Optical Diagnostic Techniques for High-Speed Flow

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AAE 519: Hypersonic Aerothermodynamics

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Why Do We Need Optical Measurements?

- Hypersonic flows are fast — need high-frequency measurements
  - Physical sensors (e.g. pressure transducers, heat transfer gauges) may only be capable of 10s of kHz to 1 MHz response
  - Photosensors can have frequency response in the 10s of MHz
- Hypersonic measurements may need to occur in harsh environments
  - High enthalpy flows, chemistry/corrosive gases
- Typically the only way to measure chemical species in reacting flows
- Optical measurements can be (mostly) non-intrusive
  - Physical probes (e.g. pitot probe, hot wire, etc.) may disturb the flow and alter the measurement you are making
  - BUT, so can optical measurements

Types of Optical Techniques

- Scattering
  - Rayleigh scattering
  - Raman scattering
- Fluorescence
  - Laser-induced fluorescence (LIF)
  - Molecular-tagging velocimetry (MTV)
- Spectroscopy
  - Coherent anti-Stokes Raman spectroscopy (CARS)

- There are MANY optical techniques out there – the one best suited for an experiment, depends on many factors
- ME 687: Laser Diagnostics for Reacting Flows – taught by Lucht

Scattering Methods

- Light perturbs energy level of molecule to a virtual state
- Molecule relaxes back to:
  - Original state → Rayleigh scattering
  - Higher (e.g., vibrational) state → Stokes Raman scattering
  - Slightly lower energy level (initial state is not a ground state) → anti-Stokes Raman scattering
- Emission of photons with certain energies, analyzed with emission spectra
- Advantages
  - Can use a single laser
  - Laser does not have to have resonance with energy levels
  - Linear process
  - Not sensitive to collisional quenching
- BUT, gives low signal and can be affected by natural luminosity (e.g. combusting flows)

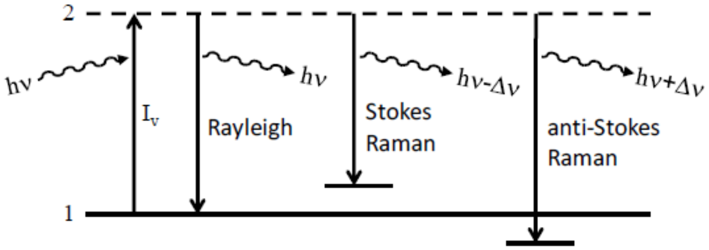


Figure 3.1. Energy level diagram indicating incident radiation, Rayleigh scattering and Raman scattering.

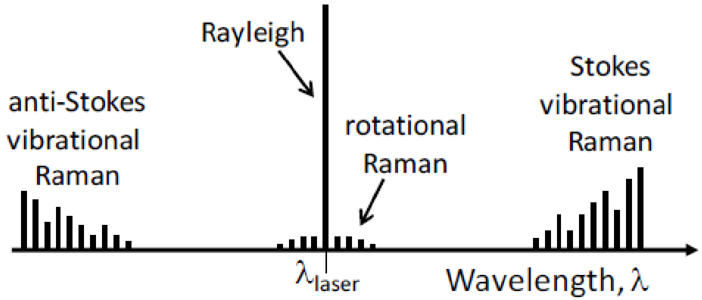
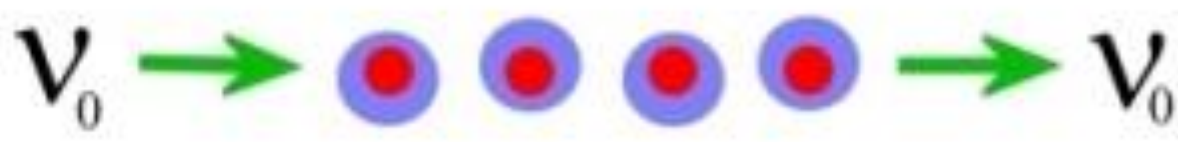


Figure 3.2. Notional Raman/Rayleigh spectra.

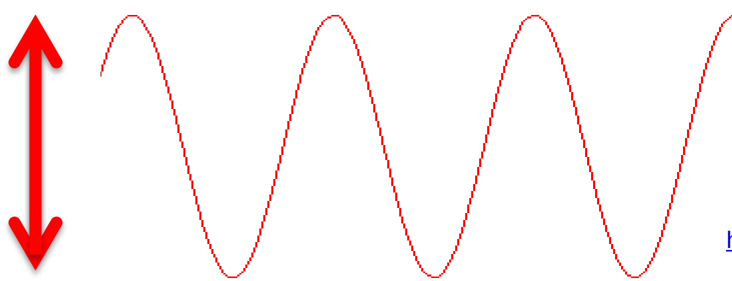
Diagrams from Bathel, Danehy, Cutler VKI lecture

Rayleigh Scattering

- Rayleigh scattering:
  - Electric field causes electron cloud to oscillate with respect to the nucleus: induced dipole



  - An oscillating dipole acts like an antenna: radiates!
    - Radiation is perpendicular to oscillation

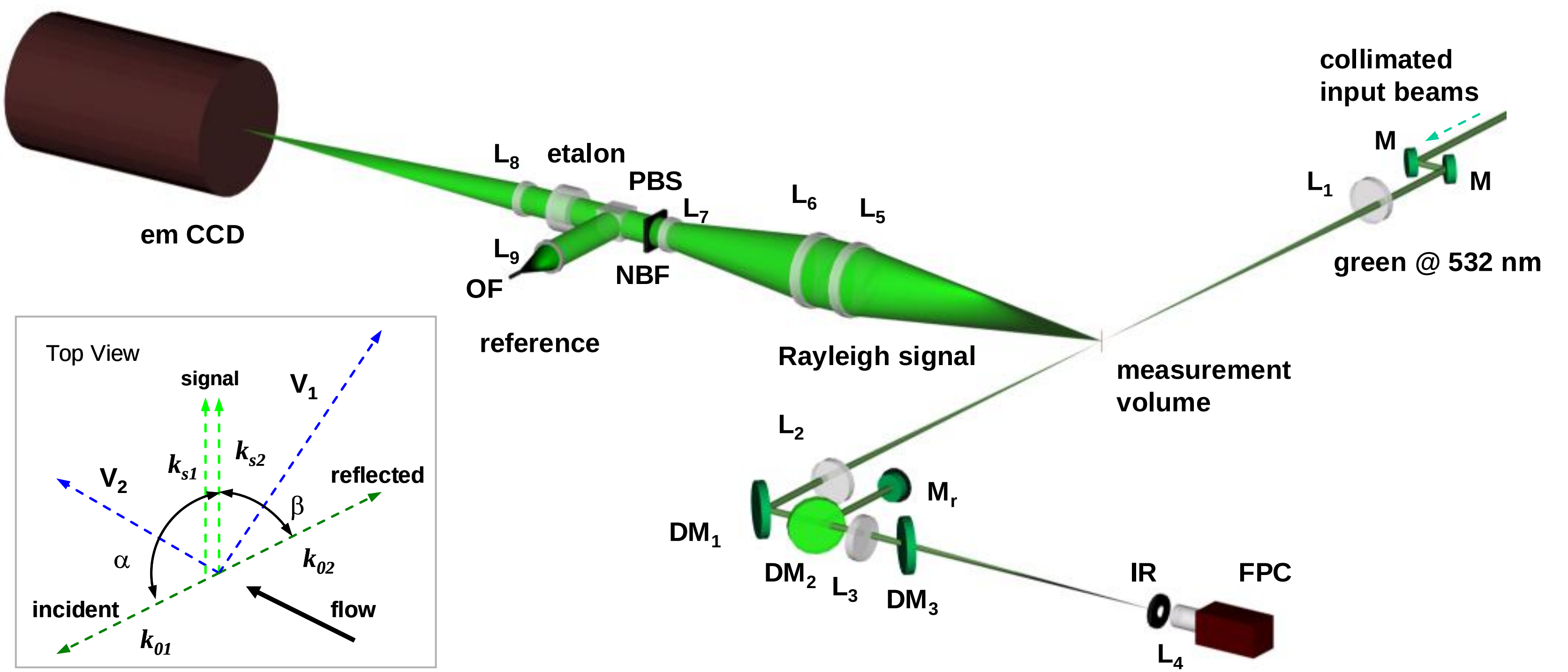


http://www.timkelf.com/Research/ResearchSERS.html

Diagrams from Bathel, Danehy, Cutler VKI lecture

Rayleigh Scattering Velocity Measurements

- Bivolaru et al., AIAA Paper 2008-236
- NASA LaRC Direct Connect Supersonic Combustor Test Facility (DCSCTF) Facility
  - Supersonic jet with combustion chamber (*H_2-air*)
  - M = 1.6, high enthalpies equivalent to M = 5.5 flight



Rayleigh Scattering Velocity Measurements

- Bivolaru et al., AIAA Paper 2008-236
- Velocity: 40 m/s precision in a 1200 m/s flow (~3% precision)

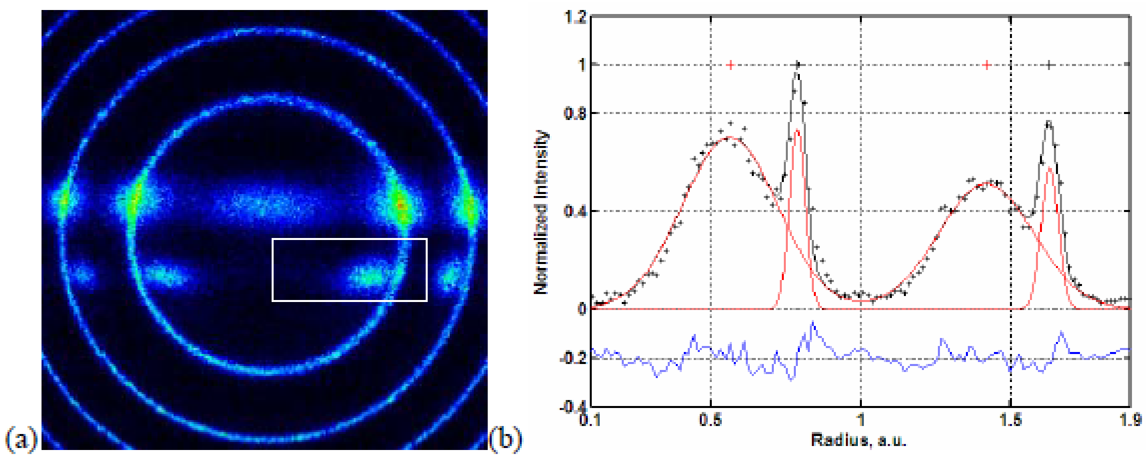
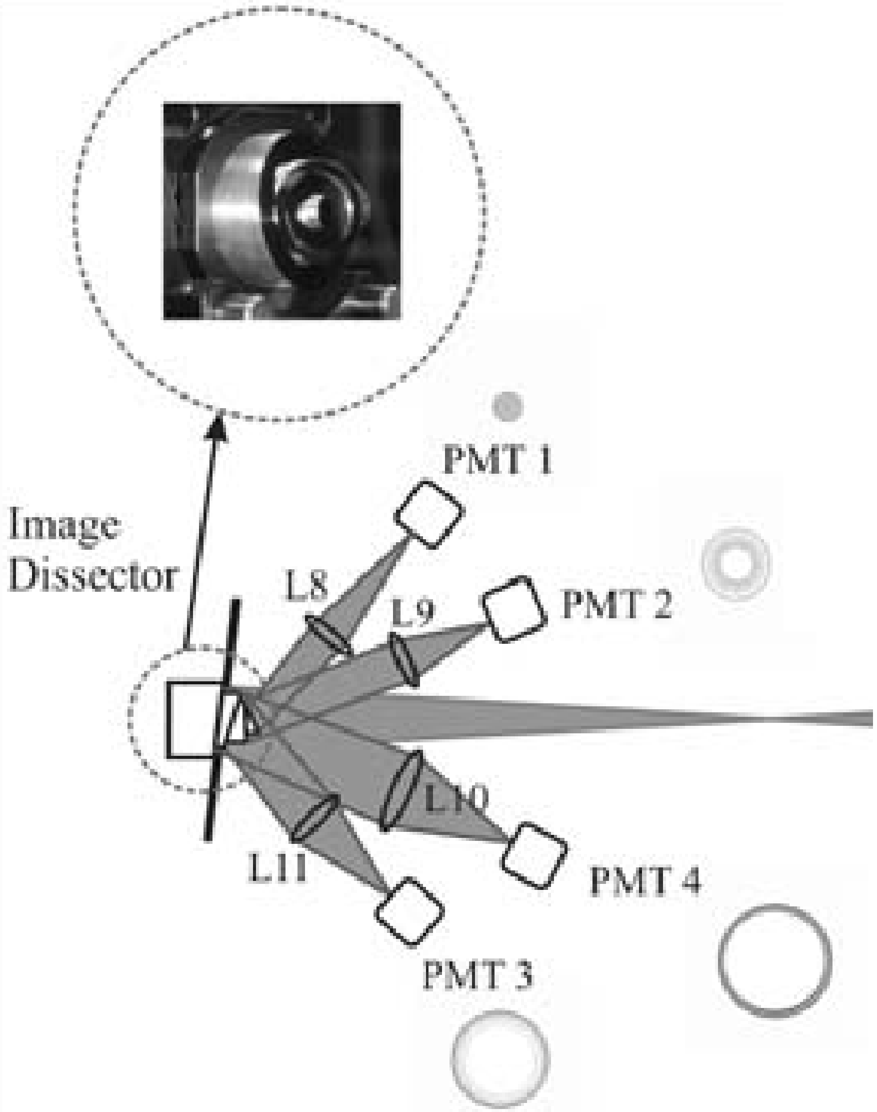
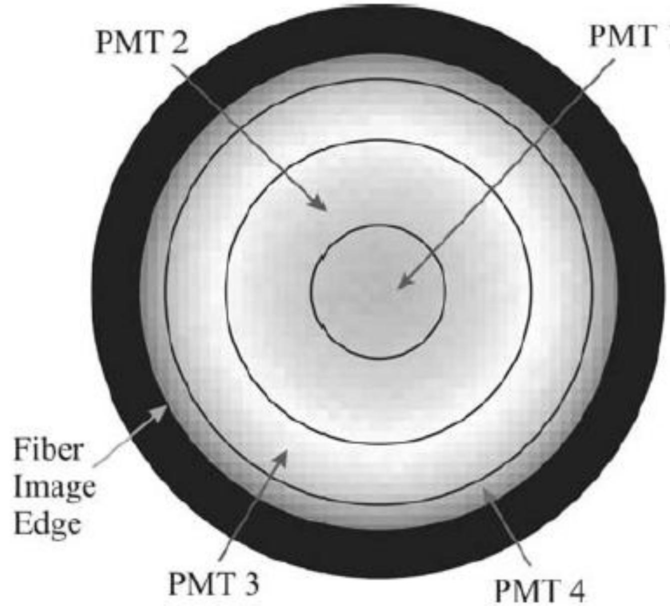


Figure 3.6. (a) Fabry-Perot interferogram of Rayleigh-scattered light obtained by laser beams from two different directions as well as laser-light, resulting in the circular pattern. (b) the linearized Rayleigh-scattered spectrum obtained from the boxed region in (a), showing best fits to the reference and Doppler-shifted light.[173] Reprinted with permission of the authors.

