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Burst-mode planar laser-induced fluorescence of nitric oxide in the Sandia free-piston shock tunnel

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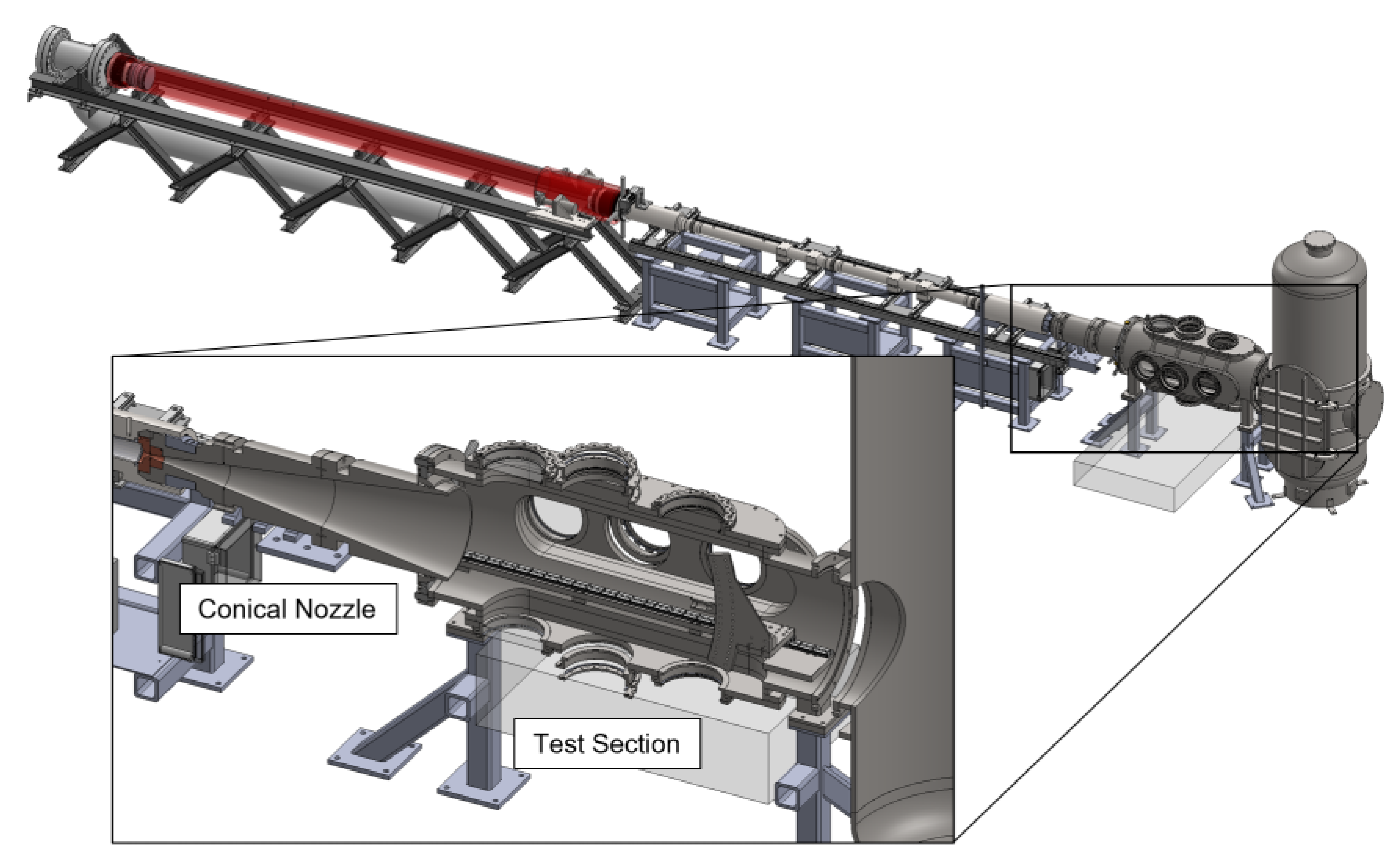
Sandia Free-Piston Hypersonic Shock Tunnel (HST)



