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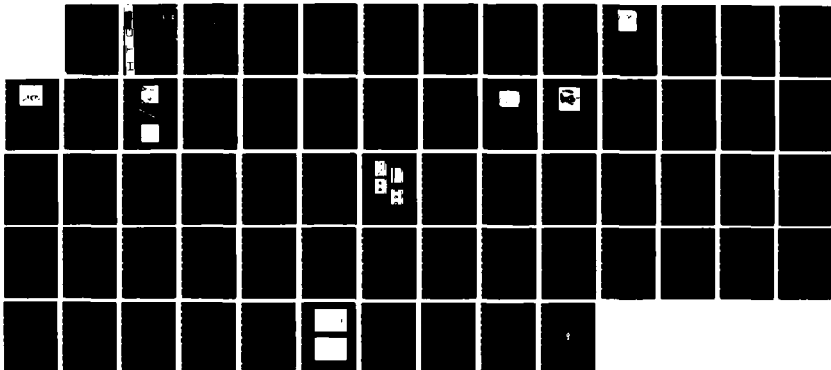
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UNIV CA HIGH TEMPERATURE GASDYNAMICS LAB R K HANSON  
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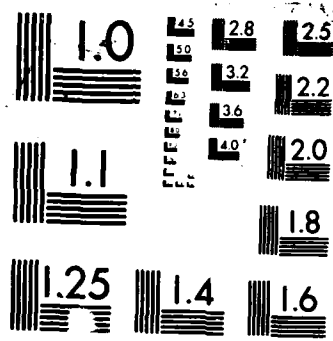
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Final Scientific Report

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ADVANCED DIAGNOSTICS FOR REACTING FLOWS

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Submitted by

R. K. Hanson, Principal Investigator

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<p>Progress is reported for the past 4 years of an interdisciplinary program to innovate modern diagnostic techniques applicable to combustion and plasma flows. Particular emphasis has been placed on research to establish digital flowfield imaging methods based on laser-induced fluorescence and Mie scattering. Significant accomplishments include the demonstration of two-dimensional imaging to measure the instantaneous (10 nanoseconds) distribution of temperature and species concentration in a plane using 100x100 and 384x576 element solid-state detector arrays. Spectroscopic strategies have been developed to permit the monitoring of several species, including Na, I<sub>2</sub>, O<sub>2</sub>, OH, CH, C<sub>2</sub>, NO and biacetyl using single-photon-excitation and C<sub>2</sub>H<sub>2</sub> and CO using two-photon-excitation. Two single-laser-shot strategies for imaging temperature have been demonstrated, one involving excitation of NO seeded as a tracer into the flow of interest and one involving O<sub>2</sub>, with the latter method showing particular promise for use in studies of heat transfer and fluid</p>			
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mechanics of air. Both temperature imaging concepts are useful over a broad range of temperature through selection of appropriate molecular transitions pumped.

A separate fluorescence-based imaging activity has involved the successful development of a method for 2-d imaging of velocity and pressure in gaseous flows. The sensing strategy is based on the Doppler effect of the molecular constituents themselves, and hence does not require the addition of particulates to the flow. Measurements have been carried out in both subsonic and supersonic flowfields of nitrogen containing trace levels of iodine vapor. Although the method is quite general, it does require a match between the laser source and an absorption transition. Work thus far has exploited the known coincidence between visible argon ion laser lines and the electronic spectrum of iodine. An important contribution made in recent work has been to demonstrate that vorticity can be extracted from the velocity field data, thereby facilitating comparisons with flowfield models in which the vorticity field and its evolution play a central role.

In addition to research on imaging of specific flowfield variable, progress is reported on the development of a next-generation solid-state camera system. Based on a high resolution (384x576 pixels) CCD camera, this system provides a substantial improvement in both the noise level of detection (reduced to 10 noise-equivalent-photons per pixel) and in the number of pixels per image (to 221,000 from 10,000). These improvements are critical to future applications of imaging methods to turbulence research where it will be necessary to quantitatively resolve a range of fluid flow scale sizes and to infer gradient information. Finally, progress in extending 2-d imaging to 3-d is reported based on rapid scanning of the imaged plane. This research provides an entry point for addressing questions concerned with the three-dimensionality of flows and with the display and use of 3-d data.

Other projects covered in this report include work on fiberoptic absorption/fluorescence sensors and research on laser wavelength modulation spectroscopy. Accomplishments in the area of fiberoptic sensors include the development and use of fiberoptic links for remote measurements of reactive radical species (NCO and CH) in high-temperature environments. Work on laser wavelength modulation has included the design and assembly of a unique, fast-scanning ring dye laser system which enables increased wavelength scan rates (by a factor of about one thousand) over commercially available systems. This new capability has been exploited in a series of shock tube and flame studies of fundamental spectroscopic parameters of transient species, such as OH, and in the development of a new, fast-response temperature-sensing strategy in high temperature gases.

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## 1.0 INTRODUCTION

Progress is reported for the past 4 years of an interdisciplinary program to innovate modern diagnostic techniques applicable to combustion and plasma flows. Research topics include: (1) digital flowfield imaging including 2-d and 3-d temporally resolved species and temperature imaging using planar laser-induced fluorescence (PLIF); (2) quantitative particle imaging in spray flames using planar Mie scattering (PMS); (3) quantitative velocity and pressure imaging using variations of PLIF; (4) advanced solid-state camera/computer systems for high-speed and high-resolution recording processing and display of flow image data; (5) fiber optic absorption/fluorescence sensors employing tunable UV, visible and IR laser sources for species measurements; (6) laser wavelength modulation spectroscopy using rapid-scanning UV, visible and IR laser sources for absorption and fluorescence measurements of species, temperature and absorption lineshapes; (7) plasma diagnostics utilizing laser-induced fluorescence and wavelength modulation techniques; and (8) laser interactions with plasmas and combustion gases.

## 2.0 PROJECT SUMMARIES

Included in this section are summaries of progress in each of six project areas. In most cases each project summary contains the following subsections: (a) Introduction; (b) Scientific Merit; (c) Status Report; (d) Publications and Presentations; (e) Personnel. Additional descriptions of this work may be found in the cited publications and in previous annual scientific reports.

### 2.1 Digital Flowfield Imaging

#### Introduction

The utility of flow visualization as a diagnostic in studies of fluid mechanics and combustion is well established. Until recently, however, most visualization techniques have been qualitative and based on line-of-sight approaches poorly suited for flows with three-dimensional characteristics. With the recent development of laser-based light scattering techniques, it has become possible to obtain spatially and temporally resolved quantitative records of flow properties throughout a plane using sheet illumination and a scattering technique such as Raman, fluorescence or Mie scattering. Such multipoint measurements essentially provide "images" of the flowfield property being monitored; as these images can be recorded on modern solid-state array detectors, coupled to a computer for analysis and display, we call this approach "Digital Flowfield Imaging." Work along these lines is now in progress at Stanford, Yale, SRI, Sandia (Livermore) and the Aero-propulsion Lab at Wright Field. As examples of the capability of these new methods, in our laboratory at Stanford we have made instantaneous (8 nsec), multiple-point ( $10^4$  points) measurements of several species (OH, NO,  $O_2$ , CH,  $C_2$ ,  $C_2H_2$ , CO and Na) in a variety of laboratory flames using planar laser-induced fluorescence (PLIF), and we have recently initiated work to provide simultaneous particle size and spacing measurements in spray flames using planar Mie scattering (PMS). The sensitivity demonstrated thus far for molecular species is in the 10's of ppm range, with spatial resolution typically much better than 1 mm. Of equal importance, we have recently demonstrated two variations of PLIF which yield temperature, and another variation which enables simultaneous measurements of pressure and velocity

(see Section 2.2) without particle seeding. These new techniques provide significant advances in measurement capability with potential scientific impact extending well beyond the field of combustion for which the methods were originally developed. Finally, we note that the extension of these 2-d imaging methods to 3-d, by rapid scanning of the illumination plane, has recently been demonstrated.

### **Scientific Merit**

Digital flowfield imaging has the potential to stimulate significant scientific advances in several fields including fluid mechanics, combustion and plasma sciences. Our research also contributes to the advancement of related technologies, such as lasers and image processing, and it adds to the fundamental data bases for spectroscopy and reaction kinetics of high temperature gases and plasmas. The Stanford program has made pioneering contributions to flowfield imaging, particularly with regard to the establishment of sensing strategies for the flowfield quantities of interest, and to the implementation of intensified camera systems which incorporate recent advances in intensifiers and array detectors interfaced with laboratory microcomputers.

### **Status Report**

Our work on flowfield imaging has been detailed in a series of papers and reports (see list at end of this section), and so here we focus only on recent activities. For convenience and clarity we provide separate status reports on: Species Imaging, Temperature Imaging, Spray Flame Imaging, System Improvements, and 3-d Imaging.

#### (a) Species Imaging

Previously we have applied PLIF to visualize OH, Na, NO and I<sub>2</sub> in several flows. Recently we have worked to develop measurement capability for O<sub>2</sub>, C<sub>2</sub>, C<sub>2</sub>H<sub>2</sub>, CH and CO as we discuss briefly below. Molecular oxygen is of particular interest in many combustion studies, but is usually considered to be inaccessible by optical techniques as it absorbs strongly only in the UV below 200 nm. In addition, fluorescence is known to be weak

owing to strong predissociation effects. Two factors mitigate this conventional viewpoint: (1) the recent development of high energy, tunable UV and VUV laser sources, particularly excimer and Raman-shifted excimer lasers; and (2) the fact that the dominant absorption transitions at high temperatures are very much stronger than the (separate) transitions normally employed for monitoring  $O_2$  at atmospheric conditions.

Following an initial literature survey of relevant past work on  $O_2$ , culminating about a year and a half ago, we have developed a set of computer codes which allow prediction of  $O_2$  absorption and fluorescence spectra as a function of temperature and of excitation wavelength (see paper 15 in list at the end of this section). The calculations are complex and will not be described here, but in summary we found that either an argon fluoride (ArF) excimer laser at 193 nm or Raman-shifted ArF at 179 nm should be well suited for detecting  $O_2$  over a range of temperatures. Subsequently, we moved to the laboratory and obtained very promising initial results. Figure 1 provides a sample instantaneous (10 nsec)  $O_2$  image obtained in a fuel-rich  $CH_4$ /air flame. This is the first digital image of  $O_2$  obtained by any method in any flowfield. Owing to the broad importance of  $O_2$  in aerodynamics and combustion, we regard this as a particularly important accomplishment. Further work to improve this technique is in progress, and at the same time we are investigating, by computer calculations with our  $O_2$  spectroscopy program, candidate schemes for visualizing temperature (see below), pressure and velocity based on  $O_2$  fluorescence.

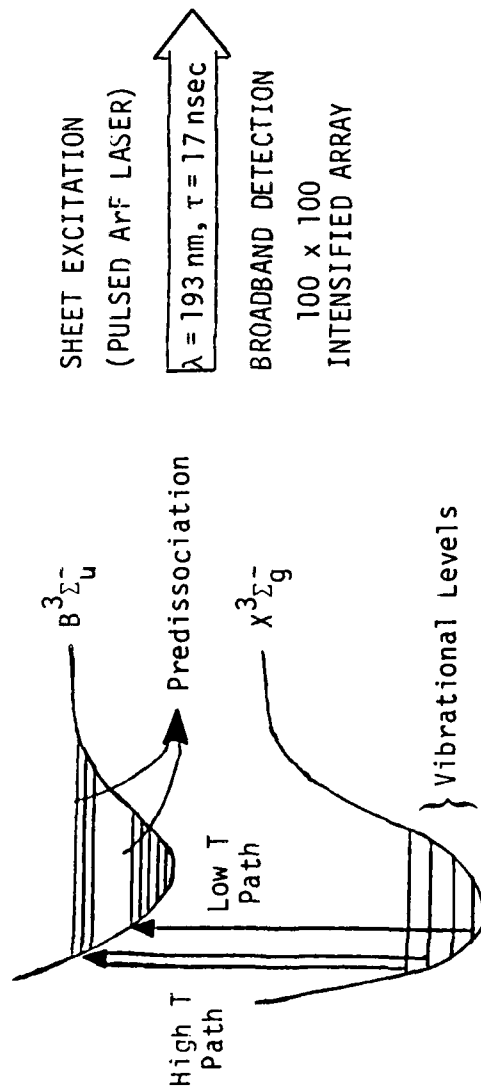
Our interest in imaging CH and  $C_2$  stems from their potential for monitoring the instantaneous flame position and thickness in gaseous diffusion flames and in burning fuel sprays. The status of the work is that we have recently obtained our first 2-d images of CH and  $C_2$  in a variety of gaseous and spray flames. This work has now been written up and submitted for publication (see papers 16, 18 and 19).

The work previously described in this section was all based on single-photon processes, that is the fluorescent emission is preceded by absorption of single photons which raise the molecule in one step from a discrete lower energy level to a discrete upper level. Recently, we have begun to explore two-photon absorption as a means of inducing fluorescence in stable

## ACHIEVEMENT

### DIGITAL FLUORESCENCE IMAGING OF O<sub>2</sub> IN COMBUSTION FLOWS

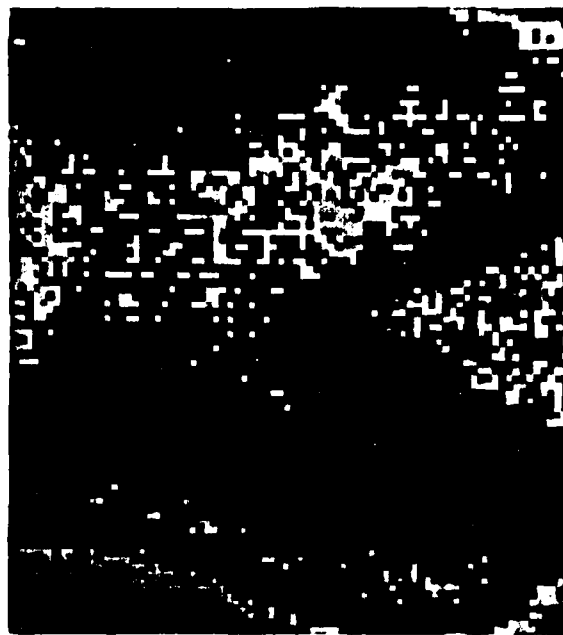
- EXCIMER LASER PROVIDES ACCESS TO UV TRANSITIONS OF O<sub>2</sub>



SHEET EXCITATION  
(PULSED ArF LASER)

$\lambda = 193 \text{ nm}, \tau = 17 \text{ nsec}$

BROADBAND DETECTION  
100 x 100  
INTENSIFIED ARRAY



Digital Fluorescence Image of O<sub>2</sub>  
Fuel-Rich CH<sub>4</sub>/Air Flame

- FIRST 2-D FLUORESCENCE IMAGE OF O<sub>2</sub>
- USE OF HIGH-TEMPERATURE TRANSITIONS INCREASES SIGNAL BY ORDERS OF MAGNITUDE
- USE OF PREDISSOCIATED TRANSITIONS ELIMINATES PROBLEM WITH FLUORESCENCE YIELD DEPENDENCE ON PRESSURE AND SPECIES
- USE OF HIGH-REPETITION RATE EXCIMER LASER ENABLES STUDIES OF FLAME DYNAMICS

Fig. 1 Approach and results for digital imaging of O<sub>2</sub>.

Hanson, Lee & Paul/Stanford U.

molecules which have no strong, accessible one-photon absorption spectra. Our initial work has been directed toward CO, a species which is of interest both because it is a stable intermediate in combustion and because it can serve as a fuel in fundamental studies. Details of this work, including successful measurements in cold CO jets, CO diffusion flames, and CH<sub>4</sub>-air flames are given in paper 24.

We also can note some related preliminary work involving two-photon imaging of fuel vapor concentration. The scheme under study involves laser-induced photofragmentation of C<sub>2</sub>H<sub>2</sub> by a two-photon dissociative process (at  $\lambda = 193$  nm; ArF laser) which produces CH fluorescence. The CH emission is thus a marker for C<sub>2</sub>H<sub>2</sub>, which in turn indicates the location of unburned fuel. Further work is continuing on this promising new method, but initial results are described in paper 19.

Finally, on the subject of species imaging, we should note that we have collaborated on another AFOSR-sponsored project (Professor C. T. Bowman, Principal Investigator) by using our equipment to obtain sets of OH images in an acoustically forced diffusion flame. These results, together with streak recording of seeded TiO<sub>2</sub> particles, are reported in papers 24 and 25.

#### (b) Temperature Imaging

Temperature is a parameter of obvious importance in characterizing reacting flowfields, and hence a scheme for quantitative imaging of temperature has broad applications in combustion and plasma-related research. An ideal temperature visualization scheme would be sensitive, easy to calibrate, and would involve, for simplicity, only a single laser source. In other laboratories, laser-induced fluorescence (LIF) was shown to be suitable for single-point temperature measurements, and recently Svanberg et al. (Sweden) and Cattolica (Sandia) have extended LIF to multiple-point measurements. In each case, however, these workers employed two laser sources and, as a result, were only able to work in steady flames. The effort at Stanford has been directed toward establishing a temperature imaging method based on PLIF which requires the use of only one laser source.

We have investigated two schemes. The first scheme is applicable when the flow can be seeded uniformly with a uniform mole fraction of a non-reactive tracer species such as NO. The laser is then tuned to excite a molecular transition with a strong temperature-dependent Boltzmann fraction. The resulting fluorescence intensity, at each flowfield point, is proportional to this population fraction and hence can be readily converted to a local value for temperature. Results of our successful feasibility study, providing instantaneous temperature distributions in NO-seeded rod-stabilized premixed flames, were published last year (see paper 12).

