Review of Results from MSE Diagnostics

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Abstract

The motional Stark effect (MSE) diagnostic has been the most successful technique to date to determine the magnetic field inside fusion-grade tokamak plasmas. The most utilized technique, MSE line polarization (MSE-LP), relies upon measuring the polarization angle of a subset of the MSE multiplet. Since its inception 25 years ago, diagnostics using this technique have been installed on the majority of the major tokamaks. A subset of these diagnostics has been very successful, elucidating important physics in plasma transport, stability, and current drive. The diagnostics and the results are reviewed. The challenges to fielding MSE-LP diagnostics on future burning plasma experiments has prompted the development of alternate methods to use the MSE emission to extract magnetic field information from within the plasma. The concepts and results from these systems is reviewed and compared to the MSE-LP technique. Other non-MSE techniques to make magnetic field measurements are also summarized.

MSE-LP systems have been fielded in many tokamaks with varying degrees of success in the 25 years since they were introduced. These systems have diagnosed literally thousands of plasma discharge and have increased our understanding of plasma transport, stability, sustainment, and other areas. The technique has been shown to provide high accuracy, high spatial resolution, and high time resolution measurements for magnetic equilibrium reconstructions. The systems are operable any time the neutral beams are firing and are non-perturbing beyond the impact of the beam, which is often desired. The analysis of the data and incorporation into magnetic equilibrium reconstructions can be done in a timely manner to provide data for real-time control.
1 How accurately to measure the internal fields?

Before we discuss techniques to measure the internal magnetic field, an important consideration is how accurately the properties of the magnetic field must be measured in order to properly constrain the magnetic equilibrium reconstructions. This is a non-trivial question to answer because the problem is non-linear and depends on the geometry, the other diagnostics used, and the desired accuracy of the q-profile or current density. A magnetic equilibrium reconstruction typically takes many different measurements into account to determine the equilibrium that best describes the measurement set. Thus it is a global optimization, making the contribution from any one measurement more difficult to discern.

Naturally, one would like the equilibrium reconstructions be as accurate as possible; however, there are trade-offs between equilibrium reconstruction accuracy and diagnostic cost and complexity. Generally, the accuracy required for physics studies is more stringent than that required for control. Sensitivity studies of physics models have been used to determine the desired accuracy of the equilibrium reconstruction. The ITER group has carefully developed desired specifications for the accuracy of reconstructions as part of their physics basis [1]. For their scenarios, an uncertainty of 10% in safety factor, corresponding to $\delta q = 0.1 - 0.5$, with a radial resolution of $\frac{\beta}{\alpha}$ and a time resolution of 10ms is desired at all times during the plasma discharge.

Numerical studies have been undertaken for a small number of equilibria to determine how well internal measurements constrain equilibrium reconstructions. One study [2] used ITER, MAST, and JET geometries included realistic boundary magnetic measurements and monotonic q-profiles with no internal transport barriers. This study concluded that measuring the magnetic pitch angle with uncertainty $\delta \gamma = 0.3^\circ, 1.5^\circ, \text{ and } 1.3^\circ$ on each device respectively at many (~ 20) points in the radius effectively eliminated qualitatively macroscopically different equilibrium solutions, though the accuracy of the resulting solution was not quantified. The general problem has been tackled most recently by Zakarov using the theory of variances [3] to develop a methodology to determine how well an internal diagnostic set can constrain equilibrium reconstructions.

Foley [4] has applied Zakharov’s methodology to determine the efficiency of constraining the equilibrium reconstructions using different internal magnetic field measurements. The study quantified the resulting uncertainty in the safety factor ($\delta q$) and pressure profile ($\delta p$) using the magnetic field magni-
Figure 1: The uncertainty in reconstructed safety factor $\delta q$ (left) and the uncertainty in reconstructed pressure $\delta p$ (right) depending on the number of internal constraints and their distribution across the plasma for an ITER geometry, using the magnetic pitch angle $\delta \gamma$ (top) and magnitude of the magnetic field $\delta B$ (bottom). Adapted from [4].

Figure 1 illustrates the correlation between the number of internal measurements, and the radial coverage of those measurements, with the accuracy of the resulting equilibrium reconstruction for an ITER plasma simulation. These results are likely representative of most mildly shaped tokamaks at medium fields, intermediate aspect ratios and typical current profiles. The calculation included magnetic pitch angle measurements (MSE-LP) and magnetic field magnitude measurements (MSE-LS) with measurement uncertainties of $0.1^\circ$ and 1mT respectively. As expected, having measurements across at least half of the diameter is required to achieve acceptable results. There are diminishing returns as the number of measurement points increases, which is more pronounced when using the magnetic pitch angle as a constraint.
Figure 2: The uncertainty in reconstructed safety factor $\delta q$ (left) and the uncertainty in reconstructed pressure $\delta p$ (right) as a function of the uncertainty of internal constraints for an ITER geometry. Using 20 points across the full radius for magnetic pitch angle $\delta \gamma$ (top) and for magnitude of the magnetic field $\delta B$ (bottom). Adapted from [4].

Figure 2 shows how the uncertainty of the internal constraints affects the uncertainty of the equilibrium reconstruction for the same ITER geometry with 20 measurement points across the full radius. It is apparent that more accurate measurements yield a better equilibrium reconstruction of both reconstructed parameters for both types of constraints. According to this analysis, achieving $\delta q = 0.1$ requires $\delta \gamma < 1.0^\circ$ or $\delta B > 10\text{mT}$. However, having measurements at $\delta \gamma = 0.3 - 0.5^\circ$ and $\delta B = 1 - 10\text{mT}$ is clearly desirable for detailed physics studies which require high accuracy to quantify discrepancies between experiments and numerical simulations.

2 Installations and results

The development of the MSE-LP system led to substantial improvements in measuring the internal profiles. The diagnostic is well established and veri-
fied. The approach was first implemented in 1989 in PBX-M by Levinton [5] and has since been installed on most large tokamaks with varying degrees of success. The last formal review of MSE-LP instruments and their results was conducted in 1999 by Levinton [6]. Listed below are the tokamaks with MSE-LP systems appearing in the literature. Included is a description of the diagnostic system and the plasma physics investigations the system has enabled. The systems are listed in order of the first publication of the system installation or result.

**PBX-M, 1989:** The first MSE-LP system consisted of a single sightline which was mechanically scannable across the plasma on a shot-to-shot basis. This system observed a 10kW beam with a time resolution of 120ms [5]. The system consisted of two lenses with PEMs viewing through a vacuum window with a tiltable bandpass filter. Many of the elements of the MSE-LP technique were worked out on this system such as the use of beam-into-gas for calibration. This system was used to test theories of the sawtooth instability. The capabilities of this system set a new bar for measuring the internal magnetic field, other groups quickly adopted the technique.

