Design of the new Imaging Motional Stark Effect Diagnostic at ASDEX Upgrade

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Introduction

Motional Stark Effect (MSE) diagnostics are some of the few diagnostics capable of providing information on the current distribution in magnetically confined fusion plasmas. However, they are typically very difficult to calibrate and to maintain due to the complexity of the systems. Imaging MSE (IMSE), on the other hand, offers several advantages over the classical approach [1, 2], for example a simpler, more economical setup and at least one order of magnitude more spacial measurements points. Like classical MSE diagnostics, IMSE systems also utilise the Stark-split D-α light from neutral beams injected into fusion plasmas. However, once collected the light is lead through a series of birefringent plates and a polariser before being imaged onto a CCD chip, forming an interference pattern. A prototype of the new diagnostic was successfully tested at ASDEX Upgrade (AUG) in 2013 [3], motivating a permanent IMSE system, which was installed for the 2015 experimental campaign. The new system has a specially designed set of optics that maximises the collected light throughput under unusual mechanical restrictions while enabling three neutral beam sources to be viewed simultaneously. In this contribution, after a brief description of the IMSE diagnostic principle, the design of the new setup at AUG will be presented.

MSE and IMSE principle

Neutral beams injection (NBI) of fast deuterium particles is used for heating and diagnostic purposes in many fusion plasmas. The particles are excited and emit D-α radiation. The line

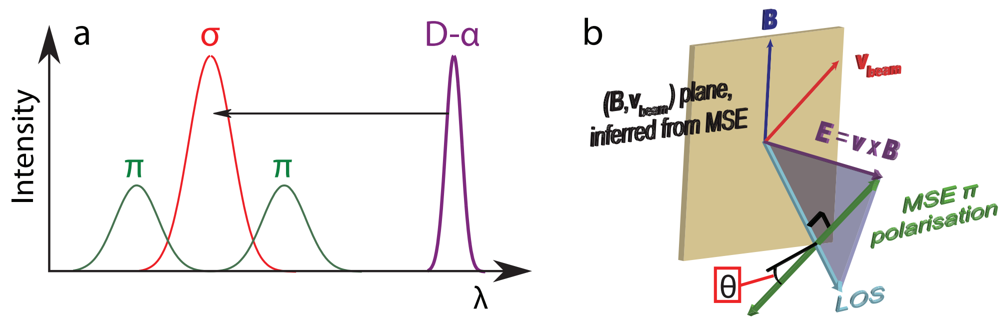

Figure 1: a: π and σ components of the MSE spectrum. b: 3D visualisation of the MSE principle: the π polarisation is the projection of **E** onto the plane perpendicular to the LOS. Knowing **E** lets us calculate the ($\mathbf{B}$, $\mathbf{v}_{beam}$) plane

emission is Doppler shifted by the particle's velocity $\mathbf{v}_{beam}$) and Stark split by the electric field in the rest frame of the atom ($\mathbf{E} = \mathbf{v}_{beam} \times \mathbf{B}$) into π and σ components (fig 1a). These are polarised parallel and perpendicular to the projection of **E** in the plane perpendicular to the line of sight (LOS) [4]. The measurement of the polarisation angle provides the direction of **E** and, therefore, the plane common to the beam and **B** (fig 1b). Depending on the direction of the LOS, a change in the direction of B (magnetic pitch angle) will have a larger or smaller impact on θ. We call this the pitch angle sensitivity of the diagnostic.

Conventional MSE polarimeters measure θ by spectrally selecting one component with a narrow filter and use a pair of photo-elastic modulators to analyse the polarisation. Because of the varying Doppler shift, each spatial point requires a very finely tuned filter, optics, sensor and digitiser. Typically, the beam is observed on 10 to 20 LOS. Unlike conventional MSE systems, the IMSE diagnostic utilises all spectral components, leading to a brighter signal. Two birefringent plates modulate the image from the beam with orthogonal interference patterns (fig. 2a). The difference in wavelength of the π and σ components is exploited by including a delay plate in the setup, which enables the components to be added constructively in the interference pattern, maximising the signal intensity, despite their orthogonal polarisations.

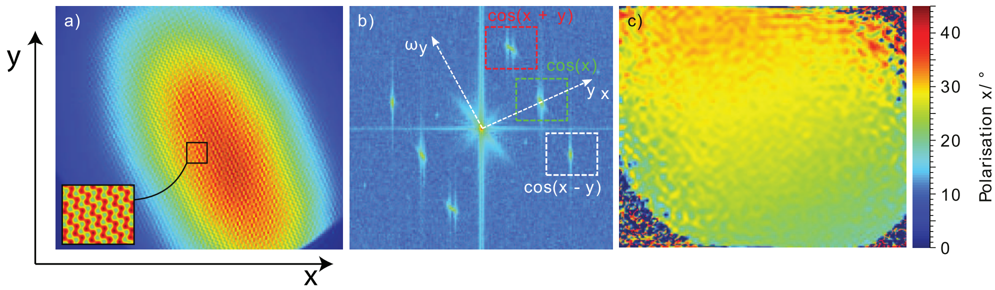

Figure 2: (a) interference pattern on the camera chip, (b) Fourier transform of the image and (c) MSE polarisation angle in 2D

The intensity on the chip is proportional to

$$\zeta cos(2\theta) + \zeta sin(2\theta) cos(x+y) + \zeta sin(2\theta) cos(x-y), \tag{1}$$

where θ is the polarisation angle, x and y are the axes on the camera chip and the fringe contrast ζ is, in a first approximation, a constant. The three components are isolated from the 2D Fourier transform (fig. 2b) and a 2D image of the MSE polarisation angle can be calculated (fig. 2c).

