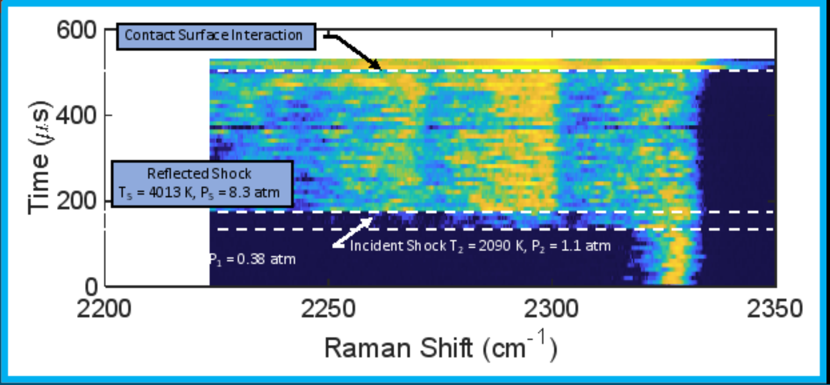
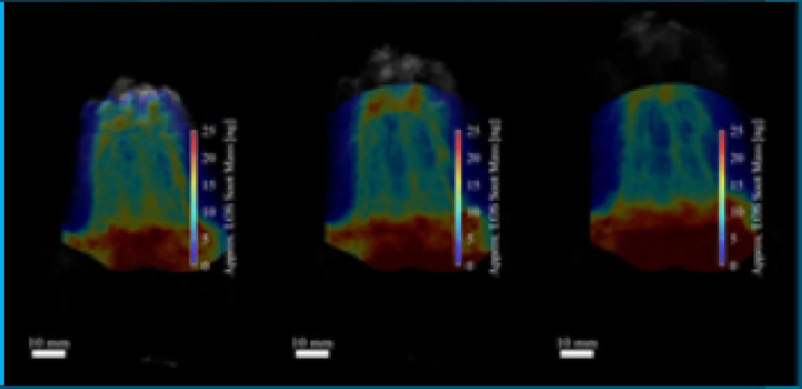
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2021-8059C

Sandia National Laboratories

Recent Progress in Optical-Based Diagnostics: Applications to Challenging Environments





PRESENTED BY

Sean Kearney

Contributions from: Raj Bhakta, Kyle Daniel, Justin Wagner, Kyle Lynch, Daniel Richardson, Dan Guildenbecher, Will Swain, Josh Hargis (Sandia)
Jason Leicht, Mikhail Slipchenko (Spectral Energies, LLC)
Daniel Lauriola, Morgan Reusch, Chris Goldenstein, Alex Brown, Mateo Gomez, Terry Meyer (Purdue)
Nick Glumac (Illinois)
Phil Varghese, Noel Clemens (Texas)

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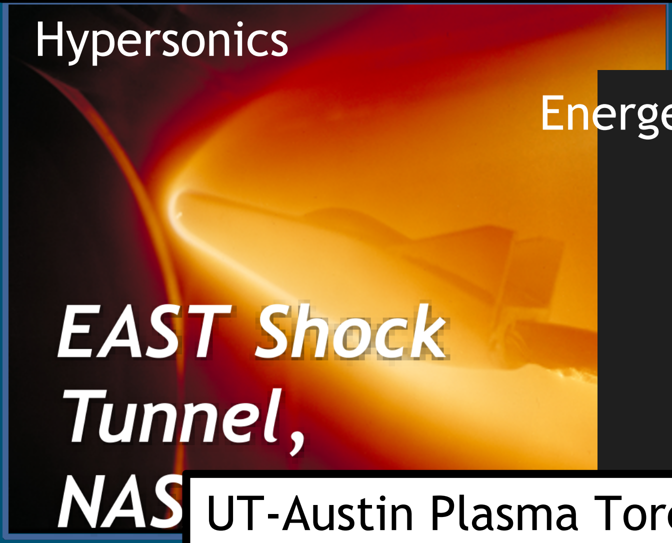
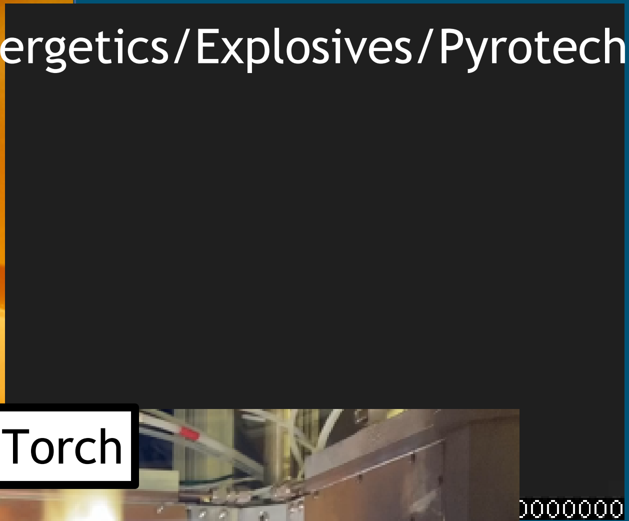
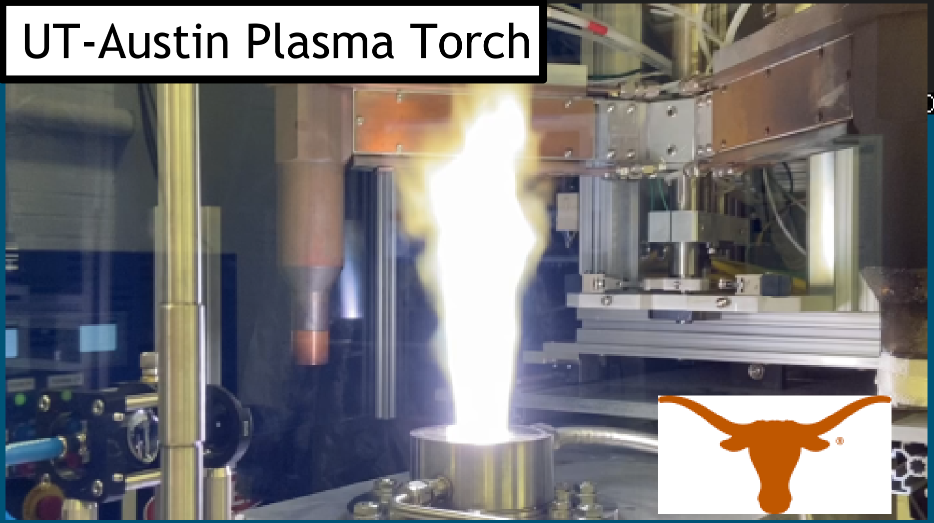
Motivation and challenges

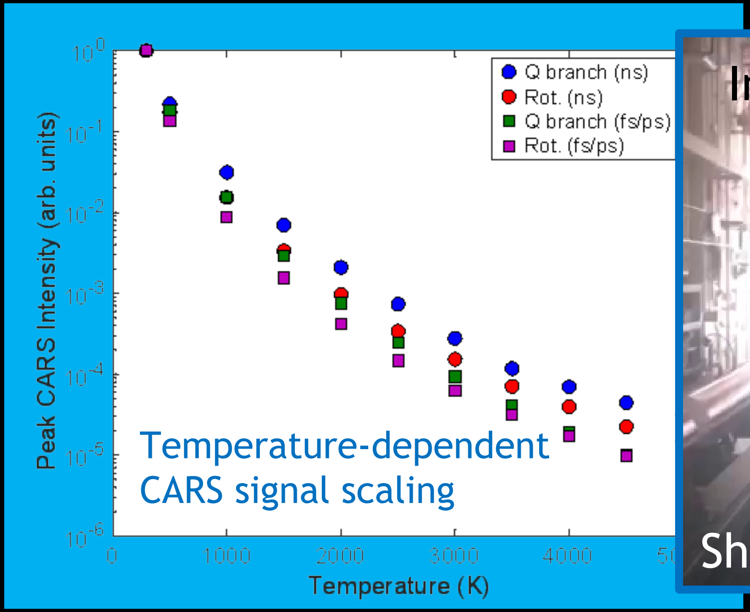
Laser diagnostics are being applied to an increasingly wider space *outside combustion*

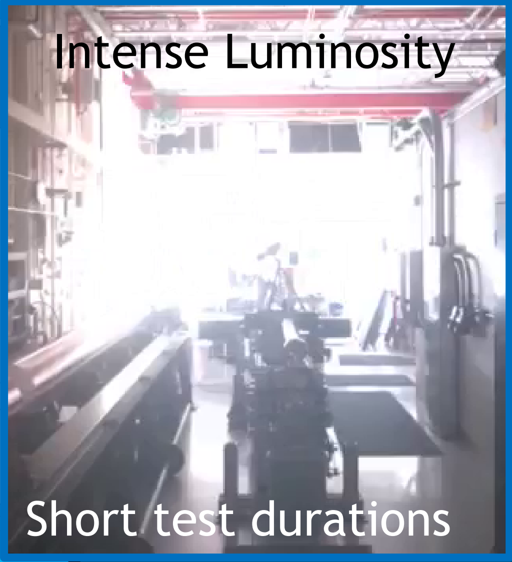




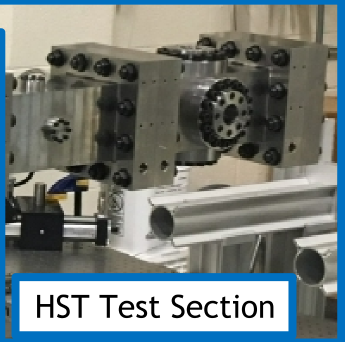


Very High Temperatures





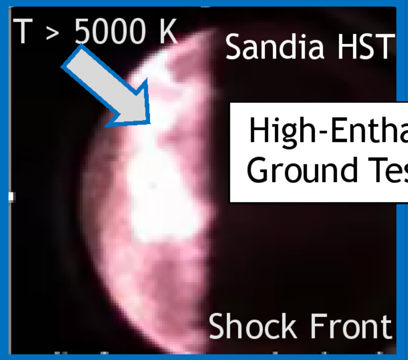
High Pressures

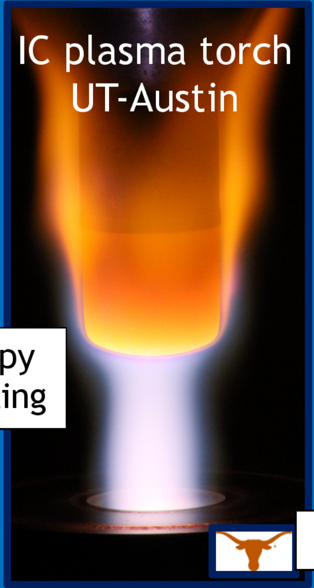


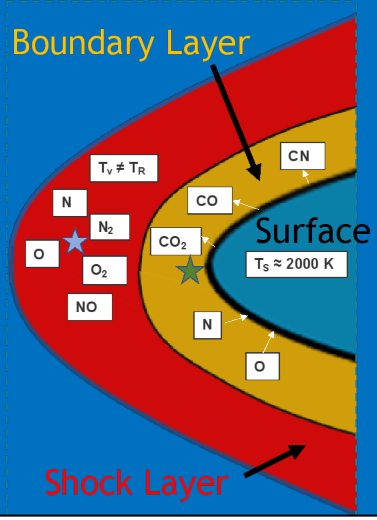
These environments present substantial measurement challenges!

Diagnostic applications at Sandia: Energetics and Hypersonics

Hypersonics development and ground testing

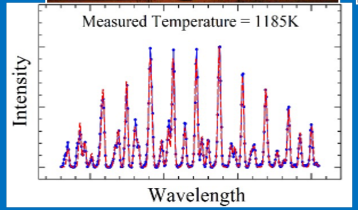




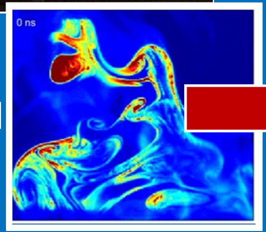


Surface Thermochemistry

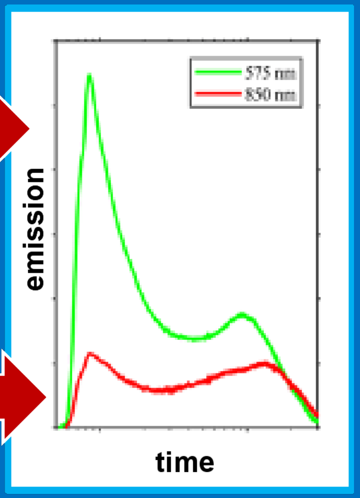
Detonation Performance and Optical Output



Temperatures (CARS/LIF/Emission/Abs)



Particulates (LII/Abs/Sampling)

