# Progress on the motional Stark effect with laser-induced fluorescence diagnostic (invited)

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The motional Stark effect with laser-induced fluorescence (MSE-LIF) diagnostic is presently under development as a new technique for measuring magnetic field pitch angle and magnitude in plasmas in a wide range of conditions. The technique is based on the observation of LIF from the set of H-alpha transitions in a diagnostic hydrogen neutral beam. As the beam passes at a high velocity through a background magnetic field, the H-alpha emission is split and polarized in a way that is dependent on the magnetic field. The magnitude can be determined from the line splitting and the direction from the polarization orientation. This paper will describe the principle of the technique and report on the present status, including the successful measurement and interpretation of an LIF enhancement phenomenon. The LIF signal from a 30 kV beam in a background of neutral gas was found to be enhanced, and the fine-structure line amplitudes were seen to vary significantly with an applied perpendicular magnetic field of 0–0.01 T. MSE-LIF for plasmas in the intermediate field range of greater than 0.1 T, and potential advantages of MSE-LIF will also be covered. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2219432]

## 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] It was originally employed in 1989 to achieve a measurement of the central rotational transform, $q(0)$, in a tokamak, and has since become the standard technique for $q$-profile measurements worldwide,[5–7] due to its high spatial and temporal resolution, accuracy, and nonperturbing nature. MSE measurements led to advances in understanding the stability of sawtooth modes,[8] tearing modes,[9] and alpha-particle driven toroidal Alfvén eigenmodes.[10] $Q$ profiles obtained with MSE were invaluable in the discovery of an enhanced confinement reversed magnetic shear configuration.[11]

The MSE technique is based on the observation of spectral emission from a hydrogen or deuterium neutral beam in a magnetized plasma. As the beam passes through the background plasma, collisions with ions and electrons cause beam neutrals to be excited and subsequently to radiate. The Balmer-alpha transition ($n=3$ to $n=2$) is easily detected, as it is in the visible spectrum, at 656.3 nm at rest, and there is typically sufficient excitation to the $n=3$ level to make a reliable measurement. As the beam moves at a high velocity through the background magnetic field in the plasma, it experiences a perceived electric field given by $\mathbf{v}\times\mathbf{B}$ and this electric field causes the spectral line to be split into a nine-line manifold, and for the individual lines in the manifold to be polarized.[12] A conceptual diagram of this splitting is shown in Fig. 1. The magnitude of the line splitting for the Stark effect in hydrogen is linear with the electric field and can be solved using perturbation theory. The polarization of the lines is governed by the direction of the perceived electric field, and the measurement of the polarization direction allows determination of the magnetic field pitch angle at the location of observation. The lines that result from transitions where $\Delta m=\pm 1$ are polarized perpendicular to the electric field, and denoted by $\sigma$ and the lines from $\Delta m=0$ transitions are polarized parallel to the electric field and denoted as $\pi$ lines. A series of views along the neutral beam as it traverses the plasma allows a set of local magnetic field pitch angle measurements. These are routinely used for equilibrium reconstruction to determine the current distribution and safety factor profile.

## II. MOTIVATION FOR ADDITION OF LASER-INDUCED FLUORESCENCE

While MSE has been highly successful at making magnetic field pitch angle profile measurements in the conditions under which it was developed, of traditional tokamaks with fields over 1 T, there are limitations that need to be addressed for successful deployment of the technique on either end of the experimental spectrum. At fields below ~0.75 T the adjacent lines in the Stark spectrum tend to overlap, reducing the polarization fraction. In a burning plasma environment such as the proposed International Thermonuclear Experimental Reactor (ITER) device, the mirror system that would be necessary to collect the light and deliver it outside of the shielding wall is likely to be significantly degraded by exposure to the plasma. The reflection coefficients may change with time even as a single plasma shot progresses, making calibration of the system an extremely challenging problem. The MSE-laser-induced flurorescence (LIF) con-