Our most recent work to establish a temperature imaging method is based on laser-induced fluorescence of  $O_2$  using either a broadband or a tunable narrow-linewidth ArF laser. An example of the complex absorption spectrum which must be considered in devising an  $O_2$  temperature sensor is shown in Fig. 2 (from paper 15) for a temperature of 1000K. This computed spectrum is clearly quite dense and involves a large number of lines within the bandwidth of a typical ArF laser (shown with a dashed line). The pattern of lines changes rapidly with temperature, however, suggesting several possibilities for measuring temperature. The simplest approach, suitable when the  $O_2$  mole fraction is known, would be to monitor the total fluorescent emission resulting from broadband ArF excitation. A calculation of the temperature sensitivity expected with this approach is shown in Fig. 3 together with validating measurements (from paper 20). This method is quite promising in terms of signal strength and simplicity of implementation, for cases where the temperature exceeds about 800K. A feasibility demonstration of this approach, applied to a heated air jet is shown in Fig. 4. These are apparently the first LIF-based, instantaneous temperature images acquired in air. For cases with relatively low temperatures, a tunable narrow-linewidth ArF laser, Raman shifted to shorter wavelengths, would be attractive. For cases where the  $O_2$  mole fraction is unknown, it may be necessary to use two lasers to infer both  $O_2$  concentration and temperature. We plan to investigate these various strategies in the coming year.

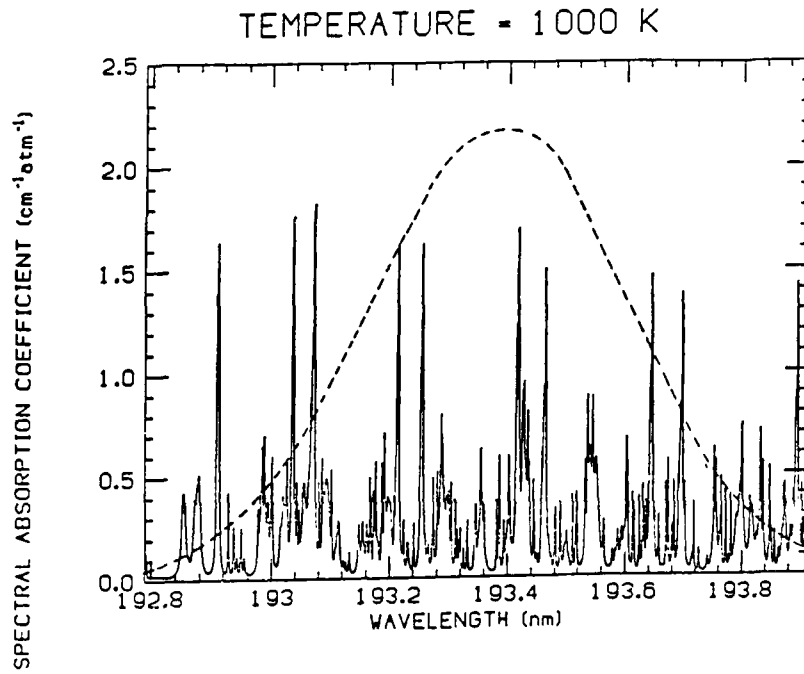


Fig. 2. Computed spectral absorption coefficient for  $O_2$  at 1000K in the vicinity of a broadband argon fluoride laser. The dashed line is a typical laser gain profile.

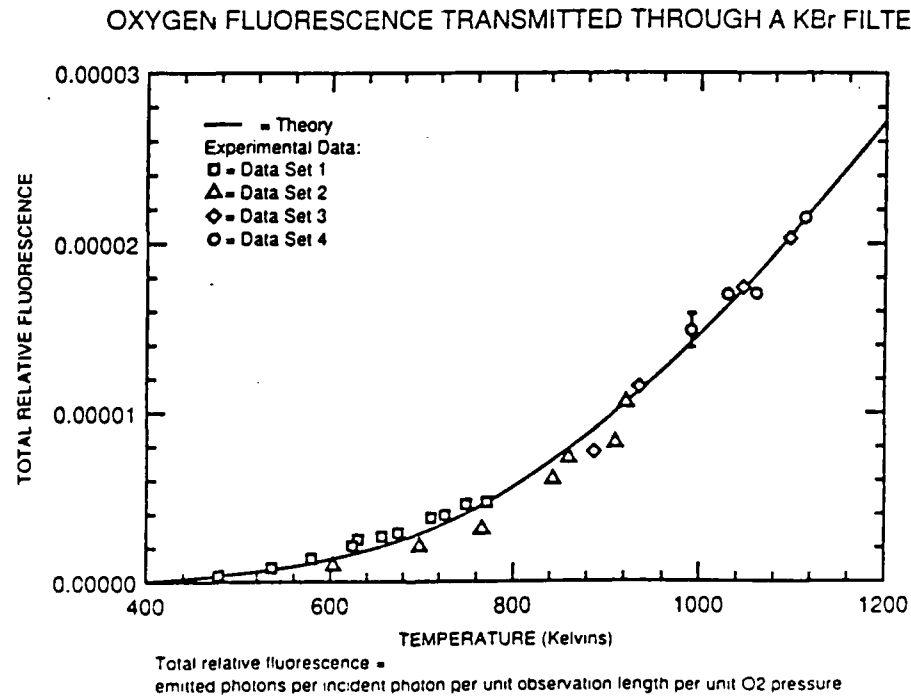
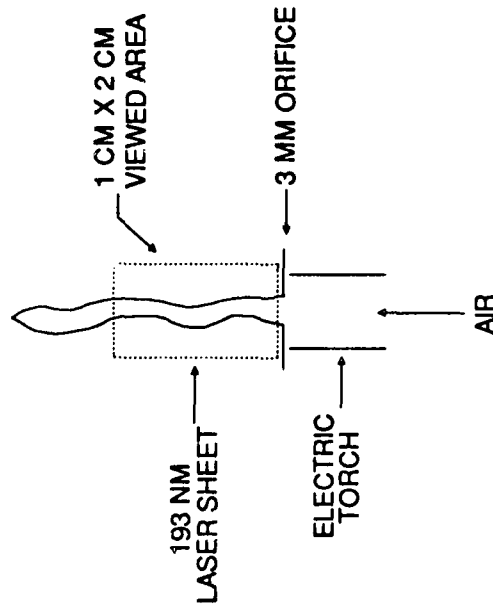


Fig. 3. Computed and measured  $O_2$  fluorescence intensity versus temperature for excitation by a broadband argon fluoride laser.

Fig. 4. QUANTITATIVE 2-D IMAGING OF TEMPERATURE FIELDS IN AIR USING PLIF OF  $O_2$

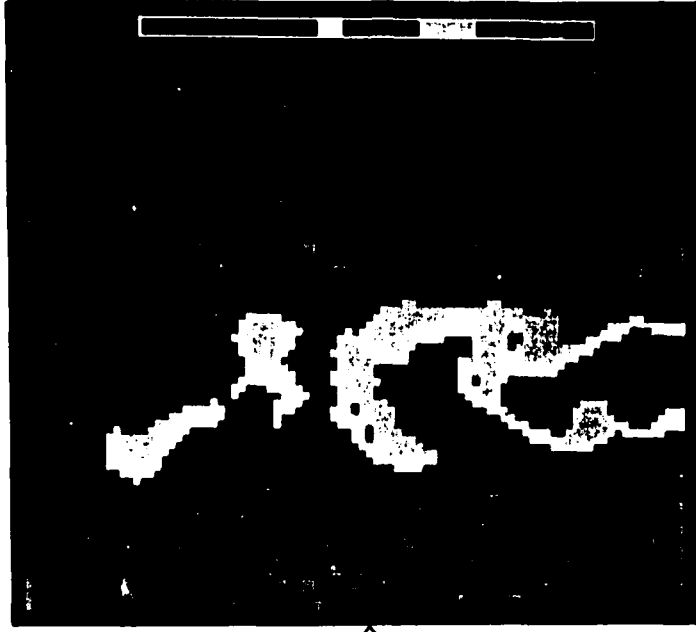
- EXCIMER LASER EXCITES UV FLUORESCENCE IN  $O_2$



SHEET EXCITATION  
(PULSED ArF LASER)

$\lambda = 193 \text{ nm}$ ,  $\tau = 10 \text{ nsec}$

BROADBAND DETECTION  
(100 X 100 ARRAY)



INSTANTANEOUS TEMPERATURE FIELD

- FIRST LIF-BASED INSTANTANEOUS SPATIALLY-RESOLVED 2-D TEMPERATURE IMAGES IN AIR
- NATURAL ABUNDANCE OF  $O_2$  ELIMINATES NEED FOR SEEDING
- THEORETICAL MODEL OF  $O_2$  FLUORESCENCE HAS BEEN VALIDATED

(c) Spray Flame Imaging

During the past two years we initiated work to establish PLIF and planar Mie scattering (PMS) techniques in evaporating and burning fuel sprays. We regard this combined development of PLIF and PMS as a logical extension of our past effort on digital flow imaging. Further, the development of such capability for measurements in two-phase flows is critical for studies in practical combustors and for fundamental research on droplet and solid propellant combustion. This work has been jointly sponsored by AFOSR and ONR.

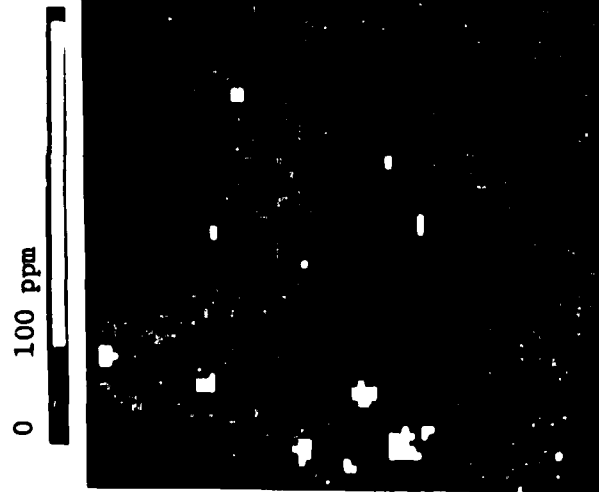
Thus far we have: (1) completed assembly of a small-scale spray combustion facility; (2) set up a laser sheet illumination arrangement and made preliminary photographic and digital imaging measurements of Mie scattering to characterize our spray flame; (3) performed Mie scattering calculations to aid in the interpretation of the PMS measurements; and (4) performed imaging experiments of OH, CH,  $C_2$  and  $C_2H_2$  in the spray burner facility. Initial results are reported in papers 16, 18 and 19 listed at the end of this section.

A schematic diagram of the approach and some representative instantaneous PLIF results for a burning spray are shown in Fig. 5. The fuel was n-heptane, flowing at a rate of about 0.2 gallons/hr from an air-atomizing siphon nozzle (Delevan). The size of the region imaged was about 8 cm x 8 cm for the OH image. The CH image is for a region about 1.2cm x 1.2cm located 6 cm above the nozzle at the top of the primary reaction zone. Very similar results have been obtained for  $C_2$ . To our knowledge, these are the first species images obtained in spray flames, and they offer exciting prospects for improving qualitative and quantitative understanding of spray flame combustion. If one views the flowfield as comprising zones of unburnt fuel, already burned gases, and instantaneous zones of reaction (flame fronts), then OH serves as a marker for burned gases and CH as a marker for the reaction zone.

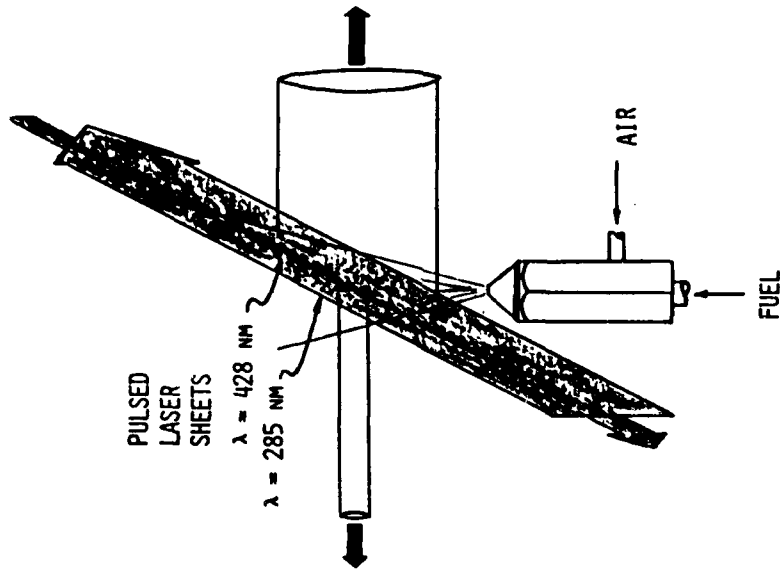
In order to complement these measurements with an image of zones containing unburned fuel, we have been exploring the use of ArF laser excitation which excites emission from  $CH^*$  ( $A \rightarrow X$ ) following two-photon

# DIGITAL IMAGING IN SPRAY FLAMES

PULSED SHEET ILLUMINATION YIELDS INSTANTANEOUS IMAGES OF MULTIPLE GASEOUS SPECIES



Digital Image of CH + Fuel Droplets  
in Heptane-Air Flame  
(1.2 cm x 1.2 cm)



Technique:  
Planar Laser-Induced Fluorescence



Digital Image of OH in  
Heptane-Air Flame  
(8 cm x 8 cm)

- FIRST 2-D SPECIES IMAGES IN SPRAY FLAME
- POTENTIAL FOR SIMULTANEOUS IMAGING OF SPECIES AND DROPLET SIZE FIELDS

Fig. 5 Approach and sample results for 2-d digital imaging of species in spray flames.

fragmentation of  $C_2H_2$ . The  $C_2H_2$  is a primary pyrolysis product of hydrocarbon fuels and thus serves as a convenient marker of high-temperature, fuel-rich zones in spray or gaseous hydrocarbon fuel flames. Our present research is aimed at developing a more complete understanding of this new photofragmentation variation of PLIF and at establishing the capability for simultaneous imaging of multiple species. The latter is critically needed to guide interpretation of the imaging results in terms of reasonable spray flame models.

The laser source for the OH and CH imaging was a Nd:YAG-pumped dye laser providing 10 nsec, 20mJ bursts of tunable radiation near 285 nm and 431 nm respectively. The ArF laser, used to excite  $C_2H_2$ , typically provided 200 mJ/pulse at 193nm. Pulsed illumination, freezing the flow for PMS imaging of the spray, was provided by the same Nd:YAG-pumped dye laser operating near 590 nm. Preliminary PMS results, proving feasibility, were given in previous progress reports (and paper 14).

The significance of this work is that it has confirmed the feasibility of both PLIF and PMS recording in spray flames. With regard to PMS imaging for characterizing the spray, it should be noted that the droplet spacing (and hence density) is derived immediately from the locations of illuminated pixels. The next step will be to demonstrate that the intensity of scattered light, imaged onto a single pixel, can be used to infer the size of the droplet imaged, and work to investigate this possibility is now in progress. Our goal is to establish the capability for simultaneous PMS droplet characterization and PLIF measurements of key species and temperature in burning sprays.

#### (d) System Improvements

A major activity during the past three years has been assembly of two second-generation solid-state camera systems and a facility for processing image data. In our early work on digital imaging we were forced to design and assemble a one-of-a-kind intensified camera and display system, using components drawn from a number of commercial sources and solving a number of interfacing and software problems on our own. This system was suitable for demonstrating feasibility of PLIF imaging in a variety of reacting

flows, but it also had several deficiencies and was not well suited for adoption by user-oriented researchers interested in acquiring similar capability. With the award of a DOD equipment grant for 1984/85, we were able to begin to upgrade our system and to capitalize on the improved performance, availability and compatibility of commercial sub-systems.

Our current image processing facility is based on a VAX-750 computer and a SUN-3/160C graphics work station, both of which are housed in the computer center of the High Temperature Gasdynamics Laboratory (HTGL) at Stanford. We now operate three camera systems, located in separate laboratory rooms, and linked to the VAX and SUN systems via an Ethernet. The VAX-750 will also eventually be linked via Stanford's own network (S.U. Net) to other computers and image processing facilities on campus. In past reports we've discussed in some detail the characteristics of these cameras and computers and presented arguments for the specific items selected. Here we focus on the status of the camera systems.

Our goals for the new solid-state cameras were to improve performance and ease of operation. Key performance parameters are noise level, spatial resolution and repetition (framing) rate. We opted for two separate systems, one with low noise and high spatial resolution, and one with programmable framing rate capability. (We call the former the High Resolution/High Dynamic Range System and the latter the Programmable High Speed System.) The virtues of the low noise system are evident in Fig. 6 which plots signal-to-noise ratio versus input photons per pixel (i.e., the "signal") for five separate arrays: intensified and unintensified Reticon arrays [(100 x 100) or (128 x 128)]; two cooled CCD arrays (Thomson, 384 x 576), one with a standard amplifier and one with a special low-noise amplifier; and a commercially available, high-framing-rate solid-state camera sold by Spin-Physics. The dashed line is the theoretical performance limit set by shot noise statistics. The right-hand boundary of the curves (at  $2.5 \times 10^5$  photons/pixel for the Reticon array and  $1.0 \times 10^6$  for the Thomson CCD array) are saturation levels beyond which the system becomes nonlinear.