Rayleigh Scattering: T, V, ρ

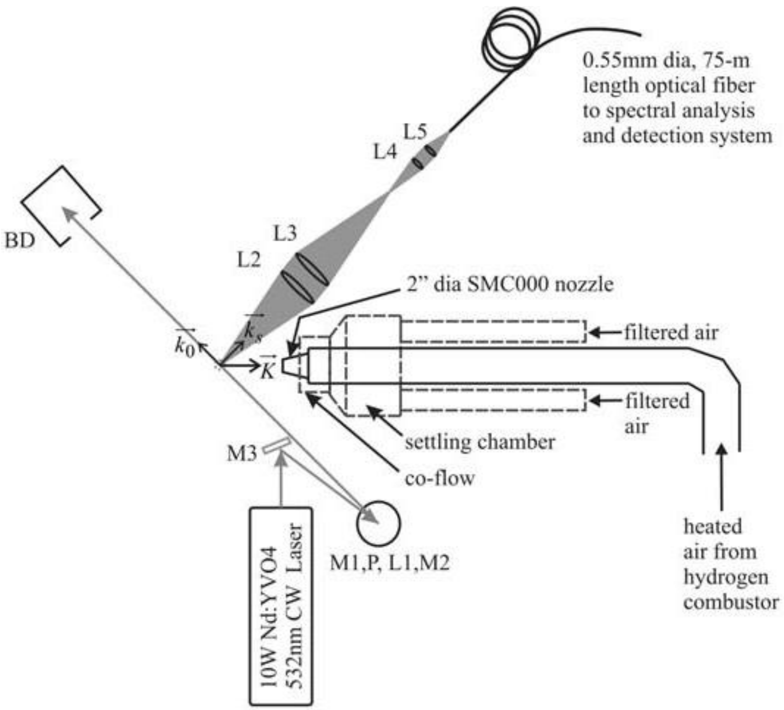


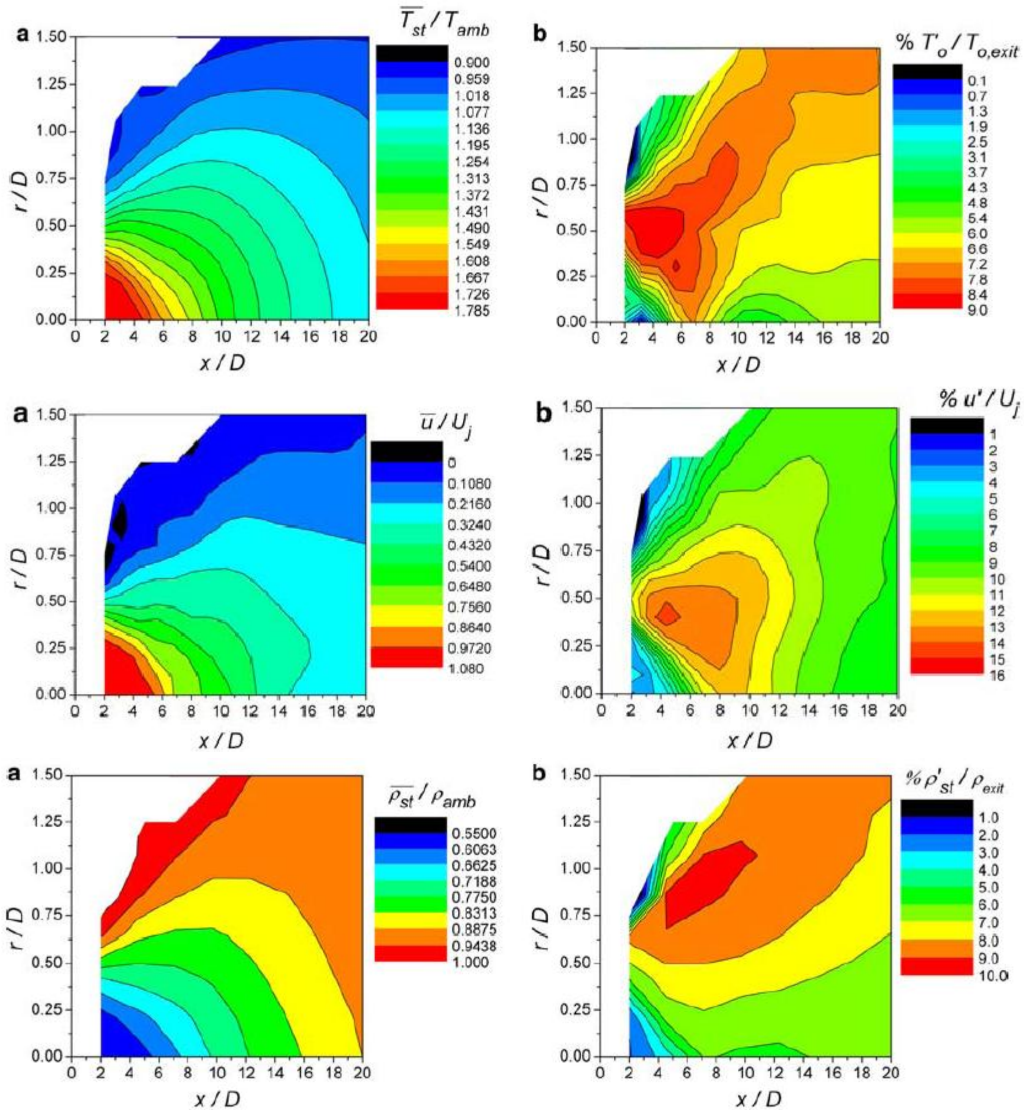


- Continuous laser excitation
  - 10 W at 532 nm
- Fiber optic collection
- Data rate: 10 kHz
- Single point measurement

A. F. Mielke and K. A. Elam. "Dynamic measurement of temperature, velocity, and density in hot jets using Rayleigh scattering." *Experiments in fluids* 47, no. 4-5 (2009): 673-688.

Rayleigh Scattering: T, V, ρ



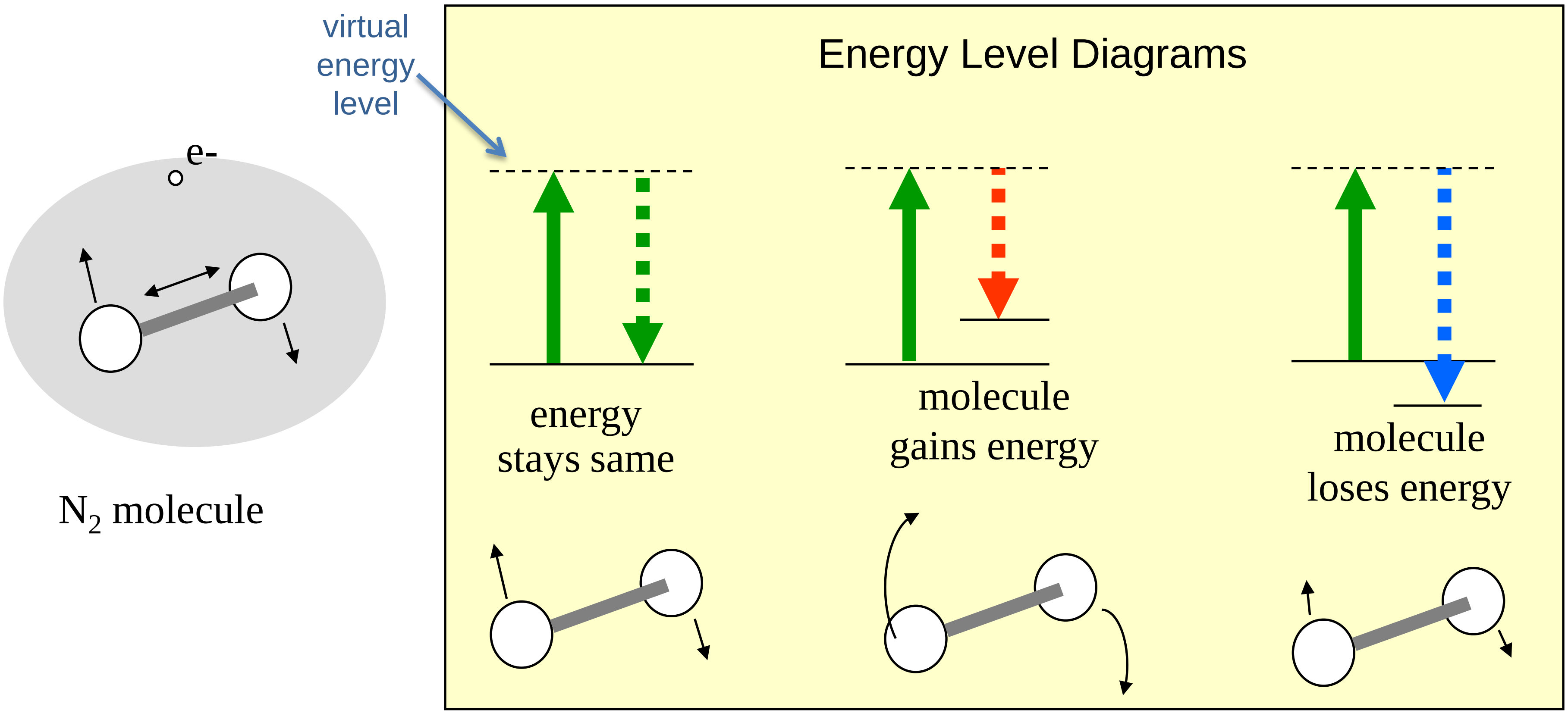


- Heated, 2" (50 mm) diameter axisymmetric near-sonic jet at NASA Glenn Research Center

A. F. Mielke and K. A. Elam. "Dynamic measurement of temperature, velocity, and density in hot jets using Rayleigh scattering." *Experiments in fluids* 47, no. 4-5 (2009): 673-688.

Raman Scattering

- Similar to Rayleigh scattering but molecules gain or lose energy during scattering process
- Raman x1000 lower probability than Rayleigh



Raman Scattering for Species Determination

- Spectra show emission lines in distinct wavelengths
- These correspond to different species, as shown.

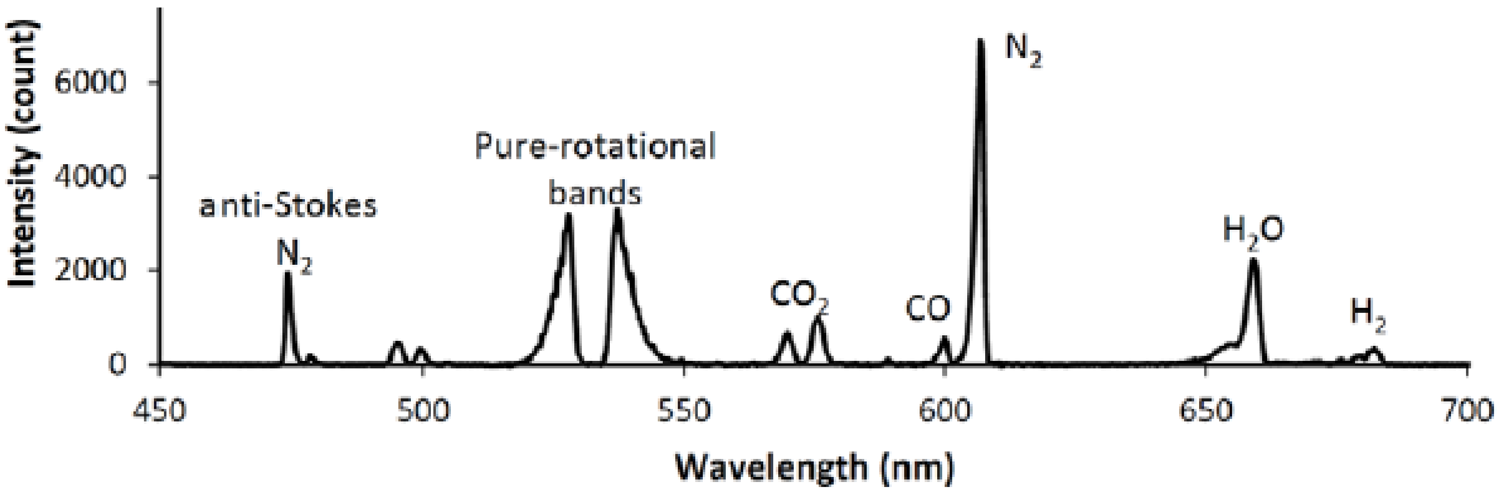
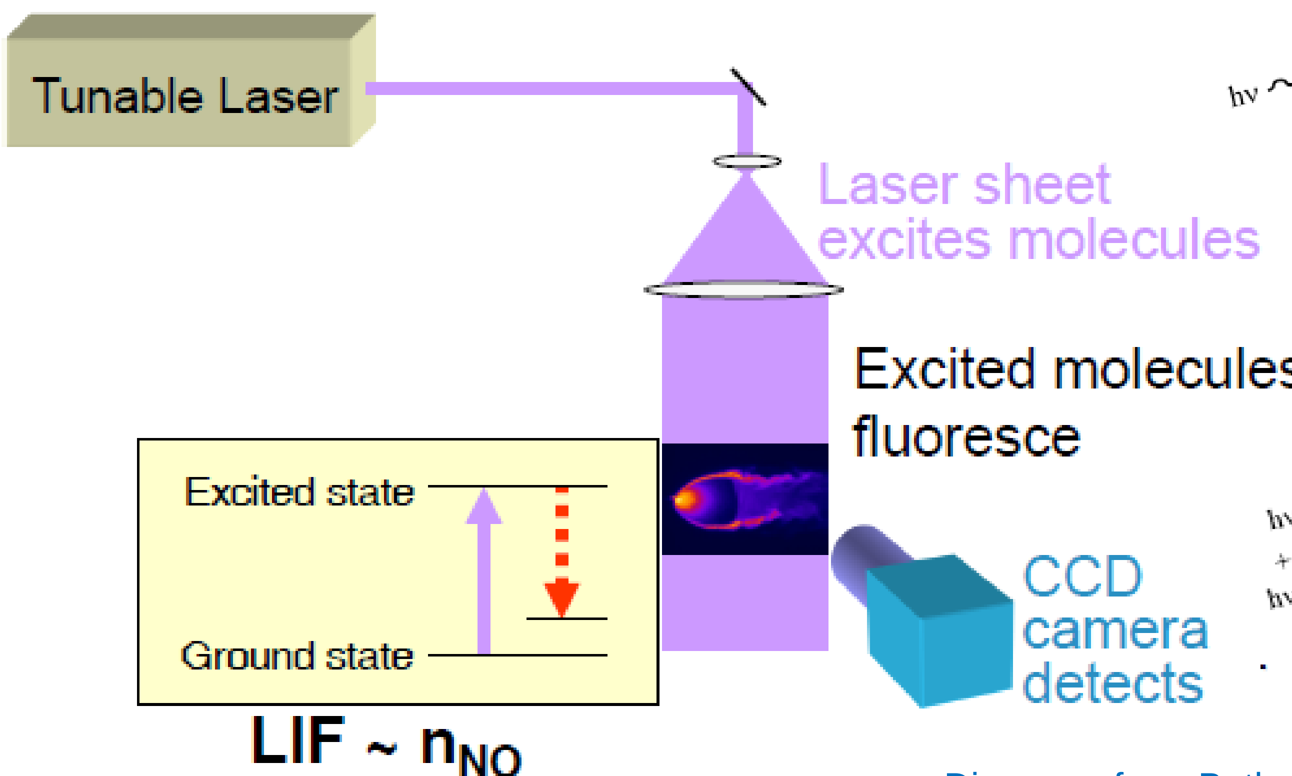
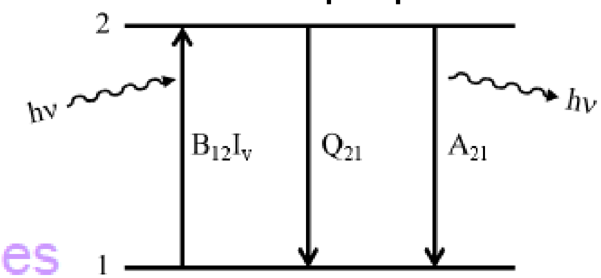


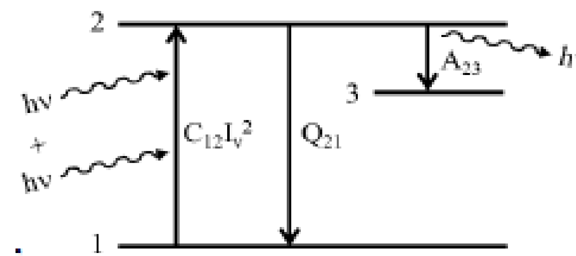
Figure 3.7. Five-hundred-pulse-average Raman spectrum in a high-pressure CH_4 air flame. The excitation laser wavelength was 532 nm. A 532 nm filter blocks Mie, Rayleigh and spurious laser scattering as well as some of the low-rotational-quantum-number rotational Raman lines. A subframe burst gating (SBG) technique was also used to subtract background emission from this spectrum.[179] Figure courtesy of and with permission of J. Kojima, NASA Glenn Research Center.

