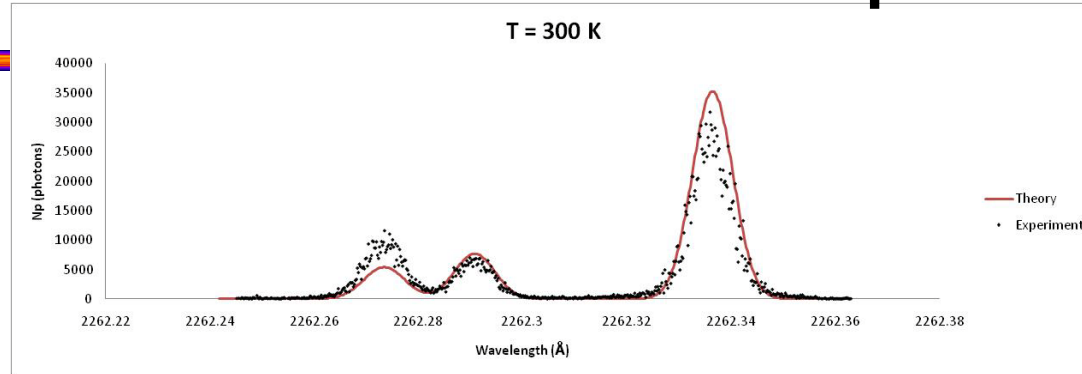
An image like this is acquired at all the wavelengths shown on the horizontal axis below.



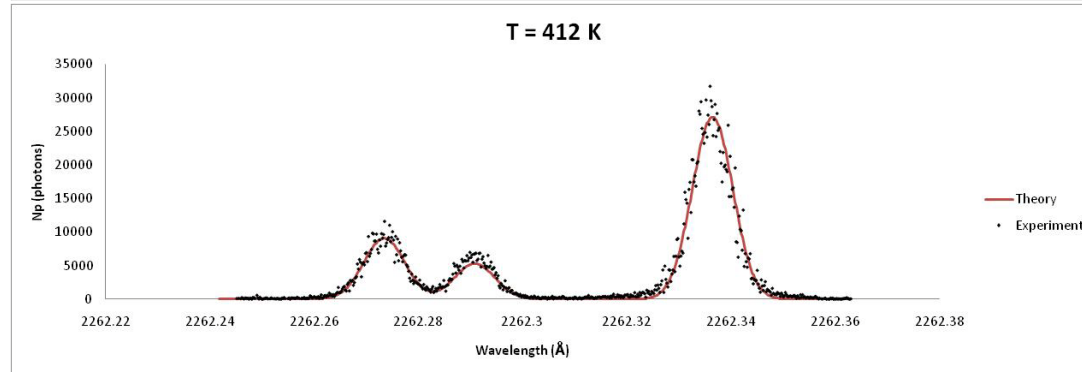
A spectrum like this is acquired at every pixel (or group of pixels).

