Using Planar Laser-Induced Fluorescence To Study Plasma Turbulence

The successful development and optimization of fusion power sources will depend largely upon learning more about plasma turbulence and its relation to transport. Gaining a greater knowledge of plasma-edge turbulence is key, as the transport of particles near the plasma's edge has a profound effect on global plasma confinement. It is in this region that the boundary values for plasma temperature and density are established, values from which internal gradients are subsequently determined. Unfortunately, theories often fail to predict transport under turbulent conditions. Researchers have now begun to utilize high-performance intensified CCD (ICCD) cameras for innovative studies designed to evaluate the potential of using planar laser-induced fluorescence (PLIF), an optical diagnostic technique, for the experimental visualization of plasma-edge turbulence. It is hoped that data acquired via PLIF imaging will lead to improved turbulence-transport models. This note discusses the recent work of Fred M. Levinton (Nova Photonics, Inc., Princeton, NJ) and Fedor Trintchouk (Princeton Plasma Physics Laboratory, Princeton, NJ).

Tokamak and PLIF Basics

One of the most promising (and successful) confinement fusion concepts today, the tokamak is a toroidally shaped magnetic field produced by a set of poloidally constructed electromagnets. As a rule, tokamak experiments use deuterium and tritium isotopes of hydrogen since this combination requires the lowest possible fusion temperatures. A current of up to several million amperes flows through the plasma, which is heated in short pulses by high-energy particle beams or radio-frequency waves to maintain temperatures in excess of one hundred million degrees centigrade. Ohmic heating and magnetic compression also help achieve the temperatures necessary for fusion.

Large temperature and density gradients near the edge of the plasma contribute to transport greater than that predicted by standard, non-turbulent theories. As Levinton and Trintchouk note in their January 2001 paper entitled "Visualization of plasma turbulence with laser-induced fluorescence" (Review of Scientific Instruments, vol. 72, #1, 898-905), although various numerical simulations and diagnostic techniques address turbulence-driven transport, the picture is still far from complete. The relation between turbulence and transport needs to be understood more fully in order to improve global plasma confinement and ultimately better the performance of fusion devices.

Levinton and Trintchouk have chosen to evaluate the potential use of planar laser-induced fluorescence to investigate plasma-edge turbulence. PLIF is a technique in which a laser source is tuned to the absorption line of an atomic or molecular species present in a given plasma. The tunable laser source is then utilized to create a sheet of light that traverses the field, exciting fluorescence via a resonant energy-level-transition process. A series of two-dimensional images is acquired by an ICCD camera. Unlike other diagnostic techniques used to examine plasma turbulence, PLIF provides high-resolution images of the phenomena occurring throughout an entire plane of interest.

Experiment Setup

The Princeton Plasma Physics Laboratory (http://www.pppl.gov) is a collaborative national center for fusion energy and plasma physics research managed by Princeton University for the U.S. Department of Energy. As described in their paper, Levinton and Trintchouk are using the lab's magnetic nozzle experiment (MNX) helicon plasma source to test and evaluate the PLIF concept. With a magnetic field of 1.5 to 3.5 kG, the MNX can run steady-state in a working gas of argon, krypton, or xenon.

The setup also utilizes a Boswell-type double saddle antenna (length = 10 cm; diameter = 4.5 cm) constructed from 0.125" copper tubing, which is wrapped on the outside of a Pyrex tube. The antenna and tube are air-cooled to under 100°C. A radio frequency (rf) power amplifier is operated at 0.3 to 1.0 kW at a frequency of 27 MHz, while a matching circuit comprising capacitors in series and parallel with the antenna is encased in an rf-shielded box next to the antenna. The resultant plasma column (length = 1.7 m; diameter = 2 cm) has a density of 5×10^{17} to 1×10^{20} m^{-3}. Electron temperature is ~5 eV and ion temperature is ~0.5 eV.

Since turbulence is usually far longer in scale parallel to the magnetic field than perpendicular to it, a laser sheet beam that allows light to be viewed parallel to the field direction is used. This enables imaging perpendicular to the magnetic field and integration along the sight-line without resolution loss. As Figure 1 shows, the laser propagation direction is perpendicular to the plasma column and magnetic field direction. A reentrant mirror situated in the vacuum vessel reflects the light towards the ICCD camera, a Princeton Instruments (PI) PI-MAX™, providing an axial view of the plasma.

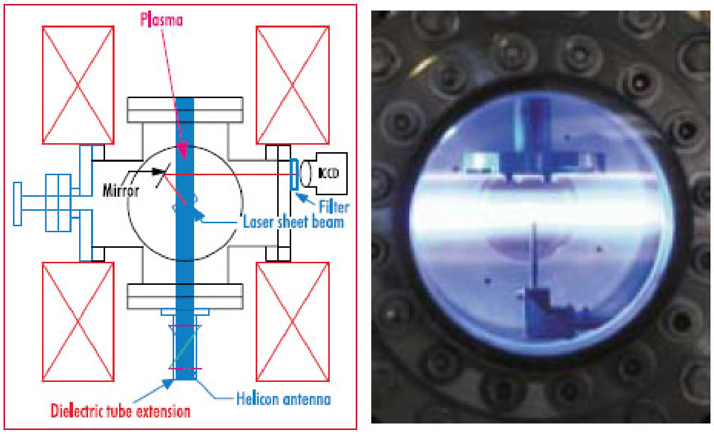


Figure 1.

