Ultrabroadband coherent Raman imaging developed for multiparameter spatio-thermochemical probing of flame-wall interactions

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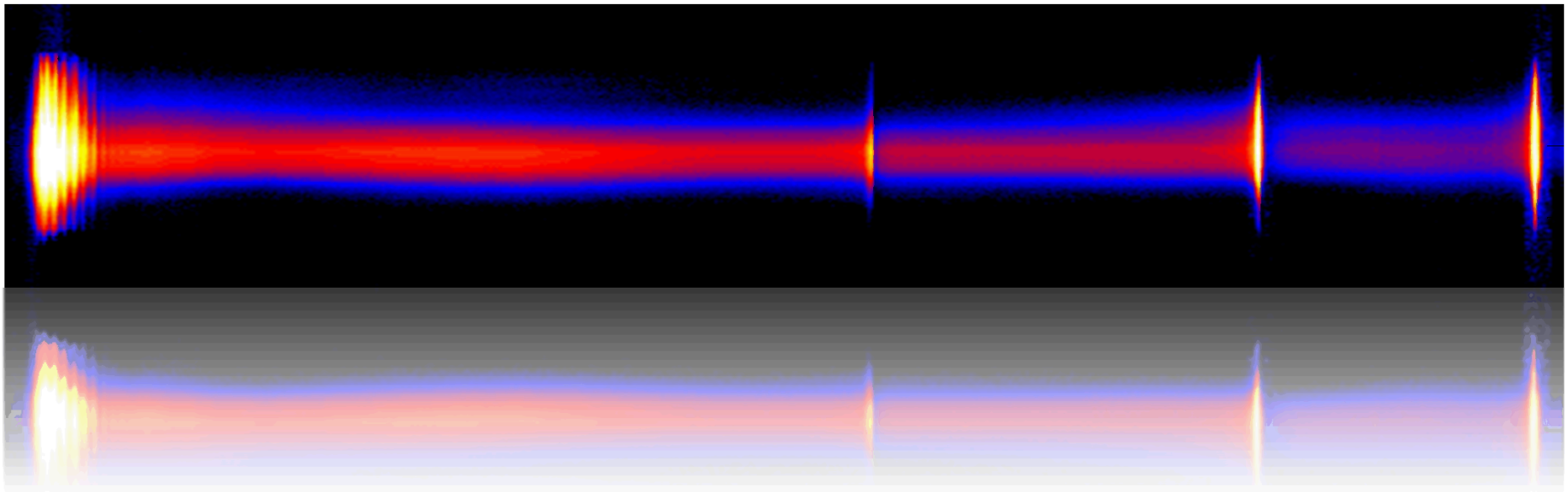


Outline of Presentation:

1. Introduction (Flame-Wall Interactions)
2. Diagnostics Development (Coherent Raman Imaging)
3. Measurement of Spatio-Thermochemical States during Side-Wall Quenching Combustion
4. Conclusions and Outlook

Flame-Wall Interactions are Important

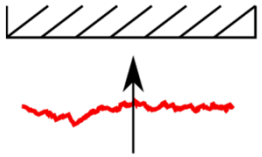
- Burned gas temperatures in combustion chambers are in the range of **1500-2500 K** and wall temperatures are between **350-750 K**
- **Heat losses** and **radical quenching** leads to flame quenching
- Incomplete combustion with **UHC, CO** and **soot** production
- Flame – wall interactions also affect **efficiency** of the overall process and **pollutant formation** [Alkidas 1999]

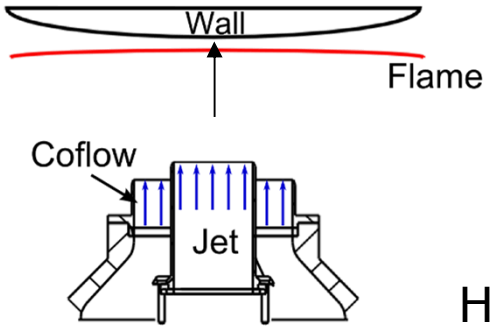
30% combustion energy in an engine is lost by heat transfer through the wall

40% of unburned hydrocarbons in engines is due to FWI

Canonical Flame-Wall Interaction

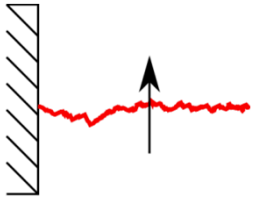
- Two pure types of flame-wall interaction
  - **Head-On** Quenchin

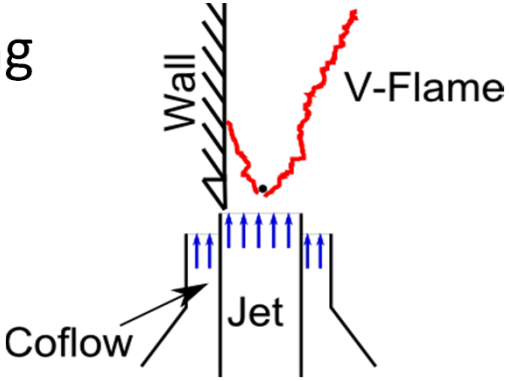




HOQ Burner

  - **Side Wall** Quenching

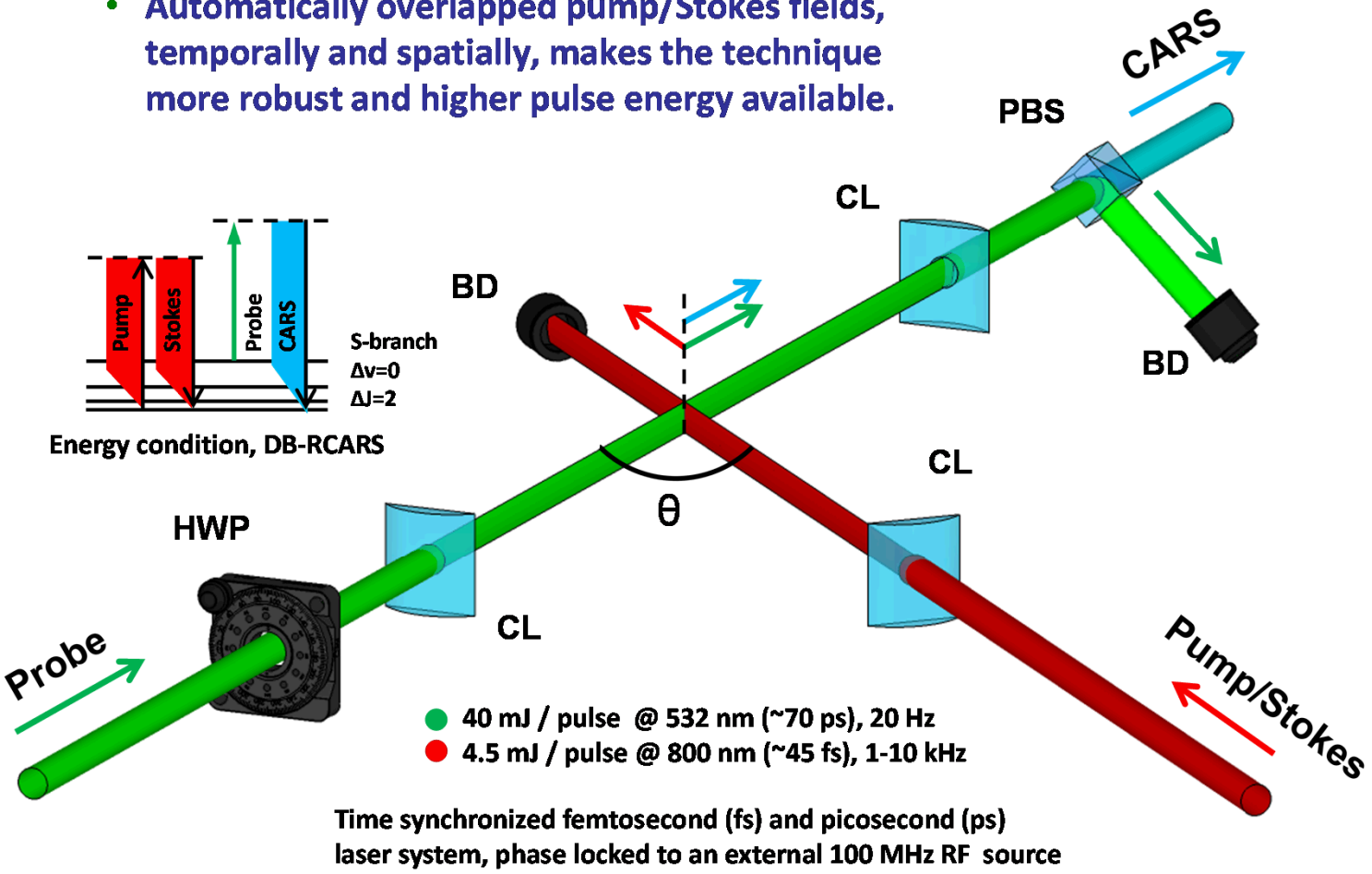




SWQ Burner

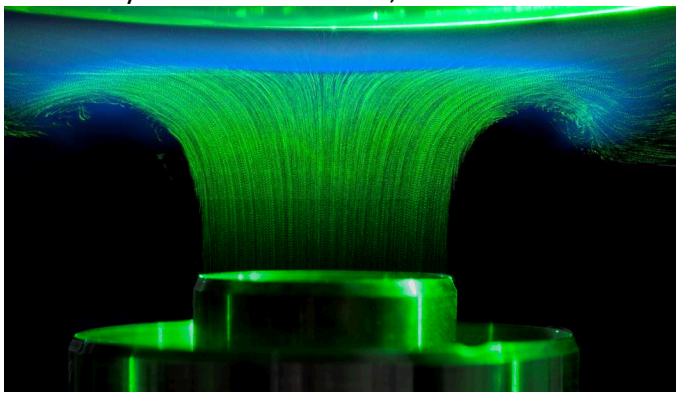
Generic two-beam phase-matching scheme for hybrid fs/ps 1D-CARS

- Improved spatial resolution (< 50 µm).
- Automatically overlapped pump/Stokes fields, temporally and spatially, makes the technique more robust and higher pulse energy available.