Fluorescence Techniques

- Planar Laser-Induced Fluorescence
  - Can also have multiple photons, nonlinear
- Measures rotational (requires a ratio of spectra), vibrational (requires a ratio of spectra), translational (from width and shape of spectral lines) temperatures
- LIF signal can also be used to measure velocity, can be combined with Rayleigh and Raman scattering measurements to measure other properties





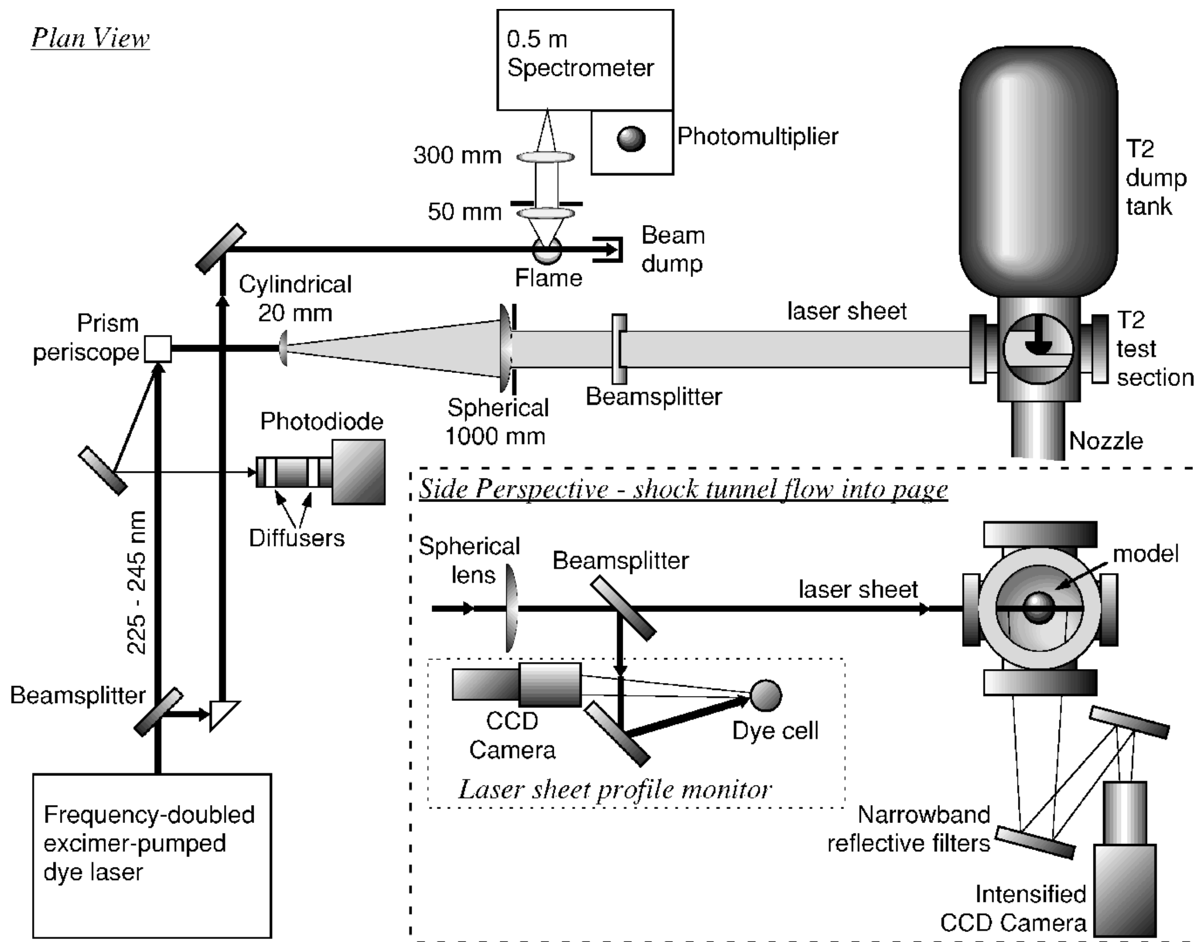


2-photon LIF, 3 level model

Diagrams from Bathel, Danehy, Cutler VKI lecture

PLIF Used to Measure Temperatures

- Vibrational and rotational temperature measurements in nozzle exit flow in T2 shock tunnel at Australian National University (ANU) in Canberra
- Air, N2/O2 mix (~98%/2%)
- M ~ 7.74
- h ~ 5.58 MJ/kg



From Palma et al, AIAA Journal, Vol. 41, No. 9, pp. 1722-1732

PLIF Used to Measure Temperatures

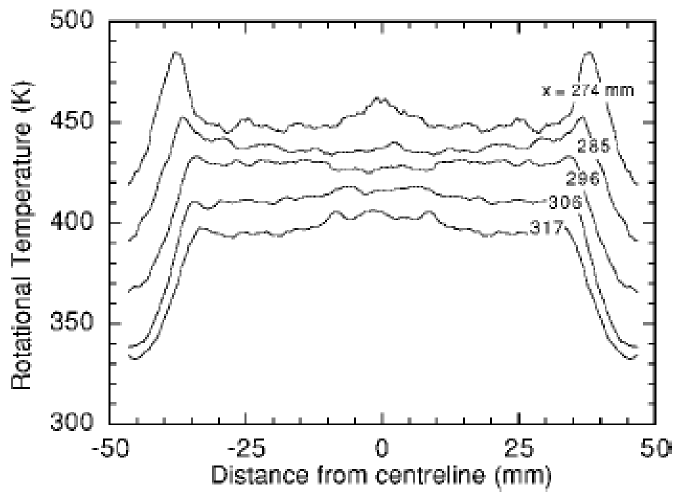


Fig. 7 Cross sections through the rotational temperature map perpendicular to flow direction at various distances from nozzle throat.

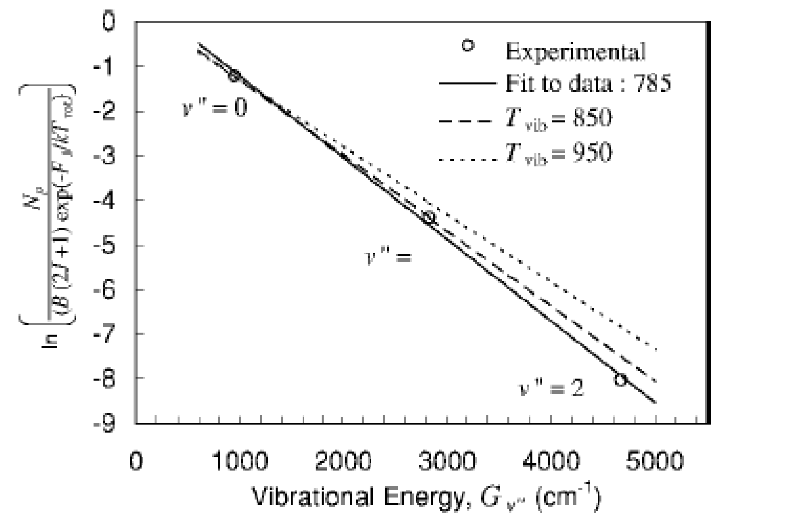


Fig. 9 Boltzmann plot obtained by plotting Eq. (12) vs $G_{v''}$. nonlinear camera response results in $v'' = 2$ signal being less than that expected from a straight line fitted to the $v'' = 0$ and 1 signals.

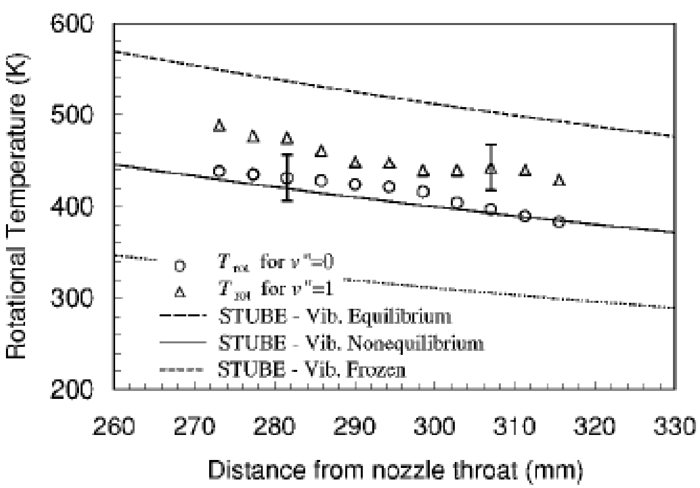


Fig. 8 Rotational temperatures along the centerline of the flow compared with STUBE calculations.

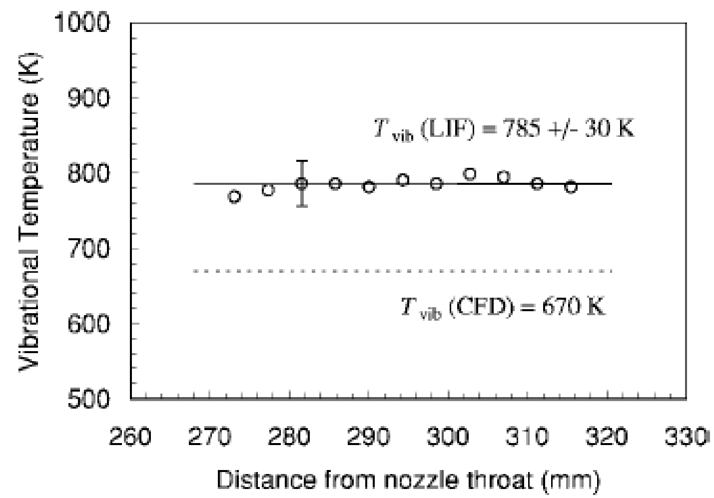
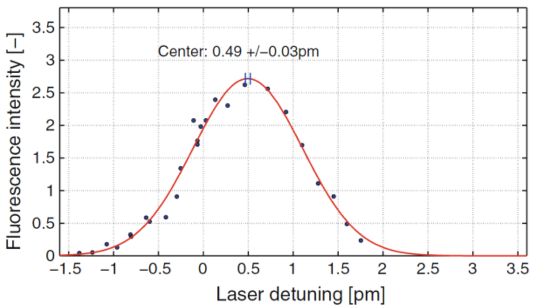


Fig. 10 Vibrational temperatures along the centerline of the flow.

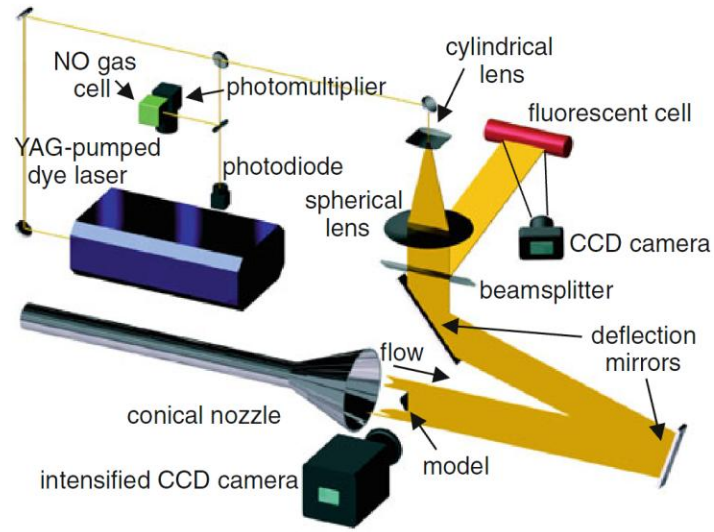
From Palma et al, AIAA Journal, Vol. 41, No. 9, pp. 1722-1732

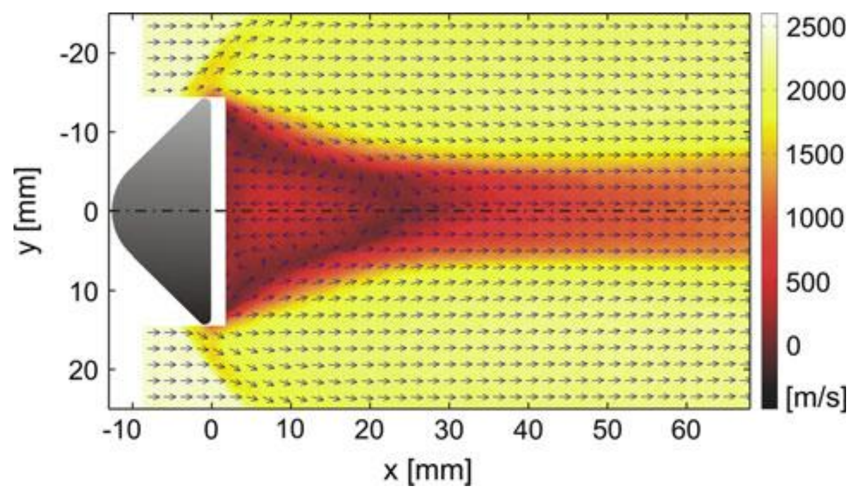
Doppler-based LIF Velocimetry

- Direct laser sheet into flow
- Acquire images with different laser frequencies
  - Measure spectrum at each point



  - Measure from two different directions to get two different velocity components
  - Do need to consider pressure shift
- Fixed frequency (single-shot) schemes also exist but less accurate (see manuscript)



