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ME 687
Advanced Engineering Optics: Laser Diagnostic Methods in Mechanical Engineering

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ME 687 Course Overview

Course Objective: Develop working knowledge of laser techniques for species concentration, temperature, and velocity measurements in complex reacting media.

Working Knowledge of Laser Techniques?
- Laser systems
- Optical elements for laser diagnostic systems
- Species spectroscopy polyatomic
- Interaction of laser radiation with the molecule or atom
- Calculation of signal levels, estimates of accuracy, precision

Complex Reacting Media?
- Laminar or turbulent flames, steep gradients in species concentration and temp, need high spatial, temporal resolution
- Collisional environment of molecule or atom is drastically different in different parts of the flame
- Collisional environment can significantly affect signal levels from laser techniques

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Review Polarization of light

understood well for infrared because of interest from atmospheric ~~sci~~ scientists

Issues in Combustion Science: Why Use Laser Diagnostics?

- Flame Chemistry - complex reaction mechanisms, importance of free radicals that are difficult to measure by other techniques, lasers do not perturb the flow and temperature fields nearly as much as physical probes

Example: $H_2/O_2/N_2$ Chemistry

Initiation Reaction

$$(1)\ H_2 + O_2 \rightarrow HO_2 + H \qquad \textit{Initiation}$$

Chain-Branching Reactions

$$(2)\ H + O_2 \rightarrow O + OH \qquad \textit{Chain-Branching}$$

$$(3)\ O + H_2 \rightarrow H + OH$$

$$(4)\ H_2 + OH \rightarrow H_2O + H \qquad \textit{Except for } (4)$$

$$(5)\ O + H_2O \rightarrow OH + OH$$

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Issues in Combustion Science: Why Use Laser Diagnostics?

Chain Termination, 3-Body Recombination

$$(6)\ H + H + M \rightarrow H_2 + M \qquad \textit{Chain-Termination}$$

$$(7)\ H + OH + M \rightarrow H_2O + M \qquad 3-\textit{Body Recombination}$$

NO Formation: Zeldovich Thermal NOx Mechanism

$$(8)\ O + N_2 \rightarrow NO + N \qquad \textit{Very Temperature Sensitive}$$

$$(9)\ N + O_2 \rightarrow NO + O \qquad \textit{High Activation Energy}$$

$$(10)\ N + OH \rightarrow NO + H$$

Lasers can be used to measure all T, all major species, O, H, OH, and NO. Temperature measurement by thermocouple compromised by radiation, perturbs flow and flame chemistry. Physical probes perturb flow.

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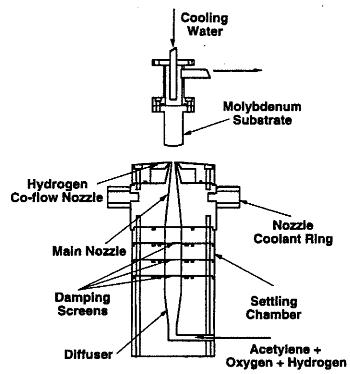
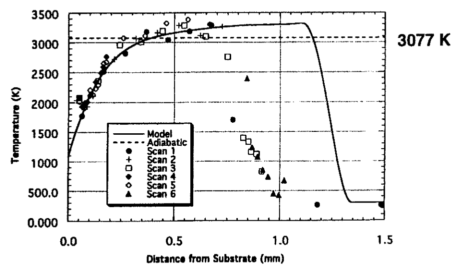
Issues in Combustion Science: Why Use Laser Diagnostics?

Stagnation Flow Diamond-Forming Flame Apparatus

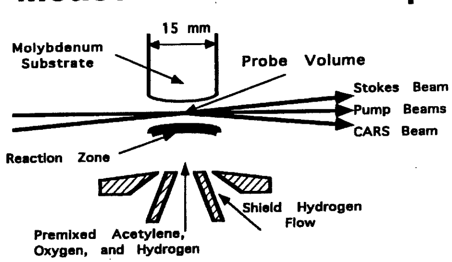


Diamond-Forming Flame Temperature Profile (Case I)



Issues in Combustion Science: Why Use Laser Diagnostics?