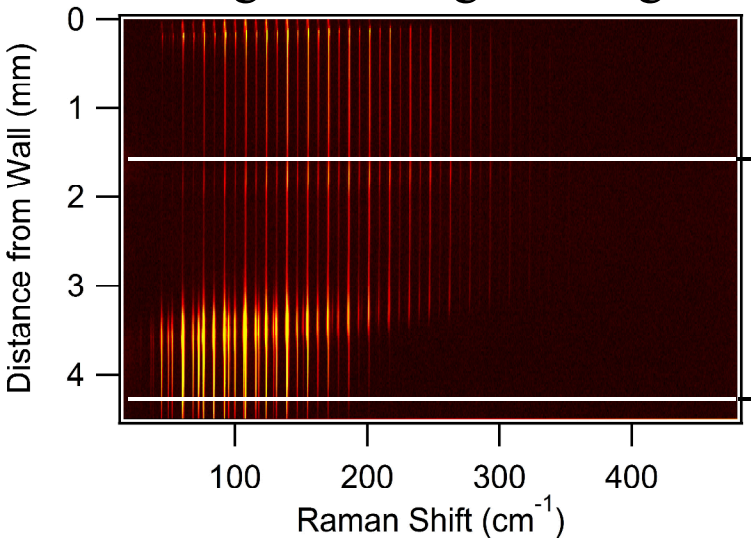
Single-laser-shot 1D-CARS measurements

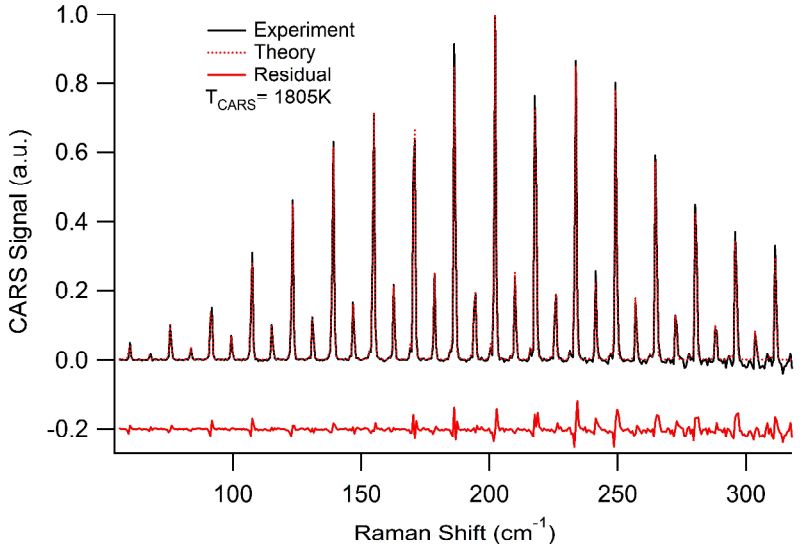
Courtesy of Andreas Dreizler, TU Darmstadt