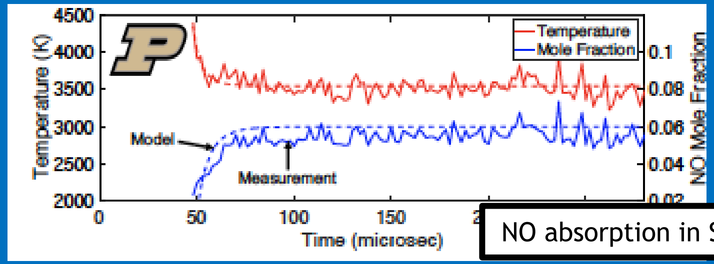


Our Partners

- Purdue
- Spectral Energies
- Texas
- Illinois

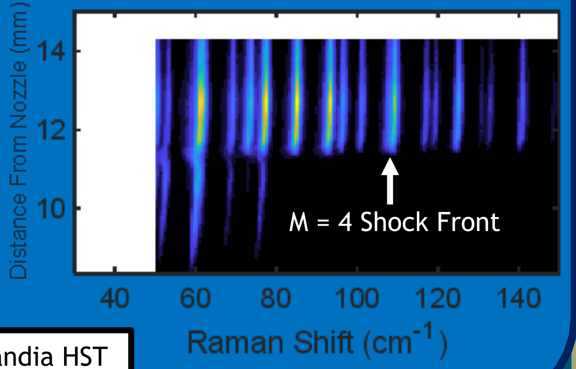
Laser Diagnostic Development

- Pulse-burst CARS/LIF/LII
- Short-pulse (fs/ps) diagnostics
- Emission/Absorption



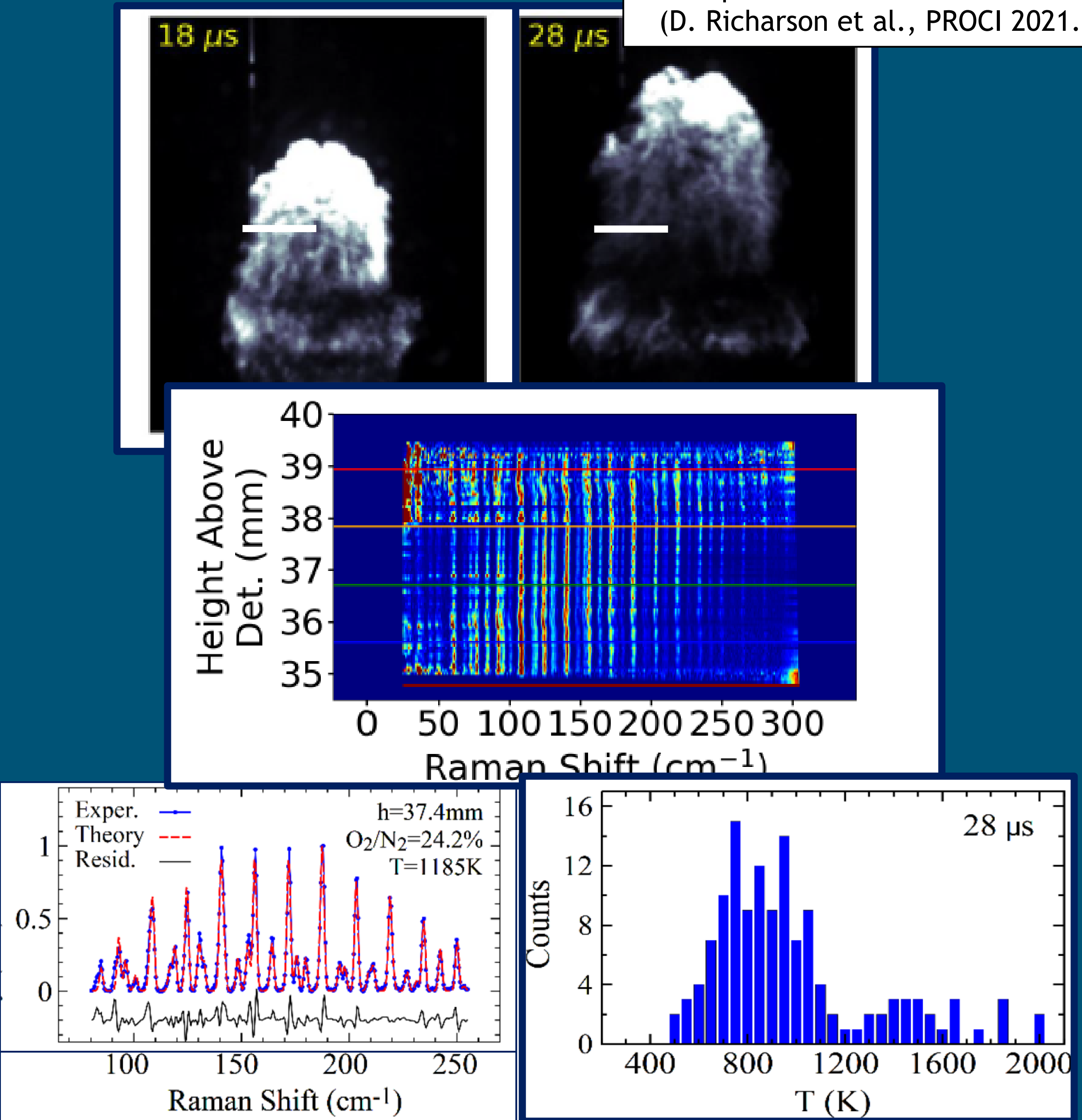
NO absorption in Sandia HST

fs/ps CARS imaging in a compressible flow

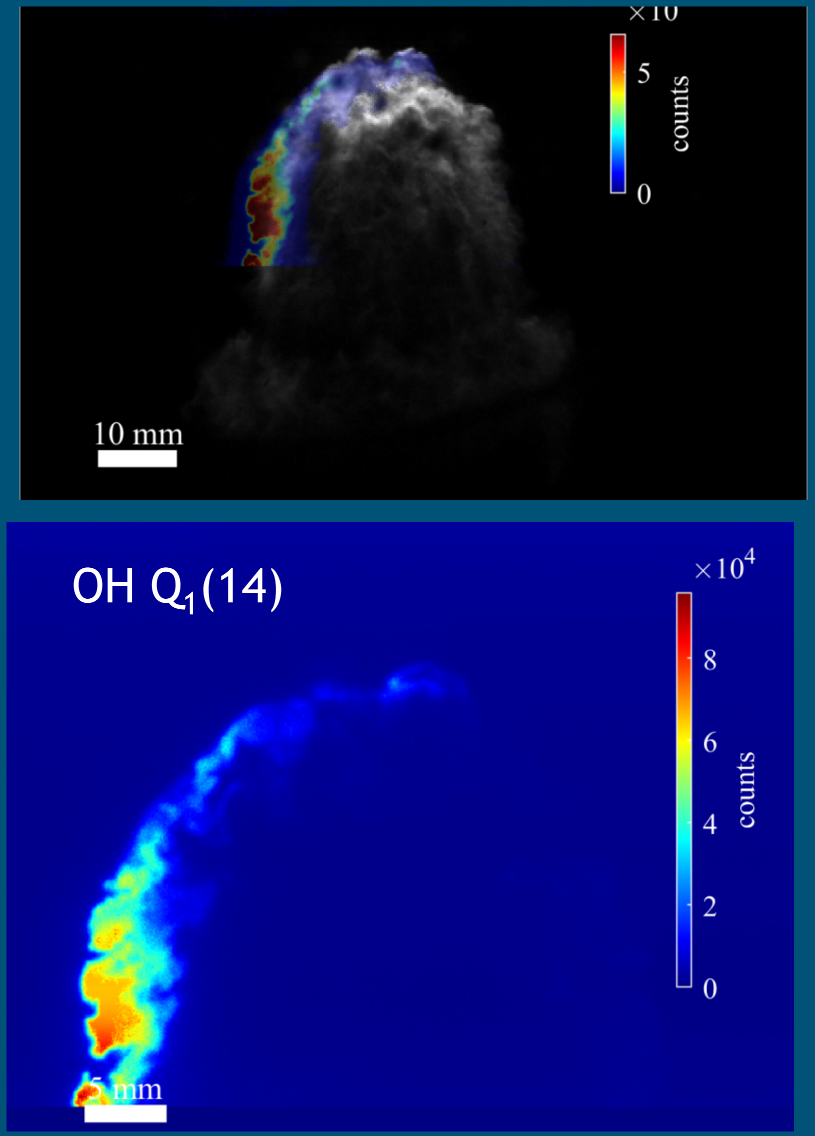


Thermometry in detonation environments: fs/ps CARS and OH PLIF

Fs/ps CARS in RP-80 detonator
(D. Richarson et al., PROCI 2021.)



OH PLIF in an RP-80 detonator



Thermometry in detonation environments: fs/ps CARS and OH PLIF

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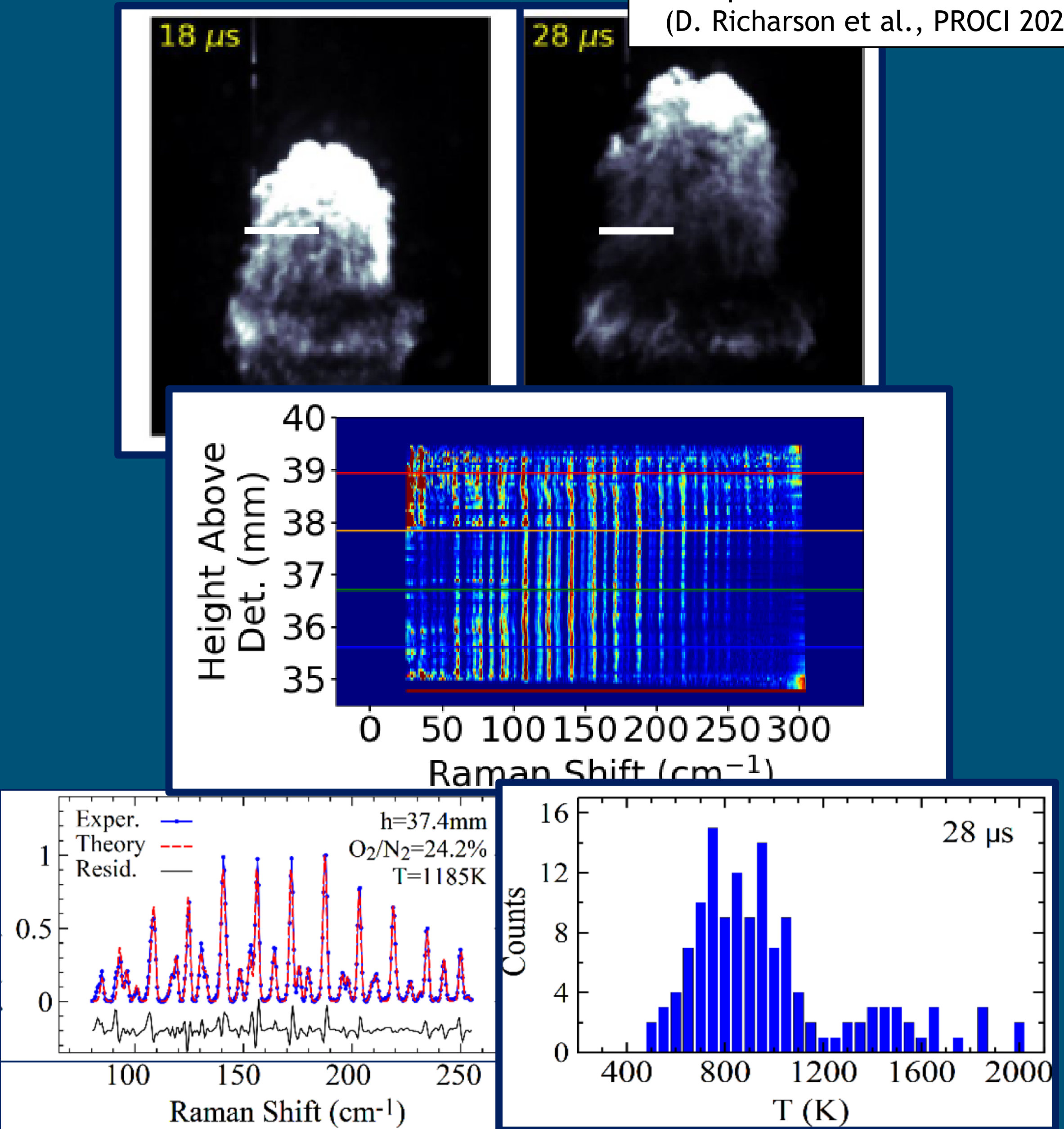
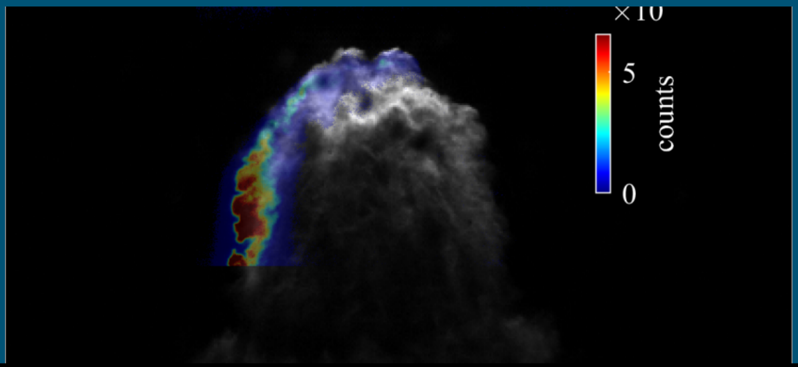


