Development of the motional Stark effect with laser-induced fluorescence diagnostic

E. L. Foley[a]
Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey

F. M. Levinton
Nova Photonics, Inc., Princeton, New Jersey

(Presented on 19 April 2004; published 1 October 2004)

The motional Stark effect diagnostic (MSE) is presently a widely accepted technique for measuring the magnetic field pitch angle in high field (>1 T) plasma devices. A hydrogen neutral beam passing through a magnetic field perceives $\boldsymbol{v}\times\boldsymbol{B}$ electric field, and its Balmer-α spectral emission is split and polarized by the linear Stark effect. The technique cannot be readily used at lower magnetic fields, due to loss of polarization fraction when lines of different polarization overlap due to line broadening which is on the order of the separation. This article describes the development of a technique to extend the capability of MSE to include lower fields (0.01 T and up) and the field magnitude as well as direction. The technique employs laser-induced fluorescence on a diagnostic neutral beam. The narrow-band laser and low energy spread neutral beam allow the observed linewidths to be significantly narrower than these observed from previously employed collisionally induced fluorescence systems. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1779616]

I. INTRODUCTION

The motional Stark effect diagnostic (MSE) has been widely applied to measure magnetic field pitch angle in high-field toroidal plasma devices[1–3] since its development.[4] This technique employs observation of the polarization direction of H-α emission from neutral hydrogen beams. As the beam neutrals move with high velocity, v, through the magnetic field in a plasma, **B**, they experience a Lorentz electric field, $\mathbf{E}=\mathbf{v}\times\mathbf{B}$, in their reference frame. It is this perceived electric field which causes the observed Stark splitting of the emission spectrum. The $\Delta m=0$ transitions (π) are polarized differently from the $\Delta m=\pm 1$ transitions (σ) with respect to the perceived electric field. When those components can be resolved, the magnetic field pitch angle can be determined. The distance between lines in the Stark shifted spectrum is linearly proportional to the magnitude of the electric field, and this measurement can be used to determine the magnetic field magnitude.[5,6]

At present, MSE measurements are limited at low magnetic fields by the overlap of adjacent lines of differing polarization. In previous MSE implementations, when the field is below ~1 T, the linewidths begin to become comparable to the separation, and the ability to make a reliable measurement is lost. As comparatively low-field alternative confinement concepts[7,8] are being tested throughout the fusion community, the need for the extention of measurement capability is great. A number of techniques for overcoming this low-field limitation are under development,[9–11] but none has yet succeeded in mapping the magnetic field magnitude or q-profile in a plasma at low field and density regimes of interest.

The dominant sources of line broadening in the Stark spectrum are usually energy spread and divergence of the neutral beam, and geometrical broadening due to collection optics. The technique described in this article attempts to overcome both of these challenges using a low axial energy spread neutral beam, and laser-induced fluorescence (LIF). The use of LIF with a narrow band laser allows the measured linewidth to be dictated by the laser and beam characteristics, rather than geometrical broadening in the collection optics.

The magnetic field magnitude can be measured by scanning the laser wavelength or beam voltage in time as the LIF signal is recorded. For a pitch angle measurement, the laser wavelength and beam voltage can be set to match a specified Stark component, and the laser polarization rotated in time. The result is a fluorescence signal varying in time at the same frequency as the polarization rotation, but with phase shift indicating the pitch angle value. This article presents initial data and describes the progress to date of the development of this technique.

II. NEUTRAL BEAM SOURCE

The neutral beam source, described in more detail in a previous publication,[12] was designed and built in collaboration with the Plasma and Ion Source Technology Group at Lawrence Berkeley Laboratory. A diagram of the present experimental setup is shown in Fig. 1. The beam source has a multi-cusp permanent magnet geometry and an external 2.5 turn, water cooled rf antenna. The source volume is roughly cylindrical with length 87 mm and inner diameter of

[a]Author to whom correspondence should be addressed; electronic mail: efoley@princeton.edu

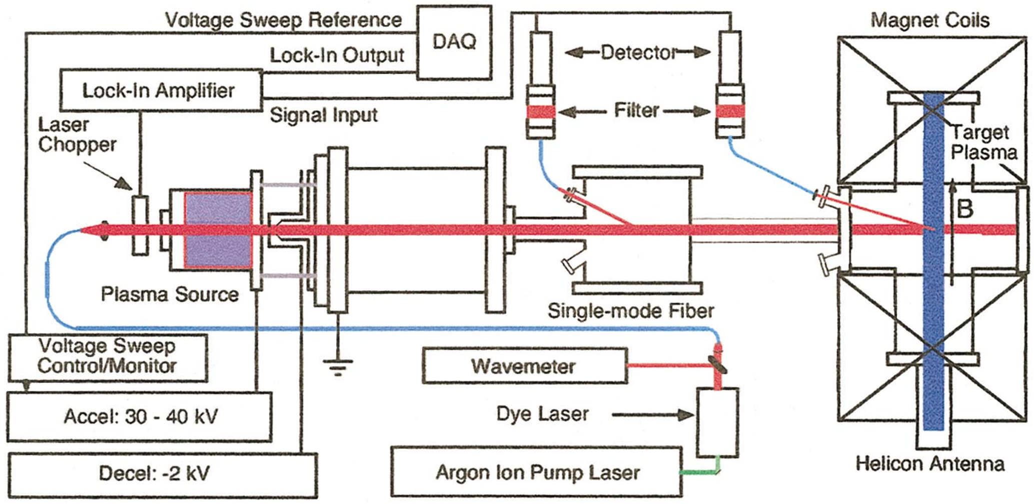

FIG. 1. (Color) Diagram of experimental setup.

