Development of two-beam femtosecond/picosecond CARS for high-fidelity thermometry in flames

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Development of two-beam fs/ps CARS for high-fidelity thermometry in flames

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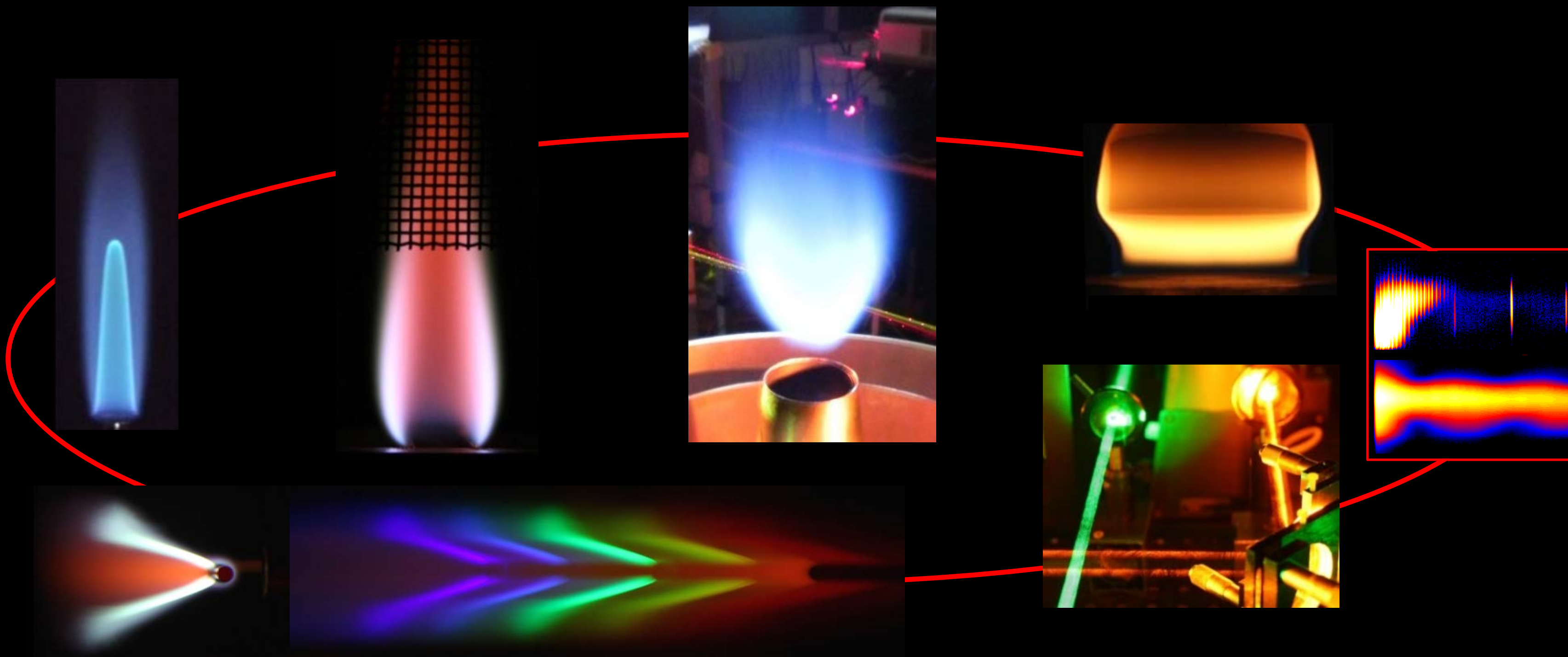
Faculty of Aerospace Engineering, Delft University of Technology



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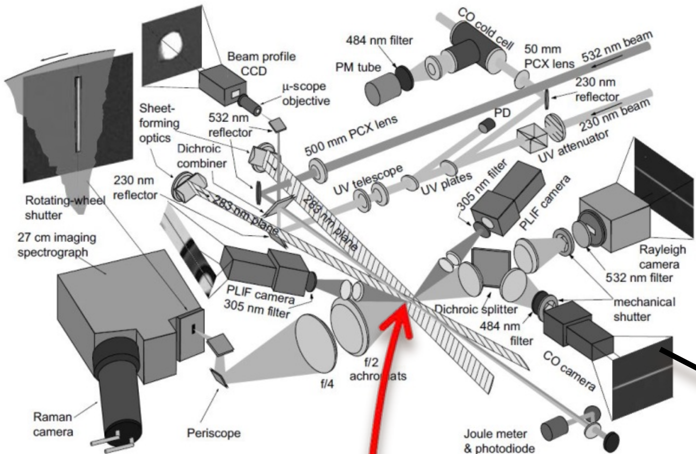
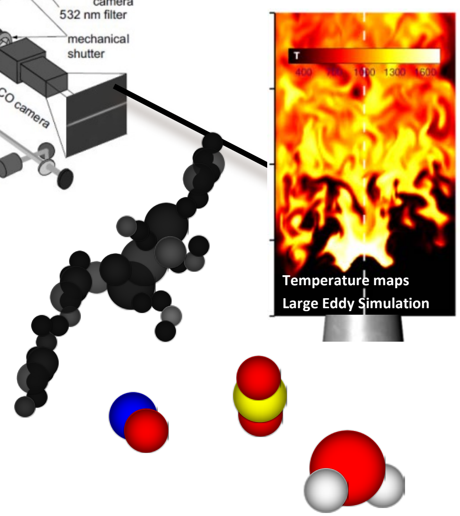
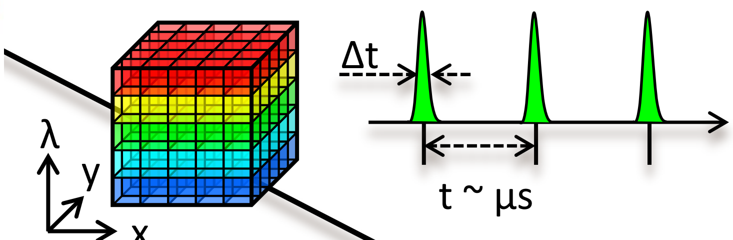
Advanced optical diagnostics are important tools for quantitative combustion analysis



1. Validation/development of a model
require multi-parameter diagnostics

3. Measurement challenges
Spatial / temporal / spectral resolution – data acquisition

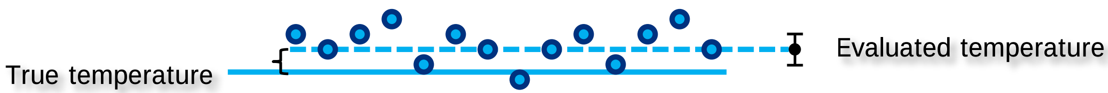




2. Parameter determination in reacting flows
(e.g. temperature, flow-field and species)

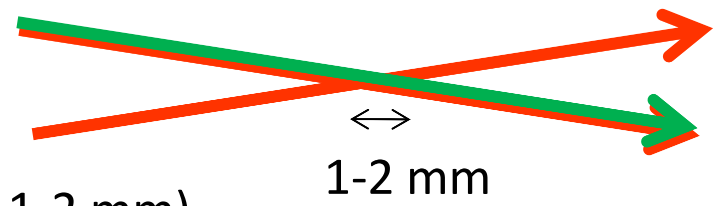
Why use CARS for flame diagnostics?