Tunnel Specifications

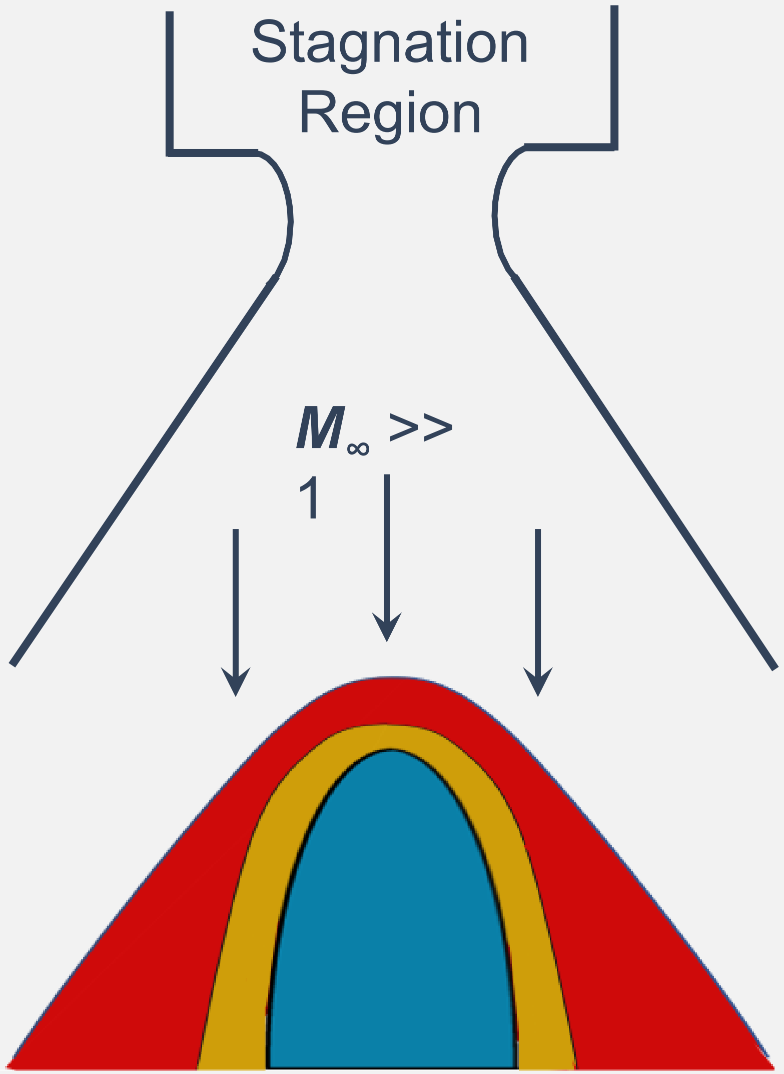
- Nozzle Exit Dia. = 0.36 m
- Test section diameter 0.5 m
- Run times of 1-2 milliseconds
- M = 8−10 (dependent on enthalpy and spec. heat ratio)

U_∞ (m/s)	H_0 (MJ/kg)	T_0 (K)	P_0 (MPa)
2850	4.6	3400	12
4060	9	6000	17

Target applications include high-temperature surface chemistry and hypersonic thermochemistry.