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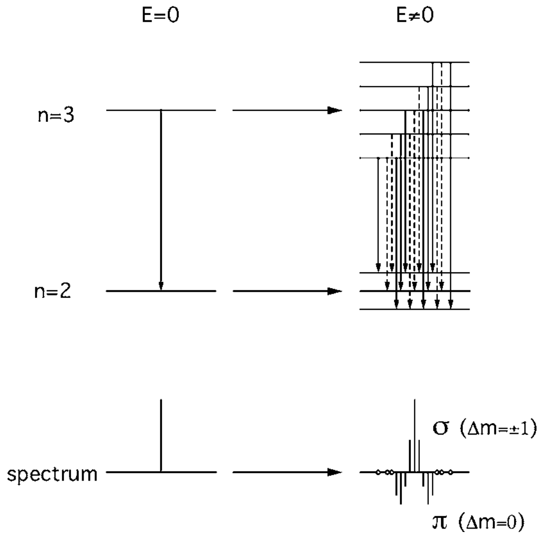


FIG. 1. Conceptual diagram of energy level change and spectral line splitting due to the Stark effect.

cept can address both of these concerns, and enable a measurement of magnetic field magnitude as well as pitch angle. These two measurements combined can be used to reconstruct the plasma pressure profile and the current profile. Additionally, when an MSE-LIF system is injected radially into a toroidal plasma, the pitch angle measurement is unaffected by radial electric fields. In conjunction with a second MSE system, the radial electric field profile could thus be directly determined.

The MSE-LIF technique involves using a laser to excite electrons from the $n=2$ to $n=3$ state, and observing the emission that is correlated with the presence of the laser. While this is a simple concept, the implementation is both complex and powerful.

The MSE-LIF technique allows measurements at significantly lower magnetic fields than are possible with traditional MSE. This is because the spectral resolution for a traditional MSE system is limited by a combination of geometric broadening, heating beam divergence, and energy spread. Geometric broadening is a phenomenon that occurs when viewing strongly Doppler-shifted emission from a fast-moving beam of particles. Due to the finite size of the viewing optics, the angle between the imaged location and one edge of the lens is different from the angle for the other edge of the lens, and so there is a smearing of the spectral line when light is collected from the entire lens. One way to counter this effect is to use a shaped aperture, which collects more light in the central vertical section of the lens where the Doppler shift is changing less, and blocks light from the edges. This reduces the available signal, and does not completely eliminate the problem.

MSE-LIF avoids this problem by using the laser to excite the transition of interest. The laser polarization and wavelength are set and measured at the laser output, and when the neutral beam is exposed to laser radiation, absorption will only occur when the laser is precisely tuned to the transition of interest in both wavelength and polarization. It is no longer necessary to make a polarization or wavelength measurement of the emission, because all of the emission that correlates with the presence of the laser is known to be from the precise transition that the laser selected.

TABLE I. Spectral line effects in NSTX.

| Line broadening in NSTX at 0.4 T | |
|---|---|
| Geometric broadening | 0.3 nm |
| Beam divergence | 0.04 nm |
| DNB parallel energy spread | 0.002 nm |
| Compare to: | |
| Separation between Stark components | 0.03 nm |
| Fine structure full width ($B=0$) | 0.02 nm |

The second-largest source of spectral broadening in a typical MSE system is the divergence and energy spread of the neutral beam that is used for the measurement. Many MSE systems use the neutral beams that are injected into experiments for the purpose of heating, and these do not have the tightly controlled parameters that would allow a precision spectroscopic measurement. The MSE-LIF concept can be used with a heating beam of sufficiently low energy spread, or with a dedicated diagnostic neutral beam, which can be engineered to the precise specifications required for a good measurement. For an example of the clear advantage of MSE-LIF in the conditions of an existing experiment, consider Table I, which compares the spectral shifts and widths from relevant effects in the National Spherical Torus Experiment (NSTX), which is presently in operation at the Princeton Plasma Physics Laboratory (PPPL), and is the first intended recipient of the MSE-LIF system. In the table, the diagnostic neutral beam (DNB) energy spread represents the limit of MSE-LIF spectral resolution. This estimate is based on a ~25 V energy spread in the beam.

Clearly, the MSE-LIF system allows spectral resolution that is significantly better than a system that relies on collisionally induced fluorescence. Combining this spectral resolution with a sweep over a wavelength range, either by varying the neutral beam voltage or the laser wavelength, enables a measurement of the magnitude of the magnetic field. This can be used to directly reconstruct the plasma pressure and current profiles.