- Most accurate technique for **thermometry** in reacting flows (wide range of operational conditions).

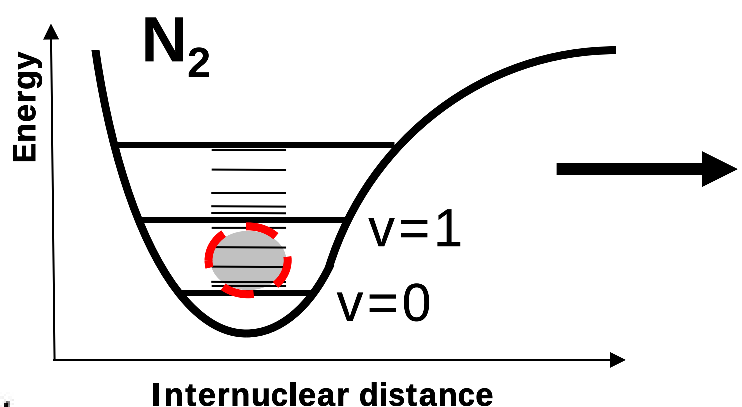


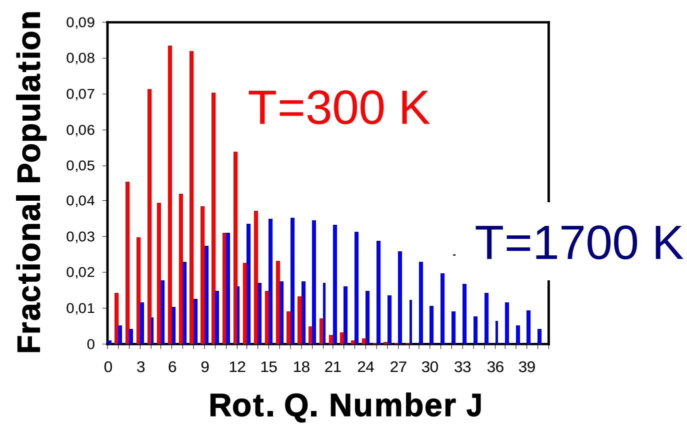
Inaccuracy ~2-3%
Single shot precision ~4-5%

- Nanosecond CARS characteristics:
  - Non-intrusive, in-situ probe
  - High temporal resolution (~10 ns)
  - High spatial resolution (~100 µm x 100 µm x 1-2 mm)



- Vibrational CARS, Rotational CARS





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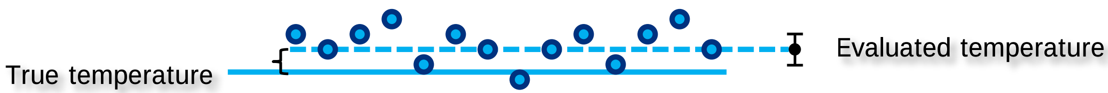

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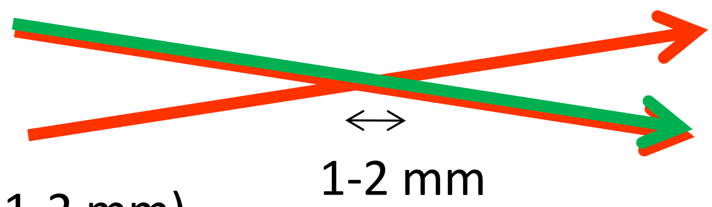
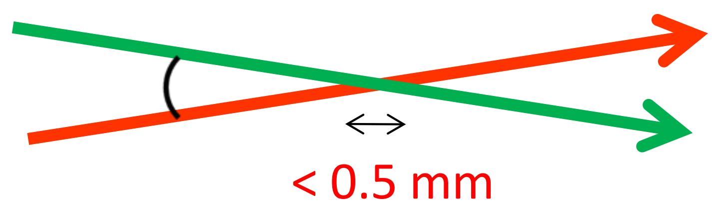


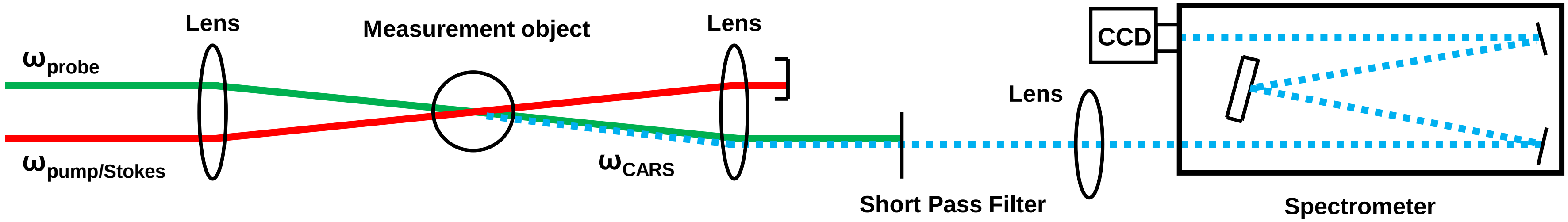
- Vibrational CARS, Rotational CARS

- Two-beam femtosecond/picosecond CARS
  – Picosecond temporal resolution
  (Near collision independent - ~~Raman linewidths~~)
  – Improved spatial resolution
  (40 µm x 40 µm x 0.5 mm)
  – 1D and 2D imaging capabilities