OH PLIF in an RP-80 detonator



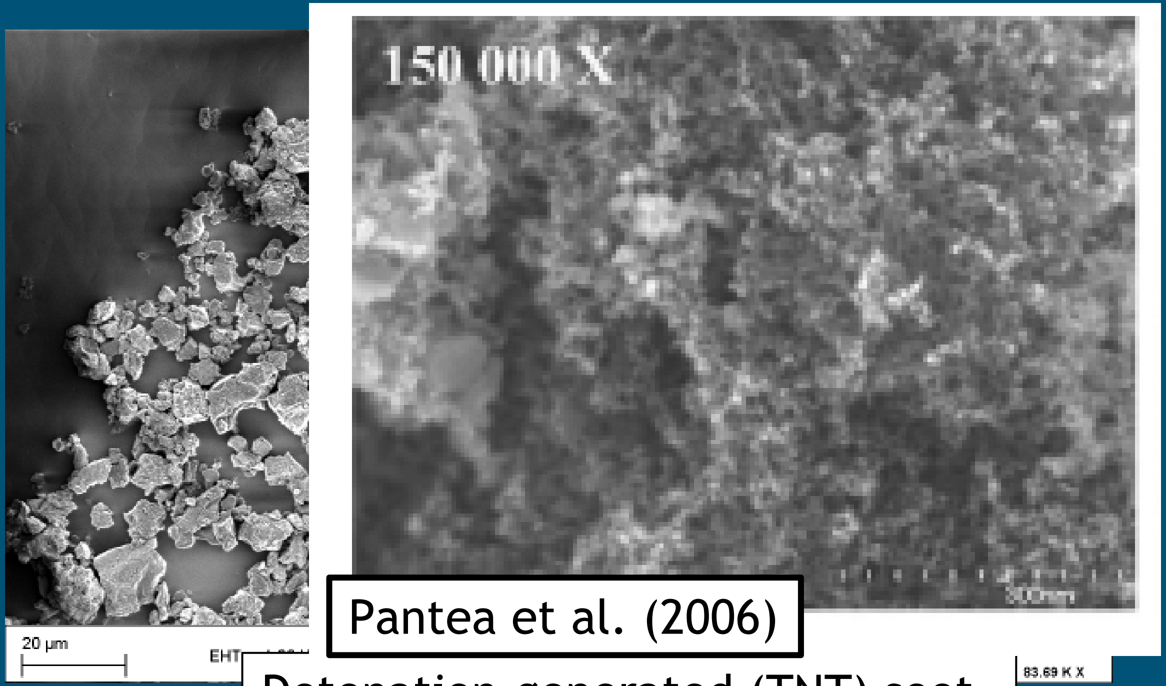
Success:
- Visualizes evolution of gas-phase reaction zones

Challenges:
- Significant UV laser sheet attenuation
- Pressure variation across field of view
  - Spatial gradients in broadening, line shift, quenching
- Spatial gradient in pressure and Doppler shift

Next Steps:
- Explore other explosives with reduced soot
- Explore different line pairs for extreme temperature thermometry
- Scale up where possible!

Detonation soot diagnostics present new challenges

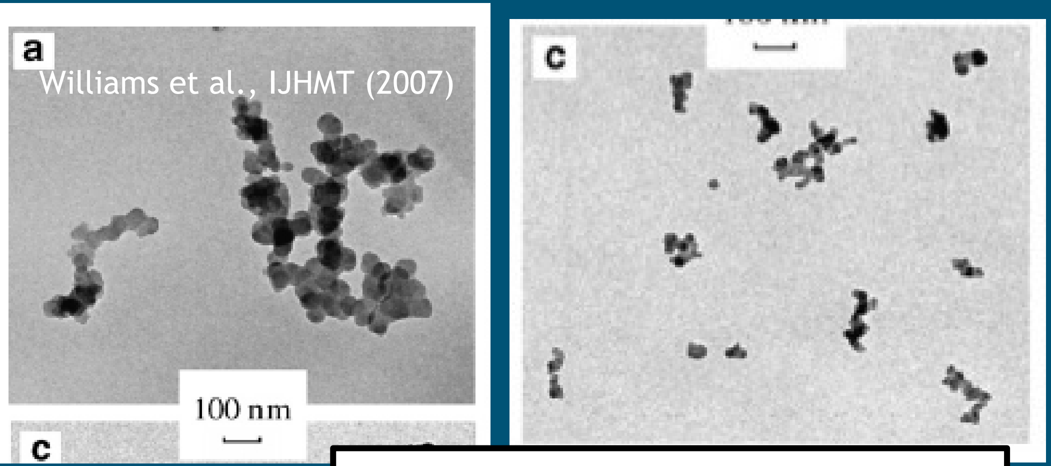
- Soot is *the* key optical emitter in explosively generated fireballs
- Carbon generated in detonation can differ from flame-generated soot
  - Diamond peaks observed in soot Raman spectra
  - Early time: very high T/P
  - Late time fireball more like air-fed combustion



Pantea et al. (2006)

Detonation-generated (TNT) soot

Laser diagnostics depend on soot optical properties
- **Refractive index**
- **Scattering**
- **Particle size and morphology**

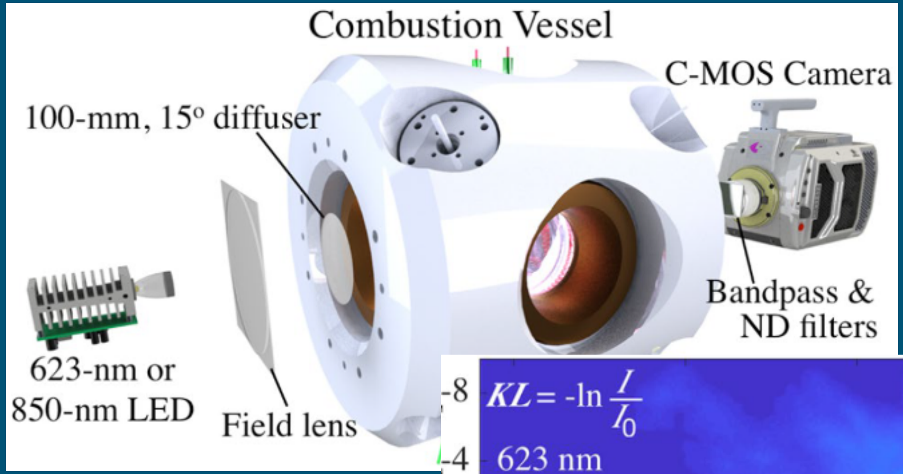


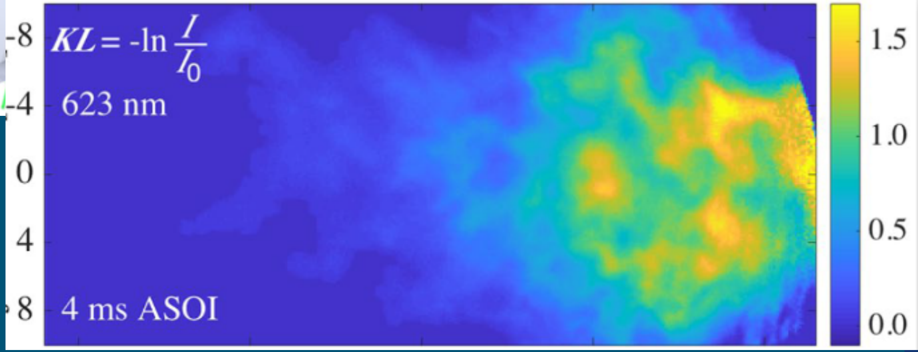
Williams et al., IJHMT (2007)

Flame-generated soot

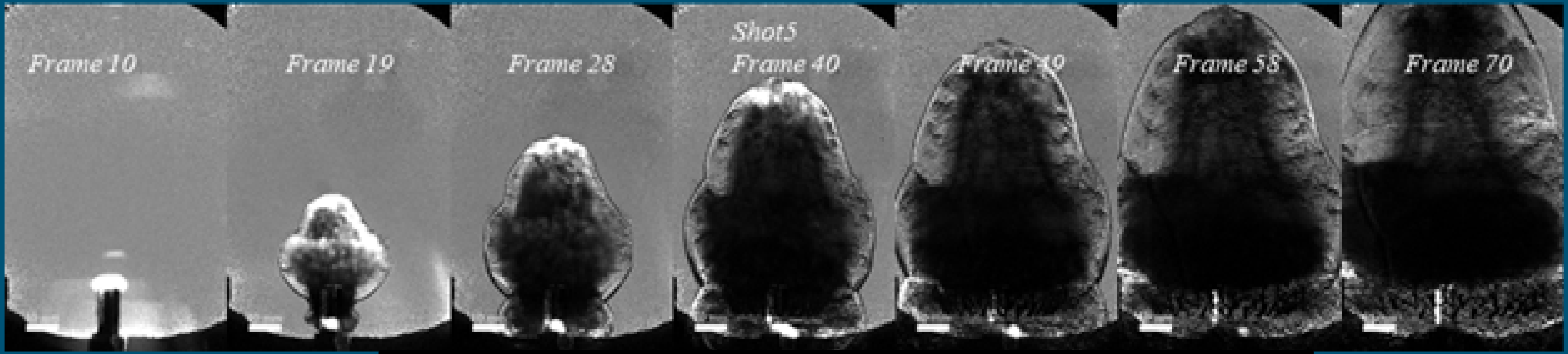
in situ diagnostics for detonation soot imaging: LII and diffuse backlit illumination (DBI)

100-kHz pulse-burst LII (Alex Brown, Mateo Gomez)





DBI imaging of diesel soot (Skeen *et al*. 2018)

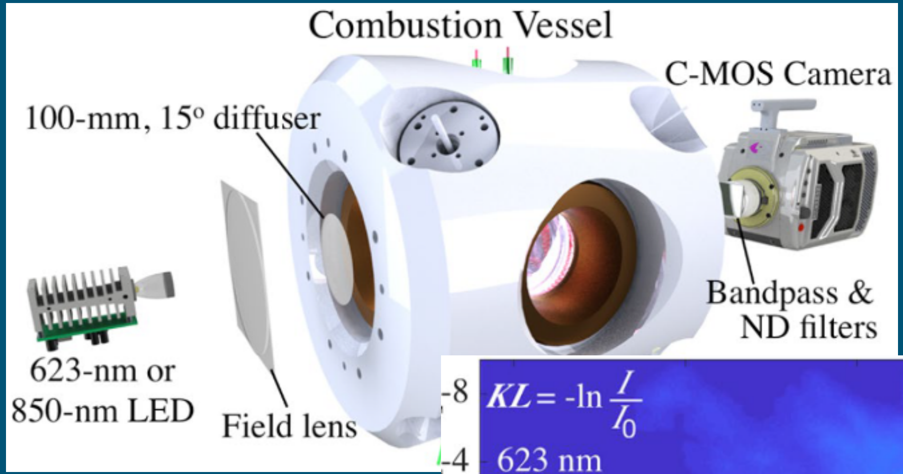


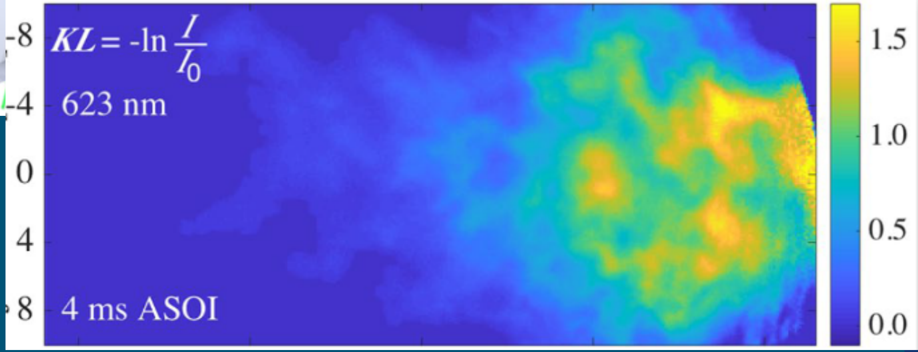
Schlieren

Detonator Soot Imaging: D. Guildenbecher, Sandia

in situ diagnostics for detonation soot imaging: LII and diffuse backlit illumination (DBI)

100-kHz pulse-burst LII (Alex Brown, Mateo Gomez)





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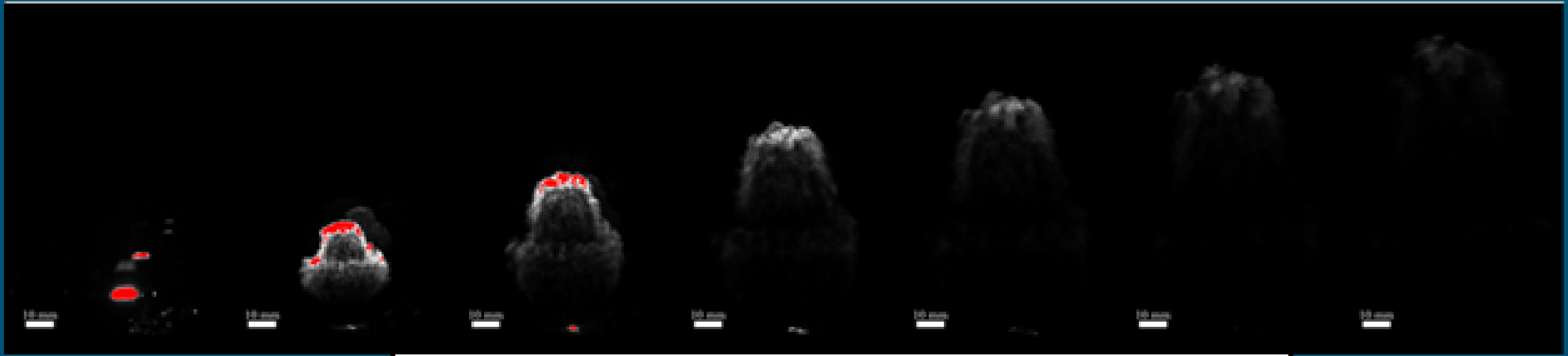
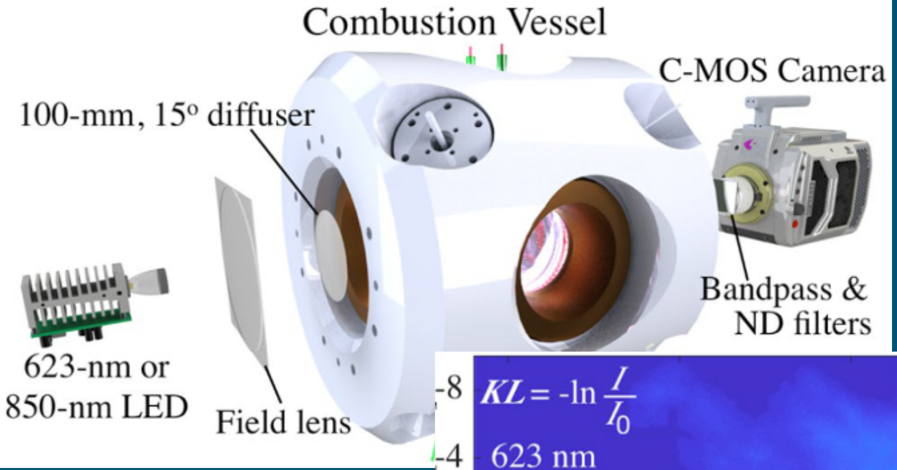


