Development of Robust Ultrafast CARS Thermometry and Species Detection (PPT)

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Development of Robust Ultrafast CARS Thermometry and Species Detection

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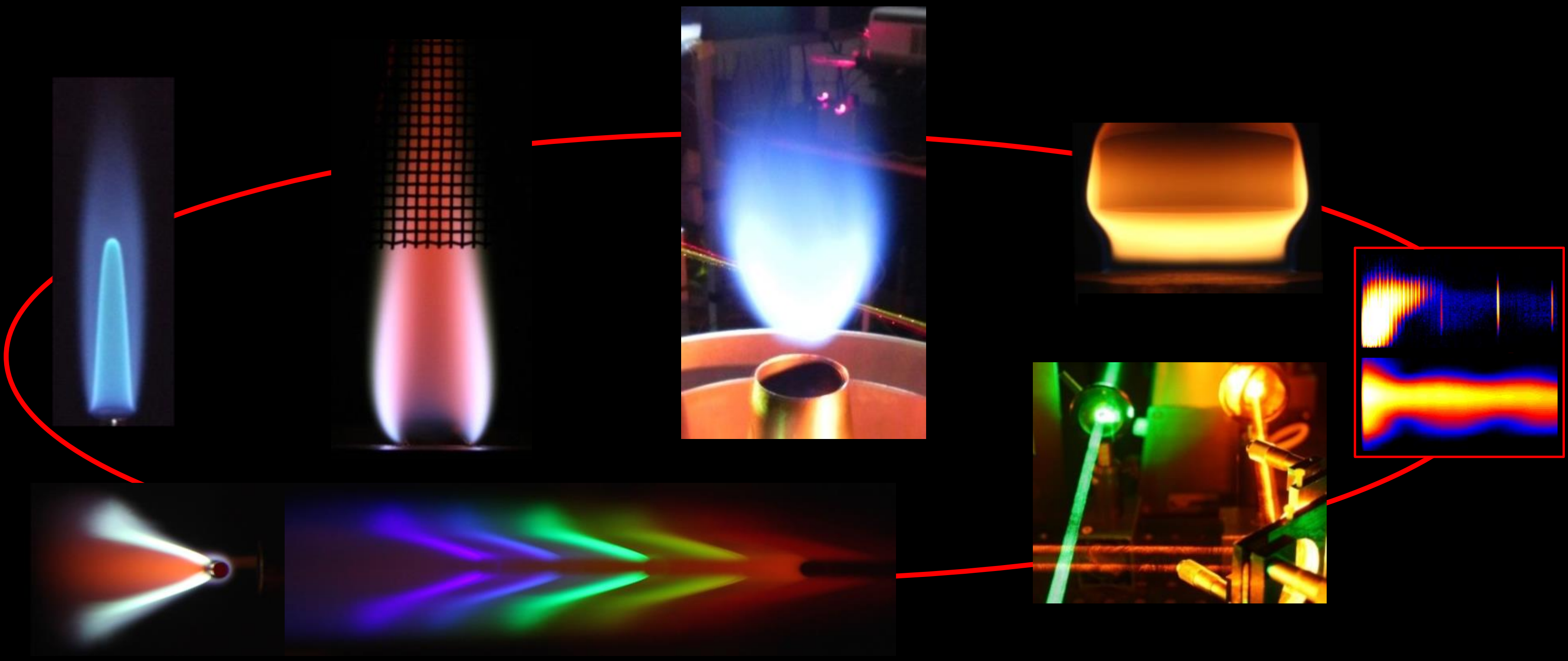

Acknowledgement:
Funding provided by NWO Domain TTW (VIDI grant)

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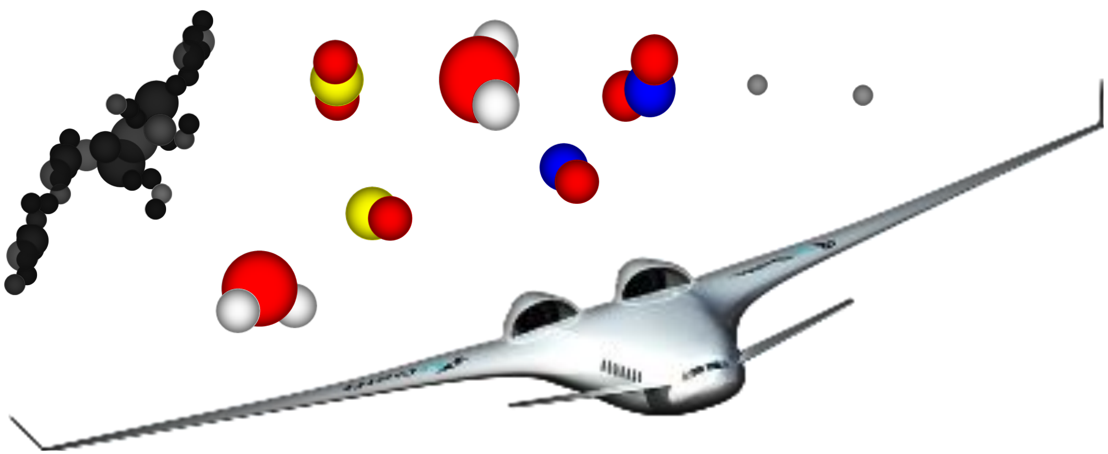
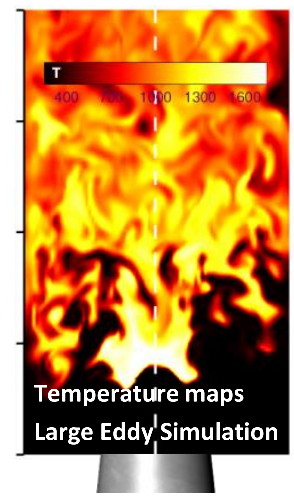
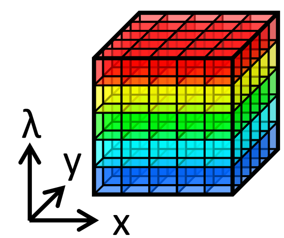
Advancing Renewable Aero-Propulsion

- **Grand challenge: air-transportation/energy security/combustion**
  - Reduced emission of pollutants from aircraft NOx, CO, CO_2, UHC, and soot





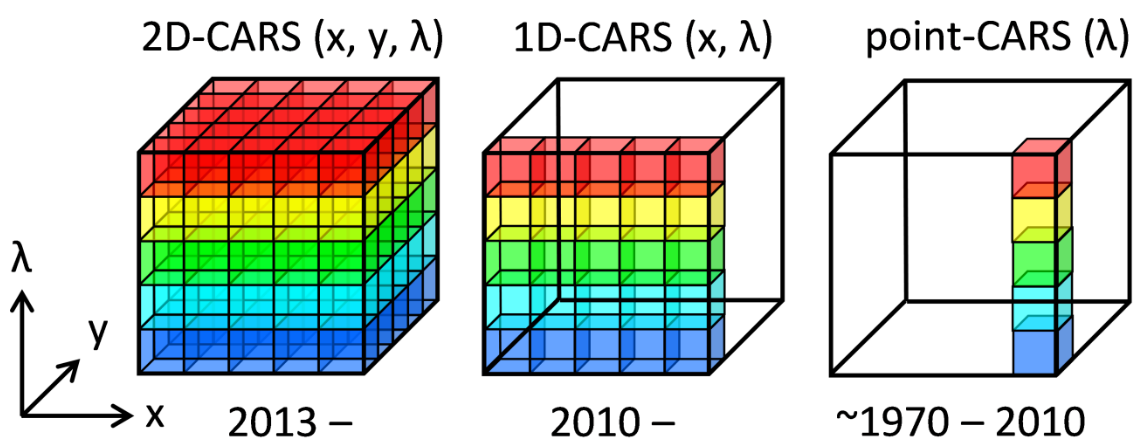


"Deep insight into multiscale chemical interactions can only be obtained from spectroscopic measurements garnered in spatial and temporal correlation."

Time- and spatially resolved optical diagnostics for combustion analysis

- Challenges: Parameter determination in reacting flows
  - Major- and transient species detection   Particulate chemistry
  - Temperature field   Mixture fraction   Flow field
  - Spatial- and temporal correlation (multiscale analysis)
- Strategy: Snap-shot coherent Raman imagery
  - Simultaneous hyperspectral imaging (x, y, λ) in a single-laser-shot.
  - Benchmarking: Accuracy, Precision, Sensitivity, Resolution and Field-of-view.