Inaccuracy < 2-3%
Single shot precision ~1%



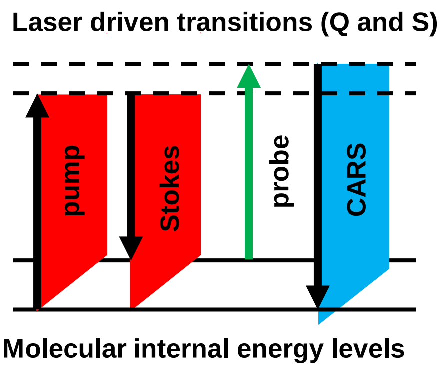
Two-beam femtosecond/picosecond CARS



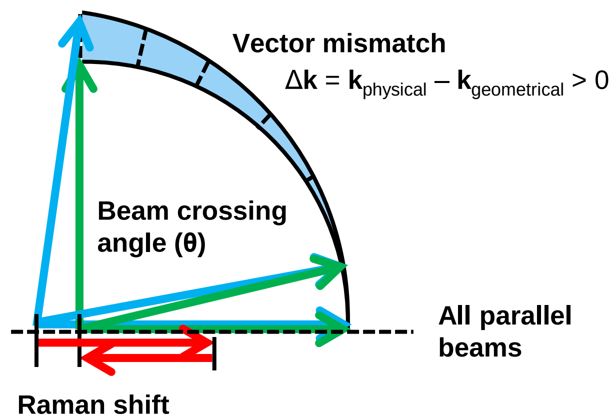
- Narrowband (picosecond) probe laser
- Broadband (femtosecond) excitation laser

Simplified generic phase-matching-scheme for CARS signal generation

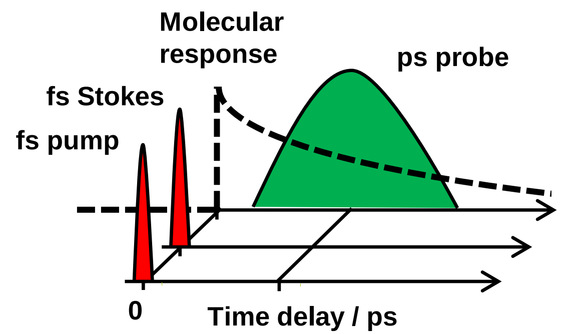
Energy conservation



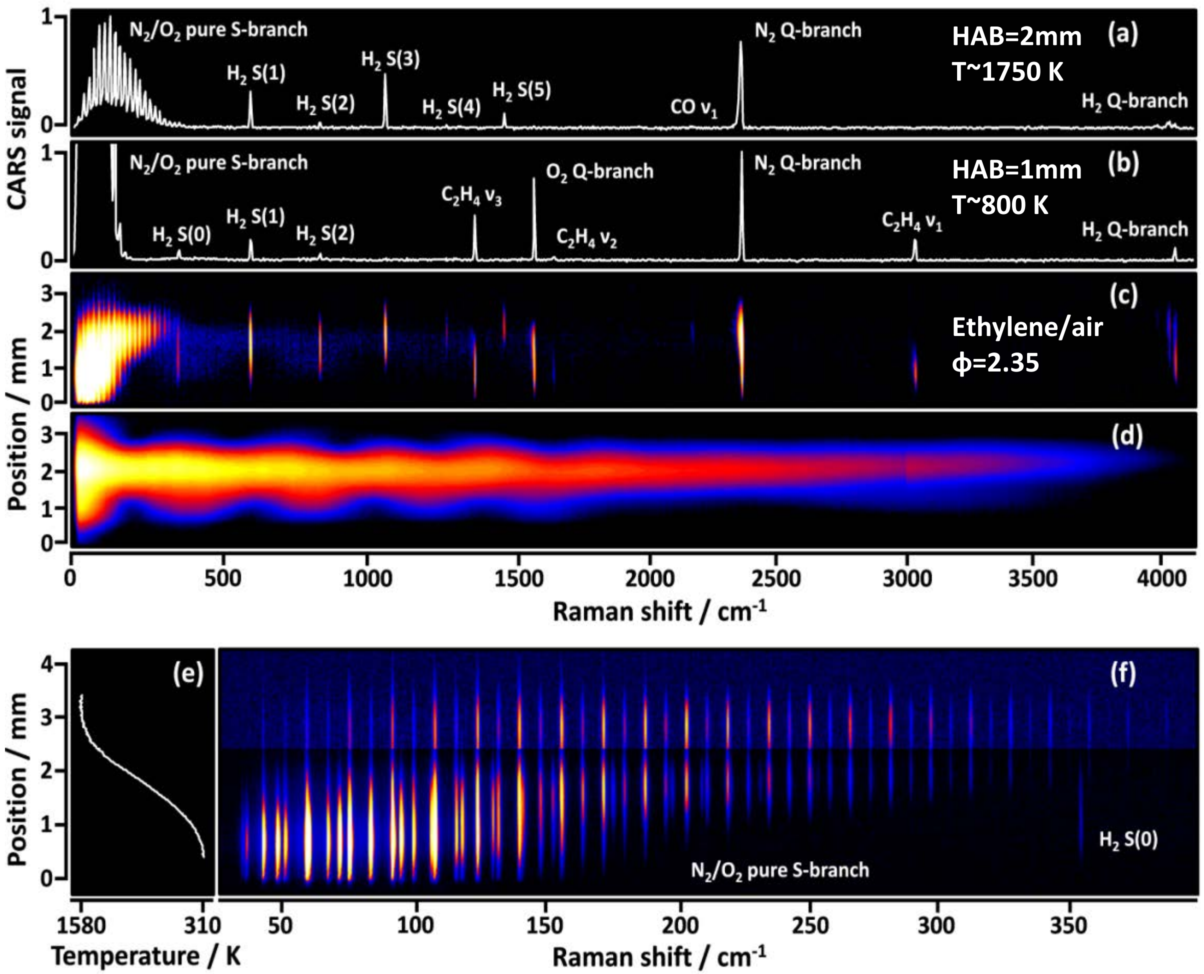
Phase-matching (momentum conservation)



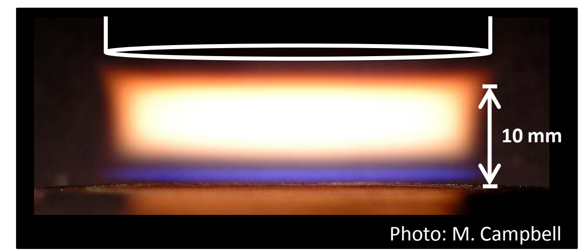
Spectroscopy in the time-domain



Direct coherent Raman temperature imaging and wideband chemical detection

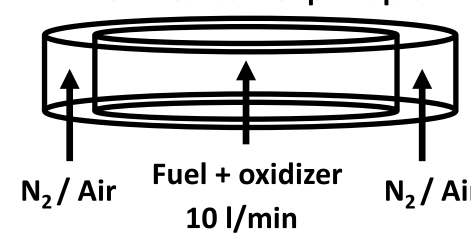


- Canonical sooting hydrocarbon flat-flame used to benchmark the new techniques.



