First Results from the Imaging Motional Stark Effect diagnostic on ASDEX Upgrade

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The study and control of a Tokamak plasma requires accurate diagnosis of the magnetic configuration. External magnetic diagnostics provide rapidly diminishing detail towards the plasma centre making internal magnetic measurements essential. Motional Stark Effect (MSE) diagnostics observe the Dα emission from injected neutral particles which is Stark-split and polarised according to the local magnetic field, transformed into their rest frame. Despite much development, MSE measurements remain challenging and typically involve complex hardware duplicated for each observed point, restricting it to a few 10s of channels. Imaging MSE is a recent development[1] that uses a CCD camera to capture a 2D image of the neutral beam emission, modulated with two interference patterns that encode the polarisation state (see Fig 1a). Unlike traditional MSE polarimeters, IMSE requires no narrow optical filters to spectrally select multiplet components, so can utilise all of the available Dα light, improving the S/N ratio. IMSE gives an order of magnitude increase in the quantity of data but it has also been shown that distributed 2D data improves tomographic reconstructions of the plasma current[2]. A proof of principle IMSE system installed on the Textor Tokamak[3] showed significant potential and variants of the system have now been installed at K-Star[4] and ASDEX Upgrade.

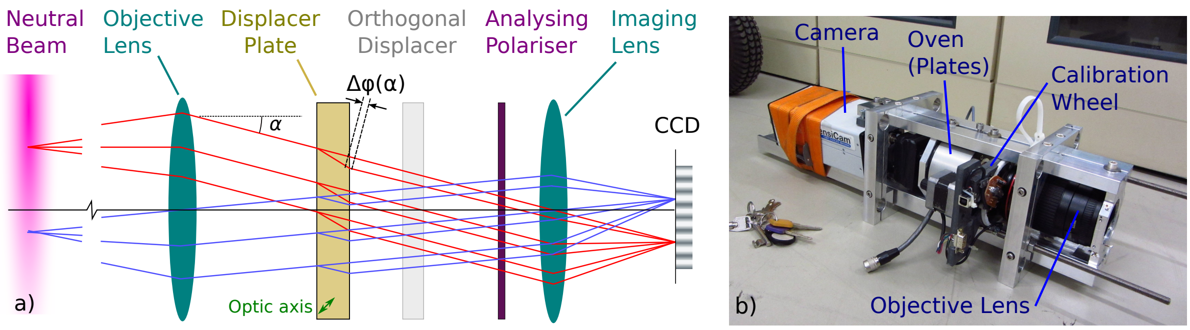

Figure 1: a) Basic IMSE system: Two lenses form an image of the beam emission on a CCD. A birefringent crystal with 45° tilted optic axis (Displacer) delays one polarisation by an angle dependant phase $\Delta\phi(\alpha)$ and with an analysing polariser creates an interference pattern across the image. A second displacer creates an orthogonal pattern and the ratio of their amplitudes relates to the input polarisation angle. b) Photograph of the compact prototype ASDEX Upgrade IMSE diagnostic.

The ASDEX Upgrade (AUG) IMSE shown in figure 1b replaced the 10-channel conventional MSE system[5] for one week with Deuterium beams, and one with Hydrogen. The objective was to show quantitative agreement within an acceptable accuracy (pitch angle $\Delta\gamma < 0.5°$) with the known aspects of the expected current profile, to demonstrate advantages of IMSE and to assess it for routine current profile measurement. The inital results of this work are reported here and the design and offline testing are presented in the diagnostics satellite conference (P6.006).

Recorded Images: The images produced take a form similar to equation 1, where (x,y) are the image coordinates, $\theta(x,y)$ is the polarisation angle and $\zeta(x,y)$ is the *spectral contrast* - a slowly varying unknown function of the spectrum.

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

Figure 2 shows a typical image from the IMSE and its Fourier transform in which the three components are identified. The ratio of the $\cos(x+y)$ and $\cos(x)$ component amplitudes yields $\tan 2\theta$. Figure 2c shows the polarisation image $\theta(x,y)$ which for AUG, relates to the magnetic field approximately as $\theta \sim 0.6\, B_z/B_\phi$. The beam emission intensity was sufficient to allow integration times down to 2ms with a VGA Sensicam imaging camera. Upgrading the camera could significantly improve the time resolution and signal quality.

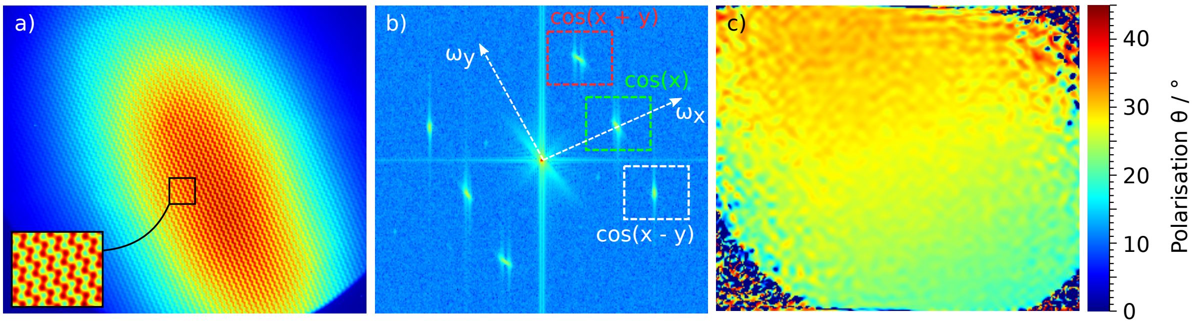

Figure 2: a) Typical IMSE image (zoomed area shows fringes), b) Fourier transform and c) demodulated polarisation map $\theta(x,y)$