60–75 mm. The 13.56 MHz rf generator (model ENI 1250) was chosen for its low amplitude modulated (AM) noise specification. AM noise at multiples of the power line frequencies contributes ~1 V of energy spread to the beam, and higher frequency noise from the generator's switching power supply contributes another ~2 V to the beam energy spread. The source is equipped with a magnetic filter to reduce energy spread due to plasma potential variation over the source volume. Plasma potential measurements performed on the source with a rf compensated Langmuir probe suggest that the ion energy spread in the source due to axial potential variation is ~5 V. Radio frequency pickup on the acceleration potential was reduced through careful shielding and filter capacitors to ~1 V. The source runs reliably from 10 to 100 mT of hydrogen gas, with input rf power of 400–1200 W. Typical operating parameters are 30 mT and 600 W rf power. It has produced a current of over 30 mA/cm^2 and has a high full energy fraction of up to 85%.

III. BEAM ACCELERATION SYSTEM

A beam of hydrogen ions is extracted from the source using a three-electrode system: acceleration voltage, deceleration voltage, and ground. The accel, a large positive voltage with respect to ground, draws the ions out of the plasma source. The decel, a negative voltage, prevents electrons from the neutralization region from being accelerated into an oppositely traveling beam which would damage the back of the source. Typical operating parameters for this work are 30–35 kV accel voltage and −2 to −1.7 kV decel voltage. The accel power supply was custom modified by engineers at Princeton Plasma Physics Laboratory (PPPL) to have extremely low ripple of <1 V via an active feedback system for low frequency ripple and notch filters for switcher noise, and to have the capability for an externally applied voltage sweep. The accelerated ions pass through a region of neutral hydrogen gas following the electrode column, where they make charge-exchange collisions and become neutral. Presently, the neutralization region is allowed to fill with gas from the beam source, though the apparatus is capable of gas injection in the neutralization cell. The electrodes are circular in cross section, with diameter 1.2 cm. The neutral beam full width at half maximum has been measured with a Farady probe at a distance of ~1 m downstream from the acceleration region, and is found to be ~1.4 cm.

IV. TUNABLE DYE LASER

The laser employed in this work is a Coherent 899-05 ring dye laser, with an upgraded dye jet and pump from Radiant Dyes. DCM dye is used with EPH solvent, giving output. power of up to 800 mW at ~650 nm, appropriate for matching the Doppler-shifted H-α line. A Burleigh wavemeter 1500 is used to measure the output wavelength, and the spectral characteristics are monitored with a Fabry-Pérot cavity. An optical isolator is inserted into the beam path before coupling to a single mode (or polarization maintaining, depending on the experiment) fiber which carries the beam across the room to the experimental apparatus.

V. HELICON PLASMA SOURCE

The target plasma for the development of this diagnostic is also used in the MNX experiment at PPPL.[13,14] The argon plasma is produced by a double-saddle-type helicon antenna with rf at 27 MHz and 1 kW. The plasma profile is ~2 cm in diameter with a peak density of $\sim 10^{13}$ cm^{-3}. The magnetic field is produced by up to 22 L-2 coils which can be connected in various configurations. The resulting field at the center of the plasma can be varied from as little as 0.01 T to as high as 0.3 T.

VI. INITIAL LIF MEASUREMENT SETUP

The experimental setup for the results reported here is shown in Fig. 1. (Note: Items in the figure are not shown at the correct relative scale.) The laser beam is expanded and collimated to approximately match the neutral beam diameter and divergence. An antireflection coated window in the rear of the neutral beam source allows the laser to pass through. The laser is tuned in wavelength to approximately

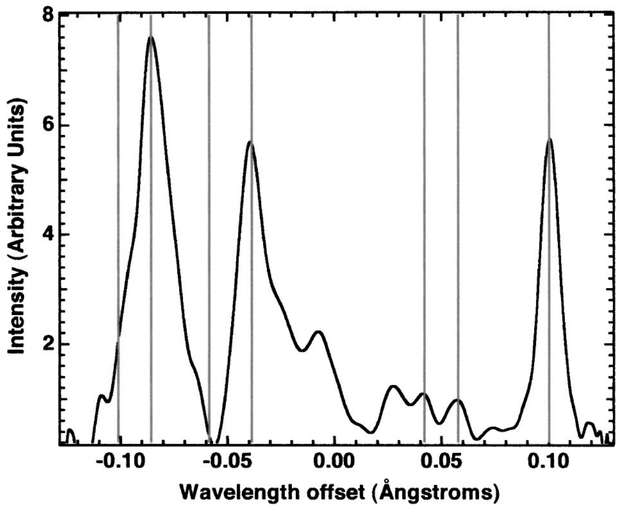

FIG. 2. LIF data of beam in neutral gas. Gray bars are Doppler-shifted Balmer-α fine structure line locations.

