Performance tests of the ASDEX Upgrade Imaging Motional Stark Effect diagnostic (IMSE)

O. P. Ford[1], J. Howard[2], R. Wolf[1],

[1] *Max-Planck Institut für Plasmaphysik, Greifswald/Garching, Germany*

[2] *Plasma Research Laboratory, Australian National University, Canberra*

Imaging Motional Stark Effect (IMSE) is a new type of MSE polarimeter[1], used to measure 2D images of the polarisation angle of neutral beam $H\alpha$ emission, for diagnosis of the plasma current profile. An IMSE diagnostic was installed on ASDEX Upgrade (AUG) to quantify the accuracy and capability of the measurement. Prior to installation, the system was subjected to a series of tests under known lab conditions to assess the ideal accuracy, choose certain operating parameters and to demonstrate several features of the method. These results are reported here, including some unanticipated effects that were discovered and mitigated. The results of the subsequent successful operation at AUG are reported at the EPS 2013 conference (O2.110).

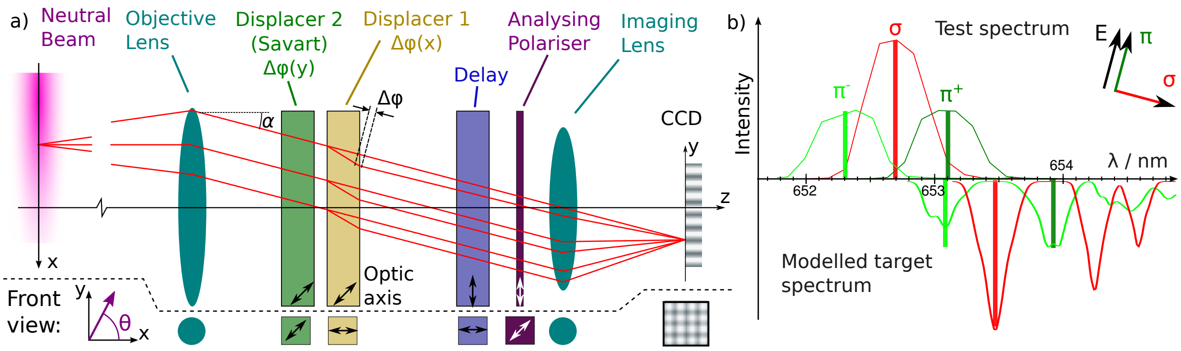

Figure 1: a) IMSE system optical layout in (x,z) and optic axis orientations in (x,y) (below). b) Simplified MSE multiplet spectra generated for test spectrum (top) and full modelled spectrum (bottom).

Measurement Principle: The complete optics for IMSE are shown in figure 1a but a simple imaging polarimeter would require only the lenses, the first displacer plate and polariser. The displacer is a birefringent crystal with optic axis tilted at 45° in the (x,z) plane. It introduces a phase shift $\Delta\phi(x)$ between E_x and E_y that depends on the incident angle α and hence on x. With the polariser, this creates interference fringes across the image with an amplitude related to the input polarisation θ as $I \propto 1+\cos(2\theta)$. For the MSE multiplet (shown in figure 1b), the fringes of the orthogonal σ and π components would cancel. A thick wave plate is introduced, adding a large phase delay $\phi_0 \sim 2\pi \cdot 10^3$ which results in a dependence of the fringe phase on wavelength λ. A careful choice of ϕ_0 ensures that the phase of the π wings are opposite from σ, causing their fringes to add. To demonstrate this and check the optimisation of ϕ_0, a test spectrum was generated by combining the image of three lamps, each polarised and spectrally filtered to mimic the modelled spectrum as shown in figure 2a. The measurement of the achieved test spectrum, compared to the expected AUG model, is shown in 1b. The available filters precluded an exact match of the spectrum centre, but the most critical feature - the σ - $\pi\pm$ separation - was matched accurately. The generated fringe patterns with and without the delay plate are shown in 2b and c which confirm the correct phase shift and constructive interference.