Burner design (Michelsen group, Sandia)

Premixed burner principle



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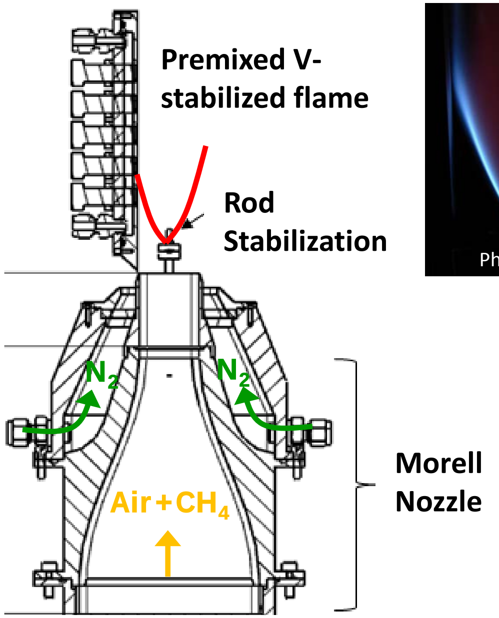
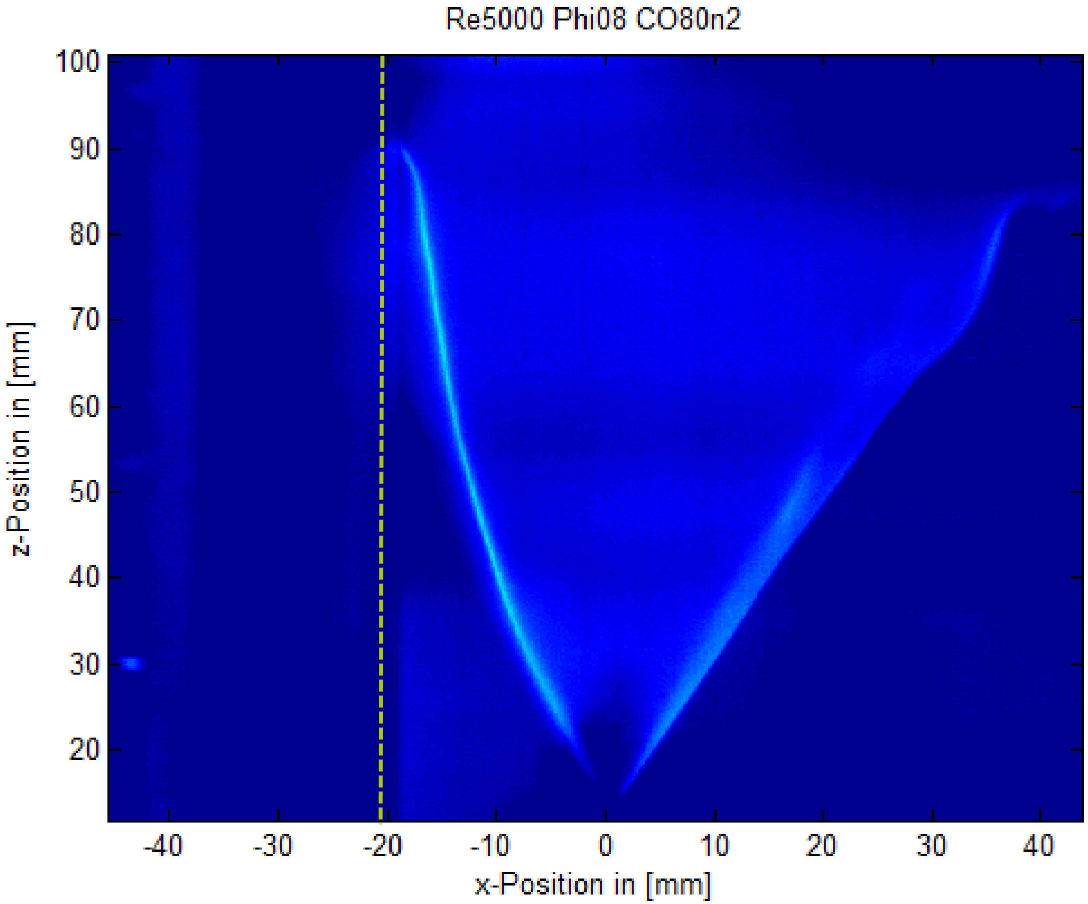
CARS imaging of flame-wall interaction

- Temperature contour mapping at side-wall quenching burner



Burner design (Dreizler group, TU Darmstadt)



- Motivation

Flame-wall interaction plays a key role in the formation of pollutants in a combustion chamber, such as UHC and CO.

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Sandia National Laboratories

CARS imaging of flame-wall interaction

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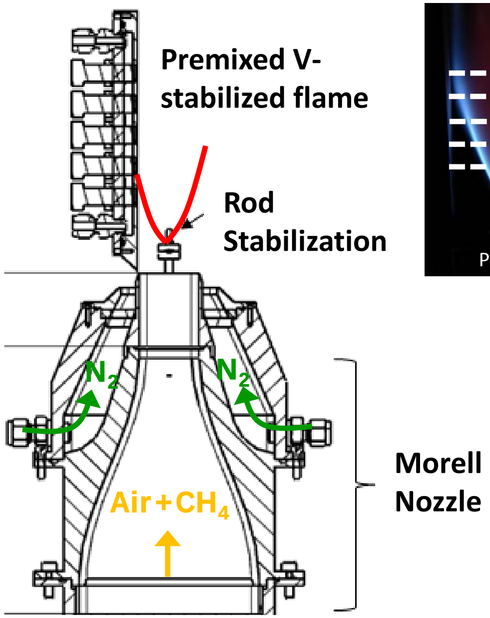