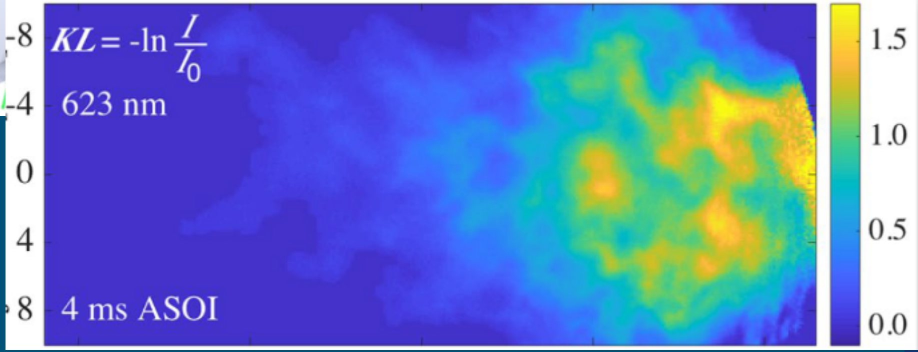
Emission

Detonator Soot Imaging: D. Guildenbecher, Sandia

in situ diagnostics for detonation soot imaging: LII and diffuse backlit illumination (DBI)

100-kHz pulse-burst LII (Alex Brown, Mateo Gomez)





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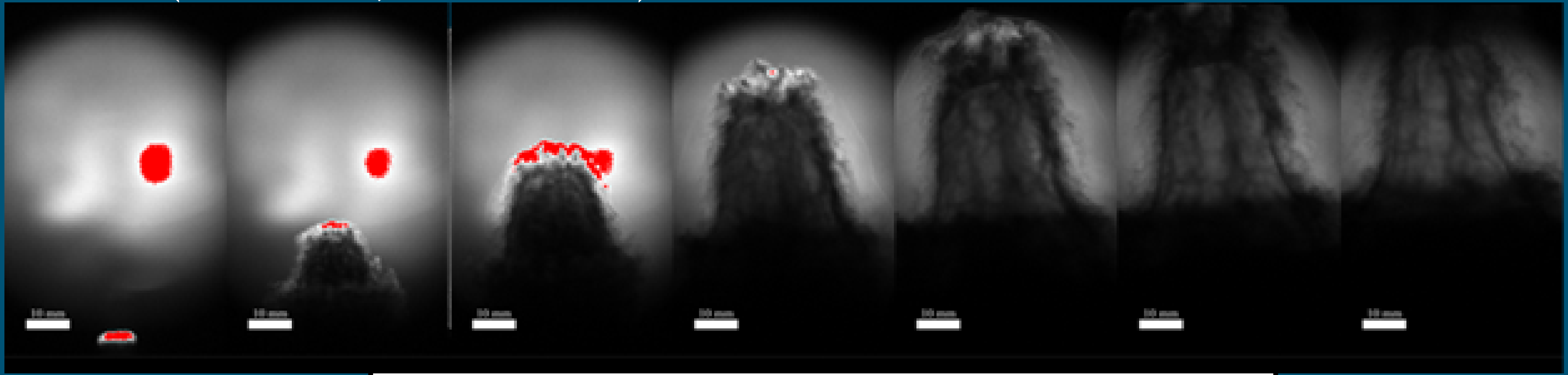

DBI

Detonator Soot Imaging: D. Guildenbecher, Sandia

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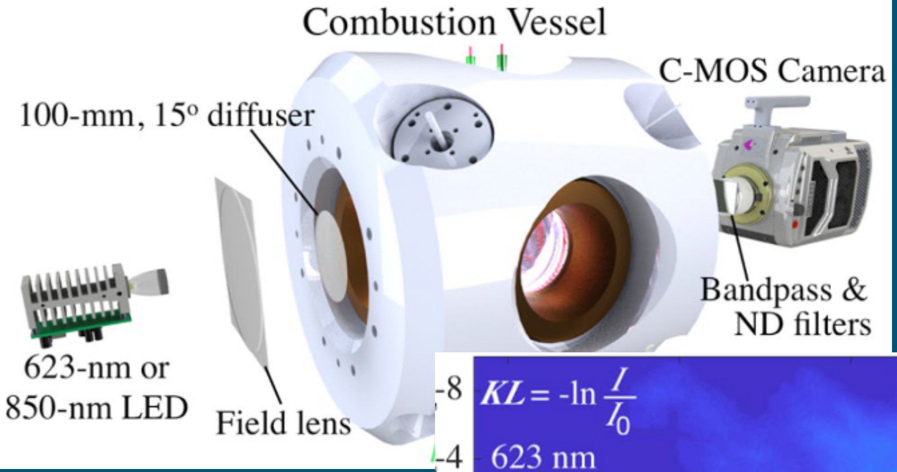
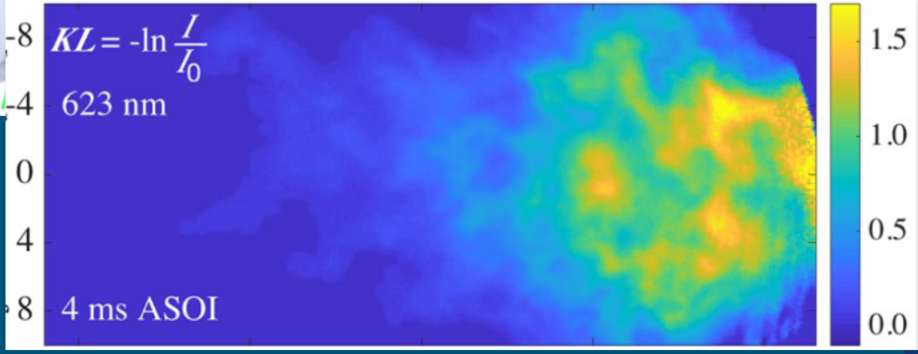
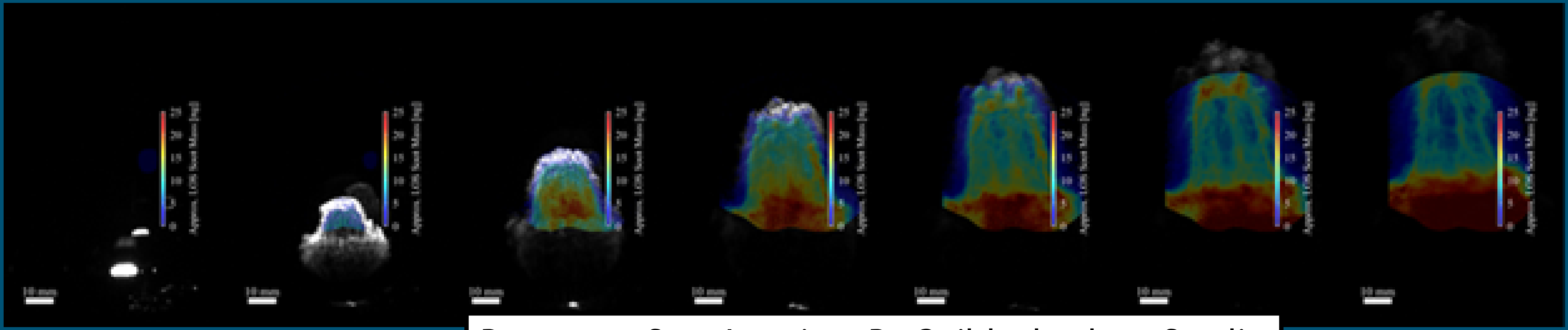




DBI imaging of diesel soot (Skeen *et al.* 2018)



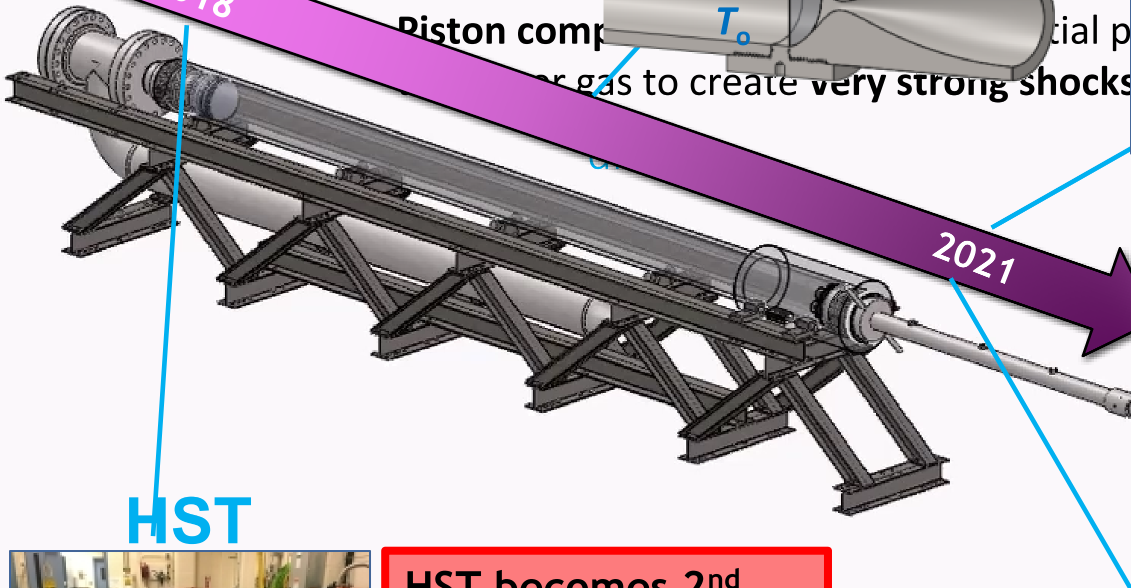
Optical Density

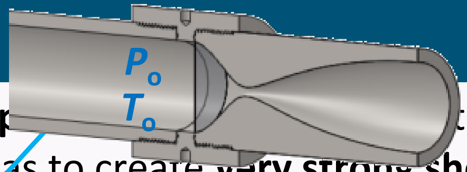
Detonator Soot Imaging: D. Guildenbecher, Sandia

Sandia Free-Piston High-Temperature Shock Tube/Shock Tunnel (HST)

Design shock tunnel for hypersonic, *reacting* flight environments

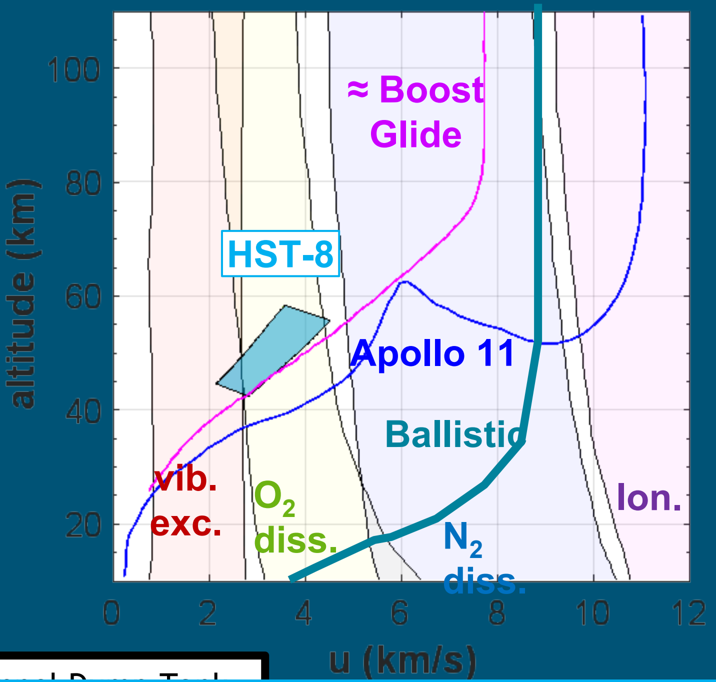
Piston comp… gas to create **very strong shocks**



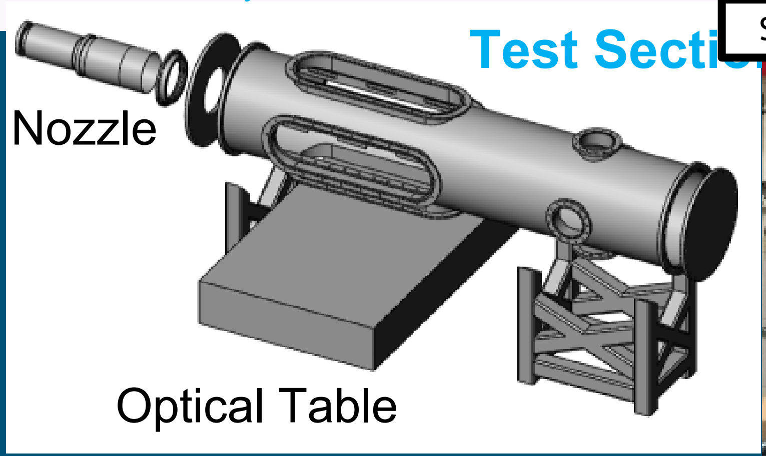


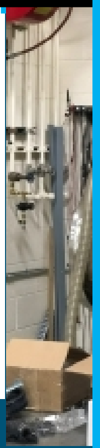
Commission Shock Tunnel

Estimated Operating Map



HST becomes 2nd free-piston tube to ever fire in the U.S.