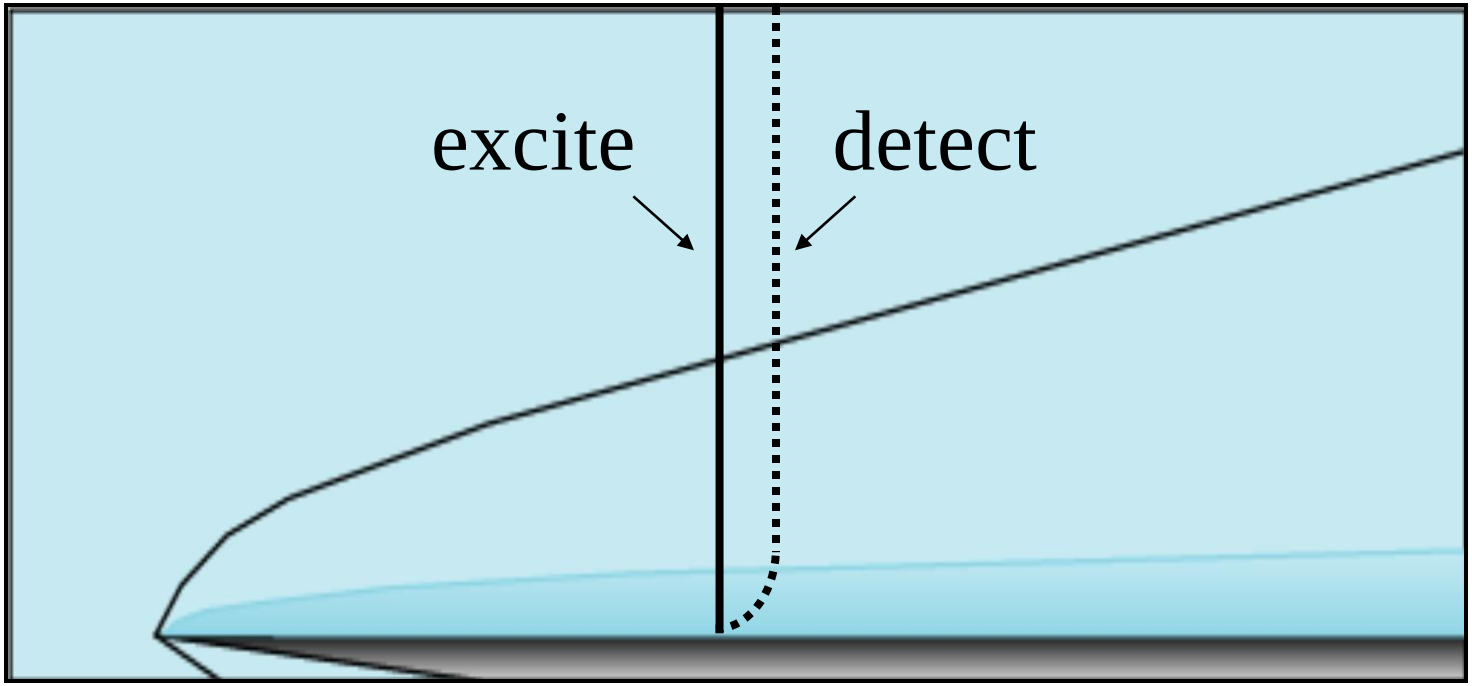


Work done in T-ADFA (Australian Defence Force Academy), UNSW – a free-piston shock tunnel, h ~ 3.8 MJ/kg, air, 2503 m/s freestream

R. Hruschka, S. O'Byrne, and H. Kleine, "*Two-component Doppler-shift fluorescence velocimetry applied to a generic planetary entry probe model*," Experiments in Fluids, 48, pp. 1109-1120, 2010

Slide from Bathel, Danehy, Cutler VKI lecture

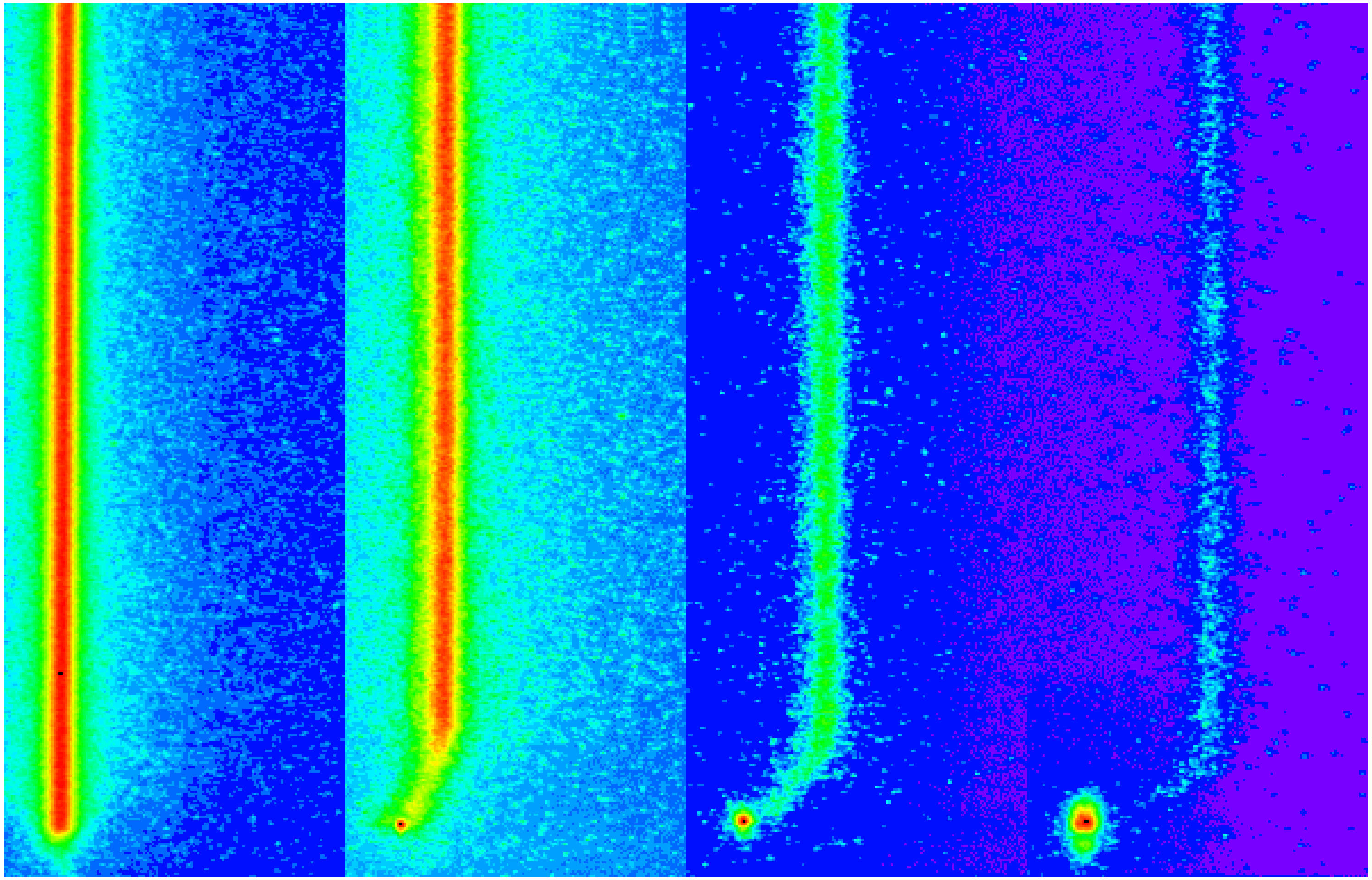
LIF Molecular Tagging Velocimetry (MTV)



- Boundary layer: slow moving gas near surface
  - Important: heat transfer, drag, separation, etc.
- Instantaneous measure of 1 velocity component
  - Can be extended to 2 or 3 components

Diagrams from Bathel, Danehy, Cutler VKI lecture

MTV: Delayed Images



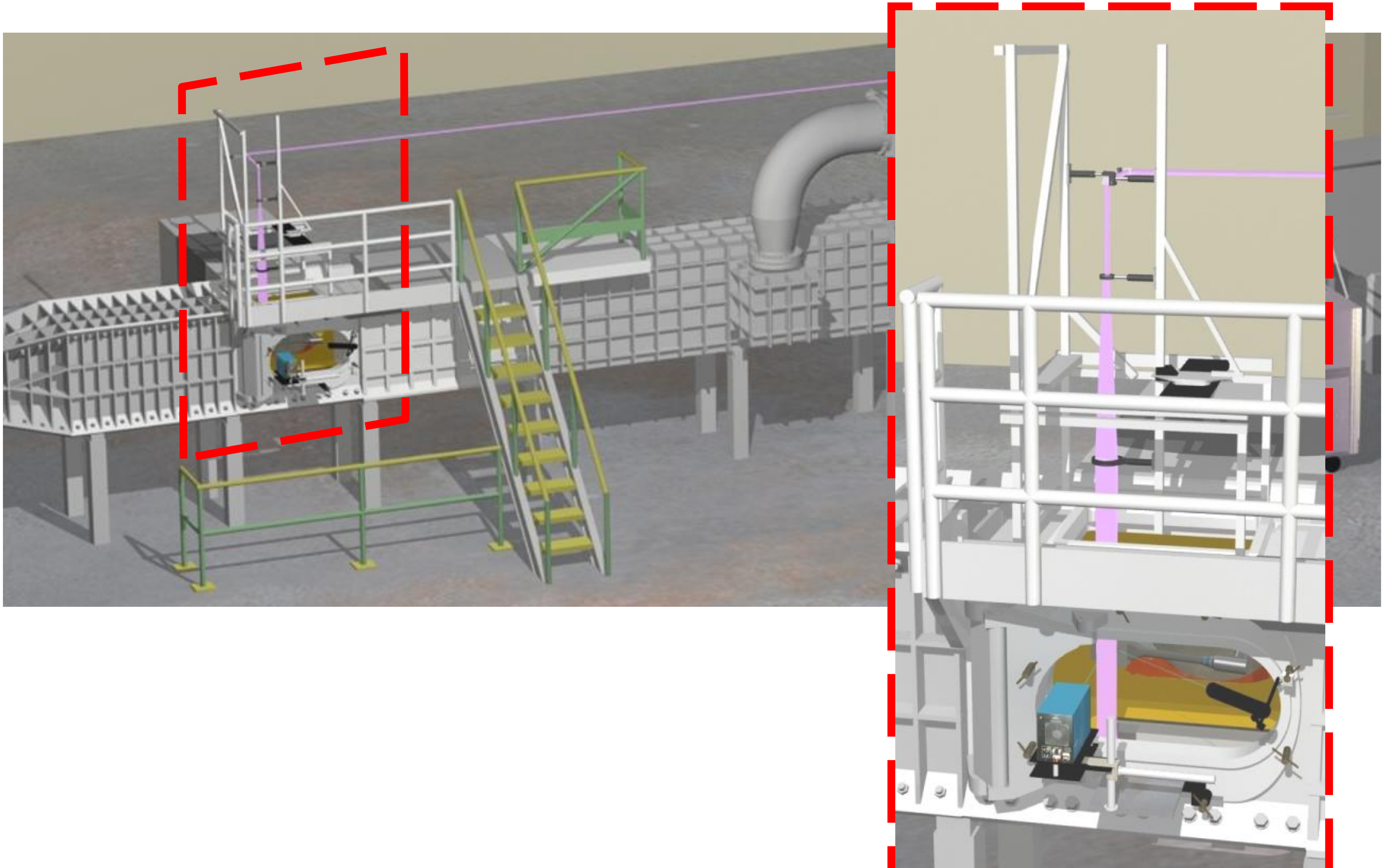
Data taken in T2 at ANU

Delay = 0 | 250 ns | 500 ns | 750 ns | ln(data) shown here

- Measurements performed on successive tunnel runs

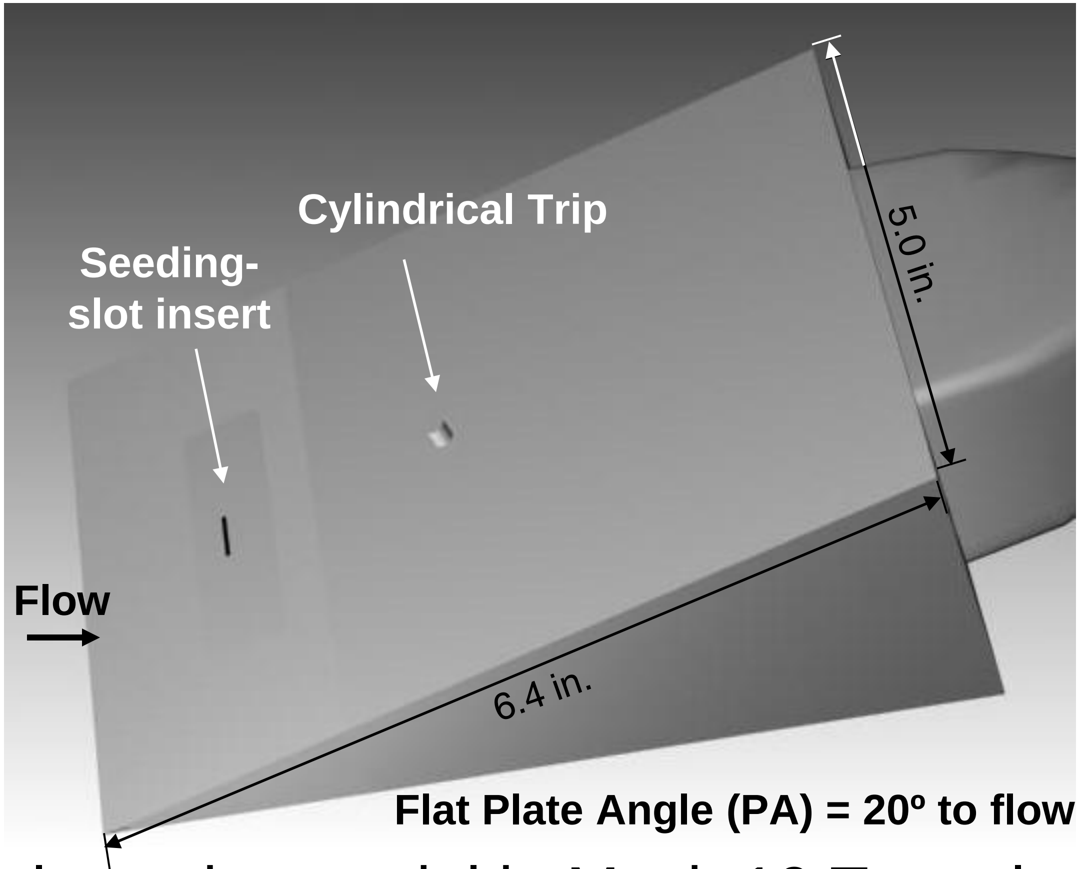
P. M. Danehy, S. O'Byrne, A. F. P. Houwing, J. S. Fox, and D. R. Smith, "*Flow-Tagging Velocimetry for Hypersonic Flows Using Fluorescence of Nitric Oxide*," AIAA Journal, 41(2), February 2003

