SAND2007-7676P

EXPERIMENTAL MECHANICS (ESP 500) Session 6 11/27/07

Introduction to lasers, laser optics, and applications

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Course Schedule

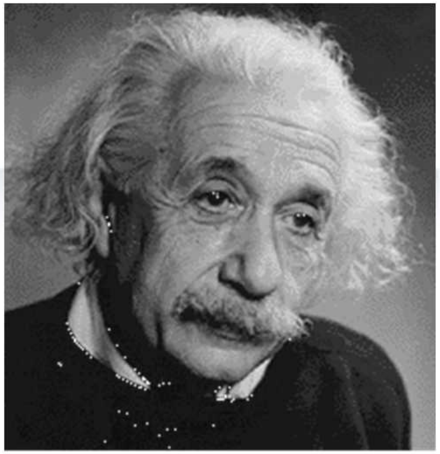
Week	Date	Topic	Instructor
1	10/16/07	Introduction, measurement basics, uncertainty	O'Hern
2	10/23/07	Data Acquisition	O'Hern
3	10/30/07	Dynamic Measurements (Transducers)	Simmermacher
4	11/06/07	Measurement of Structural Dynamic Input/Response	Mayes
5	11/13/07	Structural Dynamics Lab	Stasiunas
6	**11/27/07**	**Laser Optics and Applications**	**O'Hern**
7	12/04/07	Non-contacting measurements for solid mechanics	Reu
8	12/11/07	Digital image correlation in practice	Reu
9	12/18/07	Micromechanics	Sumali
10	01/08/08	Pressure Measurements	O'Hern
11	01/15/08	Pressure Lab	O'Hern
12	01/22/08	High Speed Photography	Nissen
13	01/29/08	Thermal Characterization	Phinney
14	02/05/08	Rheology and Complex Fluids	Grillet

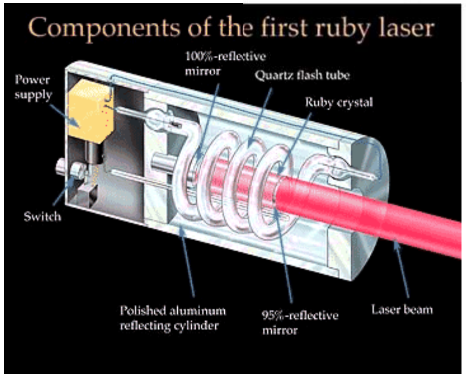
Outline

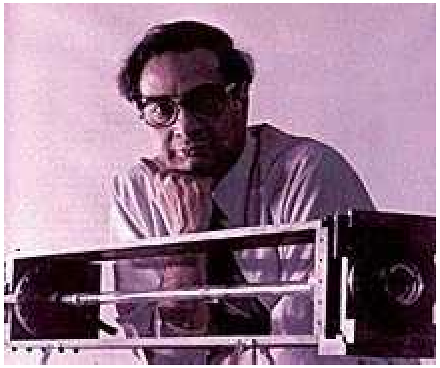
- What is a laser?
- How do lasers work?
- What is so special about laser light?
  - Coherence
  - Intensity – very short pulses
  - Monochromaticity
  - Pulse width (temporal resolution) and control
  - Speckle
  - Polarized
  - Low divergence (highly directional, collimated)
- Laser applications in Experimental Mechanics

Brief Laser History

- What is a laser?
  - Light Amplification by Stimulated Emission of Radiation
- Stimulated Emission proposed in 1917 by Albert Einstein
- First working laser
  - Ted Maiman, May 16,1960, Hughes Research Lab, Malibu, CA
    - Ruby laser (pulsed)
- First gas laser
  - Ali Javan, December 12, 1960, Bell Labs
  - First CW (continuous wave) laser



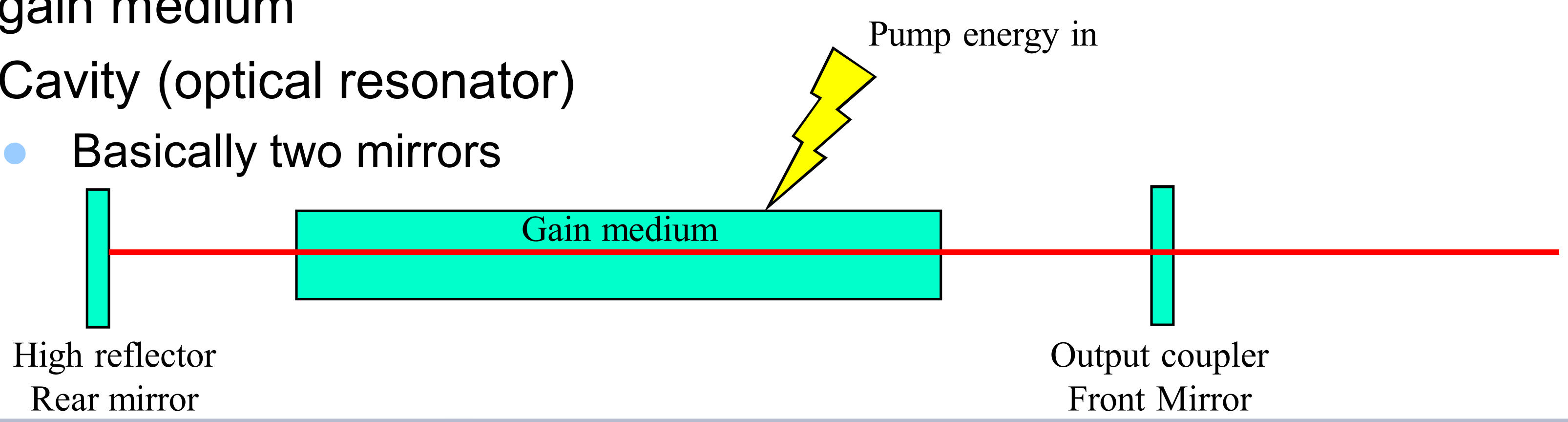




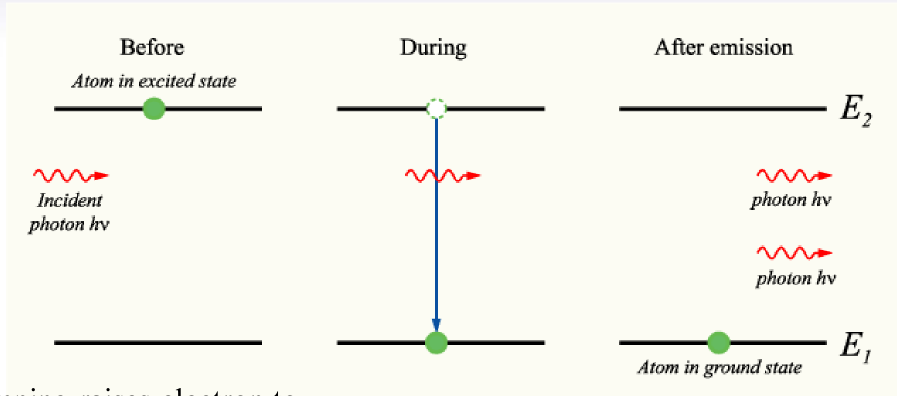
How Lasers Work

- Three major components
  1. Gain medium
     - Gas
     - Solid
     - Liquid
     - Free electrons
  2. Pump – supplies energy to the gain medium
  3. Cavity (optical resonator)
     - Basically two mirrors

When round-trip gain exceeds round-trip losses the light builds up in the cavity



How Lasers Work



Upper energy level

$E_2 - E_1 = h\nu = hc/\lambda$

Lower energy level

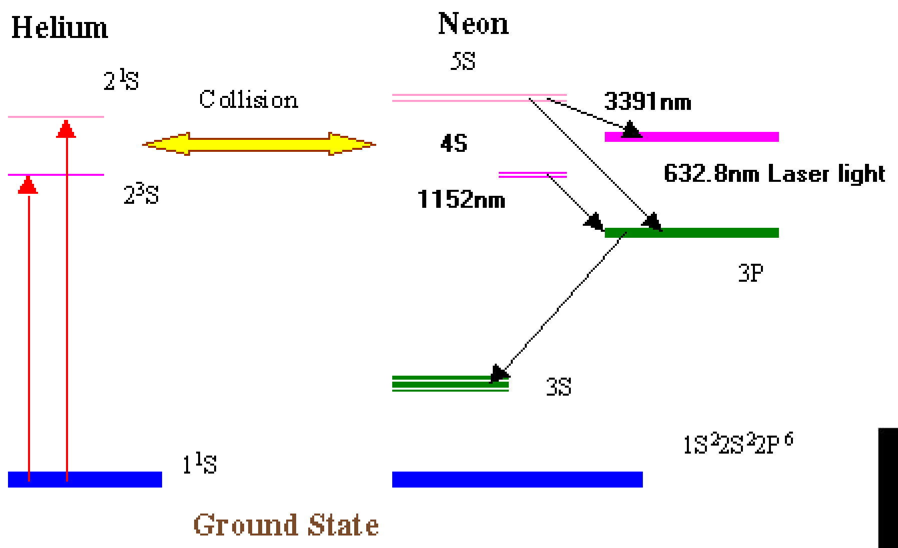
Pumping raises electron to excited state

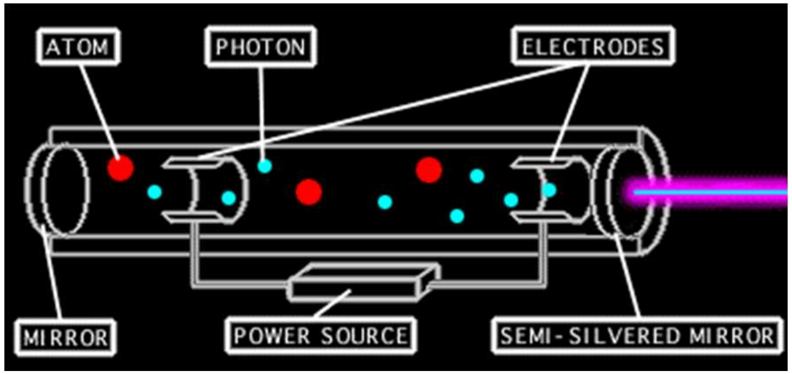
Stimulated Emission

- An electron is excited from a ground state to a higher energy state.
- It can undergo "spontaneous emission." which yields fluorescence (could be many electrons - still fluorescence).
- To get more atoms in upper level than in lower level (Population Inversion), we need to raise the atoms from lower level to upper level. This process is called pumping.
- When external EM waves of frequency ν_0 are incident on the material whose atoms initially are at energy level E2 and ν_0 is very near to the E2→E1 transition frequency, there is a finite probability that the incident waves will force the atoms to undergo E2→ E1 transition. Each such transition gives out an EM wave (a photon), while the incident wave (incident photon) still exists. Then we have two photons. This is called Stimulated Radiation.
- For spontaneous emission, the radiation is in all directions and in random phases, while in stimulated radiation, the emitted waves of any atoms are in the same direction and in phase with the incident wave.

How Lasers Work

- He-Ne energy levels





Different Laser Types

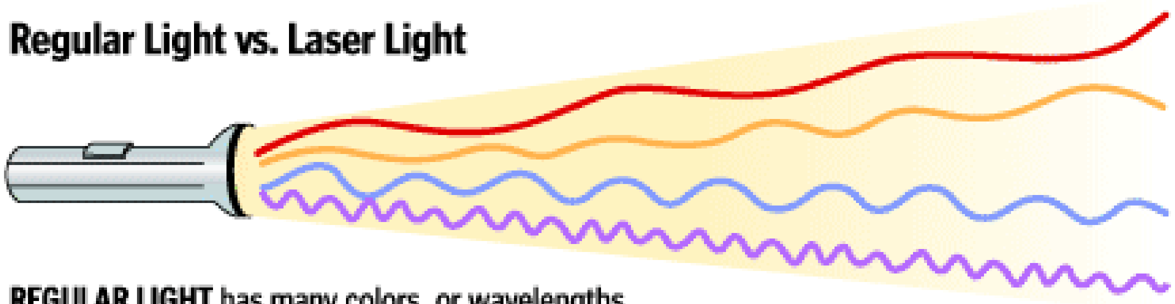
- Thousands of different lasers – mostly categorized by gain medium. Only a few major ones listed here:
- Gas
  - He-Ne
  - Argon
  - CO_2
  - Excimer
- Solid-state
  - Nd:YAG
  - Ruby
- Semiconductor
- Chemical
- Dye
- Metal-vapor
- Others

- See big table of laser types and applications at

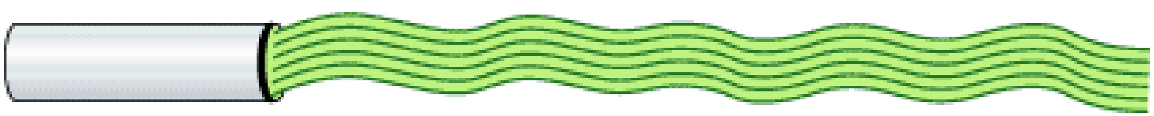
http://en.wikipedia.org/wiki/List_of_laser_types

What is so special about laser light?

Regular Light vs. Laser Light



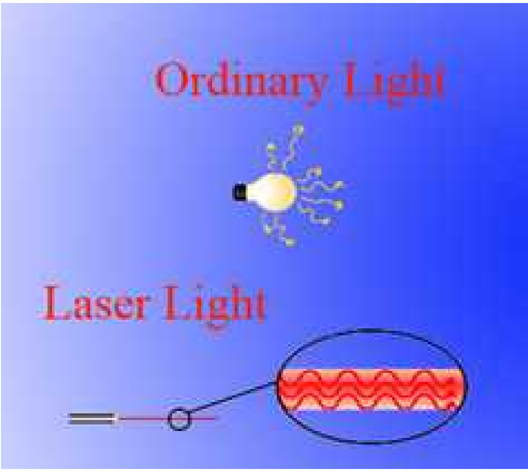
REGULAR LIGHT has many colors, or wavelengths, mixed together, creating white light. The light waves spread out as they travel.



LASER LIGHT is of the same wavelength, with all of the waves in phase, or in step, with one another. A laser is always a single color because the waves are the same length. Because the waves are parallel, a laser light stays in a tight beam for long distances.

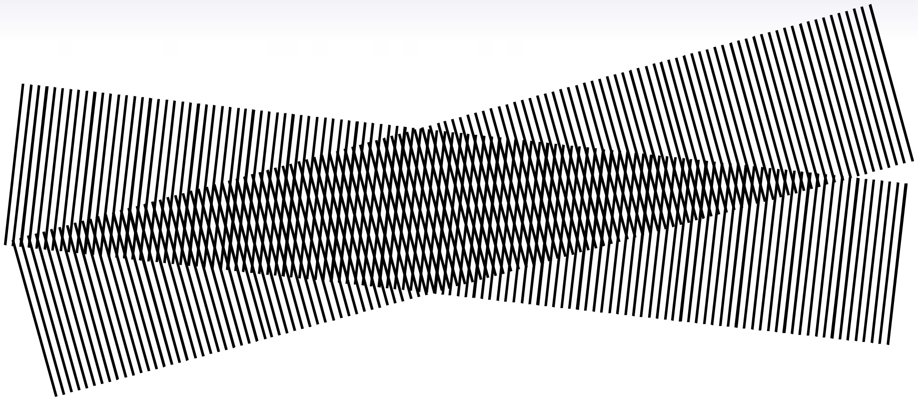
Coherence

- **Coherence** is the property of wave-like states that enables them to undergo interference. It is also the parameter that quantifies the quality of the interference (also known as the degree of coherence). In interference, at least two beams are combined and, depending on the relative phase between them, add constructively or subtract destructively. The degree of coherence is equal to the interference visibility, a measure of how perfectly the waves can cancel due to destructive interference.



- Light is said to be coherent when all the waves in a beam are oscillating at exactly the same frequency, in lock-step with one another, with their peaks and valleys overlapping perfectly. Achieving this lock-step is like making light waves march together like soldiers in formation. Normal incoherent light, by contrast, is more like a disorganized parade.
- Besides lasers, there are other sources of fairly coherent light, e.g., filtered Hg lamps

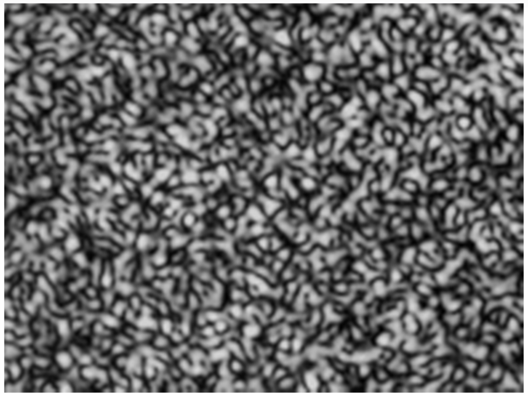
Interference



- Coherent beams interfere when combined
- Distance between fringes depends on laser wavelength and angle between intersecting beams

Speckle

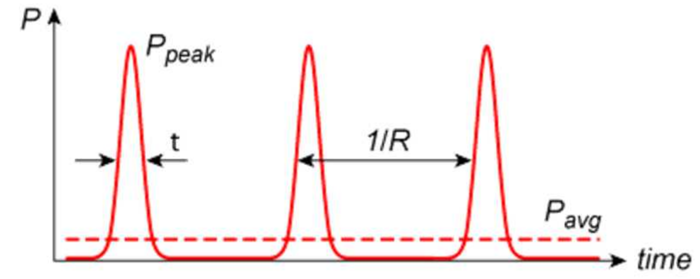
- Another interference effect



- Speckle patterns are always produced when a coherent light source is focused onto a “rough” surface (relative to the laser wavelength). It is caused by interference effects between the beams originating at the different scattering centers on the surface.