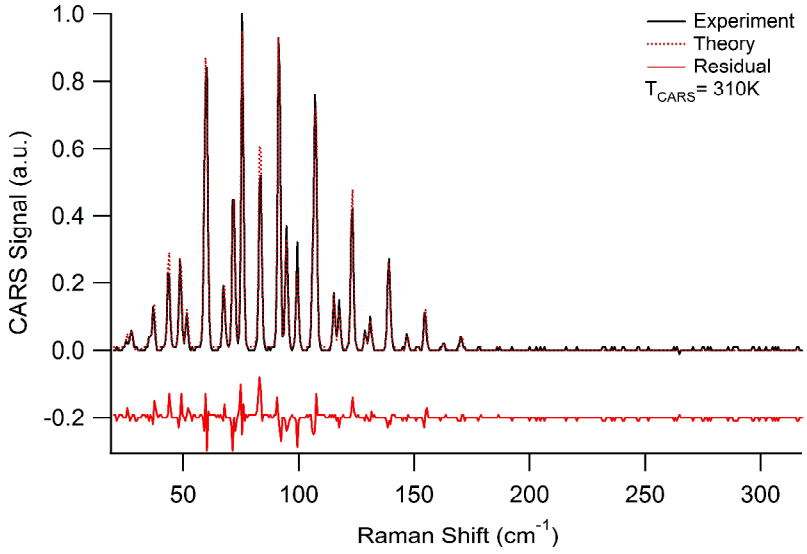


Φ=0.83, *Re*=5000

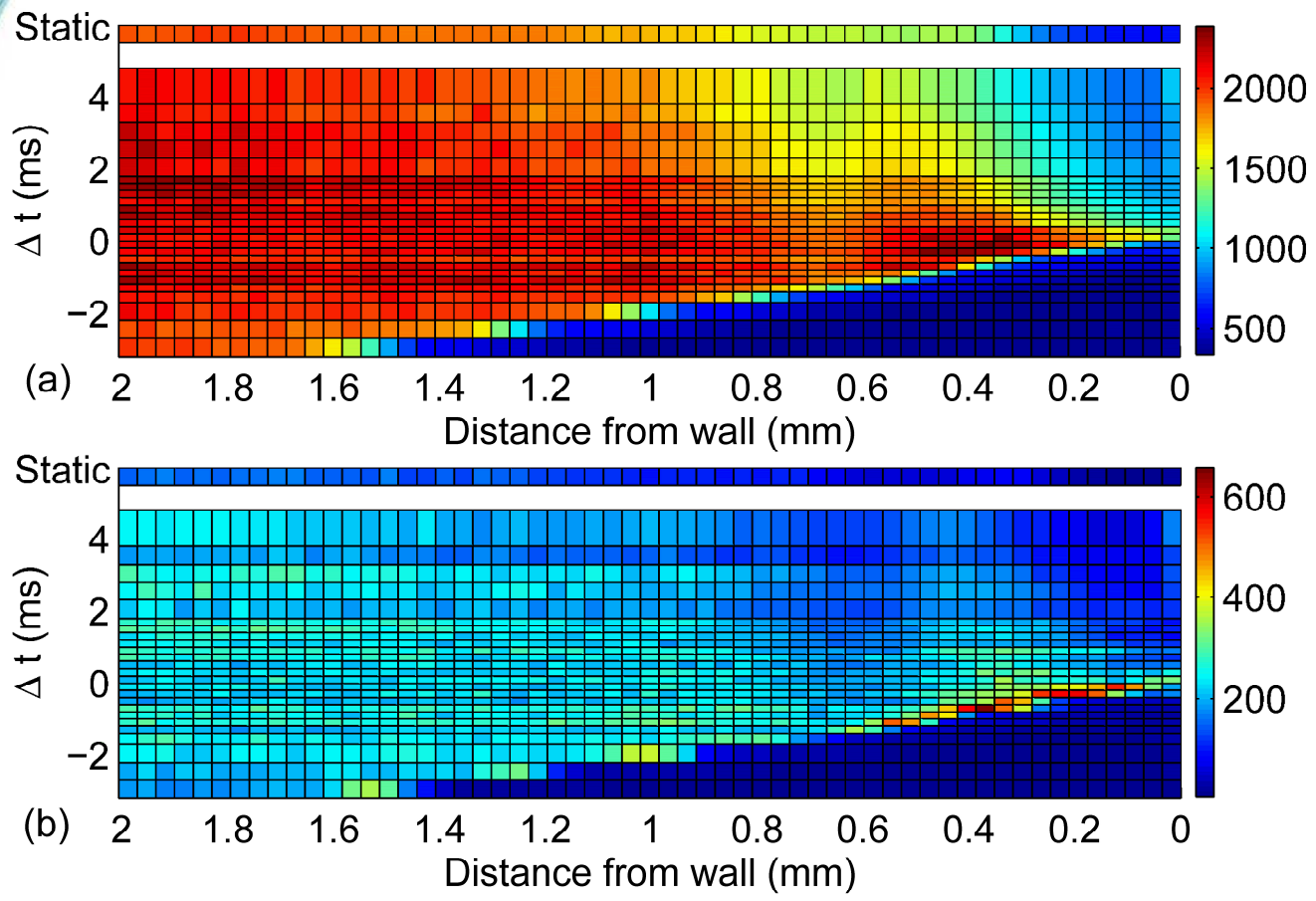
Single-shot signal image

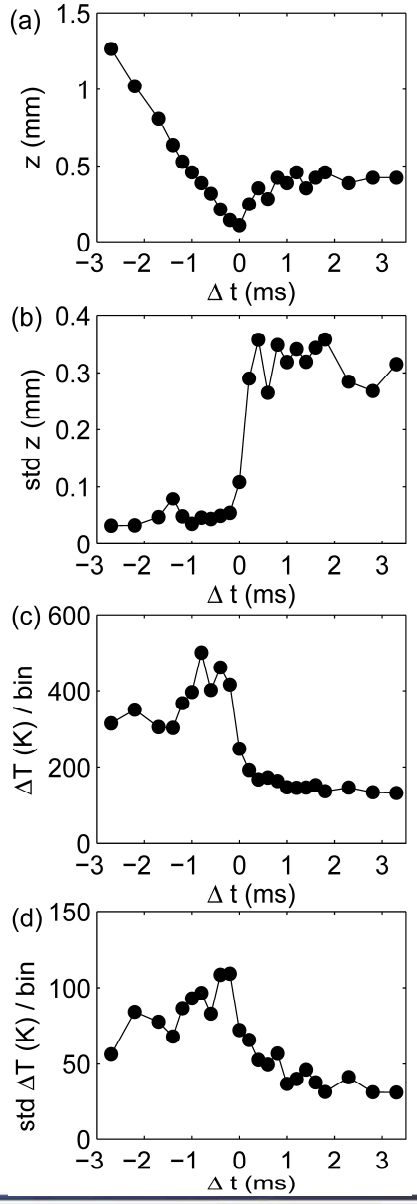






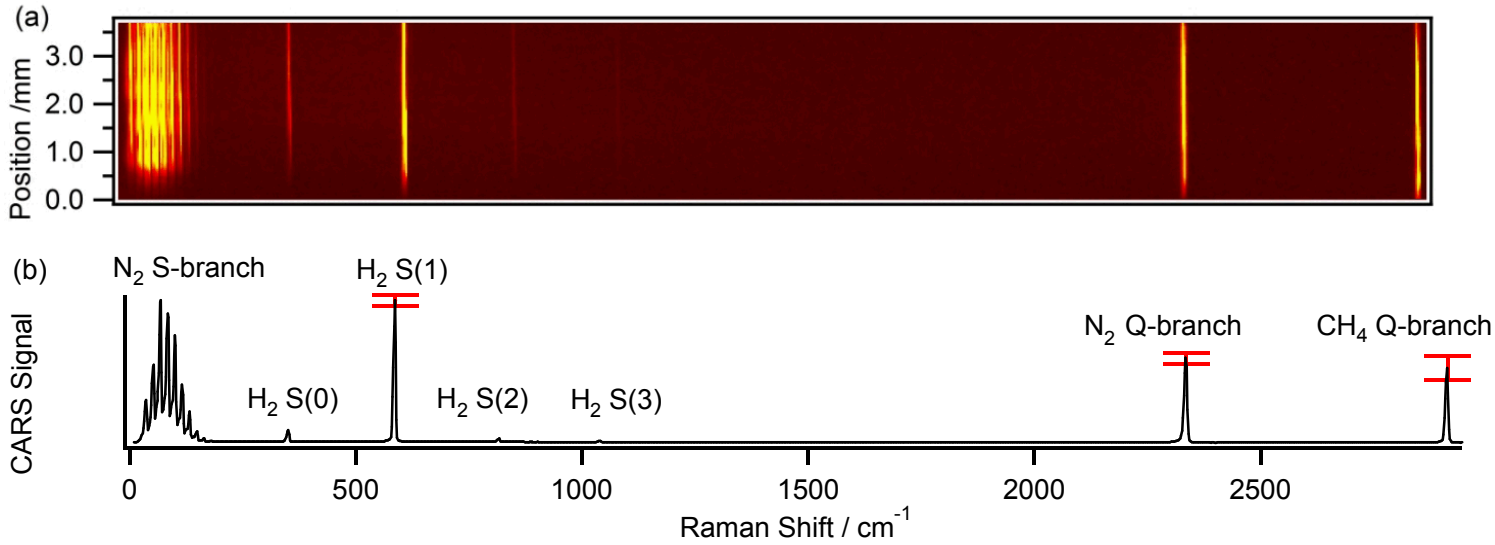
Single-laser-shot 1D-CARS measurements

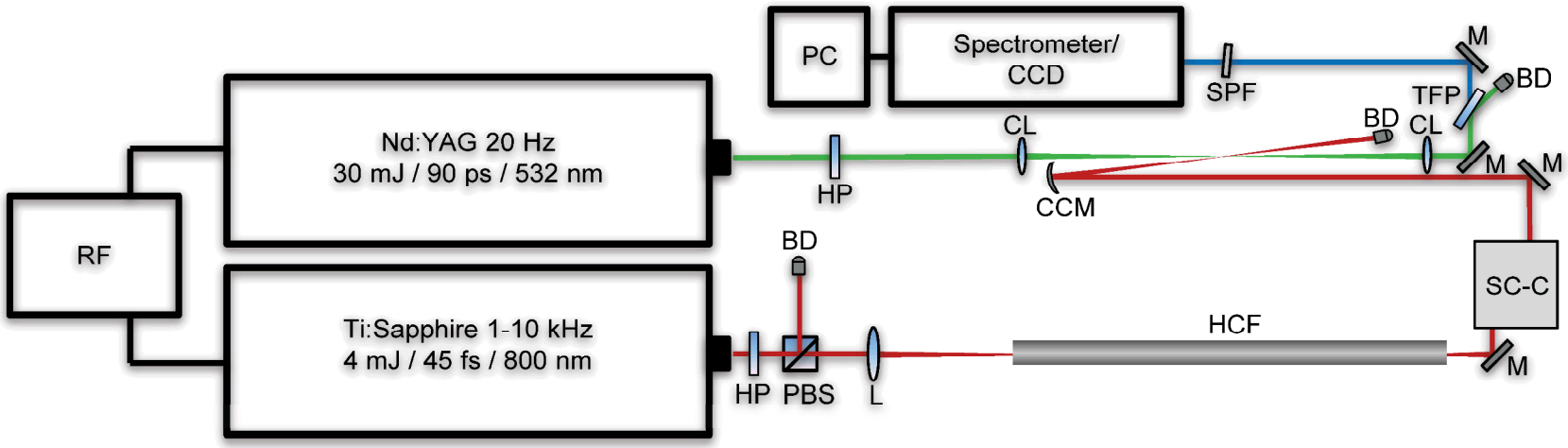




Time- and spatially dependent statistics of the 1D flame front gradient / thickness / position become possible

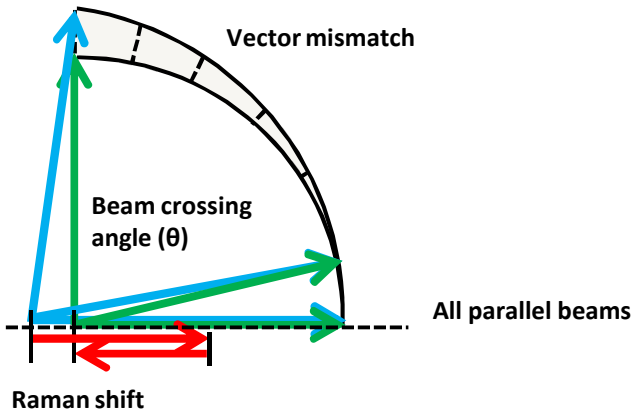
Two-beam Ultrabroadband CARS



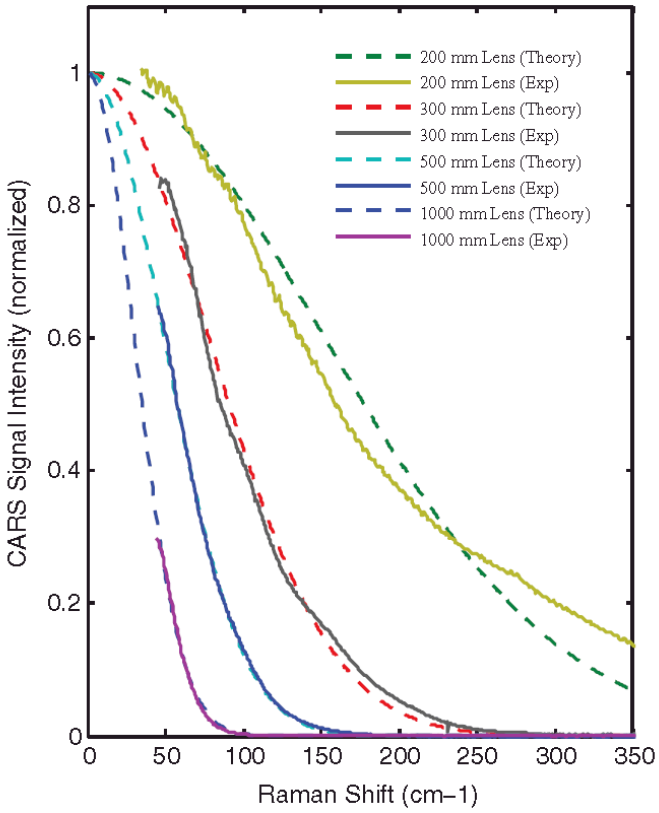


CARS Phase-Matching for Two-Beam CARS

Phase-matching condition



- Perfect phase-matching in two-beam CARS is achieved only in collinear arrangement
- Higher Raman shifts and higher intersection angles yield higher phase-mismatch



CARS amplitude buildup and signal equation:

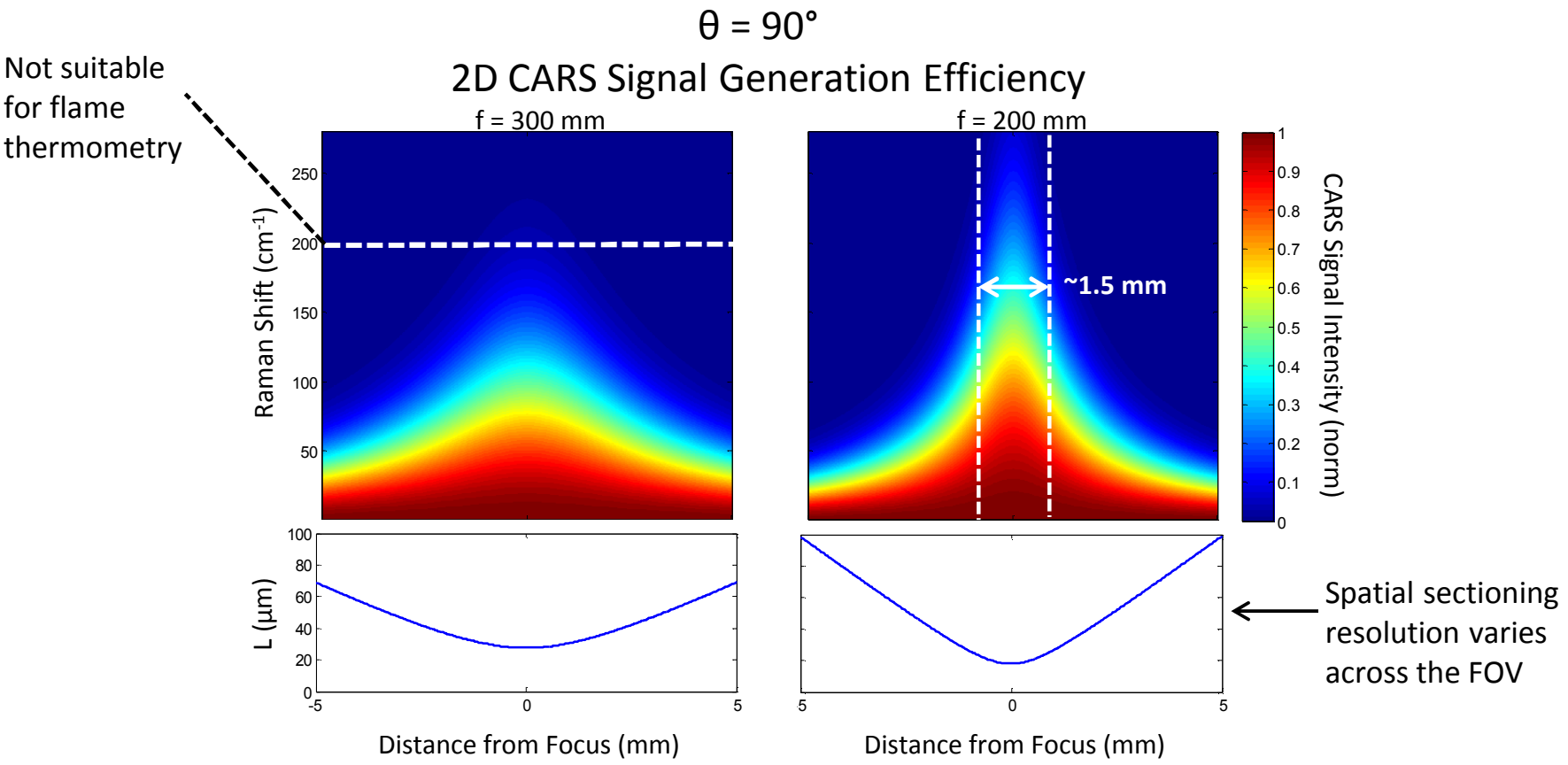
$$\int_{A_{CARS}(0)}^{A_{CARS}(z)} dA'_{CARS} = \frac{3i\chi_{CARS}\omega_{CARS}}{c\eta(\omega_{CARS})} \int_0^z A_{pump}(z')A^*_{Stokes}(z')A_{probe}(z')e^{i\Delta kz'}dz'$$