**DIII-D, 1990:** A similar, scannable system viewing a heating beam was installed on DIII-D. This system featured a unique beam splitter in place of the polarizer, allowing twice the light collection for the same sightline étendue [7]. This was quickly upgraded to a stationary eight sightline system [8] with a more complicated optical train. Diagnostic development led to the first measurement and compensation of Faraday rotation in the transmission optics. This system was the first system used to constrain magnetic equilibrium reconstructions. It was also used to co-discover the dependence of the energy confinement time on magnetic shear [9] and to determine that sawteeth lead to complete magnetic reconnection [10]. The current drive profile from beams and the bootstrap current were measured and neoclassical resistivity was tested [11].

Success with the system quickly prompted an upgrade; an additional objective lens viewing the same beam from another location with a dielectric mirror was installed in 1995 [12, 13]. This new system had increased light collection and incorporated a shutter with embedded polarizers to help determine the calibration. The existing system was
altered so the two MSE arrays could work together as a "core" and "edge" system with 16 sightlines that achieved good radial resolution across the plasma. The combined system showed that broadening the current profile along with faster plasma rotation allowed the tokamak to exceed the resistive-wall MHD stability limit, leading to record plasma $\beta$s \[14\]. The reversal of the central shear (i.e., $q_{\text{min}}$ at $r > 0$) was also shown to drastically improve energy confinement, stability, and non-inductive current fractions \[15\]. The millisecond time resolution of these systems allowed the first measurements of the current profile flattening during disruptions \[16\]. The low noise and consistent results were used to measure the non-inductive current profile \[17\] during current ramps and to evaluate fast wave current drive \[18\].

It was soon discovered that the plasma radial electric field influenced the MSE-LP measurement \[19\]. This led to a re-evaluation of the previous sawteeth results. A new system was built to independently measure the plasma $E_R$ using the view from a new third objective \[20, 21\]. This showed good agreement with $E_R$ estimates derived from CXRS measurements. The new, expanded system allowed for studies of the role of magnetic and electric field geometry in internal transport barriers \[22\] and particle transport \[23\]. The system was used to directly measure the current drive due to ECCD \[24\], the perturbed magnetic fields due to MHD modes \[25\] and the neoclassical current density \[26\]. The system was used as a sensor for the plasma safety factor in a real-time control system with ECCD and beam current drive actuators. The system provided the location of the rational $q$-surfaces to the ECCD system to target and suppress NTM’s \[27\].

The repositioning of a DIII-D neutral beam in the counter-current direction allowed much better spatial resolution for the $E_R$ measurement \[28\] by using two new MSE-LP systems installed in 2006. These two new arrays were similar to the previous ones and each used a single dielectric mirror with an eight lens optic system to transport the light to the PEMs. This system has has much better edge radial resolution ($\sim 0.25\text{cm}$) allowing it to directly measure edge current densities. DIII-D’s 65 sightline real-time MSE-LP system has recently been used to determine the loss of bootstrap current in slowly rotating magnetic islands \[29\], an accomplishment that highlights the temporal, spatial, and angular resolution of the diagnostic system. An example of this
Figure 3: From ref [29]. The change in the vertical magnetic field (z axis) in the presence of a helical \( m/n = 2/1 \) slowly rotating mode as measured using the MSE-LP system on DIII-D. The change is calculated by subtracting the MSE signals just prior to the onset of the mode. The location of the \( q = 2 \) surface and magnetic axis are indicated with dashed lines. The lower plot shows the change in the time derivative of the magnetic field as measured by pickup coils at the edge of the plasma. For reference, a change of 0.01T in \( B_z \) corresponds to a change of \( \sim 0.3^\circ \) in magnetic pitch angle in this discharge.

measurement is shown in Figure 3.

TFTR, 1992: An eight sightline system used a mirror (with no shield!) to image the TFTR heating beams [30]. The system allowed the time-resolved measurements of the sawtooth current profile dynamics [31, 32, 33], nearly concurrent with the results from DIII-D. These measurements were later revisited and revised in light of the effect of \( E_R \) on MSE measurements [19]. The system was used to measure ICRF mode conversion current drive [34], interpret the stability of TAEs [35], and investigate the physics of double tearing modes [36]. Perhaps the most significant contribution of this system was the determination that confinement improved with reversed magnetic shear [37], a result published 20 days before the same conclusion was reached on DIII-D [14]. These two papers currently have \( \approx 1000 \) citations between them.

In 1997 the MSE-LP system was expanded to 21 sightlines and a new
calibration technique that used plasma jogs was introduced \[38\]. This system was used to directly test the neoclassical resistivity \[39\] and to test the consistency of Alfvén eigenmodes with safety profile measurements \[40\]. The system was also cleverly used to measure the radial electric field by simultaneously viewing two energy component from the same heating beam \[41\].

**JT60-U, 1997:** A five-sightline system viewing a tangential heating beam \[42\] was used to measure the current driven by high energy (negative-ion) neutral beams for the first time \[43\]. It demonstrated good agreement with simulations, an important confirmation for predicting next-step device performance. The system allowed detailed study of sawteeth \[44\] and their effect on Alfvén eigenmodes and was also used to determine the driven current profiles due to LHCD \[45\] and ECCD \[46, 47\]. The MSE-LP system was expanded to include three arrays with a total of 30 sightlines \[48\] and was used to directly measure magnetic field fluctuations in the magnetic islands created by tearing modes \[49\] for the first time. The system was the primary sensor for the advanced real-time control of the current \[50\] and safety-factor profile \[51\] prior to the closure of the machine. A three-array MSE-LP system is planned for JT60-SA viewing the positive-ion heating beams. This system will be a primary real-time sensor for the control of the current and q-profile; a central mission for this new facility \[52\].

**JET, 1999:** The 25-sightline system faced a particular challenging viewing geometry, which required two dielectric mirrors that act as a prism to redirect the light down a long periscope. This optical system is held under a secondary vacuum for tritium compliance while operating at 350 \(^\circ\)C \[53, 54\]. The beam configuration on JET results in multiple heating beam sources overlapping in the MSE viewing volume, each with a different velocity vector. Therefore, the measured polarization angle is the result of weighing the different source contributions —a situation expected for ITER. By firing different heating beam sources, the MSE-LP system was used to measure \(E_R\) \[55\]. The system was used to measure regions of zero current density (called current holes) \[56\], to further understanding of internal transport barriers \[57\] due to LHCD \[58\], and was the first system to be used for real-time control of the current profile \[59\]. Contributions from multiple sources have caused
problems and the system is now operated by increasing the voltage of one of the beam sources which gives it a larger Doppler shift so it can be observed independently.

**C-MOD 2001:** This ten-sightline system views a nearly radial low power (200kW, 50keV) diagnostic neutral beam using a large complex periscope with ten lenses and three mirrors, many of which are located inside the vessel [60]. The system has significant survivability issues inside the high-field machine [61] and elucidated the issues due to secondary-emission in beam-into-gas calibrations [62] which led to the development of a robotic calibration system [63]. The system has calibration drift at the several degree level [64] prompting the use of an intra-shot calibration technique used to study LHCD current profiles [65].