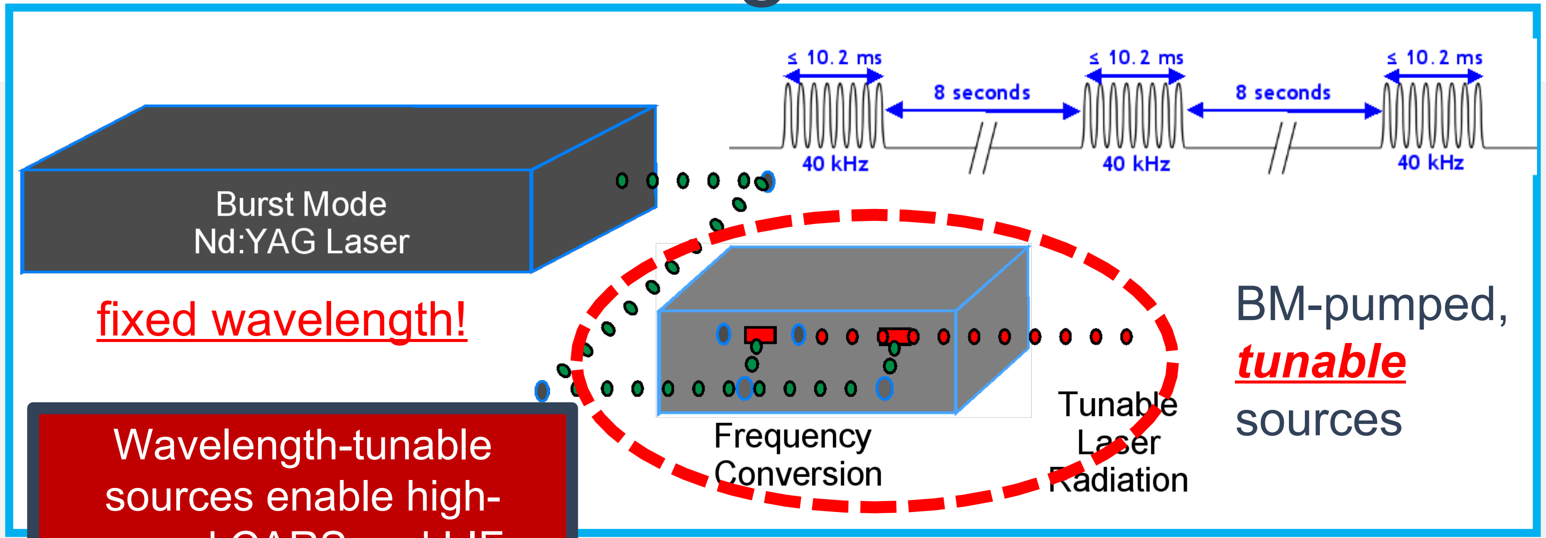
Experiments in HST

- **Complex HST Environment**
  - Stagnation region gases react
  - Gas rapidly expanded through nozzle
  - Result: thermal non-eq., *NO addition (PLIF)*
- **Free-stream characterization necessary**
  - Temperature: Pulse-burst CARS for N_2, O_2 (See Jans et al., AIAA2022)
  - Velocity: NO LIF
  - 100-kHz data with *pulse-burst laser!*
- **Examine boundary layer products**
  - Speciation/temperature of CO
    - Laser absorption (Daniel et al., AIAA2022)
    - CARS--Coherent Anti-Raman Stokes Raman Scattering (Kearney et al., AIAA2022)



Pulse-burst laser for 100-kHz laser diagnostics

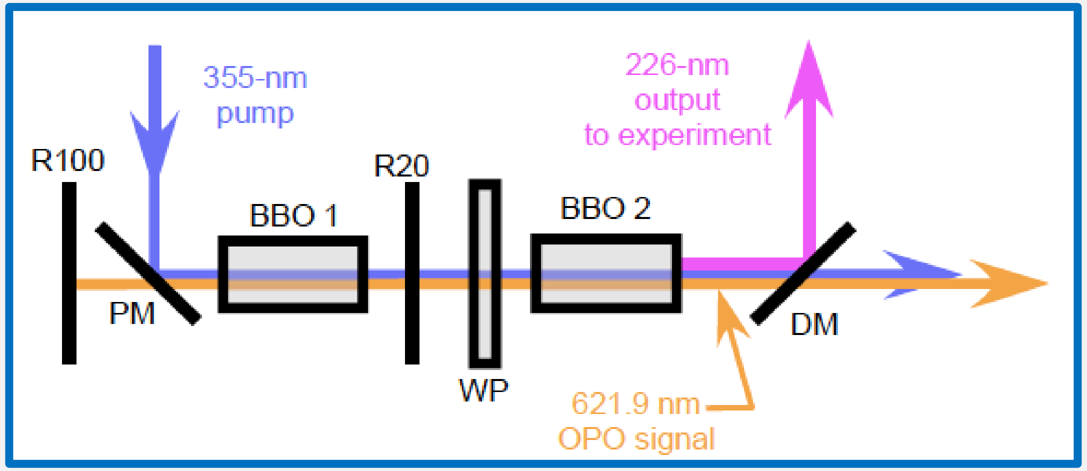
- Burst-mode lasers have allowed experimentalists to access high-speeds (10s to 100s of kHz)
- While powerful, these systems are not wavelength tunable—this prohibits application of ***chemically specific*** imaging and spectroscopic tools



Wavelength-tunable sources enable high-speed CARS and LIF

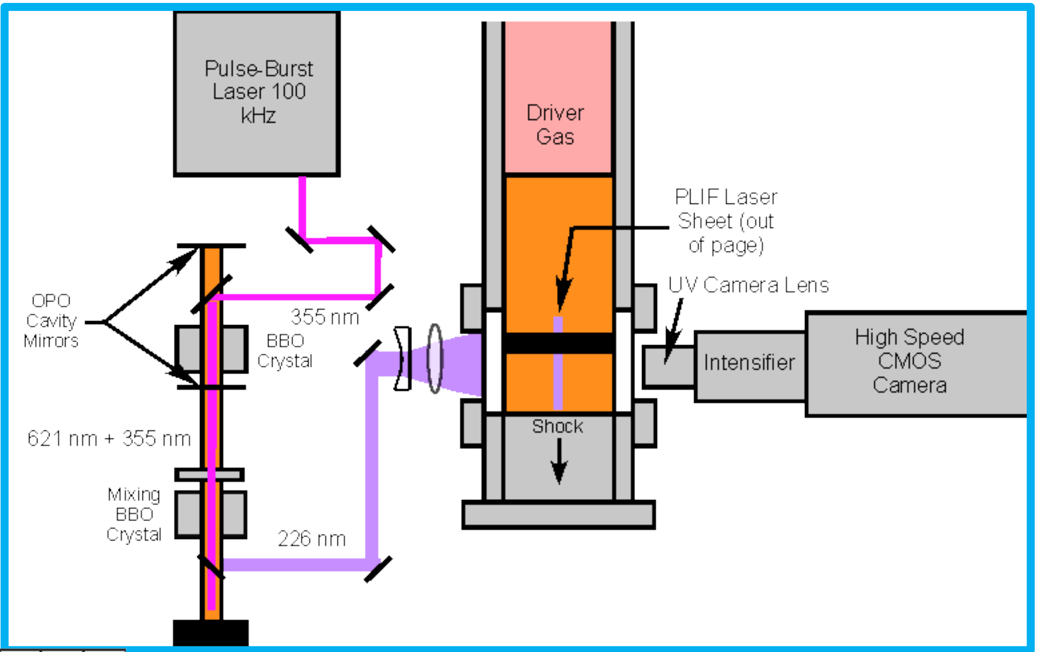
Robust OPO Design for Shock Tunnel Facility Operation