$$\sim \int_0^z e^{-az'^2} e^{i\Delta kz'} dz' \qquad \boxed{A_{CARS}(z) \sim e^{\frac{-\Delta k^2}{4a}}}$$

Nonresonant profiles collected at a crossing angle of 90˚ for four focal length lenses as compared with calculations.

2D-CARS Signals Ultimately Limited by the 2D Phase-Matching

Orthogonal beam crossing offers the highest possible 3D spatial sectioning of the CARS signal < 50 µm in all three spatial dimensions.

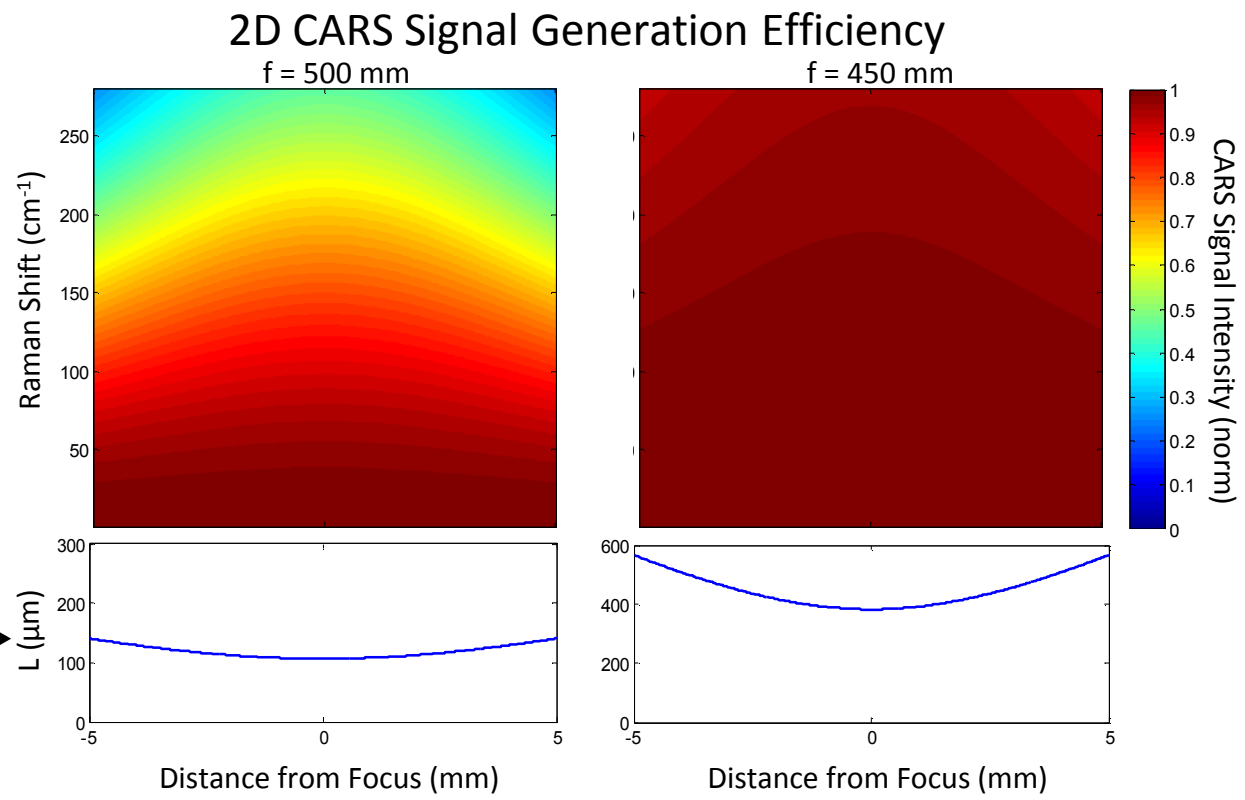


For orthogonal crossing, one must sacrifice FOV for high T assessment, or vice versa.

2D-CARS Signals Ultimately Limited by the 2D Phase-Matching

Spatial sectioning and FOV requirements dictate optimal 2D CARS setup

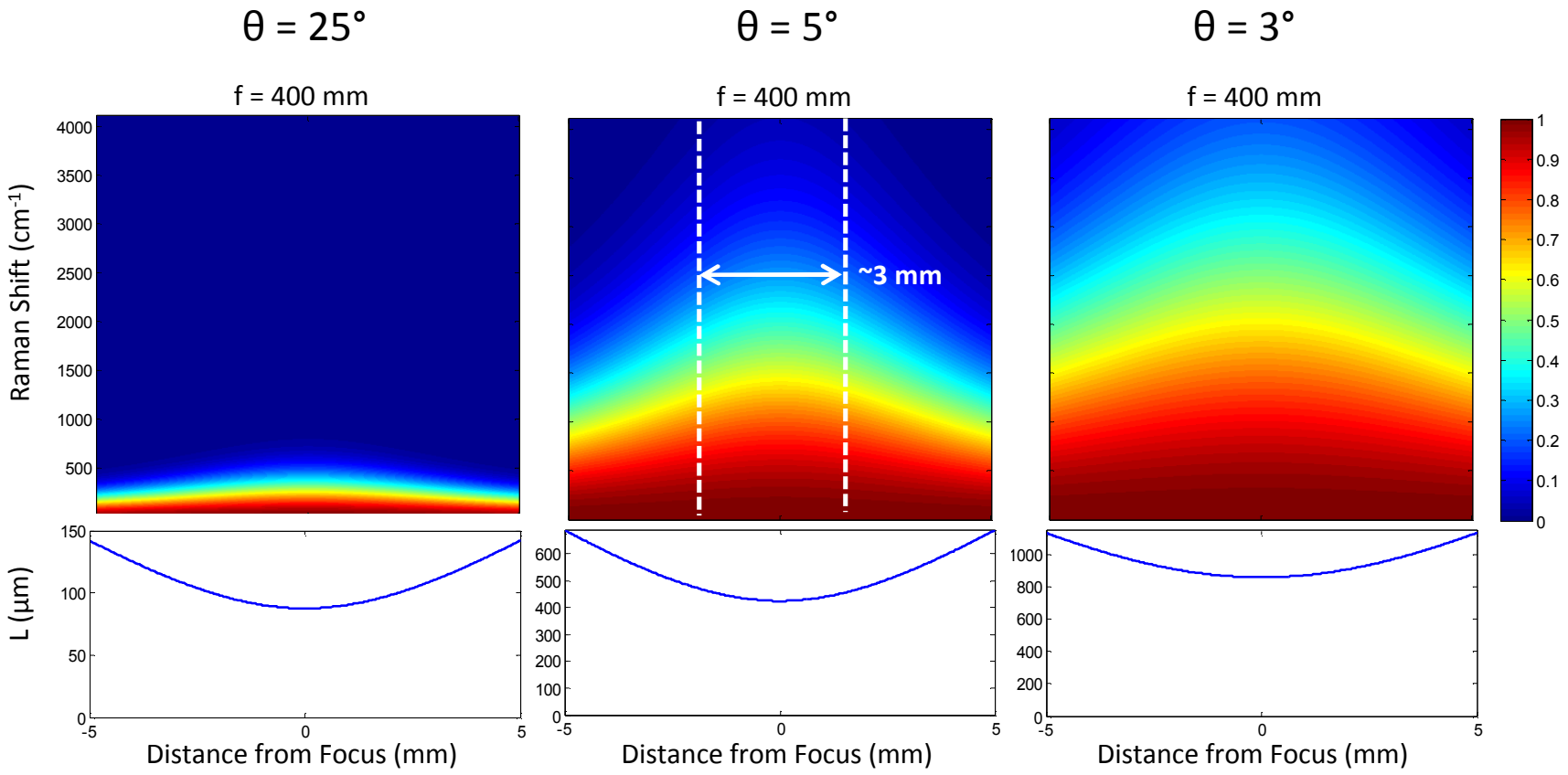
θ = 25° θ = 6°



Spatial sectioning improves rapidly with increasing crossing angle →

Two-beam 2D Ultrabroadband CARS

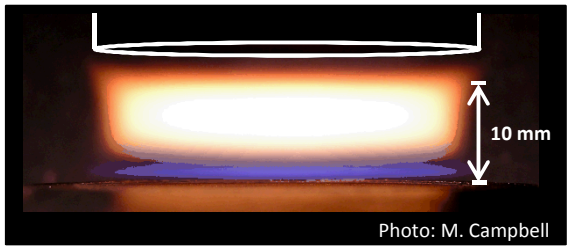
- Current experiment is optimized for the widest image with sufficient bandwidth detection AND 0.4-0.6 mm spatial sectioning resolution.
- Increased sensitivity over a wider FOV could be established with a more typical CARS probe volume of ~ 1 mm.