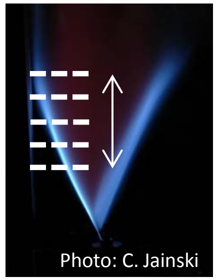

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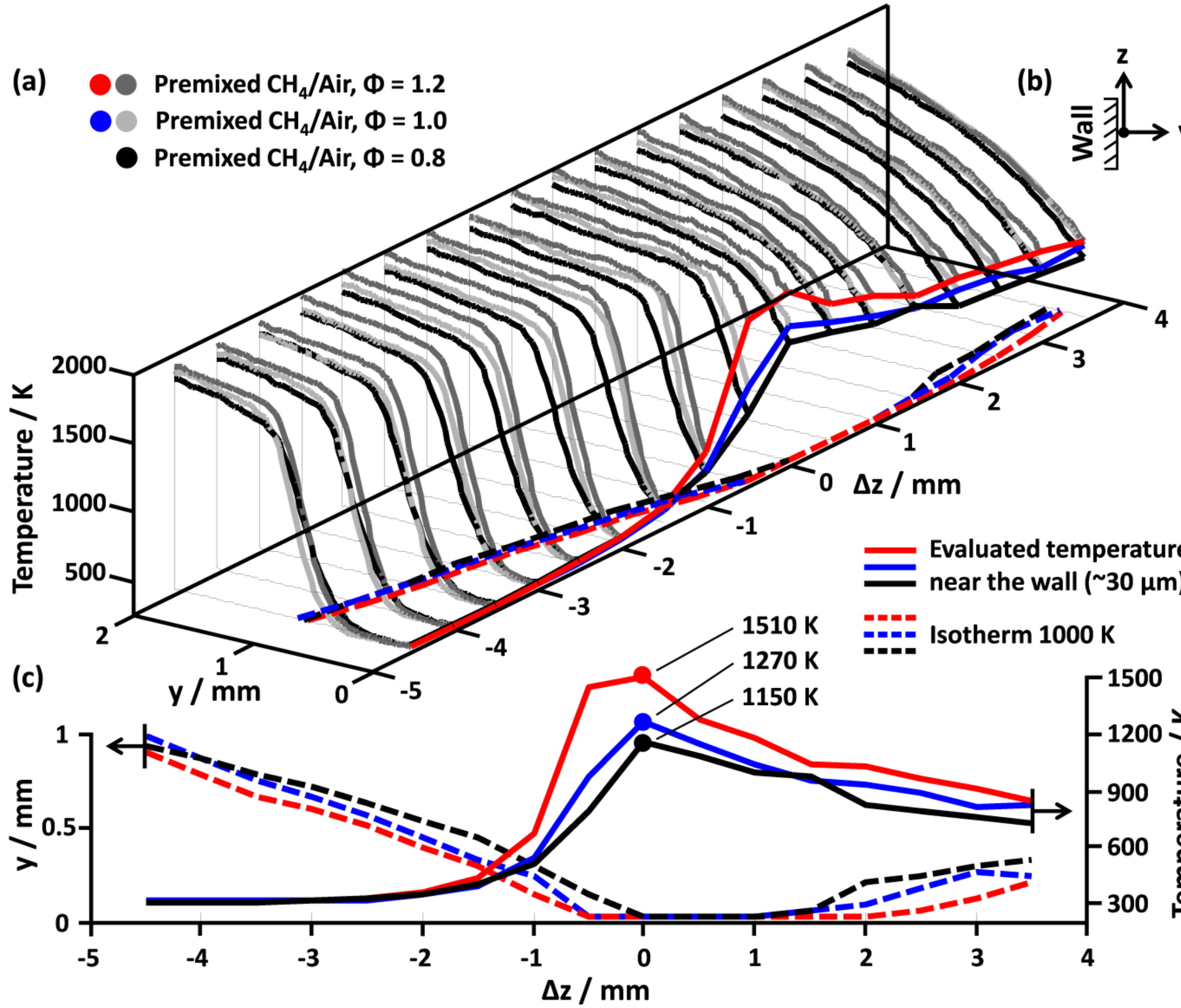

- Motivation

Flame-wall interaction plays a key role in the formation of pollutants in a combustion chamber, such as UHC and CO.

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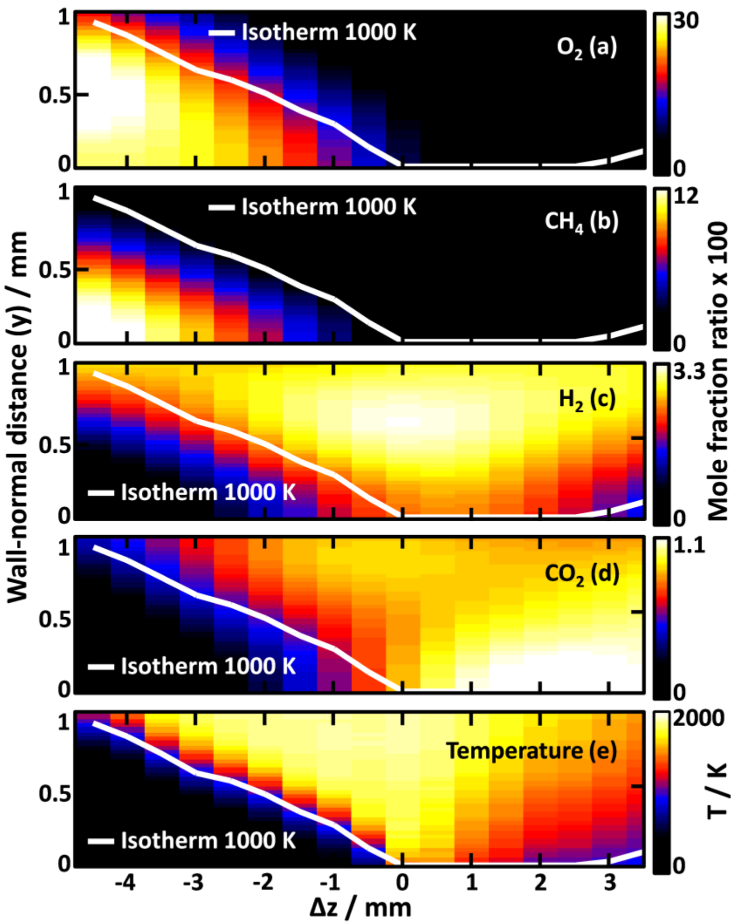
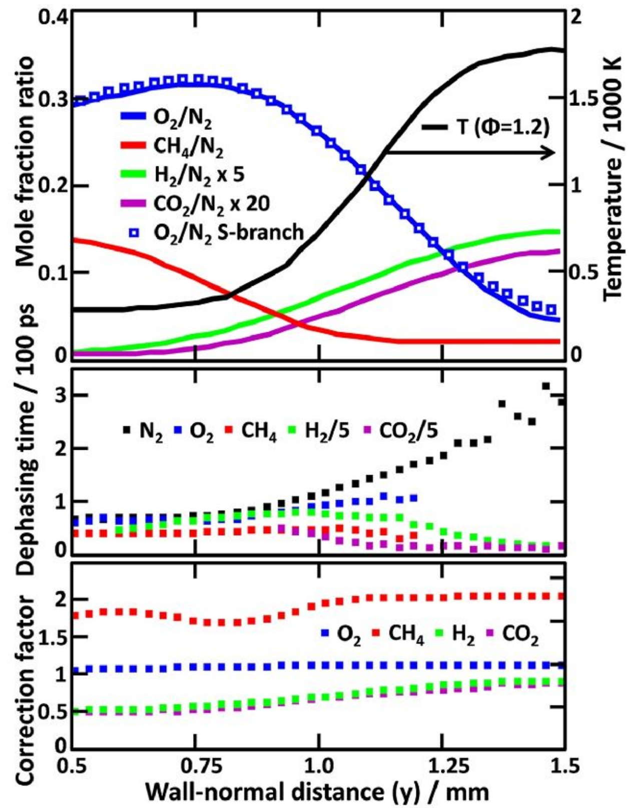
Near-wall ultrabroadband CARS imaging: Measurement of thermochemical states





Simultaneous detection of N_2, O_2, H_2, (CO), CO_2, and CH_4 is achieved.