CARS imagery in flames:



Time- and spatially resolved optical diagnostics for combustion analysis

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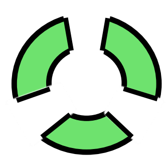
  - Benchmarking: Accuracy, Precision, Sensitivity, Resolution and Field-of-view.
- Objectives: High-fidelity experiments in combustion systems

Experiments informs theory and vice versa



Device validation

- Flameless Combustor

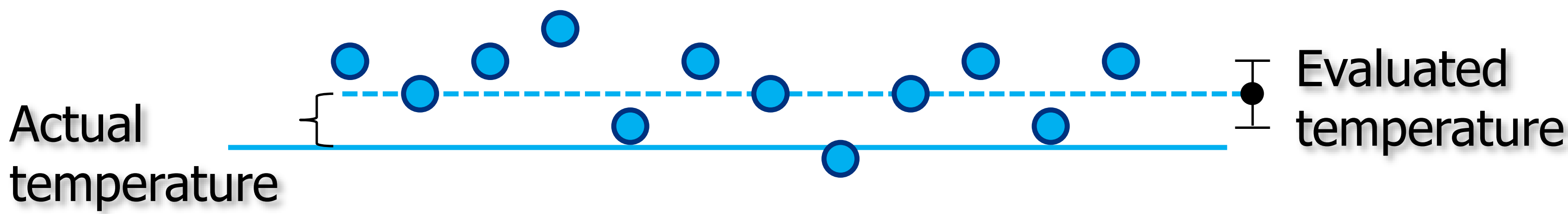
Development of predictive engineering models

Why should we use CARS?

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

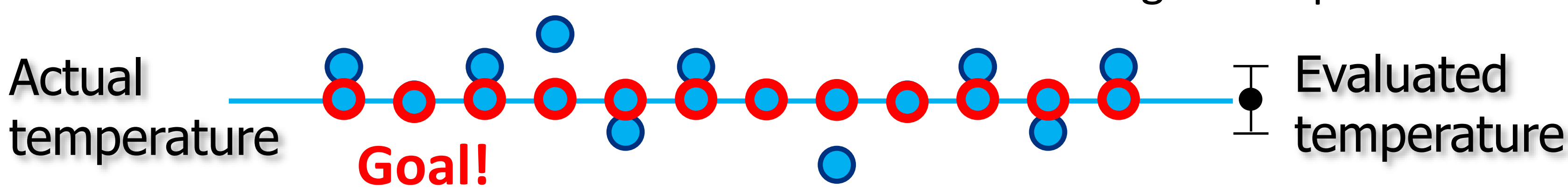
Inaccuracy ~2-3%
Single shot precision ~4-5%

Background nanosecond CARS



Inaccuracy ~0% ?
Single shot precision ~4-5%

Advanced nanosecond CARS



Improved Accuracy – Spectroscopic modelling (Raman linewidths, ...)

Improved Precision – Experimental setup (Laser system, ...)

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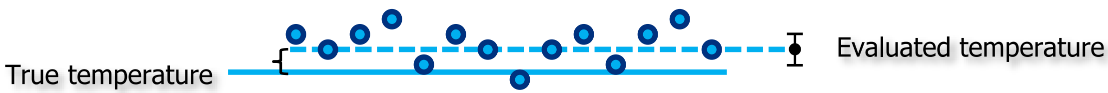
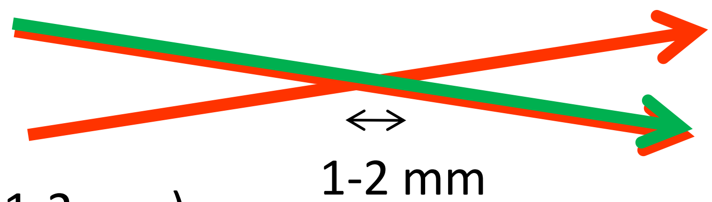
Why should we use CARS?

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

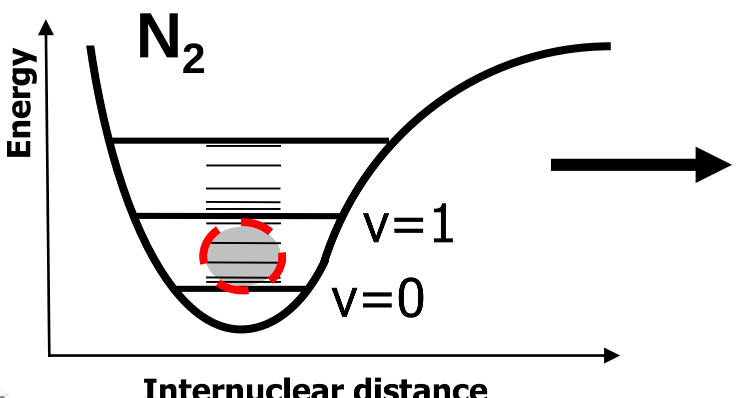


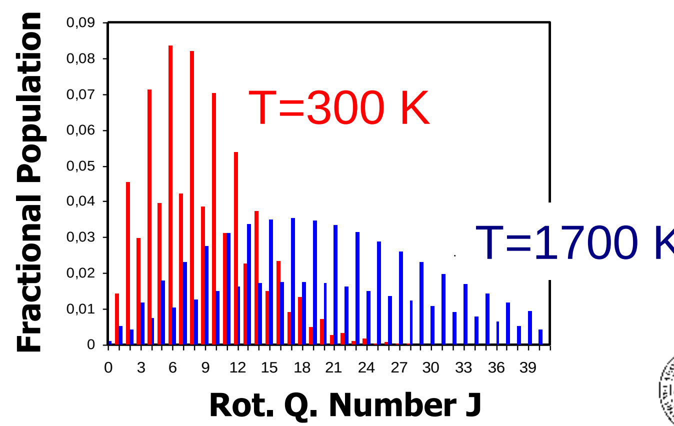
Inaccuracy ~2-3%
Single shot precision ~4-5%

- 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





Why should we use CARS?

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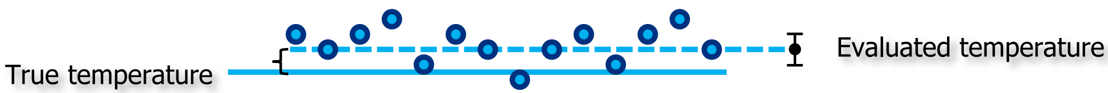

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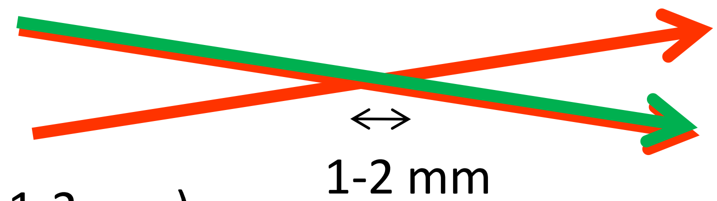
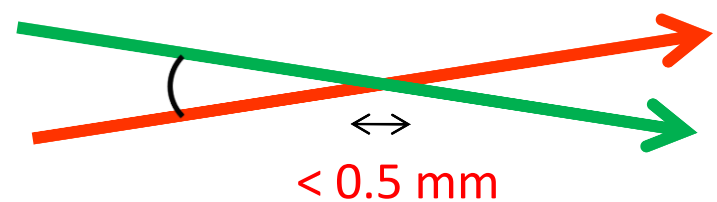


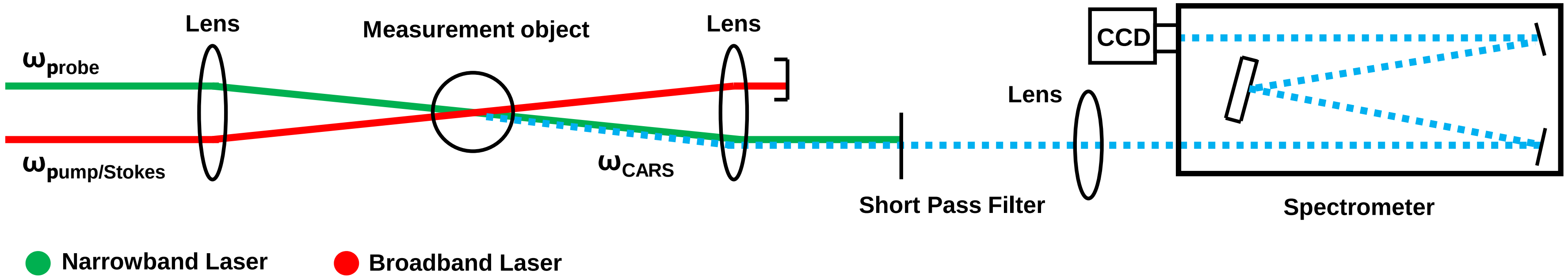
- Vibrational CARS, Rotational CARS

- 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%

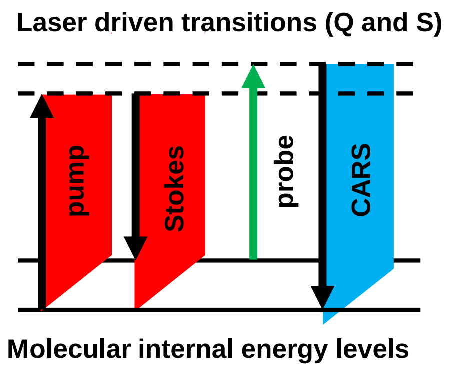


Two-beam femtosecond/picosecond CARS

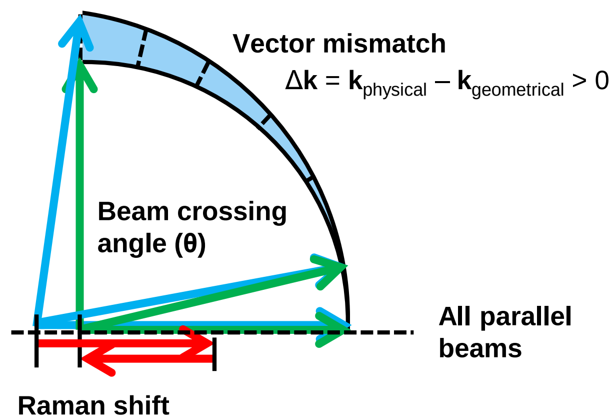


Simplified generic phase-matching- and impulsive excitation scheme.