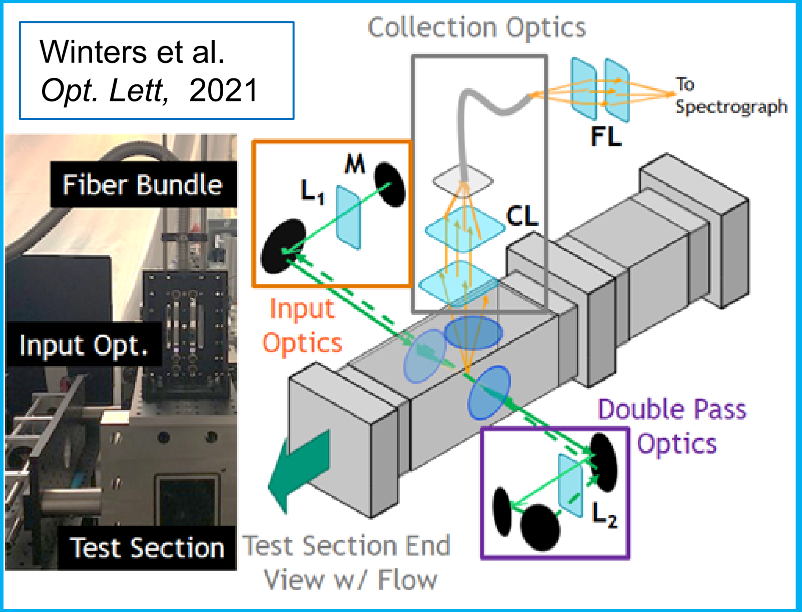




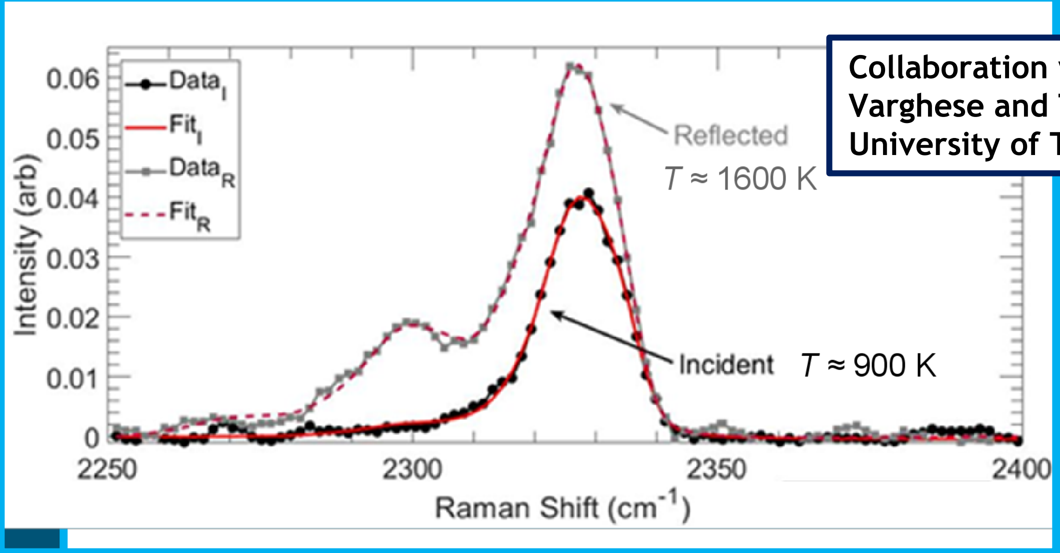
- Freestream Mach number of 8 and velocities > 4 km/s
- Enthalpies of order 10 MJ/kg and stagnation temperatures ≈ 6000 K
- Conditions are in regions of significant thermodynamic and chemical non-equilibrium

Spontaneous Raman Scattering N_2 Thermometry in the Sandia HST

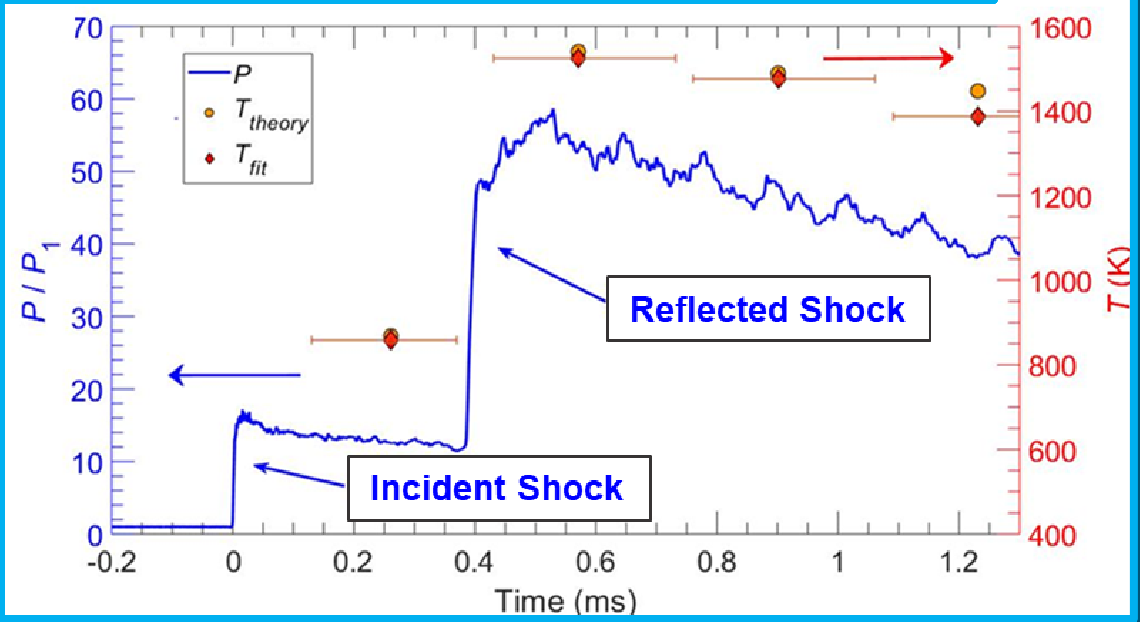
Raman-Scattering Configuration in HST



Measured and Modeled Vibrational Raman Spectra

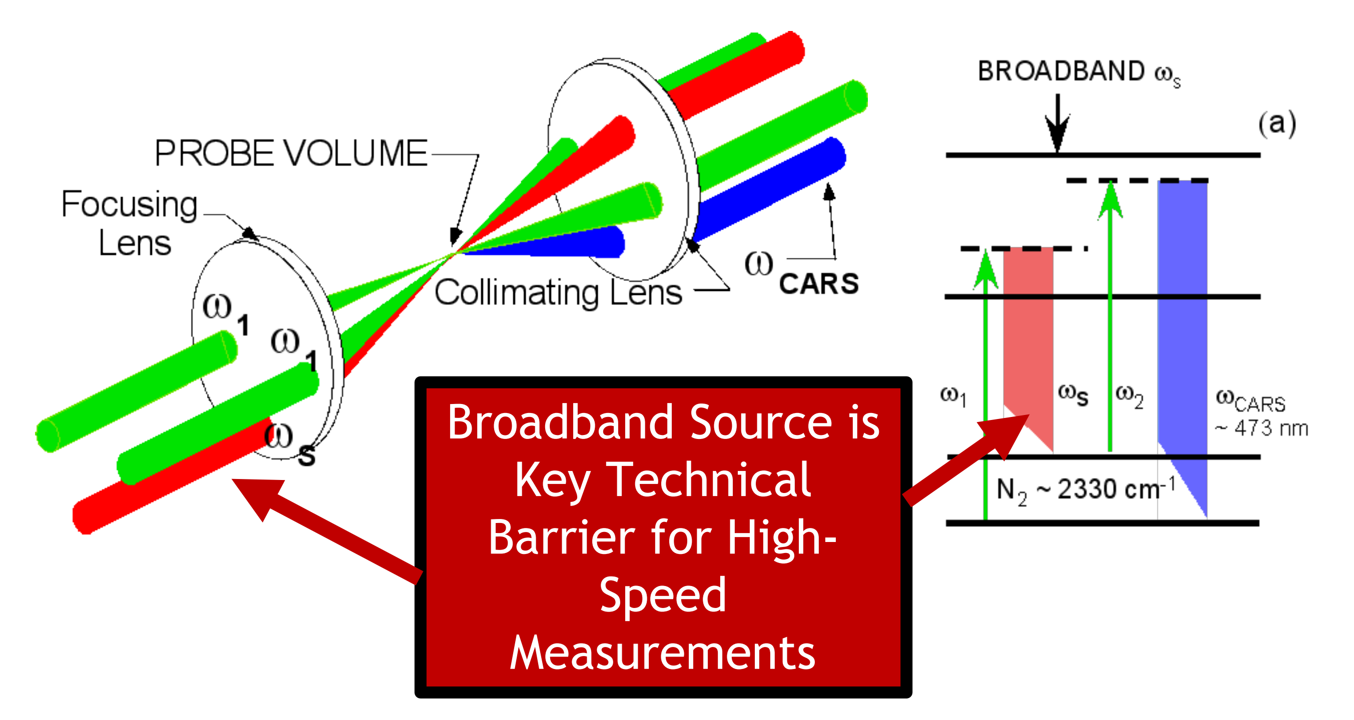


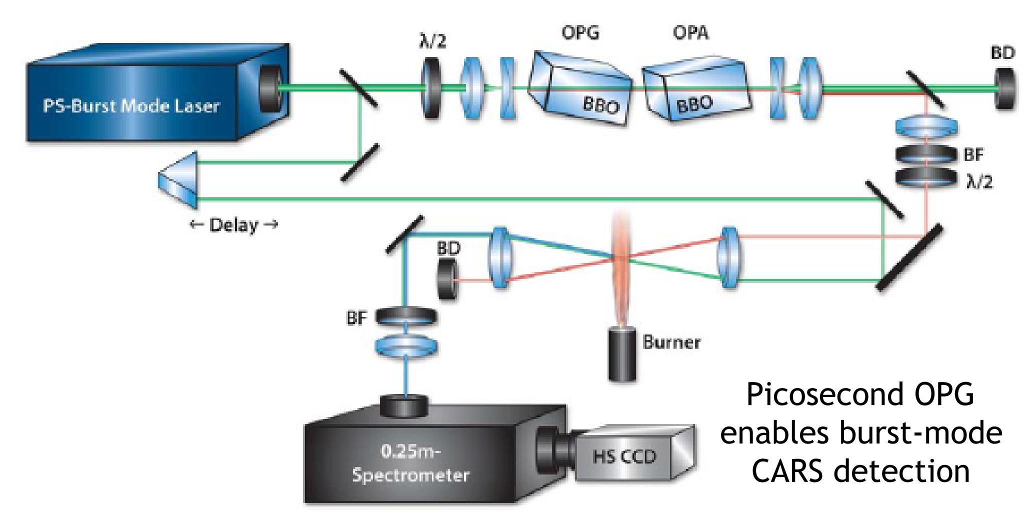
Collaboration with Prof. P. Varghese and T. Haller the University of Texas, Austin



- Raman spectra collected at 5 kHz by averaging two laser pulses with PB laser rep rate of 10 kHz (500 mJ per 200 ns pulse)
- Raman-measured temperatures are generally in excellent agreement with equilibrium calculations
- Spontaneous Raman is versatile but limited
  - Very high density
  - Very low luminosity