The excellent imaging resolution allows for thermochemical states of the thermal boundary layer to be probed to within ~40 µm of the interface.

In-situ measurement of pressure broadening coefficients

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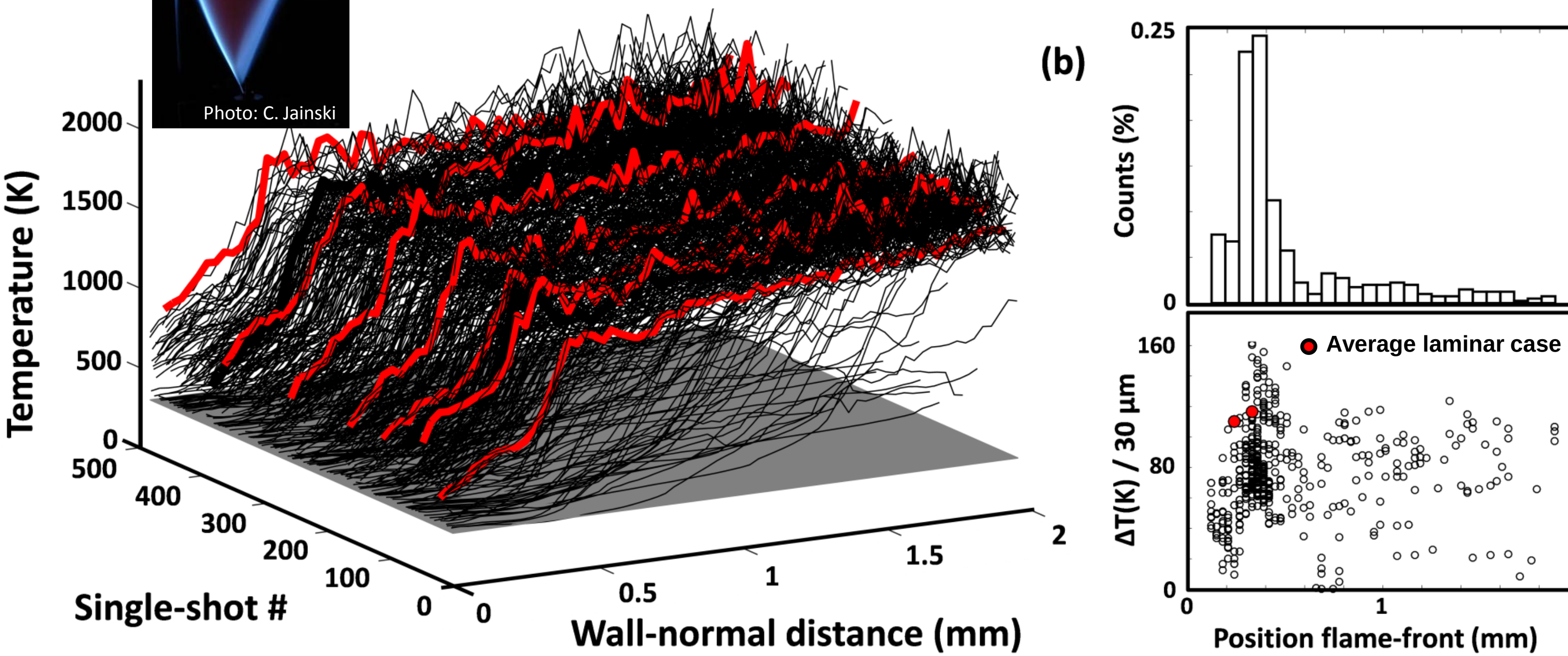
FWI at enhanced turbulence intensities

(Work-in-progress)

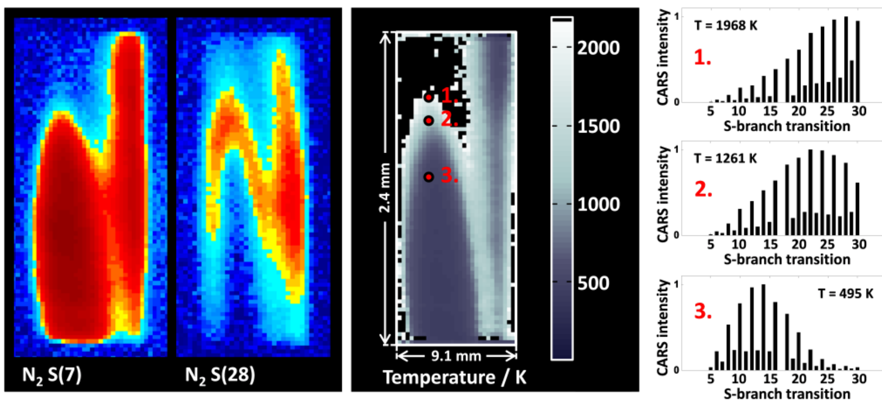
Turbulence generating grid (blockage 45%, turbulence level $u'/\bar{u}$ = 6-7%), V-flame operating in the wrinkled flamelet regime



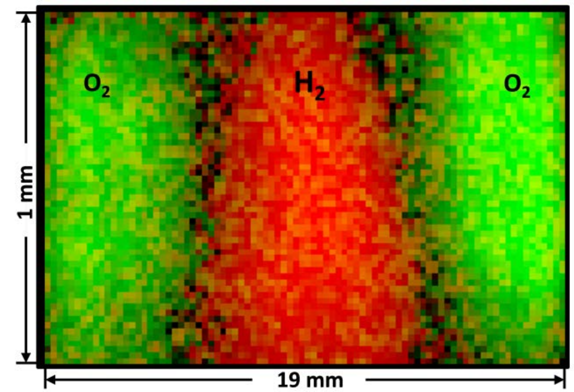
- Single-shot spatially dependent statistics of the 1D flame-front gradient / / thickness / position become possible (improving heat transfer models)