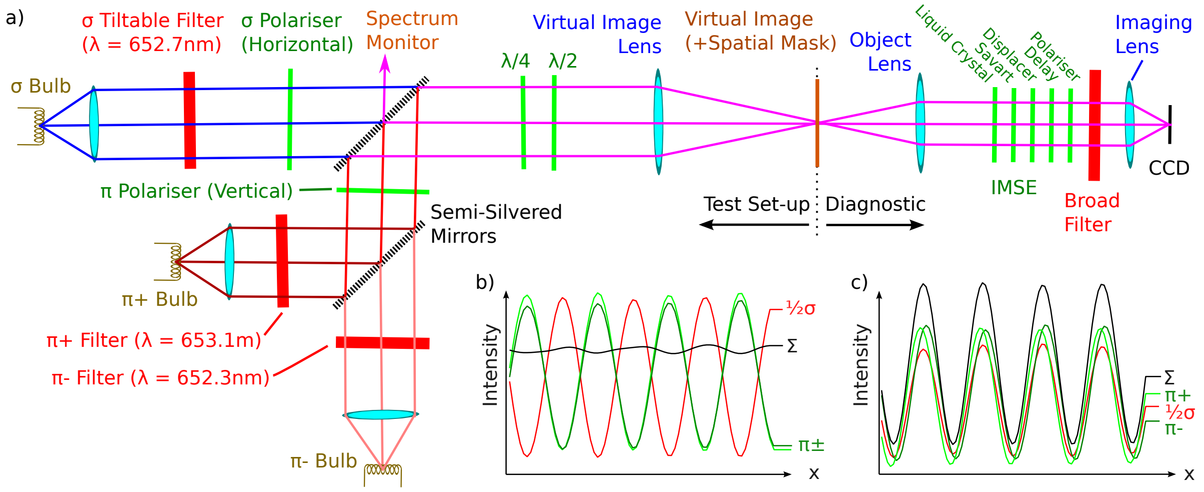

Figure 2: a) Schematic of diagnostic and experimental setup for MSE test spectrum. b) Measured pattern for σ and $\pi\pm$ and their sum with only displacer 1 giving $\Delta\phi(x)$ and c) including wave plate: $\Delta\phi(x)+\phi_0$

The large phase delay ϕ_0 also causes different wavelengths within the finite width of each component to interfere, reducing the amplitude by a factor ζ - known as the *spectral contrast*. To isolate $cos2\theta$, a second displacer is added with optic axis at 45° in (x,y) that gives a delay $\Delta\phi(y)$ and hence orthogonal fringes. It is required to have small fixed delay, so is a special type of displacer known as a *Savart* plate. The resulting image intensity has 3 components:

$$I \propto 1 \quad + \zeta_1 \cos(2\theta)\cos(x) \quad + \zeta_2 \sin(2\theta)\cos(x+y) \quad + \zeta_3 \sin(2\theta)\cos(x-y) \qquad (1)$$

In the simplest case, the ζ_is are equal so demodulating and dividing the amplitude of the first two components should give $I_{(x+y)}/I_x = \tan 2\theta$. However, initial tests gave images with spurious variation in y. The reason is that more generally, each ζ is the Fourier transform of the spectrum onto the component's spatial variable: $\zeta_1 = \int I(\omega) exp^{i\omega x} d\omega$ and $\zeta_2 = \int I(\omega) exp^{i\omega(x+y)} d\omega$. These do not cancel but the difference can be eliminated with the $(x-y)$ term, using: $\tan 2\theta = 4I_{(x+y)}I_{(x-y)}/I_x^2$ which in both simulation and experiment, removes the unwanted variation.

Intrinsic Contrast: To test the correct response of θ to input polarisation, the setup includes a motor controlled half-wave plate that rotates the complete multiplet. Figure 3a shows the measurement response which exhibits a large non-linear deviation from that expected. After considerable investigation, the cause was identified as a contrast reduction in the Savart plate due to an unexpected $\sim 1\mu m$ variation of its surface profile, shown in figure 3c. The phase mixing of light passing through different areas of the plate reduces the contrast of the components in $(x \pm y)$ by a factor μ, giving a linear scaling to $\tan 2\theta$. The mixing depends on the area of illumination so is a strong function both of the image position and the delivered input light cone. The test setup has f/9 optics, so the effect is weak ($\mu \sim 90\%$) but under f/2 illumination with a calibration sphere, it can be severe ($\mu \sim 50\%$). Since the light collection of the AUG MSE optics are not precisely known, a calibration is required and a motor controlled rotating polariser wheel was built into the IMSE system. When illuminated by the real neutral beam light, the polariser is either scanned or set at a known polarisation (optimally $\theta \sim 22.5°$), from which the calibration image $\mu(x,y)$ can be calculated and further measurements corrected. Figure 3b shows the error from expected, in the centre and four corners of the image during a $\lambda/2$ plate scan, once corrected for μ. Within the intended operating range required for plasma measurements, the response is accurate to within the required $\pm 0.2°$ for most of the image.

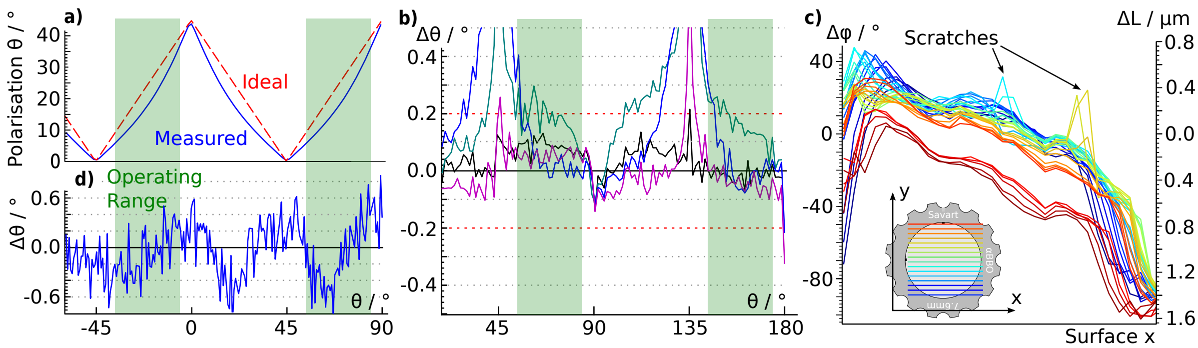

Figure 3: a) Expected and measured polarisation angle for $\lambda/2$ plate scan. b) Error at 5 image locations after correcting for Savart intrinsic contrast. c) Measured Savart plate surface profile. d) (bottom left) Error from response of phase based measurement of θ

