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A motional Stark effect diagnostic analysis routine for improved resolution of iota in the core of the large helical device

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A new Motional Stark Effect (MSE) analysis routine has been developed for improved spatial resolution in the core of the Large Helical Device (LHD). The routine was developed to reduce the dependency of the analysis on the Pfirsch–Schlüter (PS) current in the core. The technique used the change in the polarization angle as a function of flux in order to find the value of diota/dflux at each measurement location. By integrating inwards from the edge, the iota profile can be recovered from this method. This reduces the results' dependency on the PS current because the effect of the PS current on the MSE measurement is almost constant as a function of flux in the core; therefore, the uncertainty in the PS current has a minimal effect on the calculation of the iota profile. In addition, the VMEC database was remapped from flux into r/a space by interpolating in mode space in order to improve the database core resolution. These changes resulted in a much smoother iota profile, conforming more to the physics expectations of standard discharge scenarios in the core of the LHD. *Published by AIP Publishing.*
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I. INTRODUCTION

Motional Stark effect (MSE) diagnostics[1–4] on fusion devices are primarily used to make measurements of the iota profile of the plasma. On heliotrons and stellarators, due to their relatively smaller plasma current, the change in the iota profile is typically smaller than in a tokamak. That being said, the change can still be significant. For example, changing the iota profile can change the transport in the plasma and the location of the islands in the plasma and thereby the strike points on the divertor.[5–7] Therefore the MSE system on the Large Helical Device (LHD) was designed to measure the iota profile on the LHD.[8,9]

The difficultly of interpreting the MSE results in stellarators is the conversion of the MSE polarization measurement into an iota measurement. 3D reconstructions using the MSE data as an input can be done, but doing this calculation is a very time consuming process. As such, a pre-made database of magnetic reconstructions has been calculated using VMEC[10] in order to speed up this process on the LHD and allow an analysis of all of the shots on the LHD.[11] Prior analysis, described here,[11] had a problem resolving iota in the core of the LHD. This paper describes the improved analysis technique that has been developed in order to properly analyze the core MSE data.

In the core of the LHD, the previous analysis was highly sensitive to the Pfirsch–Schlüter (PS) contribution to the MSE result. A small error in the modeling of the PS current could lead to a very large error in the iota profile (see Fig. 1). The MSE measurement on the LHD is primarily dependent on B_z. As the plasma current goes to zero at the core, its contribution to B_z and therefore the MSE measurement does as well. The PS current contribution to B_z is at some nonzero value in the core that is much larger than the plasma current contribution to B_z (as seen in Fig. 2). As such a relatively small change in the PS current can have a larger effect than a large change in the plasma current on the measurement. As such, a new method has been developed that is less sensitive to the PS current in the core. This method relies on the derivative of B_z with respect to flux. This is useful because the PS component of B_z is relatively flat in the core while the plasma current contribution is not (with the slope being a function of the current magnitude and profile). This method minimizes the effect of the uncertainty in the PS current in the core of the LHD on the MSE measurements. The data in this paper are from the LHD shot number 82716.

II. BACKGROUND

The database of over 7000 VMEC equilibrium reconstructions used in this work was created with 7 different parameters. Three of the parameters arise from external parameters given by the vacuum magnetic field: vacuum magnetic axis position, quadrupole field, and the pitch parameter. The four plasma dependent parameters are central beta, pressure peaking coefficient, toroidal plasma current, and current peaking factor.[11]

The first three plasma parameters are found with Rogowski coils and the Thompson scattering system. The method used and details of the VMEC equilibrium database are described in detail here.[11] These diagnostics are relatively insensitive to the current peaking factor however.

The MSE system is therefore necessary to find the current distribution and from that the iota profile. In order to do this, the

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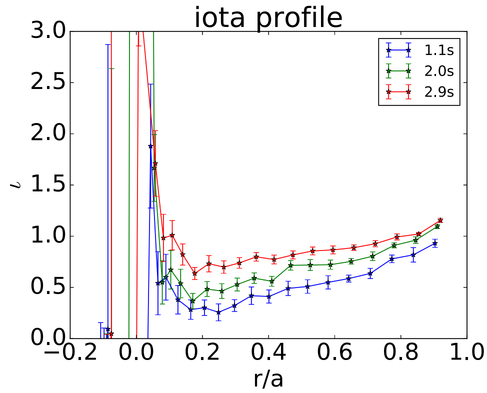

FIG. 1. The old fitting routine often gave unphysical values of the iota profile in the core region due to uncertainties in the PS contribution to the MSE measurement. Beyond r/a values of 0.3, where the relative contribution of the PS current is smaller, the fitting routine works well and the change in iota with a change in current is recoverable.