**JFT-2M, 2001:** This system is unique in that it uses a single array to observe two oppositely pointed beams (one tangentially co-current and one tangentially counter-current, each with nine sightlines). This allowed it to obtain good spatial coverage and precise $E_R$ measurements with a minimum of MSE complication [66].

**FTU, 2001:** This system viewed the low power (80kW, 40keV) diagnostic neutral beam using a complex viewing geometry with two mirrors and many invessel lenses [67]. The system did not produce published results and has since been removed.

**ASDEX Upgrade, 2001:** A ten-sightline system was installed to view a heating beam via a mirror and multiple lenses [68]. It has had significant problems with drift in the diagnostic response of several degrees and low signal intensity [69], though it is proposed for real-time control [70] of the safety factor profile. Recent results show the measurement of the electric field [71].

**TCV, 2004:** A system was proposed and conceptually designed to view a vertically oriented diagnostic neutral beam but was not constructed [72].

**Tore Supra, 2006:** A nine-sightline system was installed to view the low power diagnostic neutral beam via a complicated invessel periscope [73]. This system never worked satisfactorily due to poor signal and
wall reflections in this stainless-steel clad tokamak [74]. It and the beam have since been removed.

**NSTX, 2008:** A 19-sightline system was fielded in this low-field device (0.3 – 0.5 T) viewing the heating beam [75]. Due to the low field, the Stark spectrum is not resolvable, therefore special apertures were used to limit spectral broadening and very narrow bandpass (0.06nm) Lyot filters were developed to isolate the σ emission. This system has been used for studies of fast ion transport and their interactions with TAEs [76]. It was used to measure the non-inductive current drive, a topic of particular interest in the spherical tokamak [77]. This system has been adapted for the NSTX-U tokamak along with a MSE-LIF system to be discussed.

**MAST, 2010:** As in NSTX, the low field on this spherical tokamak created problems due to mixing of σ and π emission. However, advances in filter design enabled conventional filters with ~ 0.1nm bandpass that were successfully used in a pilot system [78]. A full system was built with 35 sightlines to view the very high power density heating beam and resulted in high time resolution (0.5ms in some cases) [79] [80]. Instead of tuning individual filter bandpasses, this system uses an innovative ”patching” technique where the correct filters are chosen for each condition from a large collection of available filters. The high spatial resolution of this system has recently been used to make current profile measurements in the pedestal [81].

**EAST, TBD:** A system to view a heating beam is under development for this long pulse super-conducting tokamak in collaboration with the team that built the MAST diagnostic.

**KSTAR, TBD:** A system is under development for this long pulse superconducting tokamak in collaboration with the team that built the MAST diagnostic and worked on the C-MOD diagnostic [82] [83].

**ITER, TBD:** A system is specified as part of the ITER diagnostic compliment to measure the current and safety-factor profiles for physics studies [84]. It will also measure the q-profile for real-time control of advanced discharges and will provide targeting information for NTM suppression via ECCD. The system’s specifications include a radial resolution of
$r/a = 0.05$, a time resolution of 10ms, and the ability to constrain the safety factor profile to 10\% \cite{1}. The system has undergone several design iterations from different teams \cite{85} \cite{86} \cite{87} \cite{88}. The diagnostic consists of two arrays: one to view the core and one to view the edge of the plasma. The system may view both the diagnostic neutral beam (96keV, hydrogen) and the heating neutral beams (1MeV, deuterium) depending on whether the heating beams are aligned for on- or off-axis current drive. The system consists of a mirror labyrinth that conveys the polarized emission from the vacuum vessel using a series of 4 – 5 curved mirrors, including an actively-cooled metal first —and likely second —mirror under direct plasma exposure \cite{87} \cite{88}. The standard dual PEM-based polarimeter is mounted behind a double vacuum window before the light is transmitted to the tritium building via optical fibers where it is then spectrally filtered and detected. It is envisioned the system will have $\sim 20$ channels to obtain the desired spatial resolution. In the most recent design available the aperture of the system is 9cm diameter with a total (i.e. all sightlines) viewing volume footprint of 1.4m x 0.4m giving a total étendue of $\sim 1.1m^2sr$ ($\sim 0.05m^2sr$ per sightline) making it the physically largest MSE-LP optical system to date \cite{88}.

Generally, the installations of MSE-LP diagnostics have operated well on the major tokamaks. However, calibration drift and polarized background has been reported on several devices and several installations were designed and installed but did not produce any significant physics results due to operational difficulties. Future devices are likely to have large optical systems that are much more complex than existing systems with many internal mirrors, some of which are plasma-facing. These mirrors will be eroded and deposited on leading to a changing polarization calibration and requiring in-situ calibration which has yet to be demonstrated in the literature. Furthermore, the polarized signal to polarized background is likely to be significantly higher in future devices compared to existing installations which predominately view high power heating beams in much dimmer plasmas.

\section{Other configurations for MSE}

The advantages and disadvantages of MSE-LP systems in part have led to explorations of other ways to use the same underlying physics of the motional

\textit{11}
Table 1: MSE-LP systems that have been installed on tokamaks to date and their reported performance.

Systems shaded in grey have reported significant problems involving polarization drift (C-MOD, TORE SUPRA, ASDEX) or background subtraction (C-MOD, TORE SUPRA, FTU). FTU and TORE SUPRA have since removed their MSE-LP systems and rely on Faraday rotation measurements in their circular plasmas. Also note that C-MOD, TORE SUPRA, FTU, and PBX-M systems view low power diagnostic neutral beams while all the other systems view the much higher power heating beams.

<table>
<thead>
<tr>
<th>Tokamak</th>
<th>Field Beam$^a$</th>
<th>View</th>
<th>Chs</th>
<th>Optics$^b$</th>
<th>Resolution</th>
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<td></td>
<td>[T] [kW]</td>
<td></td>
<td></td>
<td></td>
<td>$\Delta r$</td>
<td>$\theta_{pol}$</td>
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<td>W:3L</td>
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<tr>
<td></td>
<td></td>
<td>edge</td>
<td>9</td>
<td>S:M:W:3L</td>
<td>.09-.03</td>
<td>[12]</td>
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<td>mid</td>
<td>10</td>
<td>W:3L</td>
<td>.42-.20</td>
<td>0.1   1</td>
<td>[20]</td>
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<tr>
<td></td>
<td>core</td>
<td>8</td>
<td>S:M:W:8L</td>
<td>.12-.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>edge</td>
<td>16</td>
<td>S:M:W:8L</td>
<td>.09-.004</td>
<td></td>
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<td>.04-.06</td>
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<td>.02-.06</td>
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<td>core</td>
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<td>W:M:2L</td>
<td>?       0.1</td>
<td>20</td>
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<td>?       ?</td>
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<tr>
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<td>W</td>
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<tr>
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<td>2M:8L:W</td>
<td>0.1    ?</td>
<td>?</td>
</tr>
<tr>
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<td>M:6L:W</td>
<td>.04-.09</td>
<td>?</td>
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<td>core+edge</td>
<td>??</td>
<td>4-5M?:L:W</td>
<td>.05    0.1</td>
<td>10</td>
</tr>
</tbody>
</table>

* Used as an input into a real-time control system for the q-profile or current profile.

a Neutral power injected into the plasma by the beam source/PINI viewed by the MSE-LP system. Does not distinguish full energy fraction. All beams are 30 – 50 keV/amu except for ITER which is 500keV/amu.

b Optics are ordered from the objectives to the PEMS. S=Flat shielding glass, W=Vacuum window, M=Mirror, L=Lens. nL=n lenses in a row.

c JFT-2M has nine-sightlines viewing two beams simultaneously to obtain $E_R$, the beam with the best radial resolution is listed here.

d As currently proposed.
Stark effect in an attempt to constrain magnetic equilibrium reconstructions. These are discussed in this section in rough order of the complexity of their implementation. Each technique is outlined with its pros and cons considered in light of the challenges posed by next-generation devices.