Intensity

- Lasers can put a tremendous amount of energy or power into a very small area
- Energy: Joules
- Power: Watts (energy/time = Joules/sec)

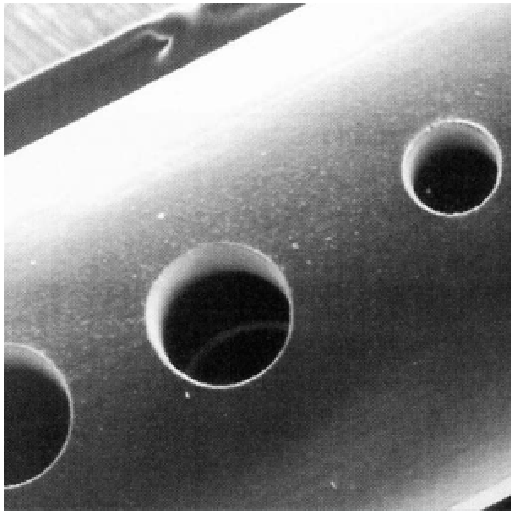


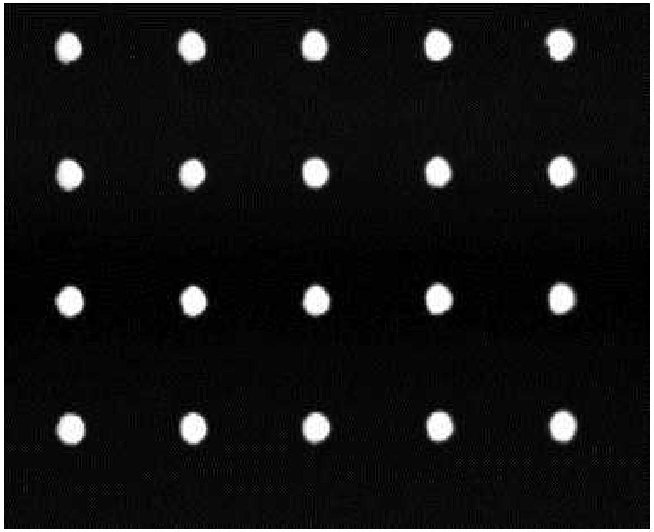
- Conversions – e.g., average power output by a pulsed laser:

  10 Hz laser, 1 J/pulse, P_{avg} = 1 J * 10 Hz = 10 W (often measured by power meter)
- Even fairly simple lasers with short pulses can produce instantaneous peak powers exceeding 10^{13} W, or several times the total installed electrical generating capacity of the U.S.
  - Example: 10 Hz Nd:YAG laser with average power output of 10 W has 1 J per pulse, each 8 ns in duration. Instantaneous power is then 1 J/8×10^{-9} sec = 125 MW instantaneous power
  - Note – lasers are not efficient electricity users

Intensity

- Fluence: Watts or Joules per unit area – up to billions of watts per cm^2
  - Sufficient to tear atoms apart, break molecular bonds, produce intense nonlinear optical effects, and melt and vaporize any material

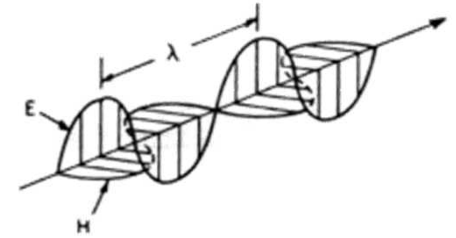




10 μm laser drilled holes in thin stainless steel

Polarization

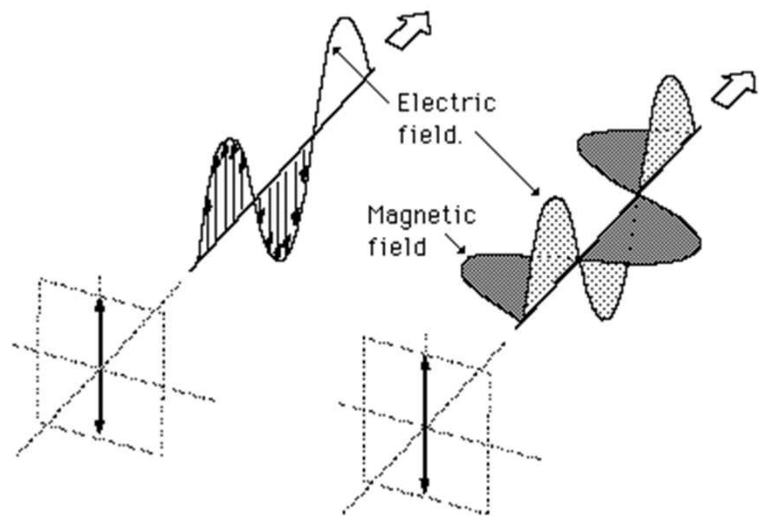
λ=wavelength, E=electric vector, H=magnetic vector.



Wave amplitude of a plane-polarized beam

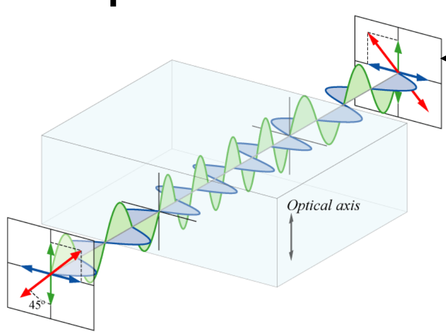
Polarization is restriction of the vibrations of the electromagnetic field to a single plane, rather than all planes rotating about the vector axis. Light is a transverse electromagnetic wave, but natural light is generally unpolarized with all planes of propagation being equally probable. Light in the form of a *plane wave* in space is linearly polarized. The plane of the polarized light electric field is called the plane of polarization.

The transverse electric field wave is accompanied by a magnetic field wave as illustrated. Various forms of polarization include random, linear (plane), vertical, horizontal, elliptical, and circular.



Polarization

- Why is polarization important?
- Only light polarized the same way can interfere
- Polarization can be used to control light
  - Pockels cell is an optical switch (voltage controlled wave plate) used as an intracavity gate (Q-switch) in pulsed lasers
- Proper polarization can prevent optical losses at interfaces between the laser beam (or lasing medium intracavity) and optical elements.



A half-wave plate. Linearly polarized light entering a wave plate results in an orthogonally polarized compared to its entrance state.

Quarter wave plate are used to turn plane-polarized light into circularly polarized light and vice versa. When a l/4 plate is double passed, i.e., by mirror reflection, it acts as a l/2 wave plate and rotates the plane of polarization to 90°.

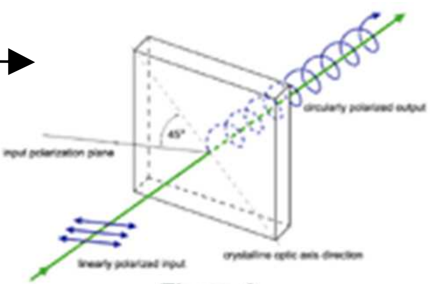
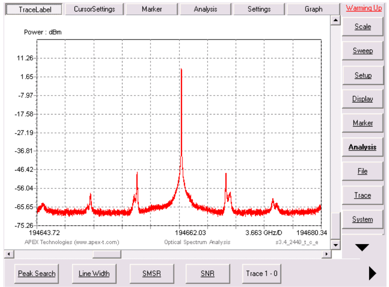


Figure 2.

Monochromaticity

- Single wavelength (linewidth = width of laser beam frequency). Much more narrow than normal light (very pure wavelength).
  - Single frequency (frequency *f* = wavelength λ/speed of light *c*)
  - Actually tight range around peak value
  - Important for filtering, spectroscopy
- This property is due to two factors.
  - First, only an EM wave of frequency $\nu = (E_2 - E_1)/h$ can be amplified. ν has a certain range which is called linewidth, this linewidth is decided by homogeneous and inhomogeneous broadening factors.
  - Second, the laser cavity forms a resonant system - oscillation can occur only at the resonance frequencies of this cavity. This leads to the further narrowing of the laser linewidth, as much as 10 orders of magnitude. Adding an etalon to the laser cavity can further decrease linewidth.



Tunable laser source
With AP2040A series side modes of a tunable laser source can be measured
Measurement resolution : 100MHz

Pulse Duration and Control

- Pulsed lasers can have very short duration pulses
- 1 ns (nanosecond) = 10^{-9} s = 0.000000001 s
- 1 ps (picosecond) = 10^{-12} s = 0.000000000001 s
- 1 fs (femtosecond) = 10^{-15} s = 0.000000000000001 s
- 1 as (attosecond) = 10^{-18} s = 0.000000000000000001 s
- Ultrashort pulses needed to excite and probe atom and molecular scale processes
- The laser operator generally has the ability to precisely control when the pulse will occur (laser labs usually filled with timing controls like Digital Delay Generators)

Directionality and Divergence

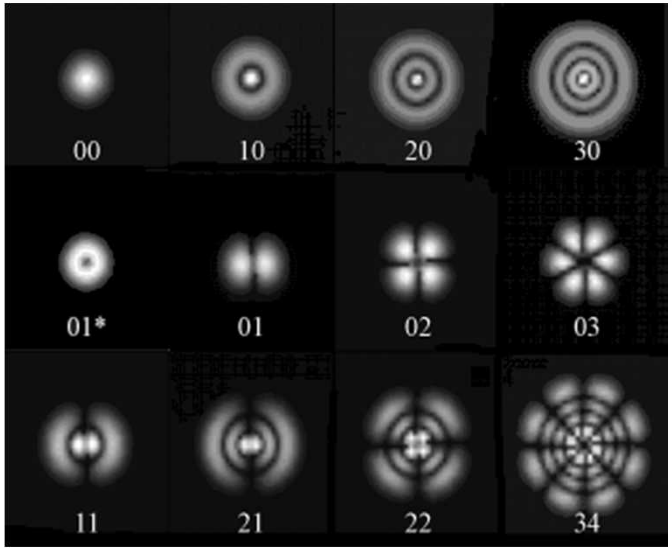
- For perfect spatial coherent light, a beam of aperture diameter D will have unavoidable divergence because of diffraction. From diffraction theory, the divergence angle θ_d is:

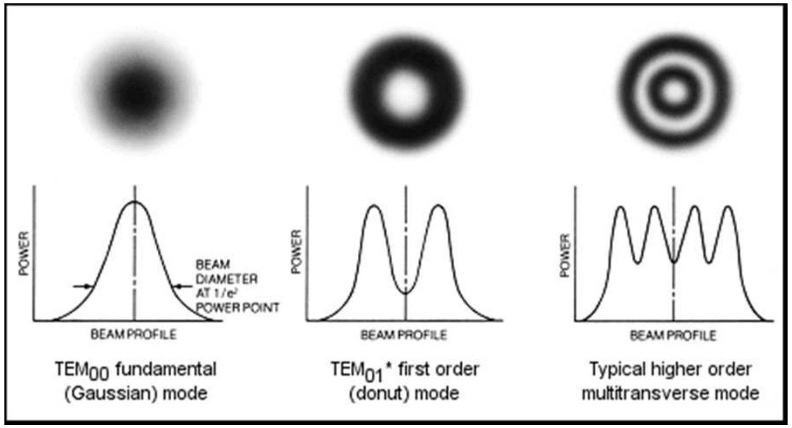
  $\theta_d = \beta \lambda / D$

- Where λ and D are the wavelength and the diameter of the beam respectively, β is a coefficient whose value is around unity and depends on the type of light amplitude distribution and the definition of beam diameter. θ_d is called diffraction limited divergence.
- ***Example:*** For laser light of wavelength λ =1.06 μm (Nd:YAG fundamental), D=3 mm, β =1.1, then

  $\theta_d = \beta\lambda/D = 1.1*1.06*10^{-6}$ m/3*10$^{-3\ m}$=0.3887*10^{-3} rad=0.022269°, cf., normal flashlight divergence is about 25°, a searchlight divergence is about 10°.

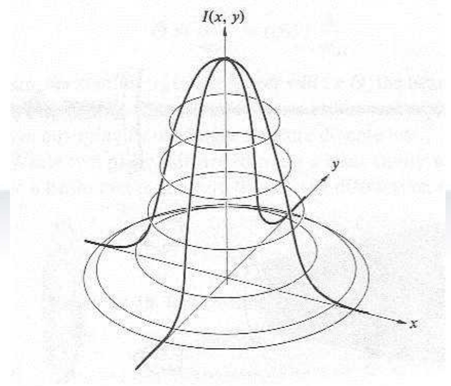
Transverse Electromagnetic Modes





- Laser transverse modes show energy distribution across laser beam – subscripts indicate number of modes in each direction
- TEM_{00} smallest beam diameter, lowest divergence, and tightest focused spot size
- Controlled by setting aperture inside laser cavity to increase losses in higher-order modes (larger diameters)

Gaussian beams



ure 13.11 Gaussian irradiance distribution.

- Zero order mode (TEM_{00}) is Gaussian
- Intensity profile: $I = I_0 e^{-2r^2/w^2}$
- beam waist: w_0

$$w = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2}$$

- Rayleigh range: z_R

$$z_R = \frac{\pi w_0^2}{\lambda}$$

- far from waist $w \rightarrow \dfrac{\lambda z}{\pi w_0}$
- divergence angle

$$\Theta = \frac{2\lambda}{\pi w_0} = 0.637 \frac{\lambda}{w_0}$$

So small diameter beam has high divergence

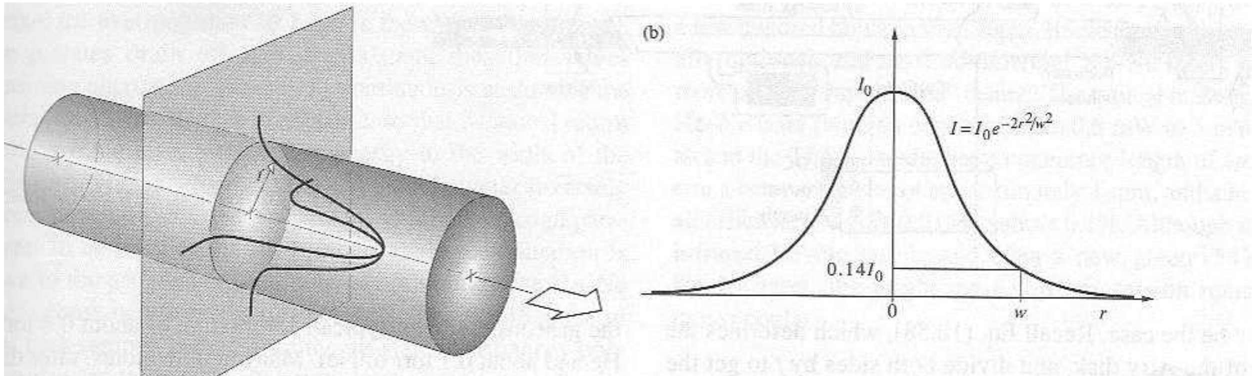
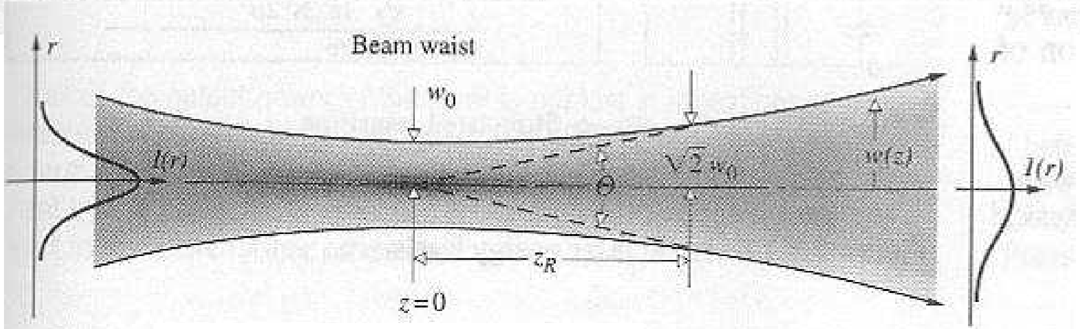


Figure 13.14 A Gaussian beam-like wave propagating in the z-direction.



Gaussian propagation

Propagation of Gaussian Beams

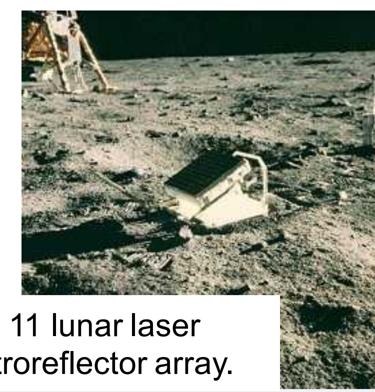
- The propagating laser beam is defined by its waist diameter or divergence angle
- Can we light up the moon by shining lasers on it?

- Distance from earth to moon 384,400 km (238,855 miles)
  - Speed of light 299,792,458 m/s
  - Laser beam will reach moon in 384400 km/299792 km/s = 1.28 s

- Size of spot on moon
  - Assume big beam (10 cm waist w_0) with very good divergence angle

$$w \to \frac{\lambda z}{\pi w_0}$$

  - w=(0.5×10^{-6} m * 3.84×10^{8} m)/($\pi *$ 0.1 m)
    = 611 m ~ 0.4 mile in diameter
    (low energy density)



The Apollo 11 lunar laser ranging retroreflector array.

Laser Safety BRIEF Overview

- References: ANSI standard, SNL classes, ES&H Manual – see these sources for the latest, most accurate information
- Definitions:
  - Maximum permissible exposure (MPE): the maximum level of laser radiation to which a human can be exposed without adverse biological effects to the eye or skin
- Classes of laser
  - Class 1: MPE cannot be exceeded
  - Class 2: Safe because 0.25 second blink reflex will limit exposure sufficiently. Only applies to visible lasers (400-700 nm). Limited to 1 mW CW, or more if duration is less than 0.25 sec or beam is not coherent. Many laser pointers are Class 2 (especially at Sandia)

Laser Safety BRIEF Overview

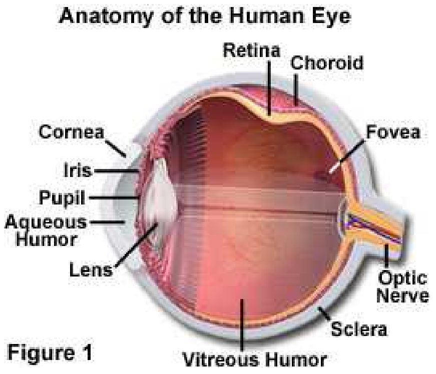
- Class 3a: Mostly dangerous in combination with optical instruments which change the beam diameter or power density. Output power may not exceed 5 mW CW. Beam power density may not exceed 2.5 mW/square cm. (Recent SNL laser pointer ban)
- Class 3b: May cause damage if the beam enters the eye directly. Generally 5–500 mW. Can cause permanent eye damage with exposures of 1/100th of a second or less depending on the strength of the laser. A diffuse reflection is generally not hazardous but specular reflections can be just as dangerous as direct exposures. Protective eyewear is recommended when direct beam viewing of Class IIIb lasers may occur. Lasers at the high power end of this class may also present a fire hazard and can lightly burn skin.
- Class 4: Output power of more than 500 mW and may cause severe, permanent damage to eye or skin without being magnified by optics of eye or instrumentation. Diffuse reflections of the laser beam can be hazardous to skin or eye within the Nominal Hazard Zone. Also a fire hazard. Commonly used in laser diagnostics applications. Also cutting, etching and surgical lasers.

Laser Safety BRIEF Overview

- Eyewear must be chosen for the specific laser wavelength
  - Eyewear that provides full protection at one wavelength may be useless at another – difficult when working with multiple wavelength setups
  - Calculate level of attenuation needed to reduce exposure to below MPE
- Level of protection defined by Optical Density (OD)

$$I = I_0 \times 10^{-OD}$$

- So OD 3 at a particular wavelength attenuates by a factor of 1000

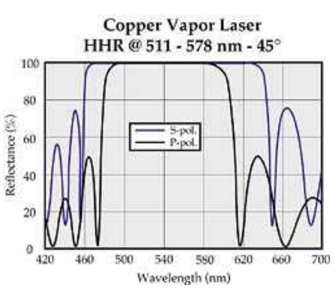


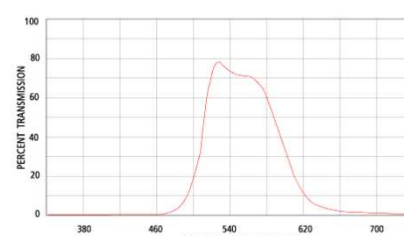
Laser Safety BRIEF Overview
Non-beam hazards

- **Electrical:** Many lasers are high voltage devices, typically > 400 V for a small 5 mJ pulsed laser, and exceeding many kilovolts in higher powered lasers. This, coupled with high pressure water for cooling the laser and other associated electrical equipment can create a serious hazard.
- **Chemical:** Chemical hazards may include materials in the laser, such as beryllium oxide in argon ion laser tubes, halogens in excimer lasers, organic dyes dissolved in toxic or flammable solvents in dye lasers, and heavy metal vapors and asbestos insulation in helium cadmium lasers. They may also include materials released during laser processing, such as metal fumes from cutting or surface treatments of metals or the complex mix of decomposition products produced in the high energy plasma of a laser cutting plastics.
- **Mechanical hazards** may include moving parts in vacuum and pressure pumps; implosion or explosion of flashlamps, plasma tubes, water jackets, and gas handling equipment.
- **High temperatures and fire hazards** may also result from the operation of high-powered Class IIIB or any Class IV Laser.