Pulse-Burst CARS: Sandia/SE/Purdue Collaboration

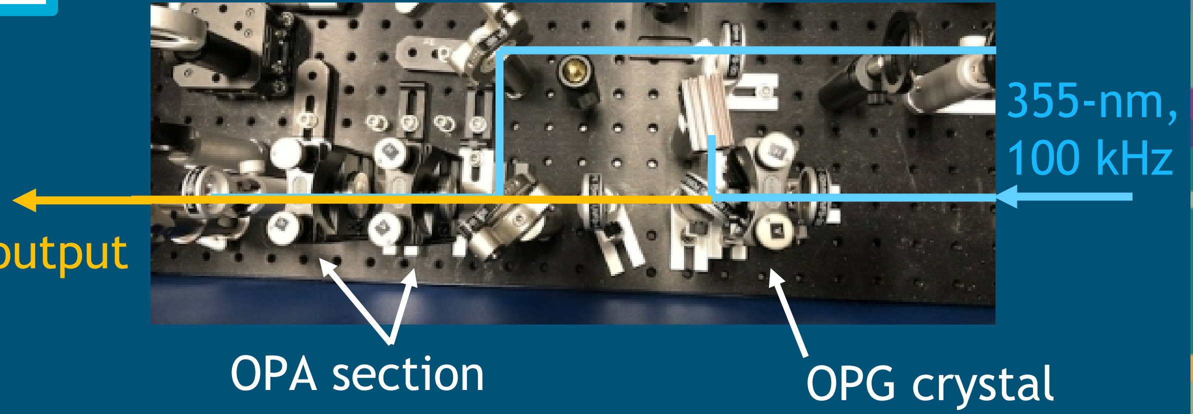




Picosecond OPG/OPA for 100-kHz broadband generation (Roy et al., 2015)

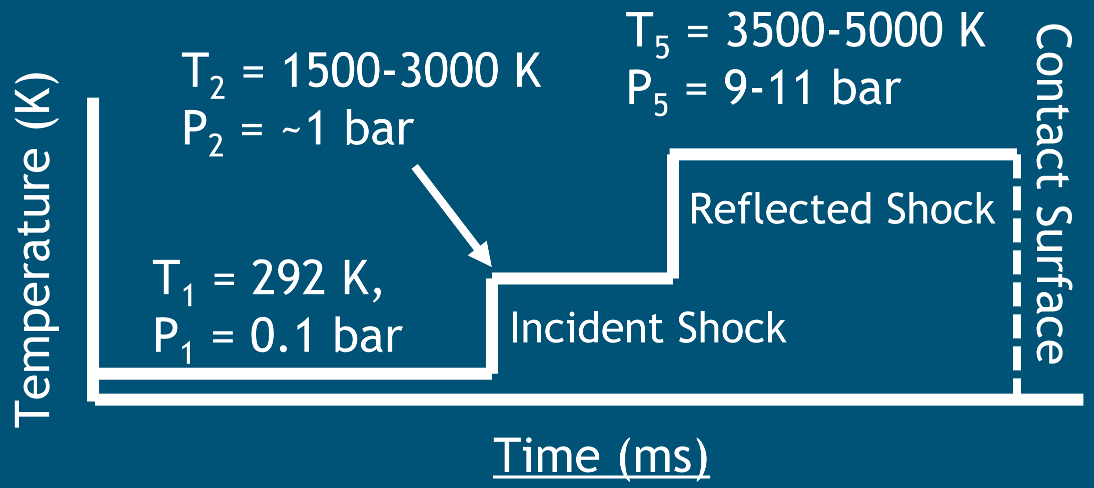
CARS enables detection in more challenging environments!

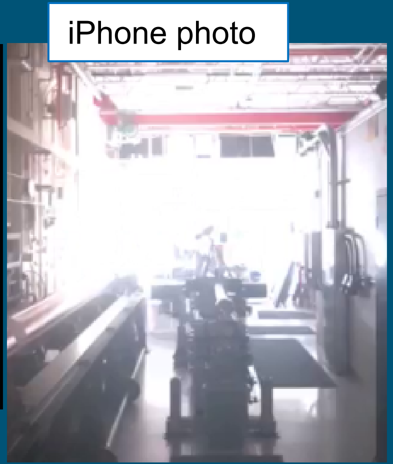
- T > 4000 K
- High background luminosity
- Higher data acquisition rates

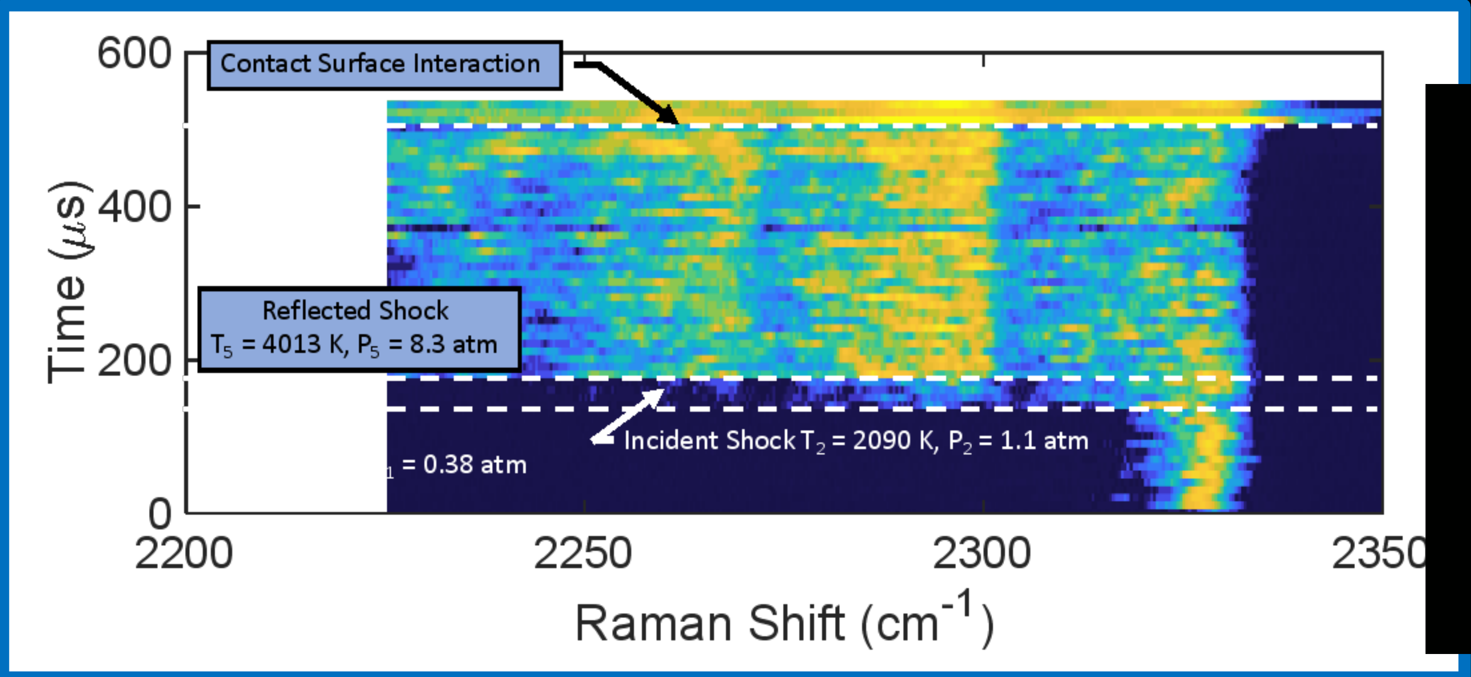


100-kHz picosecond CARS thermometry in Sandia's HST

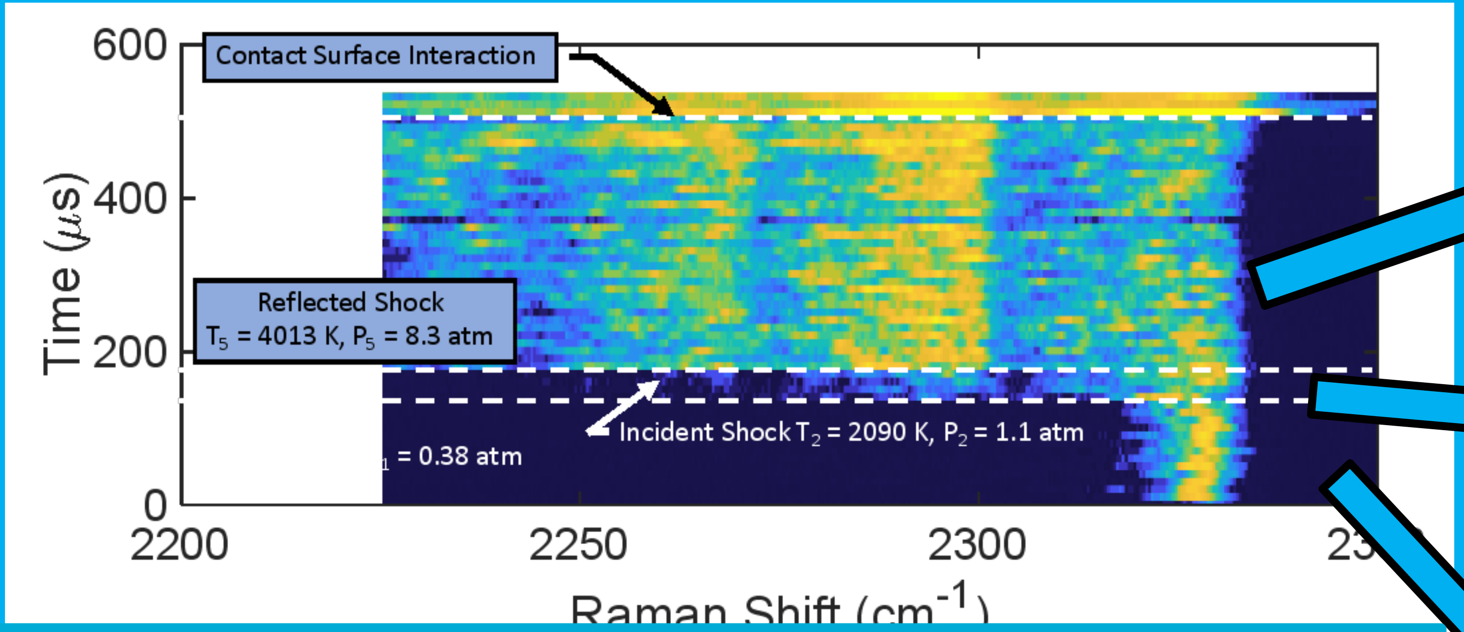
The reflected shock state yields very high temperature conditions of interest for hypersonics applications