We see that the High Resolution/High Dynamic Range System (based on the Thomson CCD with a "standard" amplifier) offers superior S/N over the Programmable High Speed System (based on an intensified Reticon 128 x 128)

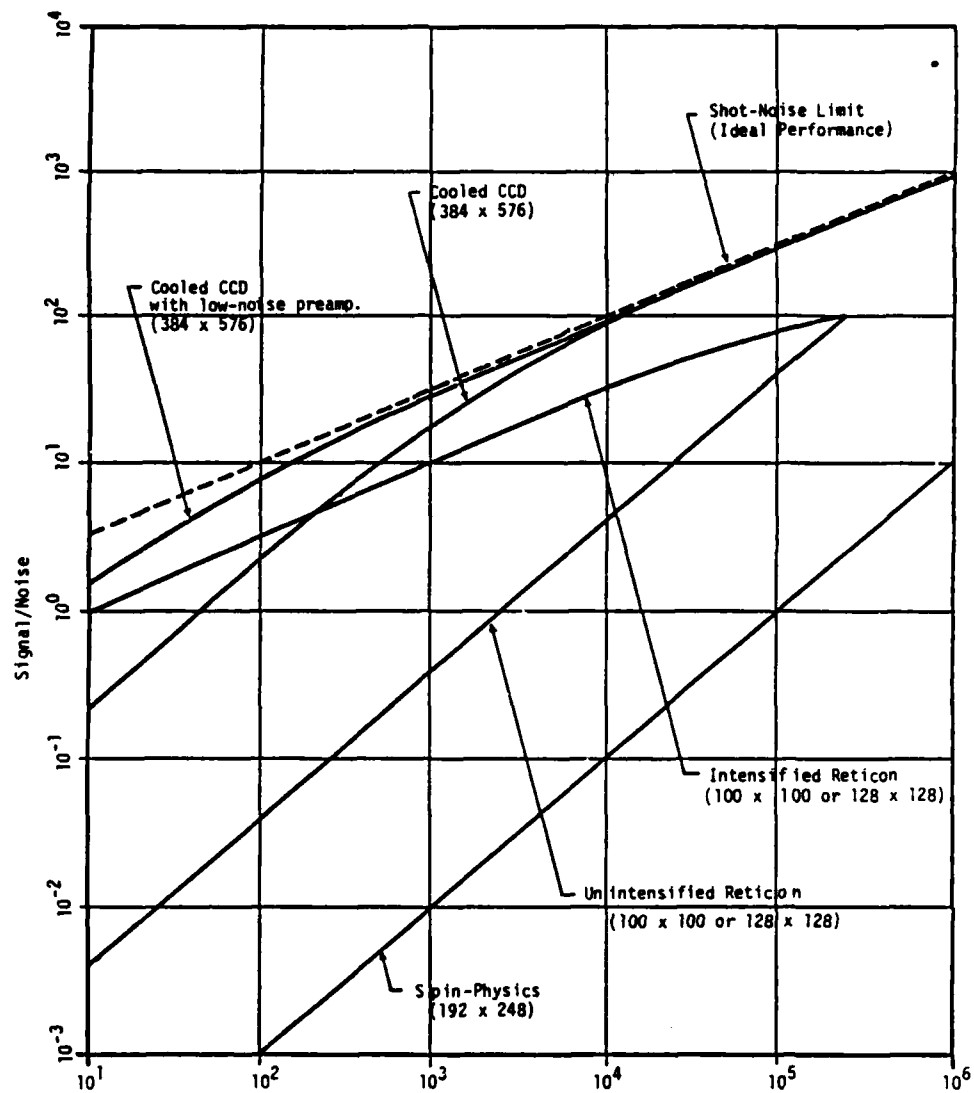


Fig. 6. Signal/noise ratio versus illumination (in photons/pixel) for four array cameras.

for light levels above 200 photons per pixel. The curves plotted are a reminder that if we seek a high S/N to enable detection of small changes in flowfield properties, it will be necessary to perform experiments with light levels near their saturation values. At saturation, the cooled CCD will yield a maximum S/N of 1000 while the intensified Reticon and Spin-Physics cameras are limited to about 100, with the Spin-Physics camera requiring a substantially higher illumination level to reach its maximum S/N. We regard the improved performance of the Hi Res/Hi Dynamic Range System as critical for many experiments, for example in turbulence studies where it may be essential to detect small changes in signal level. As can be seen in Fig. 6, the CCD system equipped with a custom low-noise

amplifier actually outperforms the intensified Reticon at all light levels, and it is unintensified, which offers significant cost and operational advantages. The Spin-Physics system is seen to have consistently inferior performance over the illumination level range of interest. The CCD array cryogenics system and camera controller were purchased as a packaged system from Photometrics and were interfaced with an IBM PC/AT computer in our laboratory.

In addition to the S/N advantages of the CCD system, the array architecture and camera controller appear to offer important advantages for analog processing (averaging) of pixel groups, and "scrolling" and "tracking" of data between exposed and unexposed pixels for fast, burst-mode recording of multiple exposures on a single frame. In this mode of operation, the array acts much like a roll of electronic film capable of storing several images. (Actually, the architecture is a double array,  $384 \times 576 + 384 \times 576$ , which provides capacity for "buffer" storage of data.) In contrasting this CCD-based system to an intensified Reticon system the primary disadvantages are: the need to interface the CCD camera to its dedicated microcomputer, since a packaged system is not available commercially; the lack of ultraviolet sensitivity with this CCD detector; and the low framing rate ( $\sim 10$  sec/frame) required to achieve ultra-low-noise performance with the CCD system.

Our decision to proceed in parallel with a programmable high-speed intensified Reticon camera ( $128 \times 128$ ) was based in part on our previous experience with such an array and the improved availability of packaged system components from Microtex, a vendor which has produced buffer memory and camera controller system components for us in the past. The system components acquired from Microtex are similar to those now on order by (or delivered to) other groups at Volvo, UTRC, GM Research Labs and Yale University, and will enable programmable trade-offs between framing rate and the number of pixels up to a rate of 2 kHz. This system is now operational except for the intensifier. Although we tried to utilize a lens-coupled intensifier to allow greater modularity of system components, the optical transfer efficiency has been found to be significantly inferior to

that achievable with fiber optic coupling of the intensifier and the detector array. Thus we've ordered a new array with a bonded fiber optic bundle. We expect delivery in February 1987, in which case the system should be fully operational by May of next year.

Example results from recent tests which illustrate the improved dynamic range and spatial resolution of the 384 x 576 Thomson array are shown in Fig. 7. In this application the high-resolution array is used to record the mixture fraction of jet fluid for the case of a turbulent jet. The single-shot (10 nsec) image is for the central plane above the jet, and the tracer used is biacetyl which absorbs conveniently at 351 nm (XeFl laser) and fluoresces in the visible. The interference-pattern appearance results from dividing the total signal range into several sub-ranges, each represented by the same set of colors. For simple flowfields this is a convenient way to display signals with a large range.

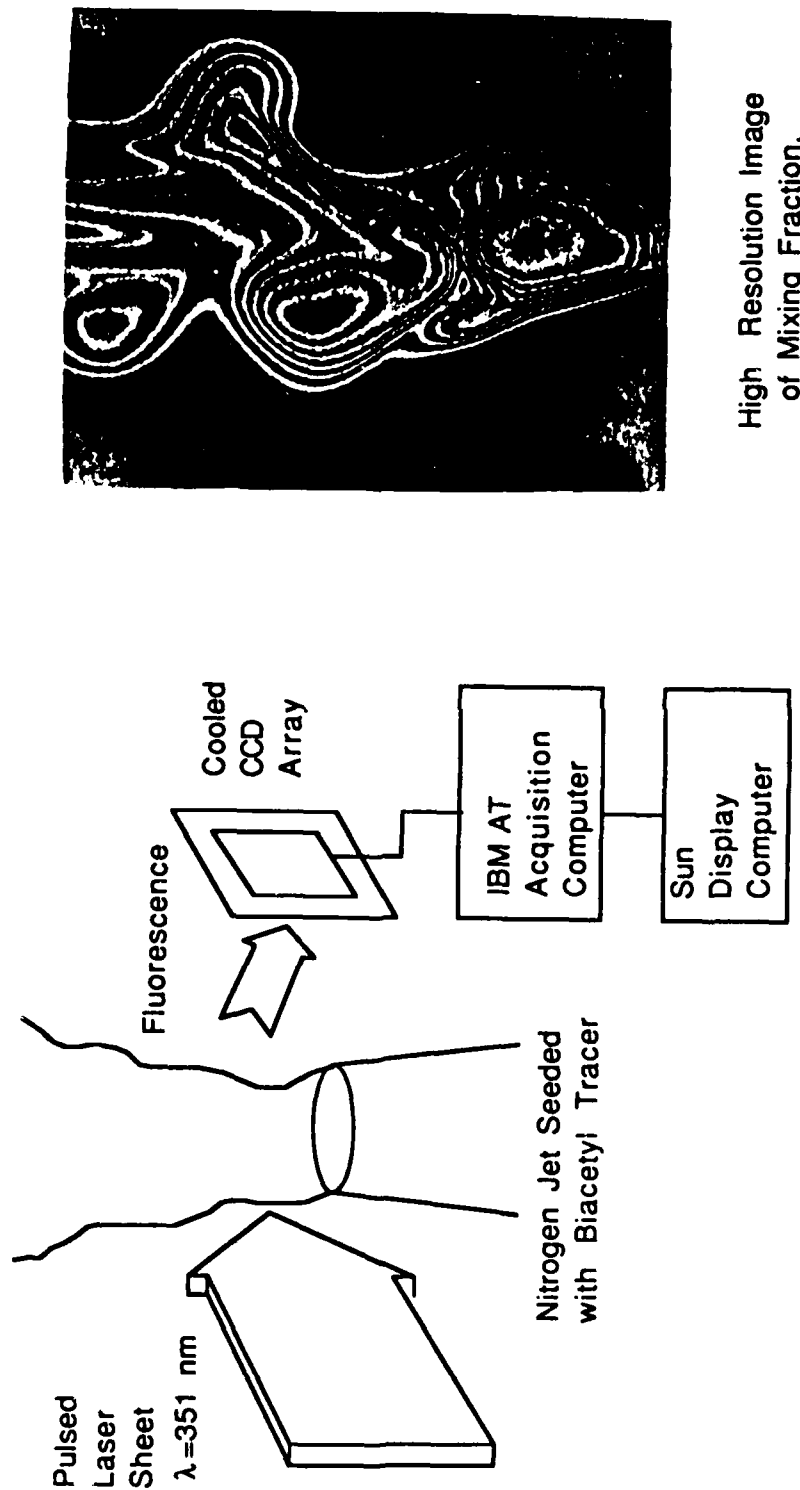
(e) 3-d Imaging

A recent extension of our work has been to record multiple planes of data, thereby generating the 3-d distribution of the imaged quantity. Thus far we have focussed on steady or repetitive flowfields, which permit slow scan rates for the illumination plane and the camera, but we have plans to increase the recording rate to allow essentially instantaneous recording of complete 3-d distributions. An example of our initial work on 3-d imaging, for the case of a biacetyl-seeded, axially forced jet, is displayed in Fig. 8. The display used is known as a "cube display," in which the data stored along three orthogonal planes are shown on the three visible faces of the cube. The positions of the planes, indicated by the white cursor lines on the cube faces, are readily manipulated using the SUN work station and software developed at Stanford (Geophysics Department). Rapid scanning of the displayed planes is also possible, providing the viewer with a sense of three dimensionality. Future work with 3-d imaging involves extending measurements to other flows and variables (e.g.,  $O_2$  concentration and temperature) and to increasing the recording rate.

Fig. 7. Planar fluorescence imaging using a high-resolution (576 x 384 pixels) CCD camera.

### High Resolution Digital Flowfield Imaging

- First use of High Resolution Array (576 x 384 pixels) for Planar Laser Induced Fluorescence.



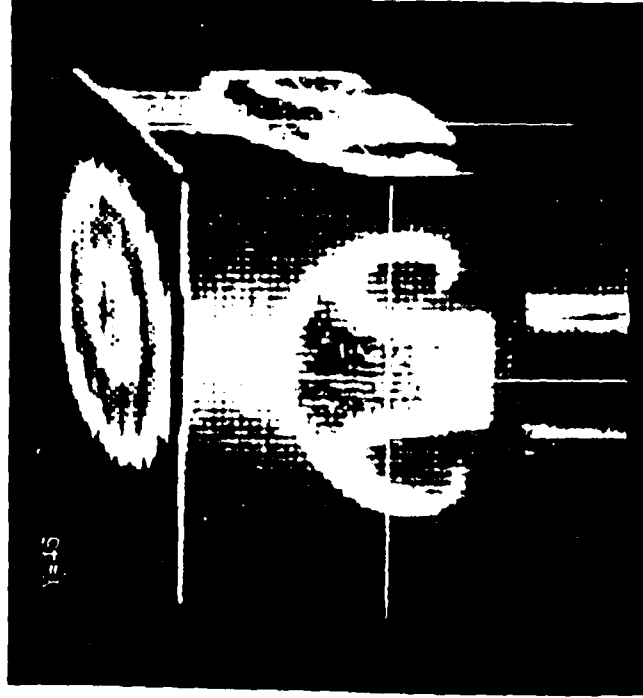
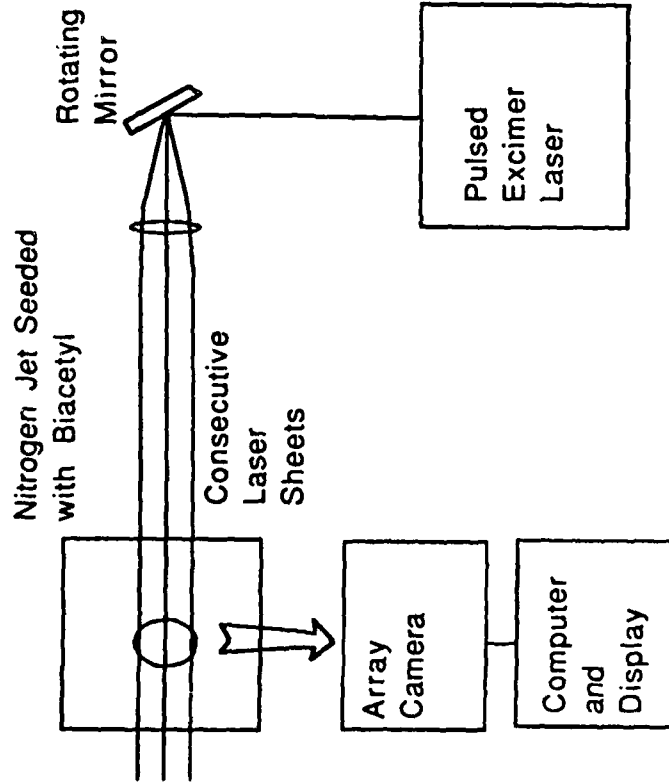
High Resolution Image  
of Mixing Fraction.

- Cryogenically cooled CCD array increases dynamic range by factor forty over present cameras.
- Improved data will enable determination of spatial derivatives, correlations, and scale sizes.
- Enables research on electronic film imaging ( rapid multi-image accumulation on a single frame).

Fig. 8. Three-dimensional fluorescence imaging and cube display of 3-d data.

### Three Dimensional Digital Flowfield Imaging

- First 3-D fluorescence imaging in gases



Cube Display of 3-D Data  
(240,000 pixels)

- Large data sets ( up to 20 megapixels ) provide thorough description of flowfield.
- Eliminates ambiguities associated with interpreting 2-D data sets.
- Allows determination of directional information of gradients and correlations.
- Gives quantitative data on asymmetries of flowfield structures.

## Publications and Presentations

### Presentations

1. G. Kychakoff, K. Knapp, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization in Combustion Gases", paper No. 82-60, presented at Fall 1982 meeting, Western States Section/The Combustion Institute, Livermore, CA. (October 1982).
2. G. Kychakoff, R.D. Howe, R. K. Hanson and K. Knapp, "Flow Visualization in Combustion Gases," paper 83-0405, presented at AIAA 21st Aerospace Sciences Meeting, Reno (January 1983).
3. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for the Study of Combustion Flowfields," paper 83-1361, presented at 19th Joint Propulsion Conference, Seattle (June 1983).
4. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for Combustion Measurements," presented at CLEO '83, Baltimore (May 1983)
5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization Technique for Measurements in Combustion Gases," presented at the Ninth International Colloquium on the Dynamics of Explosions and Reactive Flows, Poitier, France (July 1983).
6. J.C. McDaniel and R.K. Hanson, "Quantitative Visualization of Flowfields Using Planar Laser-Induced Fluorescence," presented at International Flow Visualization Symposium, Michigan (September 1983).
7. R.K. Hanson, C. Kychakoff, E.C. Rea, Jr., B. Hiller, R.D. Howe and M.A. Kimball-Linne, "Advanced Diagnostics for Reacting Flows," presented at 20th JANNAF Combustion Meeting, Monterey, CA., October 1983.
8. R.K. Hanson, "Tunable Laser Absorption and Fluorescence Techniques for Combustion Research," invited paper presented at fall meeting of the APS, San Francisco, Nov. 21-23, 1983.
9. J.M. Seitzman, G. Kychakoff and R.K. Hanson, "Temperature Field Measurements in Combustion Gases Using Planar Laser-Induced Fluorescence," paper WF3 at CLEO '84, Anaheim, June 19-22, 1984.
10. J.M. Seitzman, G. Kychakoff and R.K. Hanson, "Temperature Field Measurements in Combustion Gases Using Planar Laser-Induced Fluorescence," paper 84-66 at Western States Section/The Combustion Institute, Stanford, Oct. 22-23, 1984.
11. R.K. Hanson, "Optical Imaging and Combustion Measurements," invited paper presented at Lasers '84, Symposium on Optical Imaging of Fluids, San Francisco, Nov. 26-30, 1984.

12. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," invited paper presented at ICALEO '84, Laser Diagnostics and Photochemistry Symposium, Boston, Nov. 12-15, 1984.
13. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," invited paper presented at Winter Annual Meeting of ASME, New Orleans, Dec. 9-14, 1984.
14. R.K. Hanson, "Current Trends in Imaging Diagnostics for Gaseous Flows," invited paper TUH3 presented at CLEO '85, Baltimore, May 21-24, 1985.
15. R.K. Hanson, J.M. Seitzman, J. Jaumann, M.P. Lee and P.H. Paul, "Laser Fluorescence Imaging Diagnostics for Gaseous Flows," paper WG3 at Lasers '85, Las Vegas, Dec. 2-6, 1985.
16. M.P. Lee, P.H. Paul and R.K. Hanson, "Laser Fluorescence Imaging of  $O_2$  in Combustion Flows Using an ArF Laser," paper WSS/CI 85-15 at Western States Section/Combustion Institute meeting, U.C. Davis, CA, Oct. 1985.
17. M.G. Allen and R.K. Hanson, "Digital Imaging in Spray Flames," paper WSS/CI 85-13 at Western States Section/Combustion Institute meeting, U.C. Davis, Davis, CA, Oct. 1985.
18. R.K. Hanson, J.M. Seitzman, J. Haumann, M.P. Lee and P.H. Paul, "Laser Fluorescence Imaging Diagnostics for Gaseous Flows," paper WG3 at Lasers '85, Las Vegas, Dec. 2-6, 1985.
19. R.K. Hanson, "Laser Fluorescence Imaging of Reacting Flows," invited Chemistry Colloquium speaker, Naval Research Laboratory, Washington, Dec. 12, 1985.
20. R.K. Hanson, "Laser Fluorescence Imaging in Spray Flames," invited speaker, General Motors Research Lab Colloquium, Warren, MI., Dec. 13, 1985.
21. G. Kychakoff and R.K. Hanson, "Digital Flowfield Imaging," presented at International Workshop on Physics and Engineering of Computerized Multidimensional Imaging and Processing, Newport Beach, April 2-4, 1986.
22. P. H. Paul, M. P. Lee and R. K. Hanson, "Laser Fluorescence Imaging of Temperature Fields in Air," paper TUK 37 at CLEO '86, San Francisco, June 9-13, 1986.
23. M. G. Allen and R. K. Hanson, "Species Imaging in Spray Flames," paper TUK 38 at CLEO '86, San Francisco, June 9-13, 1986.
24. R. K. Hanson, "Fluorescence Spectroscopy and Planar Imaging," presented at Penner Spectroscopy Symposium, La Jolla, July 1986.

25. R. K. Hanson, "Combustion Diagnostics: Planar Flowfield Imaging," presented at the Twenty-First Symposium (International) on Combustion, Munich, Aug. 1986.
26. M. G. Allen and R. K. Hanson, "Digital Imaging of Species Concentration Fields in Spray Flames," presented at the Twenty-First Symposium (International) on Combustion, Munich, Aug. 1986.
27. G. Kychakoff, P. H. Paul, I. van Cruyningen and R. K. Hanson, "High-Resolution and Three-Dimensional Digital Imaging of Jets," paper WSS/CI 86-15 at fall meeting of Western States Section, The Combustion Institute, Tucson, Oct. 27-28, 1986.
28. U. Vandsburger, G. Lewis, M. G. Allen, J. M. Seitzman, C. T. Bowman and R. K. Hanson, "Flame-Flow Structure in an Acoustically Driven Jet Flame," paper WSS/CI 86-19 at fall meeting of Western States Section, The Combustion Institute, Tucson, Oct. 27-28, 1986.
29. M. G. Allen and R. K. Hanson, "Simultaneous Imaging of Species Distributions in Two-Phase Reacting Flowfields," presented at Int. Laser Science Conference 1986, Seattle, Oct. 1986.
30. R. K. Hanson, "Multipoint Flow Diagnostics," to be presented at ICALEO '86, Arlington, VA, Nov. 10-13, 1986.
31. R. K. Hanson, "Multipoint Flow Diagnostics," invited lecture at NBS, Gaithersburg, Nov. 10, 1986.
32. R. K. Hanson, "Multipoint Flow Diagnostics: Fluorescence Imaging," invited seminar at UTRC, East Hartford, Nov. 12, 1986.

### Publications

1. G. Kychakoff, R. D. Howe, R. K. Hanson and J. C. McDaniel, "Quantitative Visualization of Combustion Species in a Plane," *Applied Optics* 21, 3225 (1982).
2. G. Kychakoff, R.D. Howe, R.K. Hanson and K. Knapp, "Quantitative Visualization in Combustion Gases," AIAA Reprint 83-0405, 21st Aerospace Sciences Meeting, Reno, Jan. 10-13, 1983.
3. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for the Study of Combustion Flowfields," AIAA Reprint 83-1361, 19th Propulsion Conference, Seattle, June 27-29, 1983.
4. R.K. Hanson, G. Kychakoff, E.C. Rea, Jr., B. Hiller, R.D. Howe and M.A. Kimball-Linne, "Advanced Diagnostics for Reacting Flows," in Proceedings of 20th JANNAF Combustion Meeting, Monterey, CA., October 1983.

5. J.C. McDaniel and R.K. Hanson, "Quantitative Visualization of Flowfields Using Laser-Induced Fluorescence," in Proceedings of 3rd International Flow Visualization Symposium, Univ. of Michigan, pp. 113-117, 1983.
6. G. Kychakoff, K. Knapp, R. D. Howe and R. K. Hanson, "Flow Visualization in Combustion Gases Using Nitric Oxide Fluorescence," AIAA J. 22, 153 (1984).
7. G. Kychakoff, R. D. Howe, R. K. Hanson, M. Drake, R. Pitz, M. Lapp, and M. Penney, "The Visualization of Turbulent Flame Fronts," Science 224, 382-384 (April 1984 issue; cover article).
8. G. Kychakoff, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization Technique for Measurements in Combustion Gases," Applied Optics 23, 704-712 (1984).
9. G. Kychakoff, R.K. Hanson and R.D. Howe, "Simultaneous Multiple-Point Measurements of OH in Combustion Gases Using Planar Laser-Induced Fluorescence," 20th Symposium (International) on Combustion, The Combustion Institute, pp. 1265-1272, 1984.
10. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," Amer. Soc. Mech. Eng. AMD-Vol. 66, pp. 1-10, 1984.
11. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," L.I.A. (Laser Institute of America) Vol. 47 ICALEO (1984), pp. 98-106.
12. J.M. Seitzman, G. Kychakoff and R.K. Hanson, "Instantaneous Temperature Field Measurements Using Laser-Induced Fluorescence," Optics Letters 10, 439 (1985).
13. M.P. Lee, P.H. Paul and R.K. Hanson, "Laser Fluorescence Imaging of  $O_2$  in Combustion Flows Using an ArF Laser," paper WSS/CI 85-15 at Western States Section/Combustion Institute meeting, U.C. Davis, CA, Oct. 1985.
14. M.G. Allen and R.K. Hanson, "Digital Imaging in Spray Flames," paper WSS/CI 85-13 at Western States Section/Combustion Institute meeting, U.C. Davis, Davis, CA, Oct. 1985.
15. M.P. Lee, P.H. Paul and R.K. Hanson, "Laser Fluorescence Imaging of  $O_2$  in Combustion Flows Using an ArF Laser," Optics Letters 11, 7 (1986).<sup>2</sup>
16. M.G. Allen, R.D. Howe and R.K. Hanson, "Digital Imaging of Reaction Zones in Hydrocarbon-Air Flames using Planar Laser-Induced Fluorescence of CH and  $C_2$ ," Optics Letters 11, 126-128 (1986).

17. M.P. Lee and R.K. Hanson, "Calculations of  $O_2$  Absorption and Fluorescence at Elevated Temperatures for a Broadband Argon Fluoride Laser Source at 193 nm," Jour. Quant. Spectrosc. and Radiat. Transfer, in press.
18. M.G. Allen and R.K. Hanson, "Planar Laser-Induced Fluorescence Monitoring of OH in a Spray Flame," Optical Engineering, in press.
19. M.G. Allen and R.K. Hanson, "Digital Imaging of Species Concentration Fields in Spray Flames," 21st Symposium (International) on Combustion, The Combustion Institute, in press.
20. M. P. Lee, P. H. Paul and R. K. Hanson, "Quantitative Imaging of Temperature Fields in Air Using Planar Laser-Induced Fluorescence of  $O_2$ ," Optics Letters, submitted August 1986.
21. R. K. Hanson, "Combustion Diagnostics: Planar Flowfield Imaging," Twenty-First Symposium (International) on Combustion, The Combustion Institute, in press.
22. G. Kychakoff and R. K. Hanson, "Digital Flowfield Imaging," Proc. of International Meeting on Physics and Engineering in Computerized Multidimensional Imaging and Processing, in press.
23. G. Kychakoff, P. H. Paul, I. van Cruyningen and R. K. Hanson, "High-Resolution and Three-Dimensional Digital Imaging of Jets," paper WSS/CI 86-15 at fall meeting of Western States Section, The Combustion Institute, Tucson, Oct. 27-28, 1986.
24. J. Haumann, J. M. Seitzman and R. K. Hanson, "Two-Photon Digital Imaging of CO in Combustion Flows Using Planar Laser-Induced Fluorescence," Optics Letters, in press.
25. R. K. Hanson, "Fluorescence Spectroscopy and Planar Imaging," J. Quant. Spectrosc. and Radiat. Trans., submitted Sept. 1986.
26. U. Vandsburger, G. Lewis, M. G. Allen, J. M. Seitzman, C. T. Bowman and R. K. Hanson, "Flame-Flow Structure in an Acoustically Driven Jet Flame," paper WSS/CI 86-19 at fall meeting of Western States Section, The Combustion Institute, Tucson, Oct. 27-28, 1986.
27. C. T. Bowman, R. K. Hanson, U. Vandsburger, M. G. Allen and K. R. McManus, "Effects of Fuel-Spray Characteristics and Vaporization on Energy Release Rates and Flow Field Structure in a Dump Combustor," Proceedings of 23rd JANNAF Combustion Meeting, Johns Hopkins Univ., Oct. 1986.

## Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
George Kychakoff	Assistant Professor (Acting), Mechanical Engineering (Ph.D., March 1985)
Phillip Paul	Research Associate, Mechanical Engineering
Mark Allen	Graduate Student, Mechanical Engineering (Ph.D. expected in March 1987)
Mike Lee	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1988)
David Hofeldt	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1989)
Ike van Cruyningen	Graduate Student, Mechanical Engineering (Ph.D. Expected in June 1989)

## 2.2 Velocity and Pressure Imaging

### Introduction

Velocity measurements provide essential input for many fundamental and applied fluid mechanics studies. At present, hot wire anemometry and laser Doppler anemometry are the most commonly used techniques. Both methods have advantages and disadvantages, but in particular they are single-point diagnostics. Clearly, a technique yielding simultaneous multiple-point velocity data would represent a significant diagnostics contribution and could stimulate important advances in many areas involving fluid flow.

Our effort in this area was prompted in part by our success in imaging species at multiple points in a flow (see Section 2.1) and the growing recognition that combinations of flowfield quantities (e.g., species, temperature and velocity) may eventually be needed to test advanced flow

models. Accordingly, in 1982 we initiated an effort to "image velocity", i.e. to measure velocity at a large number of spatially resolved flowfield points leading to a computer display of velocity. Recently, within the past two years, we have conceived three important improvements in our velocity imaging scheme: one idea enables simultaneous imaging of pressure, with great significance for supersonic flow studies; the second idea involves inference of the vorticity field from the velocity data; and the third idea concerns the possible use of  $O_2$  as the molecular velocity indicator, thereby eliminating the need to use corrosive or toxic tracer species. We continue to believe that this general area of research holds still-untapped promise for diagnostics advances.

### **Scientific Merit**

The importance of velocity as a fluid flow parameter is obvious, and so innovation of an improved velocity diagnostic offers broad potential for improved scientific understanding of fluid flows. A successful diagnostic for combined imaging measurements of velocity, pressure and vorticity would represent a sufficiently large advance in measurement capability as to enable first-time observations of various flow phenomena and possible discovery of unexpected features. With respect to uniqueness, these techniques have been pioneered at Stanford, and quantitative imaging of velocity, pressure and vorticity have not yet been demonstrated elsewhere.

The concept receiving our primary attention, which is based on the velocity modulation (Doppler shift) of molecular absorption lines, offers prospects for a significant improvement over conventional laser Doppler (particle seeding) anemometry for supersonic flows, low-density flows, flows near surfaces (boundary layers) and flows with high acceleration or deceleration where particle lag is a serious problem. Extension of our velocity imaging concept to  $O_2$  would be a significant scientific achievement, owing both to the scientific challenges which must be overcome and to the large increase in the utility of velocity imaging which would result.

## Status Report

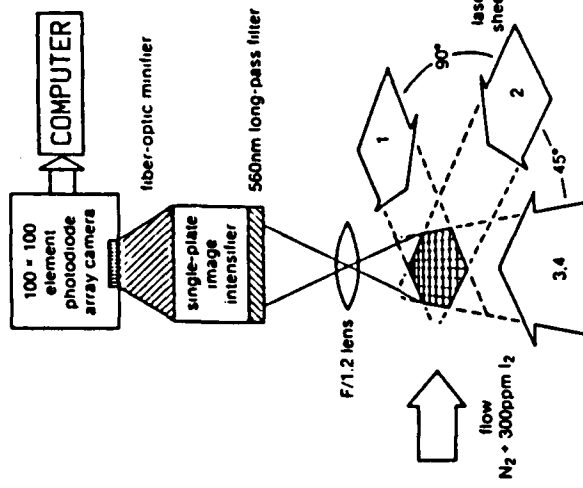
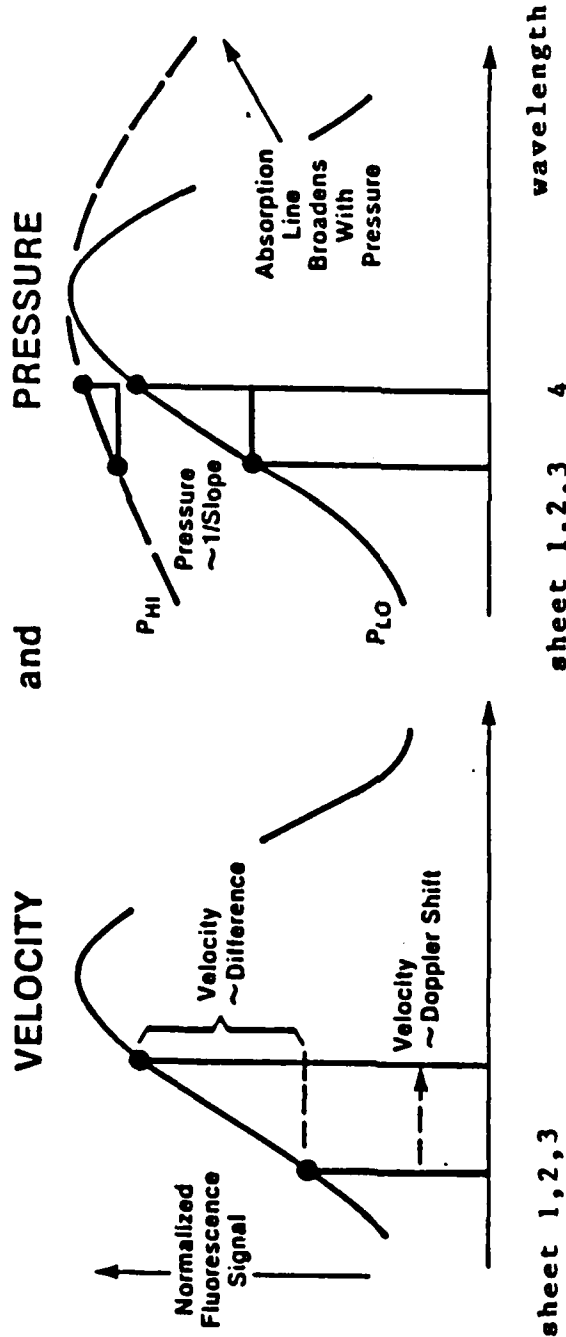
During the past four years, work has proceeded on two separate approaches. The first method, for which work has now been completed, involves "marking" specific elements of the flow using laser-excited phosphorescence of biacetyl vapor. Subsequent motion of the marked elements is observed on our intensified photodiode array. A variation of this scheme involving laser-induced formation of sulfur particulates (which can be tracked by Mie scattering) has also been investigated. Both of these projects are now completed and have been described fully in publications (see papers 3, 6 and 8 in list below) and so will not be discussed further here.

Our second scheme, and the one which we believe has the greatest promise, is based on the Doppler effect and involves imaging the broadband fluorescence from a sheet-illuminated flow using a solid-state array detector. Sketches of the experimental arrangement and the physical principle of the measurements are shown in Fig. 1. (Note that the numbering of figures is separate for each section of this report.) The flow is seeded with a tracer species and a narrow-linewidth cw laser source is used to excite a specific wavelength within a single absorption line of the tracer species. The fluorescence from a given flowfield point mirrors the absorption occurring there, which for a uniformly seeded flow may depend primarily on the position of the laser wavelength within the absorption lineshape. Since the apparent laser frequency shifts with fluid velocity due to the Doppler effect, the amount of absorption (and hence fluorescence) is a measure of velocity. Iodine ( $I_2$ ) vapor has been used in the work thus far (because it conveniently absorbs the light at visible wavelengths of tunable  $Ar^+$  and cw dye lasers), although the method is quite general and we have hopes of extending our work to  $O_2$  (see below). Velocity measurements in  $I_2$ -seeded, low temperature flows have now been demonstrated for both supersonic and subsonic cases, using somewhat different procedures. Details of the apparatus, procedures and results are available in publications 1, 2, 4, 5, 7 and 10 cited below.