Laser Optics

- Mirrors, filters, lenses, polarizing optics, etc.
- Need to know wavelength of application
- Coatings
  - Anti-reflection
  - Dichroic (selective reflection)
- Usually specify wavelength, size, expected maximum energy density, plane of polarization, incidence angle, etc.





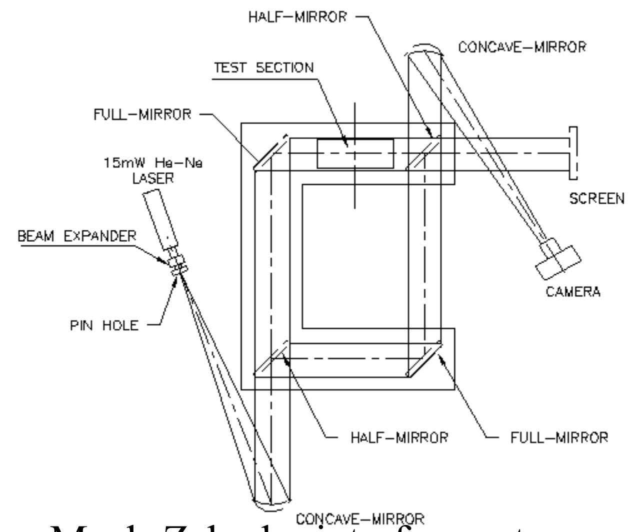
Laser Applications in Experimental Mechanics

- Interferometry
- Doppler – signal extraction (small change in big number)
  - Phase Doppler
- Holography
- PIV
  - Interline transfer CCD or high-speed camera
- Holographic PIV
- PLIF
  - Image intensification
- Combustion diagnostics: CARS, etc.
- Doppler velocimetry for solids measurements
- Etc.
- Lots of other SNL applications ...

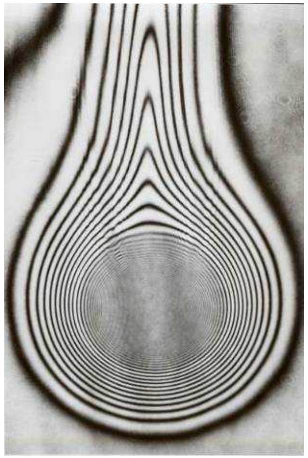
The trend is to generally to transition from point measurements to full-field measurements

Interferometry

- Laser interference technique
- Interference occurs if there is a difference in optical path length between the reference leg and the measurement leg of the interferometer
- The number of fringes in the interferogram is a direct measure of the path length difference (one fringe is one wavelength difference, etc.)
- Path length is directly related to density differences between legs, so this is a quantitative heat transfer measurement. Each fringe represents a line of constant temperature.

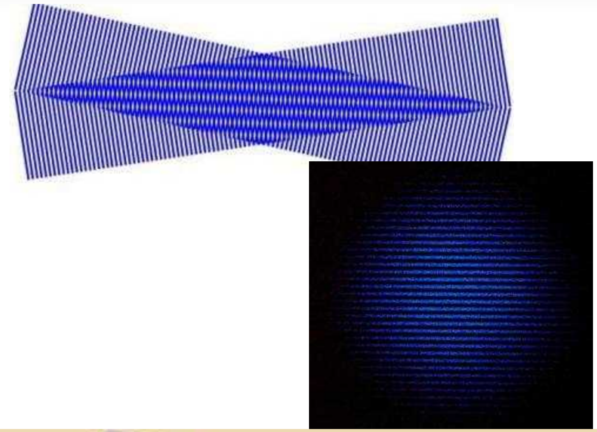


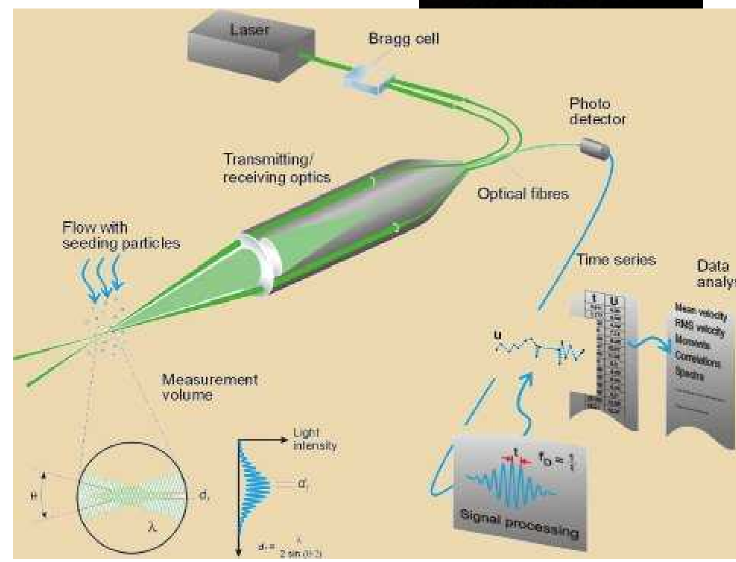
Mach-Zehnder interferometer



Laser Doppler Velocimetry

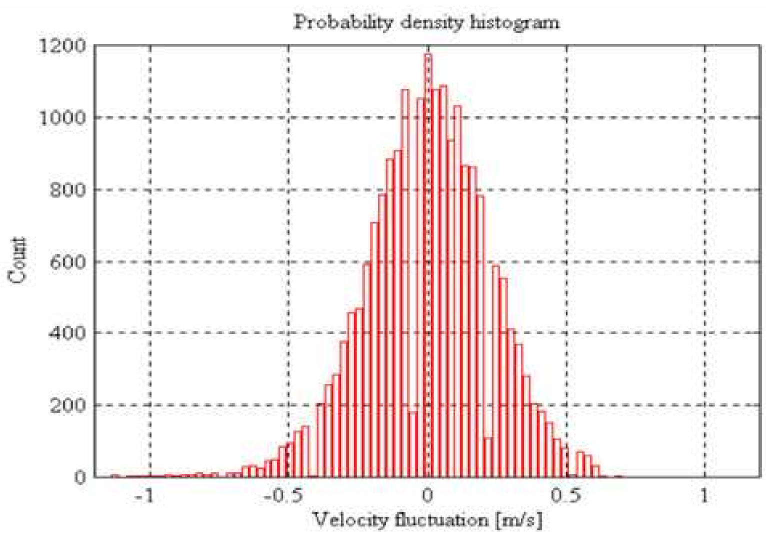
- LDV measures the velocity of particles passing through a small measurement volume, usually defined by crossing laser beams
- Fringe Model
- Multiple colors (or polarizations) to measure additional velocity components
- Doppler frequency is small change (depending on speed) in a big number (laser frequency)
- Solids applications (laser vibrometer) next week





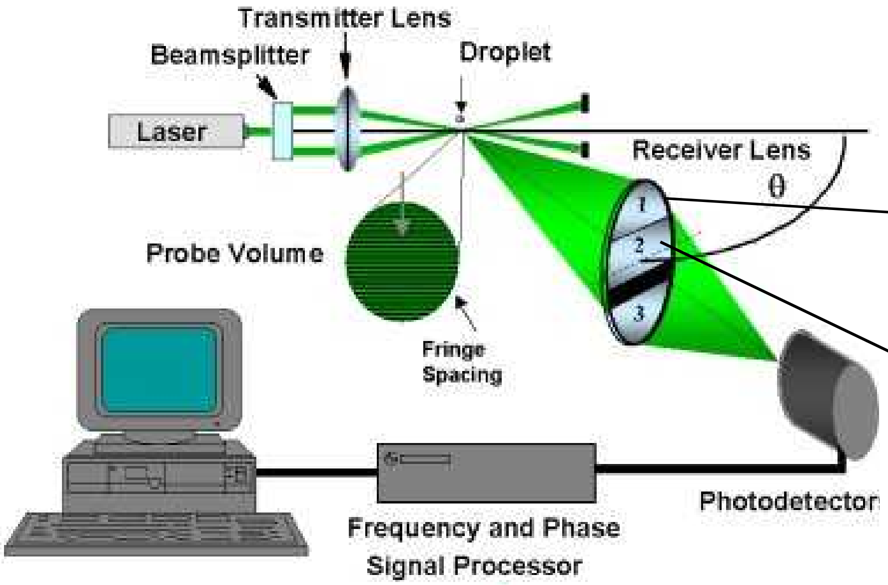
Laser Doppler Velocimetry

- Excellent point statistics
- Mapping out a flow requires traversing LDV measurement
- Therefore not preferred for mapping out transient flow fields



Phase Doppler Velocimetry with particle sizing

- PDA or PDPA (depending on manufacturer – Dantec, TSI, respectively)
- Just like LDV but additional detectors measure the phase shift of the Doppler signal between multiple (usually three) detectors



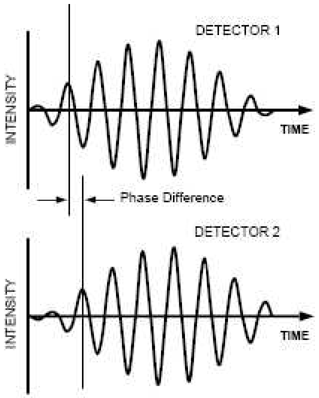
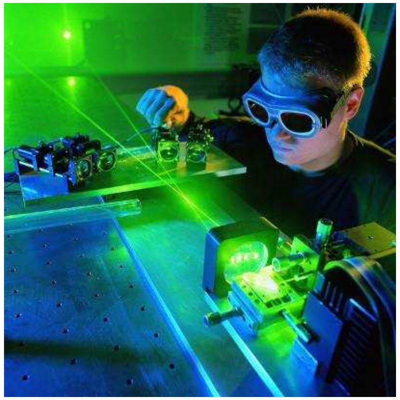


Figure 16-4. Characteristic Doppler Burst Signals

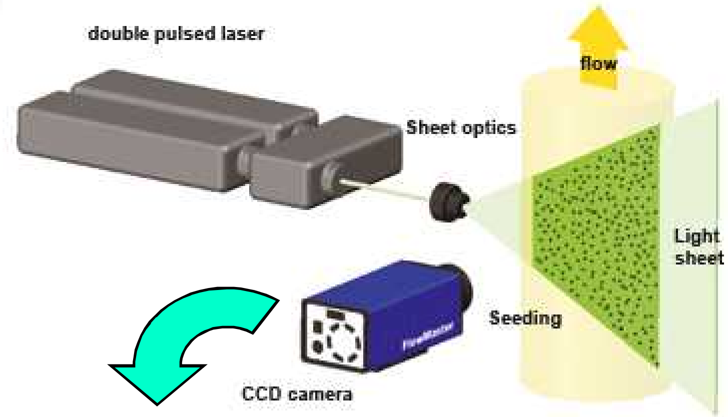


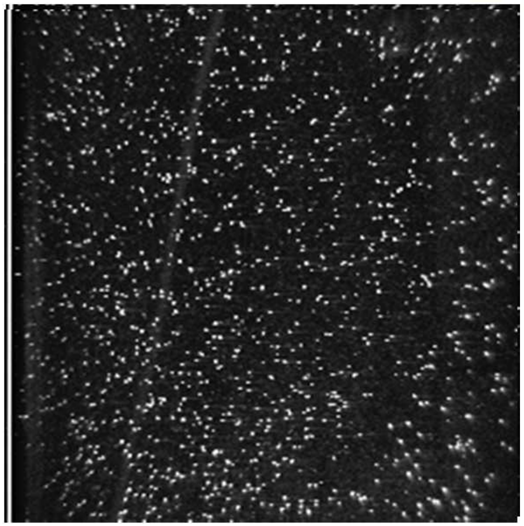
Particle Image Velocimetry (PIV)

- Very simple
- Use has grown with increased computer capabilities
- 2D with single camera
- 3D with stereo viewing (two cameras)
- Image analysis using cross-correlation software
  - Grid up image, measure particle displacement in each grid cell
  - Use known time separation between laser pulses to calculate velocity

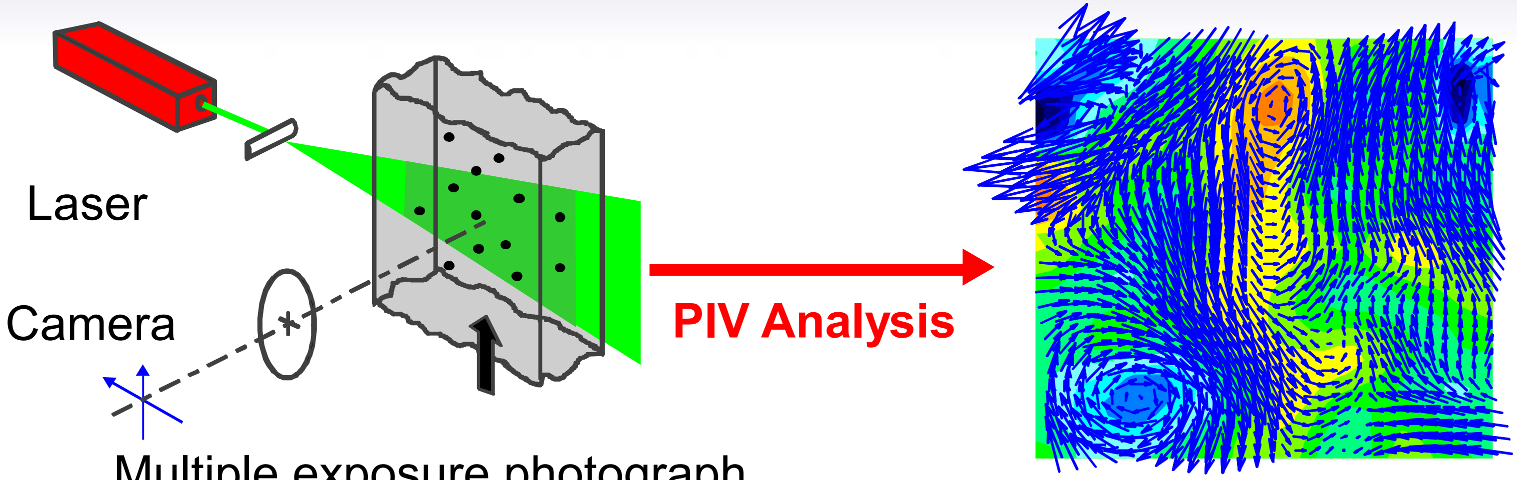
$$U = \frac{\Delta x}{\Delta t}$$

- Solid mechanics version (Digital Image Correlation, DIC) next week – measures surface displacement (strain)





Particle Image Velocimetry (PIV) Fundamentals



Multiple exposure photograph or movie with tracer particles

Velocity vector map

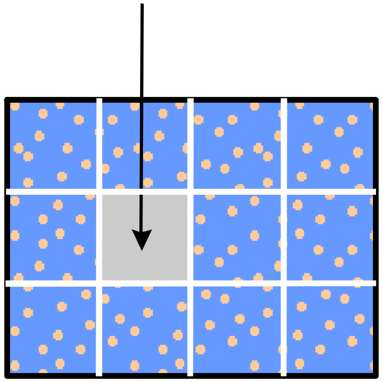
- Correlations of particle motion gives two-dimensional velocity, turbulence, vorticity, strain rate *fields* - needed for model validation
- Instantaneous - essential for unsteady flows
- Noninvasive - essential for turbulent, multiphase, or hazardous flows
- Temporal and spatial resolution up to 2 orders of magnitude (e.g., length scales 1 mm to 100 mm, time scales 0.01 sec to 1 sec)
- Complementary to point-measurement techniques (LDV, HWA) -enables judicious application in critical regions of flow

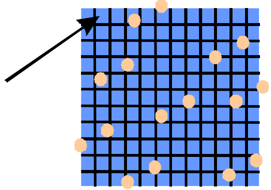
Extracting velocity vectors Cross-correlation analysis

1. The camera image is divided into interrogation areas which comprise many pixels and several pairs of particle images.

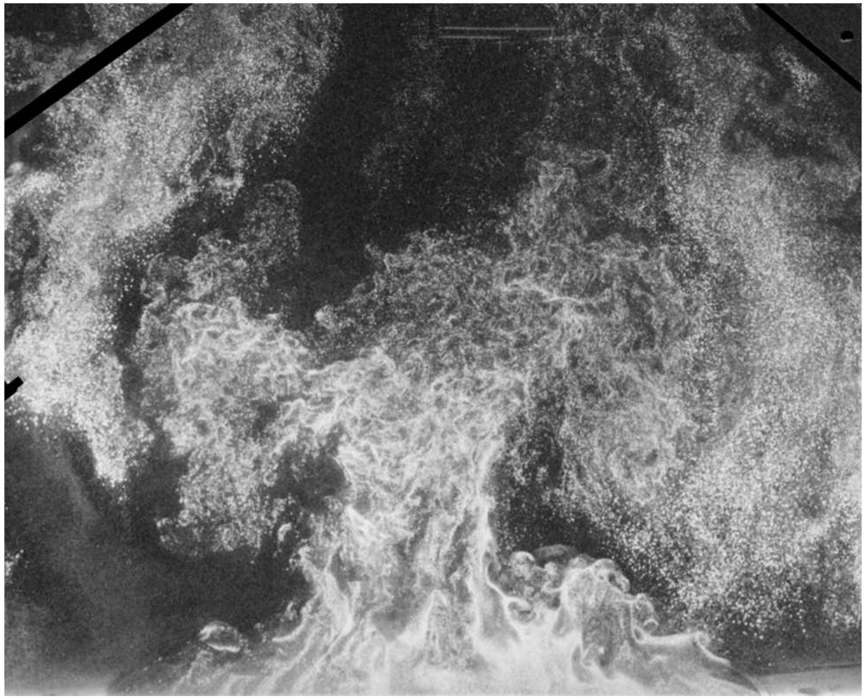
2. The velocity vector in each interrogation area is found by correlating the grey scale values of the CCD pixel.