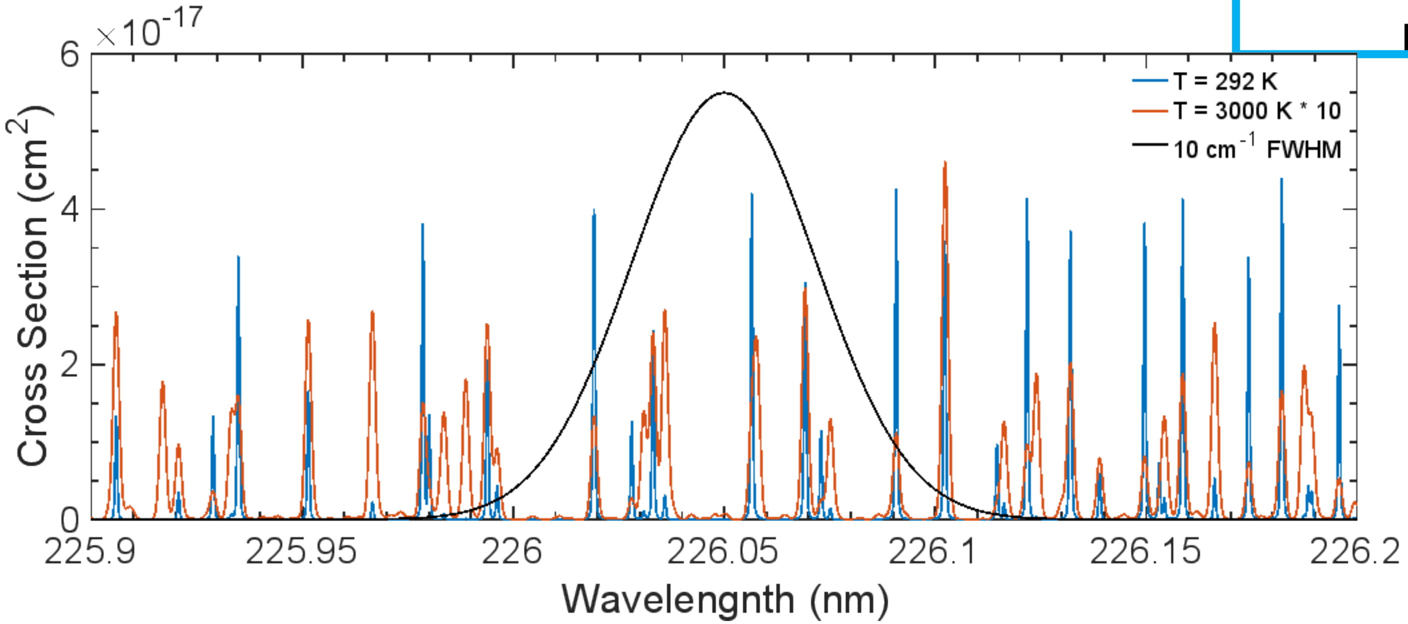
- Derived from Jiang, Hsu et al. (Spectral Energies) design
- IC pump mirror permits high 355-nm intensities
- Custom waveplate minimizes path to SFG crystal
- Single-pass pump
- Depleted pump used for SFG
- Unseeded-–output bandwidth ~10 cm^{-1} FWHM
- 1.5-2% conversion with 800-1200 μJ/pulse @ 226 nm



Nitric Oxide LIF imaging in free-piston shock-tube cylinder startup flow

- 100-kHz planar laser-induced fluorescence using pulse-burst laser and ***frequency narrow*** OPO near λ = 226 nm
- "Free-stream" is M = 2 post-shock flow induced by M = 8 shock
  - NO concentration ~4%
  - T ~ 3000 K, P ~ 1 atm



