



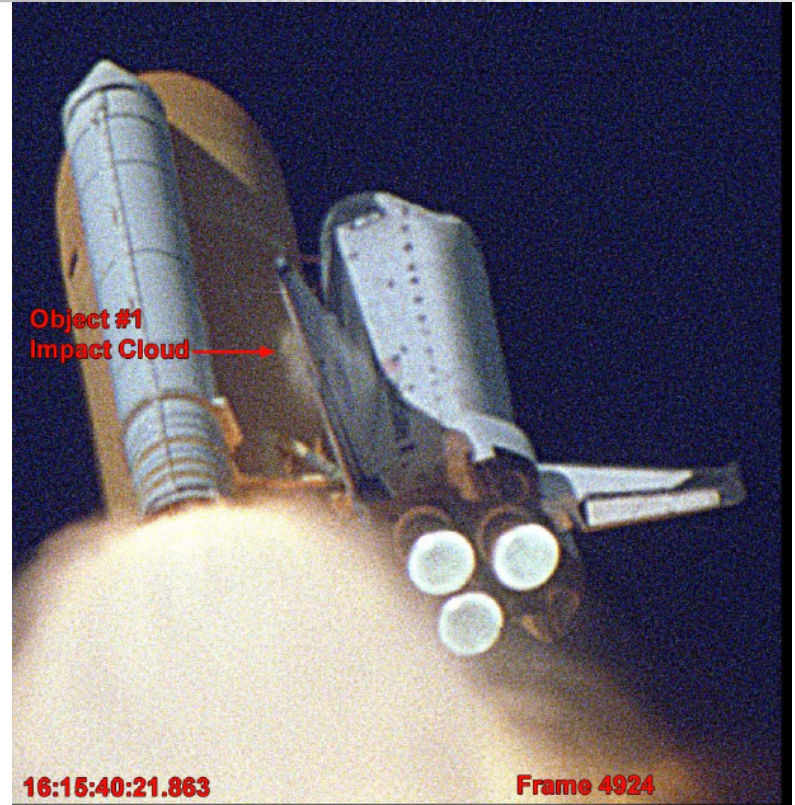
**UNIVERSITY OF
CALGARY**

Nitric Oxide Planar Laser-Induced Fluorescence Thermometry in a Hypersonic Boundary Layer

Connor C. McDougall – Graduate Student – AIAA Student Member
Dr. W. Schuyler Hinman – Postdoctoral Researcher – AIAA Member
Dr. Craig T. Johansen – Associate Professor – AIAA Senior Member
*University of Calgary
Calgary, Alberta, Canada*

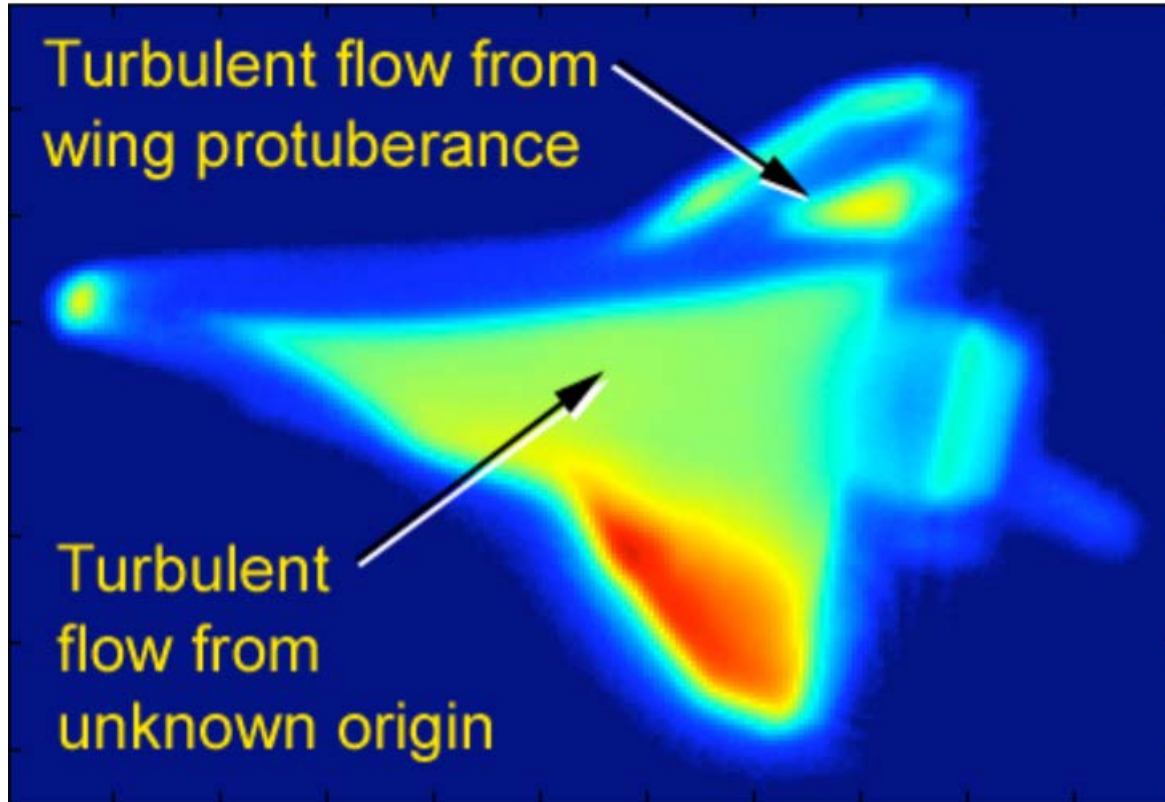
Dr. Brett F. Bathel – Research Scientist – AIAA Senior Member
Dr. Jennifer A. Inman – Research Scientist – AIAA Senior Member
Dr. Paul M. Danehy – Senior Technologist – AIAA Associate Fellow
*NASA Langley Research Center
Hampton, Virginia, United States*

Hypersonic Boundary Layer Transition and Heat Transfer



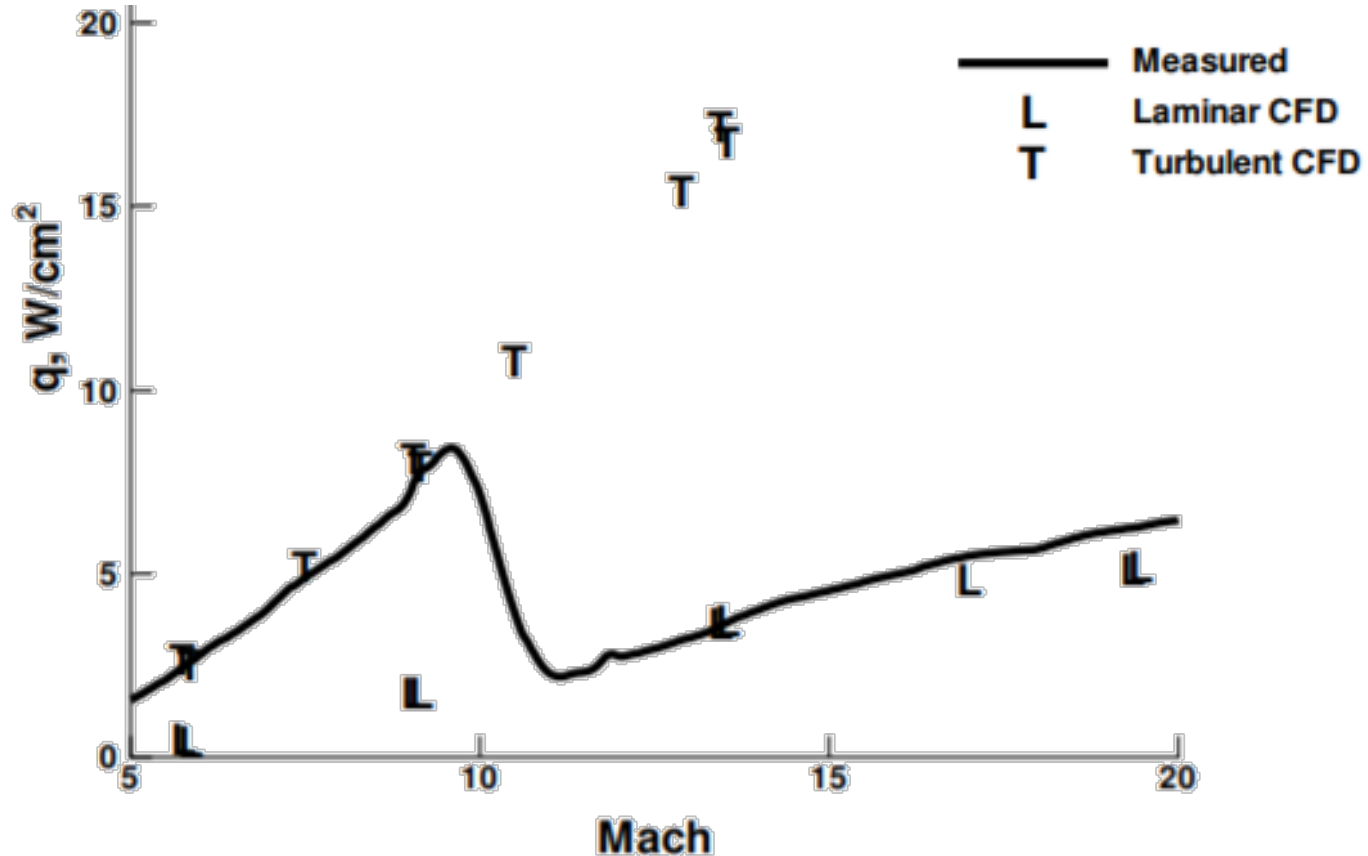
STS-107 - Space Shuttle Columbia

Hypersonic Boundary Layer Transition and Heat Transfer



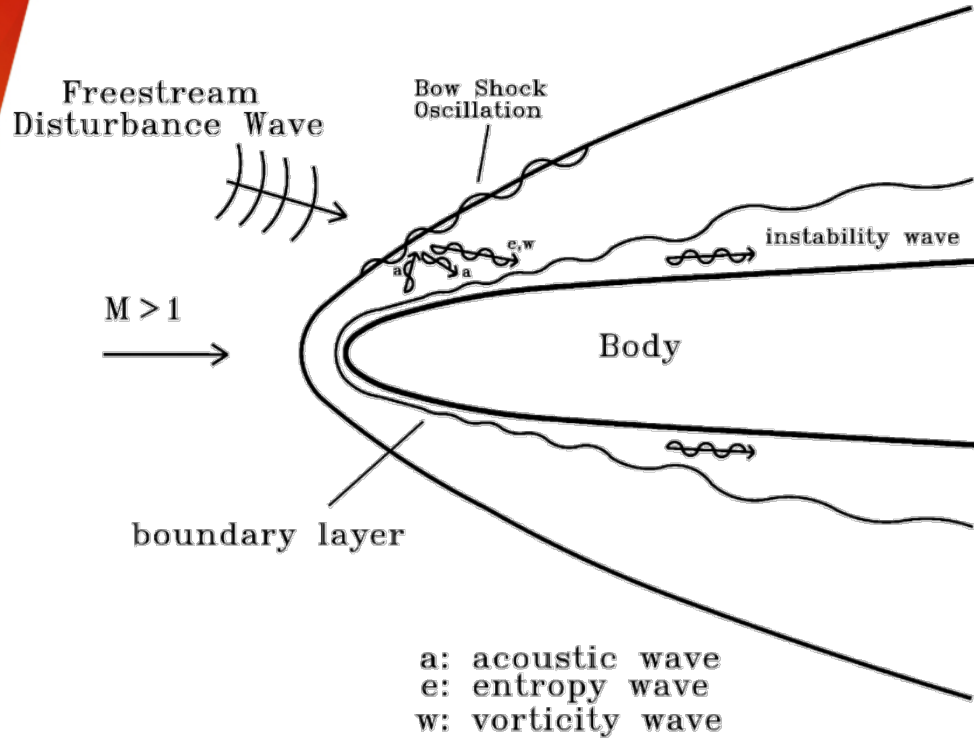
Thermal Imaging of Space Shuttle Orbiter (STS – 119),
Reproduced from Horvath *et al.*, 2010