Measurement Technique



Temperature measured along stagnation-point streamline between nozzle exit and substrate surface

Data obtained in probe volume defined by overlap of the three input beams

- ~ 50 μm in diameter
- ~ 1.5 mm long

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Spectroscopic Laser Techniques

- Development of commercialized tunable lasers about 25 years ago has led to routine use of laser techniques for probing flames and plasmas.
- Laser technology continues to advance, sometimes with dramatic impact on "old" laser techniques.
- Recent advances with actual or potential impact on flame and/or plasma diagnostics: blue diode lasers, DFB diode lasers, injection-seeded Nd:YAG lasers with > 1 J per pulse, picosecond laser systems, femtosecond laser systems, BBO crystals

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Ruby laser system single frequency

have not gone along as quickly as femtosecond

why sky is blue

nice for clean flames. (dust, soot, etc. can overwhelm it)

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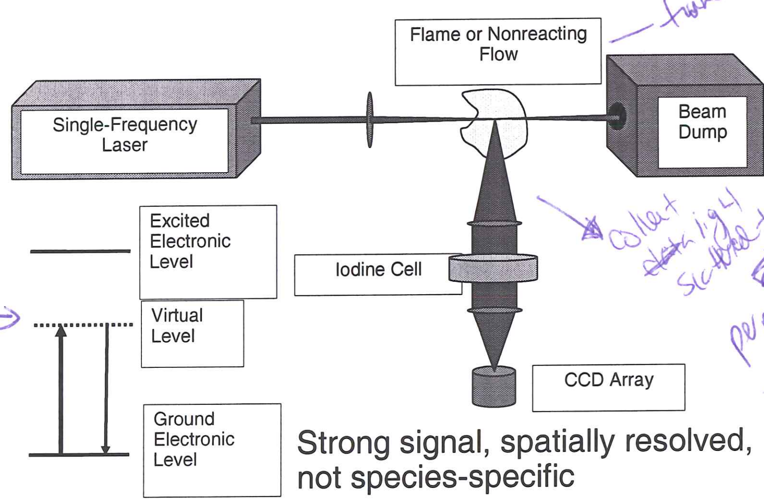
Rayleigh Scattering – Filtered Rayleigh Scattering

function of ~~...~~, density



collect ~~dark~~ light scattered perpendicular

photon absorbed & emitted by the molecule

Strong signal, spatially resolved, not species-specific

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Not straight forward to take measurements and relate to density

A+G Natural Gas

the blue flame is excited CH radicals that emit "blue" photons.

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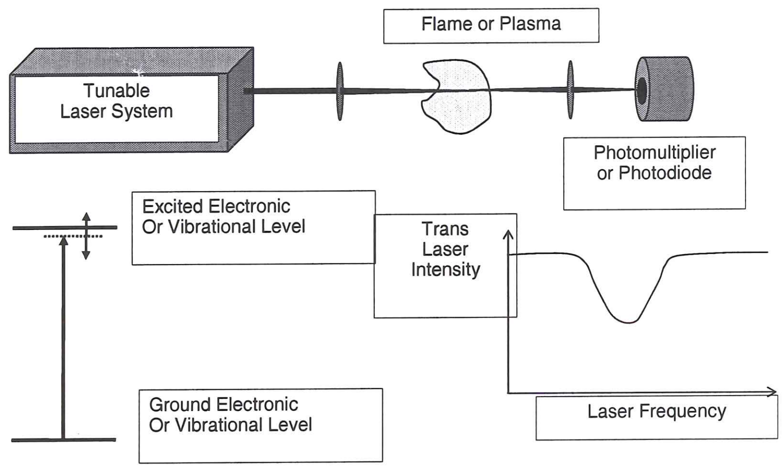
Tunable Laser Absorption



Species-specific, quantitative, path-averaged, temperature specific

soot in a camp fire makes it look yellow because the soot radiates as a blackbody

