Spectro-polarimetric optical systems for imaging plasma internal fields, structures and flows

John Howard,¹ C. Michael,¹ H. Chen,¹ R. Lester,¹ A. Thorman¹ and J. Chung²

¹Plasma Research Laboratory, Australian National University, Canberra 2601, AUSTRALIA
²National Fusion Research Institute, Daejeon, 305-333, Korea

E-mail: john.howard@anu.edu.au

ABSTRACT: Spectro-polarimetric imaging systems have opened new and better ways to study the spatio-temporal behaviour of plasma properties including current distribution, pedestal fields and the velocity distribution function of radiating species from the plasma edge to the core. Using spatial-heterodyne polarimetric techniques, these coherence-imaging (CI) systems have been deployed for motional Stark effect (MSE) imaging and charge-exchange Doppler imaging (CXRS) on KSTAR and ASDEX-Upgrade, and for passive Doppler spectroscopy of the plasma edge on DIII-D and MAST. They have also been used for Doppler imaging of low-temperature argon discharges on the linear mirror device MAGPIE at the ANU, including synchronous Doppler imaging of flow vortices associated with low frequency instabilities. We describe the diagnostic technologies, discuss the results and comparisons with simple models, and consider new applications and future developments.

A shorter version of this contribution is due to be published in PoS at:
1st EPS conference on Plasma Diagnostics

KEYWORDS: Plasma diagnostics - interferometry, spectroscopy and imaging; Nuclear instruments and methods for hot plasma diagnostics

¹Corresponding author.
1 Introduction

We describe the application of spatial-heterodyne polarization-interferometric techniques for snapshot imaging of the temporal coherence and Stokes parameters of plasma optical emission in applications such as Doppler spectroscopy and motional Stark effect polarimetry [1–3].

Doppler “coherence imaging” systems are deployed on many devices around the world. In particular, these systems have revealed the structure of impurity ion flows in the divertor and scrape-off-layer (SOL) regions of the DIII-D and MAST tokamaks [4, 5] and been deployed for charge exchange recombination spectroscopy on the TEXTOR tokamak [6]. We discuss the optical principles and instrumental details in section 2 and present new results of synchronous Doppler imaging of instabilities on a linear magnetized plasma with flow velocity resolution $\sim 1$ m/s in section 3. Polarization interferometers can also be easily adapted for simultaneous polarimetric analysis. We present recent results obtained using the imaging motional Stark effect system installed on the KSTAR tokamak in section 4.

2 Polarization interferometers for plasma spectroscopy and polarimetry

With an optical interference pre-filter to transmit only the spectral features of interest, imaging interferometers can be used to analyse the spectral or polarimetric properties of relatively narrow-band spectral scenes such as Doppler broadened emission lines or polarized multiplets. The physical parameters determining the emission spectral properties are recovered from the phase and amplitude of the interferogram at one or more appropriately chosen optical path length delays. For example, for Doppler spectroscopy, measurement of the optical coherence (fringe contrast and phase) can be related to projections of parameters such as brightness-weighted temperature and flow speed. Coherence imaging can also be used to infer spectral line ratios for isotope studies, or for measuring electron density based on Stark broadening [2].

The simplest polarization interferometer is constructed from a delay plate placed between parallel or crossed polarizers and with its fast axis at 45 degrees to the orientation of the polarizers. For light at wavelength $\lambda_0$, the plate introduces a phase delay $\phi_0 = 2\pi LB(\lambda)/\lambda_0$ between the
components parallel and perpendicular to the fast axis, where $L$ is the thickness of the plate and $B(v) = n_E - n_O$ is the plate birefringence. For quasi-monochromatic radiation, the fringe pattern at some point $(x, y)$ in the image plane is then given by

$$S = I [1 + \zeta_I \zeta \cos(\phi_I + \phi)]$$

(2.1)

