The Motional Stark Effect with Laser-Induced Fluorescence Diagnostic

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Abstract. The motional Stark effect (MSE) diagnostic is the worldwide standard technique for internal magnetic field pitch angle measurements in magnetized plasmas. Traditionally, it is based on using polarimetry to measure the polarization direction of light emitted from a hydrogenic species in a neutral beam. As the beam passes through the magnetized plasma at a high velocity, in its rest frame it perceives a Lorentz electric field. This field causes the H-alpha emission to be split and polarized. A new technique under development adds laser-induced fluorescence (LIF) to a diagnostic neutral beam (DNB) for an MSE measurement that will enable radially resolved magnetic field magnitude as well as pitch angle measurements in even low-field (<1 T) experiments. An MSE-LIF system will be installed on the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory. It will enable reconstructions of the plasma pressure, q-profile and current as well as, in conjunction with the existing MSE system, measurements of radial electric fields.

1. Introduction

The motional Stark effect (MSE) diagnostic was originally developed in 1989 [1]. It has since become the worldwide standard technique for measurement of internal magnetic field pitch angle in tokamaks, and has generated new understanding of plasma stability and transport [2, 3]. The MSE concept relies upon observation of the Balmer-alpha (n=3 to n=2) emission from a neutral hydrogen beam traversing a plasma. Typically, a heating beam is used. As the beam at high velocity, $\vec{v}$, passes through the magnetic field in the plasma, $\vec{B}$, it experiences in its reference frame a Lorentz electric field, $\vec{E} = \vec{v} \times \vec{B}$. This electric field causes the spectral emission to be split and polarized as described by the Stark effect. Traditionally, MSE has used polarimetry to determine the polarization angle of the light, and related that to the magnetic field pitch angle in the plasma. The MSE diagnostic was developed under high magnetic field (>1 T) conditions, and the lower fields of recent high-beta experiments such as the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory (PPPL) posed challenges to the technique. Nova Photonics has successfully developed narrowband, tunable optical filters to overcome these challenges and installed an MSE system on NSTX that presently provides spatially resolved pitch angle profiles, and has enabled new physics studies [4, 5, 6].

The motional Stark effect with laser induced fluorescence technique under development, MSE-LIF, incorporates a diagnostic neutral beam (DNB) and employs laser-induced fluorescence to achieve measurement of the MSE spectrum with unprecedented precision. The system will have several significant advantages over existing MSE systems. The high level of detail achieved with this diagnostic will allow accurate measurement of line splitting in the MSE spectrum. This

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measurement will be called ‘MSE-LS’ for MSE with Line Shift, to be distinguished from the traditional MSE with Line Polarization, ‘MSE-LP.’ Previous measurements of MSE line splitting have been limited in precision, and not used for equilibrium reconstruction [7, 8, 9]. The MSE-LIF technique discussed in this paper is expected to deliver a unique and extremely valuable measurement that has never been achieved: a radially resolved profile of the magnitude of the Lorentz electric field experienced by neutral beam atoms in the plasma. When accomplished with sufficient precision, this measurement can be used in conjunction with external magnetics to directly reconstruct the plasma pressure profile. Such a result would allow new understanding of magnetic field structure and plasma pressure, as well as enabling study of fast ion populations when used with background thermal pressure measurements. Additionally, the MSE-LIF system will be used to complement the existing MSE system on NSTX to give spatially resolved radial electric field profiles.

The MSE-LIF system can be implemented on experiments that lack heating neutral beams. Magnetic fields as low as a few Gauss can be resolved with the system. Even for experiments which do have a heating beam, MSE measurements cannot typically be made during plasma startup due to wall damage by neutral beam shine-thru and fast ion losses. Operation of the MSE-LIF system with its diagnostic neutral beam will be possible during the plasma startup and current ramp-up to diagnose and study current drive and other startup scenarios such as helicity injection.

Because the wavelength and polarization are set by the injected laser, the MSE-LIF system is insensitive to many issues that complicate calibration of traditional MSE systems. No actual measurement of the polarization or wavelength of collected light is necessary. The traditional MSE-LP measurement can be made with the MSE-LIF system with the incorporation of a polarization rotator on the excitation laser. Polarization effects in coatings on collection optics are not a concern, and the recently reported effect of re-neutralization [10] on the MSE signal is minimal on an MSE-LIF measurement of line splitting, though it can strongly affect polarization measurements.