MSE-LIF also allows measurement of the magnetic field pitch angle without the need for polarimetry that characterizes traditional MSE. Because the polarization information is set by the laser, the laser polarization can be rotated in time, and the total LIF signal will be periodic with a frequency of twice the rotation frequency. The H-alpha light that correlates with the laser will be sinusoidal with a phase shift from the polarization rotator that is determined by the pitch angle of the magnetic field in the observation region. The schematic setup is shown in Fig. 2.

In the diagram, the diagnostic neutral beam is shown to be injected radially. This causes the pitch angle measurement to be independent of radial electric fields that may exist in the plasma. An MSE system that uses a heating beam will be sensitive to background plasma radial electric fields, and as such an experiment with both systems can determine the radial electric field profile. This would be of great interest as it relates to turbulence suppression and other areas of study.[13]

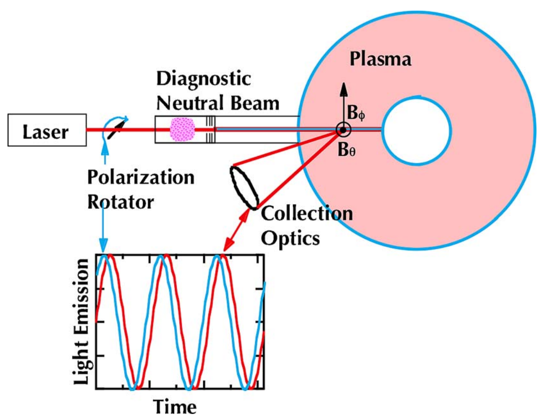


FIG. 2. MSE-LIF setup for pitch angle measurement on the toroidal confinement device.

The collinearity of the laser with the neutral beam enables the Doppler shift to match at all points for a measurement of magnetic field at any point along the beam. Also, it ensures the best possible spectral resolution.

## III. INITIAL MSE-LIF EXPERIMENTS: BEAM IN NEUTRAL GAS BACKGROUND AT LOW MAGNETIC FIELD

In our MSE-LIF development laboratory, we have built a diagnostic neutral beam with carefully controlled sources of energy spread to ensure the narrowest possible spectral lines. The neutral beam source has an external rf antenna, magnetic cusp geometry, and magnetic filter. The source was built in collaboration with the Plasma and Ion Source Group at Lawrence Berkeley National Lab and is described in detail in another publication.[14] The beam can run at voltages in the range of 30–40 kV, with current on the order of 30 mA. The beam diameter is on the order of 1 cm, and the measured divergence is 0.26° half angle. For the laser-induced fluorescence, we have a tunable ring dye laser system from Coherent with DCM dye in EPH solvent pumped by an argon ion laser at 514 nm. The initial target chamber contains neutral hydrogen gas, and magnet coils were installed to apply a magnetic field up to 100 G perpendicular to the beam direction. A schematic diagram of the laboratory setup is shown in Fig. 3.

Preliminary experiments in neutral gas revealed a LIF enhancement phenomenon at low field. The phenomenon is described in detail in another publication,[15] and will only be briefly discussed here in the context of its relevance to the next step in the development of the MSE-LIF system. The

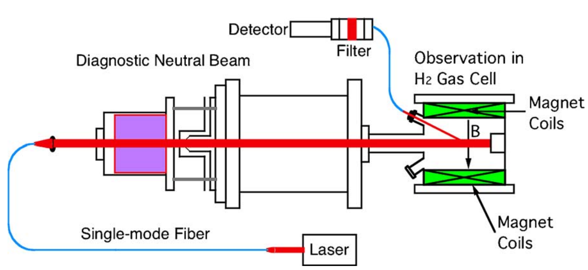


FIG. 3. MSE-LIF development laboratory setup.

LIF signal observed from the beam with no applied background field consists of transitions that are excited by the laser in resonance to remove electrons from the 2*s* state. This is because, in the absence of applied fields, this state is metastable, and its very long radiative lifetime leads to a situation where the only significant depopulation mechanism is through collisions. The radiative lifetimes of the other $n=2$ states are considerably shorter than the collision times in this experiment, so the population of the 2*s* state comes to be much greater than the other $n=2$ states.