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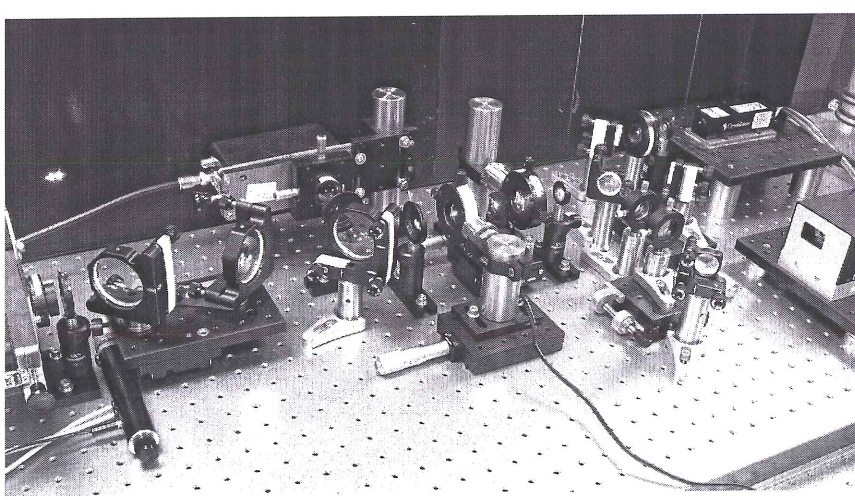
NO Sensor System



395 nm "blue"

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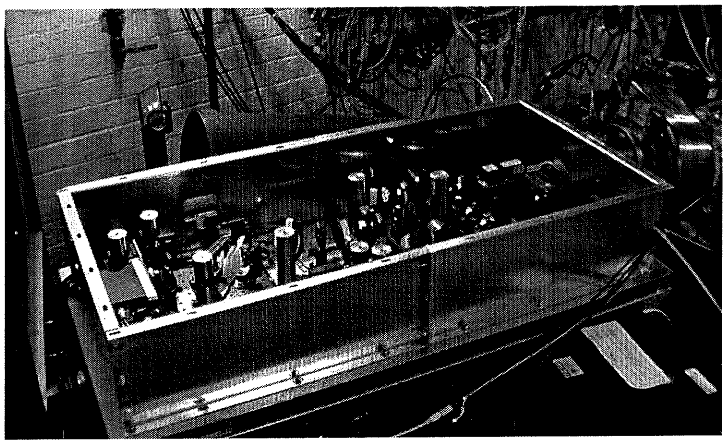
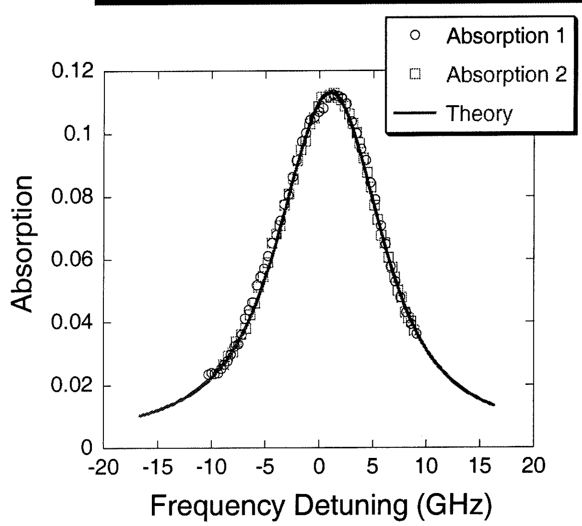
Field Demonstration: Honeywell Gas Turbine Engine



