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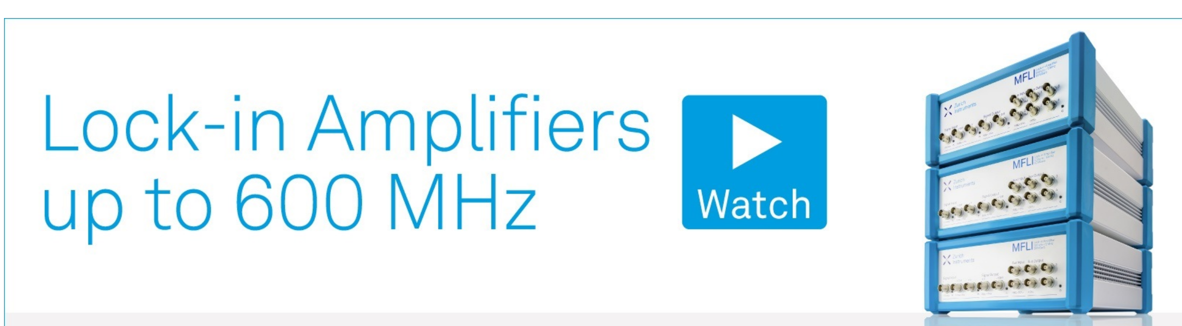

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 11D413 (2016)

A synthetic diagnostic for beam emission spectroscopy in the helically symmetric experiment stellarator

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The Helically Symmetric Experiment (HSX) has a number of active spectroscopy diagnostics. Due to the relatively large beam width compared to the plasma minor radius, it is difficult to achieve good spatial resolution at the core of the HSX plasma. This is due to the fact that the optical sightline cuts through many flux surfaces with varying field vectors within the beam. In order to compare the experimental results with theoretical models it is important to accurately model the beam width effects. A synthetic diagnostic has been developed for this purpose. This synthetic diagnostic calculates the effect of spot size and beam width on the measurements of quantities of interest, including radial electric field, flow velocity, and Stark polarization. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960068]

I. MOTIVATION

Neutral beam based spectroscopy is a widely used plasma diagnostic technique for fusion devices.[1,2] Light emitted by the beam neutrals or the impurities by interaction with the beam can provide localized spectroscopic measurements. Although it is simplest to approximate the beam induced emission as originating from a single point, in reality, the light is from a volume set by the cross section of the beam and the spot size of the view. In Helically Symmetric Experiment (HSX), due to a relatively small size of the plasma compared to finite beam width, the sightline cuts through a significant volume of the plasma. The emission from this volume can be simulated in order to compare predictions from a neoclassical model like PENTA of flow and radial electric field to experimental measurements.[3,4] Proper weighted averaging must be employed in order to accurately interpret the experimental measurements and compare them with these theoretical calculations that are typically made on a series of flux surfaces. To account for these effects, a synthetic diagnostic was developed to find the effect of the finite beam width and spot size on the measurement of electric field and flows in order to properly compare the measurement to neoclassical calculations. The model has been applied to the optimization of the MSE polarimetry system and to the interpretation of Pfirsch-Schlüter flow measurements, which are explained in Secs. III and IV.

This modeling is important for several reasons. Firstly, depending on the magnetic geometry and plasma parameters, the quantities of interest can significantly change within the sampling volume. For example, the sightline volume samples different values of the radial electric field and flow, both in magnitude and direction. This can lead to measured electric field which is different from the value at the focal point of the optics. Another effect is that there is a change in the direction of the magnetic field vectors across the sightline, especially in poloidal views near the core. This leads $\vec{v}_{beam} \times \vec{B}$ to change direction and magnitude throughout the sightline which changes the measured polarization direction and Stark splitting of the H_α light throughout the sightline. This leads to spreading in the polarization angle that will effectively decrease the resolution of the MSE polarimetry system.