where $I$ is the brightness, $\zeta_I$ and $\phi_I$ are the instrumental fringe contrast and phase, and $\zeta$ and $\phi$ are the desired variations in the fringe contrast and phase produced, for example, by the Doppler effect. The instrument response can be measured by illuminating the field of view with a suitably diffused monochromatic light source (laser beam or spectral lamp) having wavelength at or near the wavelength of interest. Issues related to characterization of the instrument function and performance are presented in detail elsewhere [1]. It is necessary to scan or modulate the interferometric path difference in order to measure the fringe properties. Polarization interferometers naturally present a number of time-domain path length modulation strategies, from electro-optic phase delay modulation, to the use ferro-electric liquid crystals for rotating the plane of polarization [7].

For snapshot applications, we have devised both quadrature encoding [8] and spatial heterodyne techniques. In the latter case, Savart plates and birefringent “displacers” produce an angle-dependent interferometric phase shear that results in approximately parallel spatial interference fringes being formed in the lens focal plane (see figure 1). We can then write the instrument phase as $\phi_I = \phi_S + \phi_0 + k_0 x$ where $k_0 x$ is the linear image-plane phase delay introduced by the shearing birefringent plate and where the wavenumber $k_0 = 2\pi d/f\lambda_0$ is set by the ray displacement $d$, the camera lens focal length $f$ and the nominal centre wavelength $\lambda_0$ [9]. The phase delay off-set $\phi_0 = 2\pi LB/\lambda_0$ is chosen to be comparable to the coherence length of the Doppler broadened spectral line as shown in figure 1. The carrier fringe phase and amplitude are recovered from the interferogram using standard Hilbert transform phase demodulation techniques.

In practice, the unshifted spatial heterodyne carrier fringe phase pattern can depart somewhat from the simple offset linear phase approximation $\phi_0 + k_0 x$. The residual systematic phase variation $\phi_S$ is obtained by uniformly illuminating the system using one or more quasi-monochromatic lamp or laser spectral lines at wavelengths at or near $\lambda_0$. To obtain the Doppler quantities, the plasma image fringe pattern is demodulated and the amplitude and phase images are normalized with respect to the calibration data to obtain images of the local fringe contrast (temperature) and phase (flow). Hereafter we assume the instrument components are known and for notational simplicity take $\zeta_I = 1$ and $\phi_S = 0$.

An advantage of the imaging approach is that background reflections can be identified from the image context and masked. Features in the background (for example port flanges or windows) can also be used to register the viewing geometry. The carrier fringe wavenumber and orientation, and the optical system magnification, are chosen to best resolve plasma features of interest. For example, as seen in figure 2, the fringe wavefront normal is chosen parallel to the plasma axis in order to maximize the system radial resolution.

Spectral lines can be split, shifted and polarized by magnetic and electric fields (the Zeeman and Stark effects respectively). The magnitude of the splitting and the polarization orientation of the multiplet components convey information about the underlying vector fields. Because the multiplets are nett-unpolarized, however, some degree of spectral discrimination is required to extract
Figure 1. Top: optical layout for snapshot imaging spatial heterodyne interferometer. A long-focal length objective lens collimates light through the interferometer such that the image is formed in the focal plane of the final lens. The shearing plate spatially separates the orthogonally polarized characteristic waves to give an angle-dependent path difference, and a sinusoidal interference pattern is formed in the focal plane after combining these waves via a final polarizer. For a uniform quasi-monochromatic source, the image registers a section of the interferogram as illustrated in the line-plot (highlighted in red).

the polarization content. Interferometers provide this discrimination through the fixed optical delay offset. Coupled with front end spatial heterodyne or temporally modulated polarimeters, it is possible to image simultaneously image all components of the Stokes vector. In passing it is worth noting that, because light that is diffusely scattered from rough surfaces such as divertor tiles tends to be unpolarized, Zeeman encoded coherence imaging offers the prospect of removing this contaminating component and providing additional information for the Doppler tomography of plasma edge and divertor flows.
### 3 Doppler imaging of steady and fluctuating fields in a linear device