Gas Turbine Measurements: High Load Condition



Absorption Results

$x_{NO} = 56\text{ppm}$

T = 750 K

$2\gamma_{coll} = 0.598\ \text{cm}^{-1}$

Scaling Factor = 1.26

Sampling Probe Results

$x_{NO} = 55\text{-}65$ ppm

T = 712-751 K

a priori

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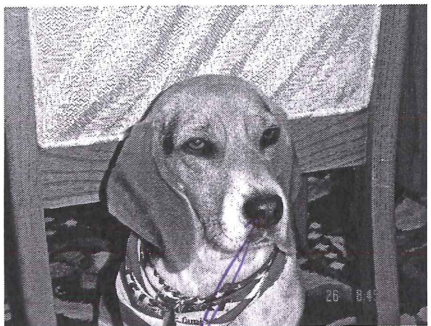
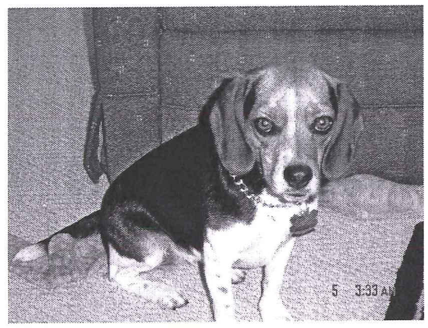
Sensors for Detection of Trace Chemical Species



Haley



Molly

keen sence of smell

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not as sensitive to incoming frequency

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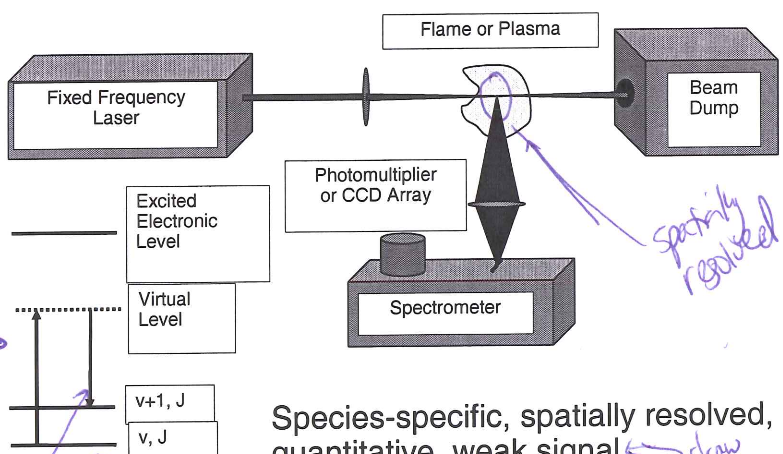
Spontaneous Raman Scattering



Species-specific, spatially resolved, quantitative, weak signal

draw back

spatially resolved

Good for clean turbulent flames

-help ful for turbulence chemistry interactions

photon is scattered

because it drops to a different level the outcoming photon is at a different frequency.

Sensitive (outcoming frequency) to molecule

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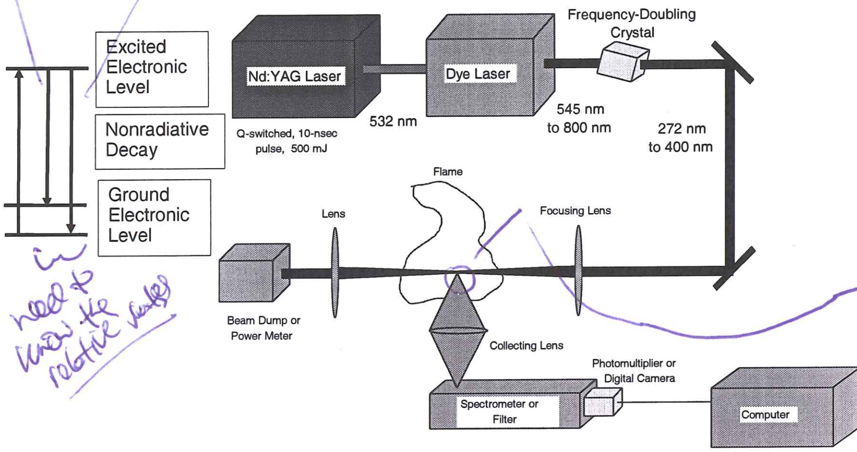
Spontaneous, so not affected by collisions

Laser-Induced Fluorescence (LIF)

realizes w/ fluoresing it off

collision → photons not emitted

absorbs at these λ's
OH 300 nm
CH 430 nm



need to know the relative states

high spatial resolution

Species-selective, spatially resolved, strong signals, complicated by nonradiative decay, not all species fluoresce

both diatomic and polyatomic ~~too~~ can fluoresce

acetone - very nice

Planar Laser-Induced Fluorescence (PLIF)