3.1 MSE lineshift approach

As previously discussed, the splitting of the Stark spectrum is linearly dependent on $|\vec{E} = \vec{v}_{\text{beam}} \times \vec{B}|$; measurement of the Stark split can be used to determine the magnitude of the magnetic field if the velocity and geometry of the beam are precisely known. The magnitude of the magnetic field relates to the kinetic pressure in the plasma making it useful in equilibrium reconstructions. In practice, the emission from the beam is collected with a periscope and transmitted to a remote high resolution spectrometer. The detected spectrum is fit using a physics model of the emission to determine the Stark shift. The magnitude of the magnetic field in the viewing volume is then determined from knowledge of the geometry and can be used to constrain magnetic equilibrium reconstructions. This configuration is typically referred to as a MSE line-shift (MSE-LS) approach.

One of the first published uses of the motional Stark effect was to determine the plasma diamagnetism due to ICRF heating with four sightlines on the JET tokamak [90]. Other designs insert a static polarization filter before the objective to reject the $\sigma$ emission. This allows the Stark split to be determined by fitting the separation of the $\pi_{-2,-3,-4}$ and $\pi_{+2,+3,+4}$ triplets whose components are unresolved. This approach works well for low-field...
machines. It has been implemented on the MST device in Madison, WI, and the GDT device in Russia with uncertainty in the magnetic field magnitude of $\sim 5\%$ [91, 92, 93] and 4% [94, 89] respectively. A fit from GDT illustrating the split of the two $\pi$ multiplets is shown in Figure 4.

In this technique, no polarization information is used and therefore the collection optics do not need to be polarization preserving. This simplifies the optical, calibration, and mirror cleaning systems. However, the difference in transmission of $\sigma$ and $\pi$ due to mirror s-p reflection ratio will likely need to be a free parameter in the spectral fit. The change in the $|\overrightarrow{v}_{\text{beam}} \times \overrightarrow{B}|$ due to changes in the plasma is small; to accurately constrain a magnetic equilibrium reconstruction the quantity must be known to $\sim 0.5\%$ in modern tokamaks as previously discussed [4]. This places very stringent requirements on the spectral detection and analysis systems. Measuring the Stark split with sufficient accuracy requires accounting for other background sources that overlap the Stark spectrum. These sources include beam halos and fast-ion and main-ion charge exchange emission. The line shape of the emission must also be very well known in order to determine the line center. The framing rate of the spectrometer camera typically limits the time resolution of the diagnostic. The need for high spectral resolution and thus high photon counts requires a large sightline étendue that generates additional spectral broadening. Furthermore, the atomic models used in the fitting of the measured spectrum are highly non-linear, requiring significant computational time making near real-time measurement difficult.

The spectral broadening mechanisms present in current-generation tokamaks with positive-ion source neutral beams and small Stark shifts create large overlap of the individual lines of the Stark multiplet, making them hard to adequately resolve for equilibrium reconstruction purposes. As of this writing no MSE-LS system has been used to constrain magnetic equilibrium reconstructions in a tokamak. However, measurements of the magnitude of the magnetic field using a $\overrightarrow{B}$-stark system (to be discussed next) have been shown to be consistent with magnetic equilibrium reconstructions constrained with MSE-LP systems [96]. It is reported that the ASDEX Upgrade $\overrightarrow{B}$-stark system has achieved agreement in the line shift between the spectral measurements and equilibrium reconstructions at the 1.5% level with a precision of 0.1% [97], and trials are under consideration on JET, KSTAR, and C-MOD.

Next-generation tokamaks will have higher magnetic fields and high en-
energy (\(\sim 1\text{MeV}\)) negative-ion source neutral beams. In these devices there will only be one energy component to fit, and the individual Stark effect lines will be well separated due to the large Lorentz electric field (\(\sim 50\text{MeV} \) on ITER). An example is shown with the simulated MSE spectrum in ITER in Figure 5. In these conditions it may be possible to determine the Lorentz electric field accurately enough to provide adequate constraints for magnetic equilibrium reconstructions. An MSE-LS system is proposed as part of the ITER MSE system [95].

3.2 \(\vec{B}\)-stark approach

Similar to the MSE-LS approach, the \(\vec{B}\)-stark approach, developed by Pablant on DIII-D [96, 98, 99], uses a spectral model to fit the emission collected by a spectrometer. However, the angle of the electric field is also of concern as is with the magnitude of the Lorentz electric field. From Equations ?? and ?? it is apparent that the ratio of \(\pi\) to \(\sigma\) emission depends on the angle between the Stark electric field and the sightline. Therefore, the measurement of this intensity ratio can be used to determine the angle of the magnetic field on a fixed sightline. (In the absence of using the line shift information, this technique is sometimes referred to as the MSE line-ratio (MSE-LR) technique.) Most of the individual lines are from different upper atomic states, mak-
Figure 6: A $\vec{B}$-stark spectral fit from diii-d with 27 physics-parameters fit. The full energy $\sigma$ and $\pi$ are shown in red and purple respectively. The important $\pi_{\pm3}$ to $\sigma_{\pm1}$ lines are identified. The half and full energy beam components are shown in orange and green respectively. The background model is shown as the dashed line. Adapted from [99].

In practice the objective element is placed at a position which maximizes the sensitivity to the intensity ratio and requires viewing the beam from off-mid-plane, but not vertically. The emission is collected and detected by a a high resolution spectrometer and the result is fit with a spectral model as in the MSE-LS approach. Figure 6 shows the collected emission (black) with the spectral model fit (red) containing 27 physics-based parameters with small residuals from the diii-d implementation.