As the magnetic field is raised, the beam atoms experience a motional electric field, and this field causes the zero-field quantum states to mix with each other. Some transitions that were previously forbidden become allowed, and so the lifetime of the 2*s* state decreases rapidly with increasing field as electrons in that state are able to decay to ground. In order to fully understand the system, where the LIF and CIF signals depend on the populations of the various states and the radiative transition amplitudes between them, the populations depend on collisions as well as radiative transitions, and the radiative transition parameters are changing with magnetic field, it is necessary to create a full collisional-radiative model that accounts for all of these effects. Such a model has been completed, and is described elsewhere.[16] The results of the model confirm the qualitative description given here.

## IV. NEUTRAL BEAM ENERGY SPREAD

The experiments in gas at low field and the modeling done to explain them were vital steps toward an MSE-LIF diagnostic in plasma. The studies revealed the actual energy spread of the neutral beam, and it was found to be on the order of 40–50 V in many conditions. Many sources of energy spread have been carefully controlled, including rf pickup on the high voltage grids, ripple on the acceleration supply, and rf line noise that generated a plasma oscillation. These and other presently controllable sources of energy spread in the beam have been reduced to under 5 V total, and the remaining energy spread is believed to be due mainly to straggling of the beam on the neutral gas that leaks out of the source into the beamline and acts as the neutralization medium. Straggling refers to the statistical process of spreading in energy of an energetic population due to collisions with a background medium. The rms straggling parameter is available in the literature[17] for energetic hydrogen ions in a background of hydrogen gas, though the regime in which the straggling can be treated as a symmetric Gaussian distribution is a higher pressure-distance product regime than the one in this experiment, and the energy range of the measurement starts at 40 kV, slightly higher than the relevant energy here.

The straggling data can be used to estimate the energy spread that would be imparted to a beam for a given line density of neutral hydrogen, and this can be compared to the line density needed to achieve a given neutral fraction in the beam. Figure 4 makes this comparison. It should be emphasized that because the experimental regime is different in the beam neutralization case here than in the straggling param-

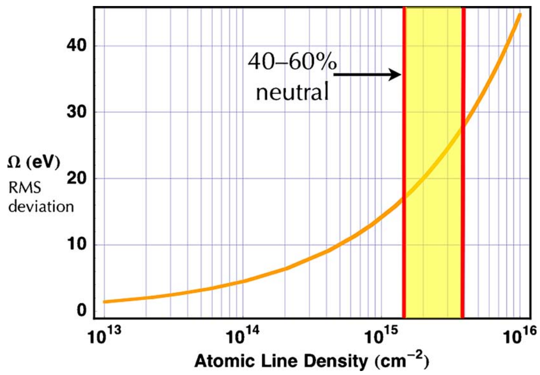


FIG. 4. Estimated beam straggling parameter vs line density for a proton beam in $H_2$ gas.

eter measurements, this calculation can only be considered as a rough estimate. The result, though, suggests that a 50% neutral beam will necessarily have a straggling width on the order of 25 V.

The regime in this experiment is one where the line density of scatterers is less than that required to result in a symmetric distribution, and the distribution is seen to be highly asymmetric. Figure 5 shows a spectrum taken with approximately 40 G applied magnetic field. There are four spectral lines in the region shown, and even though they do overlap, the asymmetry of the shape is clearly visible. The low-energy tail (toward the right in Fig. 5) due to straggling has been experimentally observed to increase with additional gas in the beamline. It would follow from this information that it would be worthwhile to run the neutral beam source at as low a pressure as possible in order to reduce the pressure in the beamline. The data in Fig. 5 are taken with the neutral beam source running at 17 mT. Scans of pressure in the neutral beam source were done, and while the large asymmetric low-energy tail was seen to decrease with lower pressure in the source (and consequently in the beamline), a symmetric source of energy spread that increases with decreasing source pressure was observed. Increased variation of plasma potential in the neutral beam source may be responsible for this phenomenon, as it has been observed in similar experiments. While ion temperature is also expected to increase with decreasing pressure, this effect is not likely to be large enough to account for the observed broadening. Figure 6 shows the tradeoff of the increasing low-energy tail, and decreasing symmetric energy broadening, with an increase of source

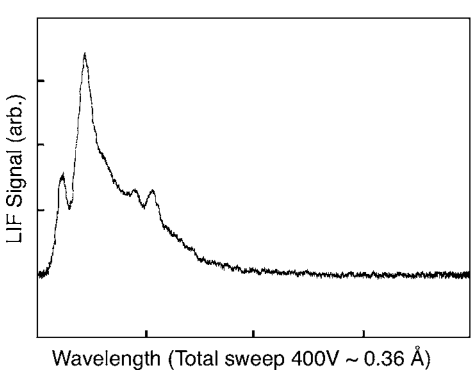


FIG. 5. Data in ~40 G magnetic field showing asymmetry of line shapes.