The MSE-LIF concept has been under development for several years, and has made steady progress towards a final system. The design of the neutral beam injector, done in collaboration with the Plasma and Ion Source Technology Group at Lawrence Berkeley National Laboratory was reported in Review of Scientific Instruments [11]. Extensive LIF measurements in low magnetic fields in neutral gas have been made, and an LIF enhancement phenomenon was observed and reported on [12]. A detailed computer model of the system, unique in its comprehensive calculation of variation of transition probabilities in magnetic fields, including the effects of fine structure, the motional Stark effect and the Zeeman effect as well as collisions with background gas has been developed [13]. Description of the status of development was made in a talk at the 2006 High Temperature Plasma Diagnostics conference, and described in an associated paper [14].

In the following, it will be assumed that the reader has access to these previous references, and more recent work will be emphasized. A significant breakthrough in the MSE-LIF project has been the design of a new laser system optimized for this application. This, combined with detailed computer modeling, has moved the diagnostic development forward to the point of planning for installation on a major experiment, the National Spherical Torus eXperiment (NSTX) at the Princeton Plasma Physics Laboratory.

2. Laser Development

Recent measurements of the Doppler-broadened linewidth of the emission from our diagnostic neutral beam show an energy spread on order 6 GHz. This is equivalent to 100 V of variation out of the 35 kV beam energy. Most of this is thought to be due to straggling in the neutralization process. In order to optimize LIF signal, it is crucial to have a good match of the linewidth of the excitation laser and the beam. In previous work, a narrow (<1 MHz) linewidth dye laser was used for excitation. This laser was only capable of resonating with atoms in a velocity range within the natural linewidth (∼100 MHz) of the desired transition. In the experimental configuration of that time, with ∼50 V (3 GHz) peak width, this meant only about 3% of the beam atoms could be contributing to the LIF signal at a given time.

In order to boost signal levels, we have undertaken the development of a laser which will allow an excellent match to the beam. The new laser linewidth will be ∼6 GHz, and the total laser power will increase significantly, from 300 mW to several Watts.

The new laser system is made possible by a series of recent developments in laser and optics technology. High power laser diodes have become available in the red wavelength range, though commercial applications for lasers at 651 nm are not very common. In order to obtain the power and wavelength we needed for this project, we searched for a development partner who had the proven ability to produce high-quality diodes near this wavelength range, and was interested in working on our particular application. We chose to work with Modulight Inc and are very pleased to report the successful development of a 10 W, 19 emitter diode bar for our project. A photo of a bar and data from Modulight are shown in Figure 1.

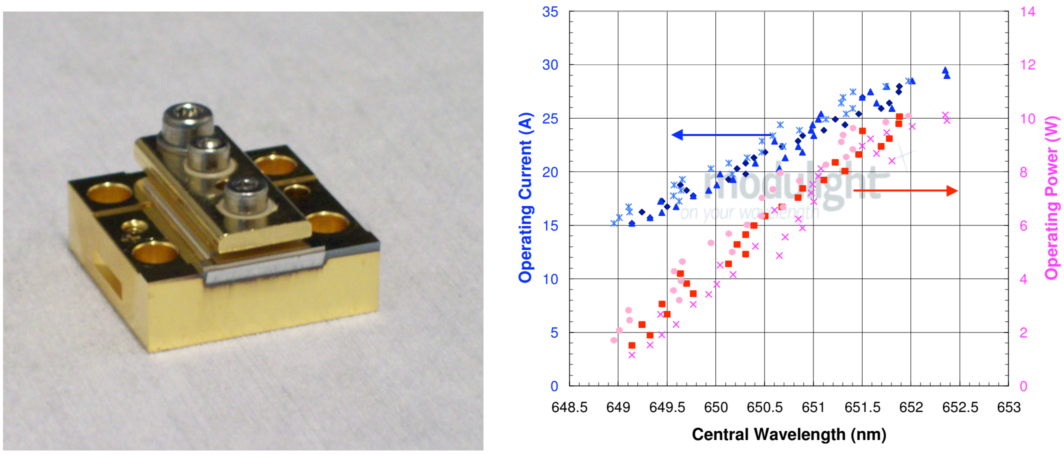

Figure 1. Left: Photo of CS mount 19 emitter diode bar at 651 nm. Right: Plot showing wavelength and power for several Modulight 19 emitter diode bars (courtesy of Modulight, Inc)