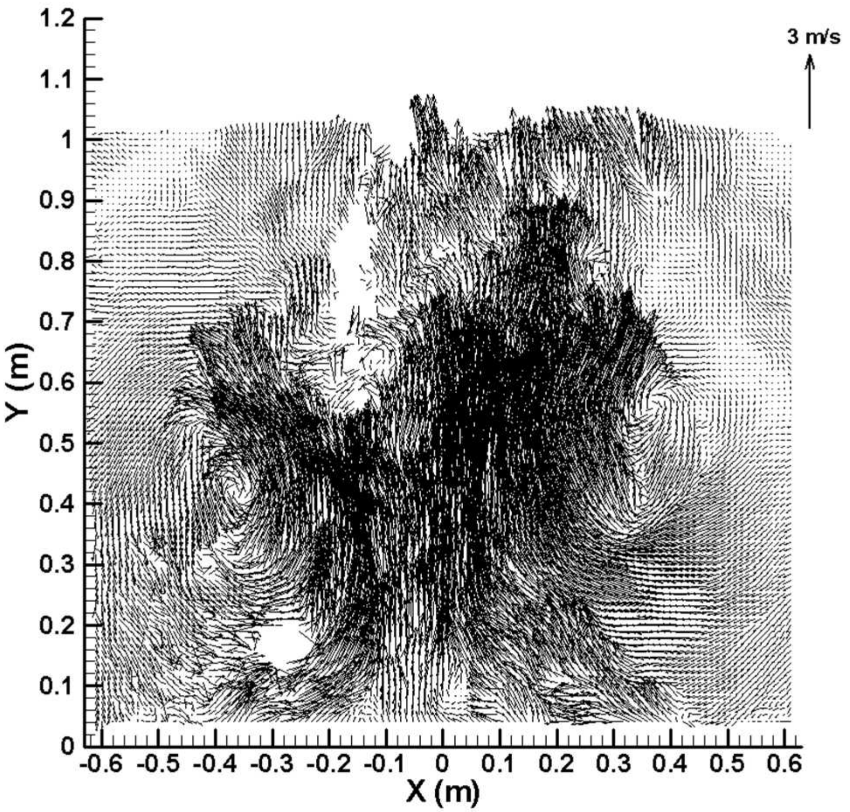
3. Cross-correlation of two images (two separate times) give a velocity vector based on the distance that the particle has moved





Helium Plume



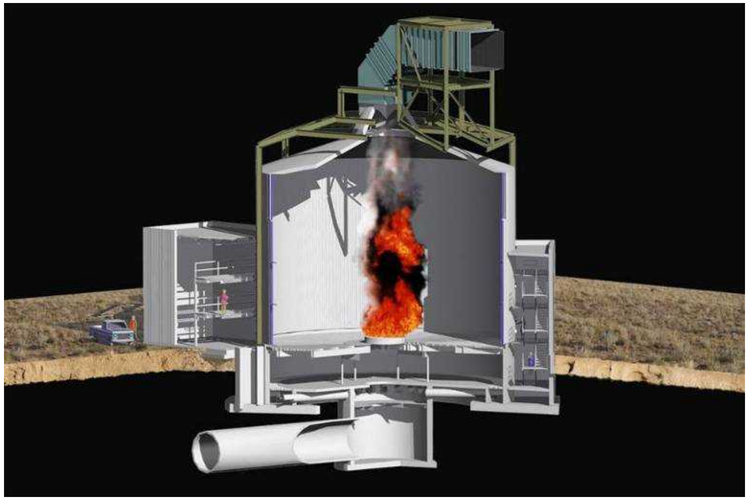


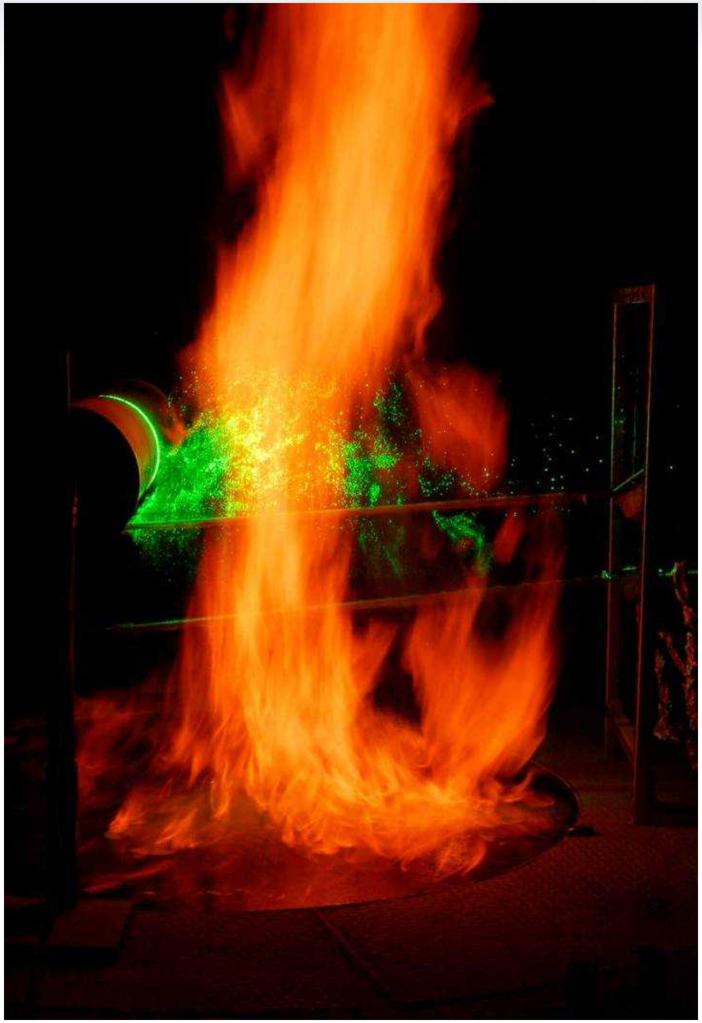
Raw PIV Image

PIV Vector Field

Fire PIV – FLAME

- Detailed measurements of velocity and concentration are needed in fires for validation of newly-developed improved computational models
- Particle Image Velocimetry (PIV) is a particle tracking technique to measure velocity
- Works by cross correlation of particles images between two images closely spaced in time





Fire PIV – FLAME

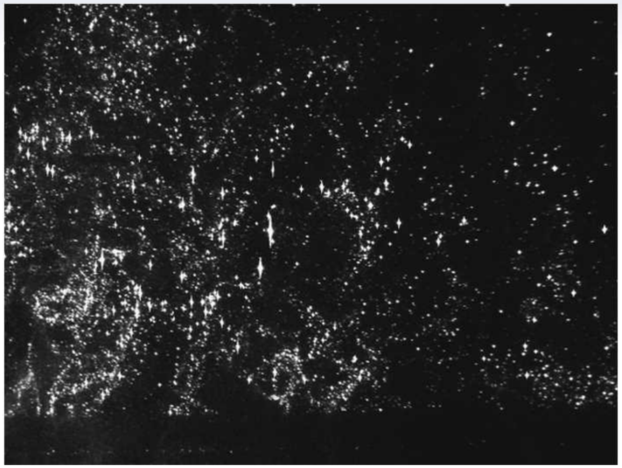


Image 1

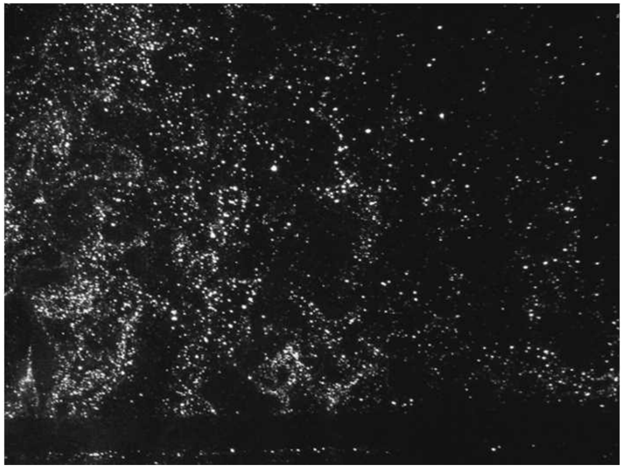
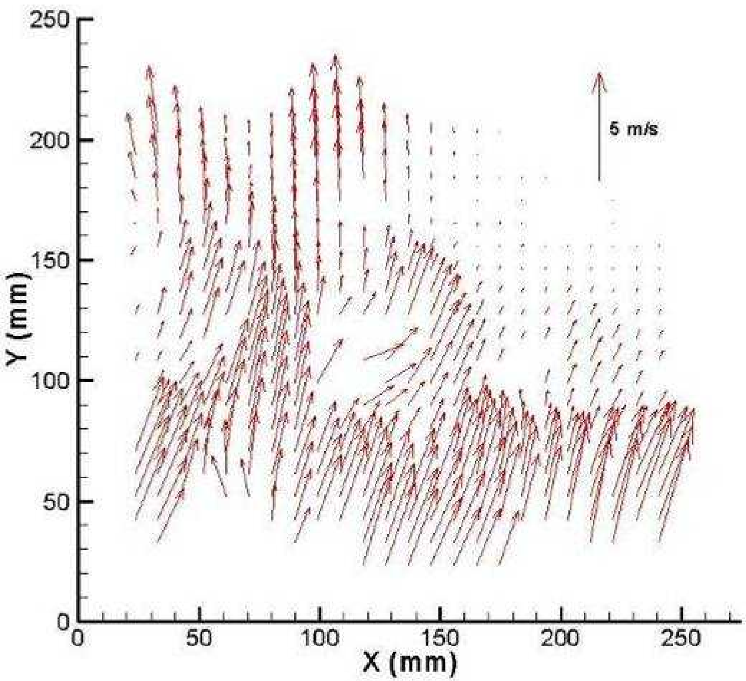


Image 2 – 700 μs later



Cross-correlation of particle images yields local velocity values throughout the field.

Velocity vector field in a 2-meter diameter methanol fire.

Planar Laser-Induced Fluorescence (PLIF)

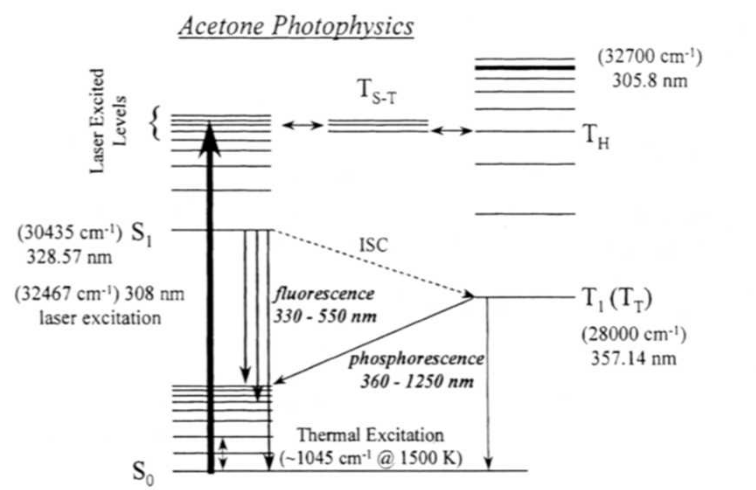


FIGURE 1 Schematic energy level diagram of acetone photophysical pathways.

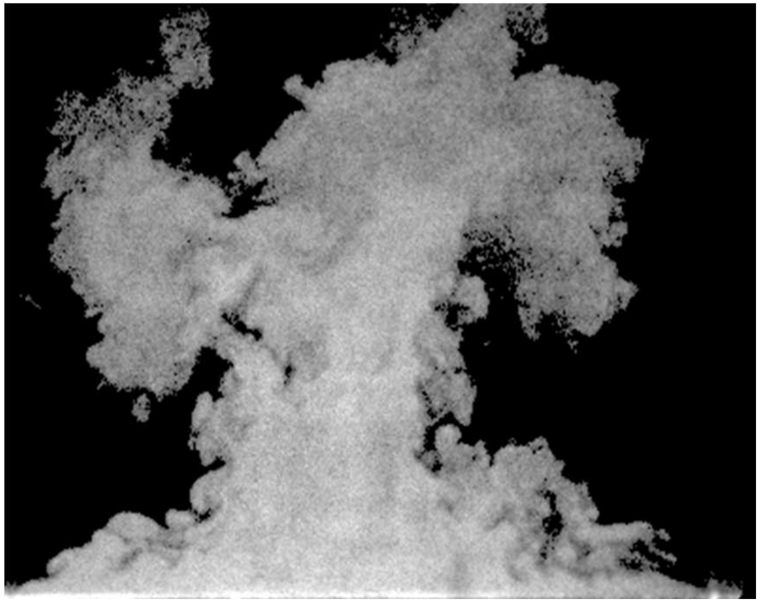
- Acetone absorption spectrum ~225-320 nm
- Broadband acetone fluorescence spectrum (350-550 nm)
- Fluorescence lifetime ~4 ns
- Complicating factors
  - Phosphorescence
  - Flammable in range 2.6 to 12.8 volume %

For weak excitation the acetone fluorescence signal $S_f(\lambda, T)$ is given by

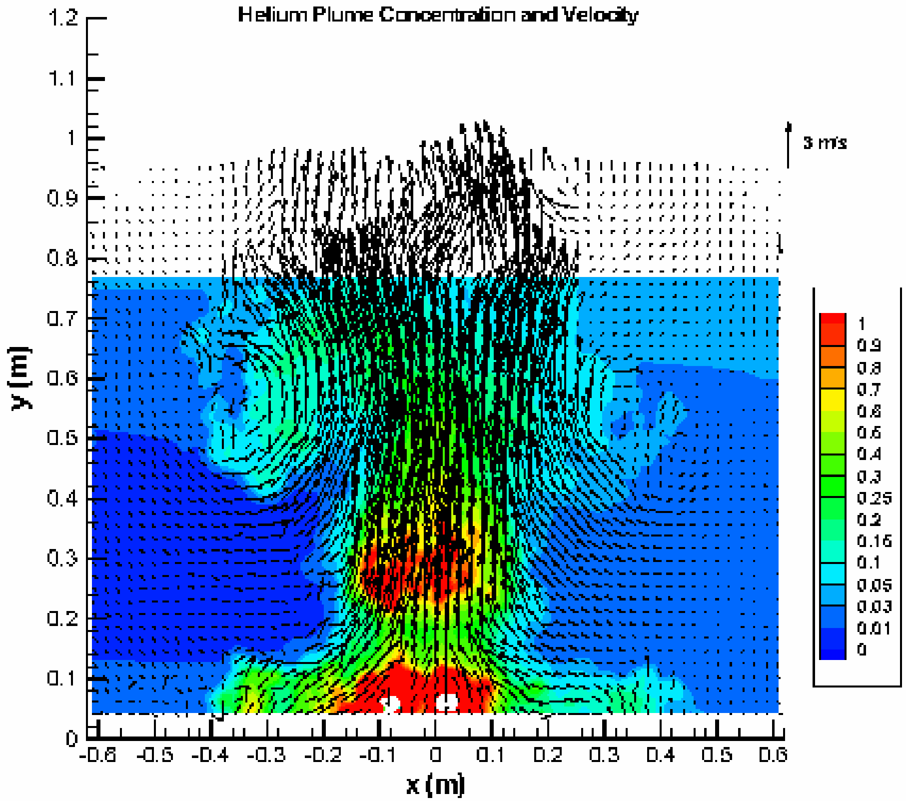
$$S_f(\lambda, T) \sim X_{acetone}\, N(T, P)\, s(\lambda, T)\, f(\lambda, T)\, I_L$$

where $X_{acetone}$ is the acetone mole fraction, $N(T, P)$ is the total gas number density, $s(\lambda, T)$ is the absorption cross section, $f(\lambda, T)$ is the fluorescence quantum yield, I_L is the laser energy, T is temperature, P is pressure and λ is the excitation wavelength. For constant T, P, and fixed λ, the fluorescence signal $S_f(\lambda,T)$ is directly proportional to the acetone mole fraction and laser energy.

Helium PLIF combined with PIV



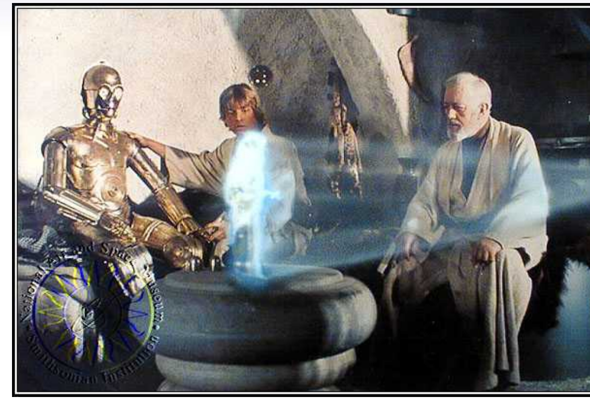
Acetone PLIF Image

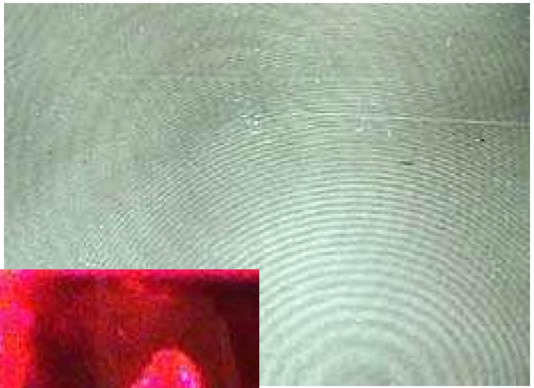


Combined helium concentration (color contours, from PLIF) and PIV velocity vectors

Holography

- A form of photography that allows an image to be recorded in three dimensions
- System of photography, using neither a camera not lens, in which laser beams create an interference pattern recorded directly on appropriate light sensitive sheet film or plates. After processing, viewing the image with appropriate illumination gives a three dimensional image.
- Relies on the coherence property of laser light. Light interference is needed. Hologram is a recording of an interference pattern.
- Very good for analyzing the three-dimensional location of objects
- More difficult to get 3D velocity, acceleration

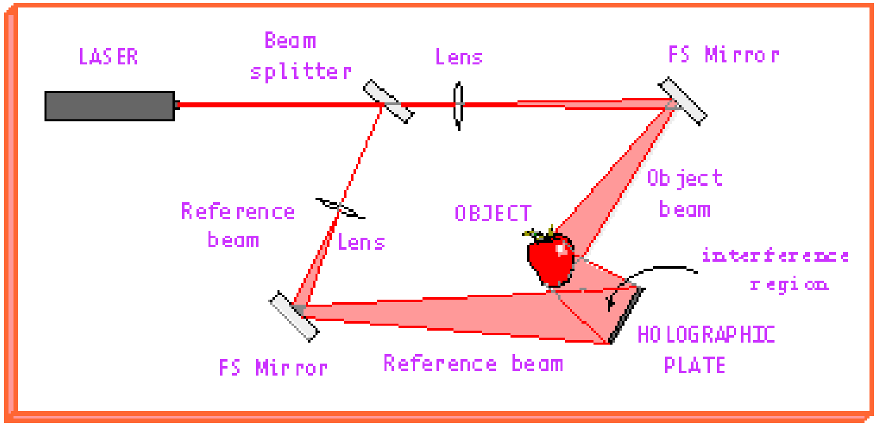




"Microscopy by Reconstructed Wavefronts"
1971 Dennis Gabor 1971 Nobel Prize

Holography

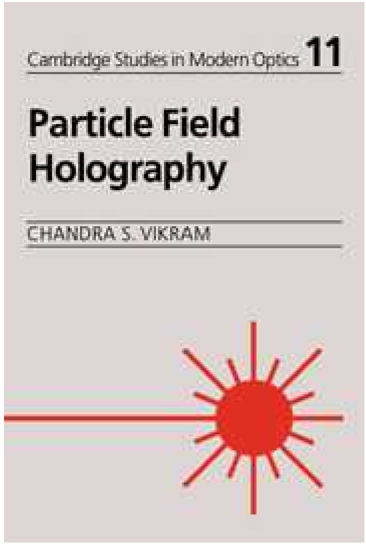
- Recording: Generally uses a reference beam and a subject beam. The interference between these two beams forms the interference pattern that is recorded.