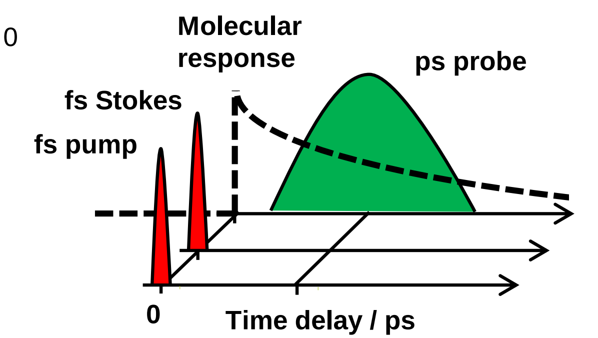
Energy conservation



Phase-matching (momentum conservation)



Spectroscopy in the time-domain



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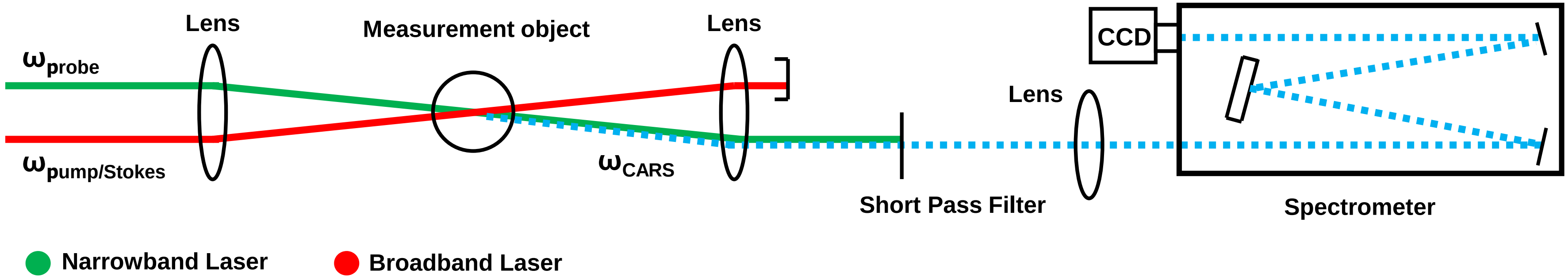
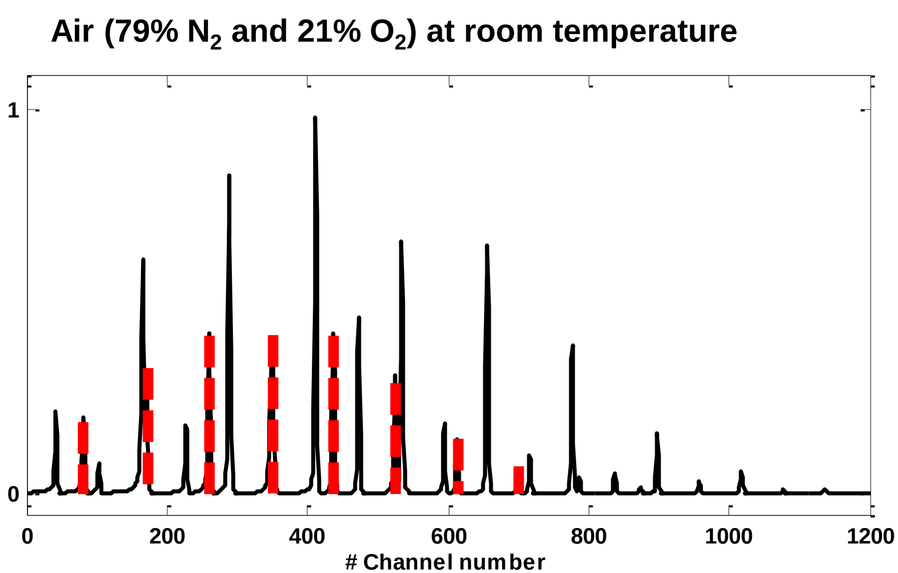
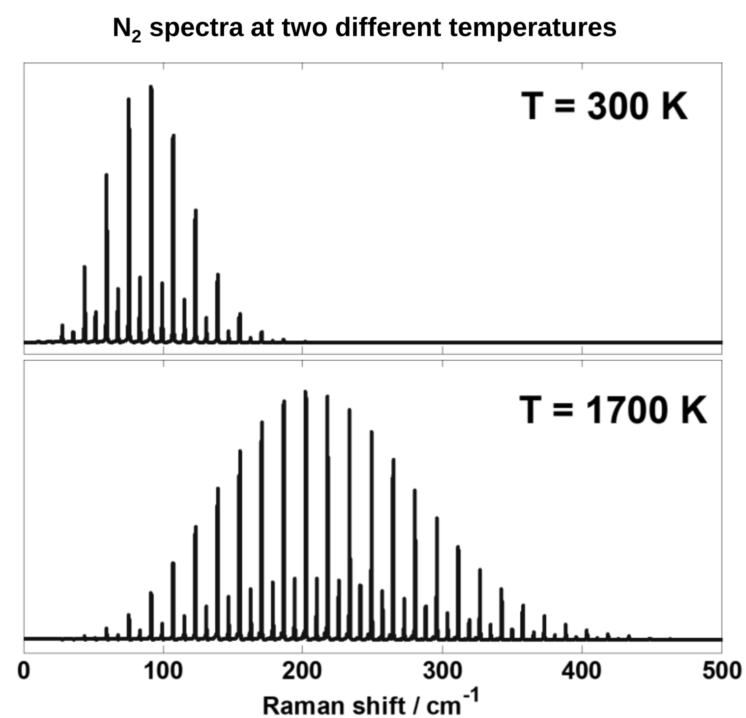
Two-beam femtosecond/picosecond CARS