In our initial work, we utilized a single laser frequency and two angles of illumination (to determine two independent velocity components), but recently we have implemented important improvements based on three

# Combined 2-D Velocity and Pressure Measurements

## Physical Principle For Simultaneously Measuring



- Two-wavelength technique is self-calibrating
- No particle seeding required
- Fast data processing; prospective technique for real-time monitor
- Potential for combined velocity, pressure and temperature measurements

Fig. 1 Approach for velocity and pressure imaging technique

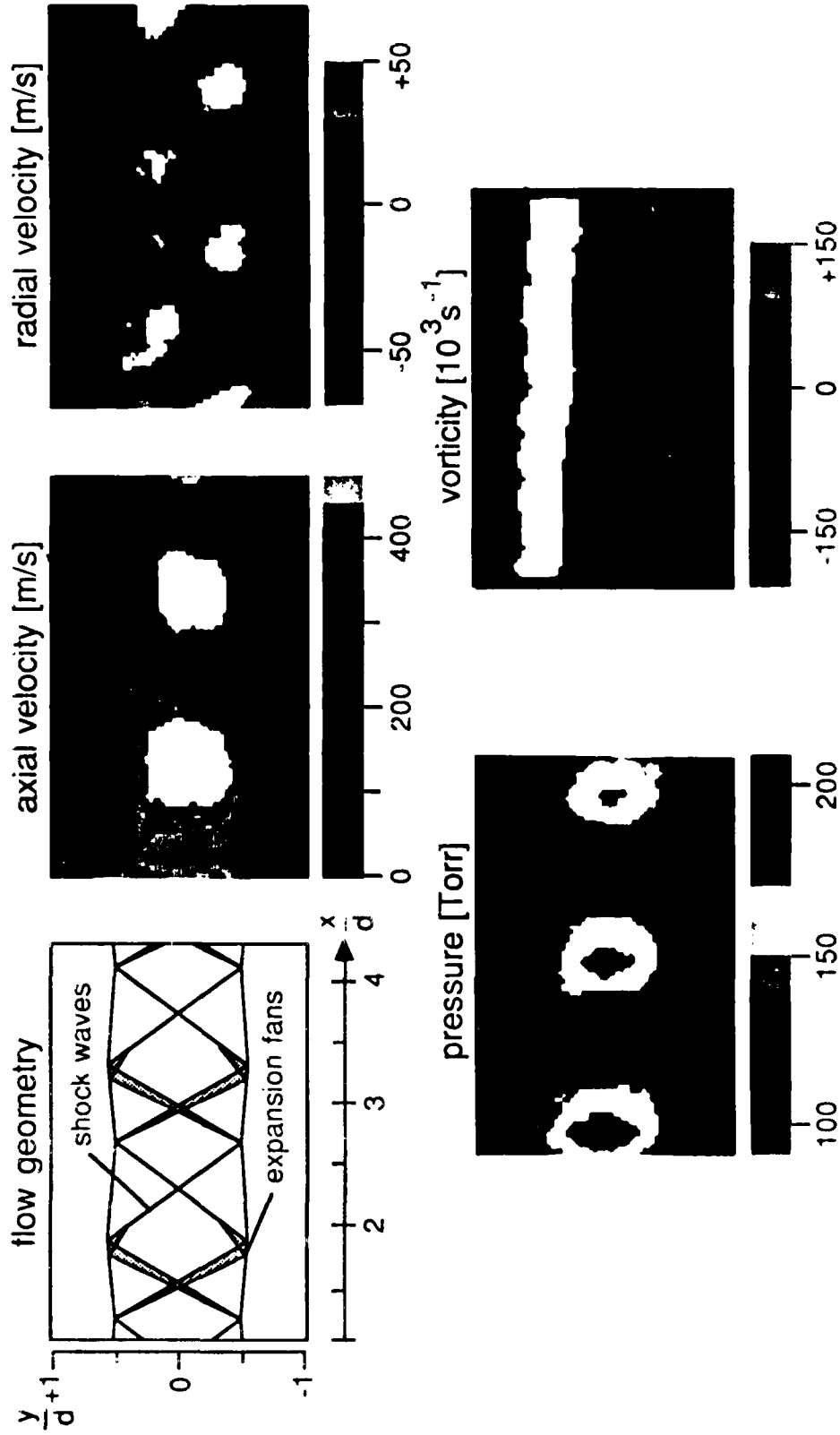
angles and two laser frequencies (see Fig. 1). In brief, we utilize an acousto-optic device or an intra-cavity piezo-driven etalon to convert the single-mode  $\text{Ar}^+$  laser output to two discrete laser frequencies separated by 100-800MHz. With this scheme, simple combinations of signals from the three directions lead directly to the velocity component for each angle. This scheme is self-calibrating and eliminates the previous requirement to know (by external calibrations) the absorption lineshape function. Of at least equal importance, this new scheme also yields a value for the slope of the absorption line, which can be a strong function of pressure, thereby enabling simultaneous imaging of velocity and pressure. This development is especially important for supersonic flow studies. Example results for velocity, pressure and vorticity in a  $M=1.5$  supersonic jet are shown in Fig. 2. Details of the velocity and pressure aspects of this work are given in a recent paper (number 10 on the list below); the conversion of the velocity field data to vorticity (i.e., the component perpendicular to the illumination plane, given by the curl of the velocity vector) is work in progress and not yet reported.

It should be noted that the present scheme uses four camera frames, one for each of the four sheets of light, i.e.,  $\pm 45^\circ$  and  $+ 90^\circ$  for laser frequency  $\nu_0$  and  $+ 90^\circ$  for frequency  $\nu_s$  (see Fig. 1), to allow determination of the velocity vector in the centerplane of the flow. Although the time required to complete the four measurements is currently about 0.25 seconds, much shorter measurement times are feasible. The sensitivity of the method, currently a few m/s, indicates the capability of the 4-beam technique to probe a variety of low and high Mach number flowfields. The simplicity of the scheme should lend itself to fast on-line data processing. The excellent spatial resolution which can be achieved is an intrinsic feature of laser-induced fluorescence techniques.

Very recently, as part of planning a research program on supersonic combustion, we've begun to investigate the possibility of performing imaging velocimetry with molecular oxygen. If an  $\text{O}_2$  velocimetry scheme could be developed, this would of course considerably expand the opportunities to employ velocity imaging in aerodynamics and combustion research, owing to the high levels of  $\text{O}_2$  naturally present in many flows of interest. Elimination of seeding trace levels of toxic or corrosive species, such as iodine,

Fig. 2 Planar fluorescence imaging of velocity, pressure and vorticity in supersonic flows.

## Velocity and Pressure Imaging Technique in Supersonic Flows

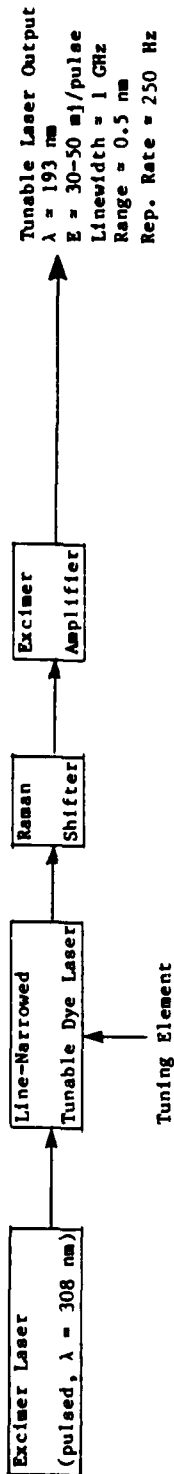


- First combined 2-D measurements of velocity and pressure
- First 2-D optical measurement of vorticity ( $\bar{\omega} = \text{curl } \bar{V}$ )

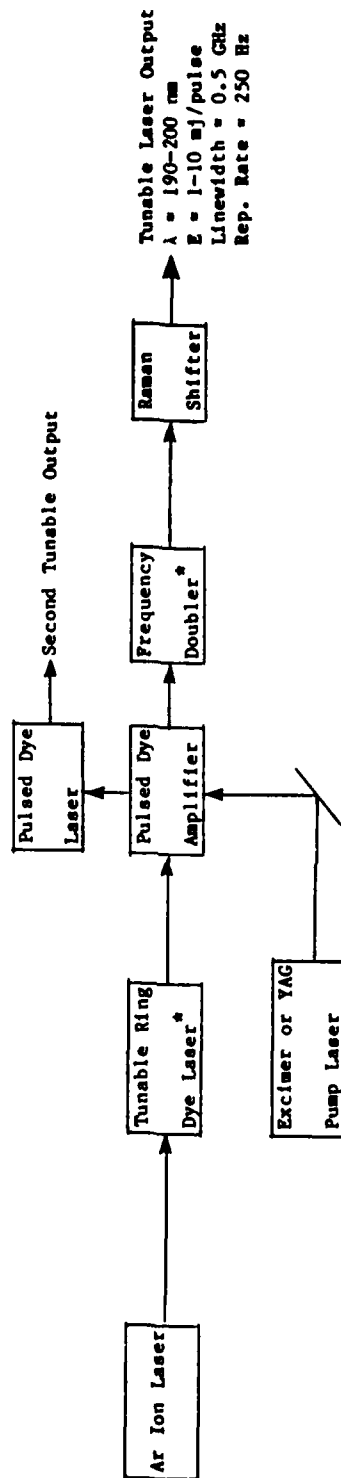
would simplify experiments considerably. But oxygen has two other, less obvious but perhaps even more critical advantages, which result from the fact that the  $O_2$  absorption linewidths are large (owing to the effect of predissociation in the excited B state of the Schumann-Runge system) and constant. The first advantage is that large linewidths allow measurements of large Doppler shifts and hence large velocities needed for supersonic flows. The second advantage, which accrues from the constancy of the linewidth and hence lineshape, is that the velocity determination is independent of the gas composition and thermodynamic state. Once we realized these attractive features of using  $O_2$ , we turned our attention to solving what we regard as the critical problem, namely the generation of suitably line-narrowed tunable radiation in the UV to excite  $O_2$  fluorescence. Our research has yielded an encouraging result, which is that these are two candidate laser systems with the proper characteristics which could be assembled from commercially available components. Schematics of the proposed systems are shown below in Fig. 3.

Both of these systems are unique and are, to our knowledge not presently available in any laboratory. Scheme I relies on a 4-step process terminating in an excimer amplifier. We project that this system would have a high energy per pulse (30-50 mj), a linewidth of about 1 GHz, and would operate at repetition rates up to 250 Hz. A potential shortcoming is that the laser would tune over only 0.5 nm, but this should be adequate for  $O_2$  measurements. Scheme II is also a multi-step laser system comprised of commercially available components. This scheme is more expensive but also has much greater versatility in that it can produce two or more simultaneously tunable output wavelengths. Thus this system would have broadly useful imaging capability for our laboratory, and would provide us with important opportunities for other new research. For the specific purpose of  $O_2$  velocimetry imaging, however, it is expected to have less energy per pulse than Scheme I. Our present plan is to pursue development of both of these unique laser systems using funds provided through URIP and regular contract awards.

SCHEME I



SCHEME II



\* It may be more efficient to locate the doubling element in the ring dye laser.

Fig. 3 Proposed schemes for production of tunable, narrow-linewidth laser excitation of  $\text{O}_2$  for velocity (and pressure) imaging.

## Publications and Presentations

### Presentations

1. J.C. McDaniel, "Velocity Measurements Using Doppler-Shifted Laser-Induced Iodine Fluorescence," presented at Thirty-Fifth Meeting of the American Physical Society, Div. of Fluid Dynamics, Rutgers U., Nov. (1982).
2. J.C. McDaniel, "Quantitative Measurement of Density and Velocity in Compressible Flows Using Laser-Induced Iodine Fluorescence," paper 83-0049 presented at AIAA 21st Aerospace Sciences Meeting, Reno (January 1983).
3. B. Hiller, J.C. McDaniel, E.C. Rea, Jr., and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Measurements in Subsonic Flows," presented at CLEO '83, Baltimore (May 1983).
4. B. Hiller and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Field Measurements in Compressible Flows," presented at the Thirty-Sixth Annual Meeting of the American Physical Society, Div. of Fluid Dynamics, Houston, Nov. (1983).
5. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," Presented at ICALEO '84, Laser Diagnostics and Photochemistry Symposium, Boston, Nov. 12-15, 1984.
6. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," invited paper presented at Winter Annual Meeting of ASME, New Orleans, Dec. 9-14, 1984.
7. R. Hanson, "Optical Imaging and Combustion Measurements," invited paper presented at Lasers '84, Symposium on Imaging of Fluids, San Francisco, Nov. 26-30, 1984.
8. B. Hiller and R.K. Hanson, "Combined Measurements of Velocity and Pressure Fields in Compressible Flows Using Laser-Induced Iodine Fluorescence," paper WG4 presented at Lasers '85, Las Vegas, Dec. 2-6, 1985.
9. B. Hiller and R.K. Hanson, "Simultaneous Measurements of Velocity and Pressure in Subsonic and Supersonic Flows through Image-Intensified Detection of Laser-Induced Fluorescence," presented at AIAA Aerospace Sciences meeting, Reno, Jan. 6-8, 1986.
10. R. K. Hanson, "Multipoint Flow Diagnostics," to be presented at ICALEO '86, Arlington, VA, Nov. 10-13, 1986.

## Publications

1. J.C. McDaniel, B. Hiller and R.K. Hanson, "Simultaneous Multiple-Point Velocity Measurements Using Laser-Induced Fluorescence," *Optics Letters* 8, 51 (1983).
2. B. Hiller, J.C. McDaniel, E.C. Rea, Jr., and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Measurements in Subsonic Flows," *Optics Letters* 8, 474 (1983).
3. B. Hiller, R.B. Booman, C. Hassa and R.K. Hanson, "Velocity Visualization in Gas Flows Using Laser-Induced Phosphorescence of Biacetyl," *Review of Scientific Instruments* 55, 1964 (1984).
4. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," L.I.A. (Laser Institute of America) Vol. 47 ICALEO (1984), pp. 98-106.
5. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," *Amer. Soc. Mech. Eng. AMD-Vol. 66*, pp 1-10 (1984).
6. C. Hassa and R.K. Hanson, "Fast Laser-Induced Aerosol Formation for Visualization of Gas Flows," *Rev. of Sci. Inst.* 56, 567 (1985).
7. B. Hiller and R.K. Hanson, "Two-Frequency Laser-Induced Fluorescence Technique for Rapid Velocity Field Measurements in Gas Flows," *Optics Letters* 10, 206 (1985).
8. F. Itoh, G. Kychakoff and R.K. Hanson, "Flow Visualization in Low Pressure Chambers Using Laser-Induced Biacetyl Phosphorescence," *J. Vacuum Sci. and Technol. B*, Vol. 3, 1600-1603 (1985).
9. C. Hassa, P.H. Paul and R.K. Hanson, "Laser-Induced Fluorescence Modulation Technique for Velocity Measurements in Gas Flows," *Experiments in Fluids*, in press.
10. B. Hiller, L.M. Cohen and R.K. Hanson, "Simultaneous Measurements of Velocity and Pressure Fields in Subsonic and Supersonic Flows Through Image-Intensified Detection of Laser-Induced Fluorescence," AIAA preprint 86-0161.
11. B. Hiller, L. M. Cohen and R. K. Hanson, "Combined Planar Measurements of Velocity and Pressure Fields in Gas Flows Using Laser-Induced Fluorescence," *Applied Optics*, in preparation.
12. B. Hiller, P. H. Paul and R. K. Hanson, "Use of an Image-Intensified Photodiode Array Camera as a Fluorescence Detector in cw-Laser Experiments," *Review of Sci. Instruments*, in preparation.
13. B. Hiller and R. K. Hanson, "Properties of the Iodine Molecule Relevant to Absorption/Fluorescence Experiments in Gas Flows," *Experiments in Fluids*, in preparation.

## **Personnel**

Ronald K. Hanson	Professor, Mechanical Engineering
Bernhard Hiller	Graduate Student, Mechanical Engineering (Ph.D. expected December 1986)
Chris Hassa	Graduate Student, Mechanical Engineering (Engineer Degree awarded December 1985)
Larry Cohen	Graduate Student, Mechanical Engineering (Ph.D. expected June 1988)
F. Itoh	Visiting Researcher from Hitachi during 1984

## **2.3 Fiber Optic Absorption/Fluorescence Sensors**

Optical fibers and fiber bundles provide new opportunities for optical diagnostics research and applications. As part of this program, we have in past years made use of optical fibers for transmitting laser light between laboratories and in the construction of intrusive laser absorption/fluorescence probes for species measurements. The recent appearance of relatively inexpensive coherent fiber bundles, suitable for transmitting images, and the anticipated commercial availability of infrared-transmitting fibers, have encouraged us to initiate new work in these areas. In the long term, we are confident that optical fibers will provide the vehicle whereby many sophisticated spectroscopy techniques, proven only under idealized laboratory conditions, can be extended to real-world applications.

## **Scientific Merit**

This research seeks to enable the application of spectroscopy-based schemes for remote measurements of gaseous properties in reacting flows. Such schemes are critically needed for flows with poor optical access or where the test environment precludes local placement of a laser source. Our

approach is unique in that it seeks to combine recently developed tunable laser sources with novel absorption or fluorescence probes. The resulting diagnostics should be well suited to meet a variety of practical measurement requirements and hence have the potential for significant impact on various scientific and engineering aspects of combustion and propulsion. In addition, our work should contribute substantially to the fundamental spectroscopic data base for high temperature gases.

### **Status Report**

Recent effort on this topic has involved preliminary planning for new research activities and completion of research projects on remote sensing of NCO and CH in shock tube kinetics and spectroscopy experiments. Other past activities have been published (see list below) and hence will not be discussed here.

With regard to project planning, we have recently completed a survey to identify manufacturers of coherent fiber bundles (for imaging) and of infrared-transmitting fibers. In summary, we found that suitable imaging fiber bundles are now available from several manufacturers, but we have postponed any further work along these lines until we have a specific need to perform imaging in a system with limited optical access. As regards infrared fibers, it appears that no American company is yet willing to deliver infrared fibers with guaranteed specifications, though the availability of i.r. fibers should improve significantly within the next two years. Also, we have conducted an unsuccessful survey of manufacturers of visible diode lasers, in the hope of finding a source of wavelength tunable solid-state lasers for use at visible wavelengths appropriate for absorption measurements of metal atoms and metal oxide molecules. It appears that the technology for such lasers is still a few years away; once available, however, these lasers should be relatively cheap and will open up a variety of practical opportunities for sensors in combustion systems.