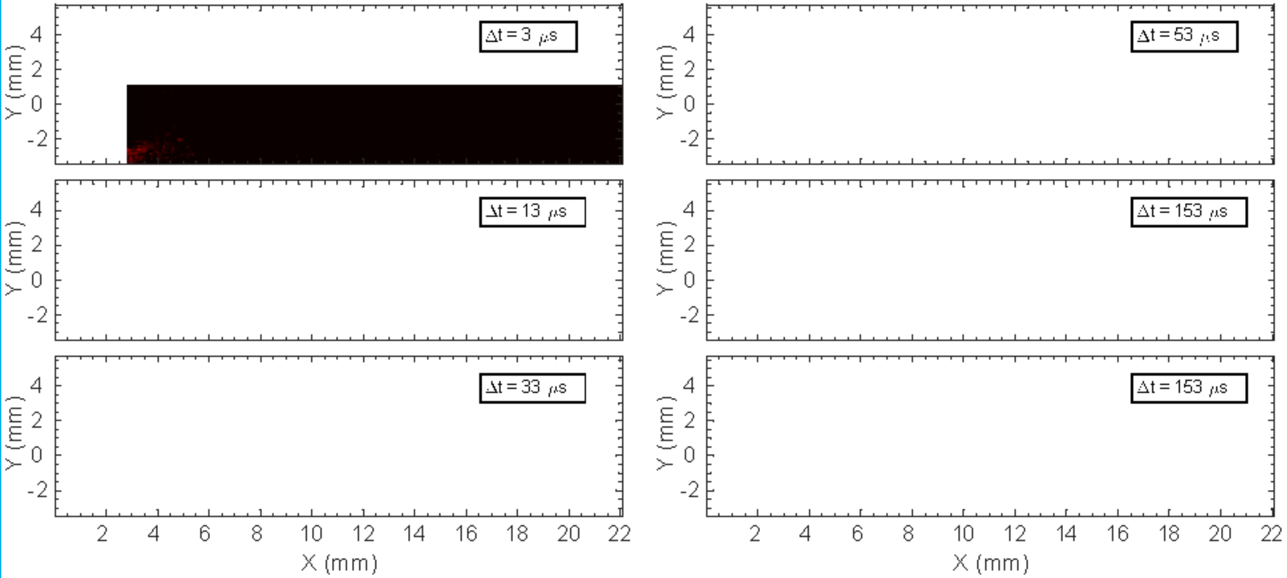


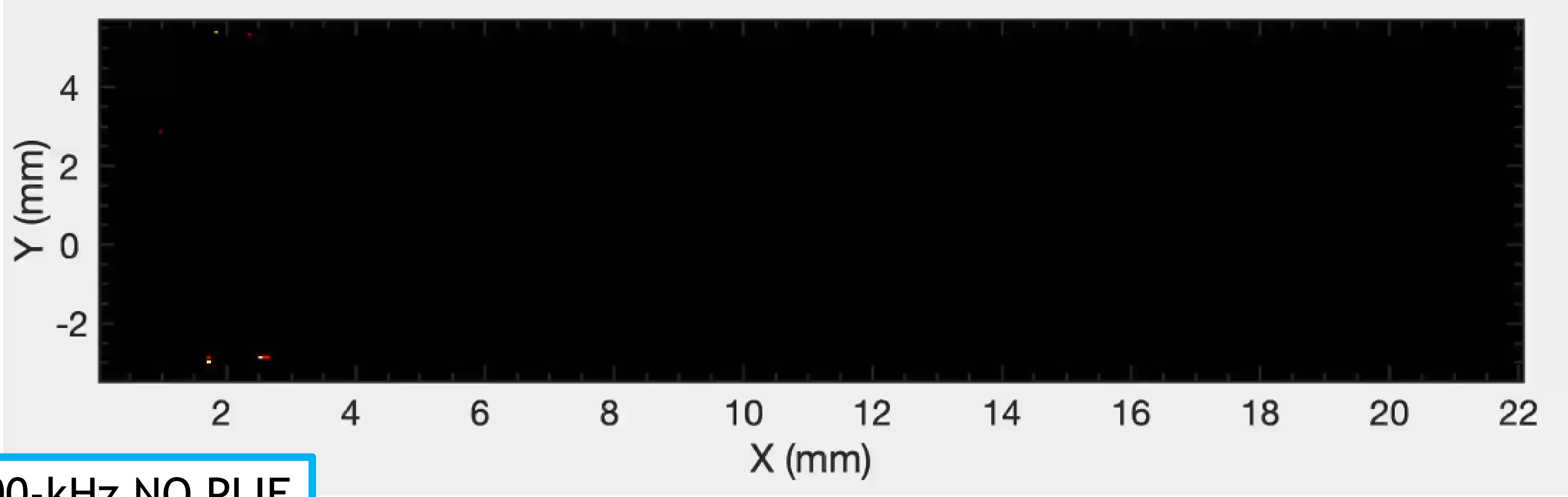
- Broadband excitation of NO
- OPO spectrum is ~10 cm-1 FWHM, tuned to 226.05 nm
- Excite multiple transitions in NO $A^2\Sigma - X^2\Pi$ bandhead region

Cylinder Wake Results

Simulated NO LIF Signal (E. Jans, Sandia)