Compared to the classical MSE, the IMSE setup is simpler and more economical, only one calibration is necessary rather than calibrating all channels independently. The 2D nature of the system simplifies the identification of reflections and provides inherent position calibration as the vessel components on the image can easily be compared to the CAD model of the machine. It also provides more information on the current distribution [5], as the system performs roughly 200 simultaneous angle measurements.

Optical design

Several toroidal and poloidal locations were considered for the permanent IMSE system installed at AUG and evaluated according to multiple criteria, such as the lack of view obstruction. The LOS must not be obstructed by limiters, tiles, or other diagnostics. A large Doppler separa-

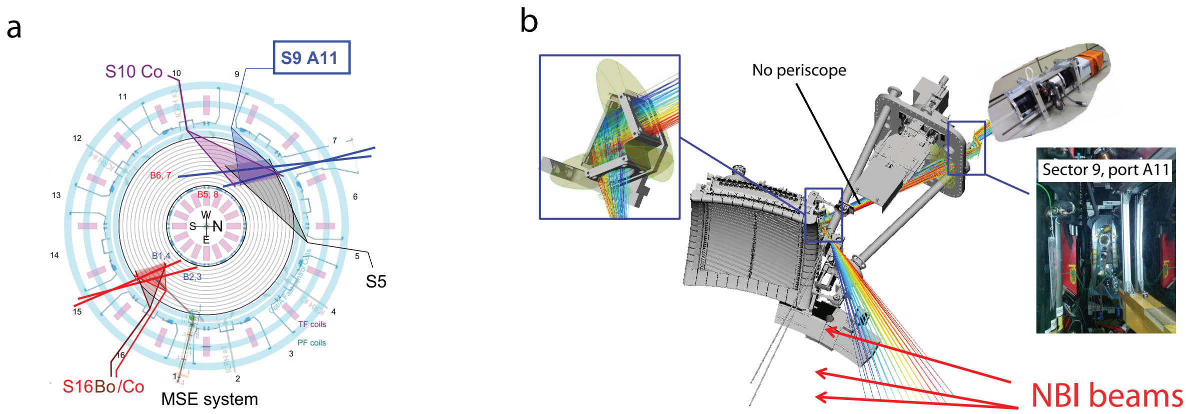

Figure 3: (a) Options for the diagnostic location, (b) 3D model of the optical relay system

tion was also a design criterion, as the MSE signal should be far from the D-α background. Blue shifted light is better than red, as this avoids contamination of the spectrum by carbon impurity lines. The location also impacts the spatial resolution. If the LOS is tangential to a flux surface, most of the light integrated over the beam width originates from that flux surface, which leads to a good radial resolution of the diagnostic. However, the pitch angle sensitivity of the diagnostic is higher if the view is not toroidal.

The best location (sector 9 port A11, see figure 3a) comes with strong space restrictions. The presence of other diagnostics in the same port (ECE, ECE imaging, heat shield temperature monitor) limits the size and positioning freedom of the mirror box, and prevents the installation of a periscope, limiting the maximum light throughput (fig. 3b). The size of the existing vacuum port was increased, albeit to only 100mm diameter. Outside the vacuum vessel, the poloidal field coil support structure and the backend of other diagnostics restrict the light path, creating the need for external mirrors.

Two boundary conditions were the starting point for the optimisation of the optical relay system, finding a compromise between field of view and total collected solid angle, and the requirement to set best resolution to the plasma centre.

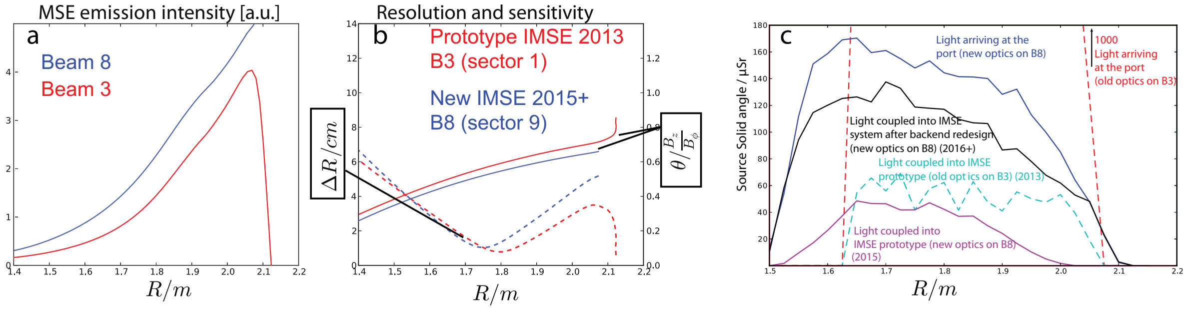

Figure 4: (a) Intensity of the beam signal at different radial locations, (b) resolution and pitch angle sensitivity versus plasma radius, (c) light cone reaching the IMSE backend