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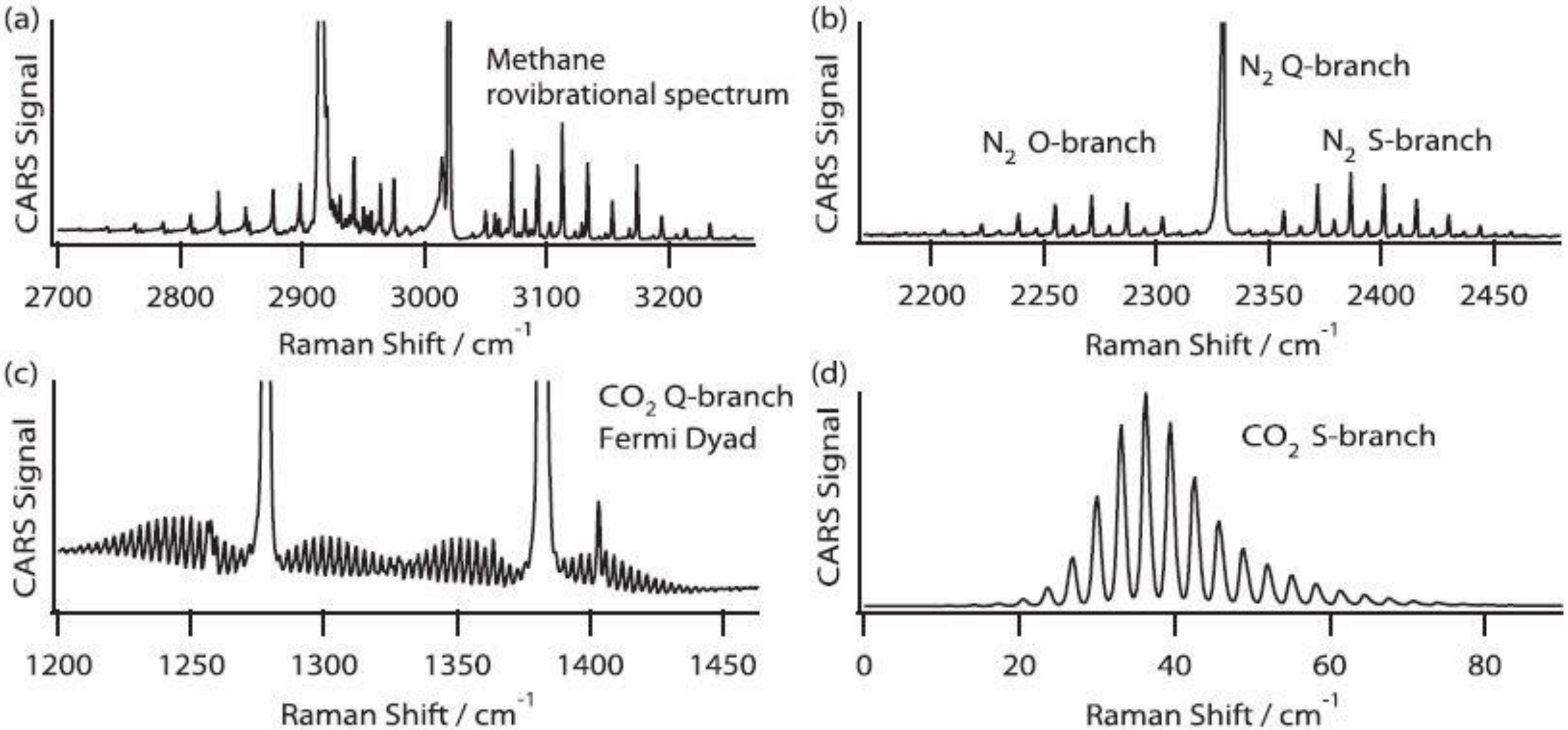
Examples of coherent Raman spectra for some combustion relevant species



- Specific selection rules (transitions)
  ro-vibrational O-, Q-, S-branch ($\Delta v = 1, \Delta J = 0, \pm 2$),
  pure-rotational O, S-branch ($\Delta J = \pm 2$)

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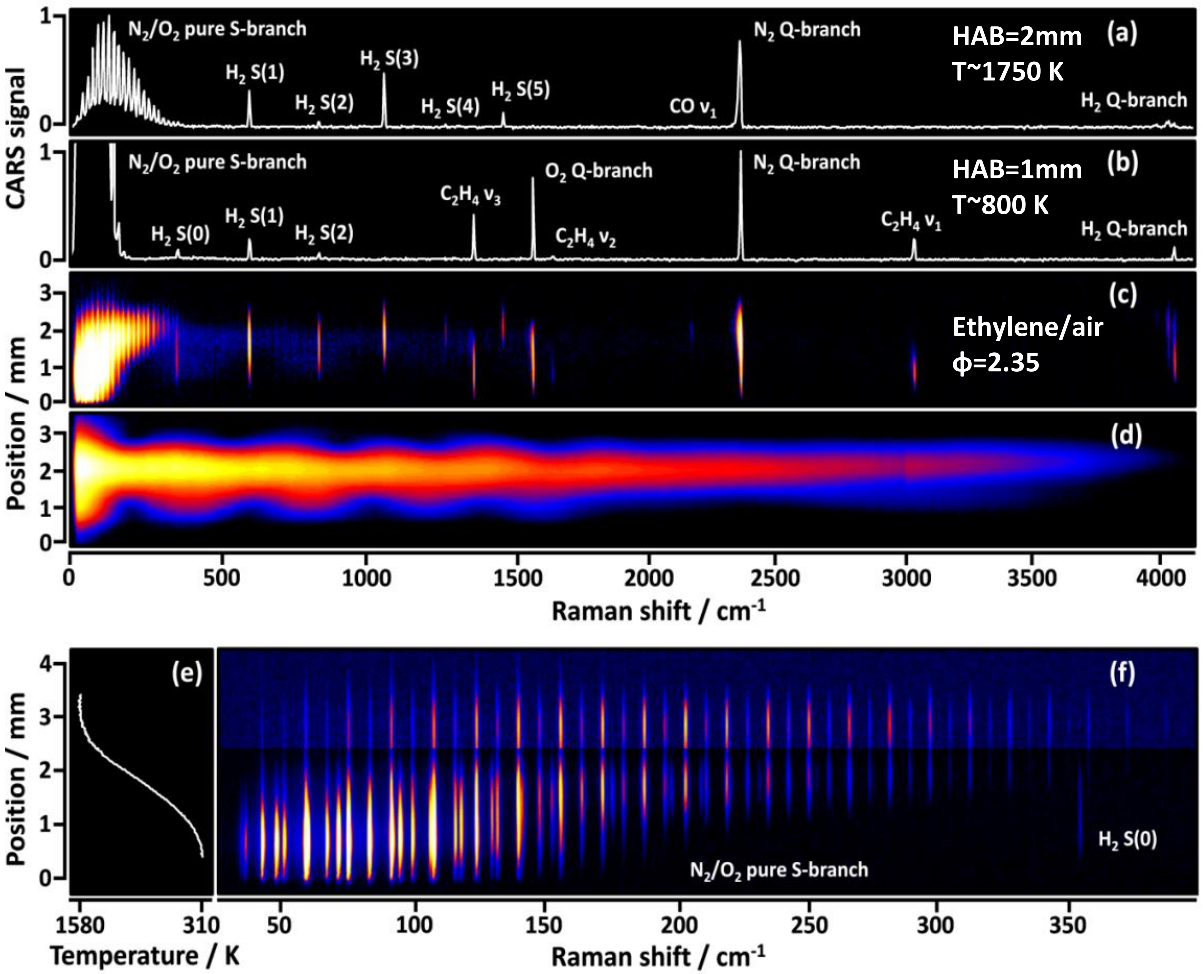
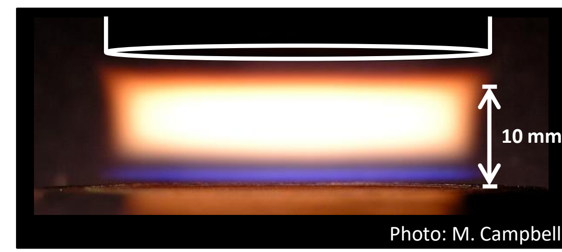
Direct coherent Raman temperature imaging and wideband chemical detection

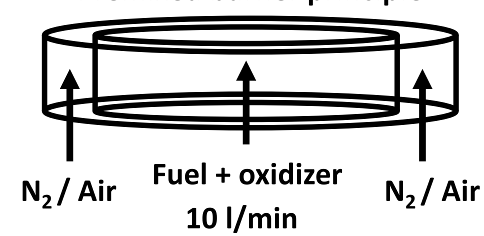


- Canonical sooting hydrocarbon flat-flame used to benchmark the new techniques.



Burner design (Michelsen group, Sandia)