Visualization of cylinder startup, U = 2.5 km/s, T = 3000 K

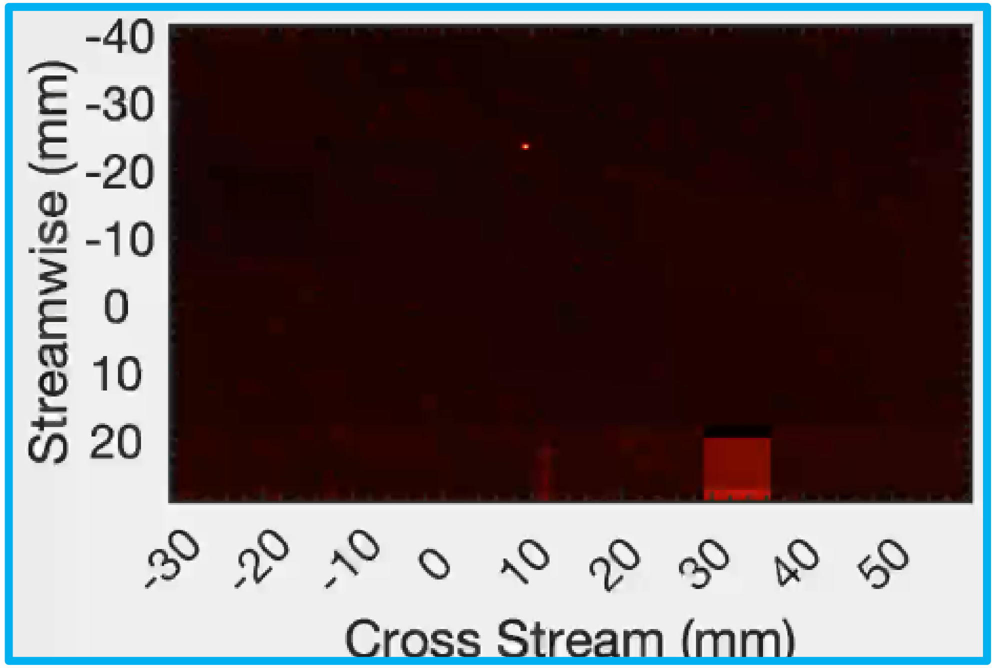




100-kHz NO PLIF

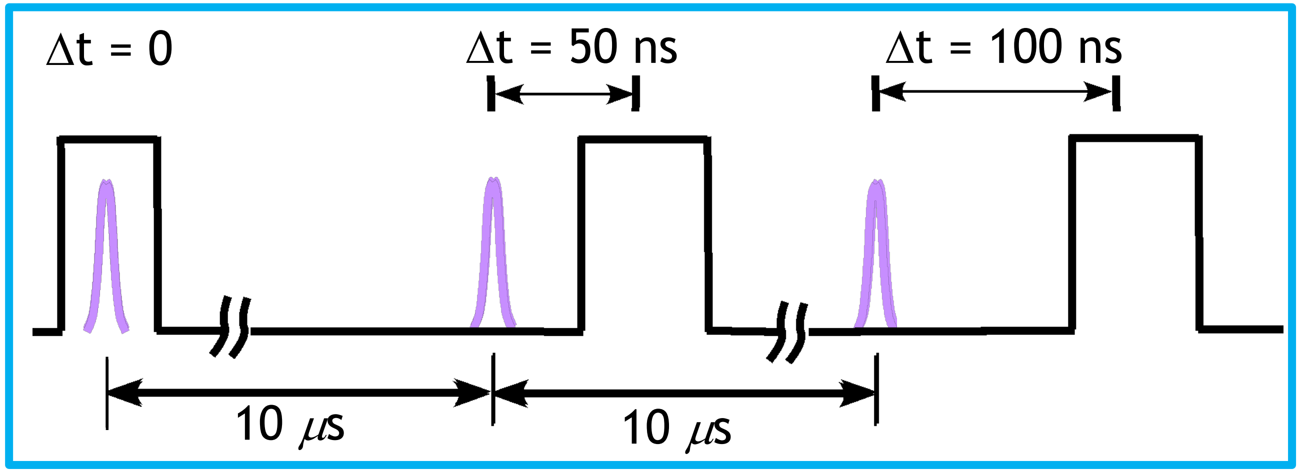
NO PLIF Imaging in M = 9 Shock ***Tunnel*** Flow

- M = 9 flight condition at ~130 kft
- Enthalpy ~ 5 MJ/kg
- NO PLIF Visualization over large, 85-mm field of view



Nitric Oxide Velocimetry

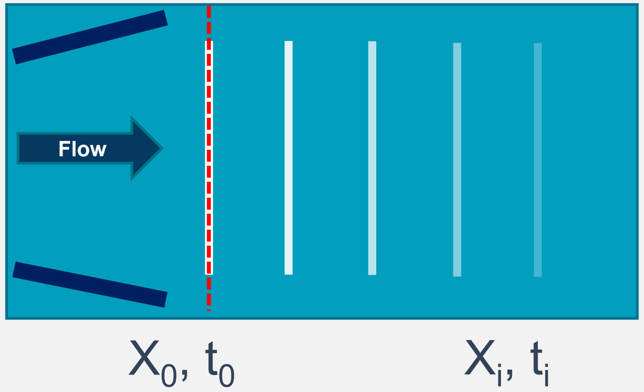
- Thermodynamic nonequilibrium conditions at nozzle exit make free-stream velocity uncertain
- At free-stream density, NO fluorescence lifetime is "long" ~ 200 ns
- Can be tracked when velocity is several km/s