Facility: 31-inch Mach 10 Air Tunnel



Diagrams from Bathel, Danehy, Cutler VKI lecture

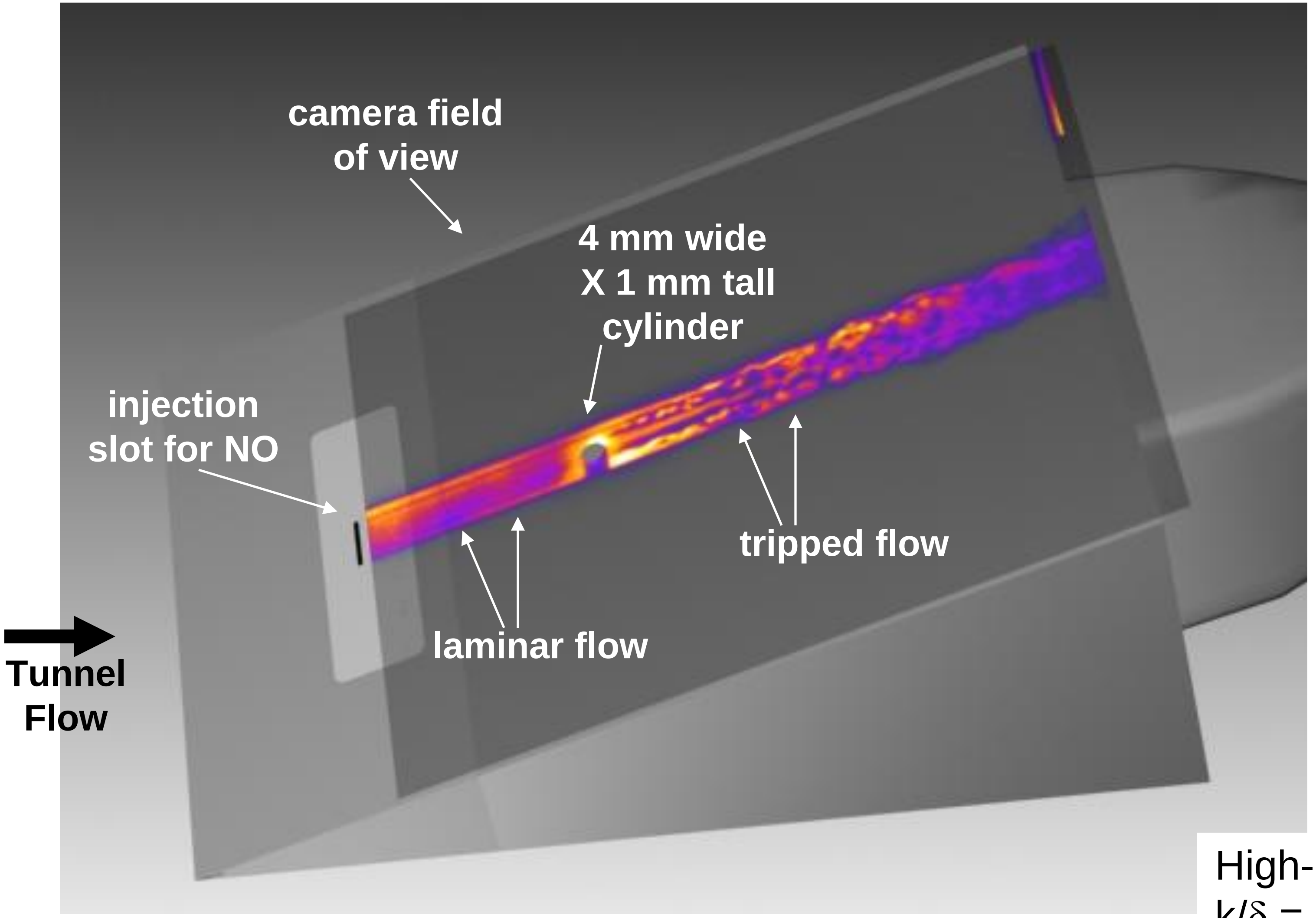
Model and Protuberances



- 20° full angle wedge model in Mach 10 Tunnel
  - Top surface: 20° wrt oncoming flow (M_e ~4.2)
- Interchangeable inserts for NO seeding and trips
- 1.0 tall x 4-mm diameter trips tested
  - δ ~ 0.7-1.5 mm, depending on conditions

From Bathel, Danehy, Cutler VKI lecture

CAD Rendering of NO PLIF Image



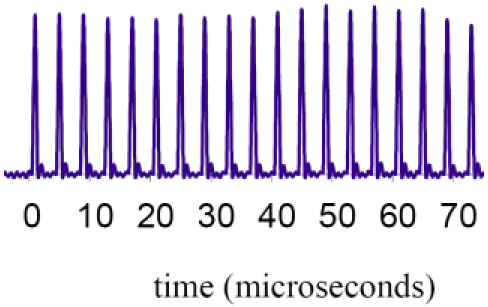
From Bathel, Danehy, Cutler VKI lecture

- Pure NO Injected from 11-mm wide slot
  - 300 sccm flow rate minimally perturbs flow
  - For NO_2 velocimetry, 10x higher flowrate used (but still laminar)

High-Re
$k/\delta = 1.4$
$M_e \approx 4.2$
$Re_{kk} \approx 5{,}000$

Diagrams from Bathel, Danehy, Cutler VKI lecture

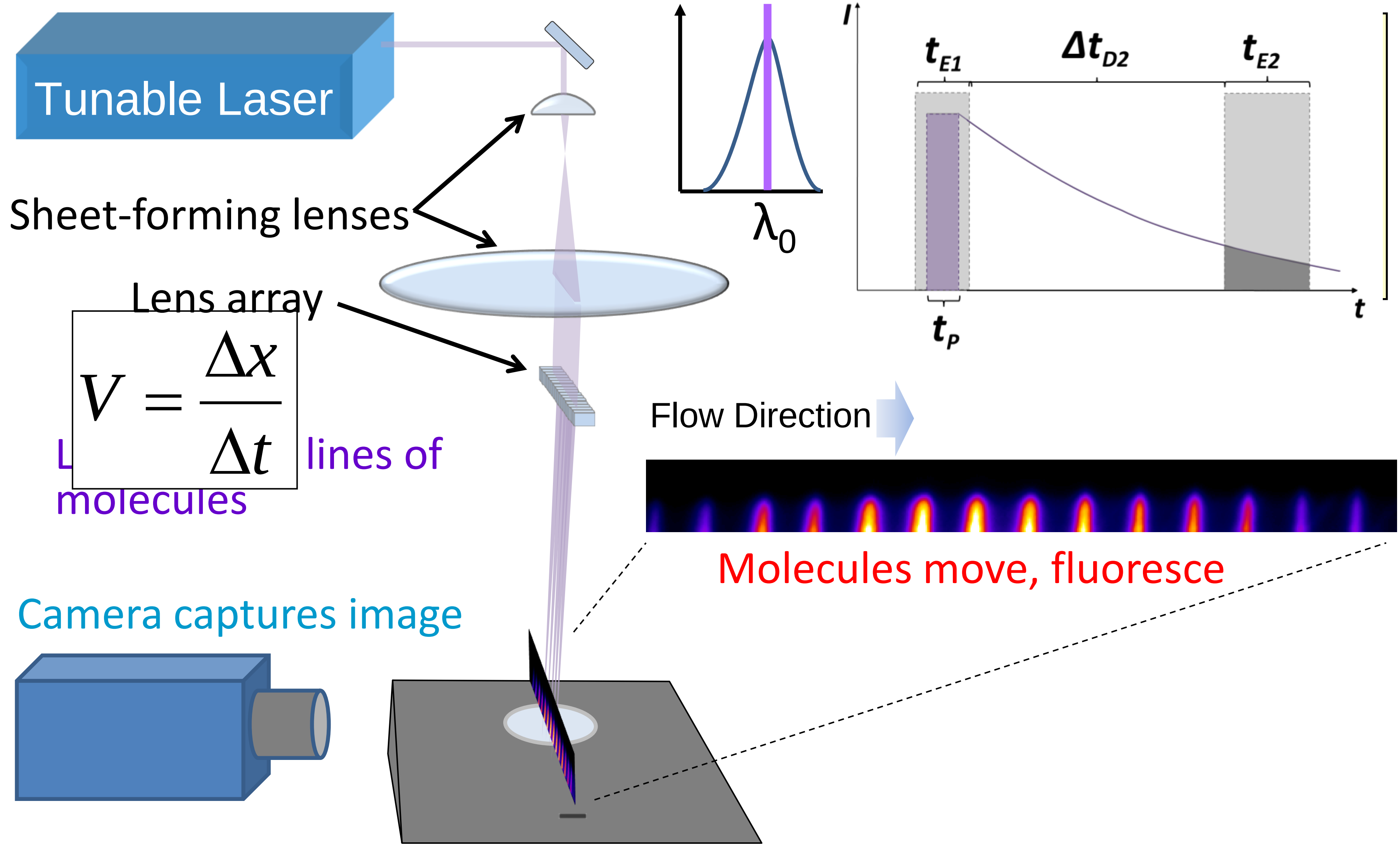
MHz Rate NO PLIF Imaging System



- Ohio State (Lempert) and Iowa State (Meyer) Universities
  - System acquires about a dozen images at a time spacing of 1 to 10 microseconds, resulting in time-accurate movies of the flow at 1 MHz – 100 kHz
  - 2 wind tunnel tests at NASA Langley Research Center

N. Jiang, M. Webster, W. R. Lempert, J. D. Miller, T. R. Meyer, C. B. Ivey, and P. M. Danehy, “MHz-rate nitric oxide planar laser-induced fluorescence imaging in a Mach 10 hypersonic wind tunnel,” Applied Optics, Vol. 50, No. 4, Feb. (2011).

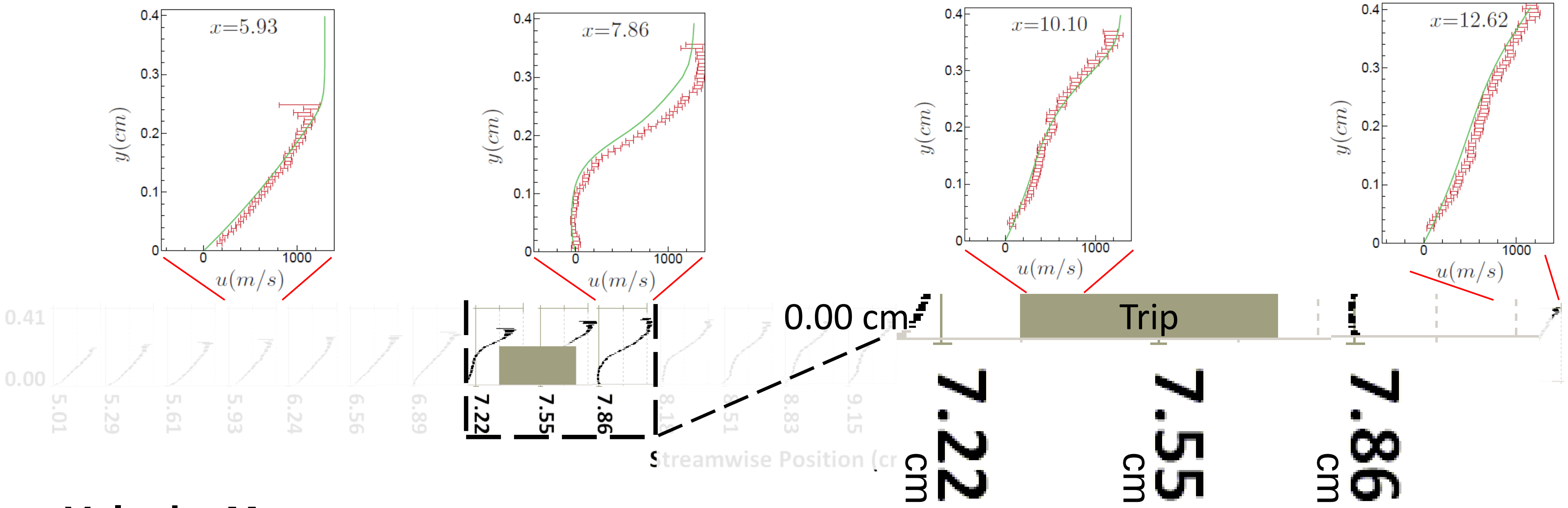
Single-laser MTV



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

Diagrams from Bathel, Danehy, Cutler VKI lecture

Single-laser MTV



- **Velocity Measurement**
  - Single-component
  - Developed thorough uncertainty analysis methodology
  - Data used in subsequent CFD study by Iyer et al. of Univ. of Minnesota (AIAA 2011-566)

B. F. Bathel, P. M. Danehy, J. A. Inman, S. B. Jones, C. B. Ivey, C. P, and Goyne, "*Velocity Profile Measurements in Hypersonic Flows Using Sequentially Imaged Fluorescence-Based Molecular Tagging*," AIAA Journal, 49(9), September 2011

Diagrams from Bathel, Danehy, Cutler VKI lecture

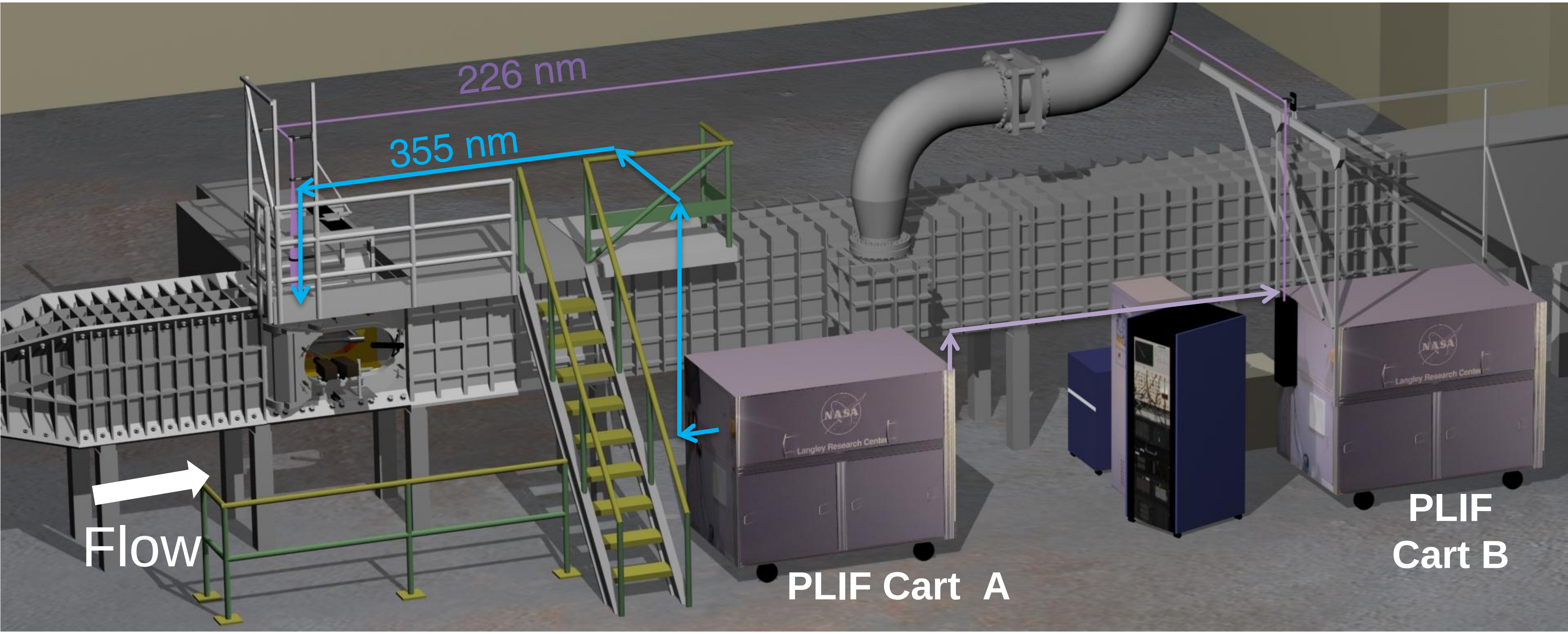
Two (or Three) laser MTV

- Typically, one laser generates a line, series of lines or a grid pattern by, ionization (LEI[126-128]), vibrational excitation (RELIEF[129-131]), photolysis, bleaching or other process. Additional laser(s) read out pattern.
  - Example: Excimer laser at 193 nm+N_2+O_2→NO
  - *Air Photolysis and Recombination Tracking (APART)*
    - Dam et al, Optics Letters, 26 (1), pp. 36-38 2001
- Method can use air constituents (N_2/O_2, O_2, N_2) or can be seeded (H_2O, N_2O, NO_2, Na, etc.).
  - We have used NO_2→NO to study transition

From Bathel, Danehy, Cutler VKI lecture

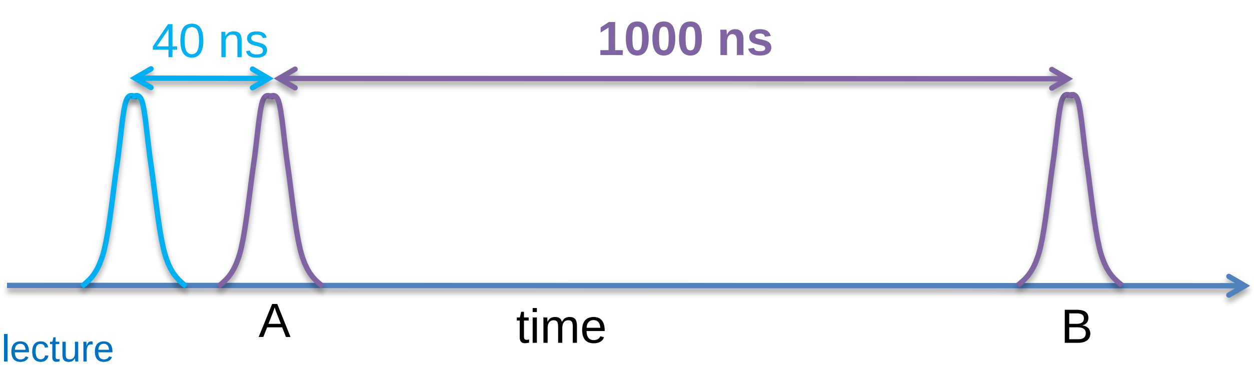
Three-Laser MTV ($NO_2 \rightarrow NO$ velocimetry)

(for details of velocimetry method, see Bathel et al, AIAA-2011-3246 and others incl. TAMU[149], OSU[150], etc.)