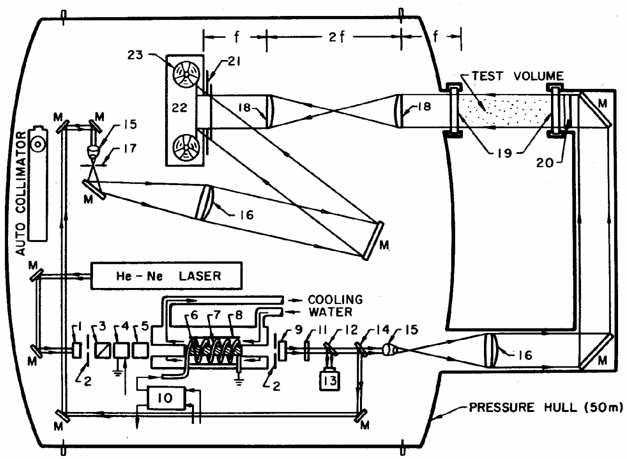
- Reconstruction
  - Illuminate with conjugate of original reference beam

Particle Field Holography

- A particularly useful application of holography
- Particle field holograms capture the instantaneous images of particles in motion
  - The hologram can be analyzed for particle sizes, shapes, locations, etc. in the reconstructed image

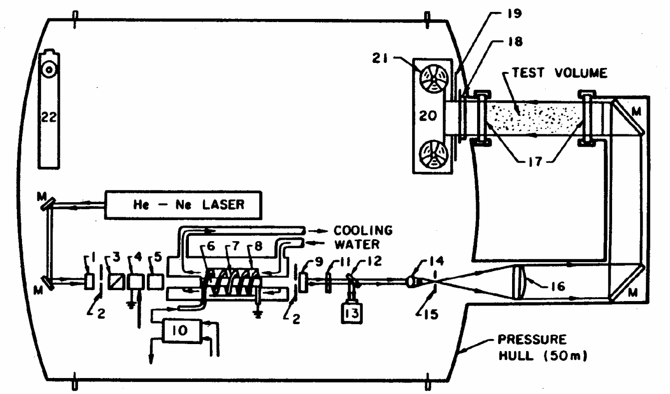


Particle Field Holography



1. BACK MIRROR
2. IRIS APERTURE
3. POLARIZER
4. POCKELS CELL
5. POLARIZER
6. RUBY ROD
7. XENON FLASH LAMP
8. REFLECTOR
9. FRONT MIRROR-SAPPHIRE ETALON
10. TRIGGER TRANSFORMER
11. NEUTRAL DENSITY FILTER
12. BEAM SPLITTER (4% REFLECTIVITY)
13. PIN DIODE
14. BEAM SPLITTER (50% REFLECTIVITY)
15. MICROSCOPE OBJECTIVE
16. COLLIMATING LENS
17. SPATIAL FILTER-10μ PIN HOLE
18. RELAY LENSES
19. GLASS WINDOWS
20. DIFFUSER
21. SHUTTER
22. AUTOMATIC FILM DRIVE
23. HOLOGRAPHIC FILM
M. MIRROR

Figure I.2.2 (b). See caption on p. 47.



1. BACK MIRROR
2. IRIS APERTURE
3. POLARIZER
4. POCKELS CELL
5. POLARIZER (OPTIONAL)
6. RUBY ROD
7. XENON FLASH LAMP
8. REFLECTOR
9. FRONT MIRROR-SAPPHIRE ETALON
10. TRIGGER TRANSFORMER
11. NEUTRAL DENSITY FILTER
12. BEAM SPLITTER (4% REFLECTIVITY)
13. PIN DIODE
14. MICROSCOPE OBJECTIVE
15. SPATIAL FILTER-10μ PINHOLE
16. COLLIMATING LENS
17. GLASS WINDOWS
18. INTERFERENCE FILTER
19. SHUTTER
20. AUTOMATIC FILM DRIVE
21. HOLOGRAPHIC FILM SPOOLS
22. AUTO COLLIMATOR
M. MIRROR

Figure I.2.2. Line drawing of the holographic camera system mounted inside submersible hull. The surrounding tank structure, return optical path and optical components are shown but not to scale. The legend identifies the major components. (a) In-line configuration (b) Off-axis configuration.

Reference beam holography setup

In-line (Fraunhofer) holography setup

Particle Field Holography

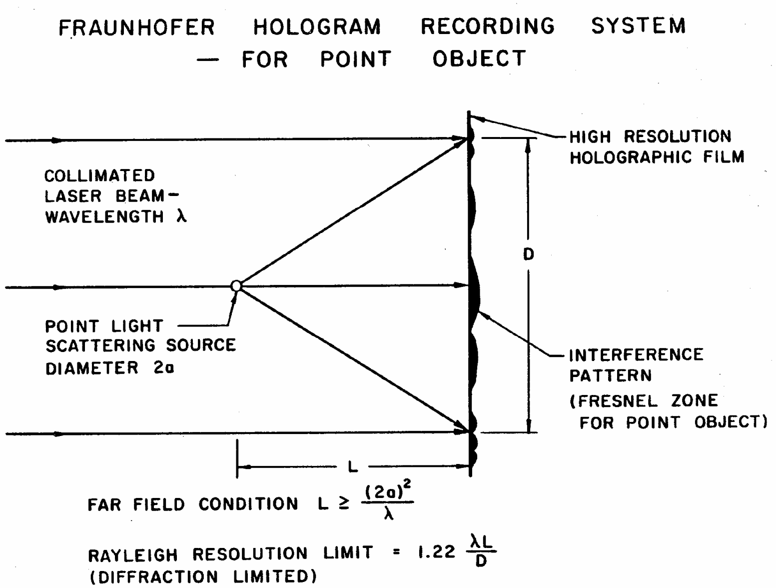


Figure I.2.1. Schematic diagram of the Fraunhofer (in-line) holographic process for a single small particle.

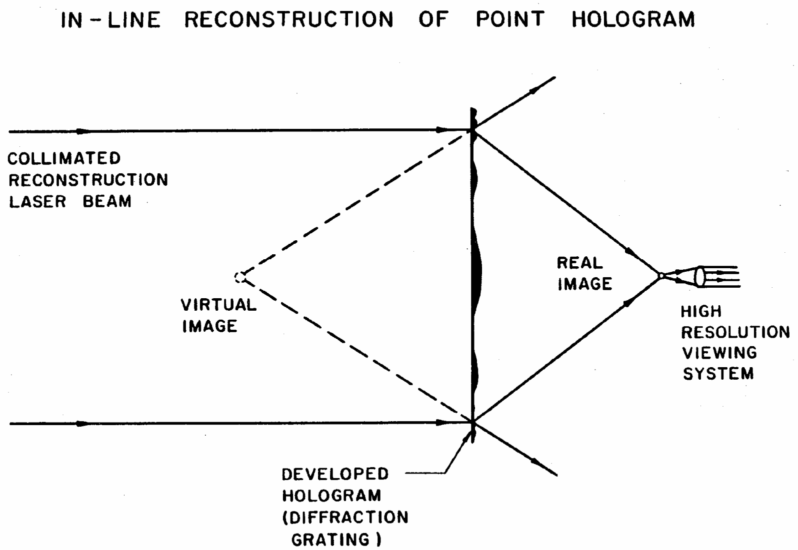


Figure I.2.8. Schematic diagram of the in-line reconstruction of the hologram of a single point object.

Particle Field Holography

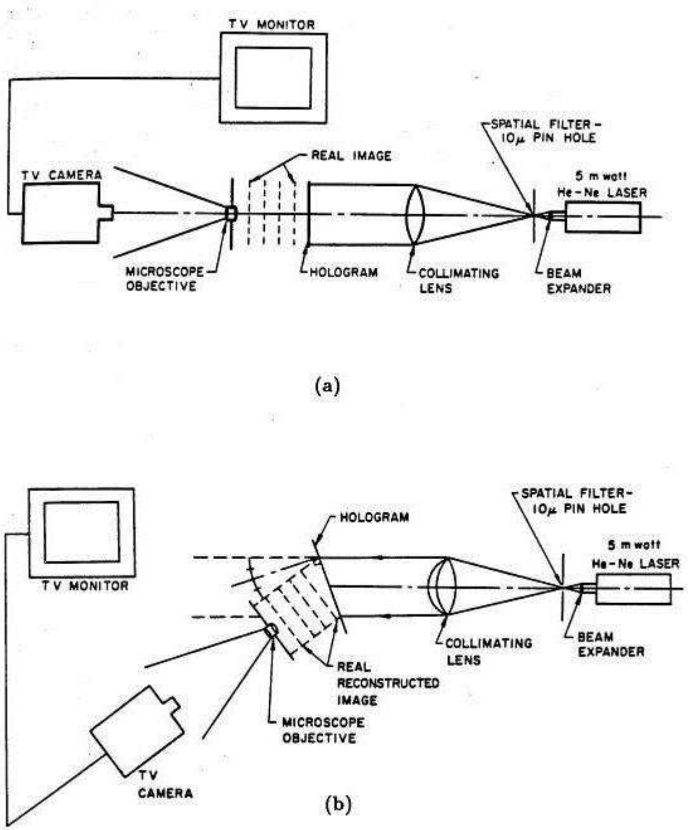


Figure I.2.9. Reconstruction systems
(a) Line diagram of in-line reconstruction system
(b) Line diagram of off-axis reconstruction system

Particle Field Holography

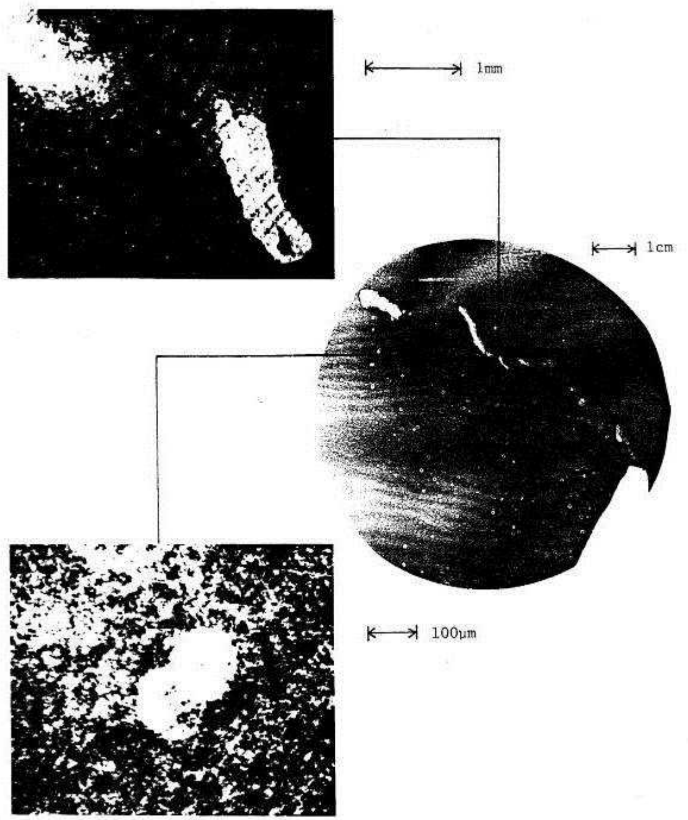
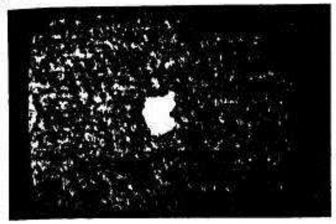


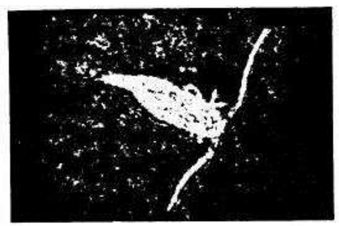
Figure II.4.24. Determination of three-dimensional velocity components from double-pulsed holographic images. Center photograph is of hologram (including tip of sharp edged plate), upper shows reconstructed image demonstrating translation of 1.7 *mm* long streamwise vortex core, and lower shows translation of 100 μm diameter bubble. Separation period between laser pulses is 200 μs. U_L=7 m/s, $\sigma_L = 0.50$, α=3.3 *ppm*.

Particle Field Holography

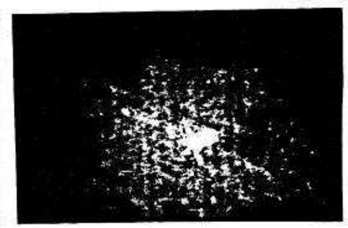


(a) Station 2, 3 *m*. 1/2 inch = 150 μm. Generic particle.

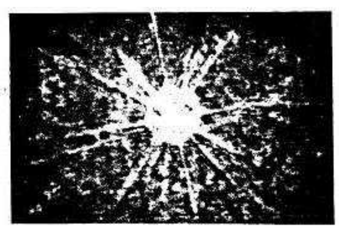
(b) Station 3, 30 *m*. 1/2 inch = 150 μm. *Chaetoceros* diatom.



(c) Station 4, 32 *m*. 1/2 inch = 150 μm. Copepod.



(d) Station 5, 6 *m*. 1/2 inch = 150 μm. Nauplius (immature stage) of copepod.



(e) Station 5, 12 *m*. 1/2 inch = 150 μm. Radiolarian.

(f) Station 5, 3 *m*. 1/2 inch = 150 μm. Dinoflagellate *Ceratium*.

Figure I.4.11. Reconstructed "particle" images from various stations and depths.

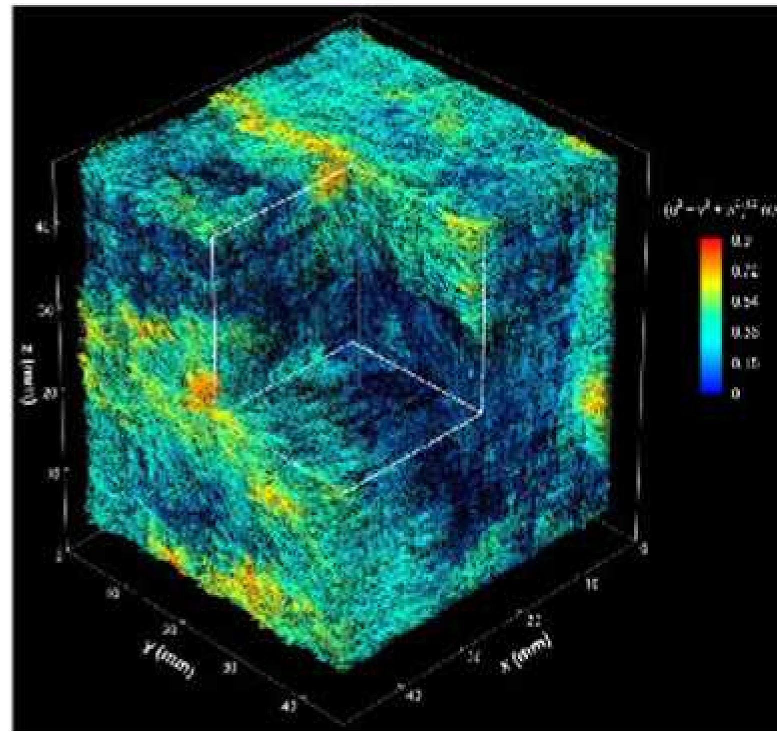
Particle Field Holography

Macro Property Measurement
Field Instrument for Aerosol Particle Sizing
Problem: Develop lightweight, portable instrument for field measurements of aerosol particle sizes
Project Activity Scope (from Technical Overview Chart): Interaction Mechanisms through Integrated Systems
PNNL Solution:
Adapted holographic photography for aerosol data capture and analysis
Developed compact, battery-powered, pulsed ruby rod laser and integrated it with a commercial camera for field use
Successfully demonstrated system use to meet client need
Capabilities Employed to Meet Client Needs: Portable, pulsed ruby laser design; novel Q-switching by laser rod deformation and mechanical resonance motion to control laser pulse operation; compact flash lamp and power supply design for laser rod excitation; camera adaptation for hologram recording; mechanical design for laser source and system integration; lab optics system for hologram reconstruction and aerosol image analysis; project reporting; open literature publication of laser and system design and performance.
Selected Links to Related Information:
Similar Technology Examples (Same or Different Application)
- Fuel Injector Aerosol Characterization
- Holography-Based Measurement Methods

Contact: Tim Peters

Holographic PIV

- Combines holography and PIV for three-dimensional velocity measurements throughout a volume



Prof. Joe Katz, Johns Hopkins U.

Background – Optical Diagnostics

Sean Kearney, 1512

- Optical physics principals are being applied to solve mechanical engineering problems

- Heat Transfer
  - Interferometric thermometry (1960s)
  - IR Imaging and Spectroscopy for thermal radiation and thermometry
  - Laser-Induced Fluorescence (LIF) Imaging of Temperature and Scalar Fields (1990s, 2000s)

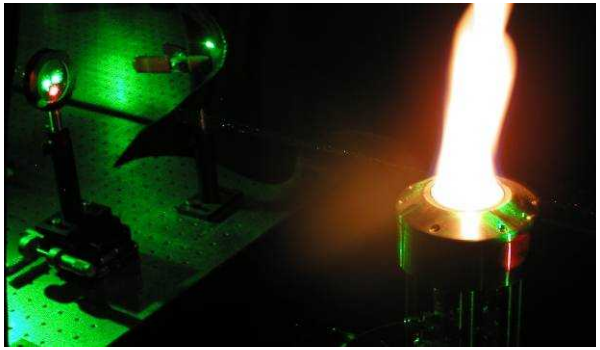
- Laser Diagnostics in particular have exploded in interest since the 1980s.

- Fluid Dynamics
  - Laser-Doppler Velocimetry (1980s)
  - Particle-Image Velocimetry (1990s)

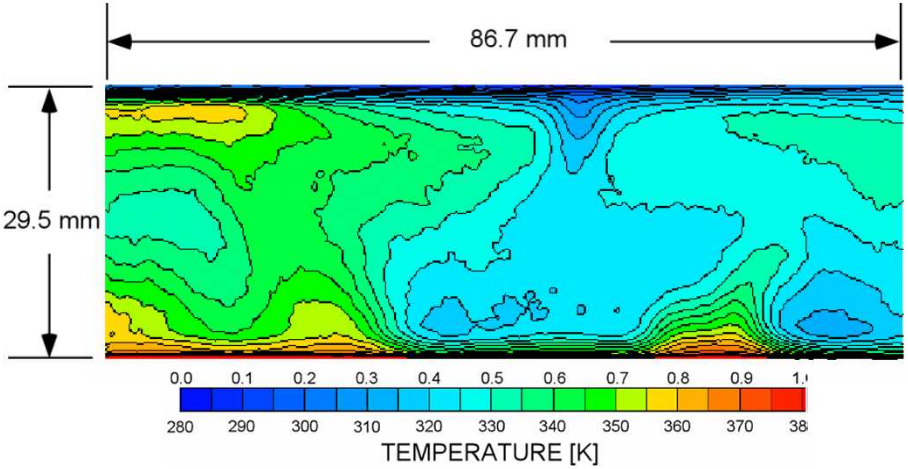
Background – Optical Diagnostics

Sean Kearney, 1512

- Combustion
  - Raman Scattering Measurements of Major Species and Temperature (1970s)
  - Rayleigh Scattering Temperature Imaging (1980s)
  - Laser-Induced Fluorescence (LIF) Detection of Radicals (1980s)
  - Coherent anti-Stokes Raman Scattering (CARS) Thermometry (1980s, 90s)
  - Laser-Induced Incandescence (LII) Imaging of Soot Concentrations
  - Numerous others: Cavity Ring-Down, Degenerate Four-Wave Mixing, Filtered Rayleigh Scattering, Polarization Spectroscopy (1990s, 2000s) Nonintrusive probing of gas, liquid, or solid media
  - Why?
    - High spatial resolution -- microns to 100s nm
    - High temporal resolution - 10 ns to even ps
    - Spatially correlated imaging is possible
    - Enables probing in hostile environments where physical probes fail



CARS Thermometry in Luminous Flames

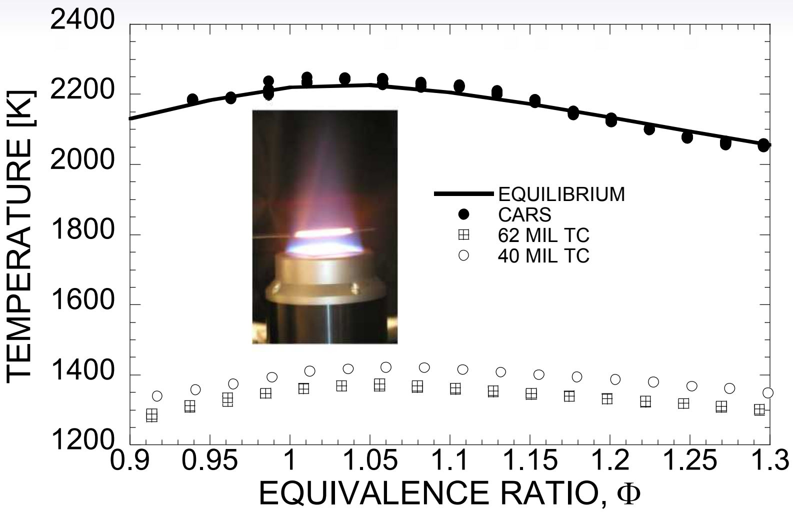


Planar LIF Imaging In Turbulent Thermal Convection

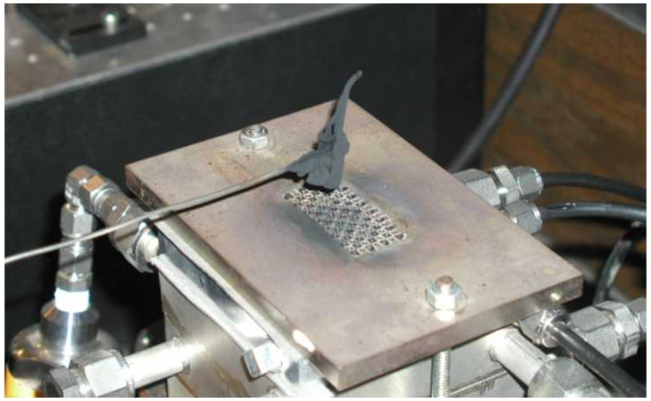
Kearney and Reyes, Exp. Fluids, **34**, 87-97 2003.