An immediate advantage of the imaging system is that the position calibration can be performed by identifying background structure in the image and fitting a single transform between image coordinates (x,y) and beam intersection coordinates (R,Z) as shown in figure 3:

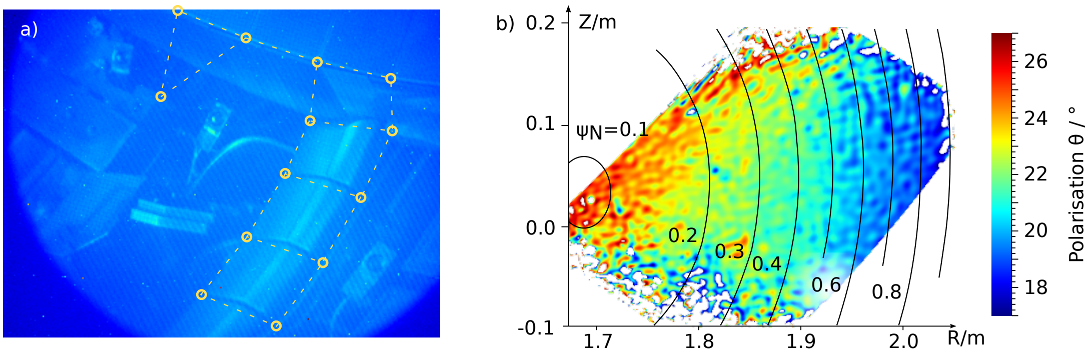

Figure 3: a) Background image (no beams) with identified known points. b) Transformed polarisation image in (R,Z) at beam intersection plane (source 3 in this case).

Comparison with standard MSE: As the AUG IMSE uses the viewing optics of the existing MSE system, raw angles can be compared directly. A plasma with a stable current profile was observed with the IMSE and repeated later with the MSE and an external polariser provided a common reference for both systems. Except for an unexplained offset of 1.0°, the agreement is good throughout the shot. Figure 4 shows the comparison with the offset removed for clarity. A single region at $R \approx 1.9m$ shows a consistent deviation due to contamination of the IMSE by polarised reflections from the poloidal limiter (seen in Figure3a). For the Hydrogen beam week, this was eliminated by an optical filter suppressing Hα light not Doppler shifted by the beam. Unfortunately, the comparison shot could not be repeated.

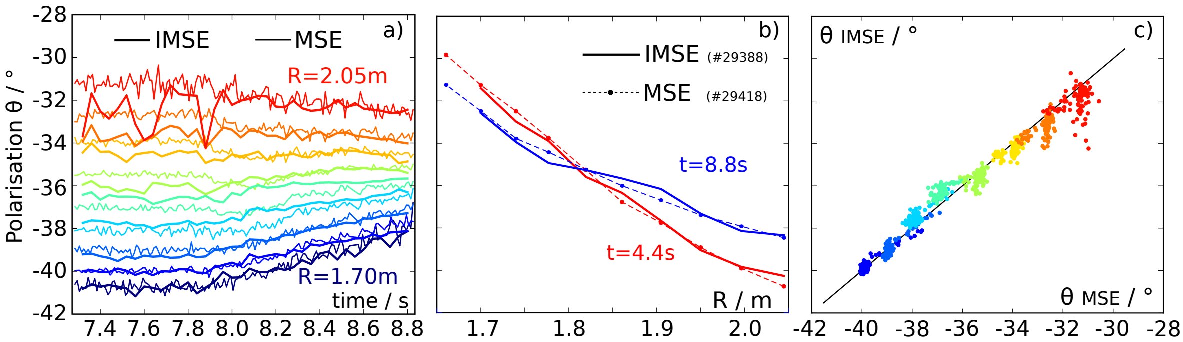

Figure 4: Comparison of MSE data and average of equivalent IMSE image region during a near identical plasma shot: a) Time traces during plasma current ramp down, b) Profiles during flat top (4.4s) and at end of ramp down (8.8s), c) Correlation over full shot. An unexplained 1.0° offset is removed from the IMSE data.