Increased Heating from Hypersonic Boundary Layer Transition

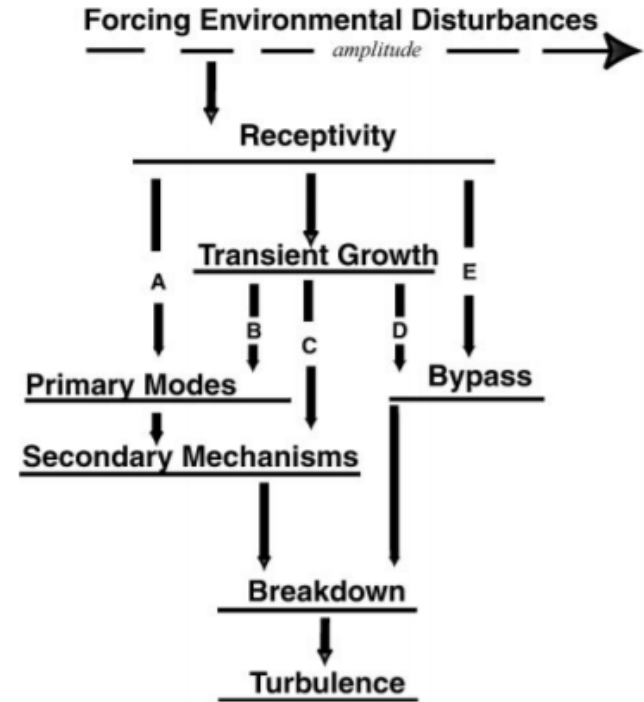


STS-119, Reproduced from Wood and Oliver (2011)

Basic Understanding of Hypersonic Boundary Layer Transition



Reproduced from Zhong and Tatini, 2003



Reproduced from Saric *et al.*, 2002

Challenges in Predicting Hypersonic Boundary Layer Transition

William Saric on Hypersonic Transition Theory [2013]

“A transition prediction scheme is just beyond the horizon. [The horizon is defined] as an imaginary line that continually recedes as you approach it”

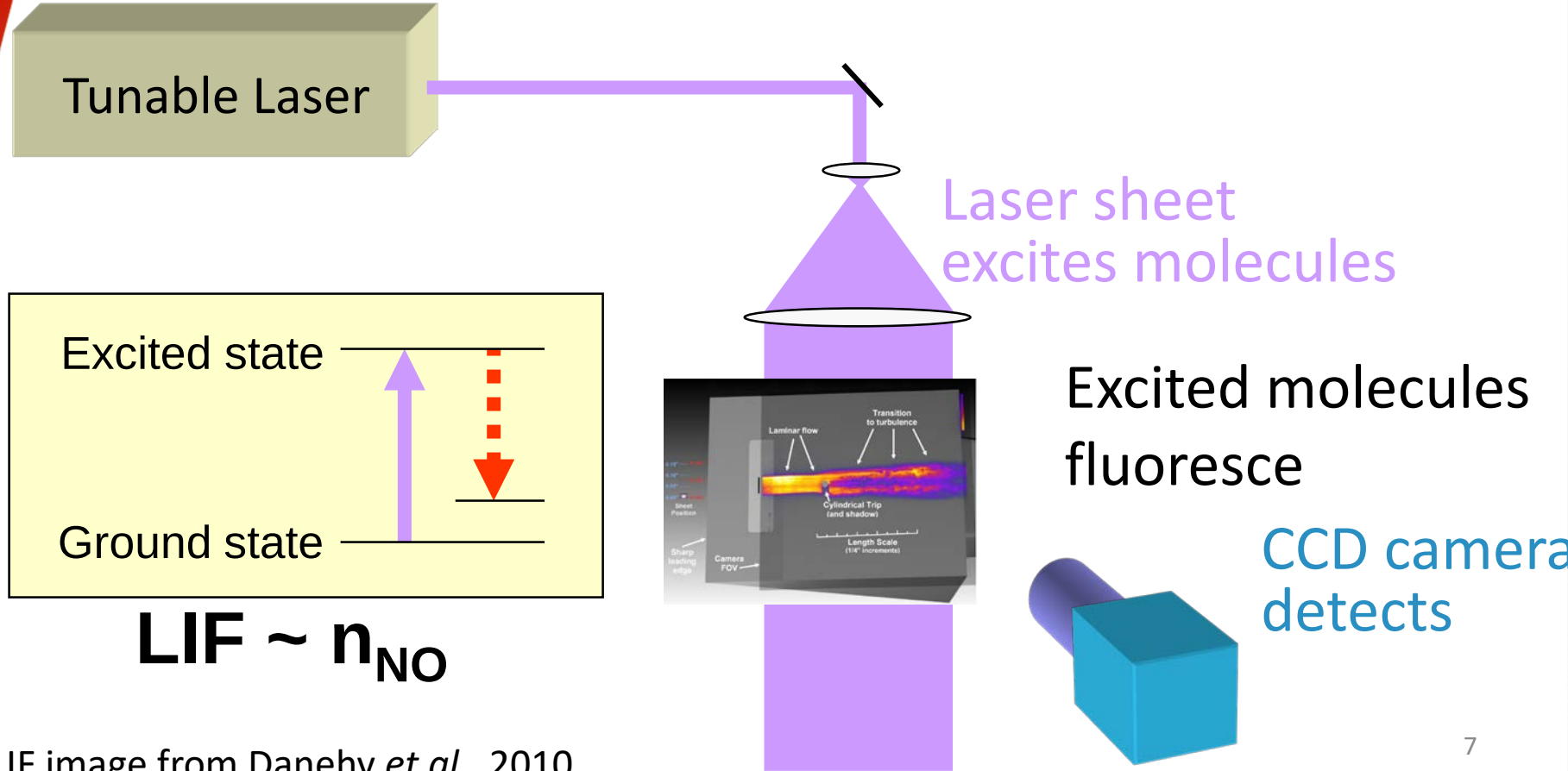
Physics-based approach for the theory required. Need validation with experiments

John Anderson on Predicting Hypersonic Transition [2006]

“To date, no theory exists for the accurate prediction of Re_T ; any knowledge concerning its value ... must be obtained from experimental data. If the desired application is outside the existing database, then an estimate of Re_T is essentially guesswork”

$$Re_T = f \left(M_e, \theta_c, T_w, \dot{m}, \alpha, k_R, E, \frac{\partial p}{\partial x}, R_N, \frac{R_\infty}{m}, \frac{x}{R_N}, V, C, \frac{\partial w}{\partial x}, T_0, d^*, \tau, Z \right)$$

Planar Laser-Induced Fluorescence (PLIF)



Temperature measurements from PLIF for high-speed flows

- Examples in literature of using PLIF to obtain spatially-resolved temperature maps in high Mach number flows:

Estruch-Samper, 2014

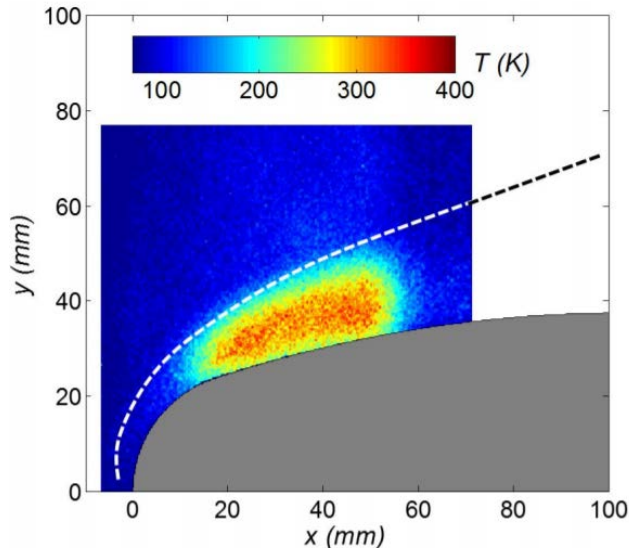


Fig. Toluene-PLIF thermometry
(approximately Mach 9)

Palma, 1999:

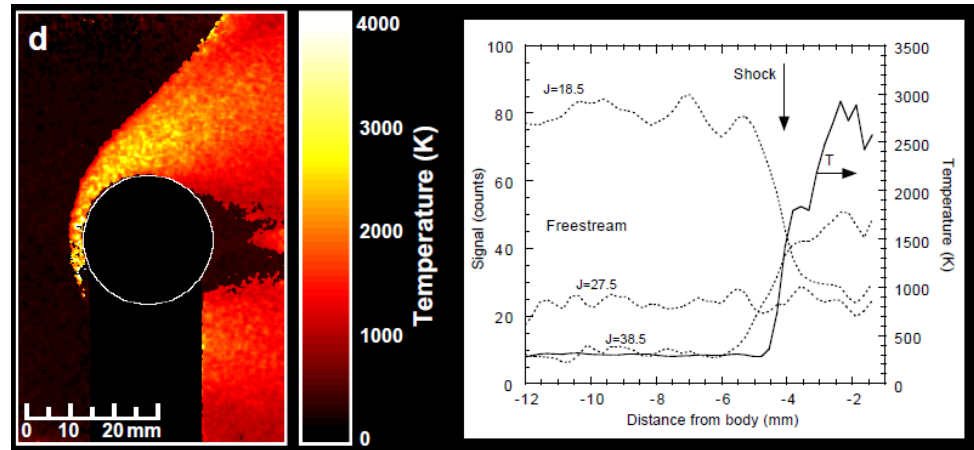
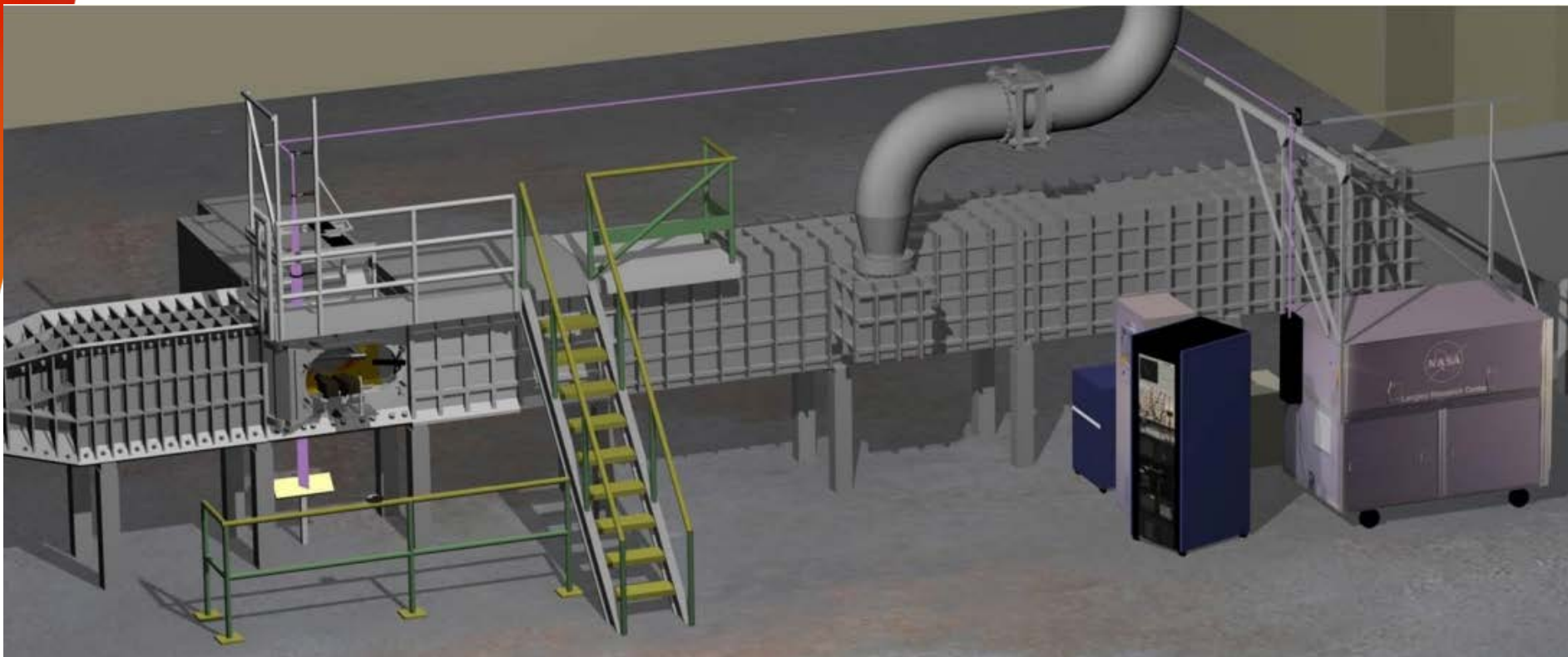


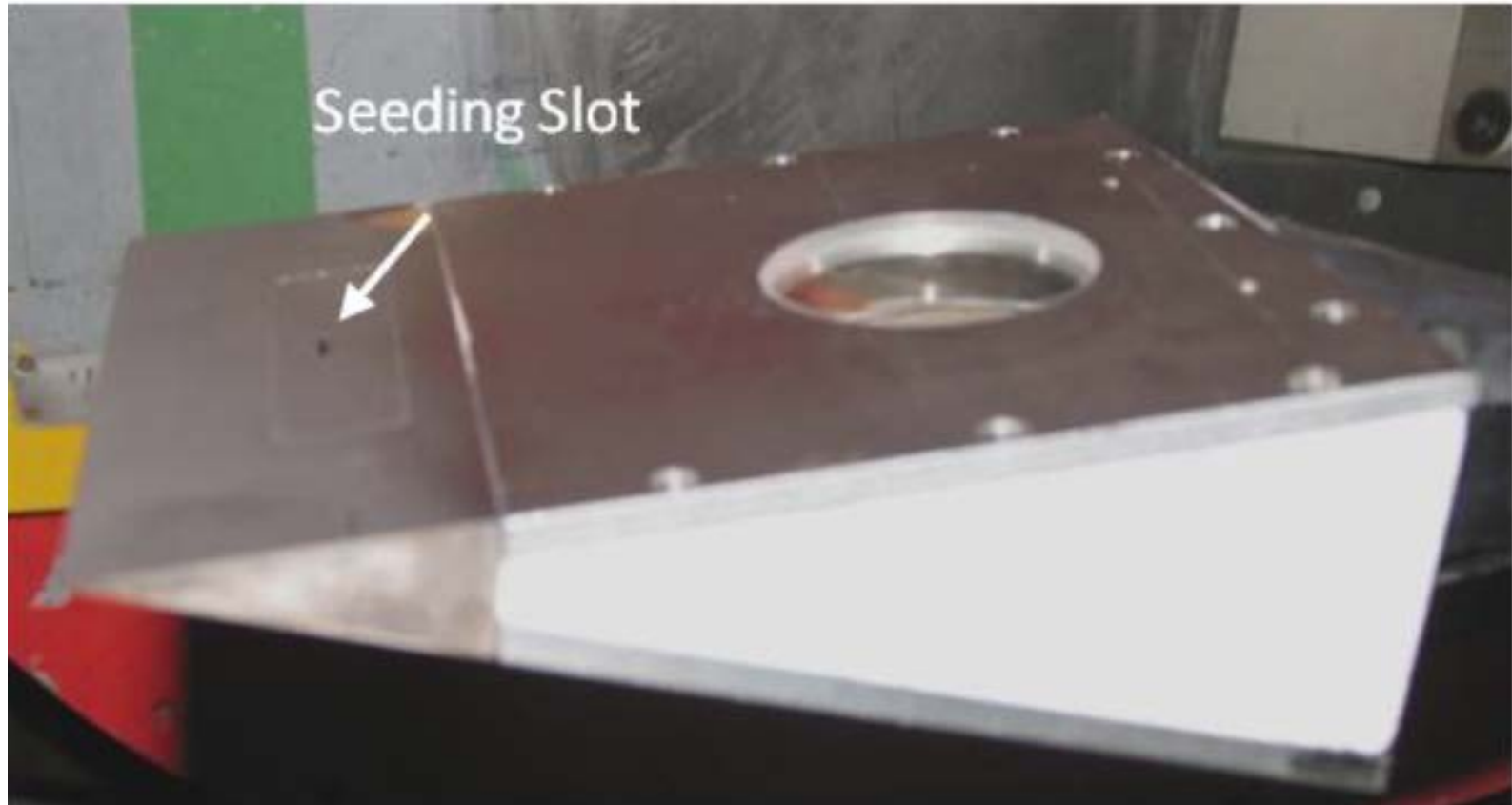
Fig. NO-PLIF thermometry on a cylinder experiment
(approximately Mach 7)

- How well does ratio PLIF thermometry work in NASA's 31" Mach 10 facility?
- Can the challenges associated with saturation and absorption be addressed to improve accuracy?
- Are there other challenges that are not immediately apparent?

- 1. Measure temperature throughout a laminar hypersonic boundary layer using NO PLIF**
- 2. Compare temperature measurements against computational fluid dynamics (CFD) simulations**
- 3. Determine limitations and potential for applying technique to more complicated flows**