II. BEAM MODEL

The neutral beam on HSX is a 30 kV, 4 A hydrogen beam with a pulse length of 4 ms.[5] An aperture at the entrance port reduces the beam to a radius of 1.5 cm at its focal point, while the average plasma minor radius is 12 cm (see Figure 1). The beam model was made by discretizing the cross section of the sightline and beam into a grid of size 0.1 mm by 0.1 mm by 0.1 mm. The flux surface averaged radial electric field and impurity ion flow are calculated using the neoclassical transport code PENTA and the magnetic field vectors, taken from VMEC, are mapped onto the 3D grid. At each point a weighting was found which was based on the beam profile, sightline optics (spot size, limits on the acceptance angle due to the fiber's NA, solid angle effects, etc.), emission cross sections, and experimental plasma parameters. This weighting was then used to find both the average value of quantities of interest and their spread for a given view.

A. Atomic physics and optics modeling

Due to the high velocity of beam particles, once the hydrogen particles are excited to the n = 3 state they can travel significant distances before decaying as H_α light. This is because the spontaneous decay rate is comparable to the beam velocity, which leads the mean free path for the HSX beam particles to spontaneous decay to be 5.4 cm. This

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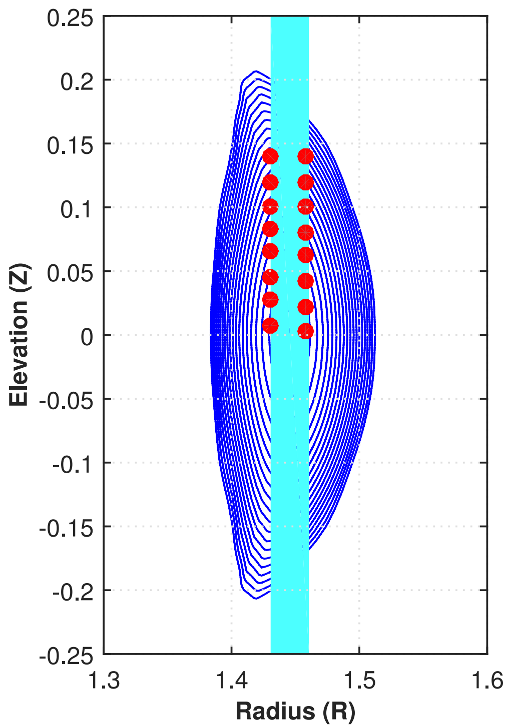

FIG. 1. Poloidal cross section of the HSX magnetic flux surfaces and the beam. The shaded region represents the 1/e width of the DNB. The CHERS views used for measuring the Pfirsch-Schlüter views cross section at the focal point is shown in red.

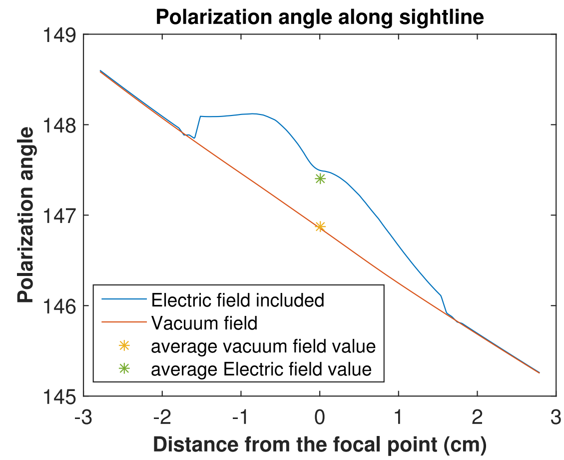

FIG. 2. Polarization angle along the sightline. The polarization angle of light emitted along the sightline with and without the inclusion of the radial electric field. The vacuum field case shows the magnetic pitch angle change across the sightline. The edge is outside the high electric field region so it sees little change in angle due to the small E_r. The beam is approximately Gaussian and has a 1/e radius of 1.5 so the core most points have the strongest weighting.

means the location of excitation and emission of H_α cannot be approximated as the same point. To compensate for this effect the excitation was calculated in the volume of the beam above the view and then the resulting emission of these excited particles was calculated within the sightline. This reduces the effect of emission on local density, because the excitation rate depends on the density at the point of excitation not emission, and makes the intensity of light a function of the density profile along the beam path.