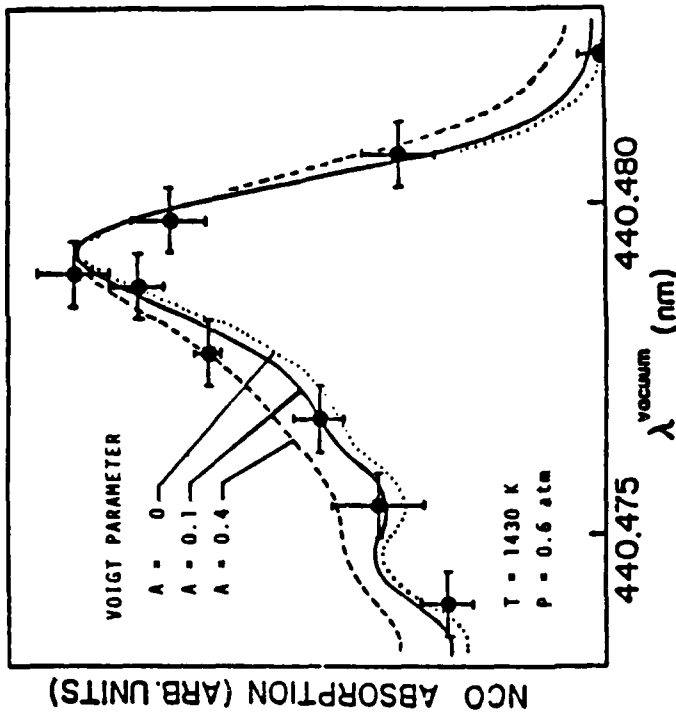
Our major activity during the past three years has been to complete measurements of NCO and CH spectral and kinetic parameters using a fiber optic absorption technique to probe these species in a shock tube. Both of

these projects have been described in detail in publications (see papers 7-10) in list below) and so only highlights will be presented here. The species NCO has been proposed, on theoretical grounds, as a combustion intermediate of some importance in connection with the chemistry of nitrogen species in combustion. Until now, however, NCO has not been detected in a high temperature system. In our work we have: investigated the electronic absorption spectrum of NCO ( $B \leftarrow X$  and  $A \leftarrow X$  bands), found an optimum wavelength for detection, modified our  $Ar^+$ -pumped cw ring dye laser to operate at this near-UV wavelength (440 nm,  $A \leftarrow X$  band), installed a 65 meter optical fiber link between the laser and the shock tube lab, and performed incident shock wave tests to evaluate the spectral absorption parameters of NCO at high temperature. Our measurements of CH were carried out with the same optical arrangements, but with the dye laser set to 431 nm, and represent the first laser-based studies of CH spectroscopy and kinetics in a shock tube.

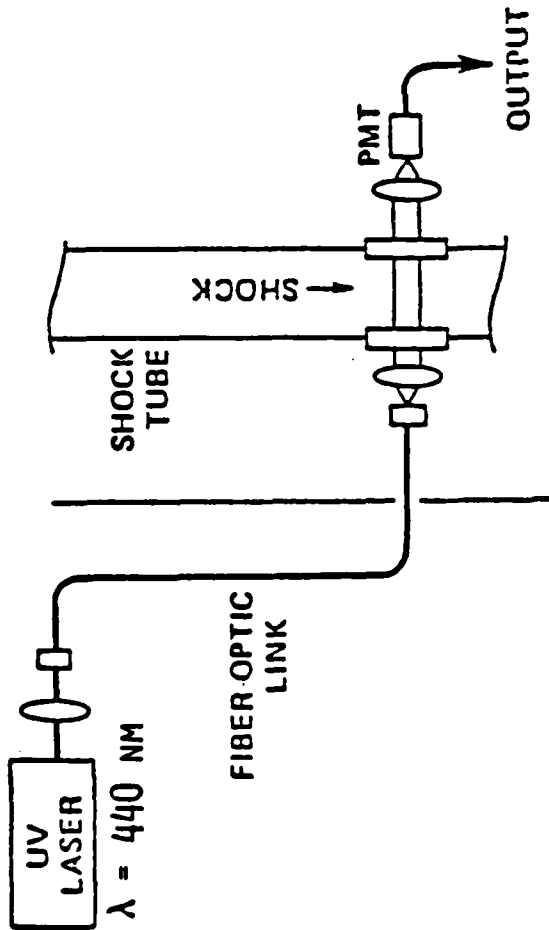
A schematic of the experiment and typical results are shown in Figs. 1 and 2. The laser source was a ring dye laser (Spectra-Physics 380A) operating on stilbene (S3) dye and pumped by the UV lines (1.9 W, all lines) of an  $Ar^+$  laser (Spectra-Physics 171-18). The output of the laser was amplitude stabilized (Coherent 307 Noise Eater), yielding power levels of 5-10 mW at the input of the 65 meter fiber link (200 micron fused silica fiber, Superguide).

In both the NCO and CH studies the quantity measured was the fractional absorption following shock-wave production of the species. Variations in the absorption as a function of laser wavelength for a fixed level of NCO, as shown in Fig. 1 (for  $T=1430K$ ,  $P=0.6$  atm), enable determination of the relevant Voigt parameter  $A$  and subsequently the collision-broadened linewidth for NCO broadened by Ar. The absolute absorption, together with the known level of NCO present, leads to a value for the electronic oscillator strength. (Details of this work appear in publication 7 below.) A sample data trace for CH absorption in shock heated  $CH_4/Ar$  mixtures is shown in Fig. 2. This record illustrates the sensitivity of the method to detect ppm levels of CH as needed for fundamental studies of hydrocarbon pyrolysis and oxidation kinetics.

**SUCCESSFUL USE OF FIBER-OPTIC LINK TO REMOTELY MEASURE SPECTRAL PARAMETERS OF NCO**



**HIGH TEMPERATURE ABSORPTION USED TO INFER NCO OSCILLATOR STRENGTH AND BROADENING FACTOR**



**Fiber-Optic Link to Shock Tube Experiment**

- FIBER OPTIC LINK ENABLES USE OF LASER SOURCES FOR REMOTE MEASUREMENTS IN HOSTILE SYSTEMS
- MULTIPLE MEASUREMENT LOCATIONS WITH SINGLE LASER DEMONSTRATED
- FIRST OBSERVATION OF NCO AT HIGH TEMPERATURES
- TECHNIQUE ENABLES DETERMINATION OF SPECTRAL PARAMETERS AT HIGH TEMPERATURES

Fig. 1 Shock tube measurements of NCO spectral absorption coefficient using a remotely located dye laser.



measurements of fundamental spectroscopic parameters in high temperature gases. This approach should enable important contributions to the scientific data base for combustion gases and plasmas.

## Presentations and Publications

### Presentations

1. G. Kychakoff and R.K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," presented at 1981 Los Alamos Conference on Optics, April 1981.
2. S.M. Schoenung and R.K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," presented at 1981 Conference on Lasers and Electro-Optics (CLEO), Washington, June 1981.
3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in Turbulent CO Diffusion Flame," paper WSS/CI 81-33 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.
4. G. Kychakoff and R.K. Hanson, "Tunable Laser Absorption/Fluorescence Fiberoptic Probe for Combustion Measurements," paper WSS/CI 81-50 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.
5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Spatially Resolved Combustion Measurements Using Crossed-Beam Saturated Absorption Spectroscopy," paper THM2 at CLEO '82, Phoenix, Az., April 14-16, 1982.
6. M.A. Kimball-Linne, G. Kychakoff, R.K. Hanson and R.A. Booman, "A Fiber Optic Fluorescence Probe for Species Measurements in Combustors," paper 82-50 at Western States Section, Combustion Institute meeting, Livermore, Ca., October 11-12, 1982.
7. M.Y. Louge and R.K. Hanson, "Shock Tube Study of NCO Kinetics," presented at 20th Symposium (International) on Combustion, Ann Arbor, Aug. 1984.
8. M.Y. Louge and R.K. Hanson, "Shock Tube Study of the High-Temperature Absorption of CH at 431 nm," presented at 15th International Symposium on Shock Tubes and Waves, Berkeley, CA., July 1985.

## Publications

1. S.M. Schoenung and R.K. Hanson, "CO and Temperature Measurements in a Flat Flame by Laser Absorption Spectroscopy and Probe Techniques," Combustion Science and Technology 24, 227-237 (1981).
2. S.M. Schoenung and R.K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," Applied Optics 21, 1767-1771 (1982).
3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in a Turbulent CO Diffusion Flame," 19th Symposium (International) on Combustion, The Combustion Institute, pp. 449-458 (1982).
4. G. Kychakoff and R.K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," The Los Alamos Conference on Optics 81, D.L. Liebenbert, Ed., Proc. SPIE 288, 236 (1982).
5. R.K. Hanson, S. Salimian, G. Kychakoff and R.A. Booman, "Shock Tube Absorption Measurements of OH Using a Remotely Located Dye Laser," Applied Optics 21, 641 (1983).
6. G. Kychakoff, M.A. Kimball-Linne and R.K. Hanson, "Fiber-Optic Absorption/Fluorescence Probes for Combustion Measurements," Applied Optics 22, 1426 (1983).
7. M.Y. Louge and R.K. Hanson, "Quantitative High Temperature Absorption Spectroscopy of NCO at 305 and 440 nm," J. Quant. Spectrosc. and Radiat. Transfer 32, 353-362 (1984).
8. M.Y. Louge and R.K. Hanson, "High Temperature Kinetics of NCO," Comb. and Flame 58, 291 (1984).
9. M.Y. Louge and R.K. Hanson, "Shock Tube Study of NCO Kinetics," 20th Symposium (International) on Combustion, The Combustion Institute, pp. 665-672 (1984).
10. M.Y. Louge and R.K. Hanson, "Shock Tube Study of the High-Temperature Absorption of CH at 431 nm," in Shock Waves and Tubes, eds. D. Bershader and R.K. Hanson, Stanford Univ. Press, pp. 827-833 (1986).
11. M.A. Kimball-Linne, G. Kychakoff and R.K. Hanson, "Fiberoptic Absorption/Fluorescence Combustion Diagnostics," Comb. Sci. & Technol., in press.

## Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Susan Schoenung	Graduate Student, Mechanical Engineering (Ph.D. awarded in June 1982)
Mark A. Kimball-Linne	Graduate Student, Mechanical Engineering (Ph.D. awarded in December 1984)
Michel Y. Louge	Graduate Student, Mechanical Engineering (Ph.D. awarded in December 1984)
George Kychakoff	Asst. Prof. (Acting) Mechanical Engineering (Ph.D. awarded in March 1985)
Anthony Dean	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1989)

## 2.4 Laser Wavelength Modulation Spectroscopy

### Introduction

Recent improvements in tuning rates of narrow-linewidth laser sources offer opportunities for establishing a new class of diagnostic techniques based on wavelength modulation concepts. Laser wavelength modulation spectroscopy refers to laser absorption or laser-induced fluorescence measurements carried out with a rapid-tuning single mode laser. This method involves quickly scanning a tunable cw laser across one or more isolated absorption transitions and recording the spectrally resolved absorption line profile using either absorption or fluorescence detection. The method is generally applicable to both infrared and UV/visible transitions, and it is particularly attractive for measurements in combustion gases and plasmas.

A primary advantage of wavelength modulation is that it provides a simple means of discriminating against continuum extinction and luminosity

effects which can seriously hinder conventional laser absorption or fluorescence measurements in two-phase combustion flows and high-luminosity plasmas. Moreover, recording the fully resolved absorption line eliminates the need for uncertain linewidth assumptions in converting measured absorption (or fluorescence) to species concentration or temperature. Over the past several years, in AFOSR-sponsored work, we have demonstrated the utility of the wavelength modulation concept for combustion measurements, first using a commercially available rapid-tuning infrared diode laser to probe i.r.-active species, and more recently using a Stanford-built rapid-tuning dye laser to probe UV-active species.

Unfortunately, rapid-tuning dye lasers, needed for accessing a variety of important radical species which absorb in the near UV and visible, are not commercially available. Recognizing the importance of such a capability, we developed (under AFOSR support) a novel and simple modification to a commercial ring dye laser which increases the scan repetition rate by three orders of magnitude (from about 4 Hz to 4 kHz) for short scans (up to  $5 \text{ cm}^{-1} = 150 \text{ GHz}$ ), and more recently we incorporated intracavity frequency doubling into the dye laser to permit access to UV wavelengths. Operation in the UV is critical for access to a variety of important combustion and plasma species.

### **Scientific Merit**

Our laboratory now has unique capability and experience with fast-tuning lasers (UV, visible and IR) and wavelength modulation spectroscopy. This capability has provided several opportunities for pioneering contributions to combustion and plasma diagnostics research. In connection with combustors where particulates or droplets are present, wavelength-modulation techniques can be applied to discriminate between the gaseous absorption or fluorescence of interest and interfering continuum extinction. For plasma flows which may be highly luminous, wavelength modulation should provide a means of distinguishing the spectrally varying signal of interest from the intense continuum background. In unsteady flows or in devices where transient phenomena are of interest, fast measurements of fully-resolved absorption or fluorescence lines can be used for time-resolved determinations of species and temperature. Finally, the significance of

fast-scanning capability for fundamental spectroscopic measurements should be noted. For example, during this program we have demonstrated the first measurements of fully resolved absorption lines in shock tube flows. Such experiments provide unique capability for obtaining a variety of fundamental high-temperature data including important quantities such as collision linewidths, oscillator strengths and heats of formation; these parameters are needed to enable quantitative absorption and fluorescence measurements of species in combustion and plasma flows.

### Status Report

The dye laser modification which enables fast-tuning laser wavelength modulation spectroscopy has been described previously (see publications 1 and 6 below). We have utilized this new laser system for two types of measurements: high-speed temperature measurements, and high-resolution spectroscopy measurements. The experiments have been conducted both in a shock tube (see publications 6, 7, 9 and 10) and in various flames (see publications 5, 8 and 9). Here, for purposes of illustrating the unique capabilities of the laser, we show recent results obtained in shock tube experiments. In these experiments, the laser was used to record fully resolved absorption line profiles of OH over a range of post-shock conditions. In brief, the center frequency of the repetitively scanning laser was set on a known UV line of OH, and the beam was passed through the shock tube to enable recording of absorption line profiles behind reflected shock waves. Mixtures of  $H_2/O_2/Ar$  were shock heated to provide relatively constant levels of OH at known conditions. These experiments provide the first fully resolved, radical species absorption spectra recorded in a shock tube, and they can be used to infer fundamental parameters, such as collision-broadened linewidths, about which very little is known at high temperatures. A schematic diagram of the experiment is shown in Fig. 1, and a sample data trace is shown in Fig. 2.

Figure 3 provides a plot of the rotational quantum number dependence of the Argon-broadened linewidth of OH at 2000K, extracted from data traces similar to that shown in Fig. 2. These are the first directly determined

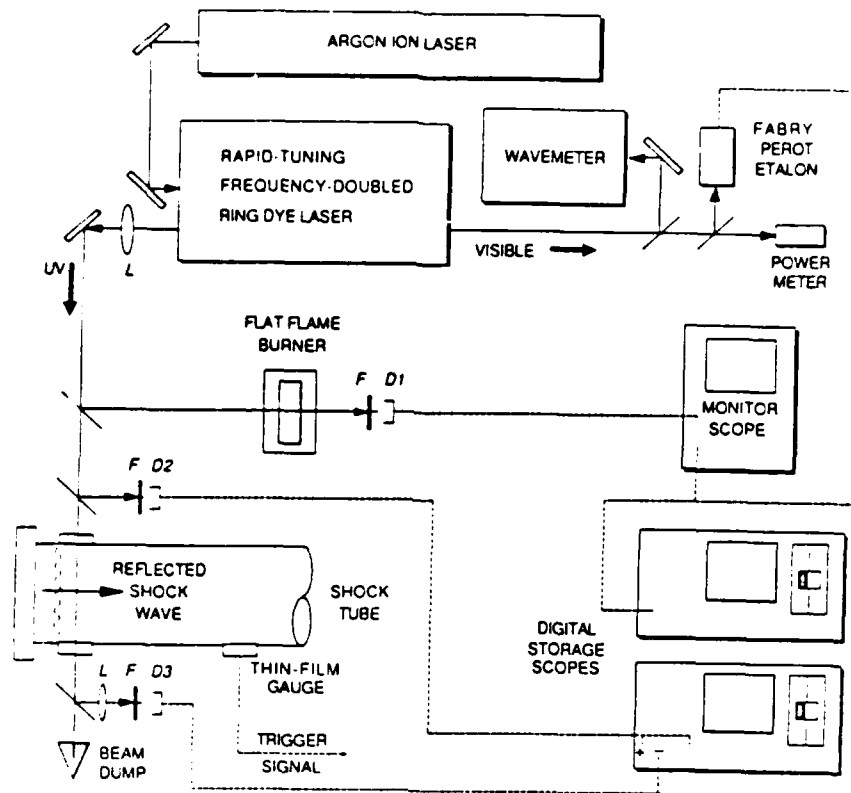


Fig. 1. Schematic diagram for fast-scanning dye laser absorption experiments behind reflected shock waves.

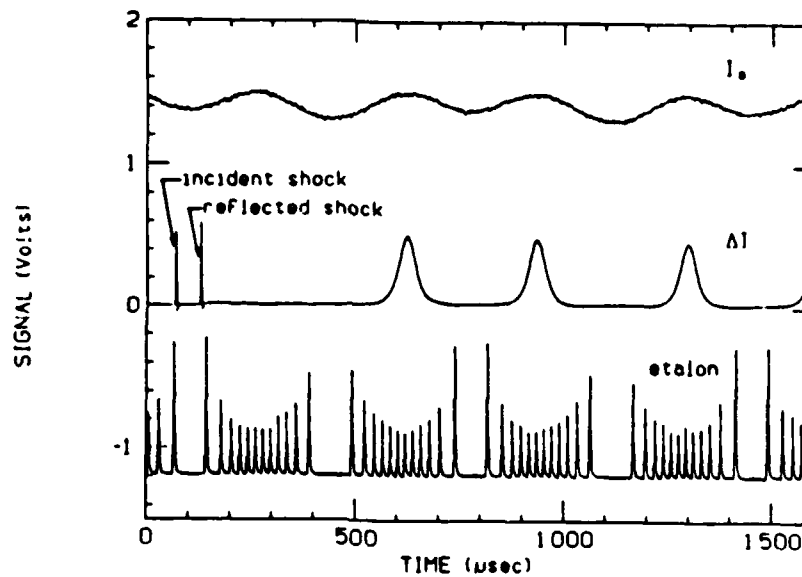


Fig. 2. Sample records of  $I_0$ ,  $\Delta I = I_0 - I$ , and etalon trace versus lab time for  $R_1(5)$  line of OH at 306.7 nm. Postshock conditions:  $T_5 = 1960\text{K}$ ,  $P_5 = 4.30\text{ atm}$ . Preshock mixture = 500 ppm  $\text{H}_2$ , 500 ppm  $\text{O}_2$ , balance Ar. The etalon fringe spacing corresponds to frequency changes of  $4\text{ GHz} = 0.133\text{ cm}^{-1}$  in the UV.