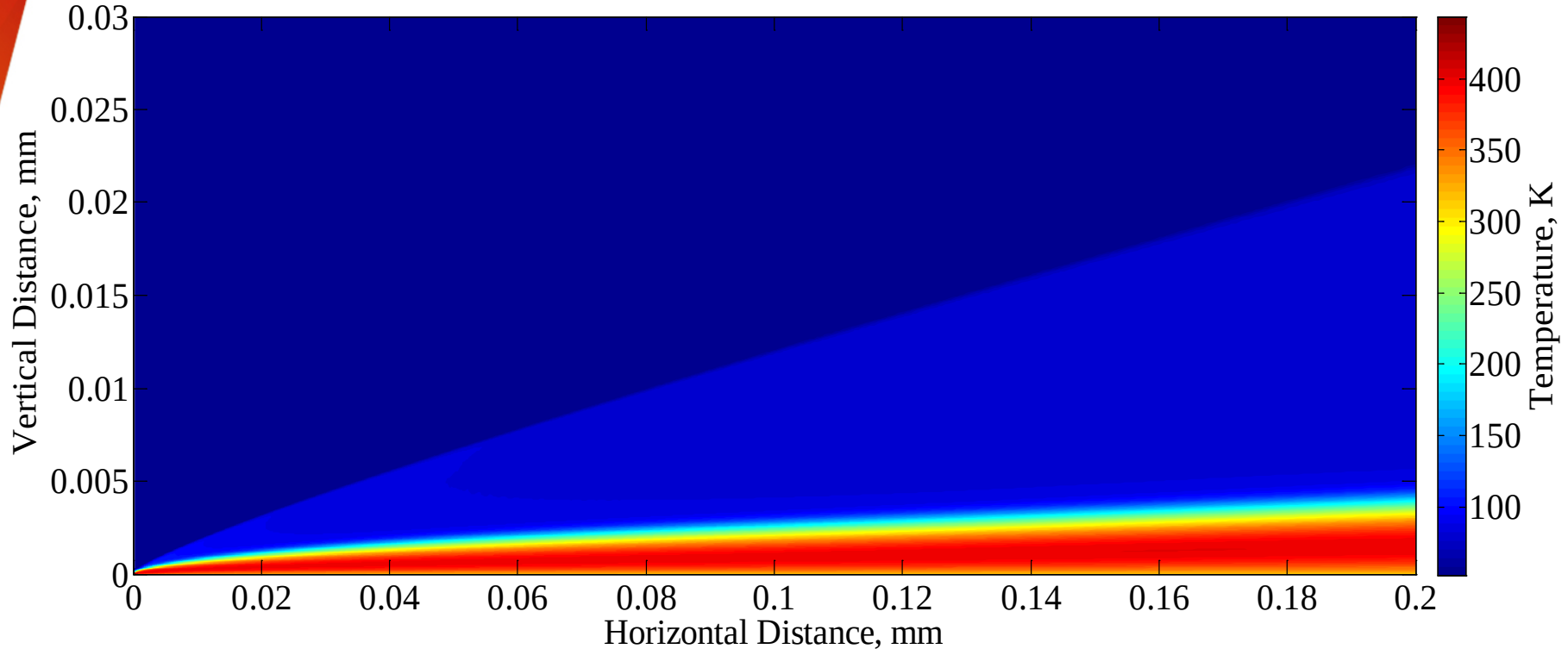


20 Degree Wedge Model



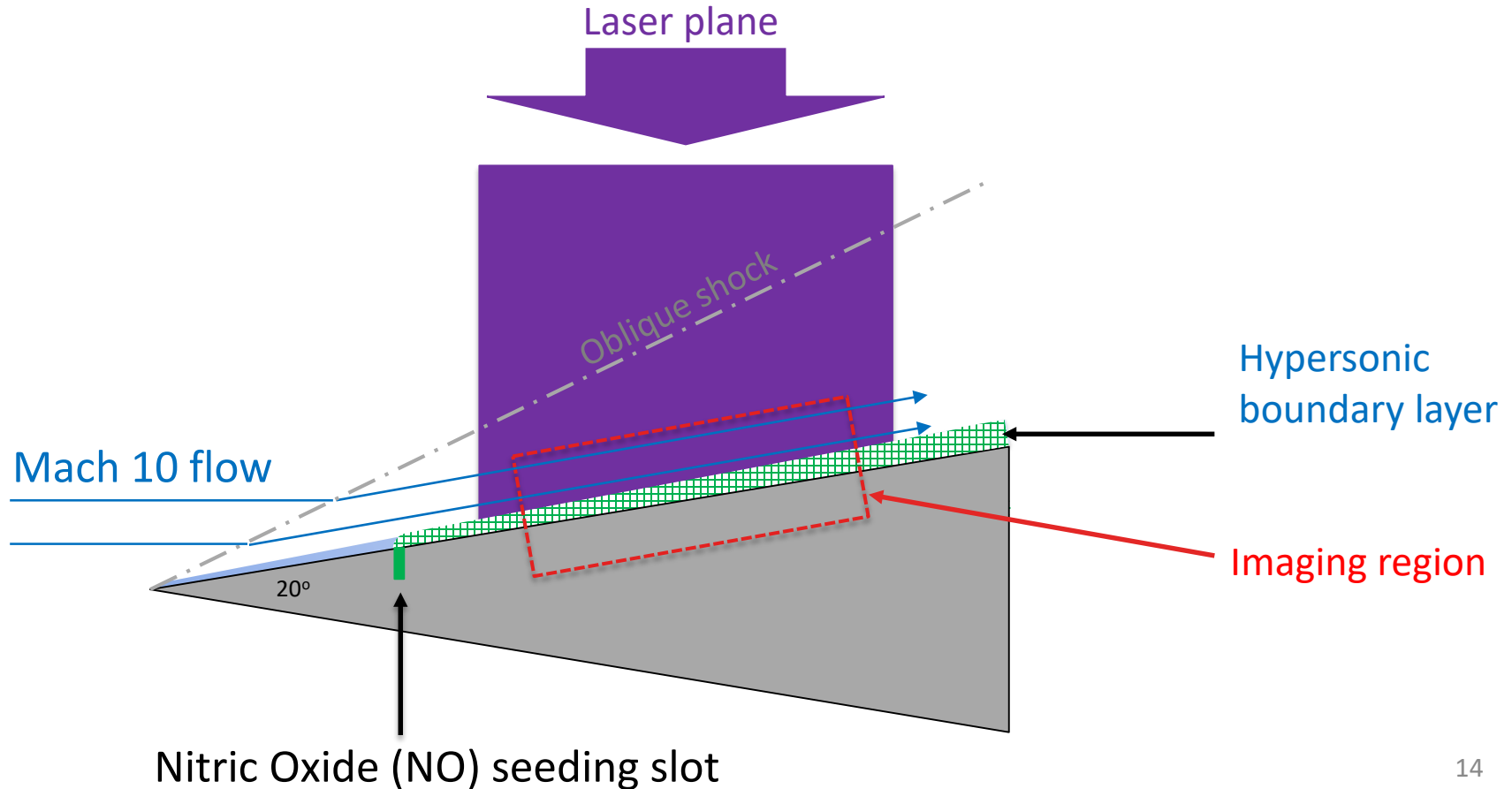
Expected Temperature Field from CFD

OpenFOAM Simulation of the Mach 10 Flow

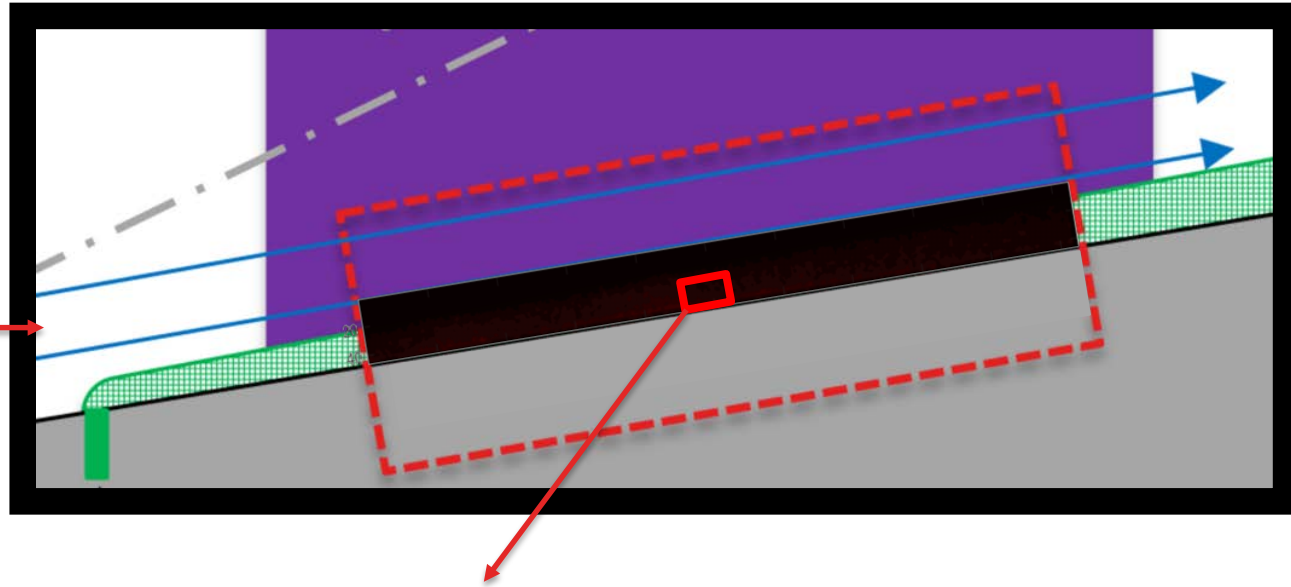
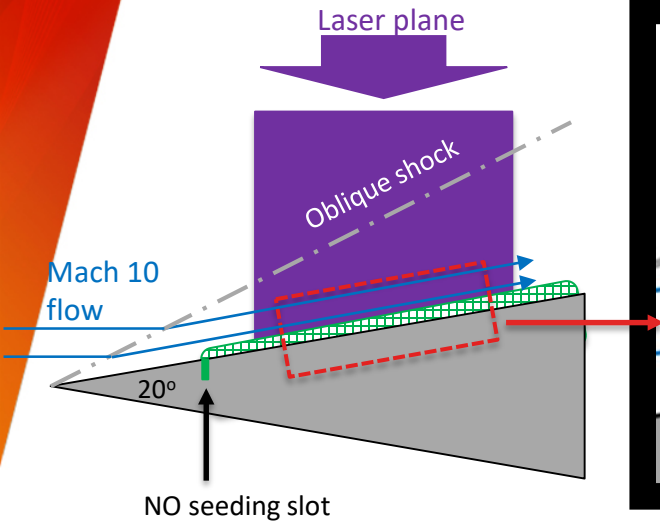