Planar Imaging System

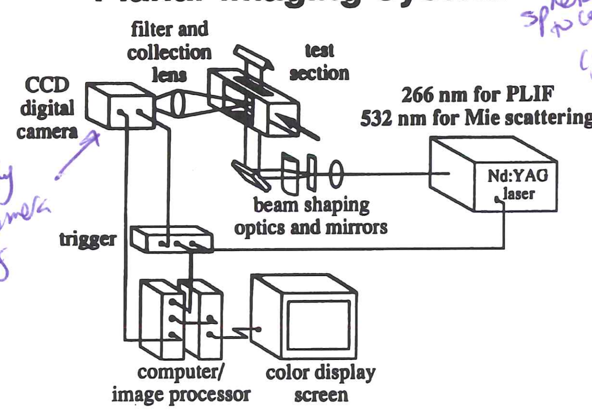
spherical → focus to center of test section

cylindrical lens, curved in 1-dimension

spreads in 1-dimension

~~Creates Sh~~ beam in

polycyclic aromatic fuels can also be excited



typically use a camera lens

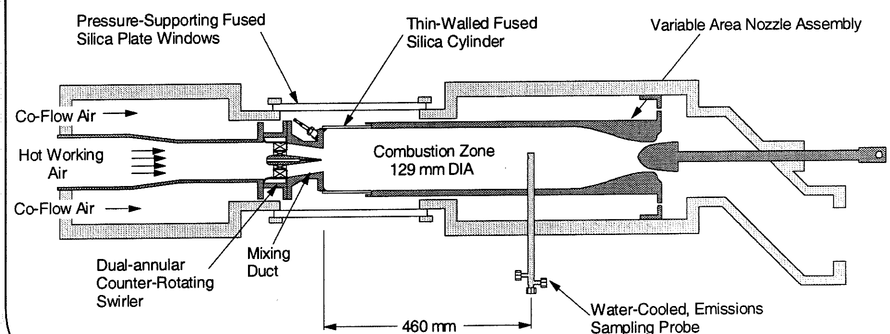
need to discriminate between this and other fluorescing species

Nd:YAG LASER
- 6-8 ns pulse, 10 Hz
- 600 mJ @ 532 nm
- 120 mJ @ 266 nm

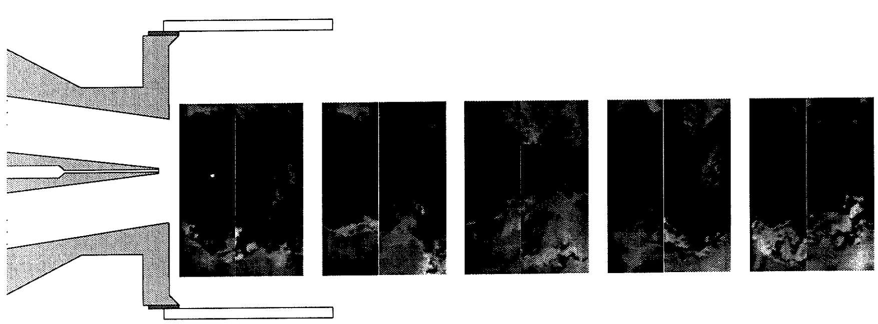
SHEET FORMING OPTICS
- spherical lens, f=500 mm
- cylindrical lens, f=-19 mm
- cylindrical lens, f=150 mm

CCD DIGITAL CAMERA
- thinned, back-illuminated sensor
- 512 x 512 pixel array

Premixed Gas Turbine Combustor Facility (UIUC)



OH Planar Laser-Induced Fluorescence (PLIF)