The intrinsic linewidth of the diode bars is 2–3 nm, far too wide for our application. In order to narrow the linewidth to match our neutral beam energy spread, we plan to use a volume holographic grating. The VHG acts as a selective mirror, feeding back into the laser only a narrow range of wavelengths, and enabling the laser system to lock and lase mainly in this very narrow wavelength range [15]. High quality VHG's are commercially available from Ondax, Inc.

The 5 to 7 GHz linewidth needed for our application is much more narrow than a typical feedback system. Figure 2 shows a diagram of the optical system and a plot of the narrow acceptance angle for the VHG. Some previous work [16, 17] has demonstrated wavelength narrowing to the $\leq$10 GHz range using a VHG, though the 765–780 nm wavelength range gives a wider VHG acceptance angle, so we expect our work at 651 to be more challenging.

Our laser emitters have a 3.4 degree (FWHM) divergence in the slow axis, and a 35.7 degree (FWHM) divergence in the fast axis. The emitter size in the slow axis dimension is 150 microns, a significant fraction of the 500 micron emitter spacing. It is actually considerably easier to achieve an excellent collimation for the fast axis, because its emitter size is on the few micron scale. An estimate of the total power that can be collimated into the VHG acceptance cone for our laser system gives about 20% in an ideal case. Real systems are never ideal, however,

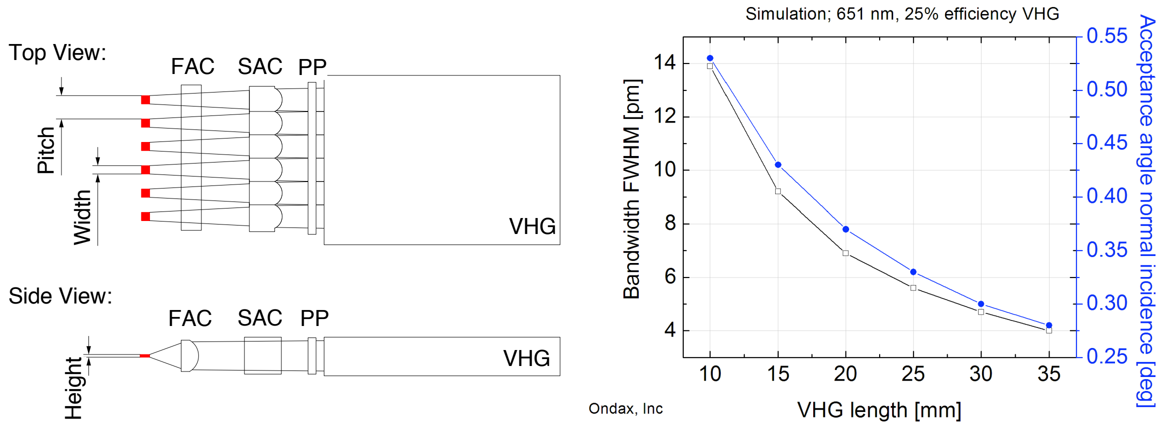

Figure 2. Left: Diagram showing layout of laser diode emitters, fast-axis collimation lens (FAC), slow-axis collimation lens array (SAC), corrective phase plate (PP) and volume holographic grating (VHG). Right: Acceptance angle vs length for volume holographic grating (courtesy of Ondax, Inc)

and slight variations in the diode emission angle and placement, as well as smile effects seen in operation, could significantly reduce that fraction, compromising the system's ability to lock in to the desired wavelength at high power. Because the collimation is so important for this application, we plan to work with compensation plate technology recently developed at Heroit-Watt University [18] and commercialized by PowerPhotonic. Their custom waveplates are individually tailored for each laser diode, and can correct for smile and alignment errors. An example is shown in Figure 3. At present, we are waiting to receive AR coated diode bars for incorporation into our VHG system.