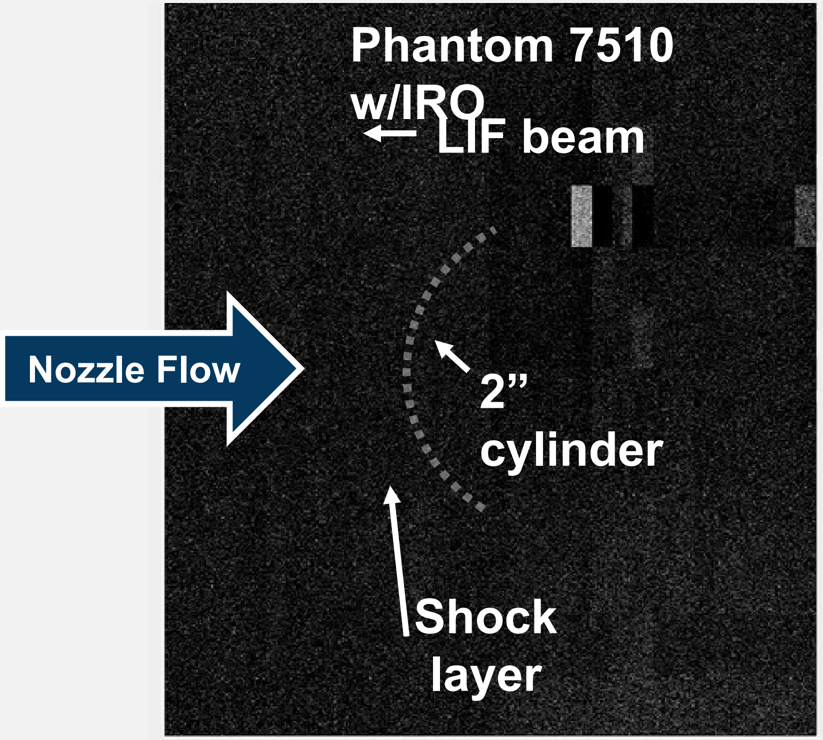


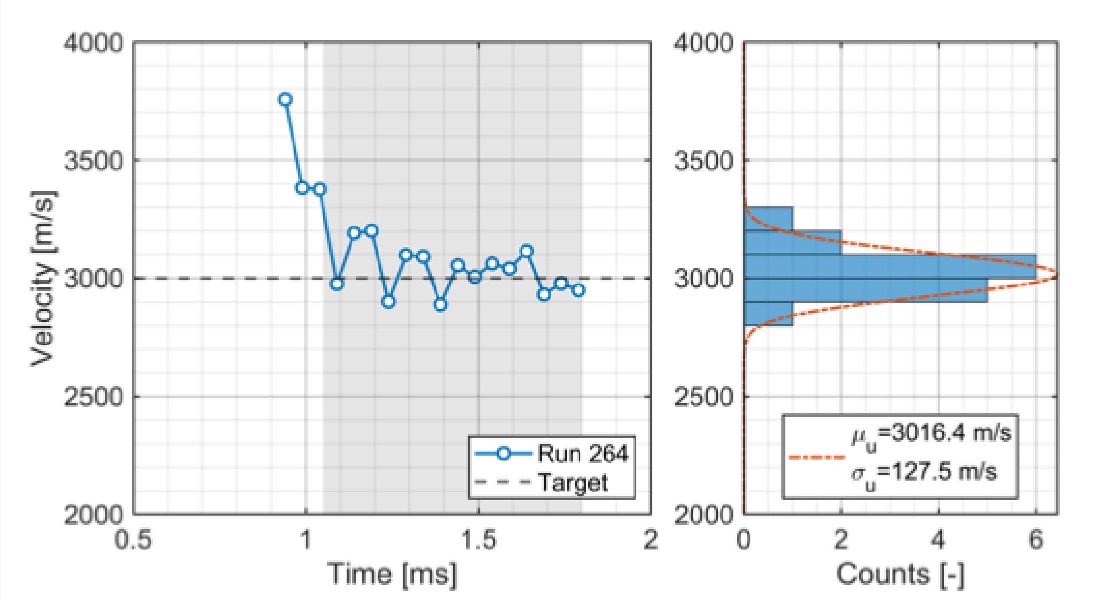
Free-Stream Characterization: Velocity

- NO is present in shock tunnel flow (X_{NO}~4-5%)
- Tracer for flow visualization
- Nitric Oxide Tagging Velocimetry
- Long fluorescence lifetime, >100 ns
  - U_∞=3 km/s = 3 μm/ns, Δt~100 ns → Δx~300 μm
  - Track NO fluorescence at high image magnification