To illustrate coherence imaging for Doppler spectroscopy, we report measurements on the MAGPIE linear magnetized pinch, a cylindrical helicon plasma 1.7 m in length and 10 cm in diameter, constructed for plasma-material interaction studies at the Australian National University [10]. For these studies, the discharge is produced in argon gas at a pressure of 2 mTorr and with 1.25 kW of helicon-wave heating at 13.56 MHz. The magnetic field varies between 0.01T at the antenna up to 0.15 T in the high field pinched region. The electron density in argon is \( \sim 6 \times 10^{18} \) m\(^{-3} \) on axis in the mirror region, with typical electron temperature 5 eV and ion temperatures \( \lesssim 1 \) eV. Under these plasma conditions an \( m/1 \) plasma instability with \( \delta n/n \sim 0.05 \) and \( f \sim 27 \) kHz is observed to rotate coherently along the length of the plasma discharge. Laser-based absorption or scattering techniques are generally required to measure such small background argon ion temperatures and flows. Using coherence imaging it is possible to use a gated intensified camera synchronously phase-locked to the quasi-steady plasma instability to obtain both the background plasma properties and phase-resolved Doppler images of the perturbations associated with the mode.

The optical setup for the measurements of Doppler broadened Ar II ion emission at 488 nm is shown in figure 2. Sensitivity to very low ion temperatures \( T_i \) (large optical coherence lengths) requires large optical delays of order \( \phi_0 = 2\pi N \), where \( N > 10^4 \) waves is roughly equivalent to the spectral resolving power \( \lambda_0/\Delta \lambda_D \), and where \( \Delta \lambda_D \) is the Doppler linewidth. This can be achieved using a field-widened interferometer constructed of 80 mm thick (4 \( \times \) 20 mm) \( \alpha \)-barium borate plates and 10 mm thick (2 \( \times \) 5 mm) lithium niobate plates. The crystal orientations and plate thicknesses are chosen so that their separate thermal phase drifts approximately cancel and the nett phase offset \( \phi_0 \) is largely passively stabilized [11]. A final interference filter transmits only the bright 488 nm line.

A 17 mm focal length C-mount lens couples light to a Schott IG-163 imaging optical fiber bundle (10 mm \( \times \) 8 mm). Light exiting the bundle is coupled to the camera photocathode using a lens pair having focal lengths 105 mm and 135 mm. The imaging system can be translated using a computer controlled stage in order to observe the full axial length of the discharge (12 positions with a separation of 40 mm). A typical raw camera image is shown in figure 2. The optical system is looking into a blackened view dump. Nevertheless, its properties have not been quantified, so there remains the possibility of some back-scattering contamination in the preliminary results presented here. A relatively low instrumental fringe contrast of \( \zeta_I \approx 0.36 \) is in part due to the large number of thick optical components that constitute the interferometer. The processed region-of-interest enclosed by the red box in figure 2 includes twenty interference fringes and spans an axial length of approximately 57 mm. The sequence of spatially overlapping images is stitched together after processing in order to create an image of the accessible axial extent of the plasma.

A phototube monitoring the fluctuating emission is used as source for a phase-locked loop circuit that produces a synchronous pulse train for gating the intensified camera (Roper Scientific IMAX 512x512). The camera image is obtained by integrating 40000 gated exposures of duration 5 \( \mu s \) (compared with the mode period of \( \sim 30 \) \( \mu s \)) for a total exposure time of 200 ms per frame. Following frame readout, the phase of the pulse train is incremented and a new image acquired. Altogether images at eight equispaced phases spanning one period of the mode oscillation are obtained at each of the twelve axial locations. The unperturbed, or background images are obtained by averaging over a full cycle of the plasma instability.
Figure 2. Top: the optical setup used for the synchronous imaging. Lenses L1, L2 and L3 have focal lengths 17 mm, 105 mm and 135 mm respectively. Bottom left: a schematic of the passively-thermally-stabilized optical system and Bottom right: a typical spatial-heterodyne interferogram of the plasma column. The fringes are aligned so as to maximize the available radial resolution. The red box is the processed region of interest.