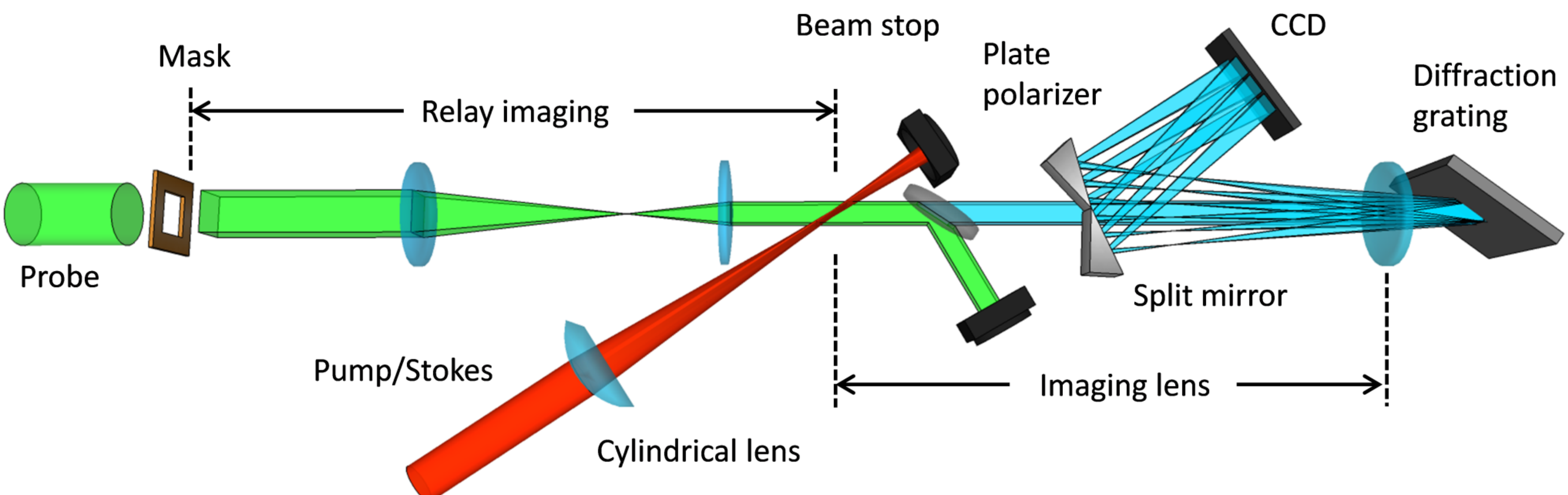
Single-shot hyperspectral CARS in the gas-phase

Temperature imaging



Wideband chemical imaging





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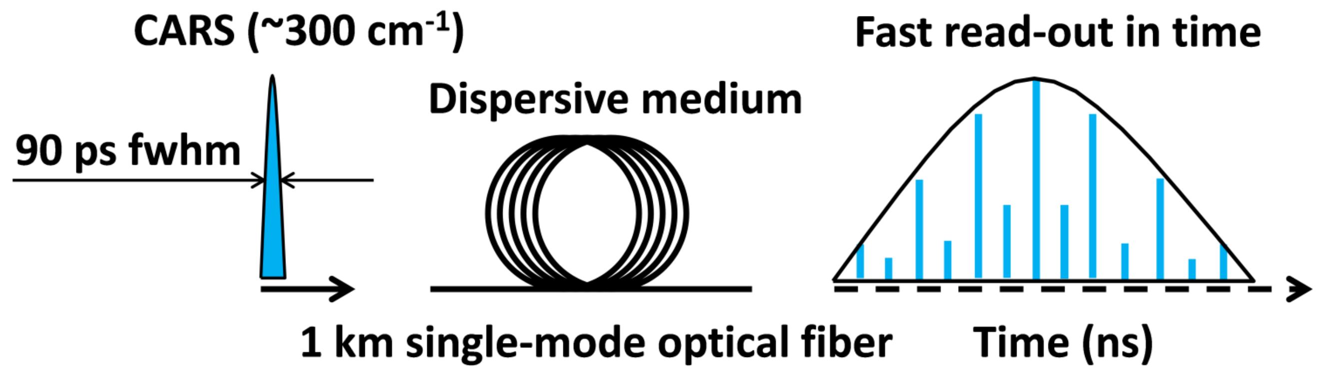
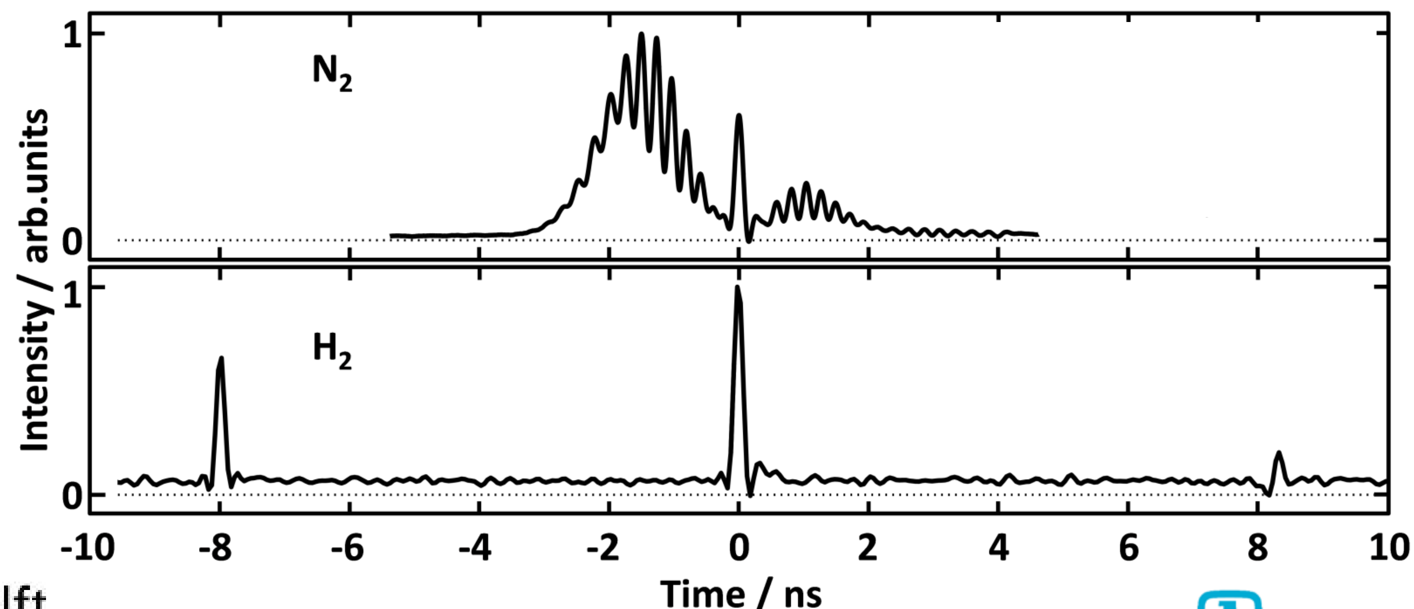
Dispersive Fourier Transform for MHz detection of CARS/CSRS signals