Thermal Measurements for Fire Testing

- Traditional thermal measurements in fires use thermocouples and related heat-flux sensors
  - Low-cost, rugged, easy to use
  - Subject to large bias errors
  - Cannot provide multiple parameters
- Optical diagnostics have great potential for high-fidelity data
  - Noninvasive: no insertion, radiation or conduction errors
  - Exploit signatures directly from the gas or particulate of interest as opposed to the response of a physical probe
  - Expensive, more difficult to use
- Recent applications to fire testing include
  - *In situ* emission/absorption probe (Gritzo *et al.*, 1998)
  - *In situ* Tunable Diode Laser Diagnostics and pyrometric thermometry (Shaddix *et al.*, 2001, 2003)
  - *Ex situ* IR-emission spectroscopy (Kearney, 2001)



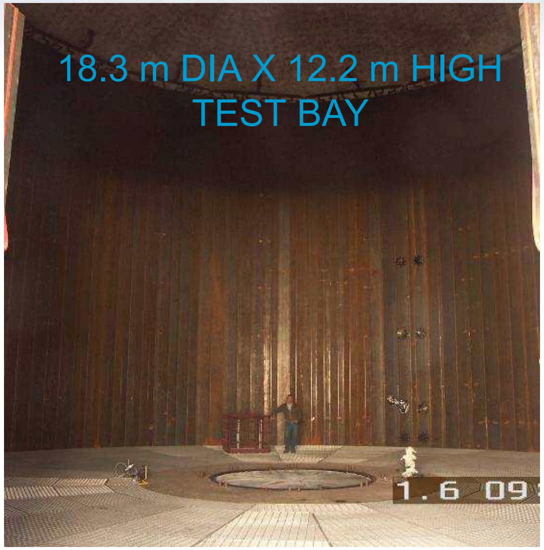
Radiation Errors in Typical TC Used for Fire Testing



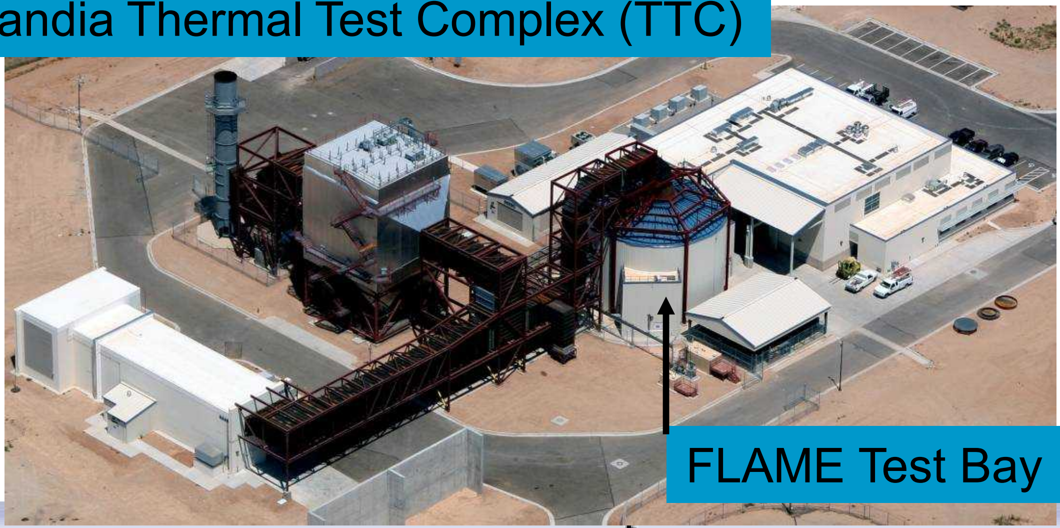
Soot Deposition on Fire TC Sensor

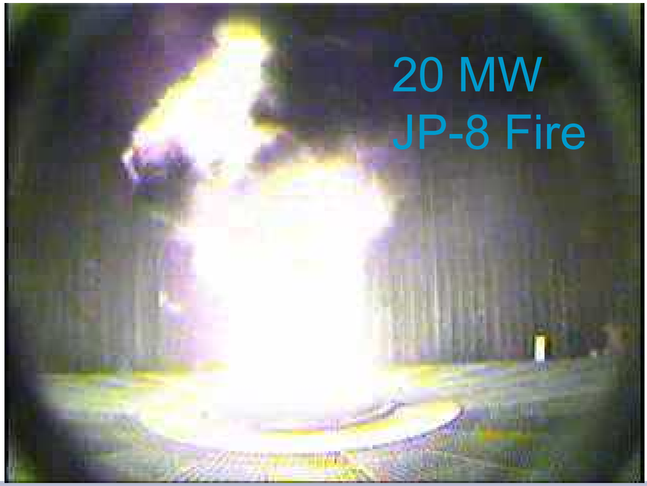
FLAME Facility Enables Full-Scale Testing with High-Fidelity Laser Diagnostics

- Fire Laboratory for Accreditation of Models and Experiments (FLAME) Facility
- Designed to facilitate deployment of optical diagnostics for full meter-scale fire testing
- Optical Access Ports and Adjacent Lab Space at East,West, and South Positions Around Test Cell
- Liquid and Gas-Fueled Fires up to 3-m in Base Dia.
- Brings Laboratory Control to Full Scale Testing



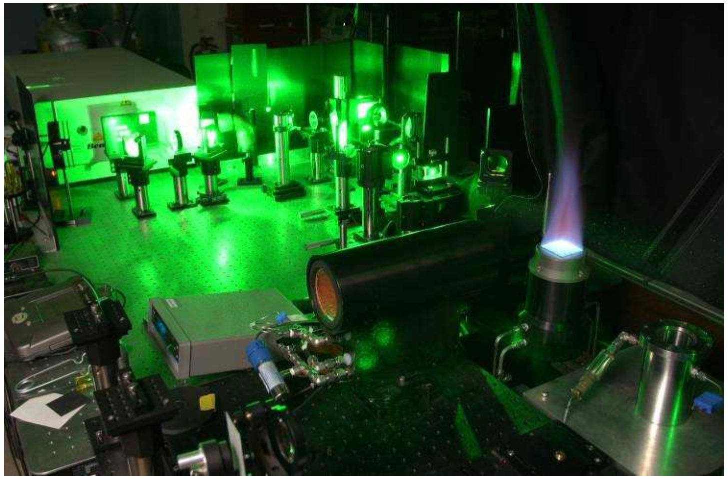
Sandia Thermal Test Complex (TTC)



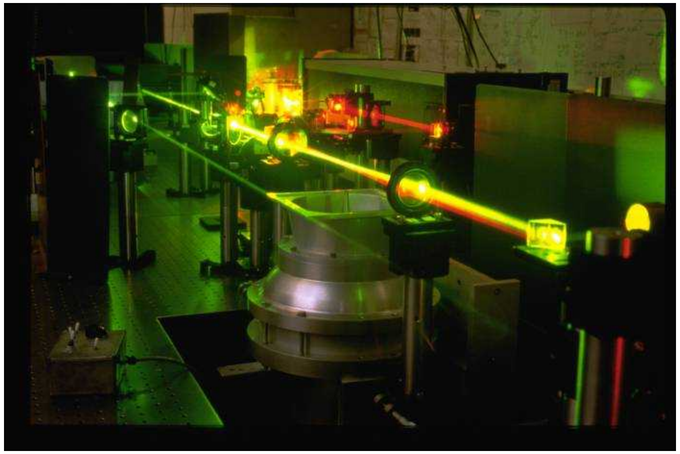


Overview

- Filtered Rayleigh Scattering (FRS) in Flames
- Coherent anti-Stokes Raman Scattering (CARS) applications to highly luminous combustion

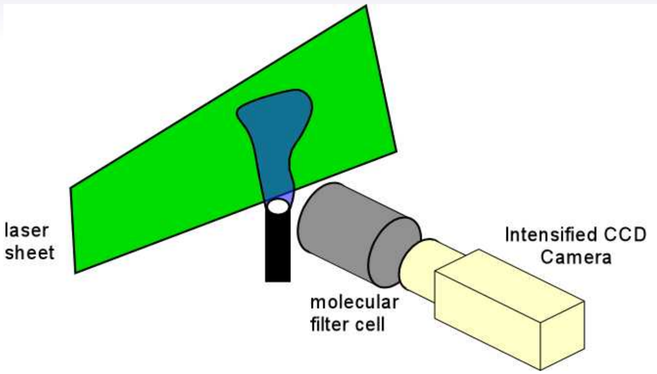


Filtered Rayleigh Scattering (FRS)

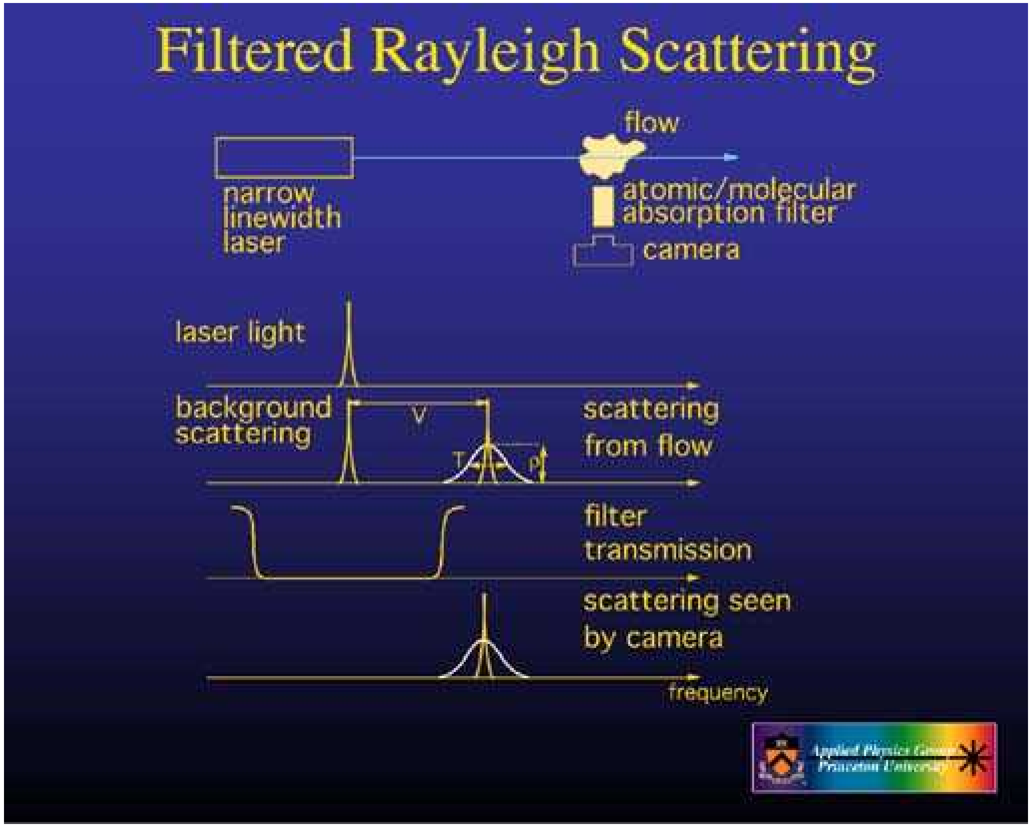


Coherent anti-Stokes Raman Scattering (CARS)

Filtered Rayleigh Scattering (FRS)

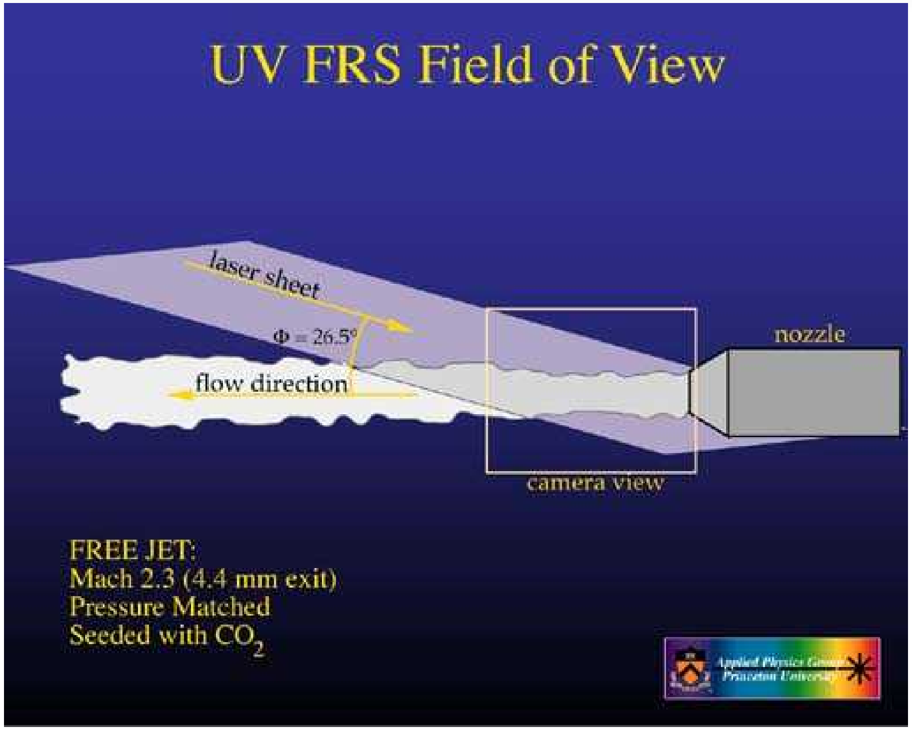


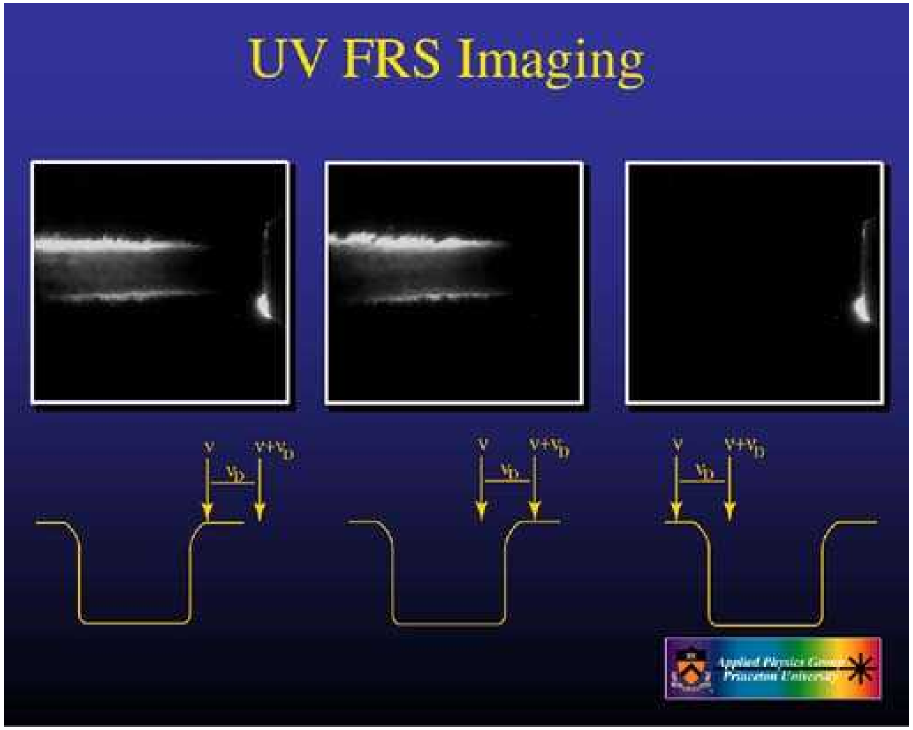
Laser sheet imaging through iodine filter



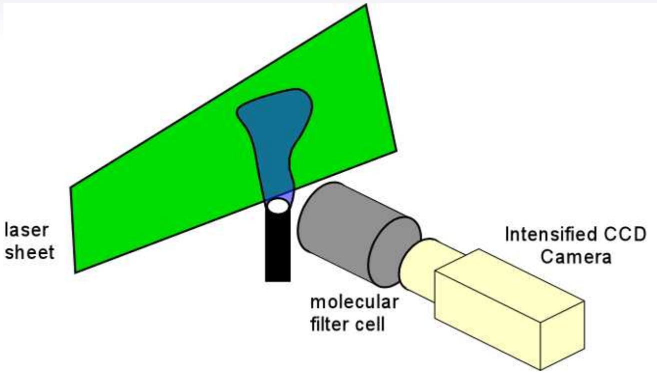
- Rayleigh scattering is scattering by particles smaller than laser wavelength (molecular scattering)

Filtered Rayleigh Scattering (FRS)