Reproduced from Arisman *et al.*, 2015

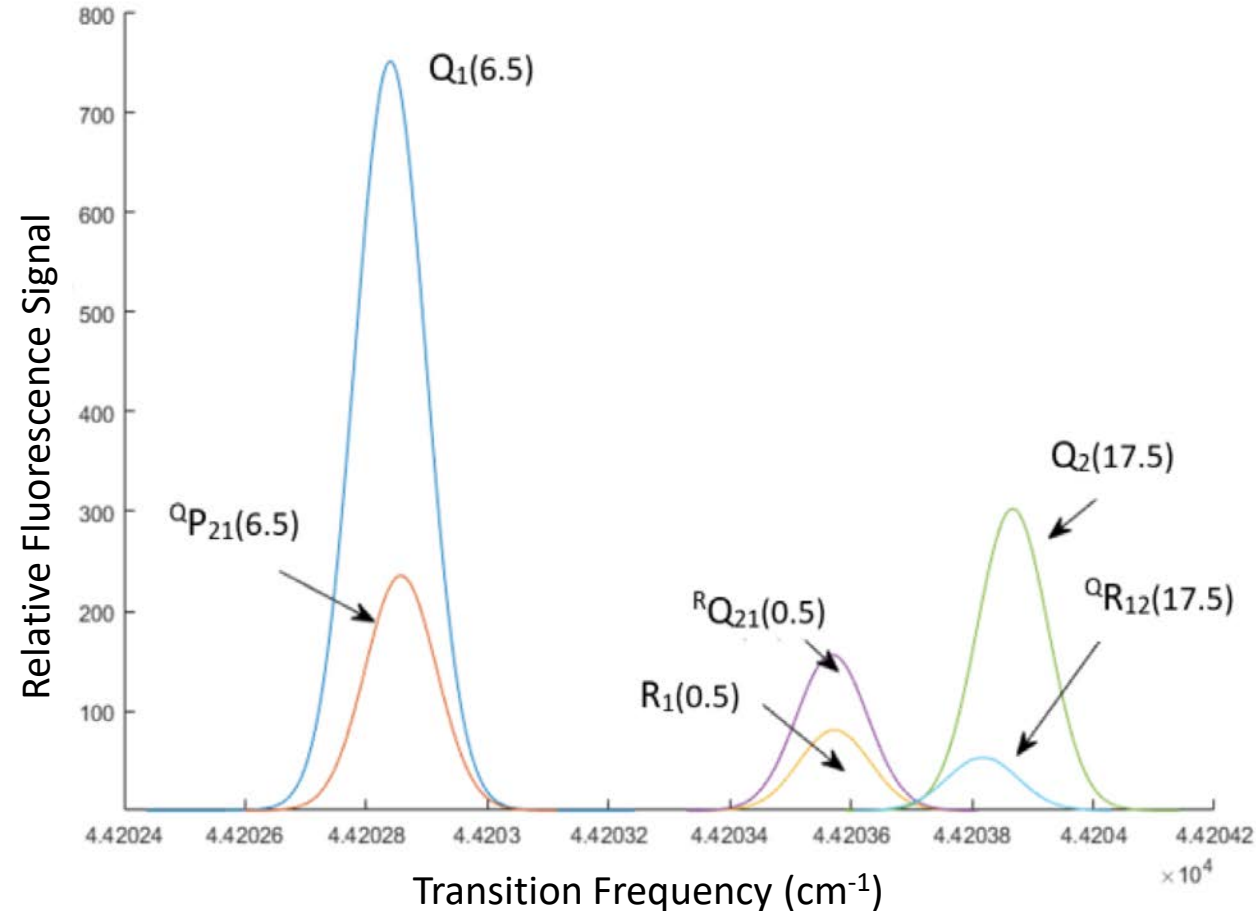
Experimental Design – Laser Set-Up



Experimental Design - Images & Spectra



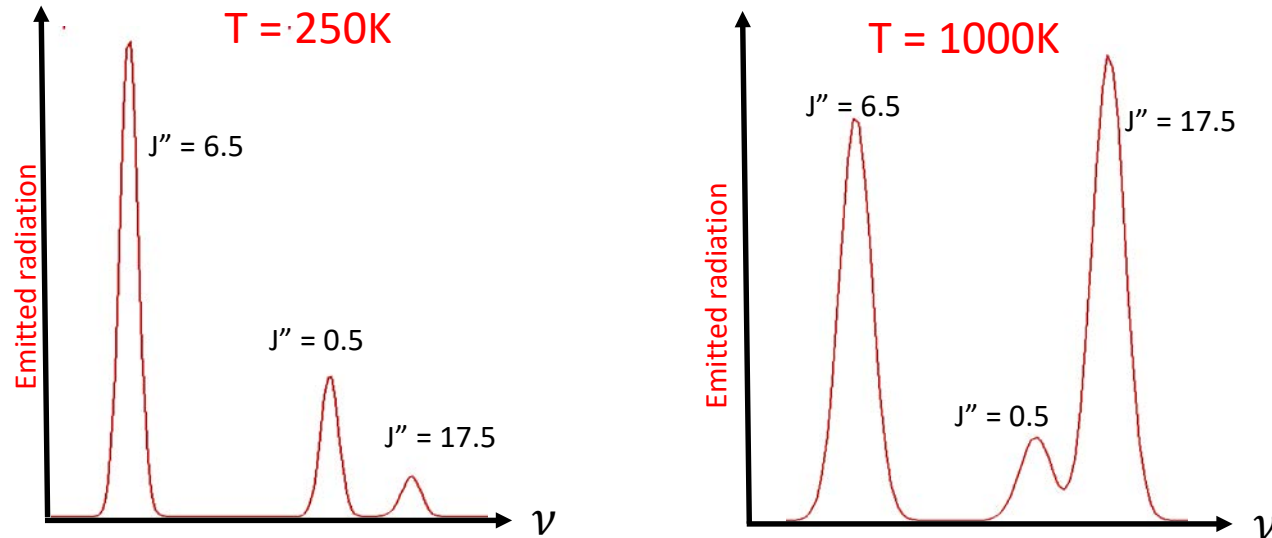
Experimental Design – Transitions



- 6 transitions were excited in this experiment
- These transitions were overlapped, forming 3 transition pairs

Analysis Methods - Temperature effects on nitric oxide transitions

- The amount of emitted radiation from each transition is sensitive to temperature:
 - Spectral width: Doppler broadening
 - Relative amplitudes: Boltzmann fraction



Note: Spectra generated using *LifBase*

Ratio Thermometry from LIF Signal Equation

$$S_f = \chi N_T B_{12} \frac{F_b}{Z} I G \Phi t_{det} V \frac{\Omega}{4\pi} \eta$$

General steady-state fluorescence equation (unsaturated)

$$F_b = (2J'' + 1) \exp \left[-\frac{1}{K_B} \left(\frac{g(v'')}{T_{vib}} + \frac{f''(J'', v'')}{T_{rot}} \right) \right]$$

Main temperature sensitivity from Boltzmann factor (want a range of J'')

$$\frac{S_{f,2}}{S_{f,1}} = \frac{\left(\cancel{\chi N_T} B_{12} \cancel{\frac{F_b}{Z}} \cancel{I G \Phi t_{det} V} \cancel{\frac{\Omega}{4\pi} \eta} \right)_2}{\left(\cancel{\chi N_T} B_{12} \cancel{\frac{F_b}{Z}} \cancel{I G \Phi t_{det} V} \cancel{\frac{\Omega}{4\pi} \eta} \right)_1} = \frac{(B_{12} F_b G)_2}{(B_{12} F_b G)_1}$$

Ratio of 2 transitions

$$S_f = \underbrace{\left(\chi N_T I \frac{\Phi}{Z} t_{det} V \frac{\Omega}{4\pi} \eta \frac{4 \ln(2)}{\pi [\Delta_D^2 + \Delta_L^2]} \right)}_{W_A} B_{12} F_b e^{-4 \ln(2) \frac{\nu - \nu_0}{\Delta_W^2}} = S_{SPM}$$

W_A Scaling factor

Spectral Peak Method (SPM)

Simpler form of LIF equation for thermometry calculations

Other Thermometry Methods Developed and Assessed

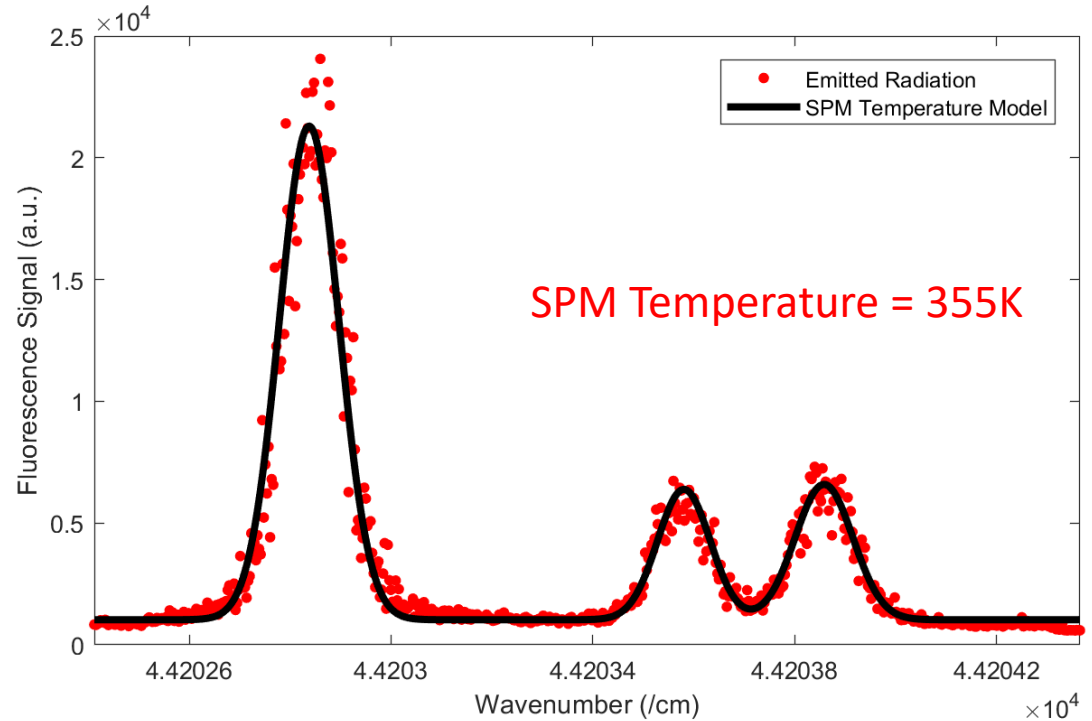
Method	Fit Equation	Description
SPM	$S_{SPM}(k) = W_A B_{12}(k) F_b(k) e^{\frac{-4 \ln(2)(\nu - \nu_O(k) - \delta_s)}{\Delta_W^2}}$	- Fits the temperature dependence in Boltzmann factor F_b
DBM	$S_{DBM}(k) = W_B(k) e^{\frac{-4 \ln(2)(\nu - \nu_O(k) - \delta_s)}{\Delta_D^2 + \Delta_L^2}}$	- Fits temperature dependence in the widths of the transitions, known as Doppler broadening Δ_D
FSFM	$S_{FSFM}(T, k) = \frac{W_A B_{12}(k) F_b(T, k)}{\sqrt{\Delta_D(T)^2 + \Delta_L^2}} e^{\frac{-4 \ln(2)(\nu - \nu_O(k) - \delta_s)}{\Delta_D(T)^2 + \Delta_L^2}}$	- Fits for temperature dependence of both F_b and Δ_D
SPM _{WCM}	$SPM_{WCM}(k) = \frac{\gamma_{us}^2}{\gamma_s^2(k)} W_A B_{12}(k) F_b(k) e^{\frac{-4 \ln(2)(\nu - \nu_O(k) - \delta_s)}{\Delta_W^2}}$	- Uses the SPM algorithm along with a saturation correction method. Width γ_s is measured and used as correction factor
SPM _{MAX}	$SPM_{MAX}(k) = \frac{W_A B_{12}(k) F_b(k)}{B_{12}(k) + B_{21}(k)} e^{\frac{-4 \ln(2)(\nu - \nu_O(k) - \delta_s)}{\Delta_W^2}}$	- Uses SPM algorithm along with a saturation correction method. Maximum saturation is assumed (Danehy 2015).