3.1 The ion temperature and azimuthal flow fields

It is convenient to express the interferogram in the form

\[ S = I + a \cos (\phi_0 + k_0 x + \phi) \]  (3.1)

where \( a = \mathcal{I} \zeta \) is the fringe amplitude. In previous works [2] it has been shown that, for a spatially inhomogeneous plasma in local thermal equilibrium with temperature \( T(r) \) and drift velocity \( \mathbf{v}_d(r) \),
the brightness, and provided that the Doppler phase shift is small, the Doppler fringe contrast \( \zeta \) and phase \( \phi \) can be well approximated by line-integrals:

\[
I = \int_L \varepsilon(r) dl \\
A = \int_L \varepsilon(r) g(r) dl \\
A\phi = \int_L \varepsilon(r) g(r) v \cdot dl.
\]

where \( \varepsilon(r) \) is the local plasma emissivity and \( g(r) = \exp(-T(r)/T_C) \). The “characteristic temperature” is given by \( k_B T_C = 2m_S c^2 / \tilde{\phi}_0^2 \) where \( m_S \) is the mass of the radiating species, and the group phase delay is \( \tilde{\phi}_0 = \kappa \phi_0 \) with constant \( \kappa \) accounting for the chromatic dispersion of the birefringent crystal [2]. The instrumental quantity \( T_C \), which is set by the chosen phase offset \( \phi_0 = 2\pi N \), is the interferometric equivalent of the grating dispersion encountered in conventional spectroscopy. The normalized plasma drift velocity is defined by \( v = \tilde{\phi}_0 v_D / c \). In response to small variations in the local drift speed \( v \), the interferogram fringe pattern expands or contracts as the phase changes, leaving the fringe visibility largely unchanged. The decoupling of these influences on the phase and envelope of the interferogram is one of the more important advantages offered by interferometry. The interferometric phase gives longitudinal line integral measurements of the vector field \( \varepsilon g v \) and so, in the cylindrical case, is amenable to tomographic inversion for the \( z \) component of the underlying vector potential [12].

Composite images of the projected background emission, temperature and flow speed are presented in figure 3. The ion emission brightness contours conform well with the magnetic field lines. The wide \( \sim 30^\circ \) angular field-of-view ensures that the raw phase images detect a non-negligible contribution from the large axial ion flow into the mirror. This is removed using symmetry to reveal a sheared rigid rotation that increases from approximately \(\omega/2\pi = 2\) kHz near the source \( (z = 100\) mm) to \(12\) kHz in the pinch \( (z = 500\) mm). The ion temperature is significantly elevated in the low density regions at the plasma edge. Part of this could be due to contamination from reflections or bright light scattered in the optical system from other regions of the discharge. Nevertheless, elevated edge ion temperatures attributed to ion Landau damping on the slow Trivelpiece-Gould wave mode near the lower hybrid resonance frequency have been observed using laser techniques [13]. The observed axial and azimuthal flow speeds are a significant fraction \( (\sim 0.5) \) of the ion thermal speed, indicating the possibility that the distribution functions are non-Maxwellian. We intend to take measurements at other delays to check this and other issues.

3.2 The perturbed brightness and flow components

We now consider the perturbed components of the interferogram due to the plasma instability mentioned above. Using subscripts 0 and 1 to denote respectively the unperturbed and oscillatory components of the interferogram, a first order analysis gives (see equation (3.1))

\[
S_1 = I_1 - a_0 \phi_1 \sin(k_0x + \phi_0) + a_1 \cos(k_0x + \phi_0)
\]
from which can be easily recovered the perturbed quantities $I_1$, $a_1$ and $a_0 \phi_1$. Applying a similar approach to equations (3.2), (3.3) and (3.4) yields the following results for the perturbed line-integral quantities:

$$I_1 = \int_L \varepsilon_1 dl,$$
$$a_1 = \int_L (\varepsilon_1 g_0 + \varepsilon_0 g_1) dl \quad (3.6)$$
$$a_0 \phi_1 = \int_L f_0 v_1 \cdot dl + \int_L f_1 v_0 \cdot dl - \phi_0 \int_L f_1 dl. \quad (3.7)$$

where the scalar field $f(r) = \varepsilon(r) g(r)$ can be reconstructed from the fringe amplitude $a = I \zeta$. The degree to which the fringe phase perturbation measurement $a_0 \phi_1$ conveys the perturbed velocity field $v_1$ depends on the relative size of the perturbed components $f_1 / f_0$ and $v_1 / v_0$, and the profile details. However, it should be noted that for the special case of rigid body flow, the flow projection and its reconstruction are identical, i.e. $\phi_0(x) = \phi_0 x \omega / c$ where the impact parameter $x$ is also the plasma radial coordinate, and $\omega$ is the flow angular velocity. In the rigid rotation case, the final two terms in equation (3.8) cancel identically and the measurement is simply an intensity weighted projection of the flow perturbation.

The magnitude and phase of the relative perturbed brightness $I_1 / I_0$ and “flow” $(\phi_1 / \phi_0) c$ projections are presented in figure 4. The brightness fluctuation clearly has a dominant $m = 1$ structure.
though the amplitude is not symmetrical. The phase of the structure does not vary significantly along the length of the discharge so that \( k_∥ \ll k_⊥ \). The wide variation in background plasma flow speed and constancy of the mode frequency implies that the mode phase velocity must vary significantly along the axis.

The complex fringe amplitude and brightness perturbations \((a_1\text{ and } I_1)\) match closely everywhere, so that the temperature perturbations associated with the mode are small and have been neglected here (i.e. \( g_1 = 0 \)). The apparent flow perturbation has a complex structure. In the magnetic mirror region it presents a clear double vortex diamagnetic flow pattern associated with the \( m = 1 \) pressure perturbation. To show this, we take the brightness fluctuation as a proxy for the mode density, ignore the variations in \( T_i \), and assume cylindrical symmetry to show that \( a_0\phi_1 \sim \partial a_1 / \partial x \).

To better illustrate, models of a notional \( m = 1 \) brightness perturbation, its associated \( \nabla p \times B \) image and their projections are shown beneath the measured projection data. A tomographic analysis of these results, with consideration of the relative phase relationships and dependence on magnetic field strength, collisionality and other parameters are deferred to a later publication.

![Figure 4](image_url)

**Figure 4.** Left: the relative magnitude and phase of the normalized mode brightness perturbation and Right: the associated flow perturbation. Below: cartoons of \( m=1 \) mode brightness perturbation and flow double vortex and their projections. See text for discussion.
Motional Stark effect imaging on KSTAR

Motional Stark effect (MSE) polarimetry of atomic emission from heating or diagnostic neutral beams is the standard method for estimating the internal current distribution in the core and edge of fusion devices [14]. We have recently developed spectrally-discriminating imaging polarization interferometers that deliver the Stokes components [3, 15] and these systems have been applied for motional Stark effect imaging (IMSE) on the KSTAR and ASDEX-U [16] tokamaks.

In conventional MSE polarimetry, the magnetic field pitch angle is estimated by isolating and measuring the polarization direction $\theta$ of the central cluster of $\sigma$ lines. Interferometric techniques can also be applied to analyse the MSE spectrum. One first notes that the incident light is already polarized so that the first interferometer polarizer can be discarded. In its place is inserted a quarter wave plate that effectively shifts the polarization orientation $\theta$ into the interferometric phase domain. The resulting interferometer signals for the $\pi$ and $\sigma$ components are:

$$S_{\sigma} = I_{\sigma}[1 + \zeta_{\sigma}\cos(\phi_{\sigma} + 2\theta)]$$  \hspace{1cm} (4.1)  
$$S_{\pi} = I_{\pi}[1 - \zeta_{\pi}\cos(\phi_{\pi} + 2\theta)]$$  \hspace{1cm} (4.2)