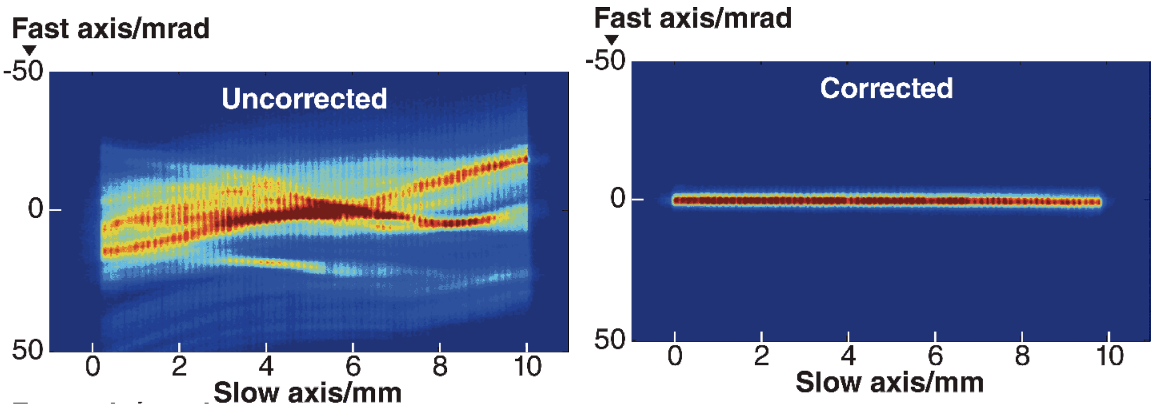

Figure 3. Phase plate correction of diode bar (courtesy of Power Photonic, Inc.)

3. NSTX Installation

Preparations for installation of the MSE-LIF diagnostic on NSTX are in progress. The DNB system will be modified significantly to fit in the available space on the NSTX platform. The hardware for installation on NSTX is shown in Figure 4. Collection optics have been designed, procured and tested, and modifications to the NSTX port cover on which they will be installed are planned for the near future.

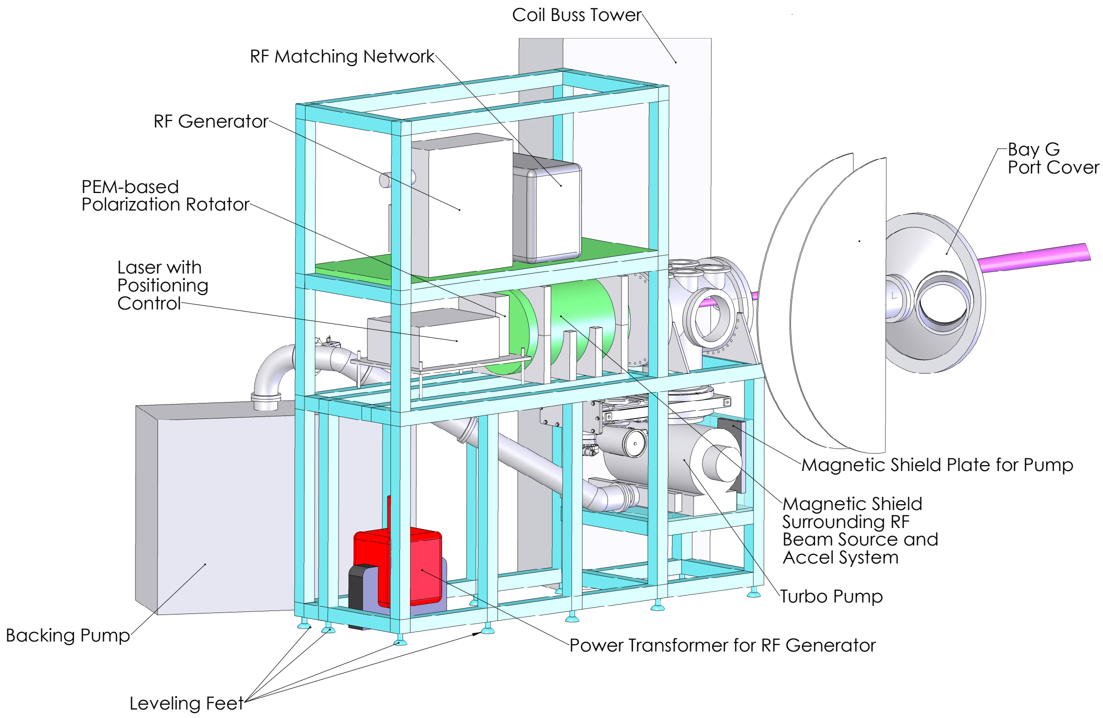

Figure 4. Diagram of MSE-LIF installation on NSTX.