As with MSE-LS, the $\vec{B}$-stark technique requires only a simple periscope and a standard high-resolution visible spectrometer and no PEMs. However, the diagnostic requires a specific viewing geometry to achieve high $\sigma$ to $\pi$ intensity ratio sensitivity simultaneously with acceptable Doppler shifts and makes implementation in a constrained geometry difficult. Perhaps more importantly, the $\sigma$ and $\pi$ emissions have orthogonal polarizations and the ratio of periscope’s polarization transmission is covariant with the $\sigma$ to $\pi$ intensity ratio. Therefore, the optics must transmit the two differently polarized components with a known and constant efficiency. Changes in mirror diattenuation due to mirror coatings will directly skew the measurement. The
\( \vec{B} \)-stark technique suffers from similar limitations as the MSE-LS approach: the emission is hard to resolve, the system requires high throughput, the fitting is highly non-linear and as a result is computationally intensive limiting the applicability for plasma control. In order to accurately determine the \( \pi_{\pm 3} \) to \( \sigma_{\pm 1} \) intensity ratio to the required \( \sim 0.5\% \), many effects must be included in the spectral fit: the upper population levels, the beam halos, the main and fast-ion charge exchange, and the visible bremsstrahlung emission must all be modeled. This makes the fitting even more complex than that required for the line shift alone. Spectral techniques with the strong background sources require high dynamic range. However, similar to the MSE-LS approach, the \( \vec{B} \)-stark technique benefits greatly from a larger line-shift-to-width ratio which will result from high energy negative ion neutral beams. For these reasons, it is unclear how the the \( \vec{B} \)-stark method scales to future devices. Advances in atomic modeling and validation may decrease the uncertainties in the fitting model, and cross-validation with other techniques may increase confidence in the method. There is speculation that the view afforded by the CXRS system on ITER may provide a platform to test the \( \vec{B} \)-stark technique.

Qualitative agreement in \( -\frac{B_z}{B_{\phi}} \) was established between the two sightline \( \vec{B} \)-stark diagnostic and the highly developed MSE-LP diagnostic in the DIII-D experiment during plasma current ramps. However, systematic differences in the line ratios at the 0.05 level —corresponding to 3\(^\circ\) in pitch angle —remained [99]. The quantitative disparity in the DIII-D experiment was attributed to a slowly changing polarization-dependent transmission ratio in the periscope, though this was never verified directly. It may be possible that the disparity is due to errors in the background model or the lineshape. The systematic error in the ratio had a density dependence up to 0.02, corresponding to 1\(^\circ\) in pitch angle. This density dependence was attributed to the fast-ion model used in the background subtraction. ASDEX Upgrade has recently installed a six-sightline \( \vec{B} \)-stark system [97] which shares the MSE-LP optics in a manner proposed for ITER. This system uses a forward-model: the emission is simulated from first principles with up to 51 free parameters and is then compared to the spectrum instead of composing the spectrum from Gaussians done on DIII-D. Recent results find a discharge- and sightline-dependent systematic error in the magnetic pitch angle derived from the \( \vec{B} \)-stark measurement of up to 17\(^\circ\) that is attributed to changes in the polarization properties of the optical system. An early 20-sightline
\( \vec{B} \)-stark-type system was installed on TEXTOR with a polarizer inserted in the periscope. It operated on the same principles as the DIII-D system, but quantitative comparisons were not made \cite{100}. A ten-sightline \( \vec{B} \)-stark-like system has also been recently fielded on the KSTAR tokamak \cite{101}.

### 3.3 Spectro-Polarimetry approach

Filtering the spectrum for polarization prior to detection by a spectrometer can provide additional information about the polarization angle of the \( \sigma \) and \( \pi \) emission and thus the magnetic field angle \cite{102}. Typically the light from a viewing volume is collected by separate sightlines (2 - 4 for the same emission volume), each of which has a different polarization filter. The light is then dispersed and detected in a spectrometer. The linear polarization angle of the light can then be determined from the ratios of intensities of the multiplet with knowledge of the polarization filtering. This can be done for both the \( \sigma \) and \( \pi \) lines using Malus’s law; by fitting the intensity ratios of the same spectral region. The Stark split can also be non-linearly fit as in the MSE-LS concept. Figure \ref{fig:concept} illustrates the concept.

This technique was first demonstrated with a four-sightline system on the TEXTOR tokamak \cite{104}. Each sightline had multiple beam splitters that split the light into four separate fiber bundles, each of which was polarization filtered, before being transmitted to a spectrometer. The polarization filters were linear polarizers at 0°, 45° and 90° and a circular polarizer. The system proved unacceptable and was upgraded to a 30-viewing volume system with an invessel periscope with a single polarizing beam splitter which split the collected emission into two orthogonal polarizations and used different fibers to transmitting them out of the vessel to a remote high resolution spectrometer \cite{105,106}. A similar system with 25 viewing volumes was installed in the LHD stellerator using a periscope that collected light from the same viewing volume with four different linearly polarization filtered sightlines. This system uses nearly co-located objectives and achieves measurements of the polarization angle with uncertainties of 1 - 5° \cite{103}. The HL-2A tokamak recently installed a similar system with two viewing volumes \cite{107}. MST, a reverse field pinch with large magnetic pitch angles, has a two-viewing volume system which collects two polarizations, achieving uncertainties in the magnetic pitch angle of \( \sim 10° \) \cite{108}.

This technique is relatively simple, requiring only standard spectrometer technology. However, the periscope design is complicated due to the need
**Figure 7:** The spectro-polarimetry based MSE system installed on LHD has 25 viewing volumes viewed from 4 co-located objectives, each with a different linear polarization filtering. The spectrum is then fit and the polarization angle determined from the contributions at different polarizations. Adapted from [103].
for multiple sightlines inside the vessel for each viewing volume. The multitude of fiber optic vacuum feedthroughs and invessel polarizers for each viewing volume add complication. Further, this technique still requires polarization preserving optics prior to the polarization filtering. Additionally, it is difficult to achieve the high accuracy required for constraining equilibrium reconstructions because the polarization angle is inferred from the ratio of intensities that pass through different optical paths and are detected by different detectors and electronics (i.e., different areas on a CCD camera based spectrometer). The use of a spectrometer carries with it all the limitations associated with the $\vec{B}$-stark and MSE-LS approaches. The spectrum is also polluted by unpolarized background light that needs to be subtracted prior to the Malus's law calculation. This can introduce large errors since the intensity of the unpolarized background can be large relative to the beam emission. Qualitatively consistent results were obtained using this technique, but it has not been demonstrated to accurately constrain magnetic equilibrium reconstructions in a tokamak.

### 3.4 MSE coherent imaging approach

An imaging MSE technique has been developed by Howard [109, 110] similar to what has been used in astronomical imaging polarimeters. This system determines the polarization angle of the emission incident on a coherence-based polarimeter. The result is a two spatial dimension image of the emission from a neutral beam. The coherence-based polarimeter consists of a series of specially selected phase and Savart plates that cause the light to interfere with itself, creating fringes on the image plane which are detected using a CCD camera. The spatial fringes on the image are computationally decoded to quantify the local fringe phase, brightness, and contrast. This system is analogous to the previously discussed PEM-based approach, except instead of encoding the polarization in time on a point detector, it is encoded in space across the 2D detector.