NO_2+355 nm → NO

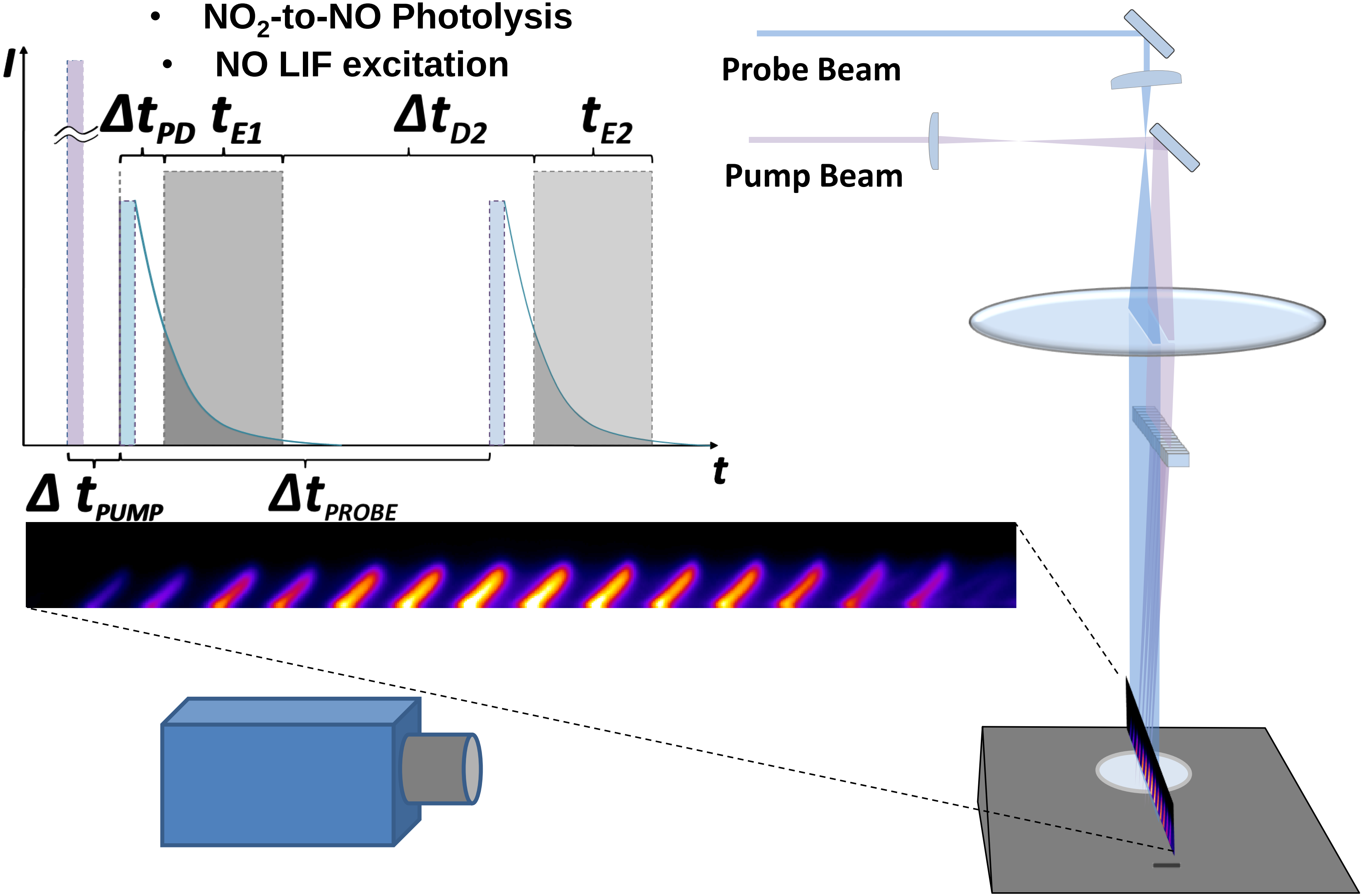
Write lines of NO into NO_2 seeded in the flow



From Bathel, Danehy, Cutler VKI lecture

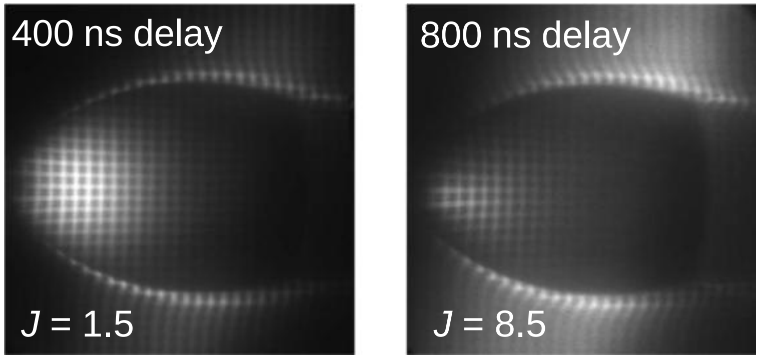
Three-laser MTV

- NO_2-to-NO Photolysis
- NO LIF excitation

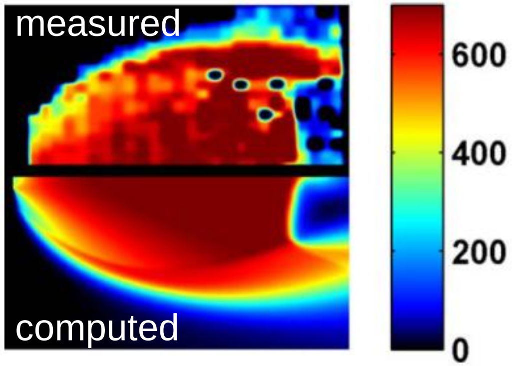


3 laser MTV: measure u, v, T

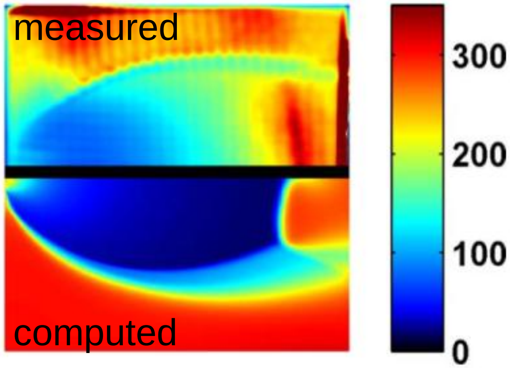
- Texas A&M has used 3 laser technique with crossed beam pattern for 2-component velocity and temperature in an underexpanded N_2 jet flow with NO_2:
  - VENOM: vibrationally excited nitric oxide monitoring
  - Excite to v' = 1 state



Raw data images



U-Velocity (m/s)
(~5% uncertainty)



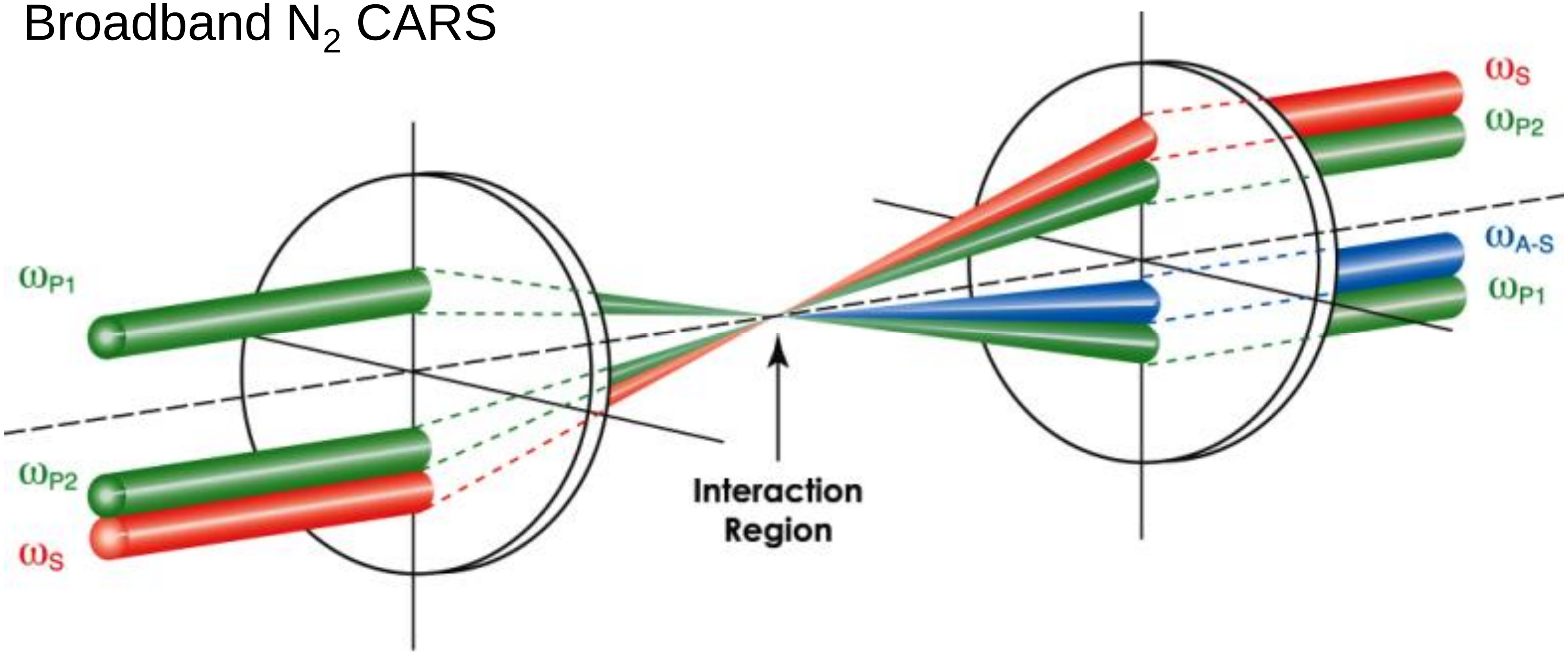
Temperature (K)
(~9-35% uncertainty)

R. Sánchez-González, R. Srinivasan, R. D. W. Bowersox, and S. W. North, "*Simultaneous velocity and temperature measurements in gaseous flowfields using the vibrationally excited nitric oxide monitoring technique: a comprehensive study*," Applied Optics, 51(9), pp. 1216-1228, March 20, 2012

From Bathel, Danehy, Cutler VKI lecture

What is CARS?

Broadband N_2 CARS



Spectrally-broad red beam +

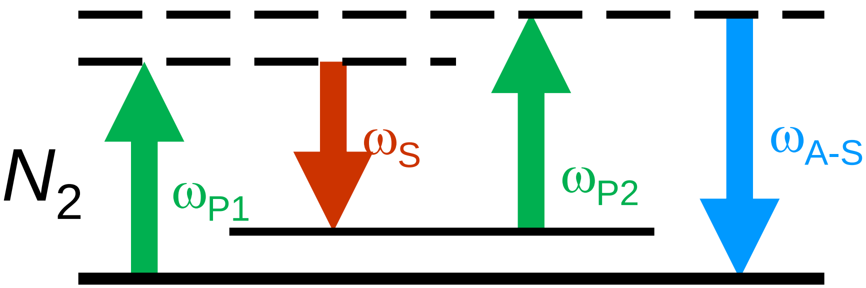
Spectrally-narrow green beams =

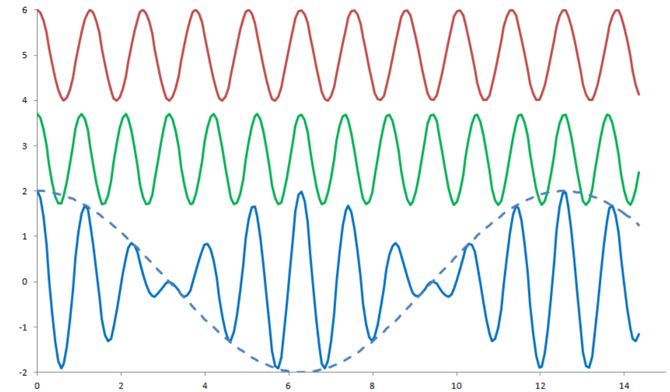
Single-shot blue CARS spectrum

From Bathel, Danehy, Cutler VKI lecture

CARS Energy Level Diagram (conservation of energy)

- Lasers: 2 Green (532 nm) and 1 Red (607 nm)
  - Frequency difference between Green and Red Probes N_2 vibrational Raman Shift

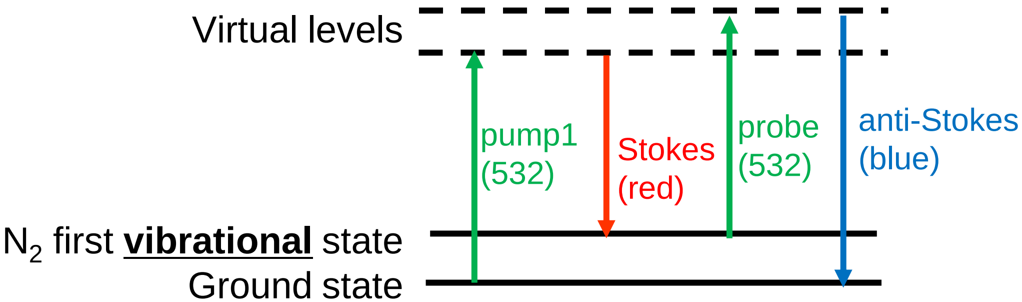




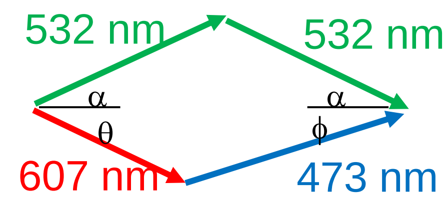
- Result: Blue signal beam at 473 nm.
  - Spatially, spectrally, temporally filter this signal
    - Good technique for luminous flows
  - Send to spectrometer equipped with CCD camera
  - Measured CARS spectra is best fit to a library of theoretical spectra on a single-shot basis (10 ns)

From Bathel, Danehy, Cutler VKI lecture

CARS Phase Matching (conservation of momentum)



Planar Boxcars Geometry



$$k_{p1} + k_{p2} = k_S + k_{A-S}$$

It is straight forward to compute the CARS phase matching angles:

N2 cars		adjust inpu	
	lambda	wavenum	angle (degrees
stokes	607	16474.46	**3.963**
pump 2	532	18796.99	**3.500**
pump 1	532	18796.99	**3.500**
anti stokes	473.4956	21119.52	**3.091**
			0.023576939
N2 Raman =	2322.528	cm-1	0.023576939
(nominal N2 = 2330 cm-1)			*3.00927E-20*

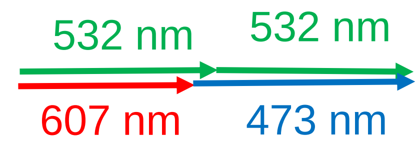
Different molecules require different angles (can get multiple signals at different spatial locations: Dual-Stokes)

From Bathel, Danehy, Cutler VKI lecture

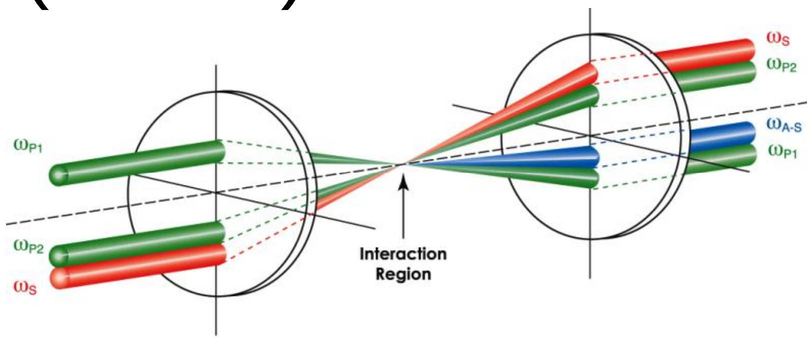
CARS Phase Matching Geometries

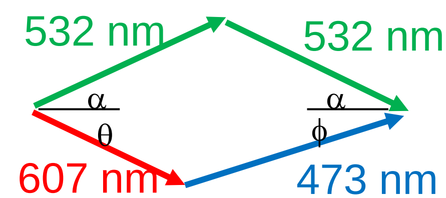
- Collinear CARS:
  - Poor spatial resolution

$$k_{p1} + k_{p2} = k_S + k_{A-S}$$

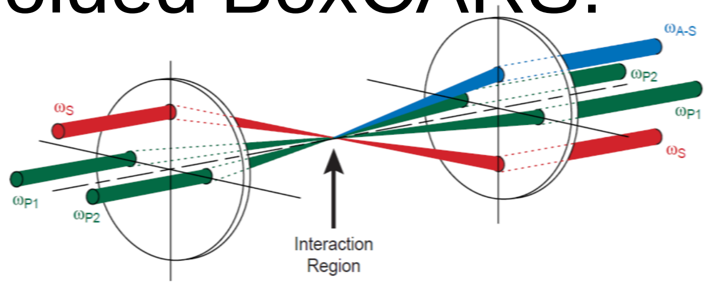


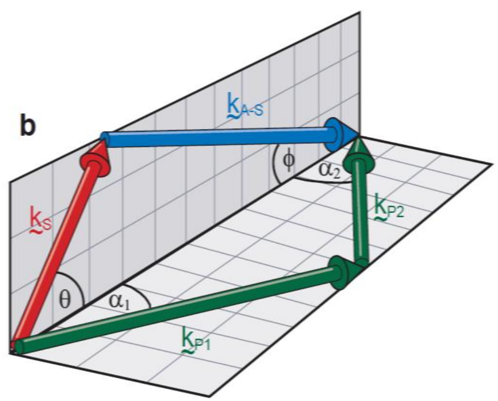
- (Planar) BoxCARS:





- Folded BoxCARS:



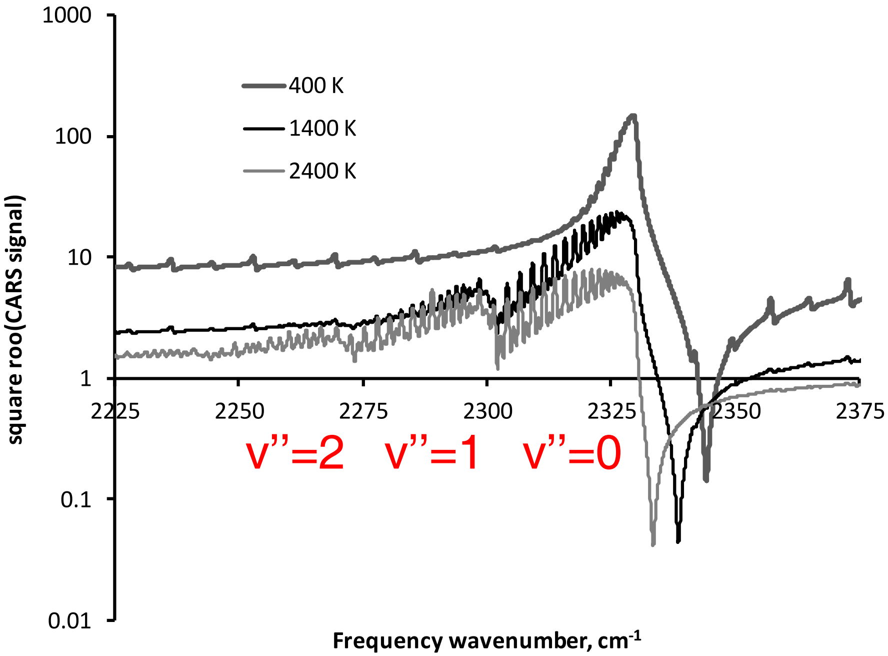


- Best spatial resolution (1.5 mm x 0.1 mm x 0.1 mm) but lower signals and affected by beam steering from turbulence

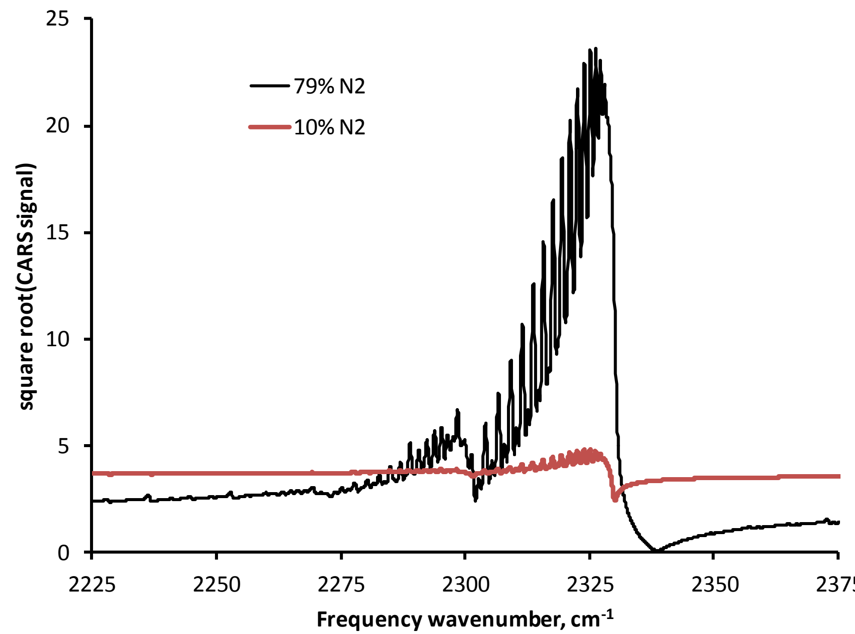
From Bathel, Danehy, Cutler VKI lecture

CARS Temperature Effects

- Effects of temperature (left) and composition (right):



Vibrational "hot band" becomes populated above 700 K

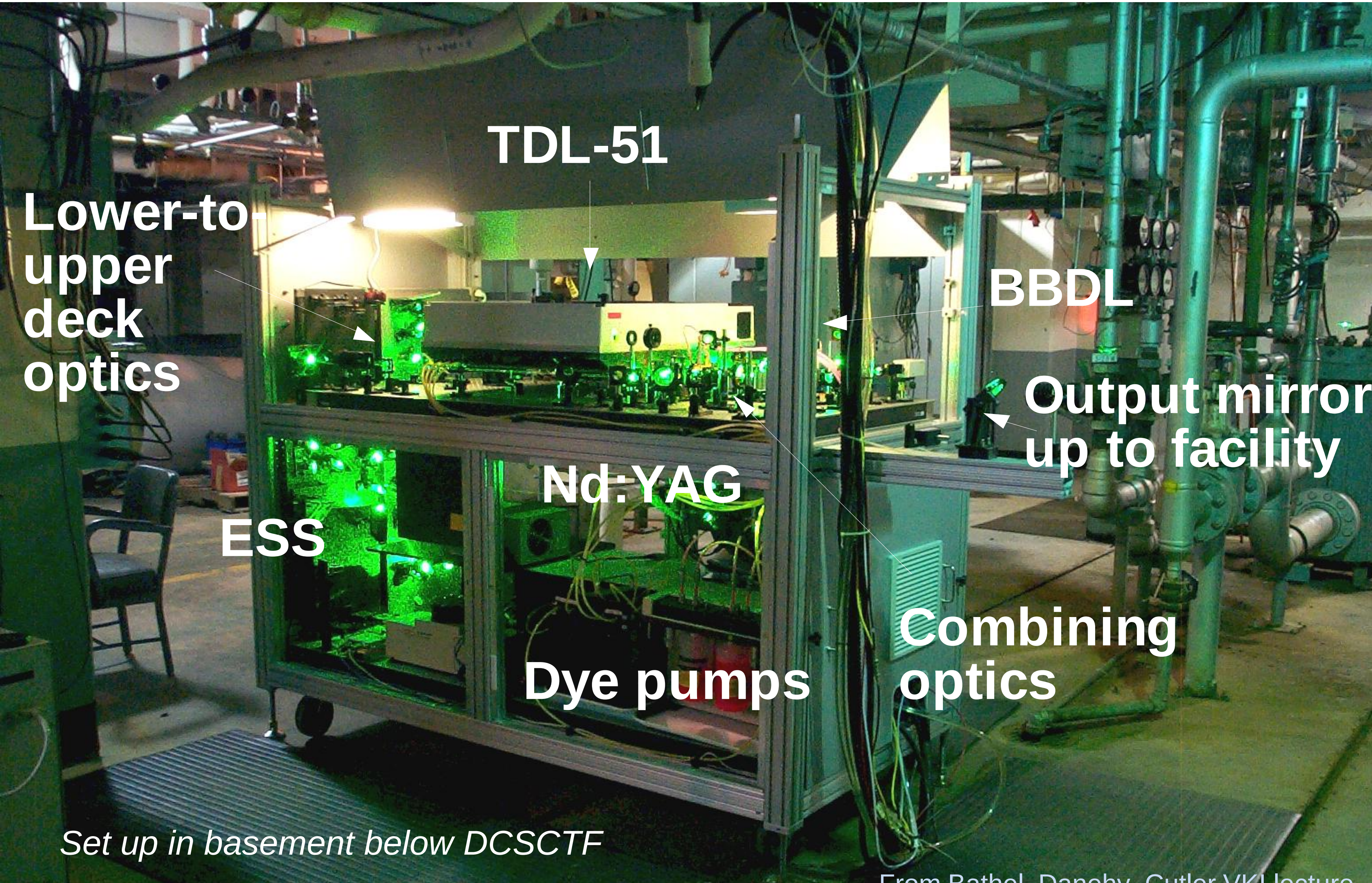


CARS spectra are sensitive to the gas composition through resonant and nonresonant parts