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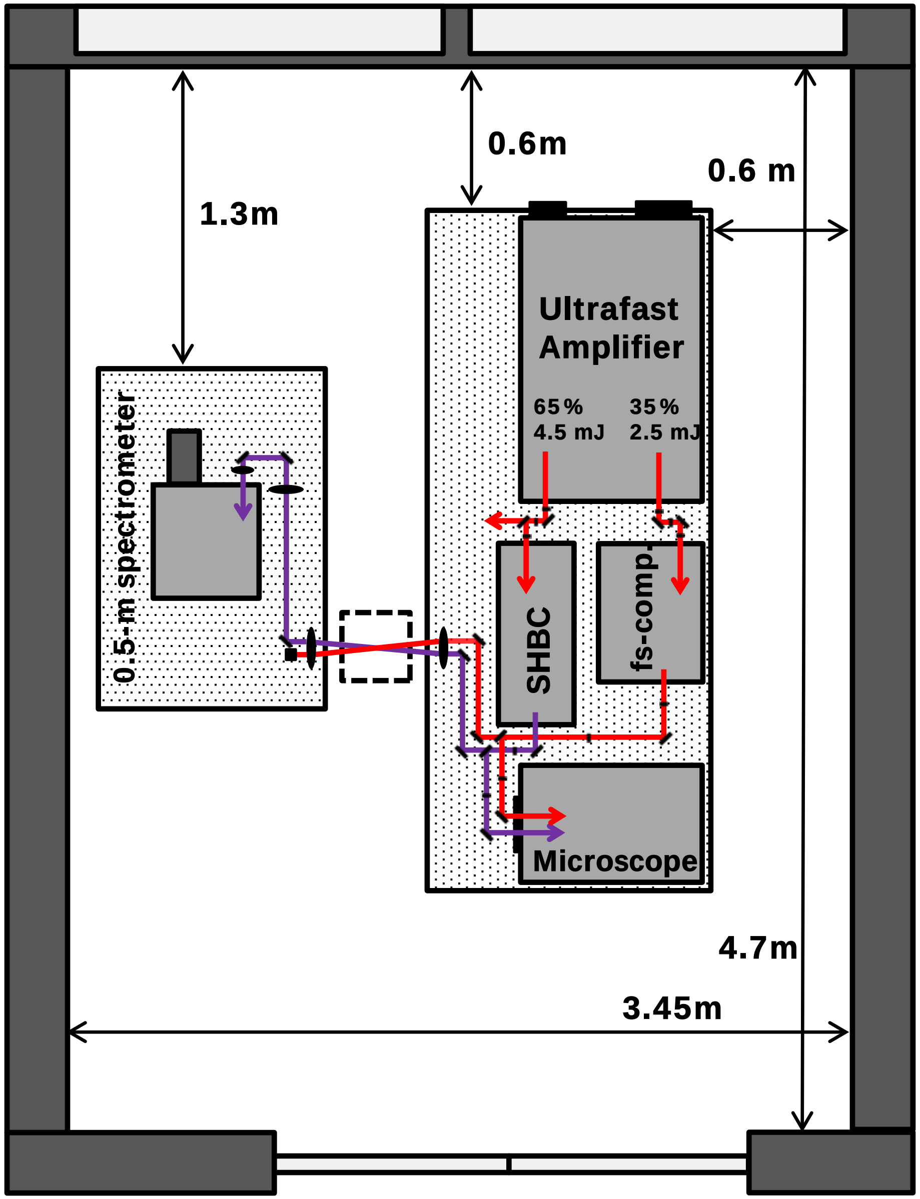
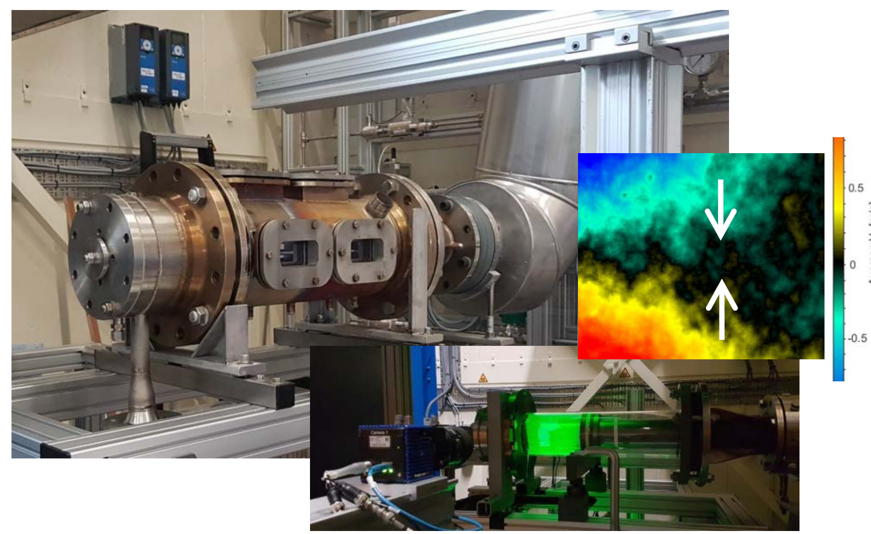


Synchronized ps/fs laser system for time-resolved non-linear optical spectroscopy/microscopy

- **Femtosecond laser (ultrafast amplifier)**
  7 mJ/pulse @ ~780-810 nm (~35 fs)
- **Picosecond laser (SHBC)**
  2.0 mJ/pulse @ 400 nm (~10 ps)

Distributed auto-ignition combustion modes with reduced NOx emission



Courtesy of: Arvind Gangoli Rao

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Current activities at TUD: *"Ultrafast Laser Diagnostics in Renewable Aero-Propulsion"*

Conclusions

- Two-beam femtosecond/picosecond CARS

- Relevant for 0D, 1D, and 2D temperature measurements in flames when high-fidelity information is needed (inaccuracy <2-3%, precision ~1%)
- Single-shot quantitative measurements for major species in combustion are within reach (species specific dephasing times, spectroscopy models)

- This ultrafast 1D-CARS technique has been successfully employed at:

    1. Flame-wall interaction burner (head-on and side-wall quenching)
    2. Sooty flames provided on a McKenna burner

- Can this advanced laser diagnostics technique be employed for measurements in engines?

- Technical challenges for the stability of operation (facility temperature and humidity control, propagating TL-beams through optical ports)