The diagram shows the laser and collection optics onthe MNX plasma source, while the image is a view from the Princeton Instruments PI-MAX intensified CCD camera.

Ion Selection

Many factors must be considered when selecting an appropriate ion for PLIF measurements, including the laser's ability to attain the pump wavelength, the power needed for saturation, and the intensity of the fluorescence signal. Performing the PLIF at saturation is important, as doing so ensures the maximum signal (and optimal signal-to-noise ratio). Furthermore, when operating at saturation, small fluctuations in laser power cause very little change in the fluorescence signal. Thus, the chance of mistaking any spatial variations from the laser power intensity for density variations in the plasma is practically eliminated.

Through both numerical and experimental means, Levinton and Trintchouk have identified several three-level schemes for Ar II, Kr II, and Xe II that provide the desired transitions within the visible wavelength range. (In a three-level scheme, the laser is tuned to one wavelength and the fluorescence is observed at another. An interference filter makes it easy to distinguish between stray light and the fluorescence signal.)

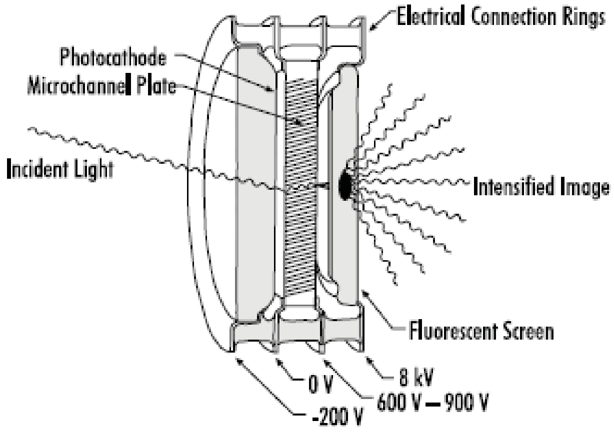
To test these ions, a tunable Alexandrite laser capable of providing the ~104 W required for saturation is used. The pulse width of the laser is approximately 80 ns with a repetition rate of 10Hz. The Alexandrite laser is a flashlamp-pumped, Q-switched oscillator stage that is tunable from 700 to 800 nm at its fundamental wavelength and from 350 to 400 nm with second harmonic generation. The intermediate range from 400 to 700 nm is covered by tuning the laser with a specially configured Raman converter. A Princeton Instruments VersArray™ CCD camera (with a 512 x 512-pixel array) from Roper Scientific is utilized to provide feedback during the precision tuning procedure.

After testing several ion schemes using an avalanche photodiode (APD) detector, an Ar II transition with a pump wavelength at 378.6 nm and fluorescence at 488.0 nm was deemed the most advantageous for the experiment. While each of the schemes tested produced a fluorescence signal significantly higher than the level of background light, the aforementioned Ar II scheme yielded a signal about 10x as great as the background.

The detection system that collects the fluorescence signal is, of course, a critical component of the PLIF experiment. The Princeton Instruments PI·MAX camera utilized by Levinton and Trintchouk is a high-performance instrument that features an image intensifier (see Figure 2) coupled to a thermoelectrically cooled CCD. Light is collected by a 58-mm f/1.2 lens, imaged onto the image intensifier, and transmitted via a tapered fiberoptic bundle to a 512 x 512-pixel front-illuminated detector.

Figure 2.

Components of an image intensifier. For a discussion of image intensifiers, refer to Princeton Instruments Technical Note: Introduction to Image Intensifiers for Scientific Imaging.

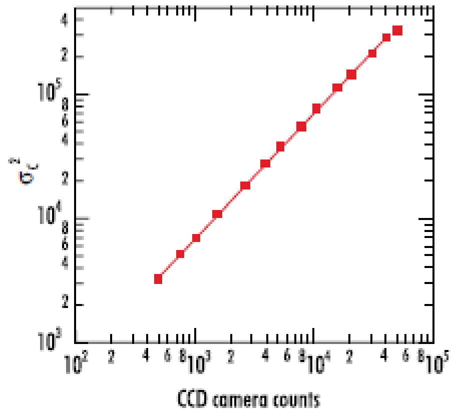


Levinton and Trintchouk cite a number of reasons for using the PI·MAX camera in their work. First and foremost, the low-noise detection system can be gated. A gating ratio exceeding 106:1 as well as a gate width of about 100 ns for a laser pulse width of 80 ns allow the PI·MAX to effectively minimize the leakage of plasma background light onto the CCD. The high gating ratio is needed because the CCD's readout time per frame is between 0.1 and 1s (depending on frame size) and the pixels are able to integrate light as the detector is being read out. Gating the intensifier prevents the CCD from detecting too much background signal.

Figure 3.

Data acquired by Levinton and Trintchouk illustrates the outstanding linearity provided by the PI·MAX system.