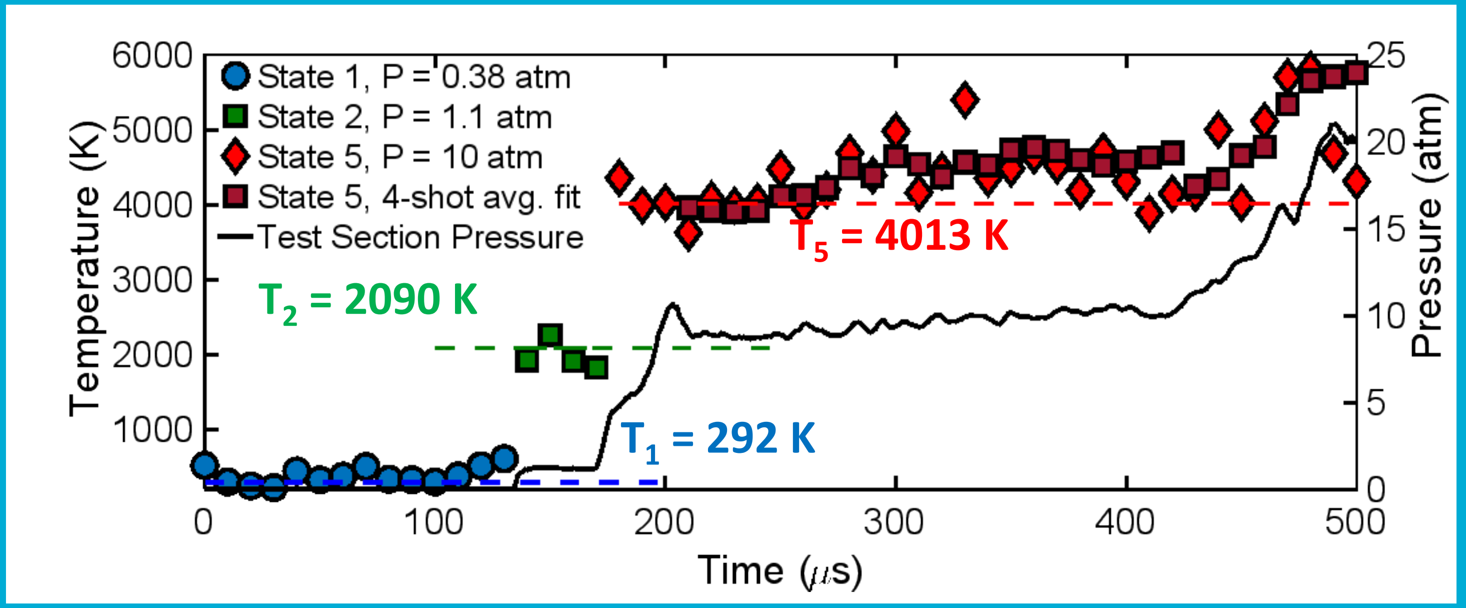


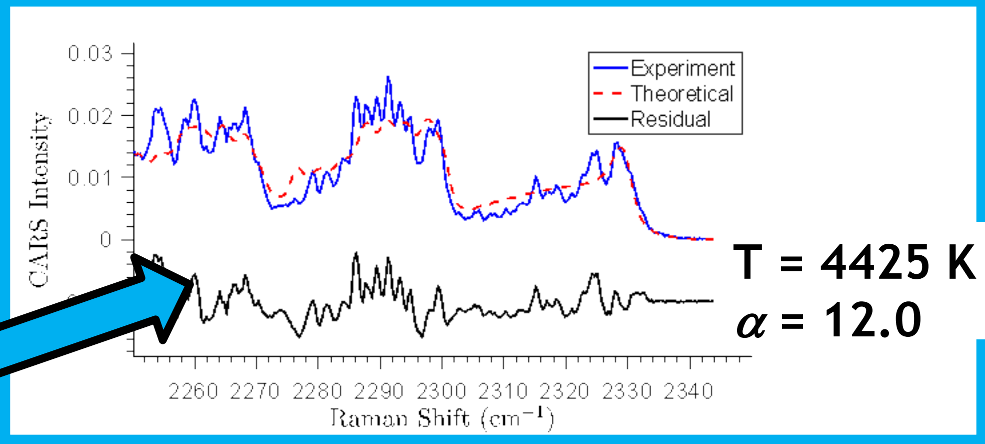


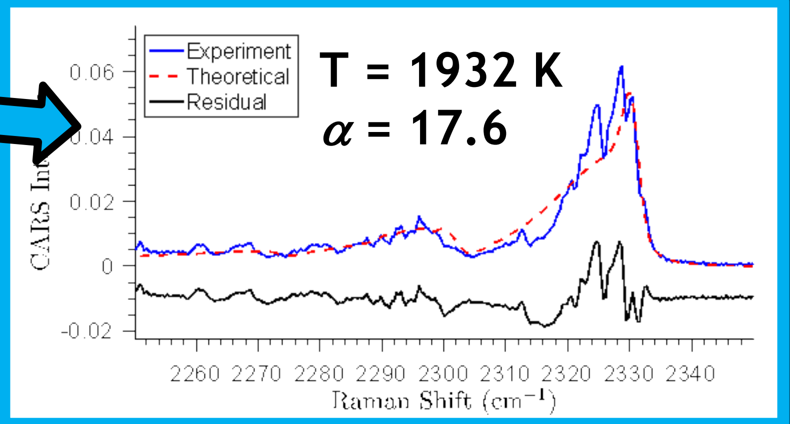


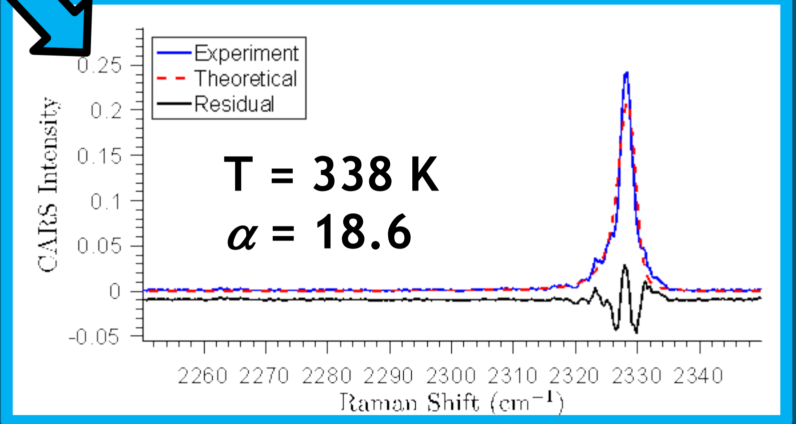
100-kHz picosecond CARS results









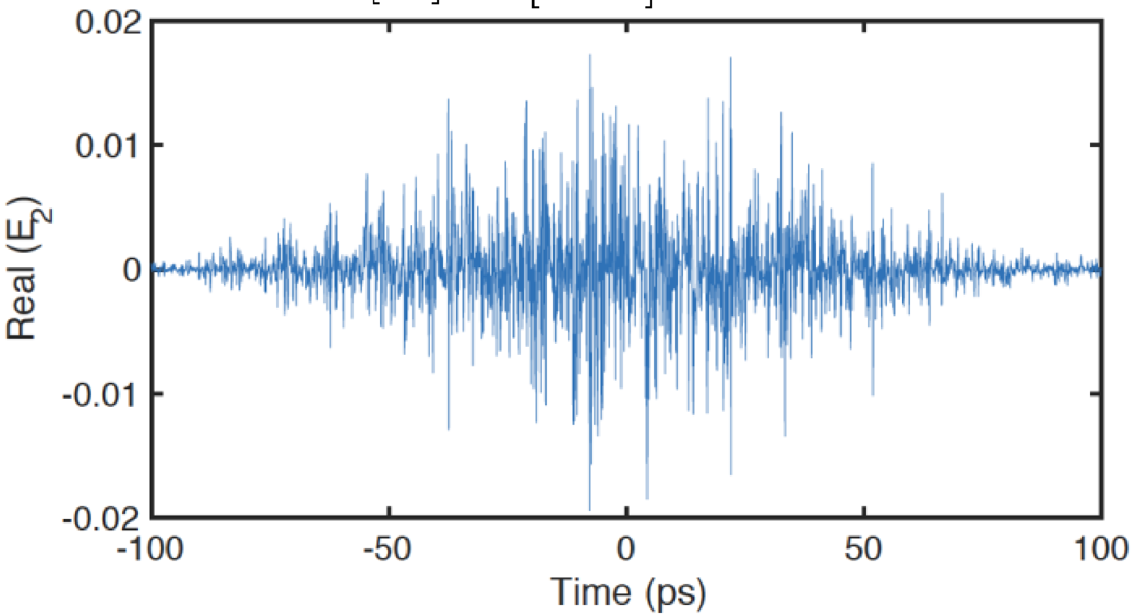


Nanosecond pulse-burst CARS can improve our measurements

Dominant source of CARS noise is the quality of the broadband pulse

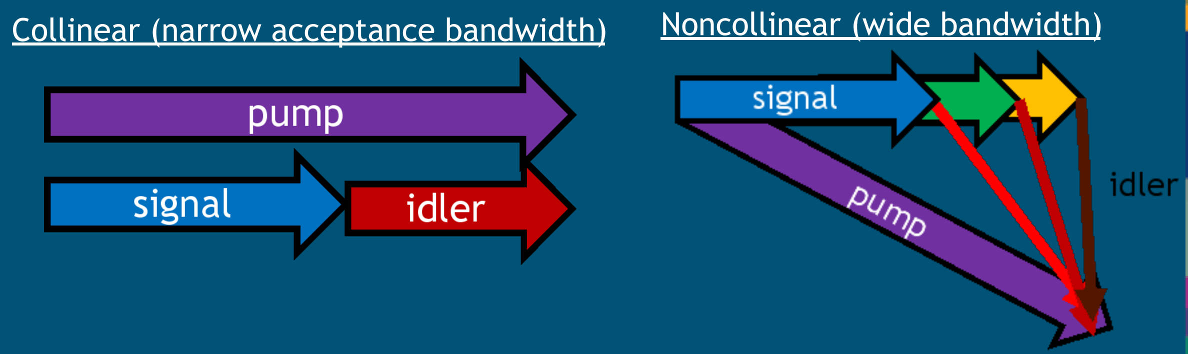
Time-Bandwidth Product

$$\Delta t[\mathrm{ps}]\,\Delta\omega[\mathrm{cm}^{-1}] \geq 14.67$$



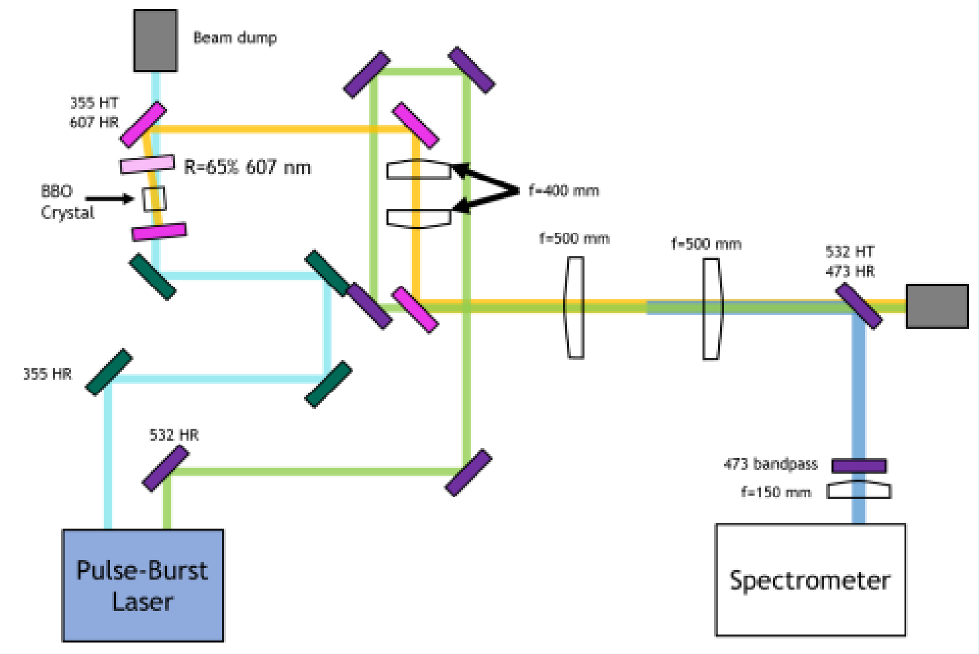
- 150-fs “coherence time”
- ~450X the Fourier transform limit
- Solutions?
  - Femtosecond pulses → transform limited
  - Nanosecond pulses → time averaging

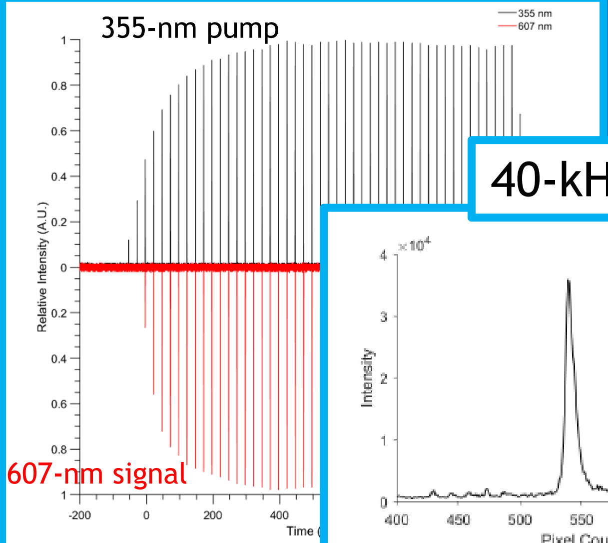
- Nanosecond pulses will result in significant averaging over Stokes pulse noise
  - 50-60 ps = 0.5-2 Raman lifetimes
  - 10 ns = hundreds of Raman lifetimes
- Reduced CARS modeling uncertainties
  - Pulse width, pulse delays, pulse shapes are much less important



NOPO matches signal and idler group velocities to phase match across wide bandwidth!

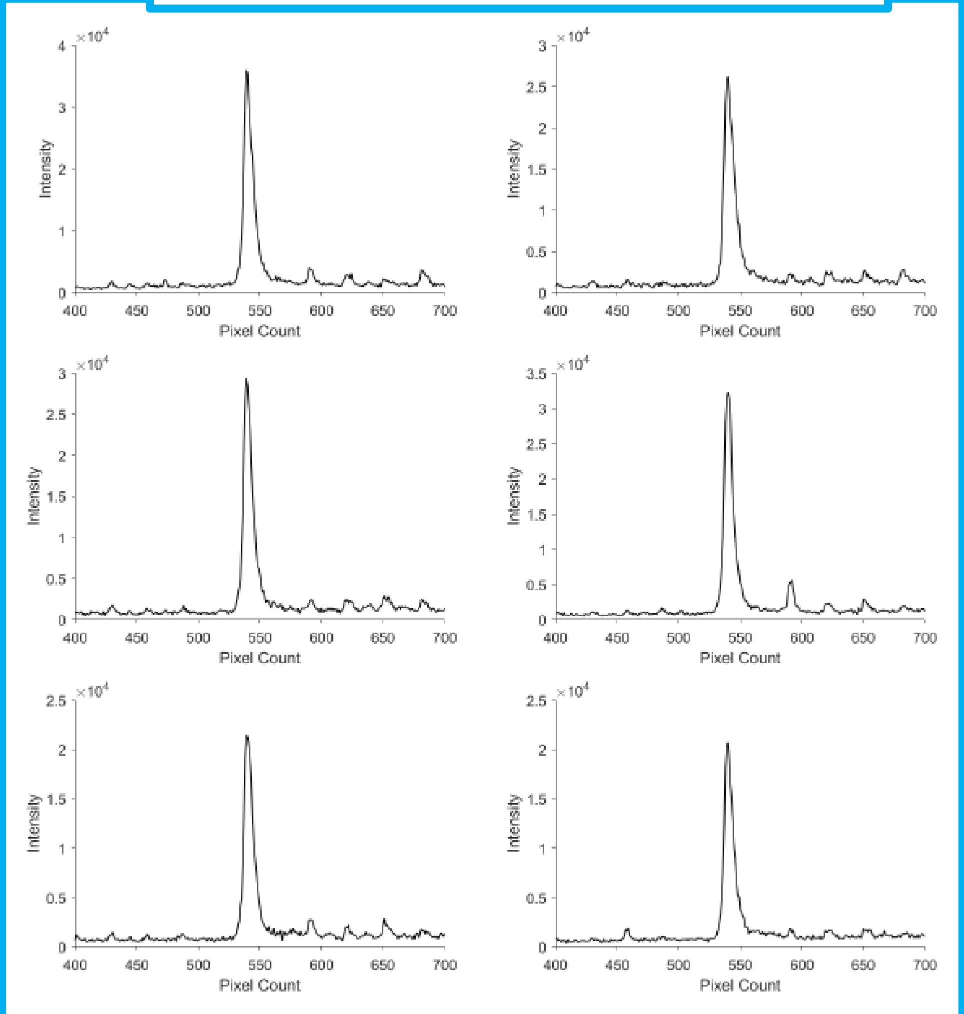
Pulse-burst *nanosecond* CARS demonstration