where for the orthogonal $\pi$ components the orientation $\theta + \pi/2$ flips the sign of the carrier. Without spectral discrimination $\zeta_{\pi} = \zeta_{\sigma} = 1$ and the fringes for the total interferogram $S_{\pi} + S_{\sigma}$ have no visibility. The interferometer path delay is therefore chosen to maximize the contrast difference $\zeta_{\pi} - \zeta_{\sigma}$ and fringes are formed across full spectral range of the Doppler-shifted full-energy multiplet as selected by a suitable wideband interference filter. The polarization orientation can be recovered by imposing an additional carrier fringe pattern [15] or by using temporal polarization modulation techniques as in the KSTAR case below [3, 17].

The viewing arrangement for the KSTAR IMSE measurements is depicted in figure 5(a) and the hybrid spatio-temporal imaging system is shown in (b). The ferro-electric liquid crystal (FLC) waveplates can quickly switch ($\approx 10\mu s$) the orientation of their axes through $45^\circ$ with the reversal of an applied low voltage bias. For small ellipticity, the two orientational states of the system give images proportional to

$$S_{\pm} = 1 + \zeta \cos[\phi(y) \pm 2\theta]$$  \hspace{1cm} (4.3)

where $\phi(y)$ is the spatial heterodyne fringe phase. The difference phase between alternate frames is $4\theta$, while comparing the sum phase $2\phi(y)$ with a calibration measurement at a nearby wavelength produces an image of the beam Doppler phase. If the Doppler phase is known, the spatial carrier alone is sufficient to encode the multiplet orientation and the FLC is not required.

IMSE is insensitive to unpolarized or broadband polarized background contamination. This is illustrated in figure 5(c) which shows the plasma image formed in the absence of the heating beam. The port features visible in the background are used to register the camera viewing parameters (position and orientation). When the beam is injected, interference fringes are formed across the full extent of the beam image as seen in (d), while subtraction of successive frames results in the nett phase image shown in (e). Because it is not necessary to isolate a Stark multiplet component for polarimetric analysis, the IMSE filter passband can be chosen to admit the full multiplet, with the result that IMSE systems can operate successfully over a range of possible beam energies. Two new capabilities offered by IMSE are the ability to obtain the axis position directly from the $B_z$...
Figure 5. (a) Arrangement of beams and viewing geometry for imaging MSE on the KSTAR tokamak. (b) The dual-state hybrid imaging system. The half-wave FLC waveplate can quickly switch its fast axis between the 45° (green) and 90° (red) orientations. (c) Plasma image without beam. The absence of interference fringes indicates that the radiation is either unpolarized, broadband or both. (d) The median-filtered beam image. The original image has dimensions 2560 × 2160 with peak photo-electron count of approximately 1000 for a 14 ms exposure. (e) The phase image 4θ obtained by calculating the phase difference between exposures in alternate FLC states.

image (under the assumption that the Shafranov shift is small), and also to be able to integrate the magnetic field inwards from the last closed flux surface to obtain directly the poloidal magnetic flux function.

To illustrate the system performance we show $B_z$ images for a 700 kA H-mode KSTAR discharge with injected beams NB1 (90 kV) and NB2 (75 kV) within the field-of-view (figure 6). The images are unfolded from the polarization angle image using the camera view parameters and under the simplifying assumption that the up-down anti-symmetric $B_r$ contribution is negligible and that the plasma radial electric field is small compared with the induced field. When the IMSE system observes multiple beams simultaneously, it remains possible to extract the pitch angle by first retrieving the relative beam intensities from the nett Doppler shift. We have not yet unfolded the mixing of the separate beam polarization angles in this case, so there is some uncertainty in
Figure 6. The extracted images of $B_z$. Left: prior to a type I ELM event and Centre: during the ELM. Note the strong edge pedestal feature in $B_z$. The dashed curves are magnetics-constrained EFIT contours of the magnetic flux surfaces.

the inferred $B_z$ which is more pronounced closer to the axis, and which may be contributing to the small vertical asymmetries in the image. The system also suffers from some systematic distortions due to non-ideal optics as discussed elsewhere [17]. Superimposed on the images are the magnetics-constrained EFIT flux contours. The pronounced radial structure in the edge pedestal is seen to contract radially inwards during the ELM event. The system performance and extended discussion of results will be presented in a following publication.