Premixed burner principle



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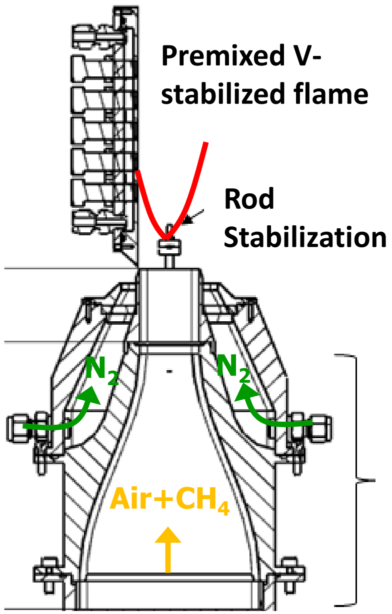
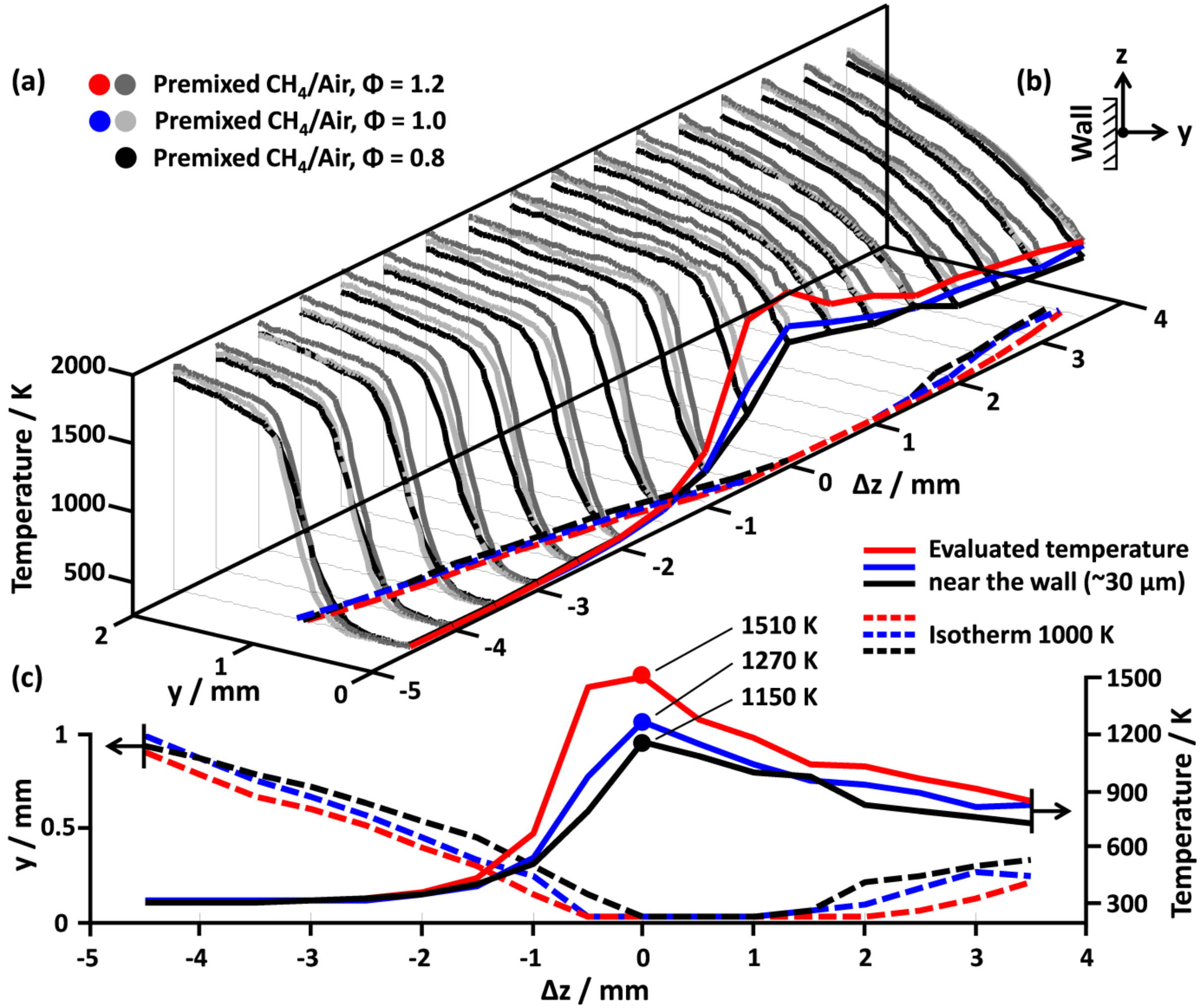
Side wall quenching burner
- 1D-CARS temperature- and chemical imaging



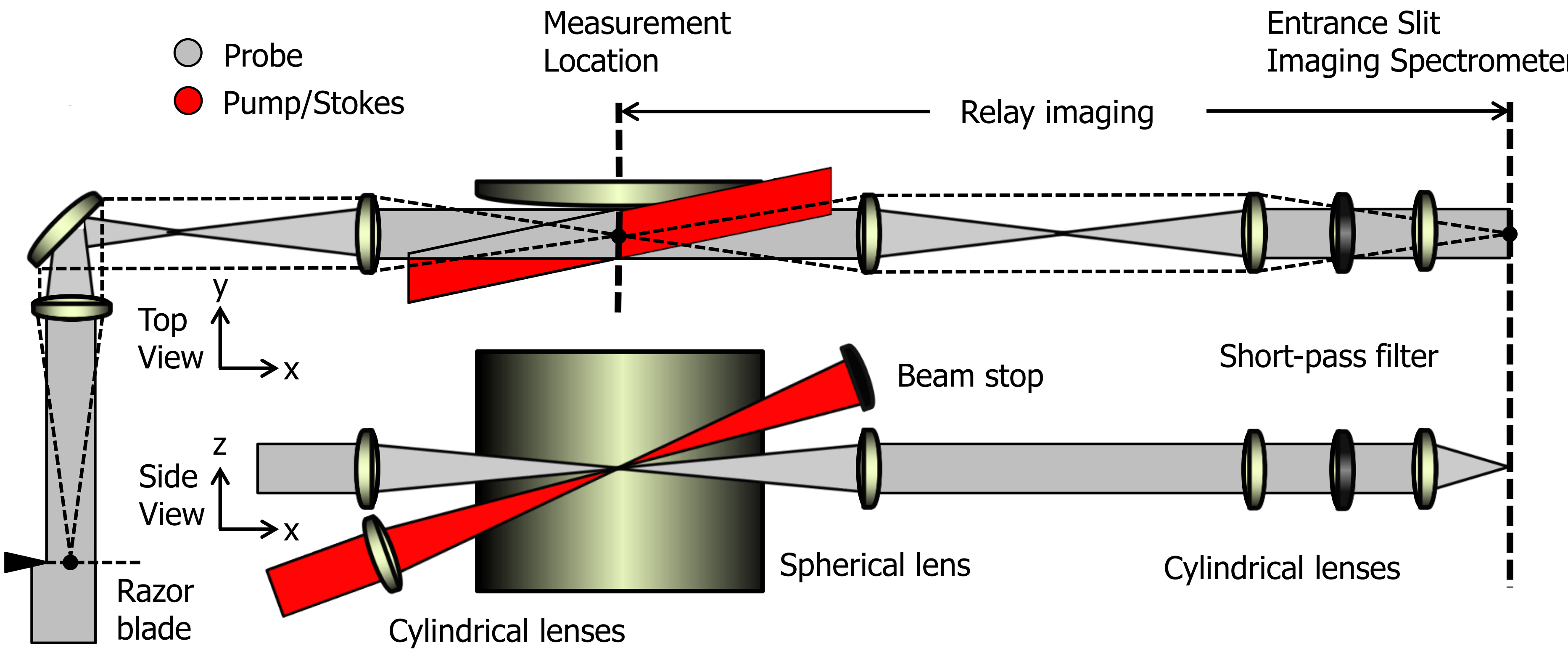
Burner design (Dreizler group, TU Darmstadt)



- Motivation

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

Two-beam 1D-CARS near-wall imaging



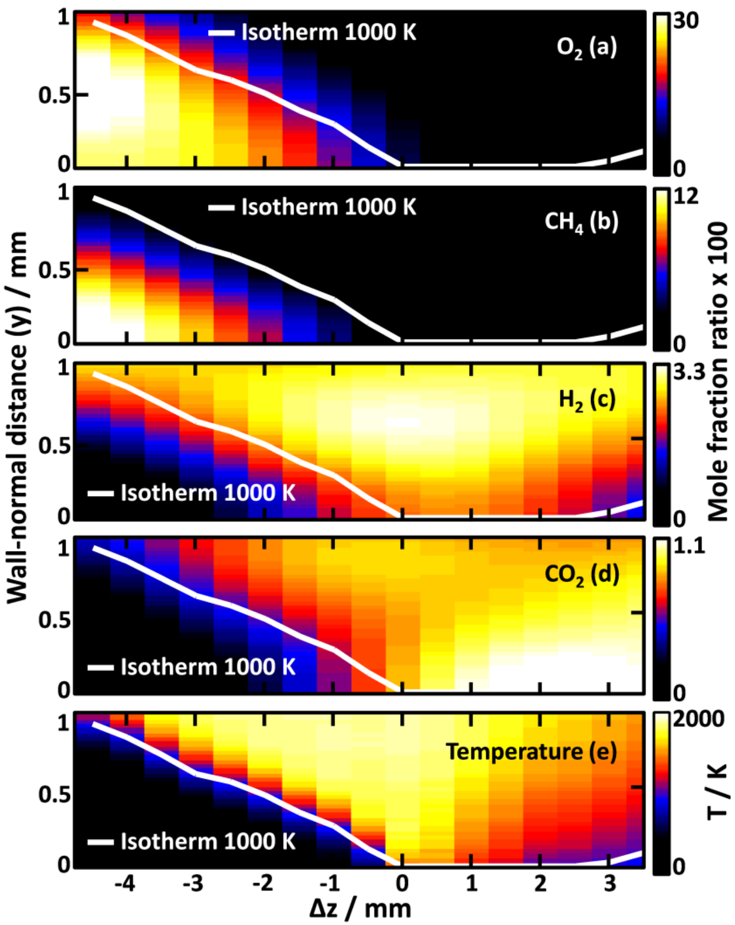
- Automatically overlapped pump/Stokes fields, temporally and spatially, makes the technique more robust and higher pulse energy available.
- Spatial sectioning (probe volume):

~ 40 µm (Beam waist) x 40 µm (Coherent point-spread function) x 0.5 mm (Interaction length).