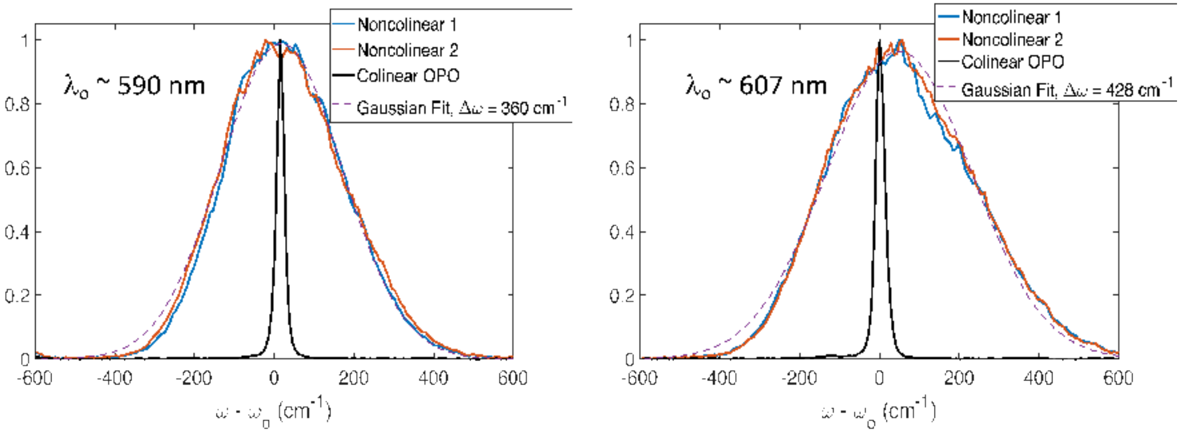


40-kHz pulse-burst-pu

40-kHz CARS spectra in room air

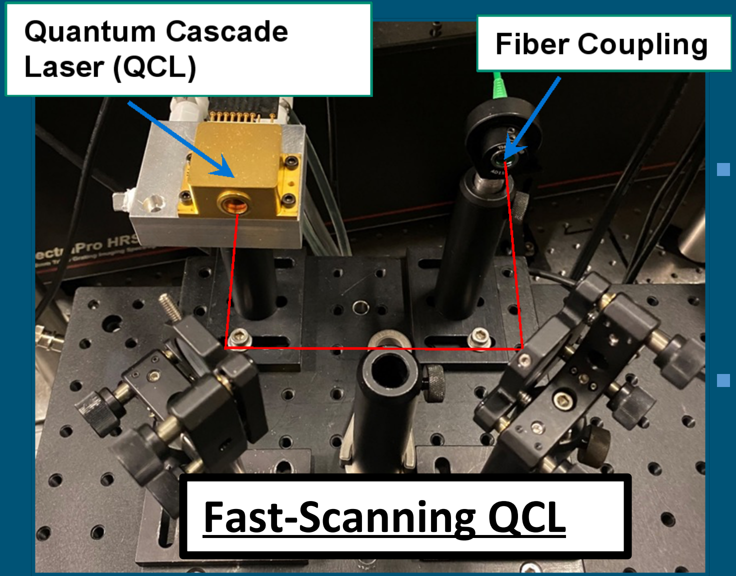


NOPO Provides Enhanced and Tunable Bandwidth

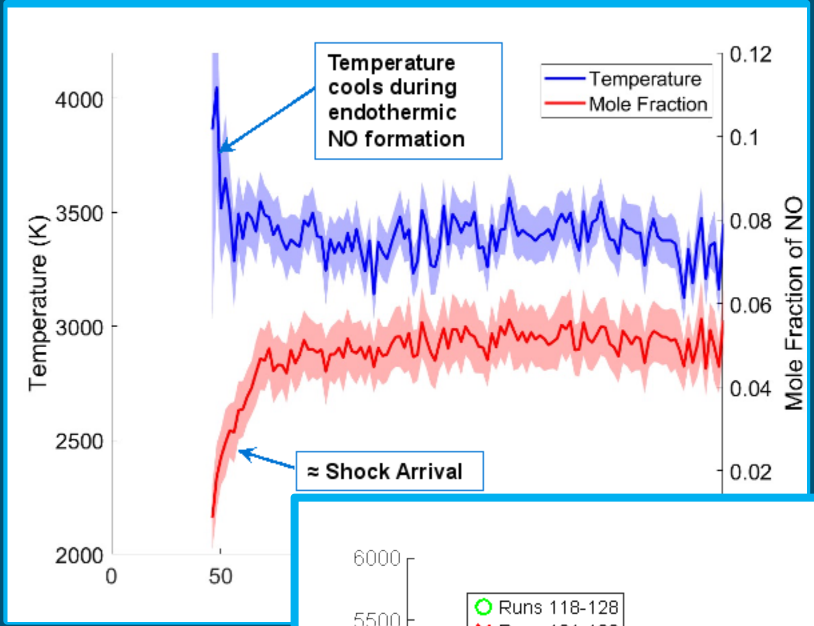


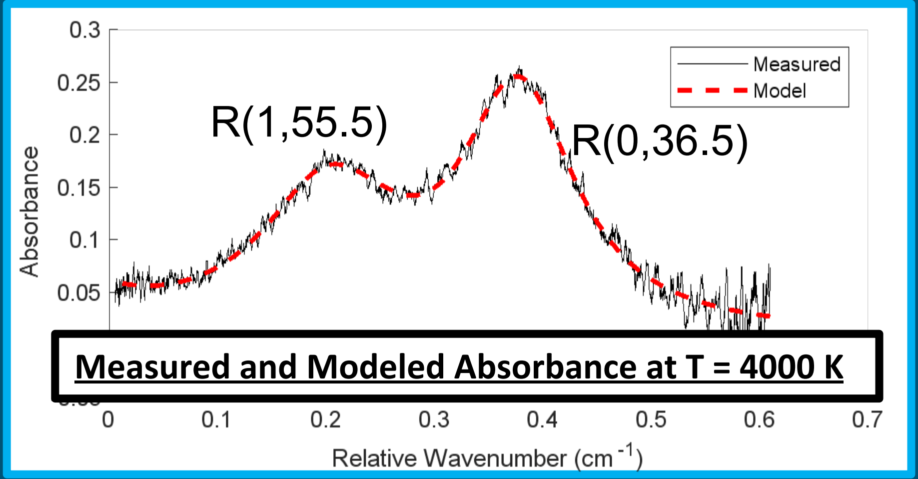
Laser Absorption Spectroscopy (LAS) in the Sandia HST

Collaboration w/ M. Ruesch and C. Goldenstein

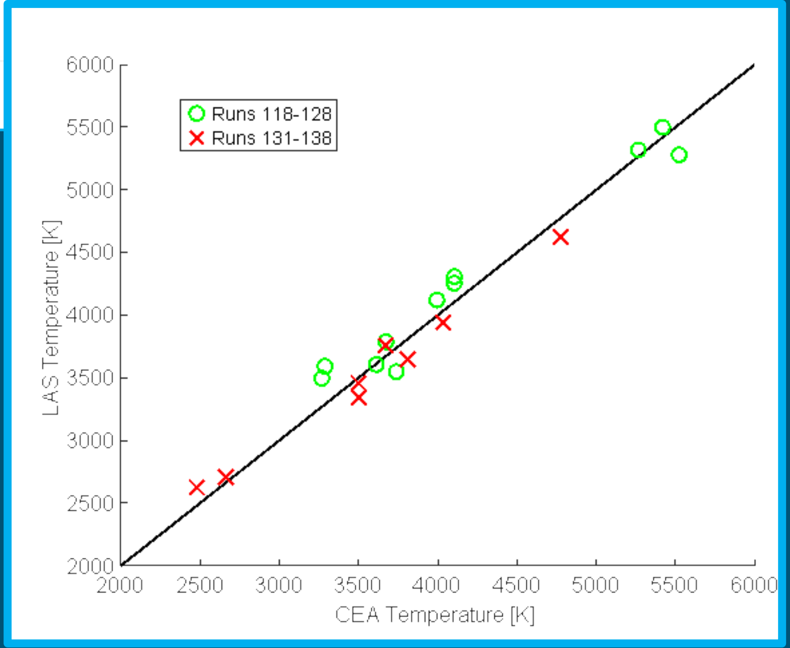


- QCL *rapidly* scans spectroscopic features in the mid-infrared
- 500 kHz is our rate record so far…

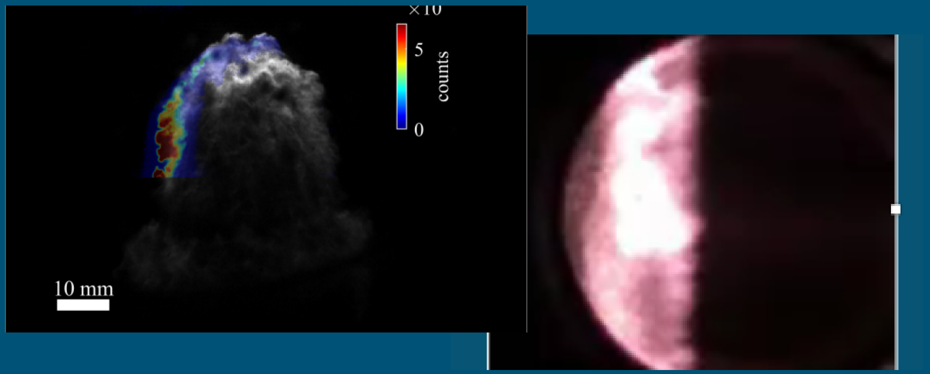




- We have measured temperatures up to 5500 K at high repetition-rates.
- Data like these inform thermochemistry models for air processed by strong shock waves.



Outlook: There are significant new opportunities for laser diagnostics in reacting gas-phase systems outside of combustion!

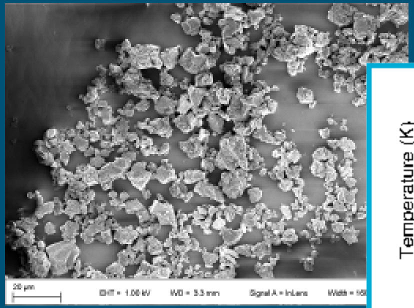


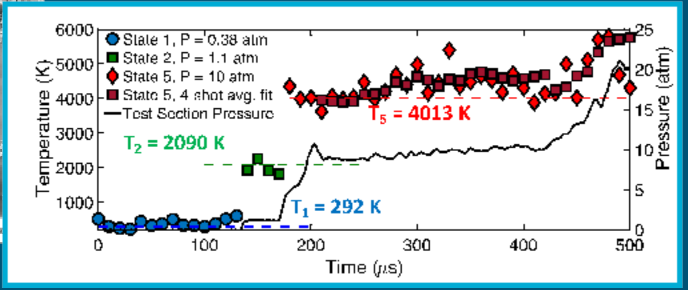
Our team at Sandia is presently focused on:

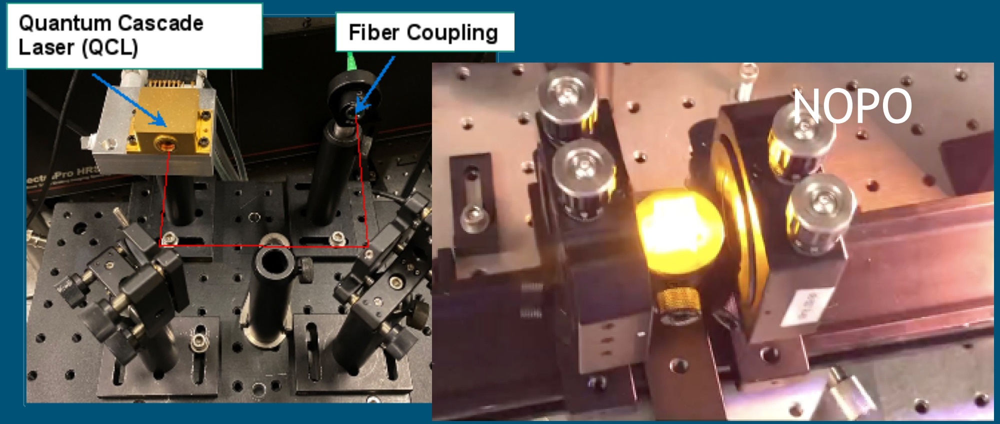
- High-enthalpy hypersonics
- Detonations and fireballs
- High-speed wind-tunnel testing (cold flow)

These problems present challenging measurement regimes

- Very high temperatures, T = 4000-6000 K and beyond
- High pressures
- Unknown optical properties and spectroscopic data (linewidths!)
- Short test times--imaging and pulse-burst at a premium!







We are applying a wide range of laser sources and techniques to these problems

- Absorption: QCL, broadband pulse-burst NOPO
- Pulse-burst imaging: LII, PLIF
- Pulse-burst ps-CARS with ns-CARS development
- Emission/pyrometry at high-speeds