Comparison to Model: A ray-traced model of the common and IMSE optics predicts the image on the CCD and the polarisation relative to the IMSE carriage vertical, including all known effects of the lenses, windows and the dielectric mirror. With the plasma, beam and MSE emission modules it forms the forward model and predicts the measured θ. This prediction is based only on the optics model and involves no calibrations[1] with the beams, vessel or forward optics other than small adjustments of the model made by fitting the ray-traced CCD image to the observed transform points in figure 3. Based on the standard CLISTE equilibrium with only external magnetic constraints, the model is expected to accurately predict θ near the plasma edge ($R > 1.95m$) but be less accurate in the plasma core. From Bayesian current tomography[6] of the external magnetics, the same edge θ and a large core uncertainty is predicted. For all recorded data, a fixed difference between the measurement and prediction at the plasma edge of 0.7° is present which, given the inaccuracy of the optics model, is surprisingly small. The variation along the beam axis, which depends strongly on the optical model, is also accurately predicted. This suggests that fitting the ray-traced image to the observed transform inherently ensures that most of the effects on θ are accurately modelled. Exceptions to this are the Faraday Rotation and the different s/p reflectances at the windows. The latter has the opposite sign for the π and σ components, so is strongly reduced for the IMSE, which mea-

[1]A calibration is required to correct for differences of the spectral contrast ζ between the 3 components of equation1. This only effects the linearity and not the absolute polarisation angle or its variation across the image

sures both. Figures 5a-c show image cross sections and time traces with the 0.7° fixed offset removed. The remaining discrepancy is likely to be the inaccuracy of the core plasma current profile. There is also significant disagreement in the variation with Z, (not shown here) which may be due to inaccuracy in the equilibrium or in the beam model and ζ, the accuracy of which have not yet been assessed. Once the Z variation is verified, the results can be used with the Bayesian current tomography to produce the 2D toroidal current distribution.

Figure 5c shows a plasma in which the all 4 beam sources were used with no change in the current profile. The measurements were partially contaminated by Dα reflection, but some important features can still be observed. The 12° difference between beam pair $1+2$ and pair $3+4$ is caused by their opposite $\pm 4.9°$ inclinations to the mid-plane and the good match of this to the prediction at the plasma edge confirms the linearity of the measurement. The difference $\theta_3 - \theta_4$ is approximately $0.2\,B_z/B_\phi$ so, although less sensitive, can provide the pitch angle in a way unaffected by unknown offset issues. The IMSE can also measure with overlapping beams for which some data was recorded. The data approximately matches predictions but a rigorous comparison cannot be made until the beam geometry accuracy is confirmed.

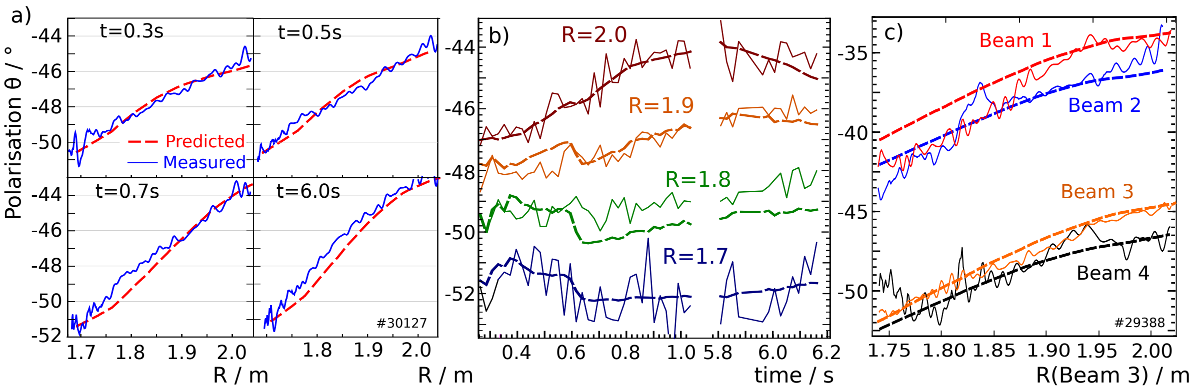

Figure 5: Comparison of measured IMSE polarisation (solid) with the full ray-traced forward model prediction (dashed). a,b) Horizontal profiles of the transformed (R,Z) images (as in Figure 3b) at 4 times points and c) time traces of 4 points along beam axis during plasma current ramp up and ramp down. d) Horizontal profiles of images when switching between the 4 beam sources. All predictions have a fixed offset of 0.7° subtracted but otherwise involves no polarisation calibration.

Summary: A new imaging MSE diagnostic was successfully installed and operated at ASDEX Upgrade. Comparisons with both the conventional MSE and predictions agree with sufficient accuracy for use as a current profile diagnostic. Using simpler hardware, the IMSE provides an order of magnitude more data and uses the full Dα spectrum, permitting sufficiently short time integration and operation with any beam source/fuel configuration. The imaging nature allows easy identification of background contamination and positional calibration.

[1] J. Howard, PPCF **10**, 50 (2008)

[2] O.P. Ford, et. al. 18th ISHW Conf. (2012)

[3] J. Howard, J. Phys. B **10**, 43 (2010)

[4] J. Howard, 18th ISHW Conf. (2012)

[5] R.C. Wolf, 25th Europhys. Conf. (1997)

[6] J. Svensson, A. Werner, PPCF **11**, 50 (2008)