Multiparameter spatio-thermochemical probing of flame-wall interactions

- Concurrent 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.



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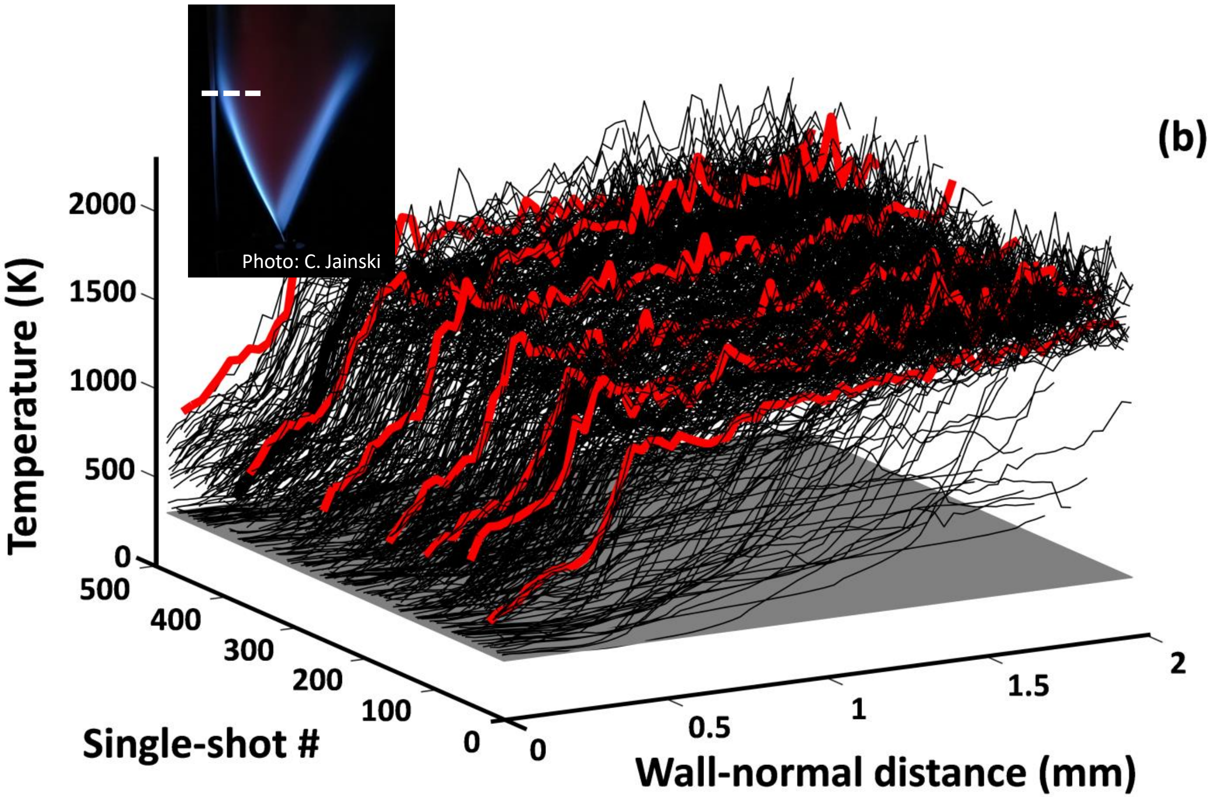
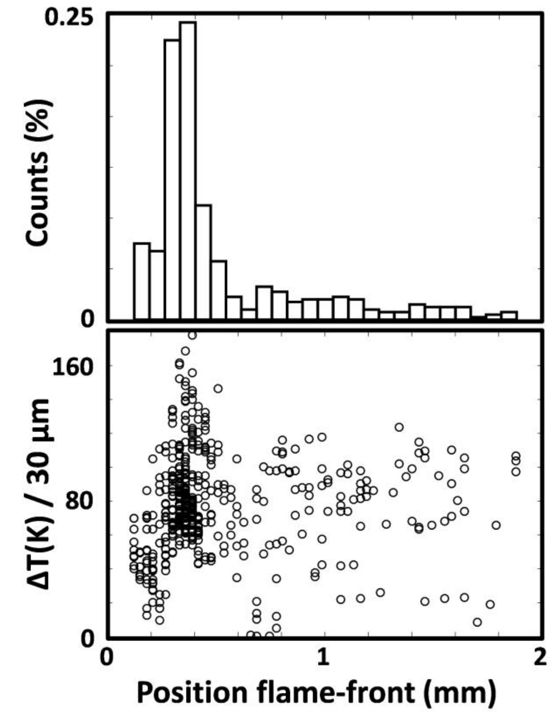
FWI at enhanced turbulence intensities

(Work-in-progress)





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

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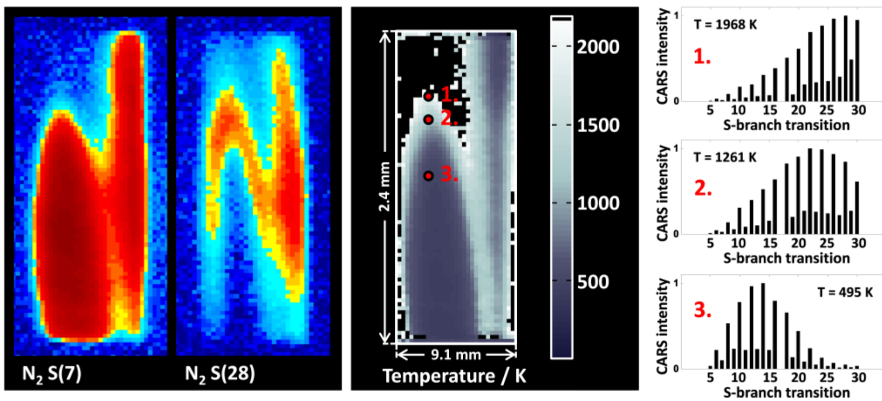
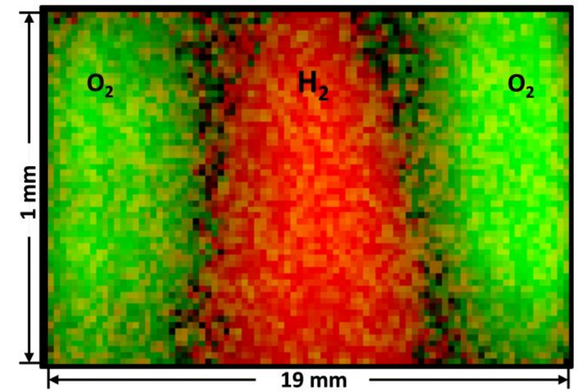
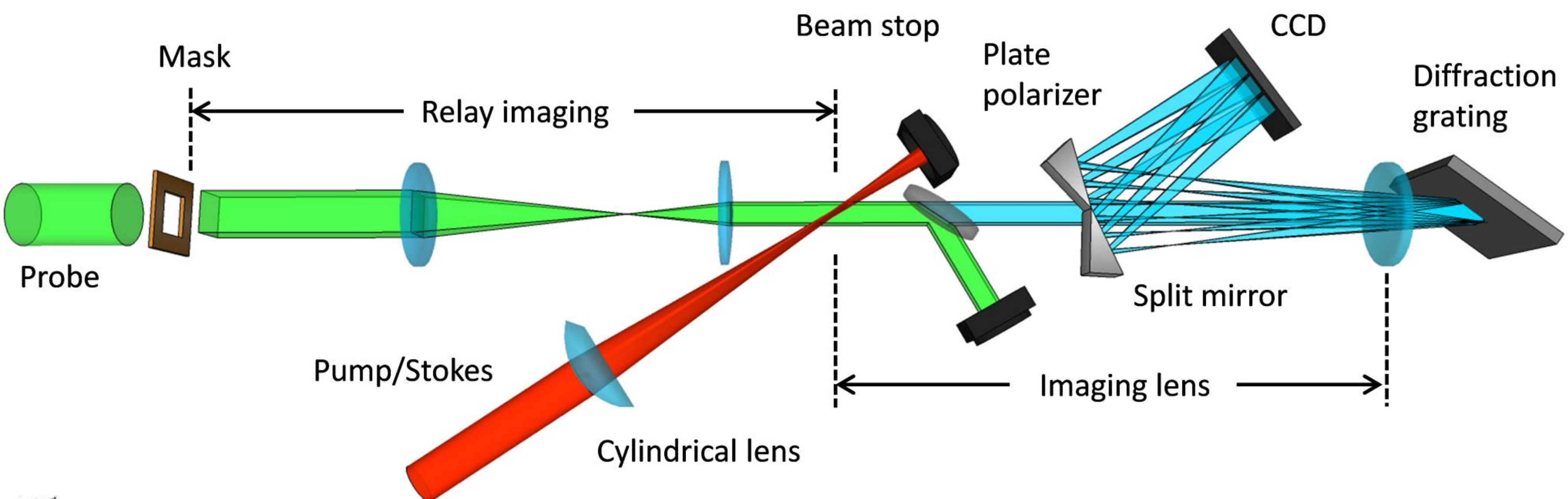
Single-shot hyperspectral CARS in the gas-phase