- Fit spectra for temperature using 5 different models

Temperature fit models:

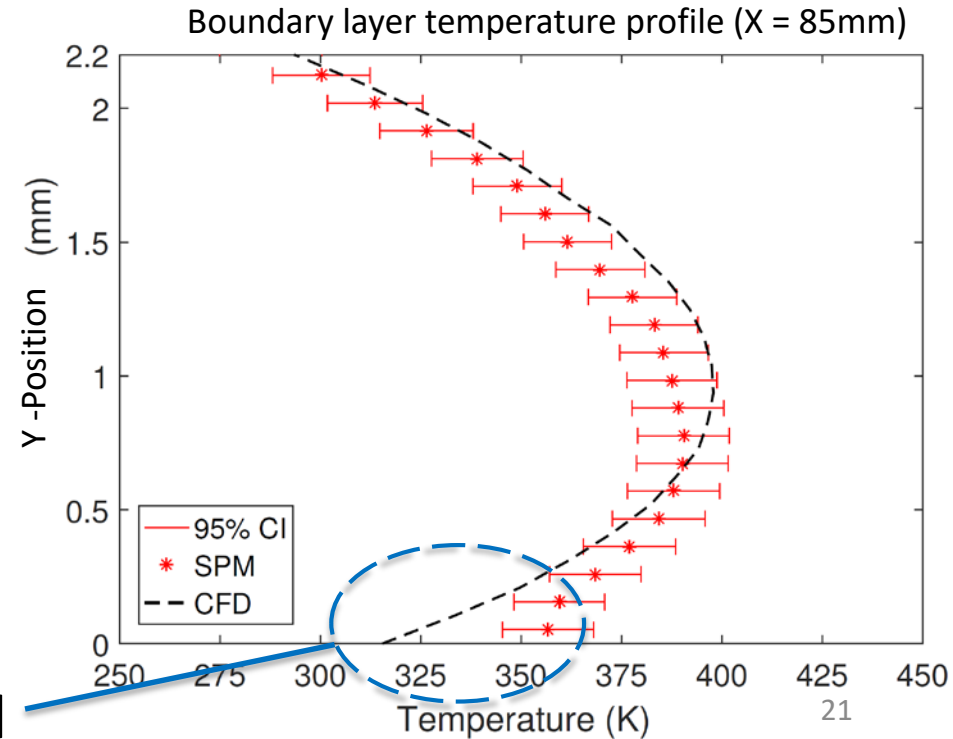
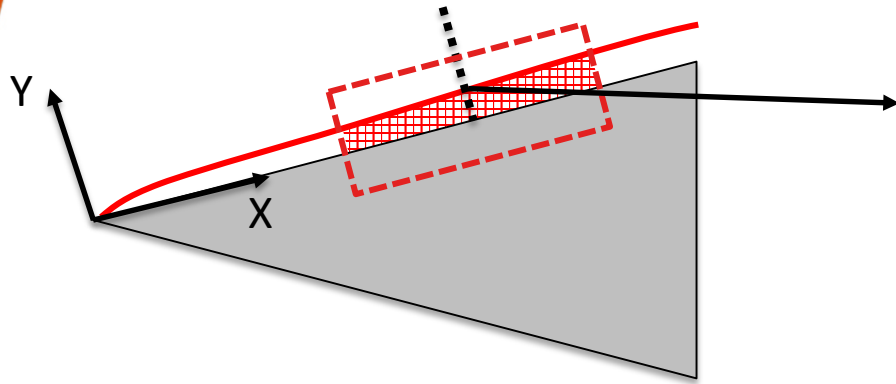
- SPM
- DBM
- FSFM
- SPM_{WCM}
- SPM_{MAX}

Increasing Physics



Results – SPM temperature measurement

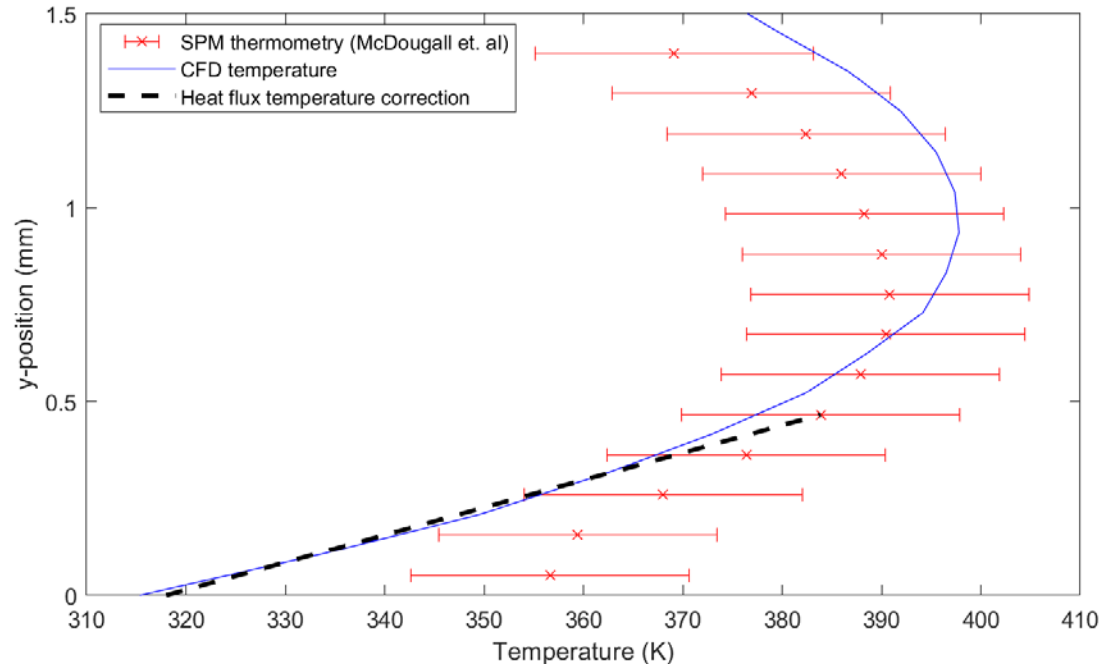
$$S_{SPM}(k) = W_A B_{12}(k) F_b(k) e^{\frac{-4 \ln(2)(\nu - \nu_O(k) - \delta_s)}{\Delta_W^2}}$$