By selecting the appropriate phase plates and geometry, the system can encode up to five spectro-polarization quantities on the image using the brightness, the contrast, and the phase of the fringes in two orthogonal directions (i.e., vertical and horizontal). When used as a MSE diagnostic, the brightness of the image gives the emission intensity, while the phase of the fringes relates to the polarization angle of the light and the contrast relates to the Doppler shift of the lines in the spectrum. Other variants of this approach
use a temporal-switching component synced to the camera frame-rate, which also encodes information in the time domain as in the MSE-LP technique. A system like this has been fielded on the KSAR tokamak and initial calibrations without a beam indicate the system can measure the polarization angle to $\sim 1^\circ$ [111, 112]. An earlier system was fielded on the TEXTOR tokamak demonstrating that the light was polarized but the polarization angle was not recovered [113, 114]. A system is under development for the ASDEX Upgrade tokamak. An example image is shown in Figure 8.

The system’s main advantage is that it provides a 2D image of the emission. This image can provide additional information for the magnetic field equilibrium reconstruction including the curvature of the flux surfaces and the Shafranov shift [115]. However, the system still requires a polarization-preserving optical periscope to transport the light from the objective to the polarimeter which is mounted outside the vacuum—in the same manner as the PEMs in the MSE-LP technique. The coherence based polarimeter is sensitive to perturbations in temperature, and the coherence system must be regularly calibrated with a 2D image to obtain calibrated fringe phase and contrast. Furthermore, the CCD camera is sensitive to neutrons, thus the system must either be installed remotely from the tokamak with a long periscope or via an imaging fiber optic link that degrades the spatial resolution of the fringes. The deconvolution of the spatial fringes is computationally intensive, making near-real-time measurement for control difficult. The required accu-
racy of the system for providing constraints for equilibrium reconstructions has yet to be demonstrated. It remains to be seen if the increased quantity of information from a 2D image is valuable enough to overcome the limitations in the MSE-imaging when compared to a traditional discrete-sightline based MSE-LP system that can very accurately determine the polarization angle at tens of locations in the plasma.

3.5 MSE laser-induced florescence approach

A relatively new technique proposed by Levinton \cite{6} and developed by Foley and Levinton \cite{116, 117} is being constructed for use on NSTX-U. Instead of relying on collisions to excite the neutrals into upper states a laser is used to pump specific states. —a common approach in biology, chemistry, and material science. The atoms then spontaneously transition back, emitting light that is detected by a series of sightlines that cross the beam/laser system. This system is referred to as a MSE laser-induced florescence (MSE-LIF) system and is of particular interest for low magnetic field devices.

In practice, a low power (~5W) laser is installed shining co-linearly with a relatively small, dedicated, neutral beam. The beam and laser are designed to allow the laser to shine through the back of the beam plasma source and down the entire beam length. As the laser frequency, or the beam acceleration voltage, is precisely swept, the laser resonates with Stark energy levels. This causes a maximum in the emission when the laser is resonant with the particular Stark line. An array of narrow-bandpass filtered detectors (i.e., not spectrometers) capture the light when the states transition back. The Stark spectrum can then be determined by relating the intensity of the detected light to the swept quantity, creating a spectrum. The Stark split measured from this spectrum is then used to determine the magnitude of the magnetic field for use in equilibrium reconstructions as proposed for the MSE-LS technique.

Another proposed mode of operation is to rotate the polarization state of the excitation laser. The atomic states of interest will be most effectively pumped when the laser polarization matches the direction of the total electric field. Hence, the orientation of the magnetic field can be deduced from the phase shift between the detected intensity and twice the polarization rotation rate. This information can then be used as a constraint in the magnetic equilibrium reconstructions, similar to the MSE-LP technique. This implementation of the MSE-LIF concept is shown in Figure 9.
This technique is qualitatively different from the previously discussed techniques in that the bulk of the technical complication occurs in the source of emission (the dedicated beam and laser) rather than in the collection and detection system. The laser can be remotely mounted and coupled to the beam’s plasma source via fiber optics or a mirror. The laser needs to have a very well-controlled frequency with a small bandwidth to provide the required spectral resolution and also must be sufficiently powerful so the pumped excitation rate dominates the collisionally induced excitation rate. Additionally, the polarization of the laser also needs to be precisely controlled and varied. However, the required laser technologies are well-established from other scientific fields.

The dedicated neutral beam must have small axial energy spread to prevent spectral broadening via to the Doppler shift, though it does not need to be large or powerful since the states are pumped instead of relying on collisions. Thus, the beam can be a non-perturbing continuously operating diagnostic neutral beam instead of a high power heating beam, though it must have sufficient energy to penetrate to the core of the plasma. Since the pumped states only reside in the intersection of the small laser beam
and the larger neutral beam, the viewing volume formed by the laser and sightline intersection is very small. High spatial resolution and small spectral broadening result due to negligible variation in the fields in the viewing volume.

Contrary to the other MSE techniques discussed, the detection system is fairly simple since only the intensity of the emission is important. A simple periscope can be used with little consideration for polarization or spectral preservation. Because the spectral information is provided by the source resonating with the atomic states in their frame, there is no spectral broadening due to Doppler shift variation across the aperture or viewing volume meaning a large objective can be used to collect significant emission without affecting the ability to resolve the Stark split. Furthermore, lock-in techniques can be used to increase the signal-to-noise ratio by pulsing either the laser or the beam. The sightlines do need to be filtered to avoid stray laser light and cold Hα emission. The viewing geometry remains similar to the other MSE techniques, though there is significantly more flexibility due to the decreased requirements for spatial resolution and polarization sensitivity. Fielding the dedicated beam on a burning plasma is more problematic due to the extension of the tritium boundary and problems from free-streaming neutrons. These issues are currently tolerated for high-power heating beams, but it remains to be seen if compromises will be made for specialty diagnostic beams.

The proof-of-principle implementation is underway with a dedicated neutral beam commissioned, laser developed, and system operated in test chambers. As of this writing the system has undergone limited tests on NSTX prior to the upgrade of that experiment. The first fully operational MSE-LIF system is scheduled to be commissioned on NSTX-U in 2015, and a time resolution of 10ms and magnetic field resolution of $10^{-4}$T is expected. As with any un-fielded new diagnostic technique, it remains to be seen what technical and physics challenges will arise. For example, the development of high energy beams with the required axial energy spread and accelerator stability has proven challenging. However, it is anticipated that the spectral broadening sources will be small and will place the technique in a spectral operating regime (line broadening/Stark shift) similar to that on next generation tokamaks with negative ion beams and medium fields. Thus this technique may provide a test of constraining equilibrium reconstructions with a MSE-LS system in future devices on an existing device. However, the MSE-LIF system does not experience some of the more problematic geomet-
ric broadening and spectral overlap sources that need to be considered in a MSE-LS system. The applicability of the MSE-LIF approach to future devices is likely achievable due to its simplified detector system, small beam, and anticipated highly versatile and accurate measurement capability. Consideration must be given to how it scales to the density range, magnetic fields and required beam voltages of a next-generation device. In addition, the implications of fielding a dedicated diagnostic neutral beam on burning plasmas must be considered.