Temperature imaging



Wideband chemical imaging





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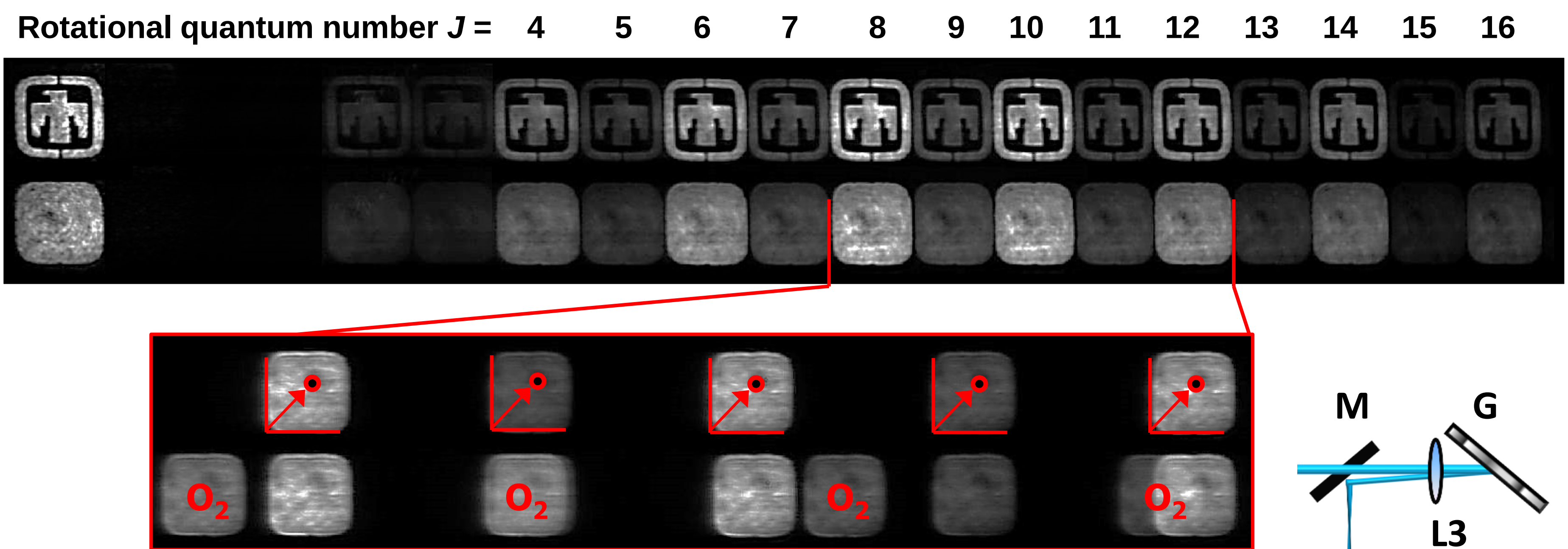
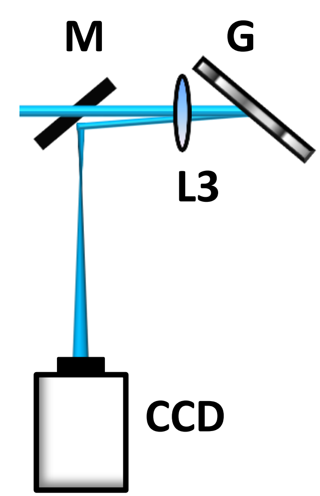
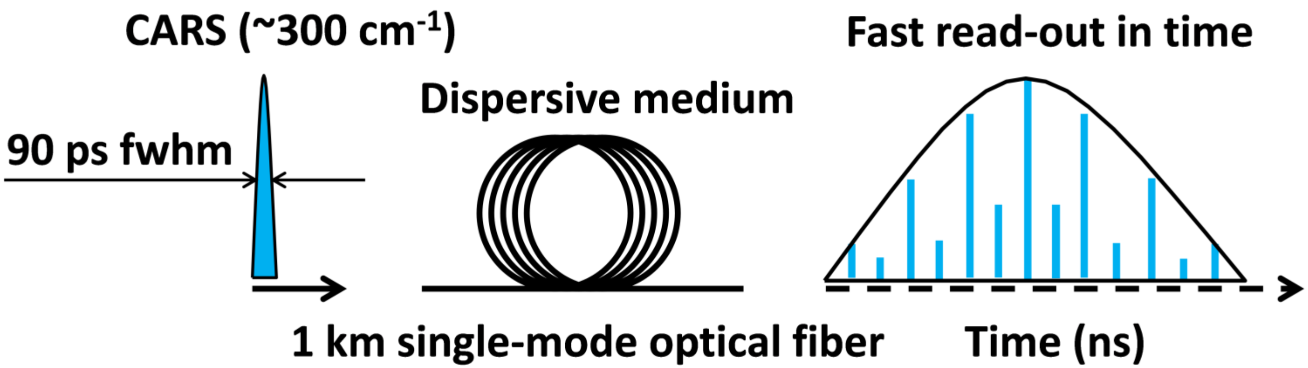
Simultaneous planar imaging and multiplex spectroscopy in a single-shot

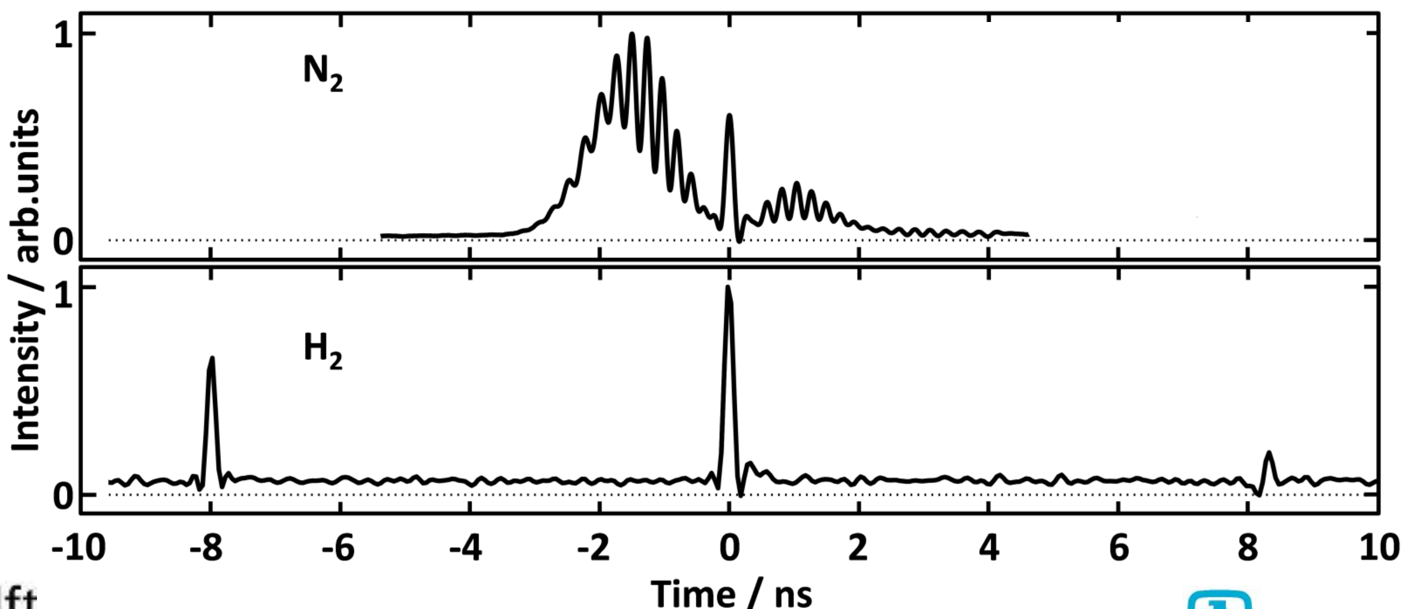




- Tunable spectral dispersion, enabling multispecies detection and probing of a larger 2D field.
- Vector diagram to orientate each location of the spatially resolved measurement.