Simultaneous temperature imaging and wideband chemical detection

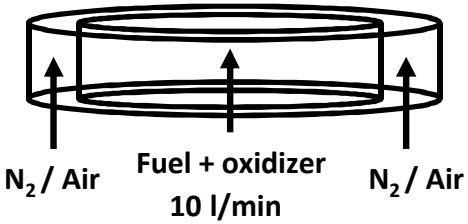
- Canonical sooting hydrocarbon flat-flame used to benchmark the new techniques.

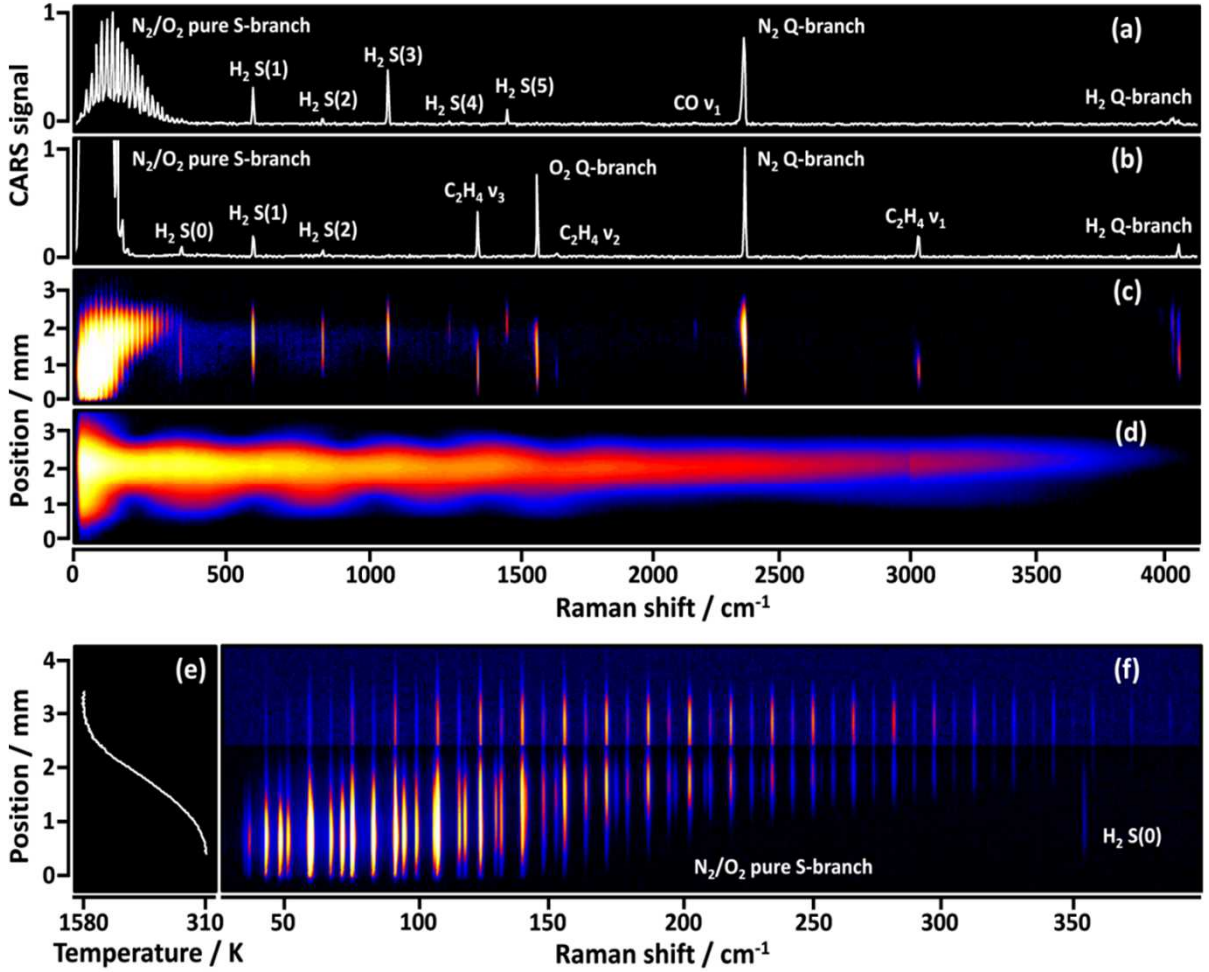
Ethylene/air flame, ϕ=2.35, N_2 shroud gas



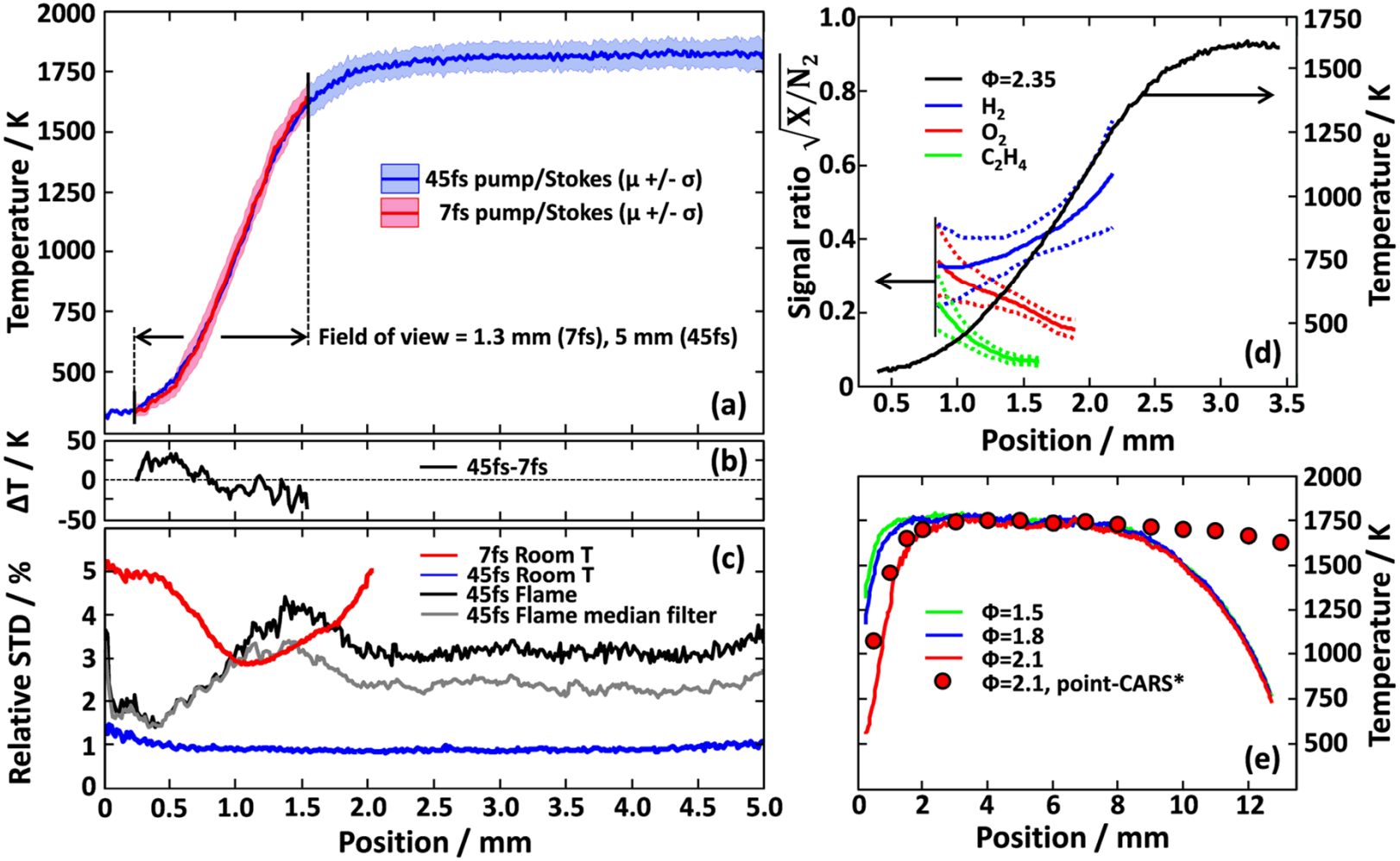
Burner design (Michelsen group, Sandia)