3.6 Verdict: alternative MSE approaches in future devices

After discussing the various types of MSE systems, we can now summarize how these techniques compare to MSE-LP systems for deployment on future devices. The results, in terms of advantages and potential problems for each type of MSE system on a burning plasma, are tabulated in Table 2.

The MSE-LP system is the only proven system. All other systems likely have difficulty with real-time capability since they require non-linear fitting the spectra, though faster algorithms and computers may help. The MSE-LIF systems have severe disadvantages because they require their own high-energy beam with specialized hardware, more openings in the vessel, a laser coincident with the beam, and effort to validate the atomic physics of the pumped system.

All systems have similar optical systems and thus substantial shared problems including the development of large, complex, robust optics with mirror cleaning systems that can be remotely maintained. However, this is a fairly common problem among tokamak diagnostics and the MSE diagnostics will likely benefit from shared resources and experience in this area. All systems observe light from a neutral beam, leading to low signal levels that will need to be overcome using high-energy beams and large étendue optics. Future devices without neutral beams will, naturally, preclude fielding any MSE variants. Such a device would need to rely on predictive modeling, FIR polarimetry, or some other —yet to be developed—technique.

The $\vec{B}$-stark, spectro-polarimetry, and coherent imaging systems are all significantly adversely affected by the mirror-based polarization aberrations, and—importantly—their variability. These effects are very similar to the MSE-LP system. These systems will require some similar form of on-line cali-
<table>
<thead>
<tr>
<th>Technique</th>
<th>MSE-LP</th>
<th>MSE-LS</th>
<th>MSE-LR or $\vec{B}$-stark</th>
<th>Spectro-Polarimetry</th>
<th>Coherent imaging</th>
<th>MSE-LIF</th>
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Table 2: Potential advantages and problems when applying various MSE techniques to next-step burning plasmas.
bration. The MSE-LS and MSE-LIF systems do not have these problems since their information is not contained in the relative intensity of polarized components or in the direct polarization angle. Instead, these systems relying on absolute calibration of spectral position. The $\vec{B}$-stark, spectro-polarimetry, and to a lesser extent the MSE-LS techniques will require the slope of the spectral transmission to be well known.

All of the systems have problems with background subtraction except the coherent imaging system, which can likely compensate for spectrally featureless backgrounds, and the MSE-LIF systems which can use modulation techniques on their dedicated beam. The background subtraction issues are particularly important for the MSE-LS and $\vec{B}$-stark systems since they will be required to very accurately subtract the total background light rather than only subtracting the polarized component as in the MSE-LP technique.

Given this picture, the most promising techniques for a burning plasma appear to be the MSE-LP and MSE-LS approaches. Each has its own challenges to overcome before becoming a reliable tool in a burning plasma experiment. The $\vec{B}$-stark, spectro-polarimeter, and coherent imaging techniques do not offer any significant advantages over the MSE-LP approach and each carry their own additional challenges. The MSE-LIF approach may be promising in the long-term—especially for future reactors which will likely not have heating neutral beams—but more development work is required. As such, it is unlikely to be deployed on the next generation of facilities.

Unfortunately, in order to create spectral conditions similar to that envisioned on future devices, the development work required to mature the MSE-LS approach is accessible only with high energy beams in moderate-field tokamaks. This combination is not currently available or planned. The ability to fit the spectrum must be validated in the presence of those sources that can skew the very sensitive fit. These sources may also be present only in burning plasmas. Further work will be required to validate the methodologies for calibrating and incorporating the measurement into magnetic equilibrium reconstructions. For this reason, a comprehensive comparison between MSE-LS and MSE-LP on the same devices would be invaluable. There is hope that experience with MSE-LIF on low-field machines may provide the required experience; however, the atomic physics regimes, background sources, and modulation schemes are substantially different. Therefore, relying on MSE-LS alone at this juncture is likely presents risk of a length development time on the first burning plasma implementation.

The MSE-LP approach benefits from having a long history of develop-
ment. Its warts are known. The diagnostic has proven its accuracy in current devices and its incorporation into magnetic equilibrium reconstructions has been theoretically, numerically, and empirically studied in detail. The results have been verified in a variety of regimes. The move to high-energy negative ion beams in medium-field devices does not change any part of the diagnostic’s operation, if anything it makes it easier. Perhaps in the future MSE-LS and MSE-LIF techniques will be deployed and relied upon in these devices due to their advantages over MSE-LP systems, but the lower risk path likely involves fielding MSE-LP on at least the first generation of burning plasma devices.

4 What techniques have been attempted

The importance of the current density and safety factor profiles is evident in the multitude of diagnostics or approaches that have been (and continue to be) devised in tokamak research to measure the internal magnetic field. It is useful to review other techniques that have been employed to measure the internal magnetic field in a hot, fusion-relevant plasma as a point of comparison to the success of MSE systems. Highlighted below are short descriptions of a selected set of the most clever, successful, or widely implemented techniques. Additional details can be found in reviews by Soltwisch [121] and, more recently by Donn [122].

Magnetic probes: Relatively simple and easy-to-interpret magnetic probes made with high melting temperature materials can be inserted into low density plasmas to measure the magnetic field at temperatures < 100eV using rapid motion in and out of the plasma. These cannot be inserted deep into the hot fusion relevant plasmas, thus their applicability is limited to the fields near the edge of the plasma in modern tokamaks. However, they remain important tools in low temperature experiments and the tokamak scrape-off layer and pedestal.

Ablation clouds: Due to the difference in thermal and particle transport along magnetic field lines relative to across them, it is thought that the transient density perturbation surrounding an ablating pellet follows the magnetic field lines. Thus, the angle of the magnetic field can be measured by imaging the line emission from the cloud of impurity ions surrounding a pellet (lithium is typically used) injected deep into the
plasma. This was done on TFTR yielding uncertainties corresponding to \( \sim 1^\circ \) \cite{123}. However, this technique is difficult to implement due to the uncertainty in whether the emission follows the field lines, the large perturbation to the local and global plasma, and the limited imaging resolution of the cloud. Furthermore, pellets have difficulty penetrating into large dense fusion relevant plasmas. The decrease in emission when the pellet crosses rational \( q \) surfaces was also used to locate these surfaces with a radial resolution of \( \frac{r}{a} \sim 0.02 \) in TFTR \cite{124}.

**Impurity polarimetry:** Another technique that has been used to determine internal magnetic fields is the Zeeman emission from impurities in the plasma. In a magnetic field, the Zeeman effect splits the line emission and the different components of the Zeeman emission are polarized. The polarization properties are related to the angle between the sightline and the magnetic field in a manner analogous to the motional Stark effect. The impurity emission can be collected and the polarization of one component or the difference in polarization of two components can be used to provide information about the projection of the magnetic field onto the line of sight in a manner often used in astronomy.