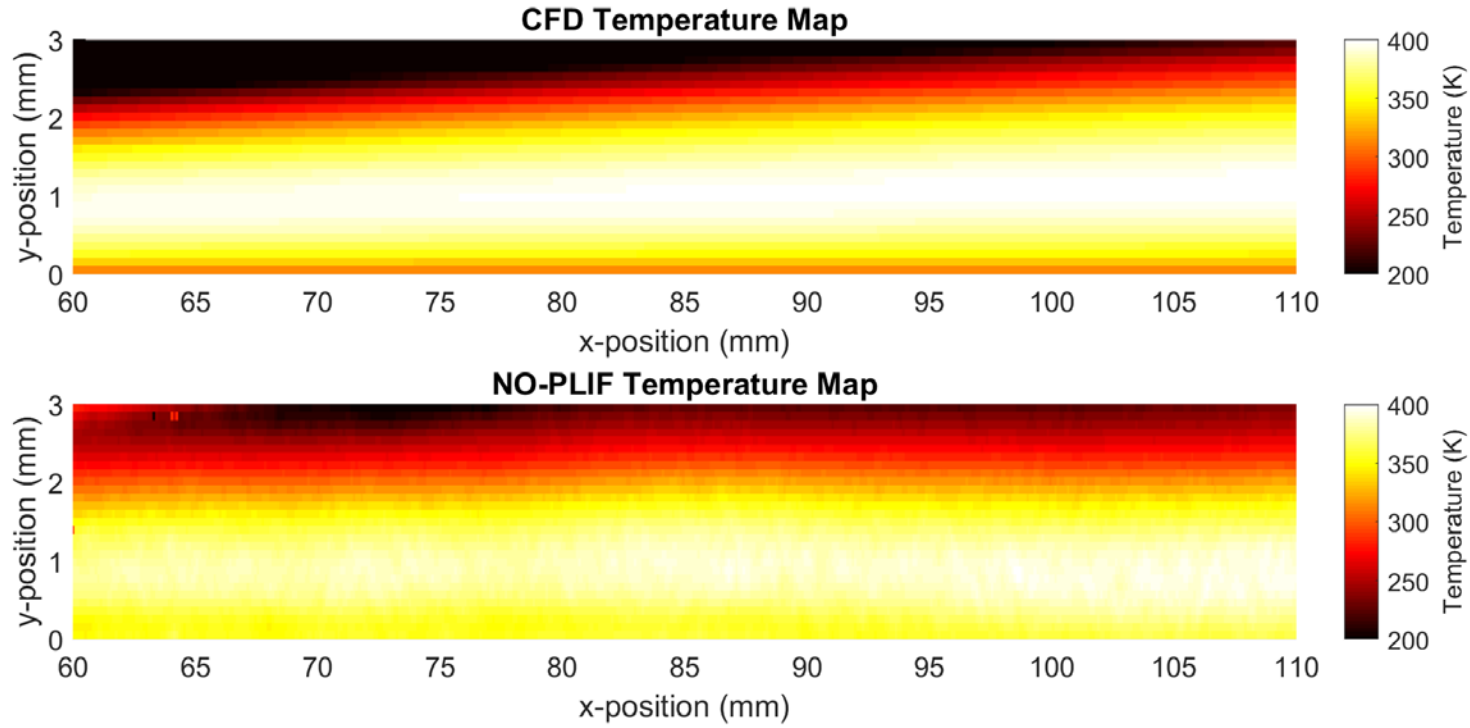
Large discrepancy at the wall

Near Surface Temperature Correction

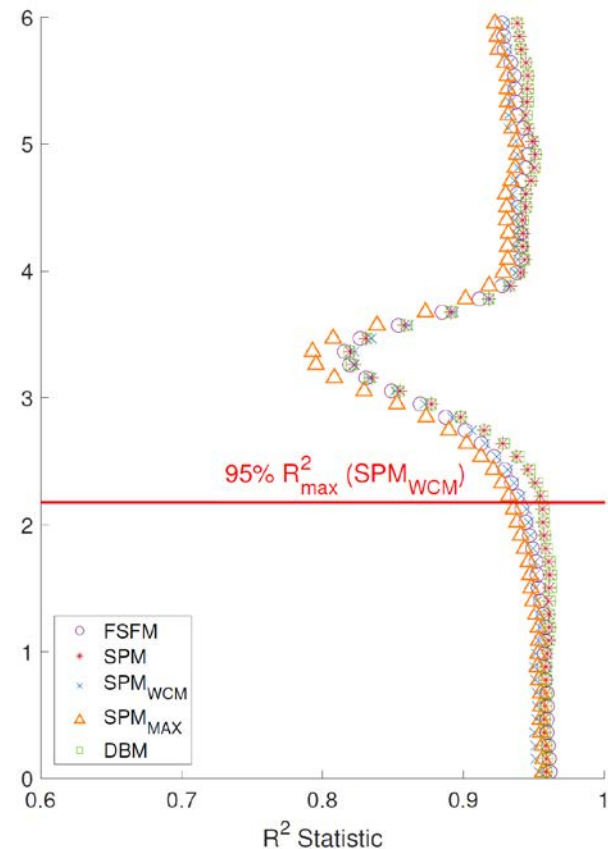
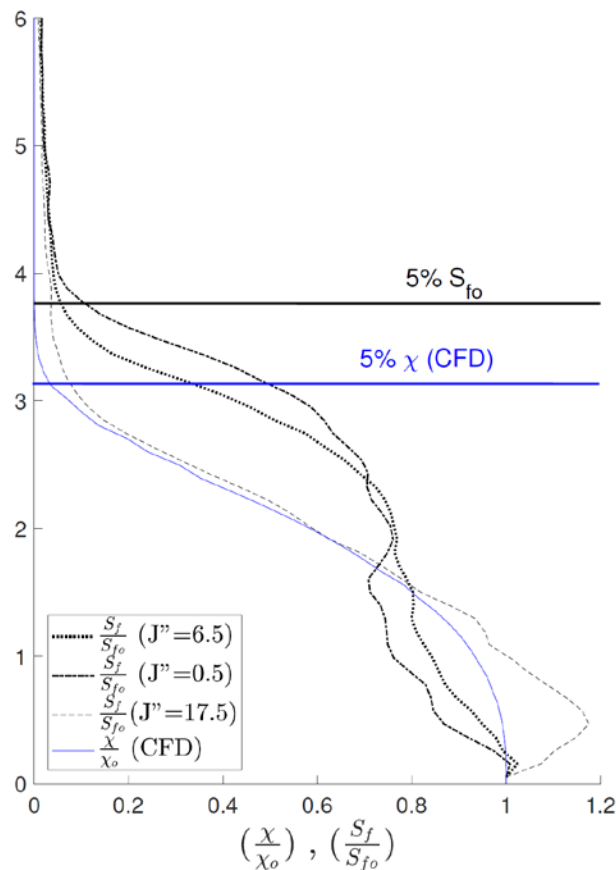
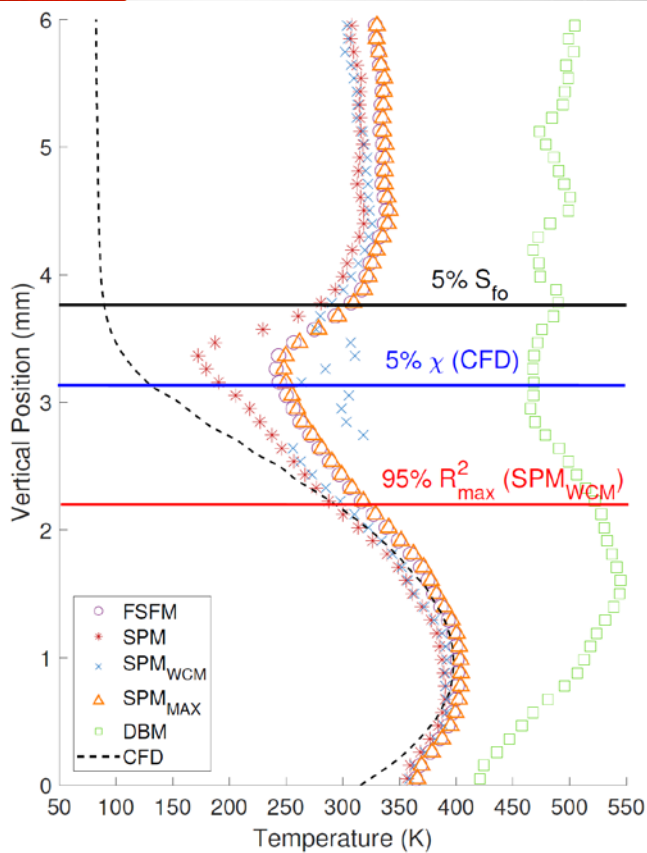
- McDougall *et. al.*, 2018.
 - Method to correct for surface temperature using NO-PLIF heat flux measurement:



Comparison of Temperature from Experiment (SPM) and CFD



Results – All Methods at x=85 mm



Boundary Layer Region	Temperature Relative Error Range (%)
$y < 0.3\text{mm}$	7.7 – 15.2
$0.3\text{ mm} < y < 2.2\text{ mm}$	3.5 – 4.5
$y > 2.2\text{ mm}$	Unquantifiable

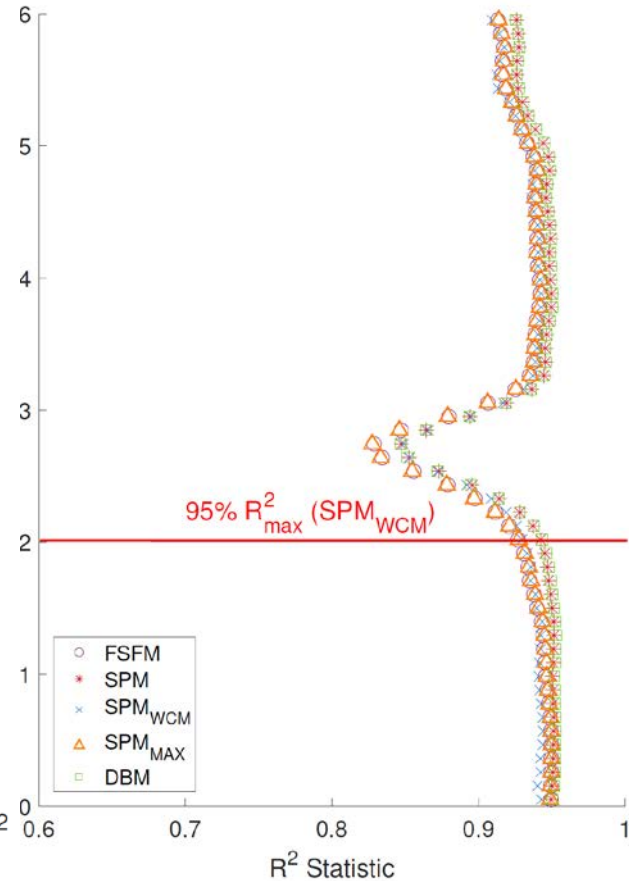
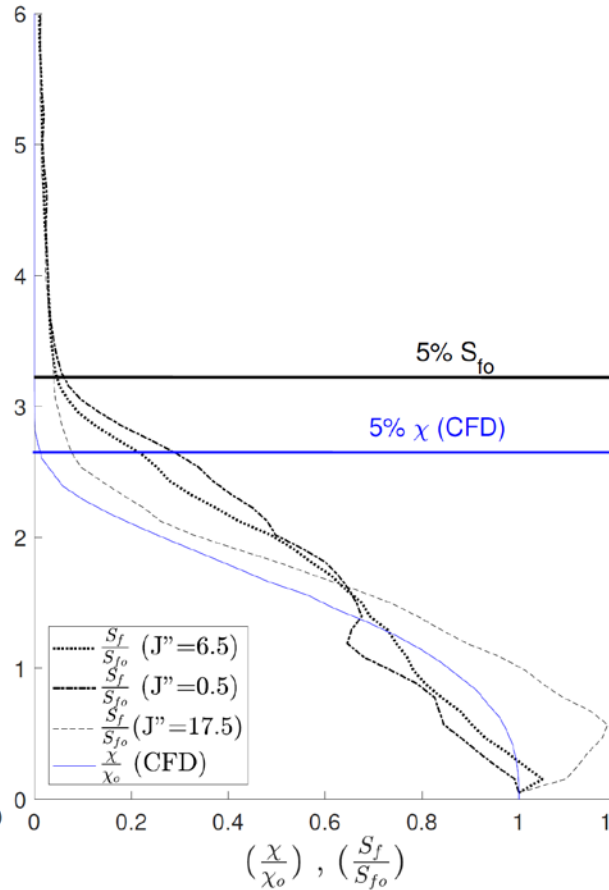
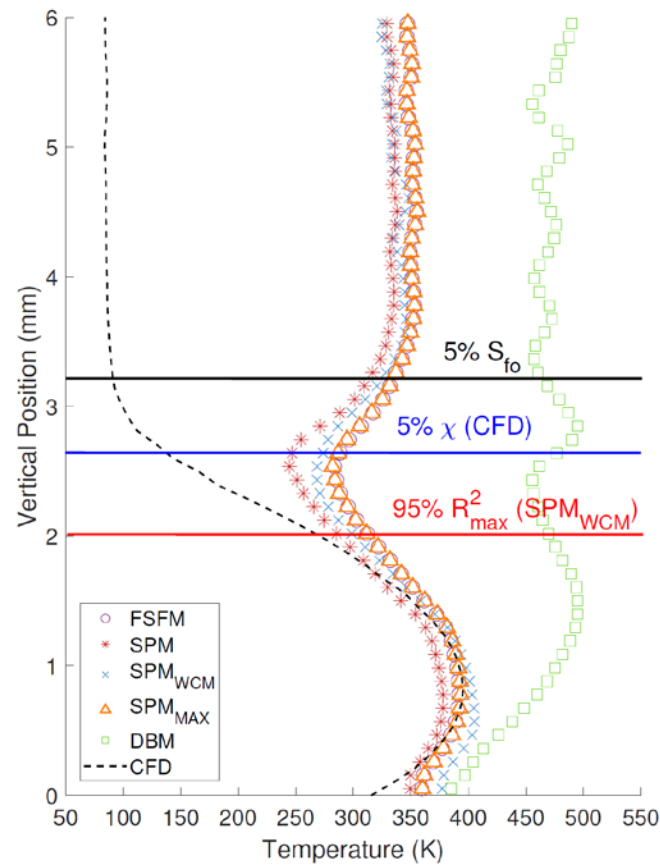
Conclusions and Recommendations for Future Work

- Good agreement with CFD in most of boundary layer
 - Discrepancy at wall
 - Discrepancy at BL edge
- Fluorescence reflection of off wind-tunnel walls is potential source of error
- More detailed uncertainty/sensitivity analysis required (e.g., saturation, absorption, and surface temperature)
- Independent surface temperature measurement is desired (e.g., TSP)
- Multiple runs with varying laser energy would be helpful in addressing saturation effects
- Extract additional quantities from the PLIF data (e.g., mole fraction, heat flux, pressure)