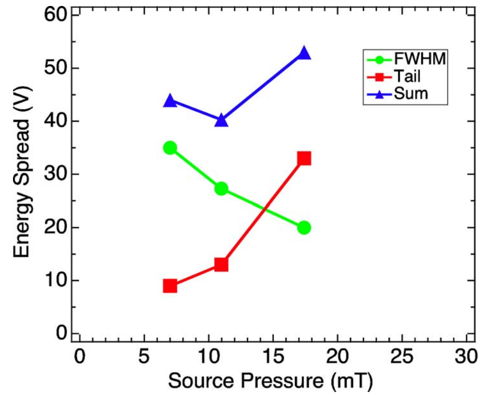


FIG. 6. Variation of neutral beam energy spread with the source operating pressure. Shown separately on the plot are the symmetric broadening (filled circles), asymmetric tail (filled squares), and the sum (filled triangles)

pressure. A redesign of the beamline is underway that will allow for greater differential pumping to create a situation where the beam source is able to run at the high pressures that appear to minimize symmetric broadening, and the beamline is reduced in pressure to reduce the low-energy tail effect. It is worth mentioning that the feature referred to as a tail in this discussion contains a considerable fraction of the beam atoms. In summary, the lowest total energy spread achieved for the neutral beam to date is roughly 40 V. Our calculations suggest that an energy spread of approximately 25 V may be the lowest achievable number for a 30–40 kV hydrogen neutral beam generated from a positive ion source neutralized in an $H_2$ gas background, because of straggling effects. It may be possible to achieve a lower energy spread for a hydrogen neutral beam generated from a negative ion source. Many sources of energy spread, including high voltage oscillation, have been carefully controlled in this experiment, and an additional symmetric broadening mechanism has been observed at low source pressure.

## V. MATCHING THE LASER LINEWIDTH TO THE BEAM ENERGY SPREAD

The laser presently used on this experiment has a linewidth of less than 100 MHz and a power of on the order of 300 mW. This should be enough to saturate the transitions of interest, but since the natural linewidth of the transitions is on the order of 100 MHz, and the neutral beam energy spread is presently on the order of 40 V, only a small fraction of the atoms in the beam are able to respond to the laser pumping at any given wavelength and time. The signal could be significantly increased if either the beam energy spread were further reduced, or the laser linewidth were increased to match the beam energy spread. In order to retain sufficient power for saturation of the transition, an appropriate laser could be pulsed. A candidate might be a frequency-doubled yttrium aluminum garnet (YAG) pumped pulsed dye laser, with pulse widths in the tens of nanoseconds, a pulse rate on the order of 100 kHz, and a pulse energy of a few microjoules.

## VI. PLASMA TESTBED WITH INTERMEDIATE FIELDS

In the previously described experiments, done with a neutral gas target, no measurable LIF signal can be observed for applied magnetic fields well over 100 G. This is understood as the result of the 2*s* state depopulation, because of its lifetime decrease with applied fields. The excitation rates for the beam in a plasma background are considerably higher than in neutral gas, and we estimate that it will be necessary to inject the beam into a plasma and have it traverse the plasma for at least 10 cm for the $n=2$ population to be significant enough to expect an observable LIF signal. Construction of an appropriate plasma testbed for MSE-LIF is underway. We have designed a flat spiral antenna helicon plasma source that will run in a magnetic field of up to 1.7 kG and an expected plasma diameter of over 10 cm.

## VII. SUMMARY AND FUTURE PLANS

The development of the motional Stark effect with laser-induced fluorescence diagnostic has made significant progress in understanding the basic atomic physics phenomena that form the foundation of successful diagnostic work. Presently, an experimental testbed is under construction that will allow the measurement to be made in a background plasma.

## ACKNOWLEDGMENTS

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