Levinton and Trintchouk observe that the detection system provides linear response through virtually the entire CCD readout range (see Figure 3). The camera is also capable of remote operation via a fiberoptic interface, which is useful (and often required) when working in high-current /high-magnetic-field environments.



In addition, the spatial resolution provided by the PI·MAX camera is also important to the PLIF experiment. Taking into account the lens, the image intensifier's 18-mm photocathode, the fiberoptic taper's reduction factor of 1.27, and the CCD's 19 x 19-_m pixels, the optical system magnification is a factor of 1/8.49 onto the detector. This figure yields a corresponding spatial resolution of 0.161 mm/pixel in the plasma, which translates to 0.8 mm when using 5 x 5 pixel-binning.

Figure 4 shows the results of imaging the PLIF emission. Each view represents an average of 20 frames of the same data. Large-scale structures are studied by subtracting individual frames from the 20-frame average to identify deviations (see Figure 5). Small-scale turbulence, meanwhile, is investigated by calculating standard deviations and performing two dimensional Fourier transforms using data from sub-regions of similar pairs of images.

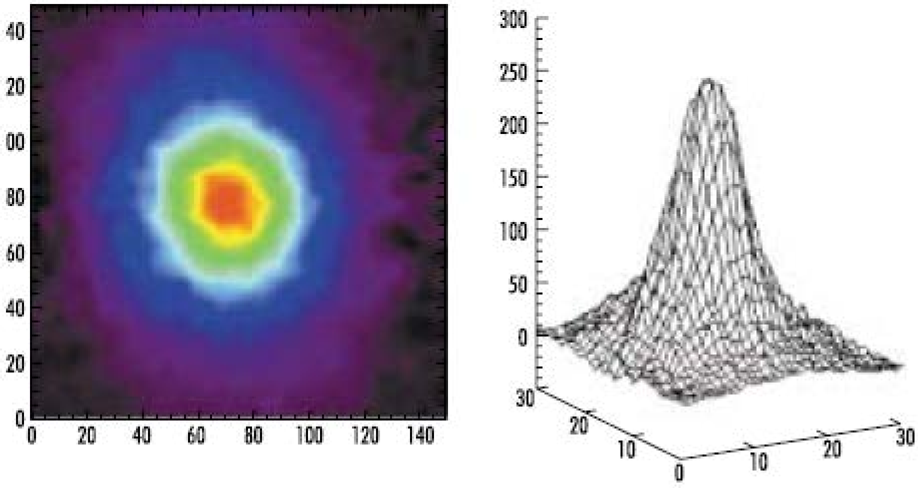


Figure 4.
This PLIF emission data, a 20-frame average, corresponds to 23.3mm along each dimension and clearly displays increasing density towards the center of the plasma.

According to Levinton and Trintchouk, PLIF imaging holds substantial promise in this area of research. Their work demonstrates that the technique can successfully measure structures and turbulence in a plasma with unprecedented temporal and spatial resolution. Future efforts will include testing the method on other devices using argon seeding to provide the ions required for PLIF. It is suggested that since passive edge measurements of visible emissions have already been utilized to observe plasma structures, an argon gas puff could eventually be used to seed the edge region of a fusion plasma.

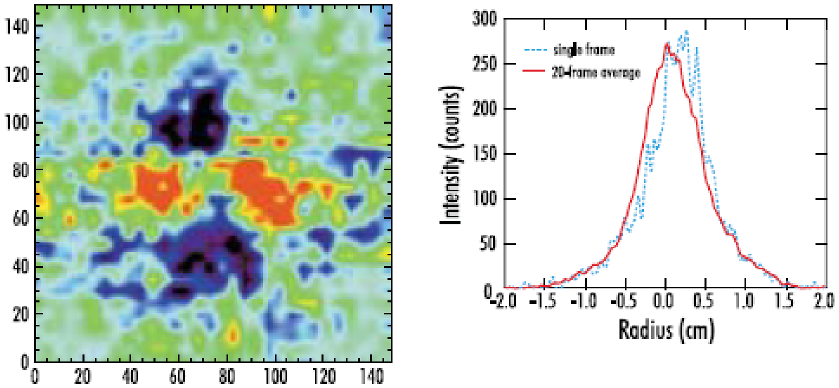


Figure 5.
Comparing the intensity profiles of an averaged image and a single frame provides information about large-scale structures (20-frame image shown).

Figures 1, 3, 4, and 5 courtesy of Fred M. Levinton (Nova Photonics, Inc.) and Fedor Trintchouk (Princeton Plasma Physics Laboratory).

References

1. A. Ben-Yakar and R.K. Hanson. Hypervelocity combustion studies using simultaneous OH-PLIF and Schlieren imaging in an expansion tube.AIAA Paper 99-2453, 35th AIAA Joint Propulsion Conference, Los Angeles, CA, June 1999.

2. A. Ben-Yakar. Experimental investigation of mixing and ignition of transverse jets in supersonic crossflows. Ph.D. Thesis, Department of Mechanical Eng., Stanford University, December 2000.

PLIF images courtesy of Drs. Adela Ben-Yakar and Ronald K. Hanson (Stanford HTGL).