Premixed burner principle

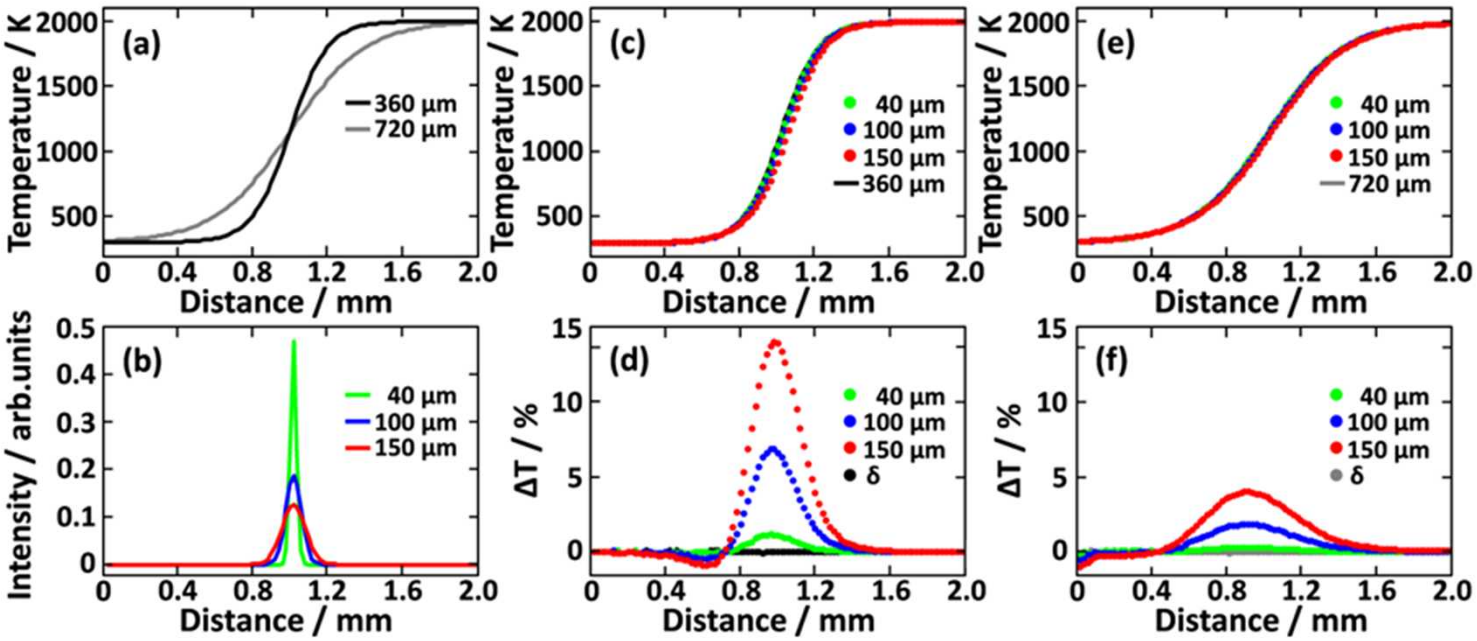




Ultra-broadband 1D-CARS diagnostic performance



Spatial Averaging Distorts CARS Imaging Results



- Realistic amounts of spatial averaging, whether by optical imaging blur or an extended probe volume, cause significant error to evaluated rotational CARS temperature profiles.

SWQ Burner

- Premixed V-stablized flame
-
-
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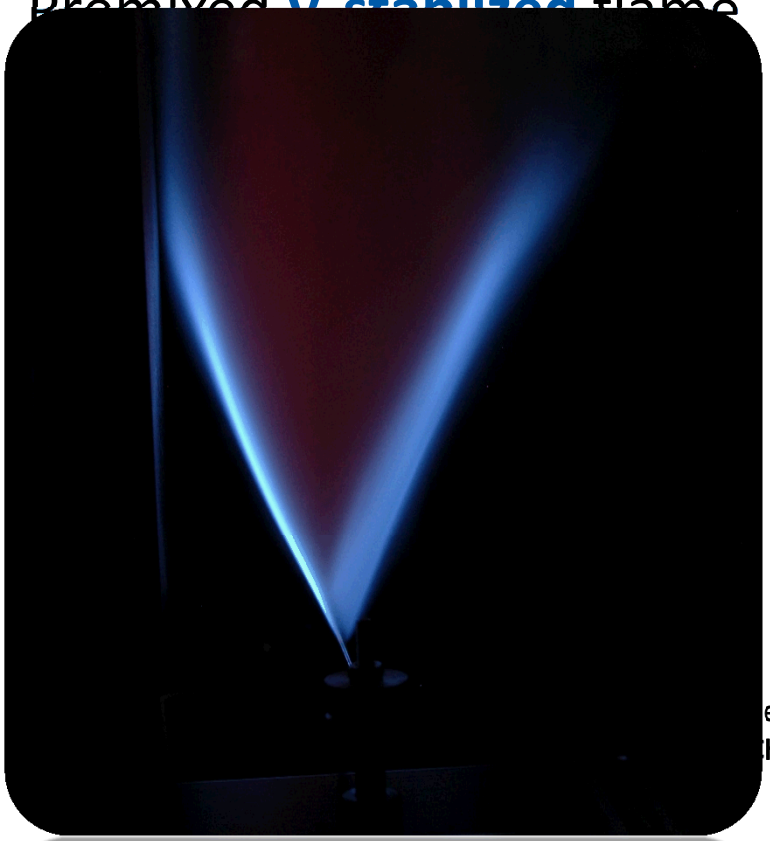

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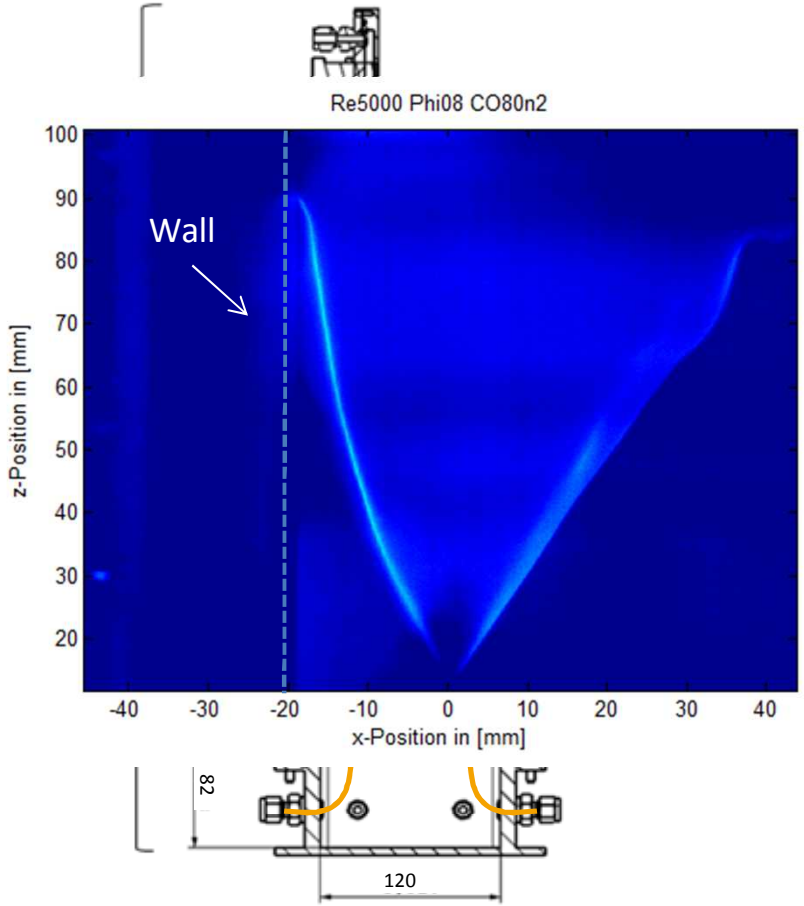
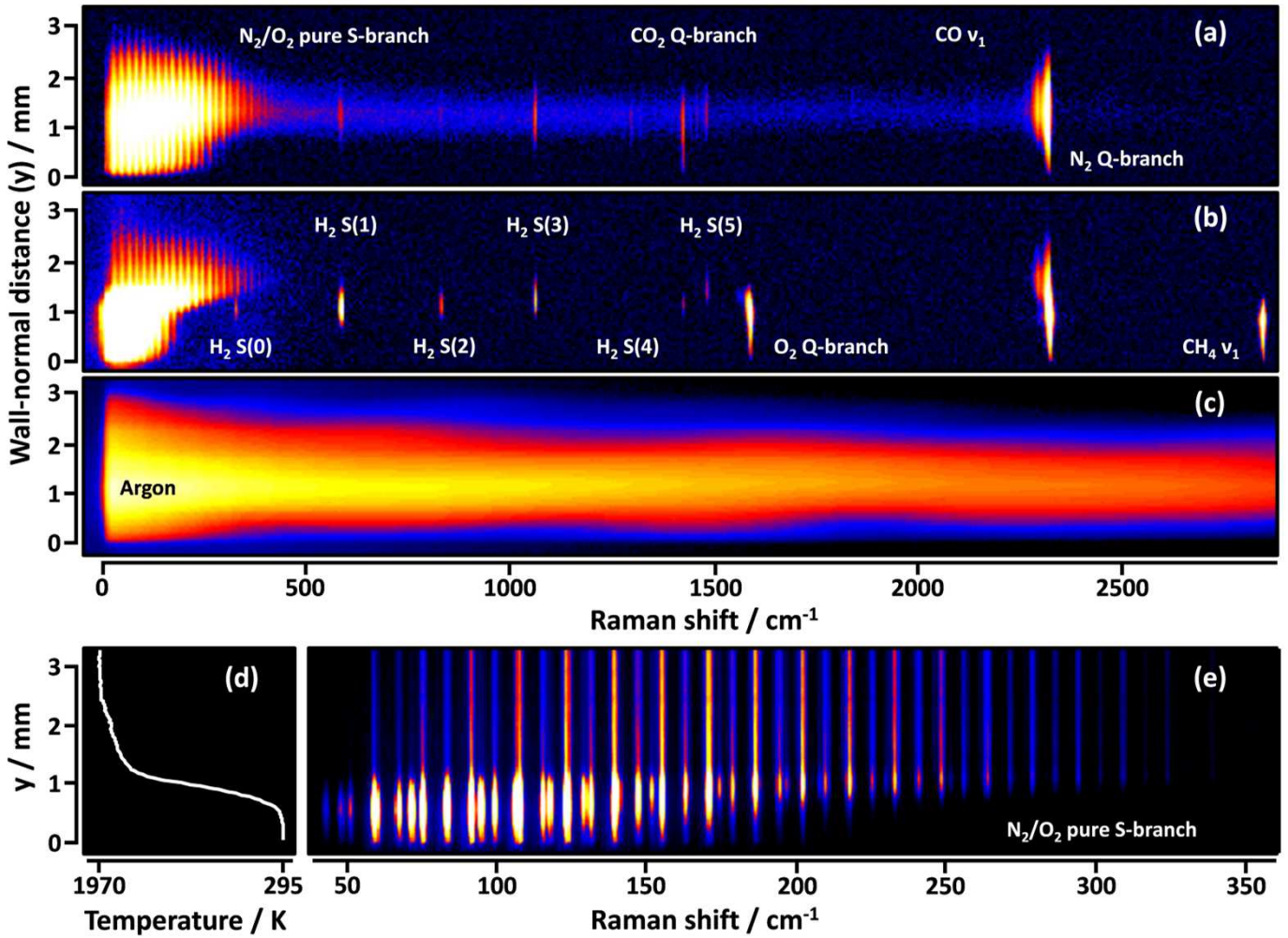
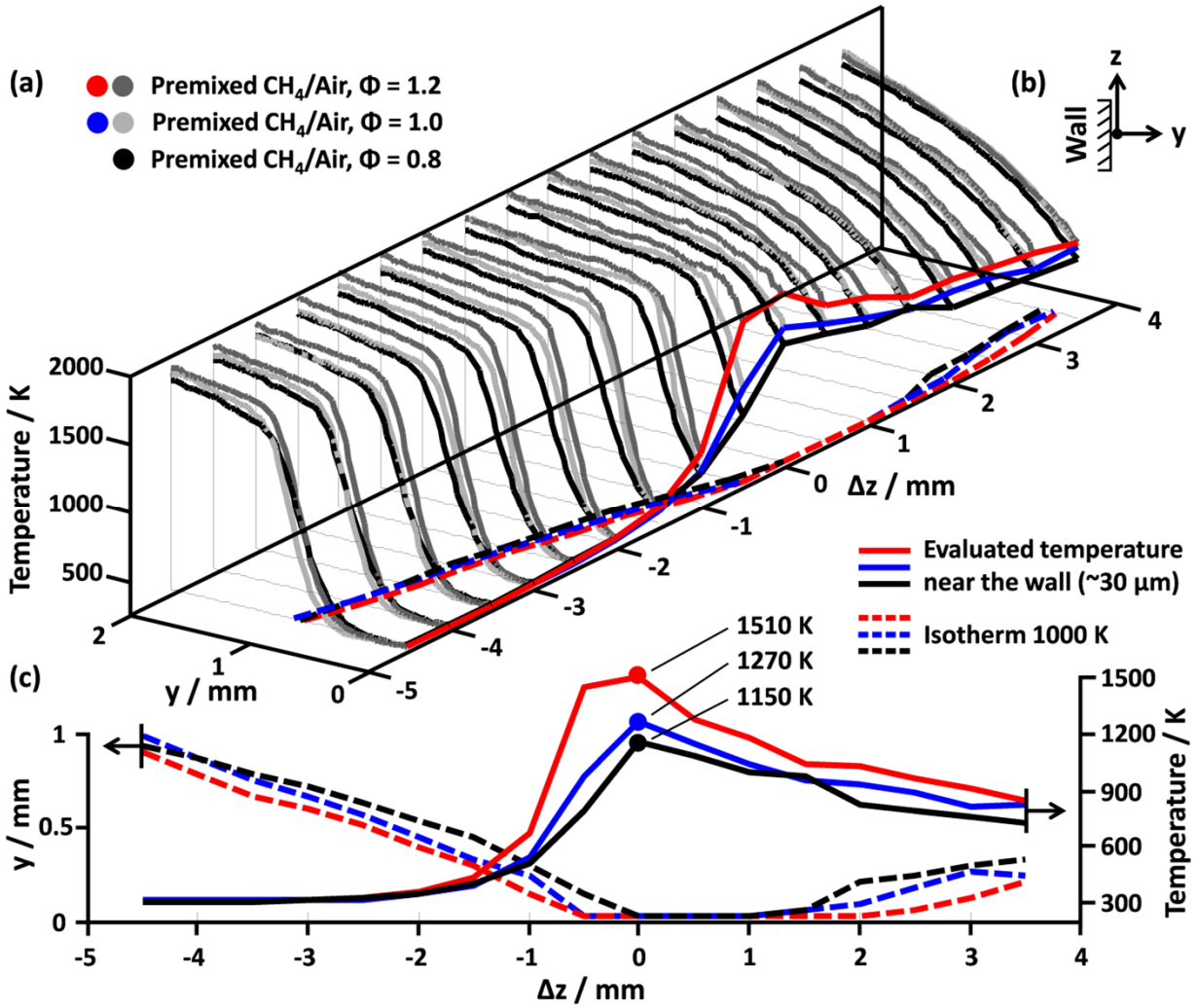