match the Doppler-shifted $H-\alpha$ transition in the beam, and then the beam voltage is swept over entire spectral region of interest. For the fine-structure data shown in Fig. 2, this range is approximately ±150 V. For the full Stark spectrum at 0.3 T of magnetic field, the required sweep would be more than 2 kV. The fluorescence signal may be collected in a magnetic field free region of the beamline, or in the center of the helicon plasma. Collection optics and fiber bundles are set up in both locations. The fiber bundles terminate at optics that focus the collected light onto the active areas of two avalanche photodiodes (APDs) after passing through appropriately chosen interference filters. The APD signal is fed to a Stanford Research Systems model SR830 lock-in amplifier, referenced to a chopper which modulates the laser light before it enters the optical fiber.

VII. RESULTS

Figure 2 shows some data obtained in a background of neural gas, with no plasma. The locations of the lines match reasonably well to those of the $H-\alpha$ fine structure lines, but the amplitudes are not consistent with those that would be expected for a statistical distribution of the electron population levels. This is evidence that l' mixing is weak in the beam's collisions with neutral gas, and is expected to be different in the presence of a plasma. Noise was smoothed out of this data for ease of viewing. Before smoothing, a typical signal-to-noise ratio is presently ~3—accounting for what appear to be spurious peaks in the figure. The data were taken at the first viewing port shown in Fig. 1, at approximately 1 m from the beam source.

VIII. FUTURE PLANS

In summary, a diagnostic for magnetic field magnitude and pitch angle is under development and has achieved preliminary results. Presently, high beamline gas pressure is limiting the neutral beam collimation and energy spread in the plasma chamber. These issues must be resolved in order to test the diagnostic in plasma and magnetic fields.

ACKNOWLEDGMENTS

This work is supported by Nova Photonics, Inc., under U.S. Department of Energy Grant No. DE-FG02-01ER54616. E.L.F. gratefully acknowledges the support of a Hertz Foundation Graduate Fellowship. The authors would like to thank D. DiCicco, V. Corso, D. Card, and J. Taylor for their excellent technical support, and E. Fredd, N. Greenough, and J. Gumbas for power supply design and implementation, and K. N. Leung, S. K. Hahto, S. T. Hahto, and S. Wilde of LBNL for useful discussions in addition to the development of the neutral beam source, and L. Grisham and P. Efthimion for useful discussions.

[1] D. Wroblewski, K. H. Burrell, L. L. Lao, P. Politzer, and W. P. West, Rev. Sci. Instrum. **61**, 3552 (1990).
[2] F. M. Levinton, Rev. Sci. Instrum. **63**, 5157 (1992).
[3] B. C. Stratton, D. Long, R. Palladino, and N. C. Hawkes, Rev. Sci. Instrum. **70**, 898 (1999).
[4] F. M. Levinton R. J. Fonek, G. M. Gammel, R. Kaita, H. W. Kugel, E. T. Powell, and D. W. Roberts, Phys. Rev. Lett. **63**, 2060 (1989).
[5] R. C. Wolf, L. G. Eriksson, M. Von Hellermann, R. Konig, W. Mandl, and F. Porcelli, Nucl. Fusion **33**, 1835 (1993).
[6] D. Craig, D. J. Den Hartog, G. Fiksel, V. I. Davydenko, and A. A. Ivanov, Rev. Sci. Instrum. **72**, 1008 (2001).
[7] R. N. Dexter, D. W. Kerst, T. W. Lovell, S. C. Prager, and J. C. Sprott, Fusion Technol. **19**, 131 (1991).
[8] M. Peng, J. Fusion Energy **17**, 45 (1998).
[9] F. M. Levinton, Rev. Sci. Instrum. **70**, 810 (1999).
[10] E. A. Reinecke, R. J. Fonck, and T. A. Thorson, Rev. Sci. Instrum. **72**, 1000 (2001).
[11] M. Gilmore, W. A. Peebles, S. Kubota, X. V. Nguyen, and A. Ejiri, Rev. Sci. Instrum. **74**, 1469 (2003).
[12] S. K. Hahto, S. T. Hahto, Q. Ji, K. N. Leung, S. Wilde, E. L. Foley, L. R. Grisham, and F. M. Levinton, Rev. Sci. Instrum. **75**, 355 (2004).
[13] S. A. Cohen, N. S. Siefert, S. Stange, R. F. Boivin, E. E. Scime, and F. M. Levinton,Phys. Plasmas **10**, 2593 (2003).
[14] F. Levinton and F. Trintchouk, Rev. Sci. Instrum. **72**, 898 (2001).