Dispersive Fourier Transform detection of short pulsed CARS/CSRS signals





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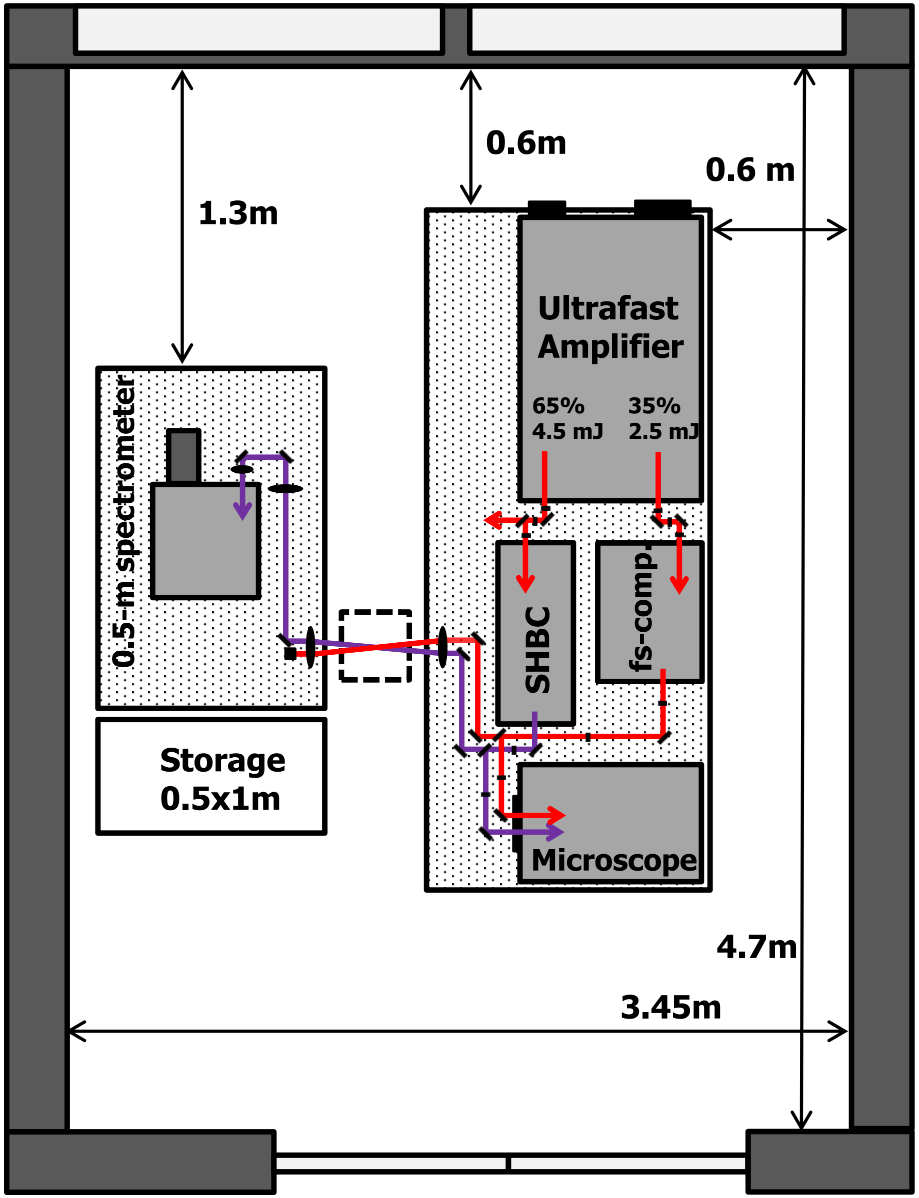
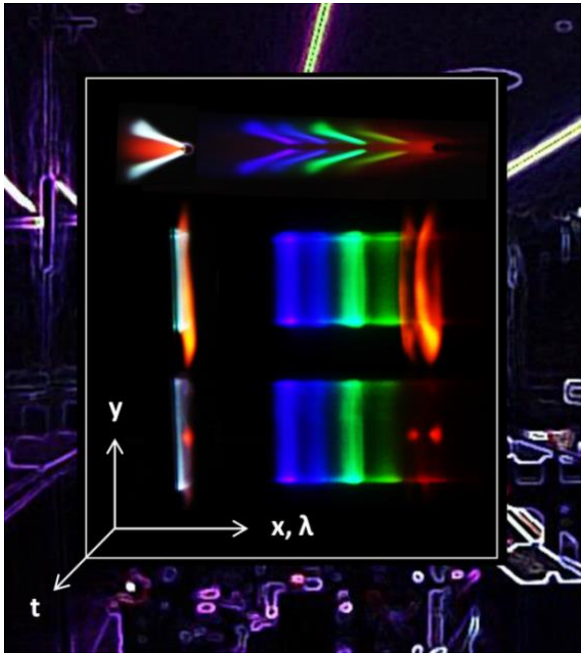


Synchronized ps/fs laser system for time-resolved non-linear optical spectroscopy/microscopy

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



Snap-shot chemiluminescence flexible hyperspectral imagery

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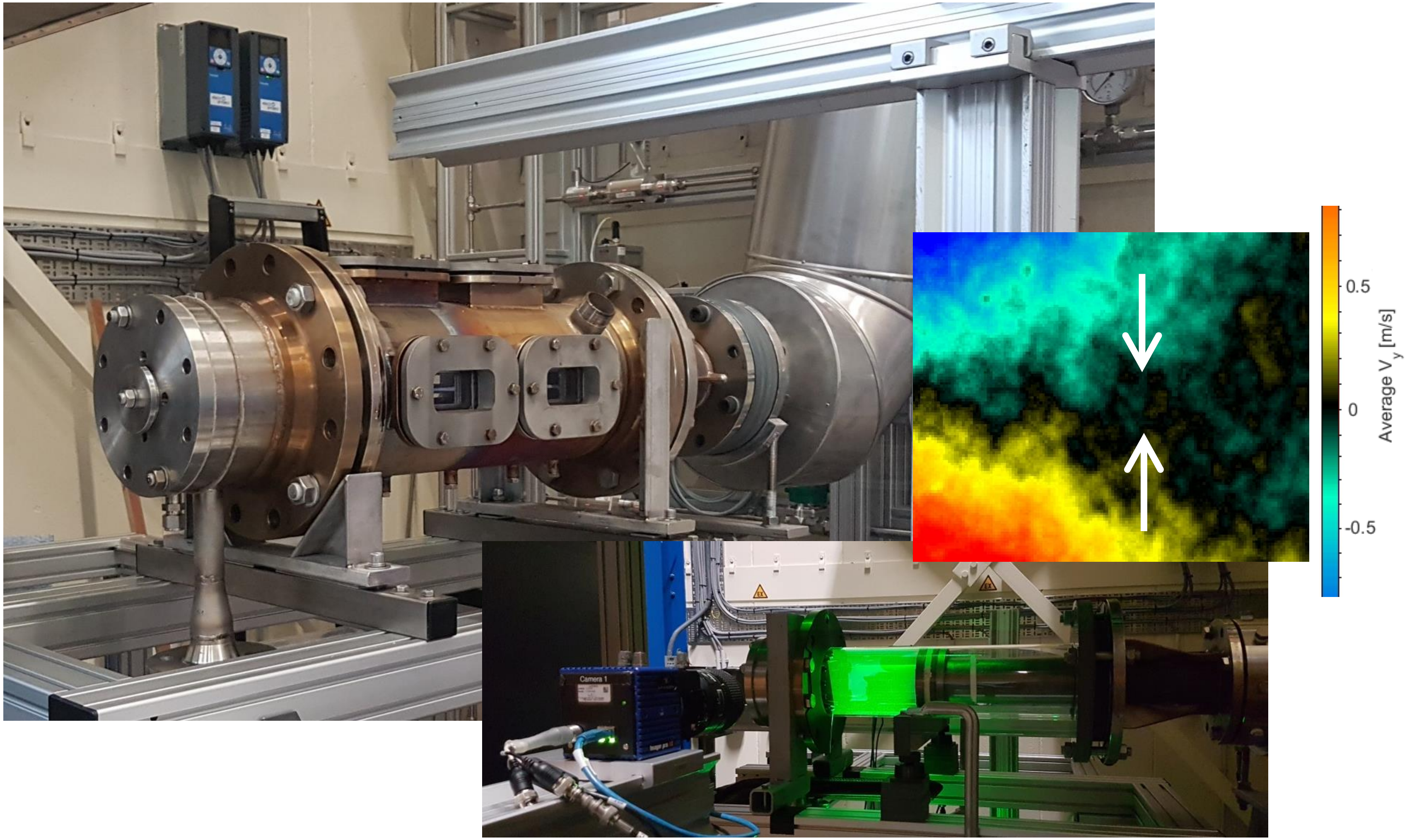
Acknowledgement:
Funding provided by NWO Domain TTW (VIDI grant)

NWO

It is equally fun to buy an air-treatment system, as it is to buy a vacuum cleaner

Distributed auto-ignition combustion modes with reduced NOx emission



Courtesy of Dr. Arvind Gangoli Rao

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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)

Thank you for your attention!

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