The DNB source will be installed on the NSTX platform where stray fields of hundreds of Gauss develop during plasma operation. A shield to protect both the source and the acceleration and neutralization regions is imperative. A two-layer shield system has been designed, modeled and optimized using 3D simulation software. A diagram of the shield and the simulation results are shown in Figure 5. The design goal of reducing the field by a factor of 1000 in the source, acceleration and neutralization regions has been met.

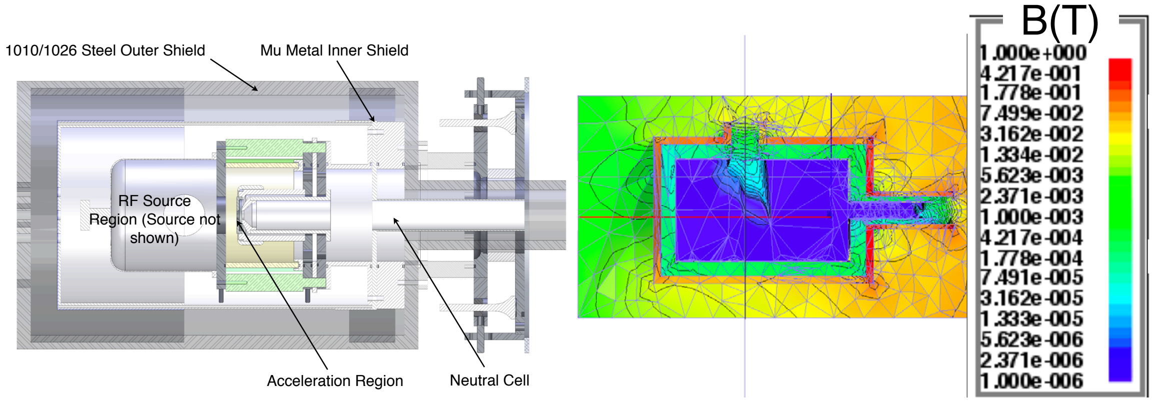

Figure 5. Magnetic shielding design and simulation results showing effectiveness for neutral beam source and neutral cell regions. The cross-section shown in the plot at right is rotated 90 degrees azimuthally from the one shown in the drawing on the left. The simulation plot on the right shows the access for the RF antenna and RF shielding at the top.

The shield involved particular design challenges beyond the reduction of magnetic field, in that the neutral beam source operates at 40 kV, and the region that needed to be shielded is under vacuum. The design presented overcomes these issues by keeping the entire shield at ground potential, and having the shield cross the vacuum boundary. We plan to have the shield nickel-plated to prevent corrosion.

4. Sensitive test of MSE-LS for ITER

The ITER plasma environment poses new challenges for optical diagnostics including the motional Stark effect. A labyrinth of mirrors must be used to transport light from the plasma out for analysis, as a direct line of sight would also transmit dangerous levels of radiation. The plasma will erode and deposit on the first mirror, changing the reflection properties. The traditional MSE measurement of polarization will be particularly susceptible to degradation in this environment. An alternative, of using the MSE-LS, or line shift approach to measure the magnetic field magnitude rather than pitch angle using collisionally-induced fluorescence, has been proposed [19]. Computational studies have demonstrated the ability of the MSE-LS approach to contribute to equilibrium reconstruction as effectively as MSE-LP [20], and the MSE-LIF system on NSTX will provide an excellent test of the concept.

5. Conclusions and Future Work

In the near term, we will be completing development of our 10 W, 651 nm, 6 GHz laser system, and outfitting the diagnostic neutral beam system with a magnetic shield for installation on NSTX. The installation of the MSE-LIF system on NSTX is scheduled for the 2010 opening, and we expect to test the system during the 2011 run year.

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