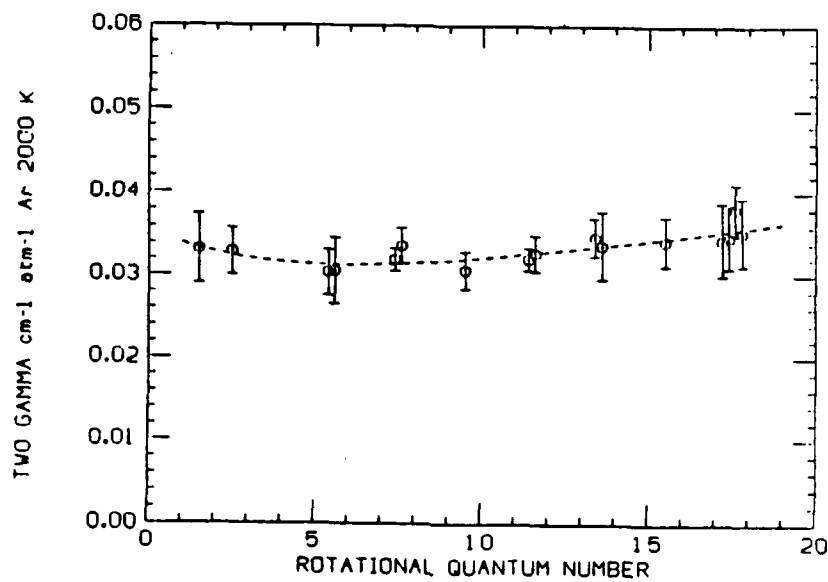


Fig. 3. J-dependence of the collision linewidth for Ar broadening at  $T_5 = 2000\text{K}$ .

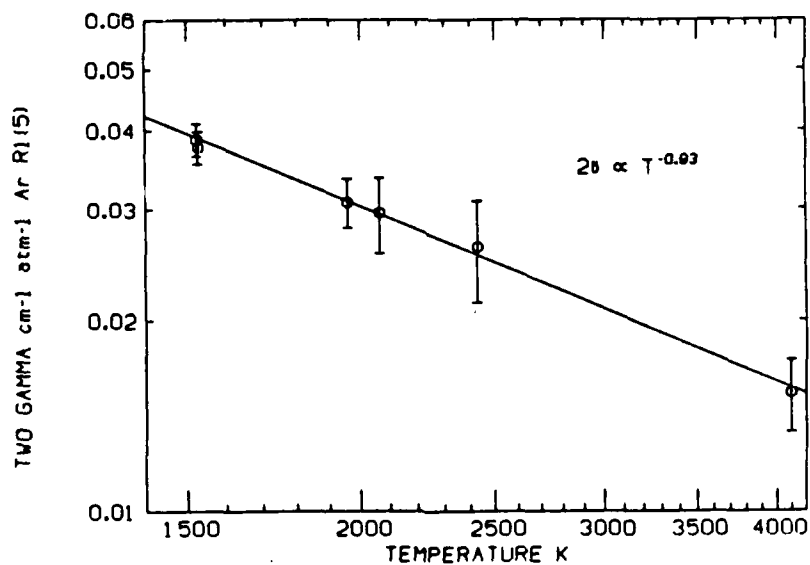


Fig. 4. Temperature dependence of the collision linewidth for Ar broadening;  $R_1(5)$  line at  $0\text{H}$ . Best-fit temperature exponent is  $n = 0.93$ .

data for this fundamental quantity. Figure 4 provides a plot of the temperature dependence of the collision linewidth for a specific rotational transition.

The practical implication of this work is that it will enable more quantitative species measurements of OH (by absorption or fluorescence) in combustion systems, but these same data also contribute importantly to the development of improved fundamental models for absorption line broadening. The related work involving rapid scanning of specific absorption line pairs for temperature measurements promises to provide unique capability for high-repetition-rate ( $\sim 5$  kHz) measurements in combustion gases and plasmas (papers 8, 10).

Current work with wavelength modulation is aimed at acquiring additional linewidth data for OH broadening by  $H_2O$  and  $CO_2$  and for NH broadening by Ar and  $N_2$ . The latter project requires a unique modification of our Spectra-Physics ring dye laser to incorporate angle-tuned frequency doubling.

#### Publications and Presentations

1. E.C. Rea, Jr., and R.K. Hanson, "Rapid Extended Range Tuning of Single-Mode Ring Dye Lasers," *Applied Optics* 22, 518 (1983).
2. E.C. Rea, Jr. and R.K. Hanson, "Fast-Scanning UV Ring Dye Laser for Combustion Research," presented at CLEO '83, Baltimore (May 1983).
3. R.K. Hanson, S. Salimian and E.C. Rea, Jr., "Laser Absorption Techniques for Spectroscopy and Chemical Kinetics Studies in a Shock Tube," in *Shock Tubes and Waves*, ed. R. Archer and B. Milton, Sydney Symposium Publishers, 595-601 (1983); presented at 14th International Symposium on Shock Tubes and Waves, Sydney, Aug. 19-22 (1983).
4. R.K. Hanson, "Tunable Diode Laser Measurements in Combustion Gases," SPIE Vol. 438, pp. 75-83 (1983); also presented at 1983 meeting of Soc. Photographic and Inst. Engineers, San Diego, August 1983.
5. E.C. Rea, Jr. and R.K. Hanson, "Fully Resolved Absorption/Fluorescence Lineshape Measurements of OH Using a Rapid-Scanning Ring Dye Laser," paper 83-66 at the fall meeting of the Western States Section/Combustion Institute, Los Angeles, CA, October 1983.
6. E.C. Rea, Jr., S. Salimian and R.K. Hanson, "Rapid-Tuning Frequency-Doubled Ring Dye Laser for High Resolution Absorption Spectroscopy in Shock-Heated Gases," *Applied Optics*, 23, 1691-1694 (1984).

7. E.C. Rea, Jr., A.Y. Chang, and R.K. Hanson, "Shock Tube Study of Collision Broadening of the  $A^2\Sigma \leftarrow X^2\Pi$  Band of OH by Ar and  $N_2$ ," submitted to Jour. Quant. Spectrosc. and Radiat. Transfer, in press.
8. E.C. Rea, Jr. and R.K. Hanson, "Rapid Laser Wavelength Modulation Spectroscopy Applied as a Fast Temperature Measurement Technique in Hydrocarbon Combustion," submitted to App. Optics.
9. E.C. Rea, Jr., A.Y. Chang and R.K. Hanson, "Collision Broadening of OH at Elevated Temperatures," paper 86-3 presented at spring meeting of the Western States Section/Combustion Institute, Calgary, April 1986.
10. A.Y. Chang, E.C. Rea, Jr. and R.K. Hanson, "Temperature Measurements in Shock Tubes Using a Laser-Based Absorption Technique," submitted to App. Optics.

### Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
E.C. Rea, Jr.	Graduate Student, Mechanical Engineering (Ph.D. Expected in March 1987)

## 2.5 Plasma Diagnostics for Energy Conversion Research

### Introduction

A relatively new element of our overall program is research on diagnostic techniques for plasmas. Primary motivation for this work arises from renewed interest in advanced space power and propulsion systems which may involve plasmas. Among the systems under consideration are thermionic converters and MHD generators for electrical power generation, MPD thrusters and beamed laser energy for propulsion, and direct production (in space) of high-power laser radiation for beamed energy. Considerable research will be needed before optimum systems for space utilization are identified, developed and placed in service, and we believe that advanced diagnostics will play an important role in such research. Furthermore, work on plasma diagnostics forms a logical and efficient extension of our current program.

## Scientific Merit

This research seeks to provide new diagnostic methods for use in studies of plasma properties and plasma phenomena. The two primary techniques which we are pursuing, namely PLIF imaging and wavelength modulation absorption/fluorescence, are novel and will provide unique capabilities for measurements in ionized gases. We intend to coordinate this work closely with other OSR-sponsored work on plasma sciences underway in our laboratory, and we expect the scientific merit and relevance of the work to be enhanced by these interactions.

## Status Report

This research is still in an early stage and our work has consisted primarily of literature reviews, paper studies of candidate diagnostic techniques, and selection and assembly of plasma facilities. On the basis of this background work, we have narrowed our selection of diagnostics topics to three approaches: (1) digital imaging of plasmas using PLIF, i.e. simultaneous multiple-point laser-induced fluorescence measurements of plasma parameters such as species concentration (including ions and electrons), temperature and electric field strength; (2) wavelength modulation spectroscopy using laser absorption and/or fluorescence; and (3) other laser scattering concepts. To put our work in focus, we are particularly interested in techniques which have promise for measurements with high spatial resolution, for example near electrodes and boundaries where discharge and erosion phenomena are of importance, and in finding new, improved measurement methods for quantities such as temperature, electron number density, ion species concentrations and electric field strength.

A block diagram indicating the laser systems to be employed, the techniques of interest, and the plasma systems to be studied, is given in Fig. 1. Two of the three laser systems indicated, providing tunable cw dye laser radiation (280-700 nm, with some gaps) and tunable pulsed dye laser radiation (220-900 nm), are already in use. The third laser system, aimed at accessing tunable vacuum ultraviolet (VUV) wavelengths by adding a Raman shifter (cell of  $H_2$  at high pressure) to our existing pulsed dye laser, is now undergoing installation. This addition will allow access to the

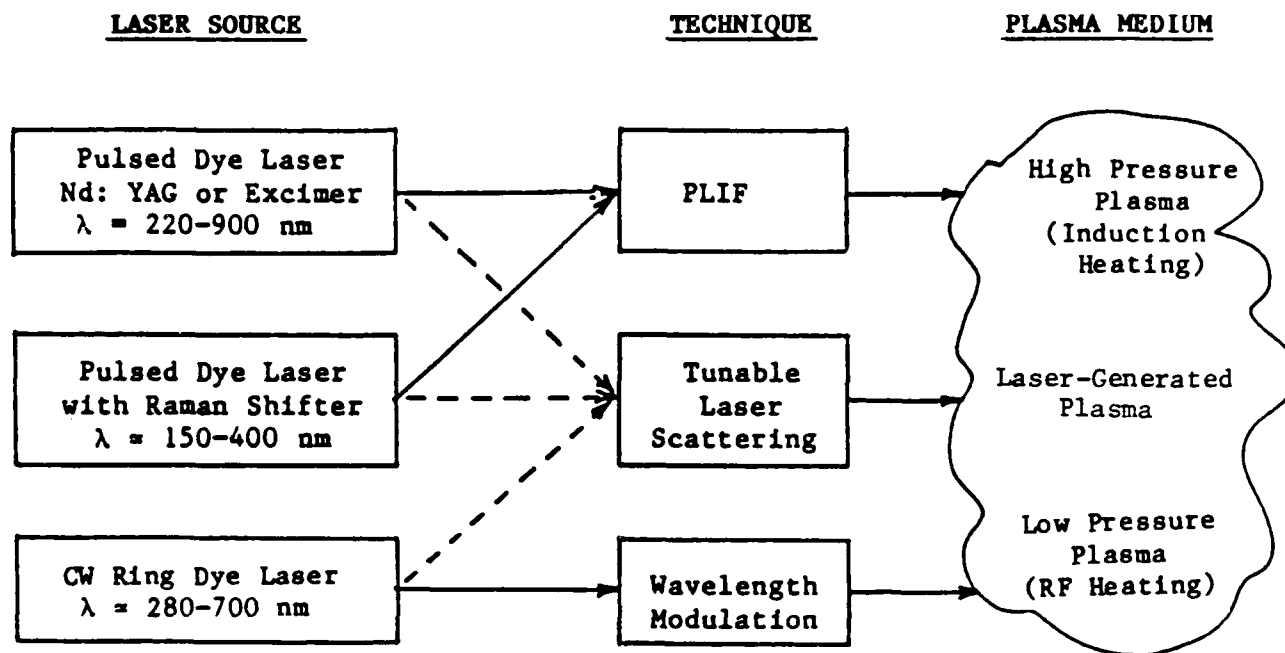


Fig. 1. Laser Systems and Techniques for Plasma Diagnostics Research.

absorption/fluorescence spectra of a variety of atomic species of importance in plasma and electrode phenomena studies.

We plan to conduct research in three separate plasma regimes: low-pressure RF discharges; high-pressure, inductively heated plasmas; and laser-produced plasmas. The low pressure facility is now complete and is in use in a study of silane plasmas. In brief, the viewing chamber is a stainless steel box, with windows on all four sides, and electrodes to be mounted on removable top and bottom plates. The chamber is coupled to an inlet gas manifold, for varying the input gas composition and flow rate, and to a vacuum pump. We have paid particular attention to optical access so that we will be able to demonstrate the ability to measure with high spatial resolution near surfaces (electrodes) and with high temporal resolution in transient discharges. Initial research is aimed at developing fluorescence-based schemes for spatially resolved measurements of Si, SiH and possibly SiH<sub>2</sub> in RF-excited SiH<sub>4</sub>-Ar plasmas at 0.1 - 2 Torr. These are species which are of general interest in the fields of propulsion and semiconductor processing.

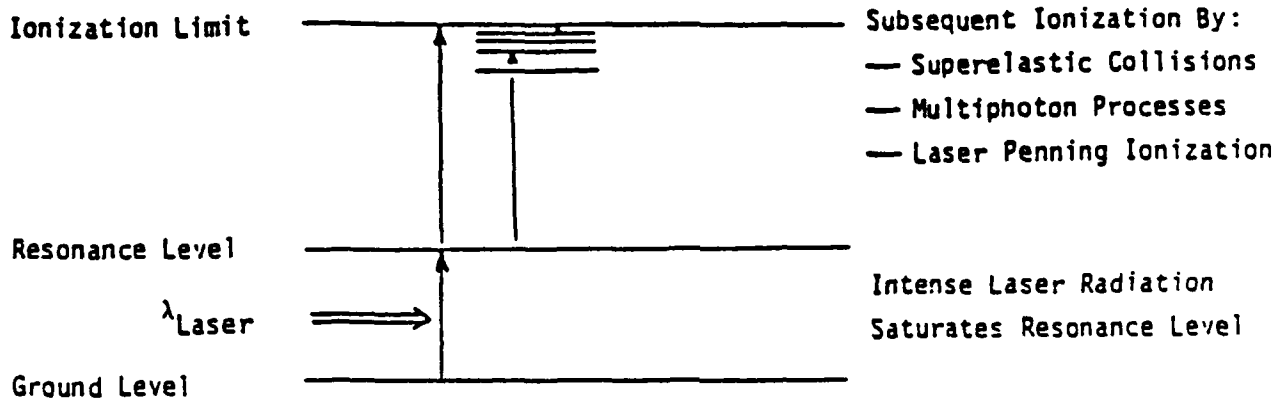
With regard to the high-pressure facility, preliminary work was conducted with a low power (10 kW) induction-heating power supply acquired on surplus, and these results led to the specification of a new 50 kW plasma torch which is now on order. (This \$125,000 system is being acquired as part of an AFOSR URIP award to Professor C. H. Kruger of our laboratory.) This system will provide nearly ideal optical access for diagnostics studies and will be useful in subsequent collaborative research (with Professor Kruger) on a variety of plasma sciences topics (e.g., plasma processing, for powders and gases; laser-plasma interactions and energy transfer; and non-equilibrium aspects of plasmas).

Our plans for plasma generation by laser heating are tentative. At present we are considering two fundamental studies, the first involving resonant excitation of alkali metal atoms, as indicated schematically in Fig. 2, and the second involving laser-induced breakdown (i.e., laser sparks) in air or hydrocarbon-air mixtures. The former scheme is attractive because of its efficiency of plasma production and because of the concomitant opportunities afforded for study of fundamental microscopic collisional and radiative processes. The latter topic is of considerable practical relevance.