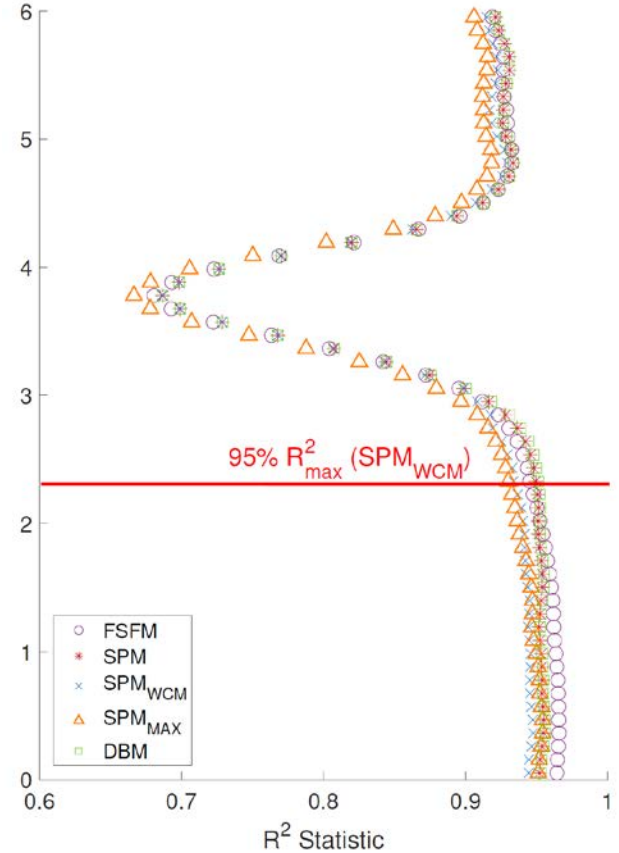
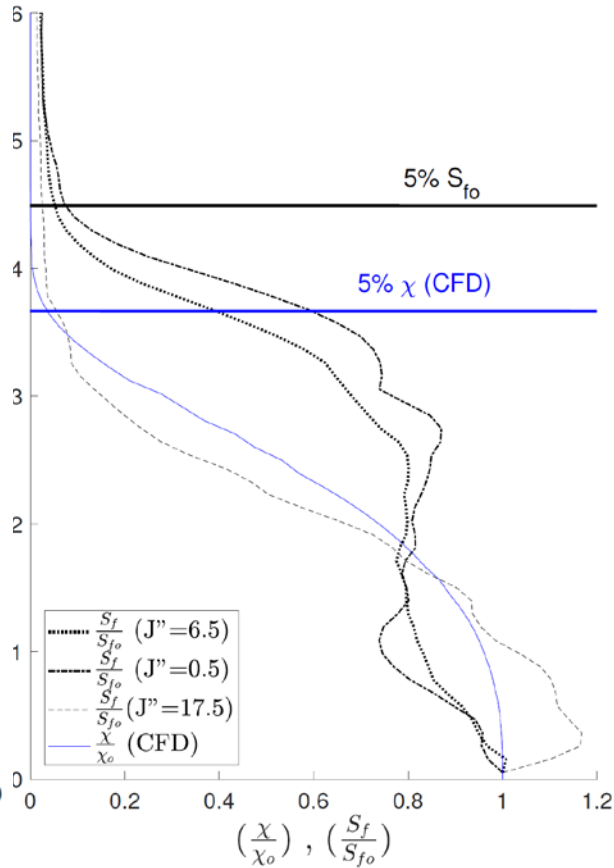
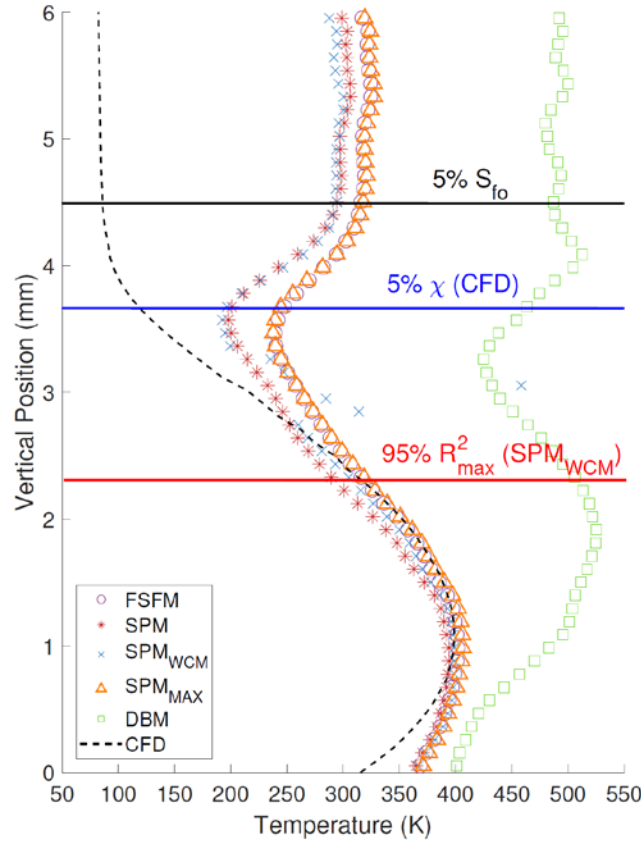
- NASA Langley Research Center
- Natural Sciences and Engineering Research Council of Canada (NSERC)

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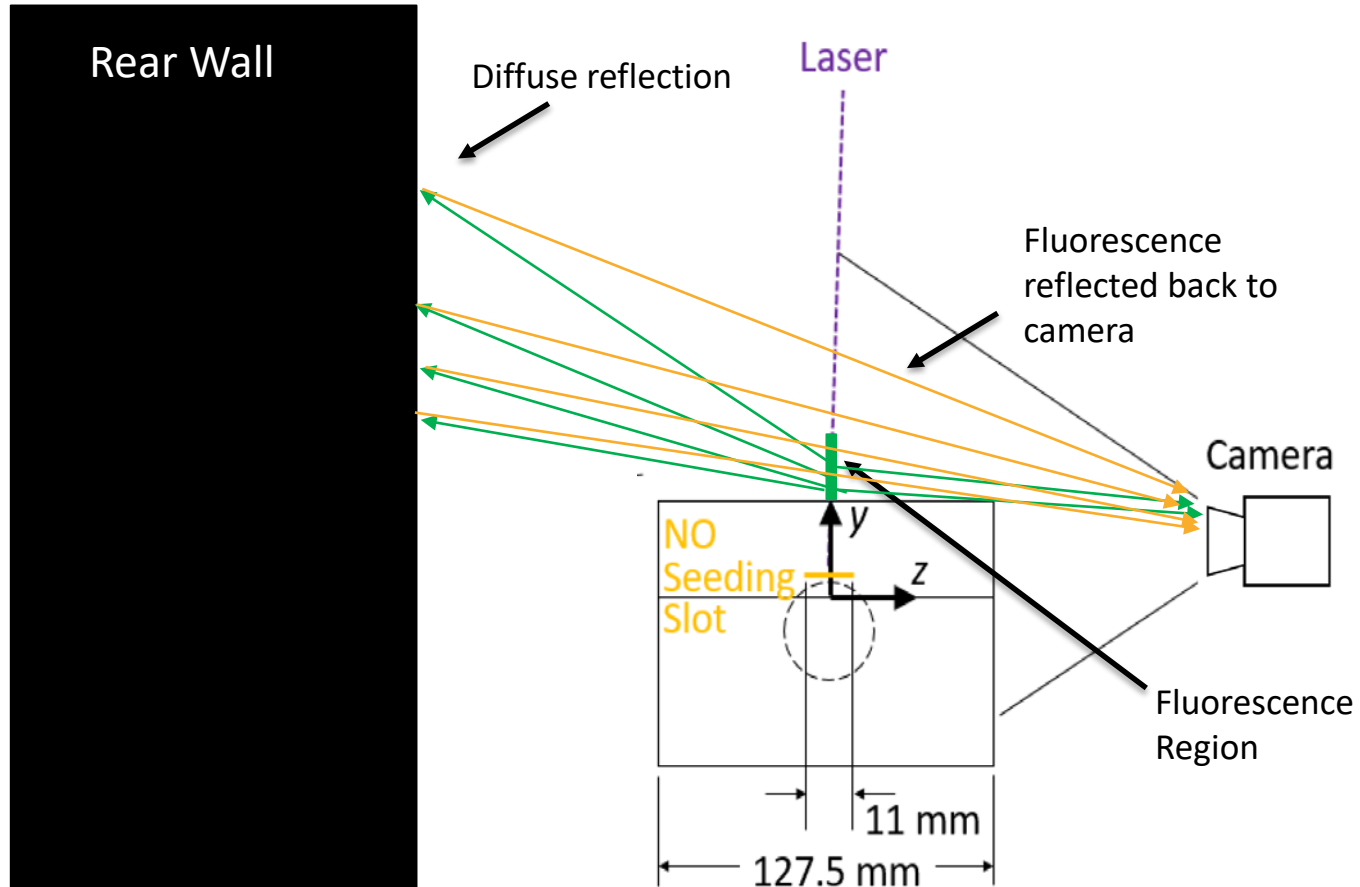
Backup – Profile x=60 mm



Backup – Profile x=110 mm



Backup - Fluorescence Reflection as Potential Source of Error



Analysis Methods - Model Descriptions

- Spectral Peak Method (**SPM**)
 - Based on Palma 1999.
 - Fits temperature dependence in the Boltzmann fraction term in the fluorescence equation.
- Doppler Broadening Method (**DBM**)
 - Based on Inman *et. al.* 2013.
 - Fits the temperature dependence in the Doppler broadening term in the fluorescence equation.
- Full Spectra Fit Method (**FSFM**)
 - Based on Palma 1999, and Inman *et. al.* 2013.
 - Combines the theory behind the above methods.
- SPM – Width Correction Method (**SPM_{WCM}**)
 - Based on Palma 1999.
 - SPM with saturation correction by measurement of relative width differences.
- SPM – Maximum Saturation Method (**SPM_{MAX}**)
 - Based on Palma 1999, and Danehy *et. al.* 2015.
 - WPM with maximum saturation assumed.

Backup – Fluorescence Equation and Nomenclature

Fluorescence Equation:

$$S_f = \frac{1}{1+s} \chi N_T B_{12} F_B I G \Phi t_{det} V \frac{\Omega}{4\pi} \eta$$

Variables

A_e	=	Einstein A coefficient (s^{-1})
B_{12}	=	Einstein absorption B coefficient (cm/J)
B_{21}	=	Einstein emission B coefficient (cm/J)
c	=	speed of light (m/s)
F_B	=	Boltzmann fraction
F_b	=	Boltzmann factor
f	=	rotational energy
G	=	spectral overlap interval (cm^{-1})
g	=	vibrational energy
I	=	laser irradiance (W/cm^2)
J''	=	rotational quantum number
k	=	transition index
K_B	=	Boltzmann constant (J/K)
m	=	mass (kg)
N_T	=	total population per unit volume (cm^{-3})
P	=	pressure (Pa)
Q	=	collision quenching ($1/s$)
R^2	=	R^2 statistic

S_f	=	fluorescence signal
S_{fo}	=	fluorescence signal on surface
s	=	saturation parameter
T	=	temperature (K)
t_{det}	=	camera detection time (s)
v	=	velocity (m/s)
v''	=	vibrational quantum number
V	=	volume probed by laser (cm^{-3})
W_A	=	FSFM, SPM, SPM_{WCM} and SPM_{MAX} scaling constant
W_B	=	DBM scaling constant
x	=	horizontal position parallel to wedge surface (mm)
y	=	vertical position normal to wedge surface (mm)
Z	=	partition function
Δ_D	=	Doppler broadening width (cm^{-1})
Δ_L	=	laser linewidth (cm^{-1})
Δ_{w_A}	=	SPM width variable (cm^{-1})
δ_s	=	wavenumber shift constant
γ_s	=	saturation broadening (cm^{-1})
γ_{us}	=	unsaturated transition width (cm^{-1})
η	=	detector efficiency
χ	=	NO mole fraction
χ_o	=	NO mole fraction on surface
ν_o	=	transition center wavenumber (cm^{-1})
ν	=	wavenumber (cm^{-1})
Φ	=	fluorescence yield
Ω	=	solid angle (sr)