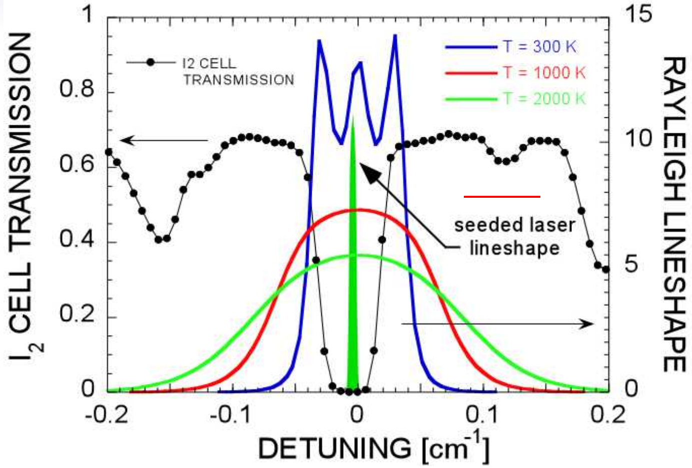




Filtered Rayleigh Scattering (FRS) for Combustion Thermometry



Laser sheet imaging through iodine filter



Temperature sensitivity – Doppler broadening

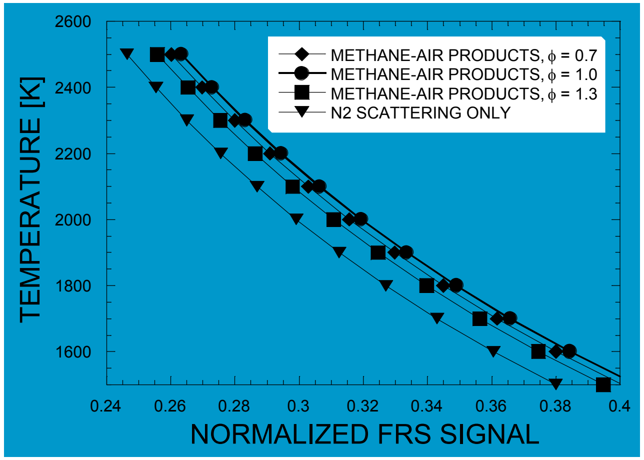
$$S(T,\underline{\chi}) = C\, I_o\, N \sum_k \chi_k \left(\frac{\partial \sigma}{\partial \Omega}\right)_k \int_{\Delta\omega} \Re_k(\omega; T, M_k)\,\tau(\omega)\,d\omega$$

Number Density
N ~ 1/T

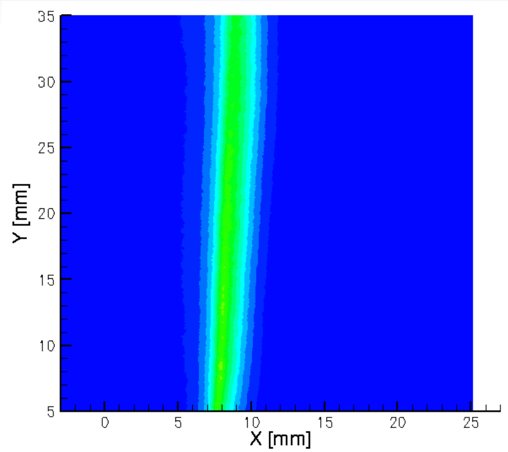
Rayleigh Cross Section
("Scattering Efficiency")

Mole Fraction of Species k

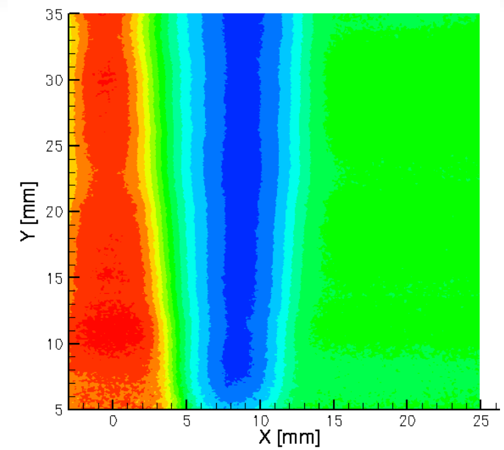
FRS Response is Sensitive to Doppler Shift (Velocity), Temperature and Composition



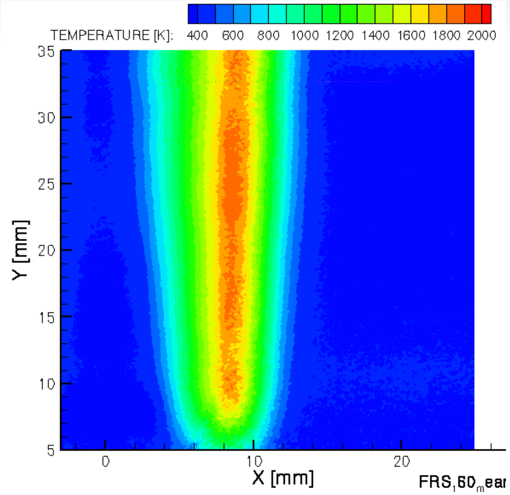
Vortex-Strained Diffusion Flame: Single Vortex Interaction



CH Chemiluminescence (Reaction Zone Marker)

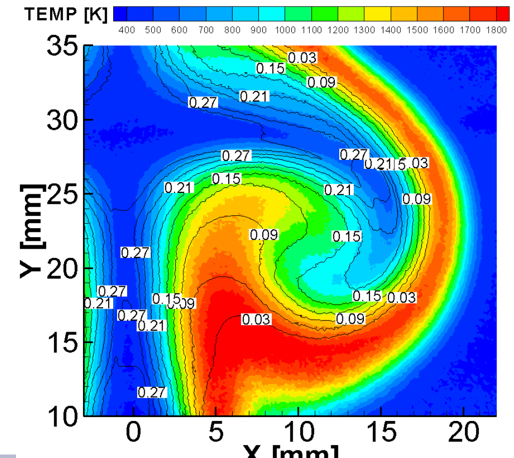


FRS Signature



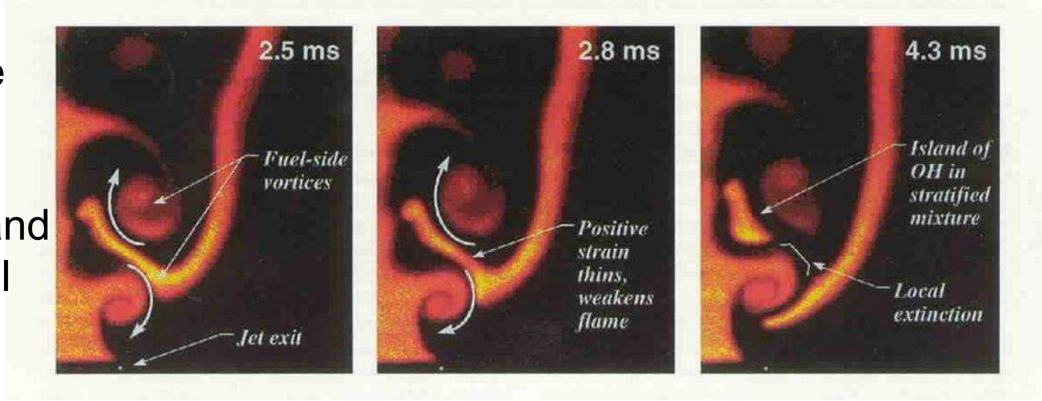
Temperature Field

- Single fuel-side vortex strains the flame at 7.5 Hz periodic forcing
- CH luminosity reveals flame-zone structure
  - Thin CH layer → + strain, large gradients, low T
  - Thick CH layer → - strain, smaller gradients, high T
- Min. temperatures in stretched flame ~ 1650 K
- Max. temperatures in thickened flame region ~ 1950 K



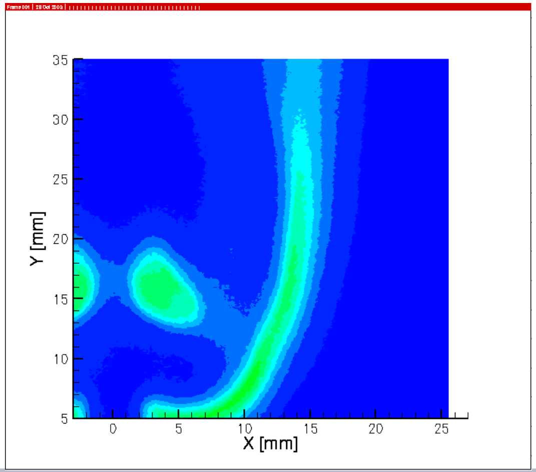
FRS-Raman Probing of Strain Induced Extinction in Flames

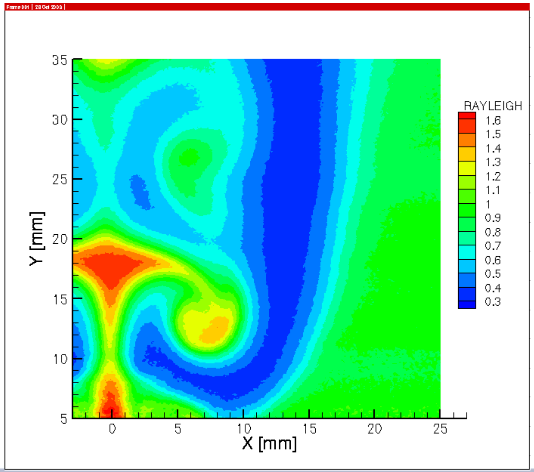
- 2-D slot flame is forced at 90-Hz where 2 consecutive vortices interact with the flame
- Strain is sufficiently high to extinguish the flame
- Facility and diagnostics allow are stable and repeatable. Permit systematic experimental probing of extinction event
- Applications to turbulent combustion modeling and modeling of fires

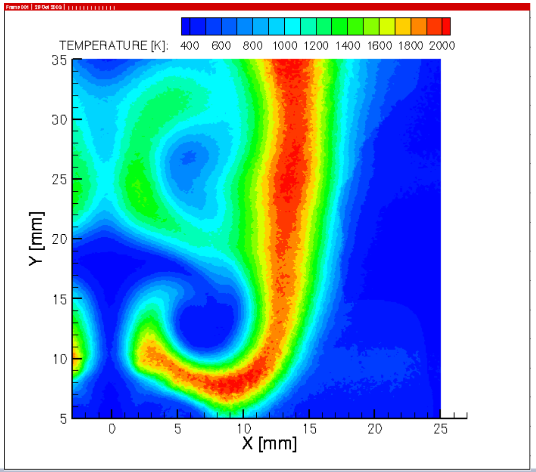


Simultaneous OH/Acetone PLIF Flow Viz.

C.J. Mueller and R.W. Schefer, *Proc. Combustion Inst.*, **27**, 1105-1112, 1998







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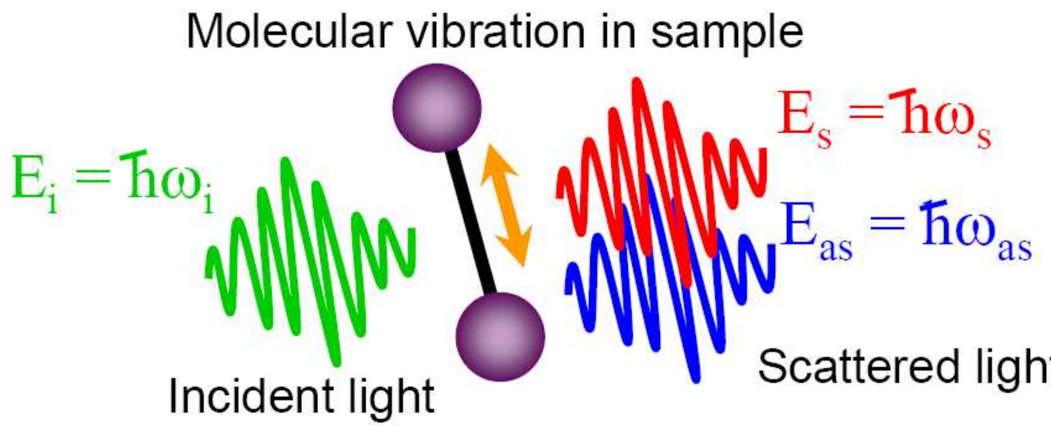
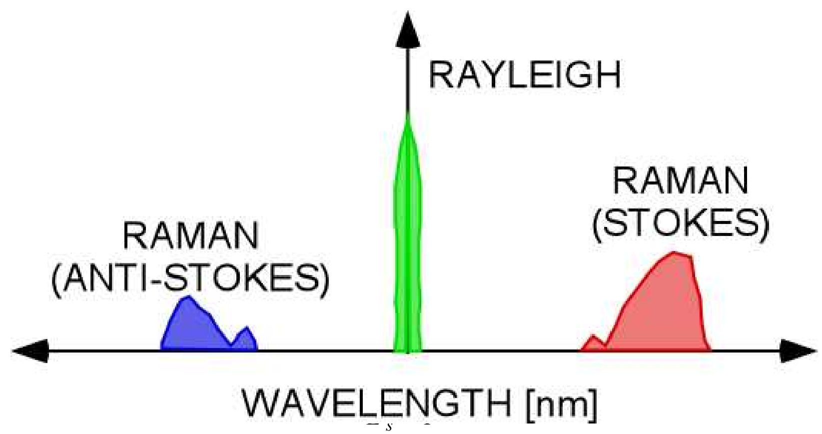
CARS Fundamentals

C.V. Raman
1930 Nobel Prize



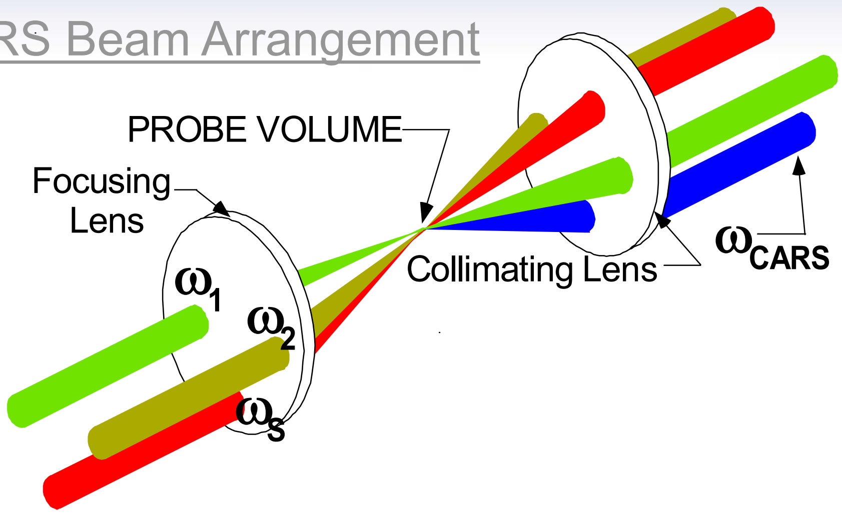


Light Scattering Spectrum

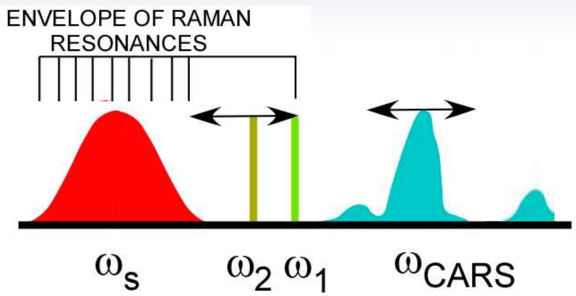
- Raman scattering is the interaction of photons and intrinsic molecular bonds

CARS Fundamentals

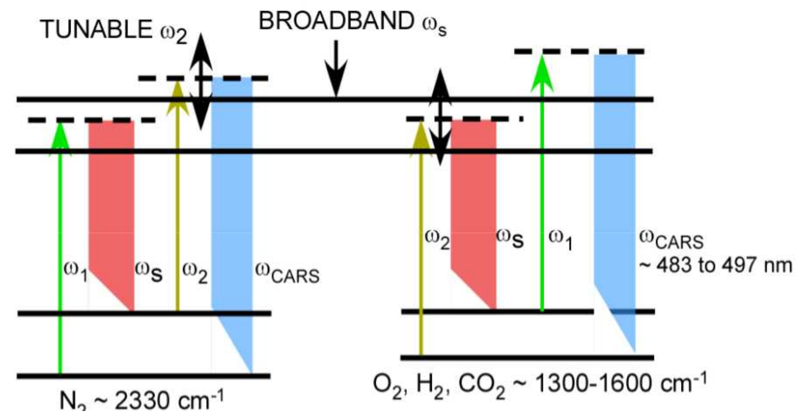
CARS Beam Arrangement



- Three pulsed laser beams (pump #1, pump #2, Stokes) crossed at a common focus
- Pump-Stokes tuning at $\omega_1 - \omega_s$ and $\omega_2 - \omega_s$ drives a Raman polarization (dipole) in N_2 and selected combustion gases
- Temperatures obtained on a single-pulse (10-ns) basis from the shape of the CARS spectra. Mole fractions from relative strength of Raman lines



Spectra of pump/Stokes/CARS Beams

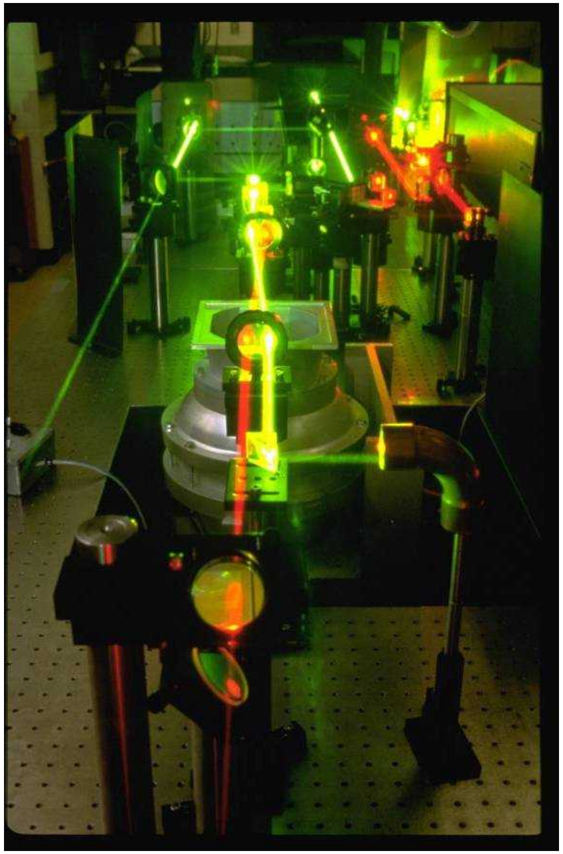


$$\omega_{CARS} = (\omega_1 - \omega_s) + \omega_2$$

Energy Level Diagrams

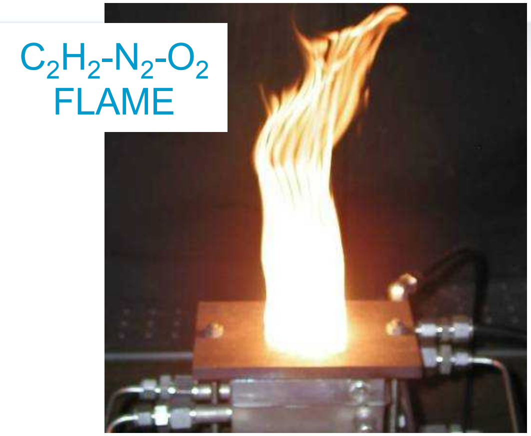
Advantages of CARS for Full-Scale Fire Testing

- Improved accuracy and spatial resolution vis-à-vis emission/absorption measurements
- Coherent laser-like signal
  - Spatial discrimination of background noise
  - Can be efficiently coupled into optical fibers for remote detection
- Blue-shifted, spectrally narrow signal beam
  - Spectrally separated from red-yellow-IR background emission
  - Can be shifted away from particle-based interference (dual-pump CARS)
  - Insensitive to soot optical properties
- CARS has a *long* history of application at large-scale
  - Jet engine exhausts (Eckbreth *et al*. 1984)
  - Coal-fired furnace (Aldén *et al*., 1985)
  - Meter-scale MHD combustor (Beiting, 1986)
  - 50-kW biomass fired furnace (Aldén, 1999)
- Sooting flames can be probed w/ dual-pump CARS
  - Ethylene fueled (Beyrau et al., 2003; Malarski et al, 2005)
  - Acetylene fueled (Kearney and Jackson, 2007)