The etendue of the optics was taken into account at each point of the discretization. Firstly, the solid angle of the light captured by the optics was calculated. Secondly, the fraction of the light that, after passing through the optic system, would strike the fiber area, and do so at an acceptable angle, was calculated at each point. This captures the fact that the effective spot size of the optics is not constant across the viewing volume.

III. MOTIONAL STARK EFFECT (MSE) MODELING

Motional Stark Effect (MSE) polarimetry can be used to measure the q profile and electric field within a plasma.[6] On HSX, the MSE system was designed to measure the radial electric field. In order to optimize the resolution to E_r, a scan of views and spot sizes was examined with this model.

The MSE modeling calculates the stark splitting, Doppler shift, and the polarization of the H_α light[7,8] at each point of the grid. The profiles are then summed over each grid point, with proper weighting, to yield a final spectrum and polarization as a function of wavelength. This profile was input to a model for the PEM (photoelastic modulator) system[8] and filter to model the output signal of the diagnostic. The model shows that there is a spreading in the polarization angle throughout the sightline (see Figures 2 and 3). There is also line broadening due to changes in the stark splitting and Doppler shift within the sightline volume, but this effect is calculated to be small compared to the total broadening measured by a spectrometer.

The results presented in this paper assumed that the beam levels were statistically populated.[7] The low density and relatively small size of the HSX plasma may make this assumption invalid. Including a non-statistical beam population model could increase the accuracy of the MSE calculation. Measurements and modeling of this effect on HSX can be found in Ref. 9.

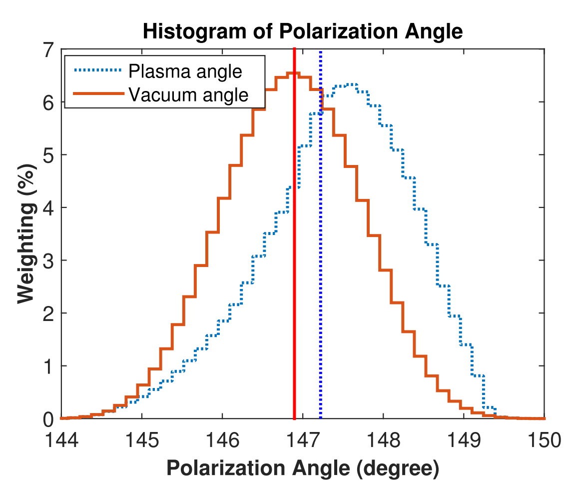

FIG. 3. Histogram of polarization angle. The electric field causes a shift in the mean polarization angle, but it does not change the distribution uniformly. This is due to the fact that the magnitude and effect of the electric field are largest near the core of the beam but small near the edge of the beam. The vertical lines are the mean values of the angle and the difference between the mean values is 0.537° for this view.

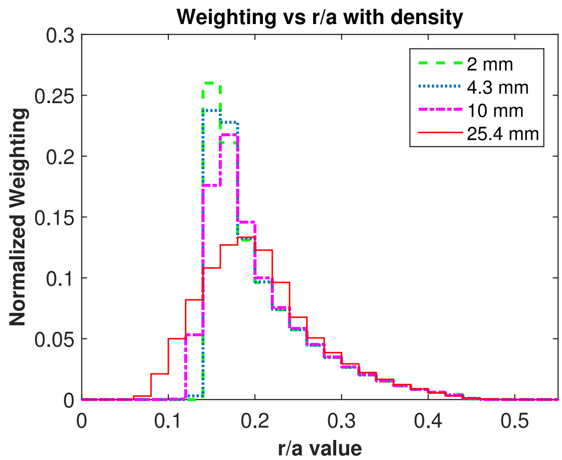

FIG. 4. Histogram of signal vs r/a for different optical spot sizes. The radial resolution is primarily limited by the beam width until the spot size diameters are near the beam width. This allows for a larger fiber with a correspondingly larger spot size to be used without sacrificing resolution in order to collect more light.