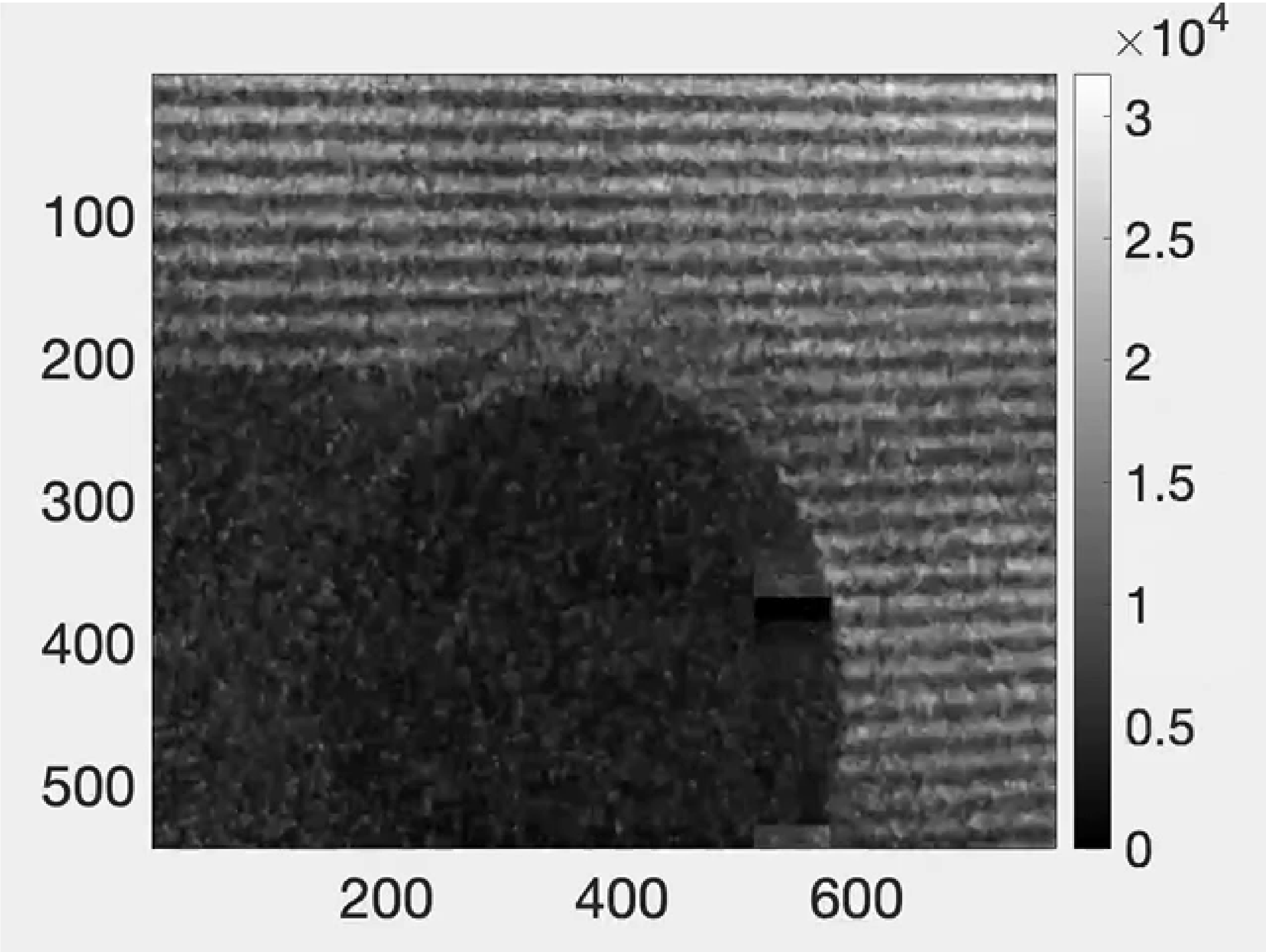
LIF beam tracks flow







2D Nitric Oxide Velocimetry?



Summary and Conclusions

- Shock-tunnel conditions are impacted by non-equilibrium processed in the nozzle
  - Elevated nitric oxide, ~4%
  - Nonequilibrium T_{vib} (Jans, AIAA2022)
- 100-kHz burst-mode NO PLIF provides effective visualization of NO during transient shock tunnel processes.
- A robust, wideband OPO design performed well *for visualization and velocimetry* during shock-tunnel entries
  - Pulse energies in excess of 1 mJ/pulse at 226 nm
  - 1-cm^{-1} bandwidth pumps multiple rotational transitions
- Free-stream molecular velocimetry demonstrated with a single laser pulse
  - 40-kHz effective data rate
  - 2D velocimetry possible in high-speed, *low-pressure* regions?