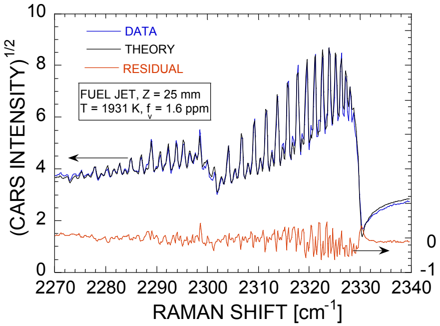


Dual-Pump CARS Results from Heavily Sooting Laboratory Flames

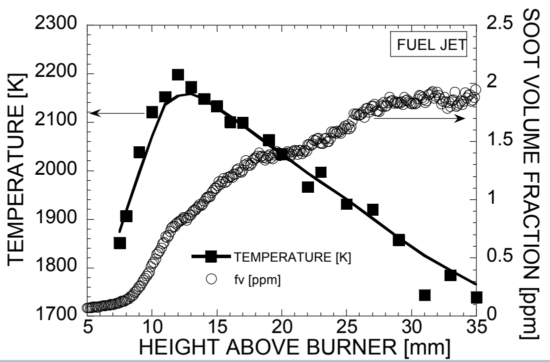
- We have successfully demonstrated CARS thermometry in heavily sooting acetylene fueled flames
- Valid CARS measurements for soot loadings of <u>at least</u> 2.2 ppm have been demonstrated
- This degree of soot loading is comparable to what is observed in hydrocarbon pool fires



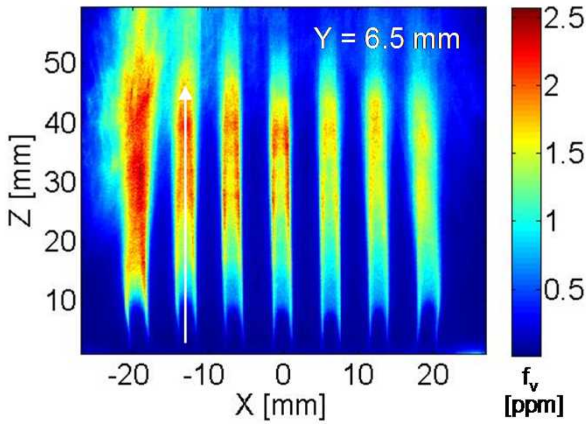
"Propellant Simulating" Burner Provides an Array of Heavily Sooting Fuel Jets



Theoretical Fit to CARS Spectrum from Fuel Jet



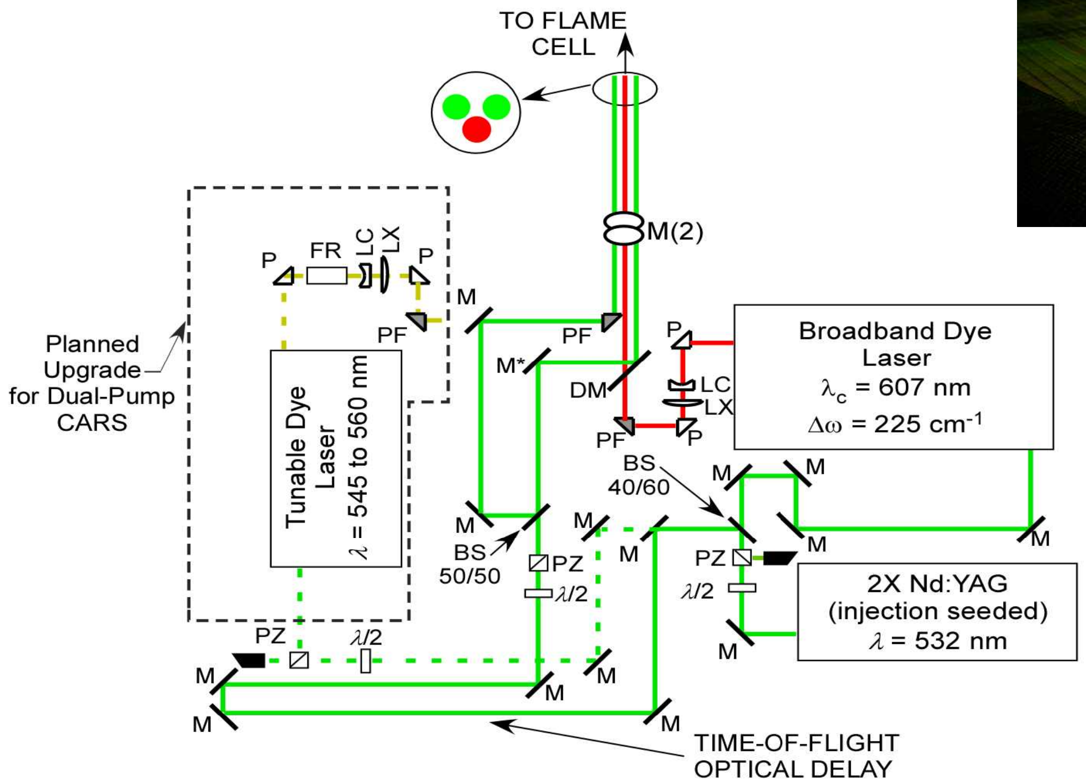
Temperature (CARS) and Soot (LII) Profiles Along Fuel-Jet Axis



Laser-Induced Incandescence (LII) Measured Soot Volume Fractions

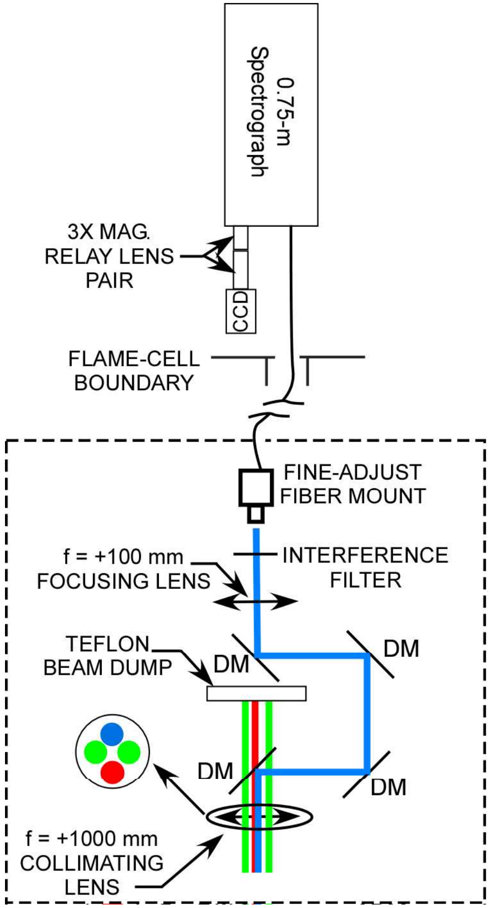
CARS Beam-Delivery System (FLAME West Lab)

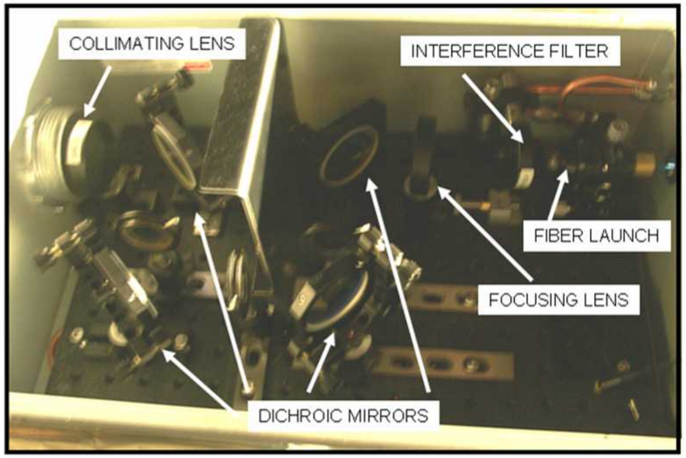
- Setup is shown for frequency degenerate pump beams
- Dual-pump implementation is similar



CARS Signal-Collection Optics (FLAME Test Bay and East Lab)

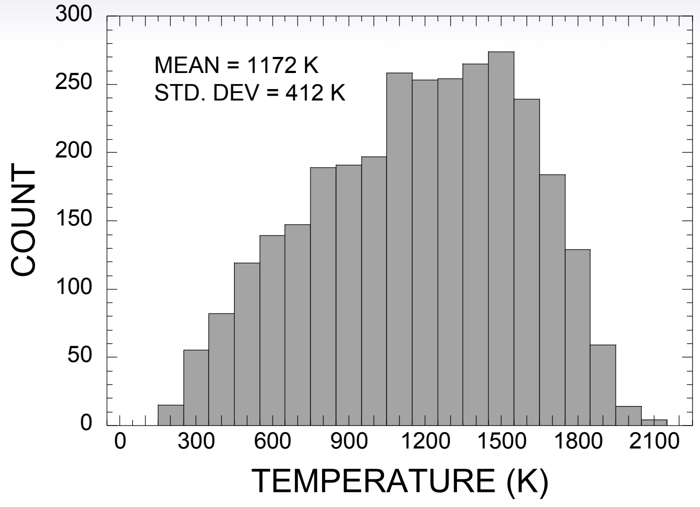
- Beam steering prohibits mirror coupling over the 12-m path
  - CARS signal is coupled into a 100-μm core fiber located ~ 1.5 m from the probe volume
- Lower limit for collection efficiency ~ 10%.
  - A key limitation when single-pulse data are required!
- CARS signal seems to couple only to low-order fiber modes, improving collection efficiency

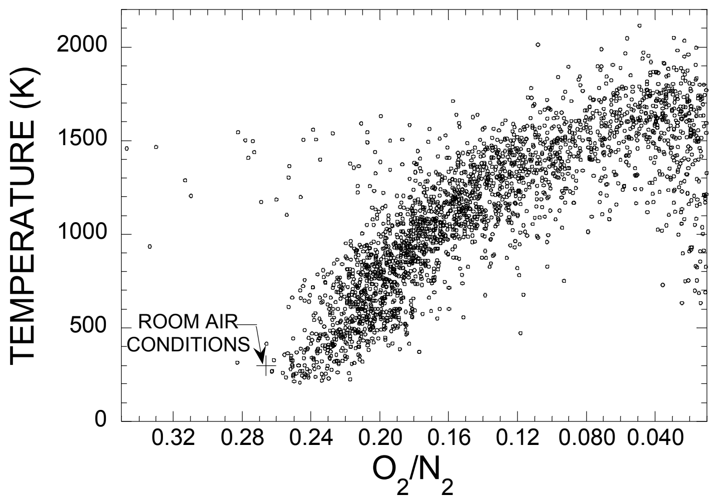


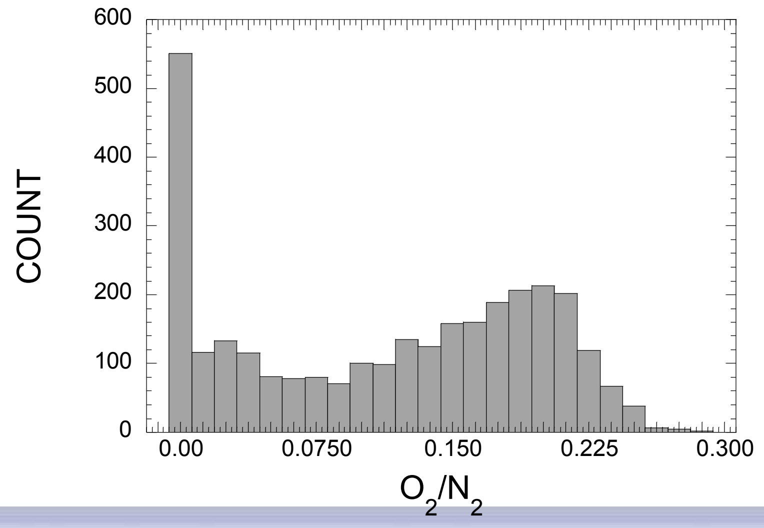


Dual-Pump CARS Results – Methanol Pool Fire

- Measurements at a single point, ~1/2 diameter above fuel-pan center
- Temperature pdf skewed toward low values; mixing of cool gas toward center of fire plume
- Bimodal pdf for relative O_2/N_2 measurement.
- Temperature/O_2 scatter reveals distinct correlation for fuel-lean combustion gases







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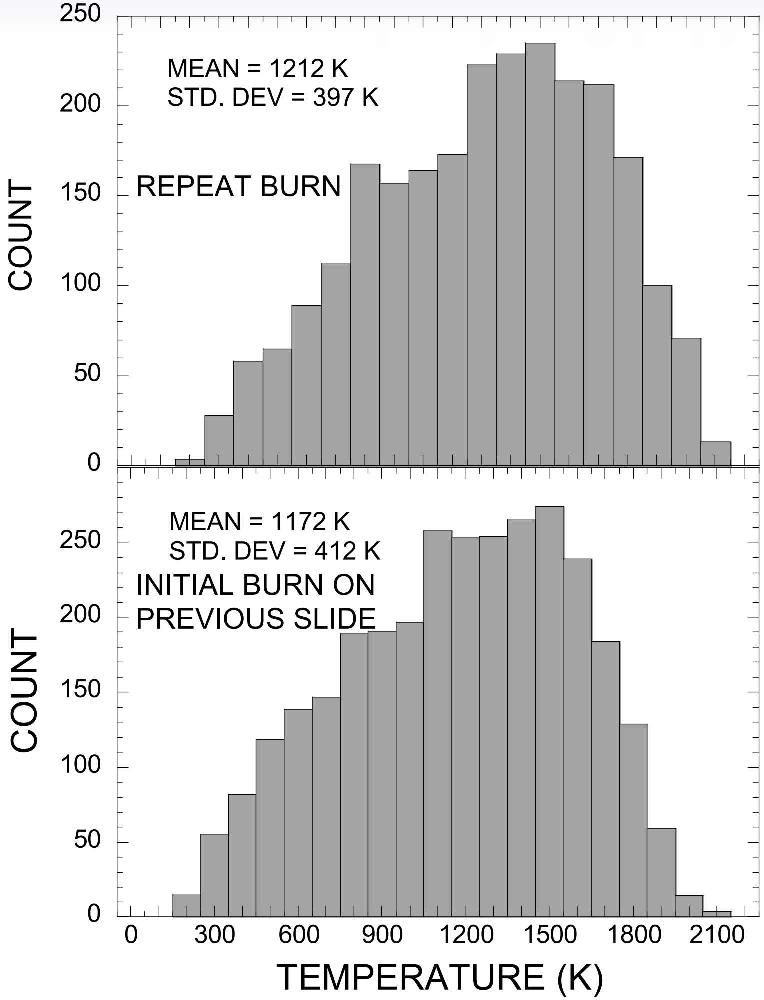
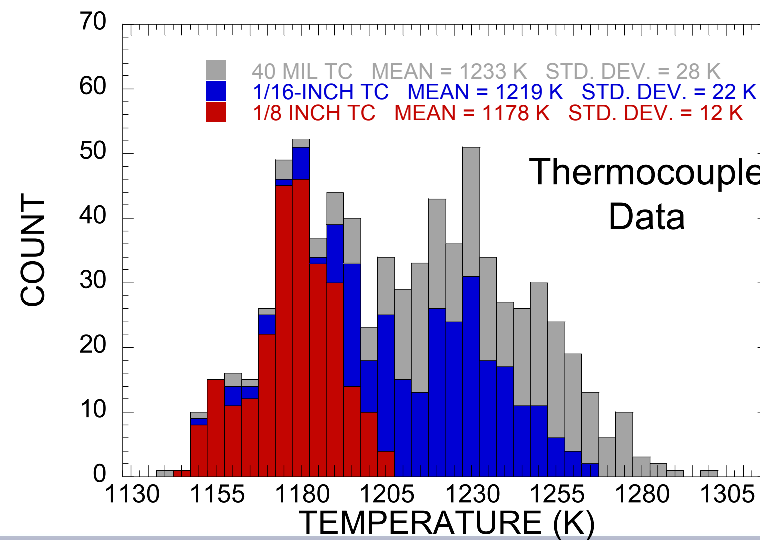
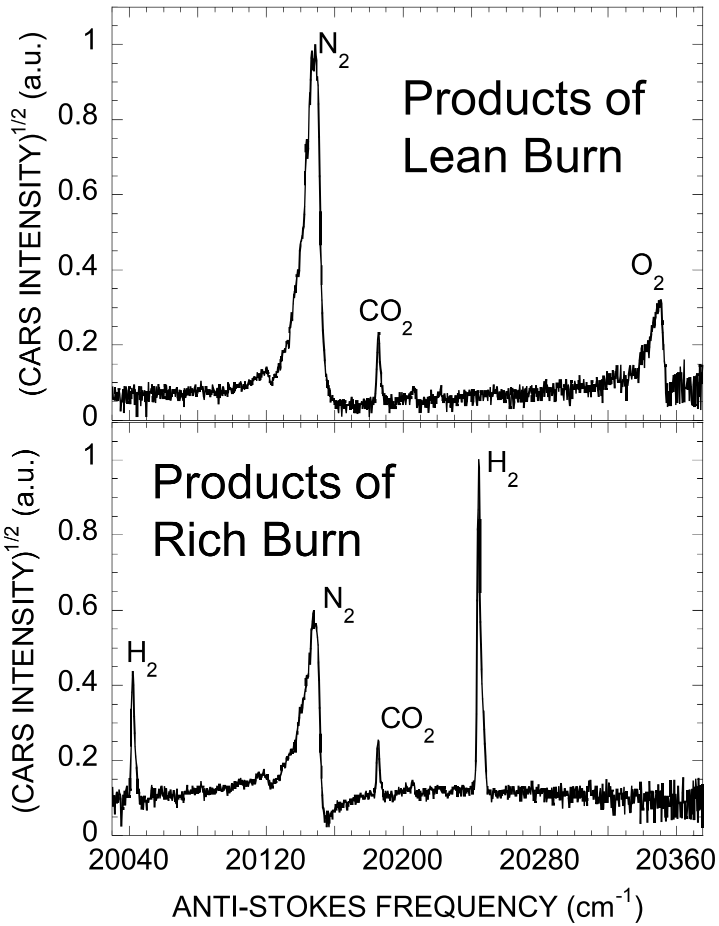
Repeat Burn Reveals Repeatability and Comparison to Thermocouple Temperatures



- Fire structure is repeatable in FLAME facility
  - CARS mean temperatures from different days are within 40 K
- PDF shape and std. dev. also exhibit excellent repeatability
  - CARS mean temperatures in good agreement with TC data
- TC's do not respond to fluctuations



Initial Spectra from a Sooting Methanol/Toluene Pool Fire



- Next step is the addition of soot
- More challenging test of optical diagnostics
    - Absorption/Emission Interference
    - Strong Raman features of laser-produced C_2
- Soot levels are well-controlled using methanol/toluene liquid fuel blends
- Initial results from moderately sooting fire appear promising
- Temperature O_2/H_2/CO_2 measurements seem feasible

Many other laser applications

- Medical
  - Eye surgery
  - Ear surgery
  - Hair removal
  - Tattoo reversals and skin problems
- Dental
- Materials processing
  - Welding, cutting, drilling
  - Heat treatment
- Nuclear Fusion
- Surveying
- Communication
- Entertainment
- Laser printing
- Ranging
- Pointers
- Many, many other applications

DIY Lasik surgery