However, the Zeeman splitting is often unresolvable due to the thermal Doppler broadening of the impurities; therefore heavy species (Ti or Fe) are used to minimize this effect. These species are in high ionization states, existing in a shell of emission in the plasma. The collected emission represents a line-integrated measurement through this emission shell and must be inverted in some manner to obtain local measurements. This technique was employed on the TEXT tokamak with marginal success; measurements of the line integrated poloidal field with uncertainties of \( 0.005 - 0.01T \) \cite{125} were reported. This corresponds to line-integrated magnetic pitch angle uncertainties of \( \sim 0.2 - 0.4^\circ \). This technique does not scale well to next step devices due to the lack of impurities in the core of hot dense burning plasmas.

**Zeeman polarimetry:** Some of the limitations of the impurity-Zeeman polarimetry method can be overcome by introducing a particle beam of neutral impurities. The beam is mono-energetic and therefore has little thermal broadening. Furthermore, the localization of the emission to the intersection of the beam and sightline provides good spatial resolution.
However, few species have sufficiently strong emission and large, simple Zeeman shifts to be spectroscopically resolvable. Lithium is one such species, having strong emission at 670.8nm. Polarization measurements of a lithium beam was used to measure fields on ASDEX to study the effects of lower hybrid current drive [126]. Experiments on TEXT achieved pitch angle uncertainties of $\sim 0.5^\circ$ by employing a similar technique. In this case the emission was dominated by laser-induced florescence through pumping the states [127] in manner similar to the MSE-LIF proposal to be discussed later in this Chapter. Unfortunately, lithium beams do not penetrate deep into the plasma due to their large ionization cross-section — these experiments were all done at low-density with low signal to noise ratios. Therefore, this diagnostic technique is limited to measurements of the edge magnetic field in modern tokamaks. It has been successfully utilized in this role with pitch angle uncertainties of $\sim 0.5 – 0.2^\circ$ on DIII-D [128] and with pitch angle uncertainty of $\sim 0.1^\circ$ in JT60-U [129], providing high spatial resolution equilibrium reconstructions of the edge current density.

It is also possible to measure the Zeeman polarization from an ablation cloud generated by lithium pellets injected deep into the plasma core. This technique was demonstrated on TFTR with an uncertainty in pitch angle equivalent to $0.6^\circ$ and was used as input into magnetic equilibrium reconstructions [130], though with limited spatial and temporal resolution.

Heavy ion beam probe: Instead of injecting neutral particles into the plasma, injecting charged particles and measuring the deviation of their trajectory can also be used to measure the magnetic fields. The particles require a large Larmor radius to allow them to enter the field, execute a curved orbit, and exit the field in a single pass. Therefore heavy ions are used, and so this technique is typically called the heavy ion-beam probe (HIBP) [131]. Trajectory-integrated information about the poloidal field is obtained by measuring the toroidal displacement of the ions as they exit the plasma. This technique has been used on various tokamaks but has not demonstrated the accuracy necessary for equilibrium reconstructions. Its implementation in larger, higher field devices is difficult due to the large Larmor radius requirement and a difficult detector implementation.
MHD localization: Theory indicates that plasma instabilities, such as resistive tearing modes, occur at rational safety factor surfaces. Hence, measuring the radial position of MHD modes can indicate where the rational safety surfaces occur in the plasma. The theory has been well verified using equilibrium reconstructions utilizing MSE-LP systems in many tokamaks. However, this technique only provides the q-profile values at a few isolated points instead of a detailed profile. Furthermore, this technique relies on advanced diagnostics and analysis to localize the MHD inside the plasma. Importantly, this technique requires the presence of large-scale MHD which is often unwanted and actively avoided.

FIR Polarimetry: The utilization of the Faraday rotation of a laser penetrating the plasma, sometimes called polarimetry (not to be confused with the polarimeters to be discussed in relation to the MSE-LP diagnostic), is the most successful non-MSE-based technique for determining the internal magnetic geometry. As the plane-polarized laser traverses the plasma, its phase shifts ($\Delta \varphi$) due to the Cotton-Mouton effect and its polarization rotates ($\alpha$) due to the Faraday effect:

$$\Delta \varphi \propto \lambda^3 \int_B n_e B_{\perp}^2 \, dz$$
$$\alpha \propto \lambda^2 \int_B n_e B_{\parallel} \, dz$$

where $n_e$ is the electron density, $B_{\parallel}$ is the magnitude of the field parallel to the laser propagation, $B_{\perp}$ is the magnitude of the field perpendicular to the propagation direction, and $\lambda$ is the wavelength of the laser. Note the phase shift and rotation scales strongly with wavelength and thus far infrared lasers are typically used. This technique was last reviewed in 1999 by Segre [132].

This technique is inherently chord integrated. However, the magnetic field profile in the plasma can be determined using an array of laser cords in a poloidal fan via an Abel inversion. The inversion process benefits greatly from using many laser chords that cover the majority of the plasma cross-section, preferably from multiple source positions (i.e., from upper and equatorial ports). The inversion requirement makes this technique harder to interpret and implement than a local
measurement. This is particularly true in diverted tokamaks which can have a variety of plasma shapes and positions leading to many degrees of freedom in the inversion. Additionally, the magnetic field information (which is a projection onto the laser path) is convolved with the plasma density profile. The laser chords are typically reflected from the inner or far wall by retro-reflectors, returning to the entrance window where the change in polarization can be measured by comparison with the launched polarization, which decreases noise due to vibrations. In modern systems, two lasers with slightly different frequencies are used to measure the polarization rotation by launching RHCP and LHCP light and monitoring the phase change between them. Successful systems use a third laser mounted co-linearly with the other two to function as an interferometer. This configuration measures the line integrated density on the same path as the Faraday rotation measurement, making the deconvolution of the density from the field more robust.

FIR polarimeter systems have been installed and used as constraints in equilibrium reconstructions on JET [133], TORE SUPRA [134], and MST [135]; the later two are circular limited machines which greatly simplifies the inversion process. A combined polarimeter/interferometer system is planned to complement the MSE system for magnetic field measurements on ITER utilizing ∼ 15 chords from two poloidal fans [136], but is not intended as a primary magnetic diagnostic.

Polarimetry systems envisioned for next-step devices are complicated by the need for many retro-reflectors mounted inside the vessel. These retro-reflectors are delicate optical components, are hard to implement, difficult to shield, and become degraded due to plasma exposure requiring a scheme to replace them periodically. The light is also free-space coupled to the sensitive analysis equipment requiring long, evacuated beam-lines in next-generation facilities. Furthermore, the accuracy required for physics studies requires low noise and many chords from many different angles compounding system integration challenges.

Other techniques: Other techniques include analyzing the absorption and reflection of radio and microwaves (which depend on the magnetic pitch angle) [137], firing armored crystal bullets through the plasma while measuring the Faraday rotation in the traveling crystals [138], inver-
sion of soft X-ray emission, modifications to the Thomson scattering spectrum and excitations of plasma waves. None of these techniques have been shown to reliably provide accurate information and most have significant integration challenges for future burning plasma devices.

References