Ultrabroadband 1D-CARS Enables Simultaneous Detection of Species Profiles and Thermometry



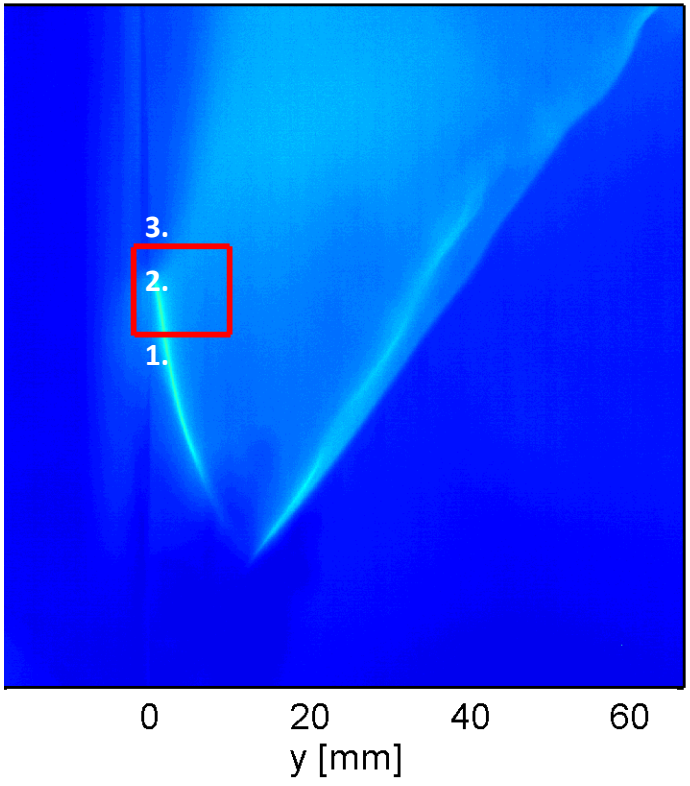
High Fidelity 1D Temperature Imaging is Achieved Across the Thermal Boundary Layer

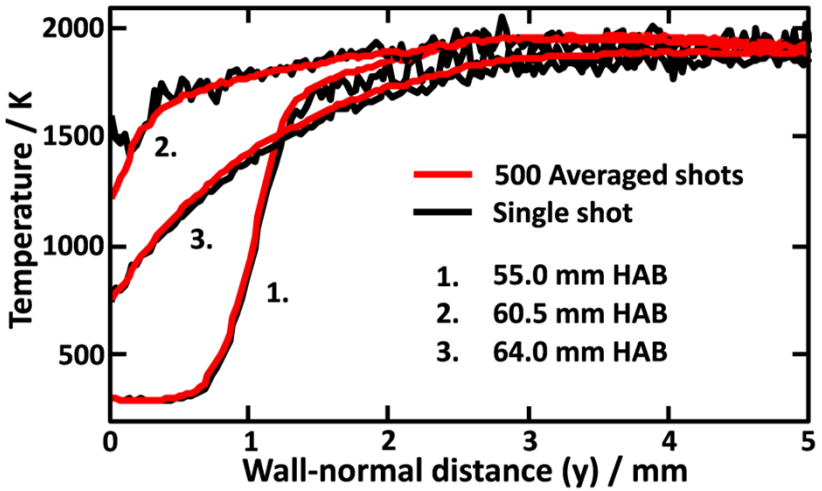
- High accuracy / high precision thermometry (1-2% error levels, and STD)
- 1D imaging enables simultaneous detection of flame-front position and gradient



High Levels of Precision are Achieved Even in the Quenching Zone

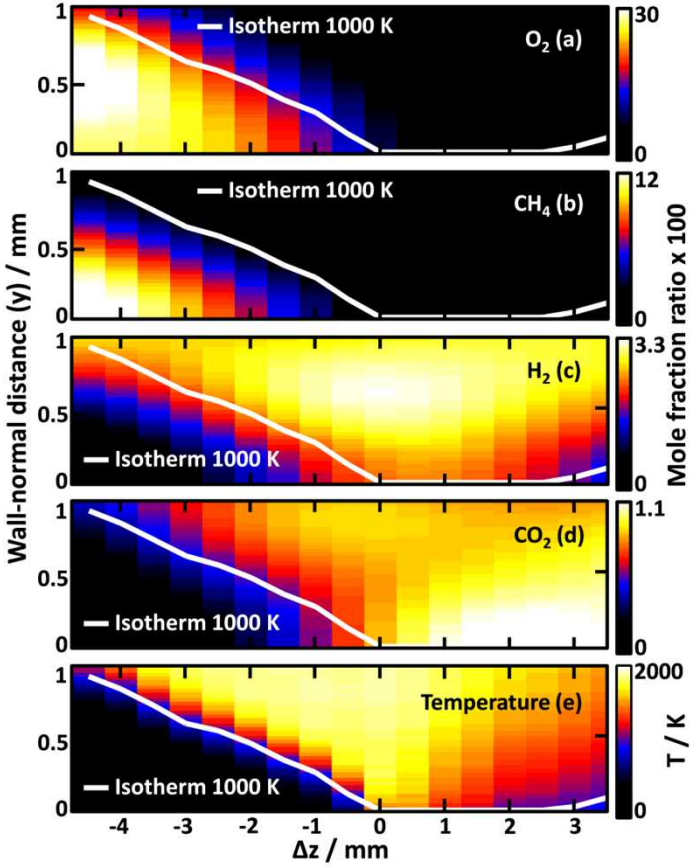
1. Pre-Quenching and Unburned Reactant Zone
2. Quenching Zone
3. Post-Quenching Product Zone

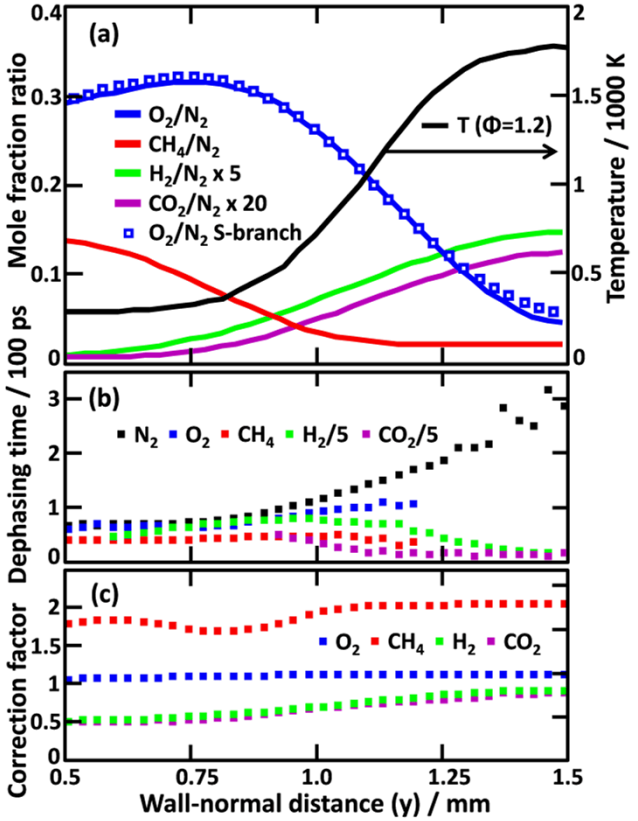




Even in the most difficult zone (nearest the wall at the moment of quenching) single shot measurements exhibit excellent precision.