Contamination and resolution: A beneficial side effect of the contrast reduction due to ϕ_0 is that polarised wide-band radiation should not produce a fringe pattern and hence not affect the measured polarisation, unlike traditional polarimeters. To test this, a strong polarised wide band source ($\sim 3nm$) was introduced to the test setup. The addition can be clearly seen in figure 4a and yet no discernible effect can be seen on the polarisation image in figure 4b. The same is true for narrow-band unpolarised light.

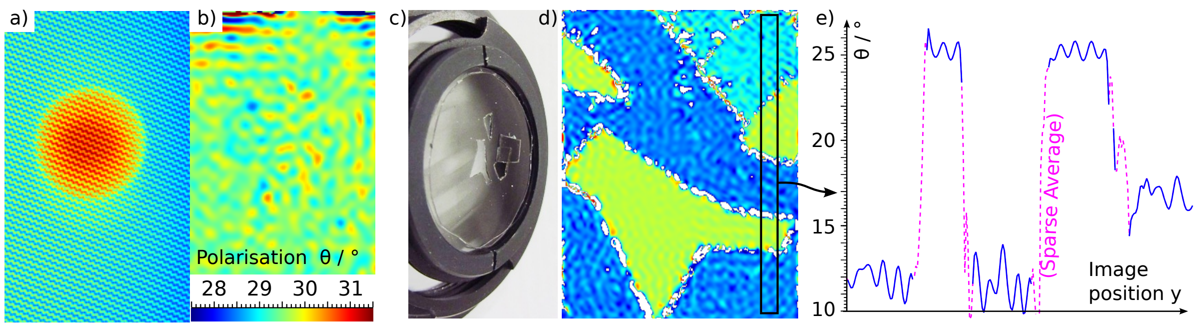

Figure 4: a) Image including polarised wide-band contamination and b) associated inferred polarisation angle. c) Polarising spatial mask with d) resulting polarisation image and e) cross-section profile.

To confirm that local changes in the polarisation angle can be distinguished and to assess the spatial resolution of the demodulation, a spatial mask (shown in figure 4c was inserted at the virtual image plane, before the diagnostic. Holes in the mask allow the full MSE multiplet through while the rest of the image is re-polarised at a different angle. Figure 4d and e show the resulting θ image and a single profile. Sharp changes are observed without any significant effect on the neighbouring regions. Changes faster than the fringe period often produce imaginary results (white in the image), for which a sparse average for the region shown is used. The S/N ratio in the re-polarised areas is poor due to the low effective transmittance of the polariser.

Alternative operation modes: It is expected that Stark-Zeeman coupling will produce a small ellipticity ε in the MSE emission. Ellipticity adds components in $\sin(x \pm y)$ to equation 1 so the ε information is held in the phase of the $(x \pm y)$ components. Since this phase is also dependent on the spectrum, ε cannot be isolated without a calibration. Alternatively, including a $\lambda/4$ plate in front of the Savart plate exchanges the θ and ε information. The IMSE allows both modes with a switchable $\lambda/4$ Ferro-liquid crystal (FLC). When off, the amplitude ratio carries θ and the phase carries ε and vice-versa when on. The amplitude measured ε was tested by adding a rotating $\lambda/4$ plate to the test setup but the test was inconclusive because the $\lambda/4, \lambda/2$ and FLC do not accurately match their design specification. The extraction of θ from phase (FLC on) was also assessed as the principle measurement technique (as in [2]). Figure 3d shows the θ error for a scan of the $\lambda/2$, with the MSE test spectrum, in which it can be seen that the both the noise and systematic deviations are slightly larger than for the amplitude derived θ. The phase measurement has the advantage that it is unaffected by the Savart intrinsic contrast μ, but the disadvantage that it depends on the spectrum so requires a calibration with the real beam spectrum at a known angle. The amplitude based θ was shown to be insensitive to spectrum changes by tilting the test spectrum filters and therefore chosen for the primary AUG measurement. To allow investigation of the phase and ellipticity information at a later date, some data was recorded with the FLC switched on/off for alternating frames.

Summary: The performance of the ASDEX Upgrade IMSE system was tested with a mock MSE multiplet spectrum. Some issues with the measurement process were identified but after appropriate modifications, accuracy within the required $\delta\theta < 0.2^\circ$ was achieved over most of the image. Measurement of the net-unpolarised MSE multiplet, insensitivity to broad-band background and spatial resolution were all demonstrated and some alternative measurement options were investigated.

References

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

[2] J.Howard, J.Chung, Rev. Sci. Instrum. **83**, 10D510 (2012)