The field of view was chosen to see 3 beams, after which the system was optimised for maximum light throughput, given the space restrictions. Without considering the finite imaging capabilities of the lenses and the IMSE backend, the resolution at the plasma centre is limited to 1cm by the beam width and the diagnostic geometry (fig. 4b). The pitch angle sensitivity, the ratio of polarisation angle and pitch angle, is roughly 0.5, while the speed of the optics is f/2.7. The beam emission intensity of source 8 is higher than source 3 (fig. 4a), but the light cone coupled by the new system is slightly smaller than in the prototype tests of 2013 on the old MSE optics (fig. 4c). Therefore, the initial performance will be similar to the prototype tests, which yielded less noisy and faster measurements than the conventional MSE [3]. The amount of coupled light is expected to double after the planned redesign of the IMSE backend.

The imaging properties of the optical relay system were optimised with a custom 3D ray tracer. After several thousand optimisation steps in different considered scenarios, the best compromise between cost and imaging quality consisted of six custom lenses, of which two were aspherical to correct for spherical aberration. With this configuration, the optics achieve a resolution of 0.5cm at the beam. Since this is better than the 1cm resolution imposed by the beam width (cf. fig 4b), further optimisation would not improve the diagnostic resolution.

Two lamps were installed in the field of view of the diagnostic for absolute angle calibration [6]. The beam from a wavelength tunable laser is led into the vacuum vessel via optical fibres, then through a collimating lens and finally a polarising filter to provide a source of polarised light.

Materials used in the permanent system

Since most glasses are subject to Faraday rotation, an effect that rotates the polarisation angle of polarised light in the presence of a magnetic field parallel to light path, the lenses must be made of a special material. Most existing MSE systems use Schott SFL6 because of its low Verdet constant. However, SFL6 is not available any more. We tested different samples of Schott and Ohara glass at magnetic fields up to 80mT and calculated their Verdet constants at 656nm:

SCHOTT NSF6	28°/(T m)	± 1°/(T m)
OHARA BSL7Y	869°/(T m)	± 150°/(T m)
OHARA S-FSL5	-675°/(T m)	± 9°/(T m)
OHARA TIH6	8°/(T m)	± 17°/(T m)

Since the samples provided were not ideal for optical measurements, some measurement errors are relatively high. However, the Faraday rotation in TIH6 is clearly the lowest. It was chosen to substitute Schott SFL6 for the lenses and a polished and optically coated cylindrical sample will be tested at magnetic fields up to 2T in the near future to characterise it more accurately. However, TIH6 is very susceptible to thermal stress and tends to crack with fast temperature variations. Therefore, a 5mm thick fused silica protection cover was mounted in front of the first lens to absorb most of the radiation from the plasma. The vacuum window is also composed of fused silica, and a coil was mounted at the port such that the magnetic field can be directly measured and the Faraday rotation included in the analysis code, as fused silica has a relatively high Verdet constant of 200°/(T m) so that the varying vertical and radial control fields must also be considered.

The ratio of p/s polarisation intensity reflected by the three mirrors must be close to 100% for the IMSE system to measure the correct polarisation angle. Furthermore, no phase shift must exist between the p and s components. The quality of the mirror is more crucial than for the existing MSE system, as three mirrors had to be installed. The theoretical p/s ratio of the installed mirrors is 99.97% and within our measurement capabilities a perfect ratio was measured in tests.

Conclusions and outlook

A new 2D imaging MSE system was designed, built and installed at the AUG tokamak. The optical design was optimised such that three beams are visible in its field of view and light throughput was maximised within the strong space restrictions. A sharp image is obtained by correcting aberrations with custom aspherical lenses. An alternative glass with low Faraday rotation, TIH6, was found to replace the obsolete Schott SFL6. An accuracy of roughly 0.3° in pitch angle is expected for the new system. First measurements are expected in the first weeks of the 2015 campaign of AUG.

Next steps include the redesign of the IMSE backend. Larger filters and crystals, as well as a custom collimator lens will be used in order to couple more light. If the light throughput is sufficient, a faster camera will be installed to increase the time resolution of the diagnostic, currently 10ms. Furthermore, the calibration lamps and the mirror box will be equipped with shutters during the next opening of the AUG vessel to prevent the coating of optical components during boronisations and the resultant drift of the calibration.

Acknowledgements

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