From Bathel, Danehy, Cutler VKI lecture

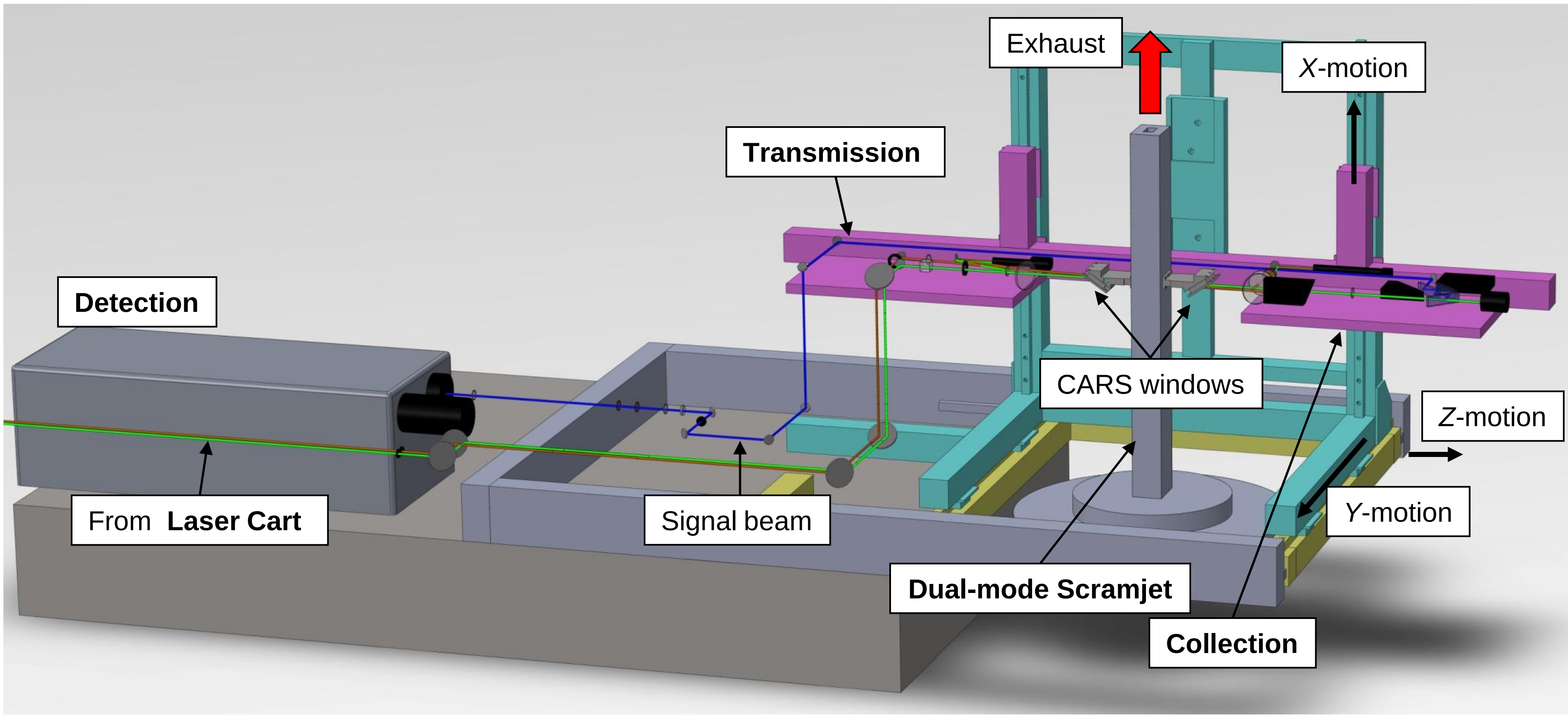
NASA/GWU Mobile CARS System

→ Simplifies/speeds set up in facility



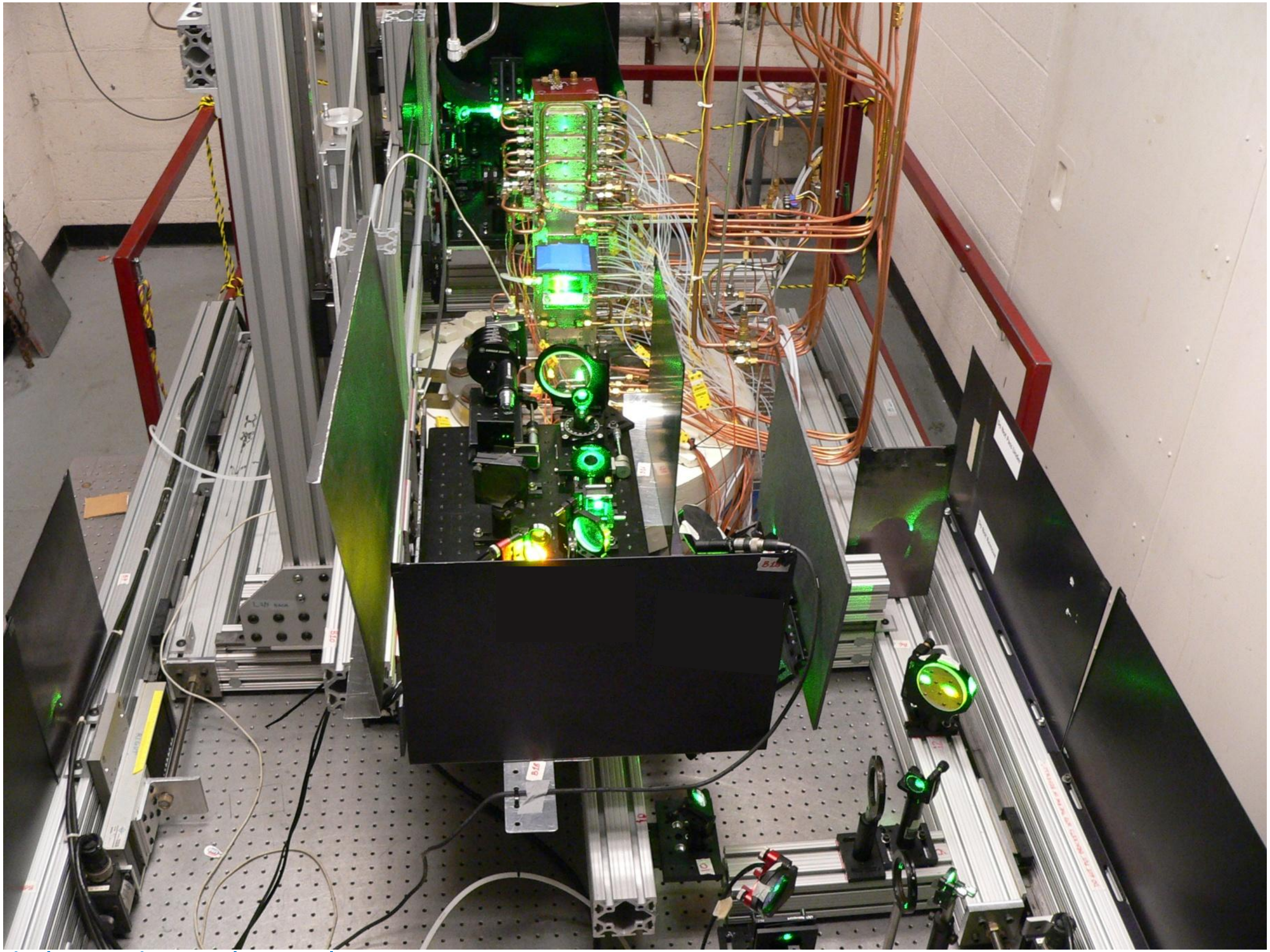
From Bathel, Danehy, Cutler VKI lecture

Setup at UVa: Optical System 2



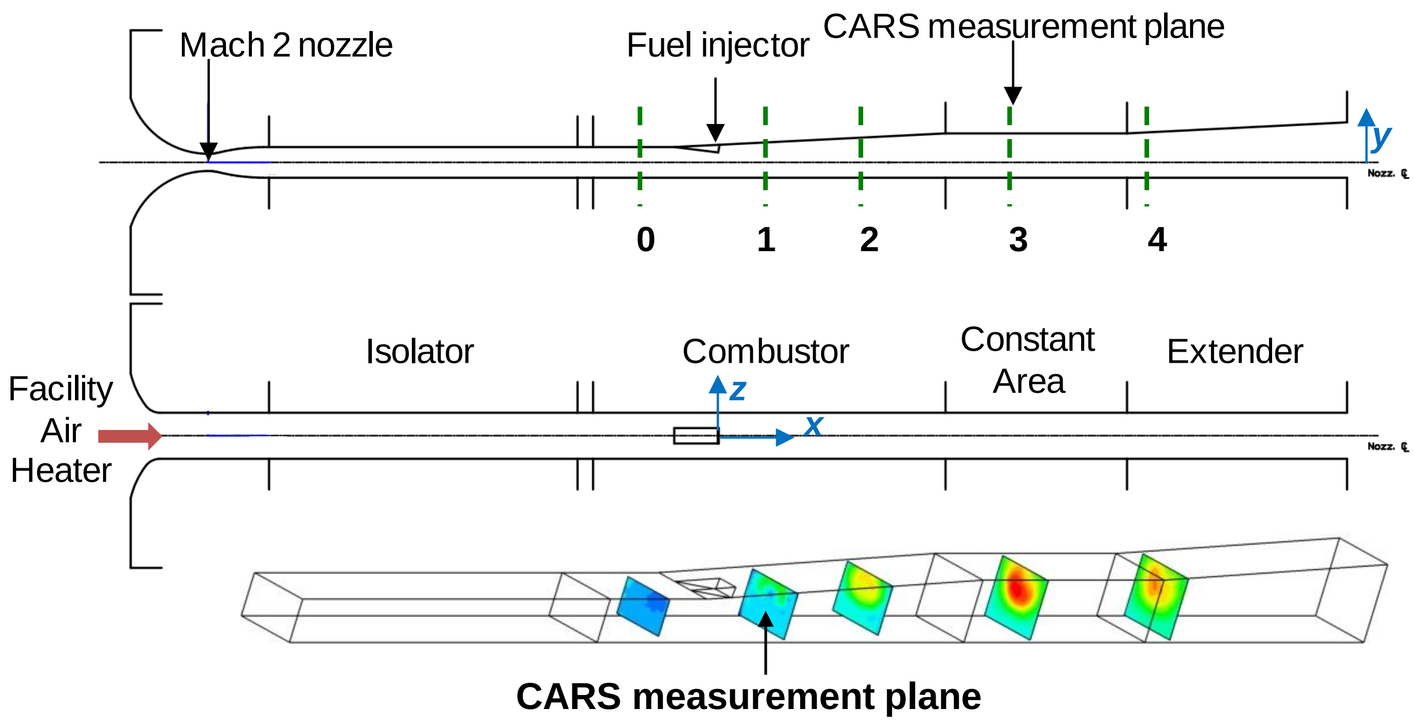
From Bathel, Danehy, Cutler VKI lecture

Transmission stage and test section at UVa



From Bathel, Danehy, Cutler VKI lecture

Facility / Dual Mode Scramjet at UVa

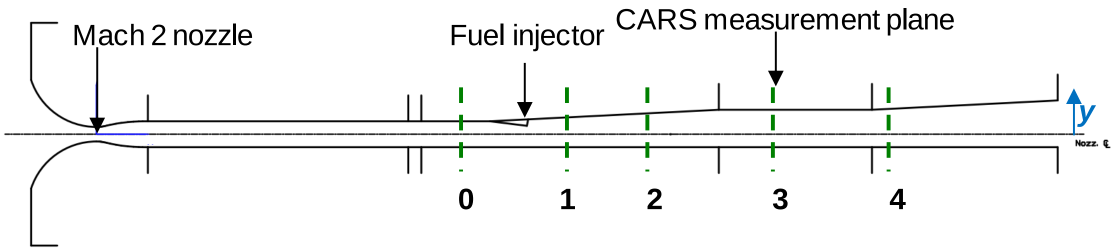


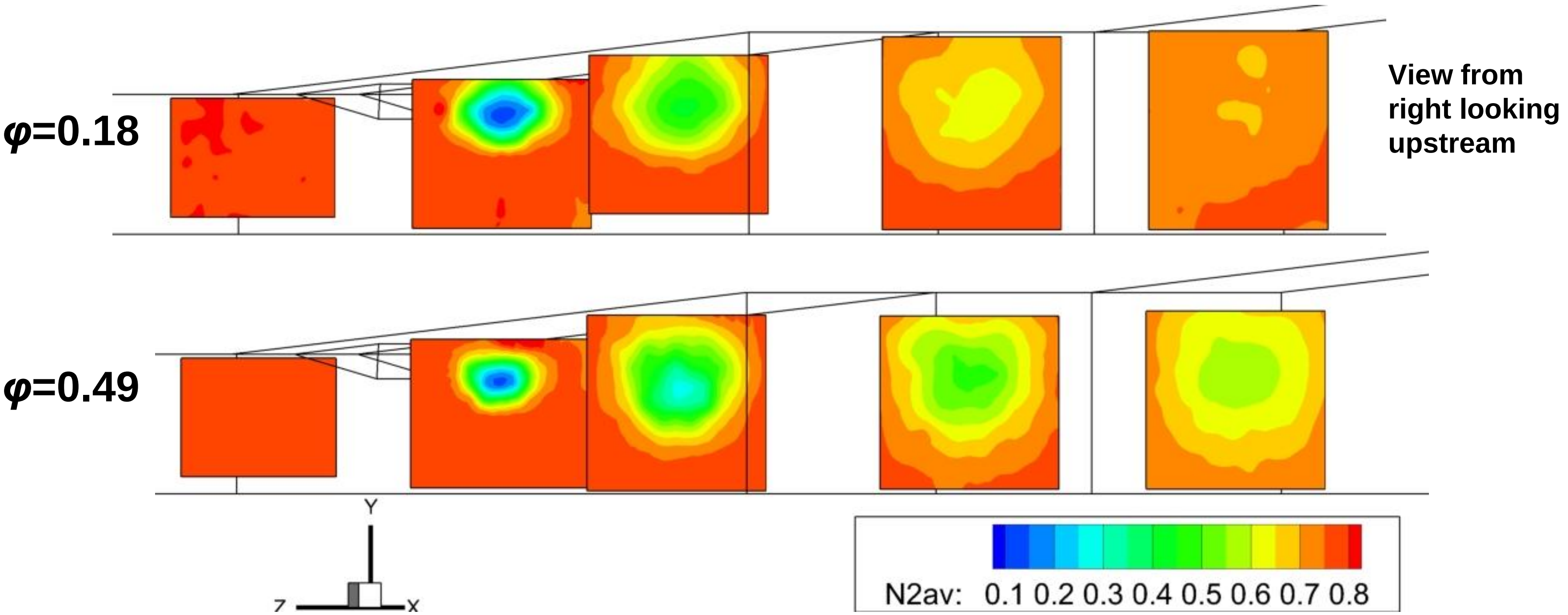
- Electrically heated clean air, nominal $T_t = 1200$ K, $M = 2$ nozzle
- Long test times allow large data sets at steady inflow conditions
- Highly turbulent flowfield
- Good optical access

From Bathel, Danehy, Cutler VKI lecture

Contours of Mole Fraction N_2

- Since inert shows overall mixing





From Bathel, Danehy, Cutler VKI lecture

CARS compared with CFD (LES from NC State)

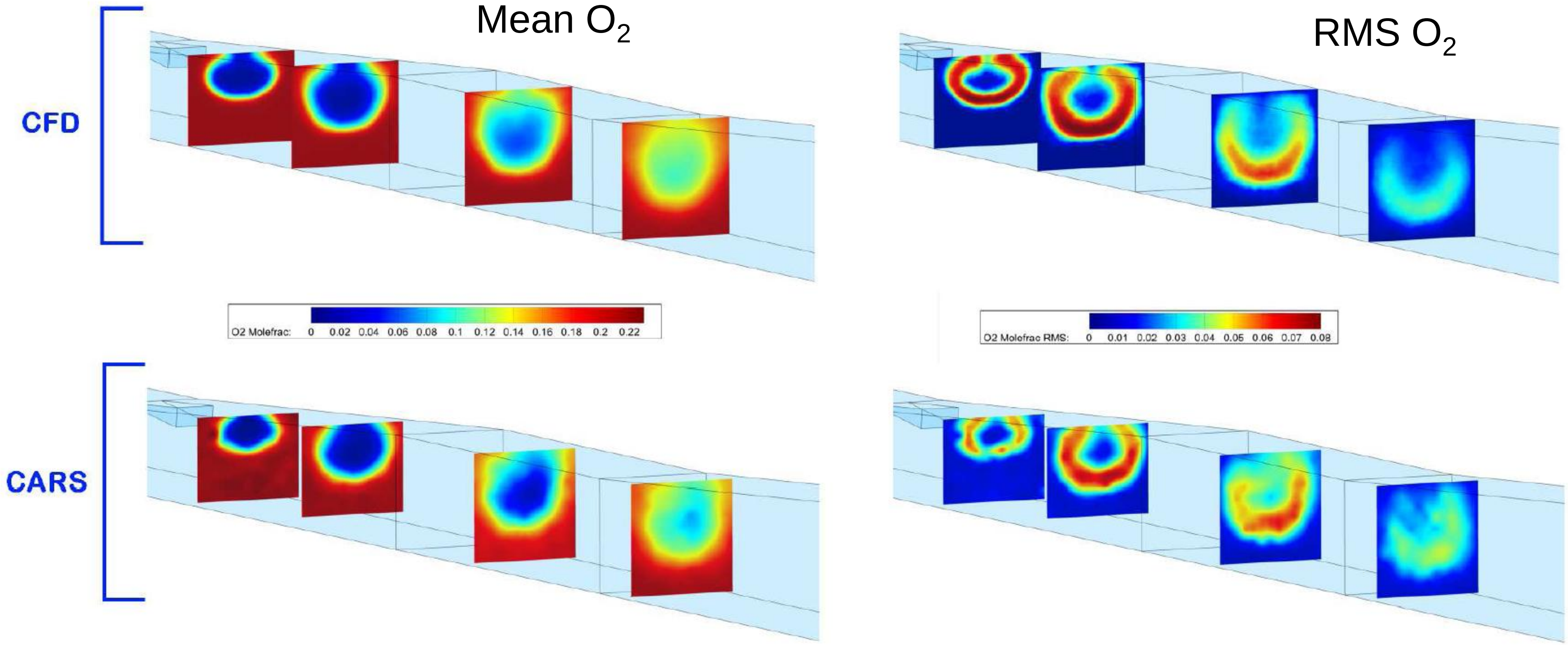


Figure 9. Comparison between CARS and O_2 concentration and RMS fluctuations for '0.17' equivalence ratio.

Same facility at UVa, computations from NC State

- CARS provides valuable quantitative comparison data
  - Fulton, Edwards, et al, (Configuration C) AIAA-2013-0117, 2013

From Bathel, Danehy, Cutler VKI lecture

Other Techniques Not Discussed Today

- Background-oriented schlieren (BOS), focused schlieren, deflectometry
- Laser differential interferometry (LDI), focused laser differential interferometry (FLDI)
- Tunable diode laser absorption spectroscopy (TDLAS)
- Femtosecond laser electronic excitation tagging (FLEET) – diatomic nitrogen, Raman excitation plus laser-induced electronic fluorescence (RELIEF) – diatomic oxygen, air photolysis and recombination tracking (APART) – NO fluorescence
- Degenerate Four-Wave Mixing (DFWM)
- Laser-induced thermal acoustics (LITA)
- And many more….

Summary

- Optical techniques have advantages and disadvantages, strengths and weaknesses
  - High frequency, survivability typically not an issue, multiple properties measured simultaneously
  - Signal-to-noise, accuracy/precision/uncertainty, expense, time
- Sometimes can be the only way to get data from a facility, sometimes cannot provide the necessary precision required
- Takes experience and care