Effect of Rotational Temperature

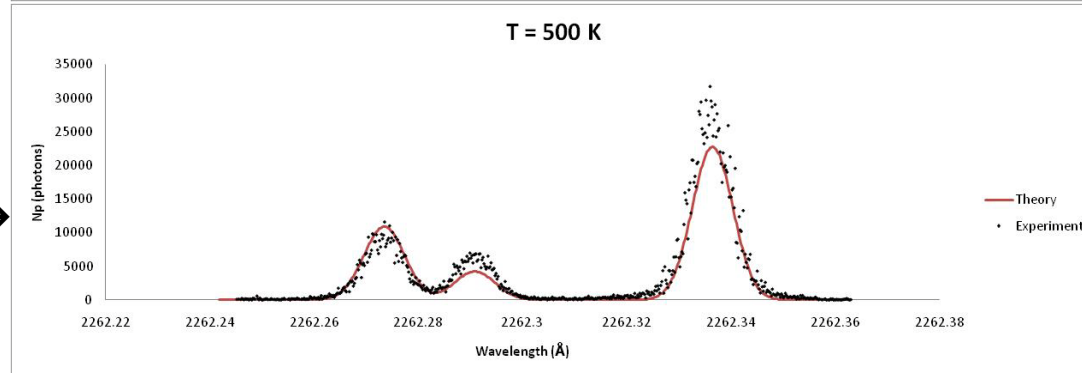
T too low →



Best Fit →

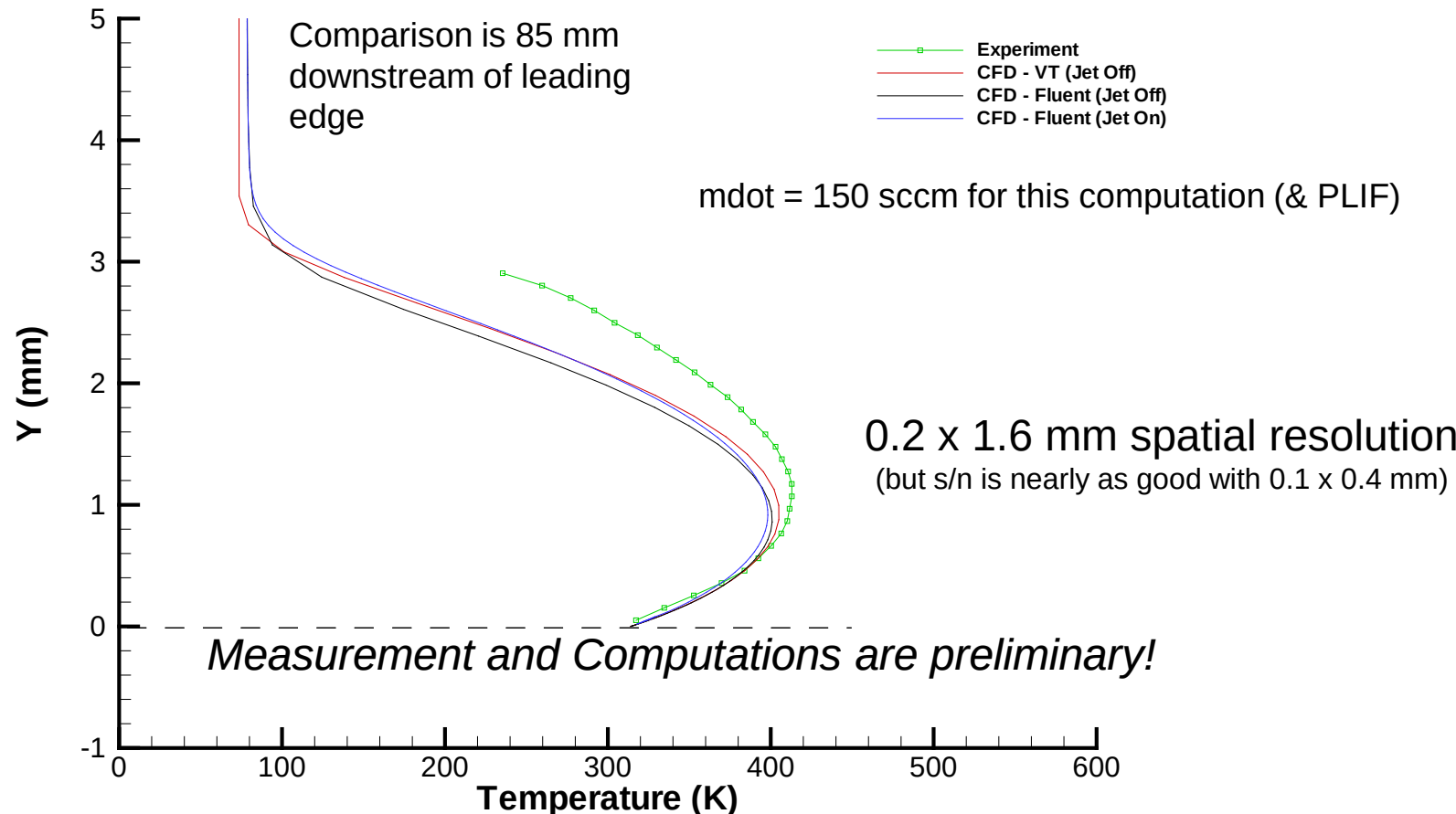


T too high →



- Spectra show good temperature sensitivity in temperature range of interest.
- Also they show good signal-to-noise ratio. Most of the scatter is caused by laser energy variations, which we could measure and correct. Could seed less NO.

Rotational Temperature Measurement: preliminary comparison with CFD



- There is a finite effect of jet blowing on thermal boundary layer thickness.
- Shows progress but lots of work to do on thermometry: validations in lab.