References

[1] J. Howard, Electrooptically modulated polarizing fourier transform spectrometer for plasma spectroscopy applications, Appl. Opt. 41 (2002) 197.
[2] J. Howard, C. Michael, F. Glass and A. Danielsson, Time-resolved 2-d plasma spectroscopy using coherence imaging techniques, Plasma Phys. Contr. F. 45 (2003) 1143.
[3] J. Howard, Snapshot-imaging motional Stark effect polarimetry, Plasma Phys. Contr. F. 50 (2008) 125003.
[4] J. Howard et al., Doppler coherence imaging and tomography of flows in tokamak plasmas (invited), Rev. Sci. Instrum. 81 (2010) 10E528.
[5] S.A. Silburn et al., Coherence imaging of scrape-off-layer and divertor impurity flows in the Mega Amp Spherical Tokamak (invited), Rev. Sci. Instrum. 85 (2014) 11D703.
[6] J. Howard, R. Jaspers, O. Lischtschenko, E. Delabie and J. Chung, Imaging charge exchange recombination spectroscopy on the TEXTOR tokamak, Plasma Phys. Contr. F. 52 (2010) 125002.
[7] J. Chung, R. König, T. Klinger and J. Howard, Time resolved coherence-imaging spectrometer on WEGA stellarator, Plasma Phys. Contr. F. 47 (2005) 919.
[8] J Howard, High-speed high-resolution plasma spectroscopy using spatial-multiplex coherence imaging techniques (invited), Rev. Sci. Instrum. 77 (2006) 10F111.
[9] J. Howard, Coherence imaging spectro-polarimetry for magnetic fusion diagnostics, J. Phys. B-At. Mol. Opt. 43 (2010) 144010.
[10] B.D. Blackwell, J. Caneses, C. Samuell, J. Wach, J. Howard and C. Corr, *Design and characterization of the magnetized plasma interaction experiment (magpie): a new source for plasma-material interaction studies*, Plasma Sources Sci. T. 21 (2012) 055033.

[11] R. Lester, Y. Zhai, C. Corr and J. Howard, *Coherence imaging for ion temperature and flow measurements in a helicon plasma source*, in preparation (2015).

[12] J. Howard, *Vector tomography applications in plasma diagnostics*, Plasma Phys. Contr. F. 38 (1996) 489.

[13] E. Scime, R. Hardin, C. Biloiu, A.M. Keesee and X. Sun, *Flow, flow shear, and related profiles in helicon plasmas*, Phys. Plasmas 14 (2007) 043505.

[14] F.M. Levinton, R.J. Fonck, G.M. Gammel, R. Kaita, H.W. Kugel, E.T. Powell, and D.W. Roberts, *Magnetic field pitch-angle measurements in the PBX-M Tokamak using the motional Stark effect*, Phys. Rev. Lett. 63 (1989) 2060.

[15] J. Howard and J. Chung, *Spatial heterodyne stokes vector imaging of the motional Stark-Zeeman multiplet*, Rev. Sci. Instrum 83 (2012) 10D510.

[16] O.P. Ford, J. Howard, M. Reich, J. Hobirk, J. Svensson and R. Wolf, *First results from the imaging motional Stark effect diagnostic on ASDEX upgrade*, in Proceedings of the 40th European Physical Society Conference on Plasma Physics, 2013, 02.110.

[17] A. Thorman, C. Michael and J. Howard, *A high spatial resolution stokes polarimeter for motional Stark effect imaging*, Rev. Sci. Instrum. 84 (2013) 063507.