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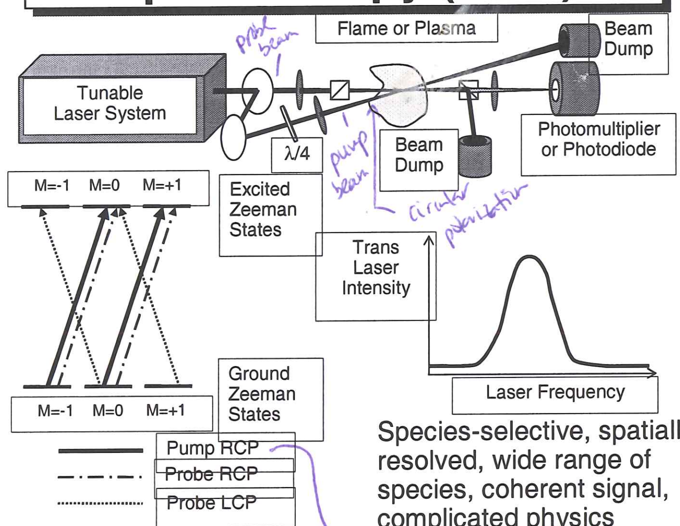
Laser-Induced Polarization Spectroscopy (LIPS)



Species-selective, spatially resolved, wide range of species, coherent signal, complicated physics

right circ polarization

basically a spatially resolved absorption

→ species don't have to have a fluorescing band

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signal rides on an absorption beam

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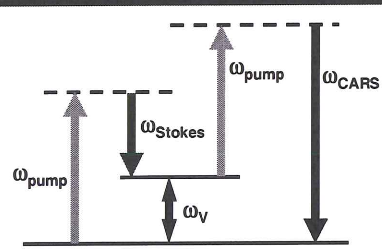
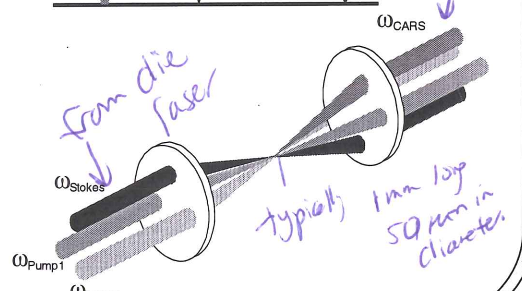
Coherent Anti-Stokes Raman Scattering (CARS)

- Conventional "Single-Pump" CARS
- Noninvasive
- Coherent Laser-Like Signal
- Spatially and Temporally Resolved
- Excellent Gas Temperature Data (especially at higher temperatures)

use coherent beams





One of the more useful techniques

- can get quantitative measurements of T, even in sooty flames

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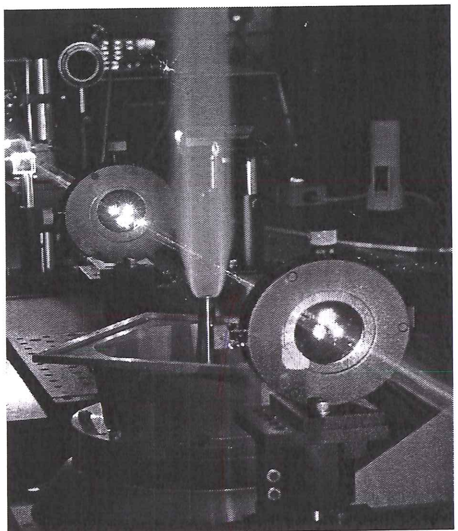
Triple-Pump CARS Experiments



Triple-pump CARS measurements performed in laminar hydrogen/air diffusion flame.

Simultaneous acquisition of single-shot H_2/N_2 and H_2/O_2 spectra demonstrated.

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4 laser beams into the flame

Species are mie scatter

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Other Laser Diagnostic Techniques

- Particle Imaging Velocimetry (not a Spectroscopic technique)
- Resonant Four-Wave Mixing, Degenerate Four-Wave Mixing (DFWM)
- Photoacoustic Spectroscopy ? few applications in combustion
- Resonant Photoionization Spectroscopy, Resonant Multi-Photon Photoionization Spectroscopy (REMPI) — very sensitive and tunable, but you need to put physical probes in the flame and hard to know what is being detected by the probe
- Laser-Induced Incandescence (LII) use to detect soot

use a laser to excite soot

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