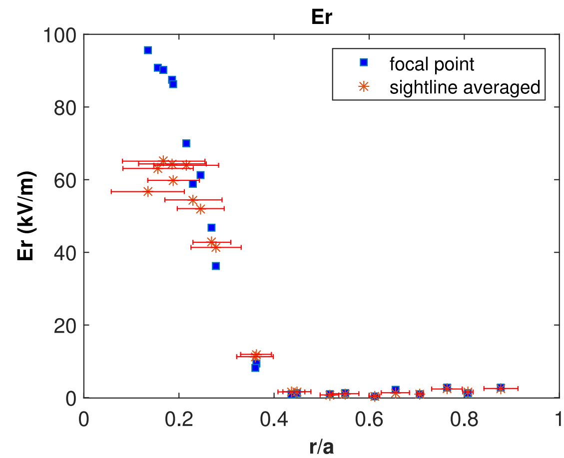

FIG. 5. E_r calculation. The E_r at the focal point of the optics is higher than the sightline averaged values in the core. The focal points sample the high electric field region, but the size of the region is small compared to the sightline volume. In the edge the gradient in E_r is small so the larger sampling volume has little effect. This effect is seen in both PS views and MSE views. The radial spread of the view is plotted for the averaged view.

The model was also used to find the change in expected signal with a change in spot size or viewing location. As expected, when the spot size increased, the signal level went up, which would improve the signal to noise ratio, but the spatial resolution decreased due to a larger sample volume. The effect on resolution was small for spot sizes smaller than the beam width, where the beam width effectively set the spatial resolution (Figure 4). As such, a fiber was chosen to give a spot size around 10 mm in diameter. Using these calculations, a fiber was chosen to match the etendue of the system for this spot size.

IV. PFIRSCH-SCHLÜTER FLOW MEASUREMENTS

The charge exchange spectroscopy diagnostic in HSX has been recently used to measure the Pfirsch-Shlüter component of the parallel flow. For this purpose, flow measurements are made on the inboard and outboard side of the plasma, within the beam width (see Fig. 1). This measurement can be used to calculate the radial electric field in the plasma. For the Pfirsch-Schlüter views the quantities of interest were the radial electric field and the geometric factors needed to calculate the Pfirsch-Schlüter effect. In order to look at the inboard and outboard side of the plasma, the views look toroidally and at the edges of the beam. This leads to a smaller signal than a view at the core of the beam, but it is more localized due to effectively viewing less of the beam width. Despite the better spatial resolution, the PS factors and E_r at the focal point of the optics are significantly different than their values averaged over the sightline (Figure 5). This arises for two reasons, firstly, the views are not perfectly toroidal (the non-toroidal component is largest in the core views). This leads to sampling across flux surfaces with different values of E_r. The second effect arises from the steep gradient in beam density and, to a lesser extent, plasma density within the view. This effectively shifts the viewing location towards the center of the beam and into a region with different electric field and PS factors. This effect is more important in the core than in the edge views due to the fact that the change in E_r and PS factors due to the shift towards the center of the beam has a greater effect in the core.

V. CONCLUSION

Significant changes (up to 50%) are seen between the sightline averaged signals and the signal modeled from only the focal point on HSX. This was seen in calculations of flow and E_r for HSX plasmas. This effect is important if the quantities of interest change within the sampling volume, as is the case in HSX. Reducing the beam diameter or looking more at the edge of the beam can reduce this effect, but in HSX these options are not viable. Therefore, properly modeling the beam is necessary to analyze the results from beam emission diagnostics on HSX.

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