Near-Wall Ultrabroadband CARS Imaging: Measurement of thermochemical states





In-situ measurement of pressure broadening coefficients

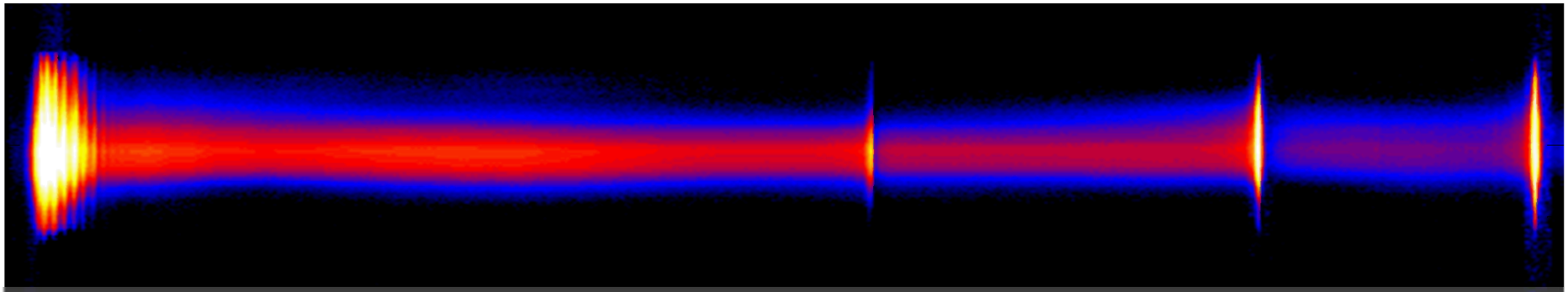
Stimulated Raman cross-section

Demonstrated the simultaneous 1D coherent Raman detection of N_2, O_2, CH_4, CO_2, H_2, and even CO as well as thermometry.

Summary

- Our technique for 1D CARS imaging has matured into a single-shot temperature assessment capable of applied measurements across the thermal boundary layer near walls.

- Demonstrated the measurement of spatio-thermochemical states during quenching via simultaneous 1D coherent Raman detection of N_2, O_2, CH_4, CO_2, H_2, and even CO as well as thermometry.



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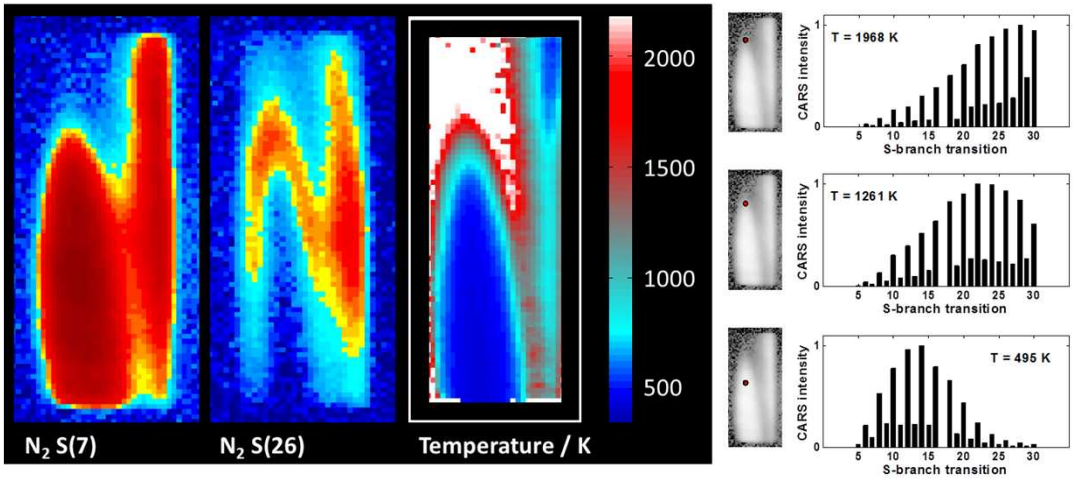
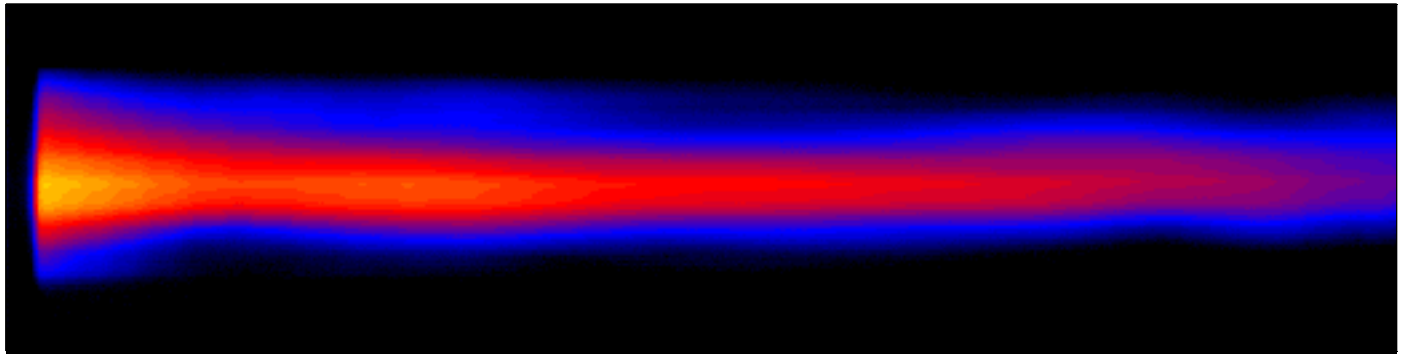
Looking to the Future

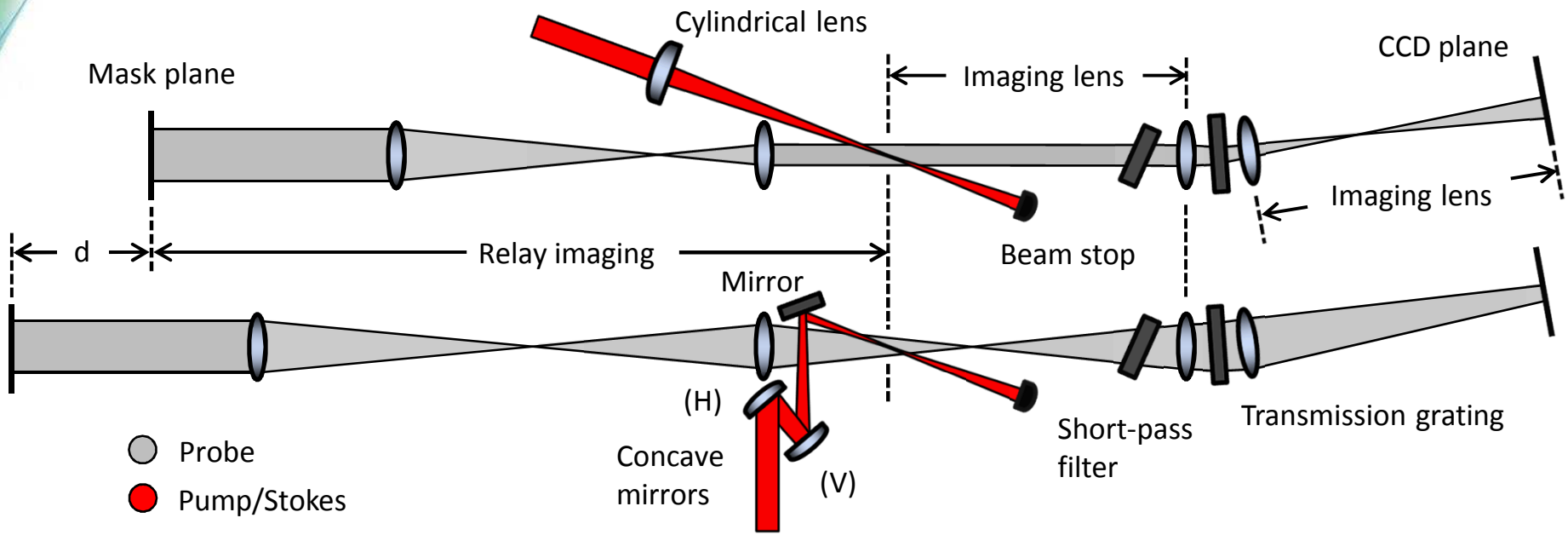
Ultrabroadband 2D-CARS during Flame-Wall Interactions



Simultaneous measurement <u>nonresonant excitation profile</u> to improve single-shot precision in ultrabroadband Raman species detection



Two-beam 2D Ultrabroadband CARS



- Astigmatic focus allows full use of available beam irradiance
- Expanded beam through detection optics -> only spectral filter required for probe suppression