The status of our work on plasma diagnostics is that we have reviewed a variety of candidate measurement ideas, leading to the three categories of techniques noted above, and one student is now proceeding to develop planar laser-induced fluorescence (PLIF) for low- and high-pressure plasma measurements. A schematic diagram of the planned approach, and a listing of some key attributes, is given in Fig. 3. We anticipate delivery of the plasma torch by the end of the year, at which time we will begin to set-up a PLIF system and establish procedures for monitoring the properties of interest: ion concentrations, temperature and electron number density. As an example, our plan for electron density ( $n_e$ ) is to make use of the known relationship between the Stark-broadened absorption lineshape function and  $n_e$ . We intend to excite three (or more) different wavelengths within a specific absorption line (see Fig. 3), and to use the ratio of the resulting LIF signals (at each flowfield point or pixel) to establish the width

## PLASMA GENERATION BY RESONANCE LASER EXCITATION

- Intense pulses of resonance laser radiation provide a new, efficient method for creating, maintaining and heating plasmas



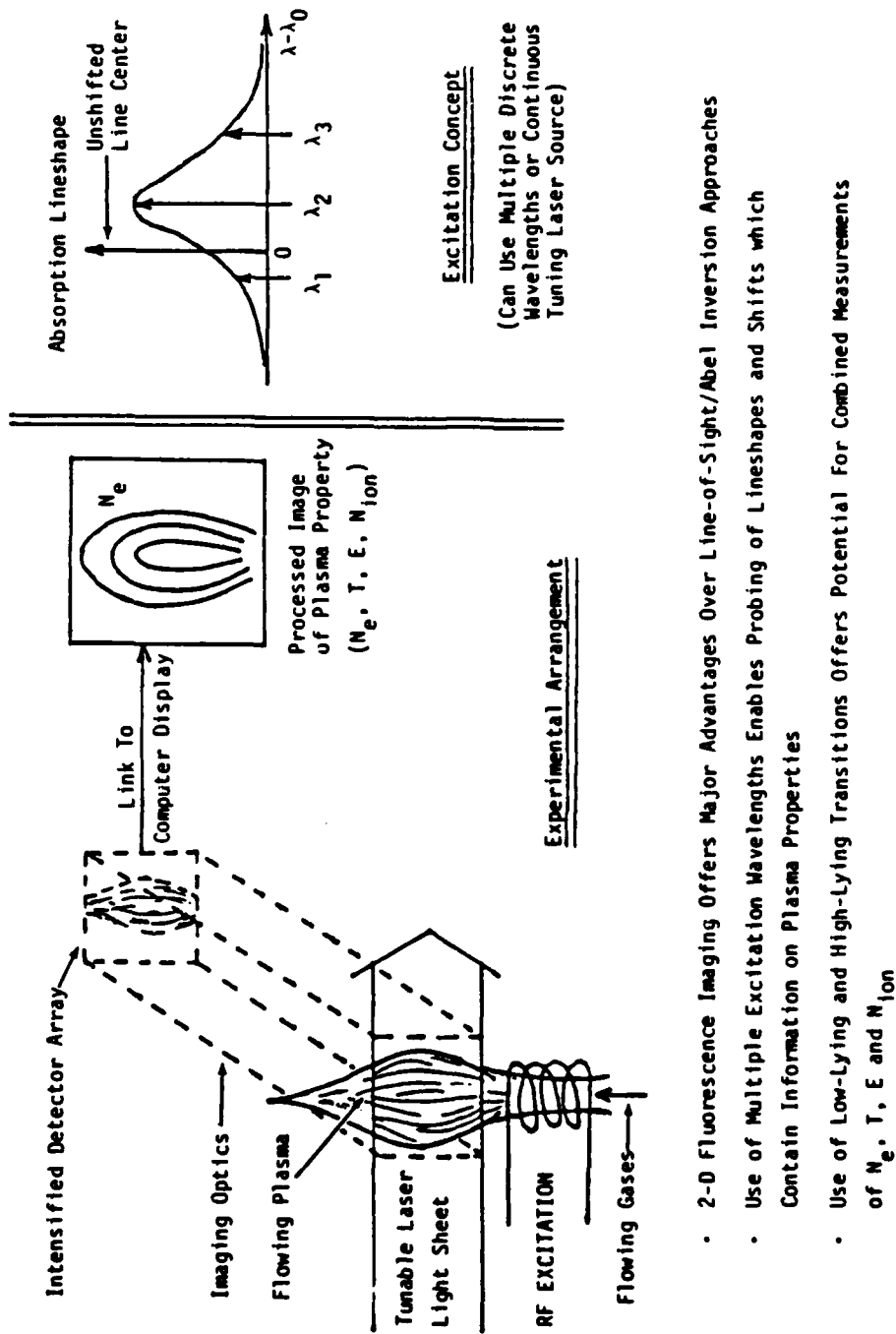
ENERGY LEVEL DIAGRAM OF  
IONIZATION PROCESS

- Superelastic laser energy conversion presents several advantages over inverse bremsstrahlung plasma heating
- Extremely rapid plasma heating is relevant to development of x-ray lasers
- Resonance excitation is well suited for studies of fundamental microscopic collisional and radiative processes in plasmas
- Technique relevant to production of plasma guid channels, needed to transport charged particle beams in future particle-beam fusion reactors

Fig. 2. Overview of concept of plasma generation using resonance laser radiation.

FLUORESCENCE-BASED IMAGING TECHNIQUES FOR QUANTITATIVE 2-D PLASMA MEASUREMENTS

- Use of array detectors to record planar laser-induced fluorescence offers potential for quantitative imaging of plasma properties



- 2-D Fluorescence Imaging Offers Major Advantages Over Line-of-Sight/Abel Inversion Approaches
- Use of Multiple Excitation Wavelengths Enables Probing of Lineshapes and Shifts which Contain Information on Plasma Properties
- Use of Low-Lying and High-Lying Transitions Offers Potential For Combined Measurements of  $N_e$ ,  $T$ ,  $E$  and  $N_{ion}$

Hanson/Stanford University

Fig. 3 Key features of PLIF as a plasma diagnostic technique.

and shift of the line, and hence  $n_e$  as well as possibly  $T$ . Some calculations to select optimum wavelength positions within a line, and to select suitable species and transitions, are already in progress to guide the experiments. In most respects, the experimental PLIF arrangement will be similar to that employed in our combustion research.

The second category of techniques to be explored is wavelength modulation spectroscopy. In brief, we wish to explore the utility, for plasmas, of the same approaches we are currently establishing for combustion measurements. The wavelength regions we can access with our fast-tuning cw UV/visible and ir laser systems are somewhat limited, and so one of our first activities is to become more familiar with the absorption/fluorescence spectra of the species accessible in plasma torch or low pressure plasma facilities. Once these plasma facilities are operational, we will conduct an absorption-based spectral survey of the plasma to identify suitable spectral features which can be used in our work to establish measurement strategies. Our hope is that fully resolved fluorescence measurements will yield, through the apparent linewidths or line shifts, information on plasma properties such as electron concentration or temperature, in addition to the local species concentration for the absorbing neutrals and ions.

### **Publications and Presentations**

None

### **Personnel**

Ronald K. Hanson	Professor, Mechanical Engineering
Phillip Paul	Research Associate, Mechanical Engineering
Doug Baer	Graduate Student, Mechanical Engineering (Ph.D. Expected in June 1988)
Jerry Seitzman	Graduate Student, Mechanical Engineering (Ph.D. Expected in June 1988)

## 2.6 Laser Interactions with Plasmas and Combustion Gases

### Introduction

Recently, as an outgrowth of our diagnostics research, we have become interested in various laser-material interactions such as laser interactions with plasmas, solid surfaces, particle (or droplet) clouds and combustible gases. Each of these areas pose scientifically interesting research problems pertinent both to the proper understanding of laser diagnostics which utilize high power lasers and to the broad field of energy conversion. Our diagnostics capabilities provide a convenient entry point to research in these areas, and accordingly we have initiated work on two topics: (1) laser-plasma interactions; and (2) interactions of tunable lasers with fuel-oxidizer systems for ignition of combustible mixtures or perturbation (energy addition or chemical changes) of already burned gases. The latter area is often described as photo-enhanced combustion.

### Status Report

In the area of laser - combustion interactions, we have one project recently initiated in the laboratory and another project still in the planning phase. The project now in the experimental phase involves laser ignition of flowing, premixed  $\text{CH}_4$  and air. The gases exit a 2 cm diameter tube, with a velocity of about 2 m/sec and a cold flow Reynolds number of 2700, and are ignited intermittently about 2 cm above the exit plane of the tube with a focussed (30 cm focal length lens) ArF laser. The laser wavelength and pulse energy are 193 nm and 100 mJ respectively. The monitoring diagnostic is a tunable XeCl laser set to a wavelength of 308.3 nm corresponding to the  $Q_1(4)$  transition of OH, and configured for planar laser-induced fluorescence imaging. The experiment is fairly repeatable, allowing accumulation of data for various time delays after the initial laser pulse and for different locations of the detection plane. The primary forms of OH data are: (1) time histories of the OH field in the central vertical plane passing through the center of the focal point; and (2) 3-d distributions of OH at fixed delay times, acquired by recording the PLIF images for different positions of the vertical plane.

Example results for time histories are shown in Figs. 1 and 2, the former providing information on a relatively short time scale and the latter showing results over longer times. These results are very recent and have not been fully interpreted, but the following qualitative picture of the primary processes is emerging. At very early times, within the brief (10 nsec) length of the laser pulse, the gas becomes ionized and then heated (by inverse Bremsstrahlung absorption) to a high temperature, essentially becoming a hot microplasma ball. Shortly thereafter, gasdynamics effects become important, including propagation of a shock wave and subsequent cooling of the plasma ball. At some point the combustible gas mixture begins to react, with chain-branching kinetics becoming important. If insufficient energy has been deposited, for the kinetics of that particular mixture, then ignition of the complete gas stream will not occur: alternatively, if enough energy is deposited then combustion extends downward to the burner surface and a stable flame appears. The overall process thus involves multiple phases, beginning with laser formation of a plasma, subsequent laser interaction with the plasma, and then transition to combustion with concomitant competition between chain branching and chain termination processes, and finally the interaction of flame propagation with buoyancy and turbulence effects. At fixed energy, the outcome is a function of equivalence ratio, with fuel lean and rich limits being observed for ignition.

These initial experiments are quite encouraging and serve both to highlight the range of fundamental phenomena which can be investigated with combined laser excitation and detection schemes and to demonstrate the utility of planar imaging for investigating complex combustion phenomena. We thus plan to continue our effort in this area. In planning our work, we will review the status of related research underway in other laboratories, particularly that of Miziolek at BRL who is currently supported by AFOSR and is a leader in this research area, in order to ensure that the programs are complementary in nature.

Our second project in the area of laser-combustion gas interactions, still in the planning stage, is based on the conviction that tunable lasers offer opportunities for stimulating and controlling chemical reactions in combustible systems. Basic research possibilities range from fundamental

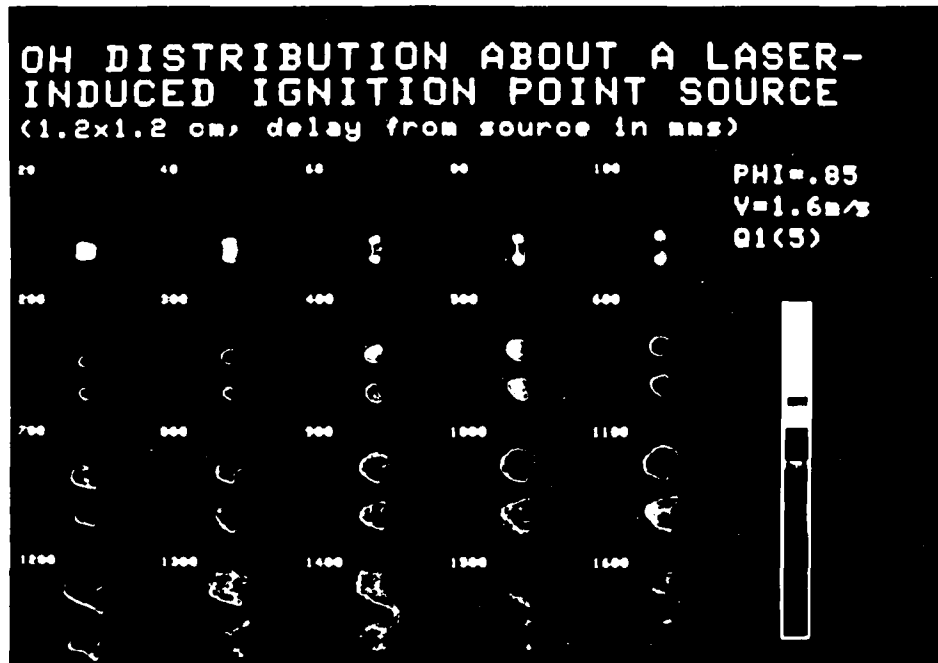


Fig. 1. Short-time sequence of planar OH distribution following deposition of laser energy at a point in a flowing  $\text{CH}_4$ -air mixture. Times are in microseconds, beginning at 20  $\mu\text{sec}$  after the pulse, and the region viewed is 1.2 x 1.2 cm.

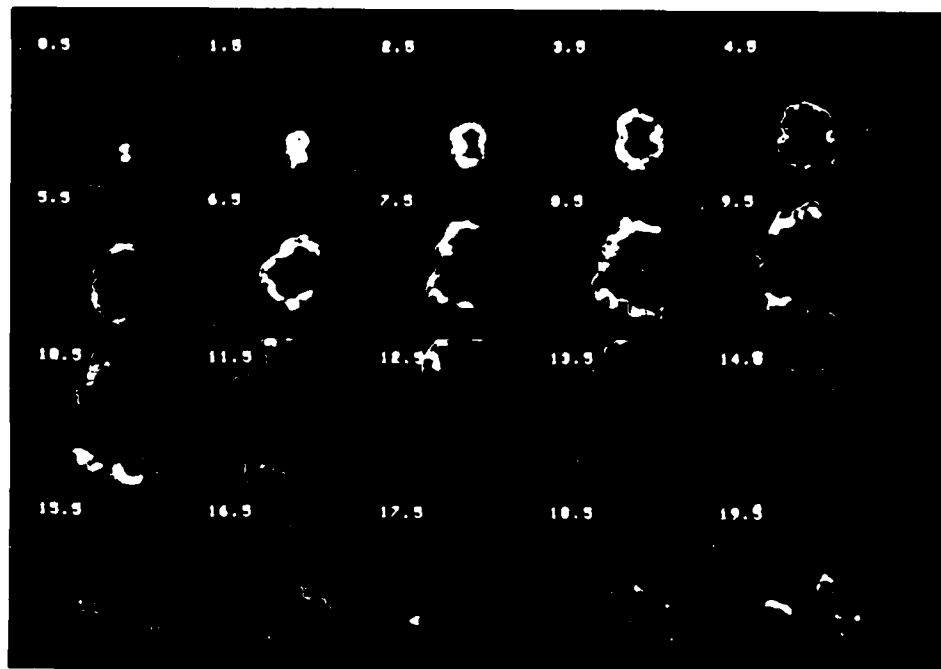


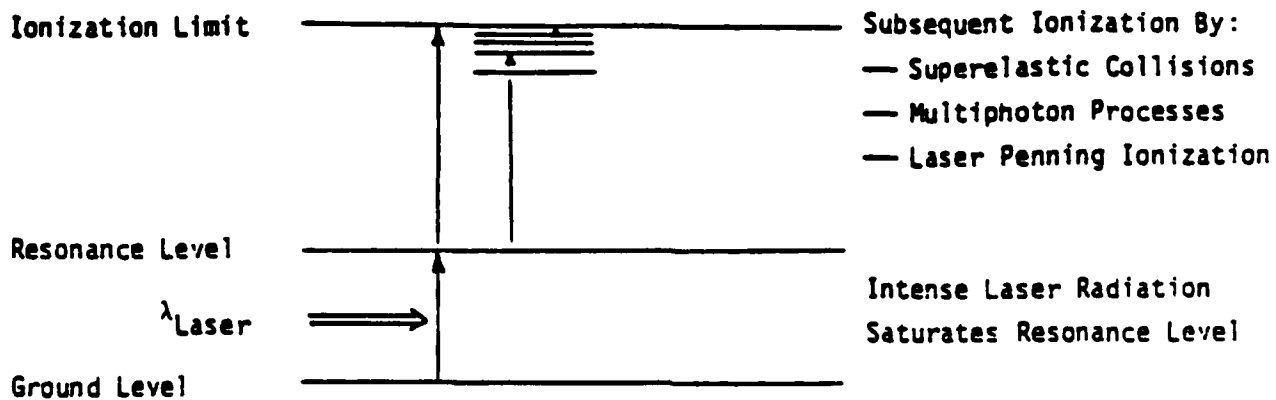
Fig. 2. Long-time sequence of planar OH distribution following deposition of laser energy at a point in a flowing  $\text{CH}_4$ -air mixture. Times are in milliseconds, beginning at 0.5 milliseconds, and the region viewed is 8 cm x 8 cm.

studies of chemical kinetics (including ignition) to questions of beamed energy transfer to combustion media (for propulsion applications or safety/damage studies). With regard to chemical kinetics, for example, we believe that laser photolysis using a tunable excimer laser together with shock wave heating offers exciting prospects for a unique new approach to studying reactions of reactive radical species at high temperature. The basic idea is to shock heat gases and then trigger specific chemical reactions in the high temperature gases using tuned-laser photolysis. In the area of radiative coupling to combustible media there are interesting fundamental and practical questions as to whether tuned laser radiation could (by influencing the temperature or radical concentrations) be used for improved control of combustion phenomena, for example in damping of oscillatory behavior or in enhancing ignition or flame stabilization in difficult flows (e.g. supersonic combustion). Finally we note the need for fundamental studies of radiative absorption coefficients at very high intensity levels in high temperature gases where non-linear absorption phenomena will become important. At present our work involves design of a first-generation laser photolysis experiment in a shock tube.

With regard to laser interactions with plasmas for either production or perturbation of a plasma, we are pursuing the concept of plasma generation using resonant laser excitation, which should provide an efficient method for creating, maintaining, and heating plasmas. A schematic diagram highlighting this idea and its attributes is shown in Fig. 3 (also shown as Fig. 2 in Section 2.5). This approach provides a means of studying fundamental microscopic collisional and radiative processes involved in plasma production and needed in modeling plasma behavior in a wide range of applications. Our literature review suggests that limited experimental work has been devoted to the study of this new class of dense plasma production which provides for example extremely rapid heating rates. The fast changes in free electron temperature achievable create the possibility of providing an intense source of high frequency (short wavelength) radiation. Additionally the superelastic laser energy conversion has several potential advantages over inverse Bremsstrahlung interactions as a means for coupling laser energy into a plasma.

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Fig. 3. Overview of concept of plasma excitation using resonance laser radiation.

Our current planning involves consideration of possible facility designs and selection of experiments suitable for identifying and quantifying important collisional and radiative interactions present when a gaseous medium is subjected to a sudden pulse of intense laser radiation tuned to the resonance transition of an atomic species. Precise monitoring of the time-dependent behavior of the bound states of the atom beginning with the saturation in the lower levels and extending through ionization burn out, would be used to provide an understanding of the fundamental physical processes taking place in these laser-excited plasmas. Species of interest are atomic sodium argon or hydrogen heated in a static cell or in a flowing system using either microwave heating or our induction-heated plasma torch. Laser sources would include a tunable pulsed dye laser for excitation and both a tunable cw and pulsed dye laser for fluorescence-based detection of the atomic states and plasma parameters.

#### **Publications and Presentations**

None

#### **Personnel**

Ronald K. Hanson	Professor Mechanical Engineering
Jerry Seitzman	Graduate Student Mechanical Engineering (Ph.D. expected in June 1987)
Phillip Paul	Research Associate, Mechanical Engineering

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