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 independently controlled electromagnets. As a rule, theoretical experiments use deuterium and tritium isotopes of hydrogen since the combination releases the lowest possible fusion temperatures. A current of up to several million amperes flows through the plasma, which is heated to 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 to 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, neutral-fluid theorems. 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, 199-205), although various numerical simulations and diagnostic techniques address turbulence-driven transport, the picture is still far from complete. The variations 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 ~5 eV and ion temperature is ~0.5 eV.

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 that paper, Levinton and Trintchouk are using the kdi’s magnetic racetrack experiment (MRX) tokamak plasma source to test and evaluate the PLIF concept. With a magnetic field of 1.5 to 3.5 TG, the plasma can be steadily driven in a working gas of argon, neon, or xenon.

The setup also utilizes a Brewster-type double-saddle scheme (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 coupler is operated at 0.3 to 1.0 V at a frequency of 27 MHz, while a matching circuit comprising capacitors in series and parallel with the antenna is arranged in an RF-diffused line next to the antenna. The resultant plasma column (length = 1.7 m; diameter = 2 cm) has a density of 5x10^18 m^-3 electron temperature is ~10 eV and ion temperature is ~0.5 eV.

Since turbulence is usually for 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 sightline without resolution loss. As Figure 3 shows, the laser propagation direction is perpendicular to the plasma column and magnetic field direction. A neutral mirror situated in the vacuum vessel reflects the light towards the ICCD camera, a Princeton Instruments PI-MAX™ CCD camera (with a 512 x 512 pixel array) from Roper Scientific is utilized to provide feedback during the precise-tuning procedure.

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 to saturate, 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 minimizing 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.)

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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.

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The setup also utilizes a bow-tie type double-saddle resonator (length = 10 cm; diameter = 4.5 cm) constructed from 0.125” copper tubing, which is wrapped on the outside of a Pyrex tube. The resonator is 70 cm in length and was fabricated using standard laboratory techniques. The plasma column (length = 1.7 m; diameter = 2 cm) has a density of 5x10^19 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 magnetic field and integration along the sightline without resolution loss. As Figure 1 shows, the laser propagates parallel to the plasma column and magnetic field direction. A neon lamp situated in the vacuum vessel reflects the light towards the ICCD camera, a Princeton Instruments PI-MAX intensified ICCD 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 immunity 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 instability 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 the 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 these two wavelengths.)

To test these ions, a tunable Albrecht Lin laser capable of providing the 10.7 W required for saturation is used. The pump wavelength of the laser is approximately 80 ns with a repetition rate of 10 Hz. The Albrecht Lin is a broadband, Q-switched oscillator-tunable laser that is tunable from 700 to 800 nm in its fundamental wavelength and from 350 to 500 nm with a 2% harmonic generation. The intermediate range from 600 to 700 nm is covered by tuning the laser with a specially configured Raman scheme. A Princeton Instruments Tektronix™ CCD camera with a 512 x 512 pixel array from Roper Scientific is utilized to provide feedback during the precise tuning procedure.

The detection system that collects the fluorescence is a Princeton Instruments PI-MAX camera with a 512 x 512 pixel array from Roper Scientific, capable of providing the ~10^-6 sensitivity required to achieve high-signal-to-noise ratio measurements. A gating scheme is needed because this CCD’s readout time per frame is between 0.1 and 1 s (depending on the frame rate) and the plateau time is generally in the range of 10-20 ns, which is much longer than the level of background light, the aforementioned Ar II scheme yielded a signal about 10x as great as the background.

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 fiber optic interface, which is useful (and often required) when working in high-current / high-magnetic-field environments.

### The detection system that collects the fluorescence signal is, of course, a critical component of the PLIF experiment. The Princeton Instruments PI-MAX cameras utilized by Levinton and Trintchouk is a high-performance instrument that features an image intensifier (see Figure 2).

Figure 2. Components of an image intensifier. For a discussion of image intensifiers, refer to Roper Scientific Technical Note #3, “Image Intensifier: BSi Scientific Imaging.”

Levinton and Trintchouk cite a number of reasons for using the PI-MAX cameras in their work. First and foremost, the low-noise detection system can be gated. A gating ratio exceeding 10^6:1 is available, as is a gate width of about 100 ns for a laser pulse width of 80 ns to effectively minimize the leakage of background signal into the CCD. This high-gating ratio is needed because this CCD’s readout time per frame is between 0.1 and 1 s (depending on the frame rate) and the plateau time is generally in the range of 10-20 ns, which is much longer than the level of background light, the aforementioned Ar II scheme yielded a signal about 10x as great as the background.

The PI-MAX ICCD camera system was used by Levinton and Trintchouk to study plasma turbulence. The experiment setup and laser-induced fluorescence (PLIF) technique are described in detail in their paper. The Princeton Plasma Physics Laboratory (PPPL) is a collaborative national center for fusion energy and plasma physics research managed by Princeton University for the U.S. Department of Energy. The setup utilizes a Bow-tie type double-saddle resonator (length = 10 cm; diameter = 4.5 cm) constructed from 0.125” copper tubing, which is wrapped on the outside of a Pyrex tube. The resultant plasma column (length = 1.7 m; diameter = 2 cm) has a density of 5x10^19 m^-3. Electron temperature is ~5 eV and ion temperature is ~0.5 eV.

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