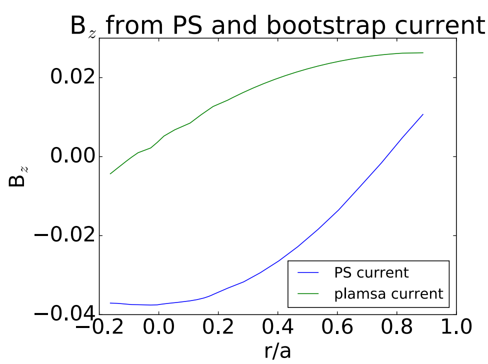

FIG. 2. The profile of B_z along the measurement points of the diagnostic is plotted. The plasma current contribution to B_z goes to zero in the core but the slope with respect to flux is nonzero. The PS current is nonzero in the core but the slope is approximately equal to zero in the core. Therefore using the derivative of B_z with respect to flux can minimize the effect of the uncertainty in the PS current on the analysis.

change in the iota and polarization angle from the vacuum to the plasma was calculated for each VMEC equilibrium at every measurement point. The previous method uses the change in the angle and iota data from a scan of the plasma current (±5 kA/T) and current peaking factors to find a linear relationship between the change in the polarization angle and iota (as seen in Fig. 3). The linear fit is then used in conjunction with the experimental change in angle to find the change in iota.

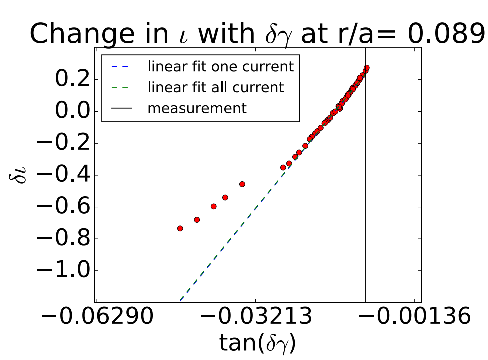

FIG. 3. The VMEC database is used to find the change in the polarization angle (γ) and iota with a scan of currents and current profiles. The scan of the VMEC equilibria polarization angle and change in iota are plotted in red. The relationship is generally linear, which allows fitting to be done to find the experimental change in iota from a given MSE measurement. The experimentally measured change in angle is the vertical line. The fit using the scan of currents is almost the same as the fit using only the experimental current at this radius value. The outputted iota value can be seen in Fig. 1.

III. IMPROVEMENTS TO THE FITTING ROUTINES

The old analysis technique works well in the mid-radius region ($0.3 < r/a < 0.75$). There are two regions that can experience problems in the old analysis routine: the core and to a lesser degree in the edge. In the edge, the iota profile can be known from the total current inside the plasma. The old routine takes a fit of a scan of currents and current peaking factors, but using a current scan is problematic due to the fact that the iota value at the edge is set primarily by the current, not by the polarization angle. Therefore, using a current scan can lead to bad fits as can be seen in Fig. 4. To correct this problem, in the edge only the experimental current was used in the fitting. The magnitude of this effect is small for most shots however. The larger problem with the old analysis was in the core.

A. Part one: The effect of the PS current

As previously mentioned, in the core the uncertainty in the PS current can greatly affect the calculation of iota. Near the core, the dependency between the measured polarization angle and iota becomes very steep, which makes a very small change in angle that leads to a large change in iota (see Fig. 3). This can be problematic because there is also a change in the polarization angle from the PS current. This is primarily due to the shift of the magnetic axis from the PS current. Due to the steep dependency of the polarization angle and iota, a small error in the offset from the PS current can lead to a very large, unphysical error in iota in the core, as seen in Fig. 1.

In order to reduce the effect of the PS current on the measurement of iota, a new analysis method was developed that had a smaller dependency on the PS effect. This method takes the derivative of the polarization angle and iota with respect to the flux taken from the database and, using a scan of current

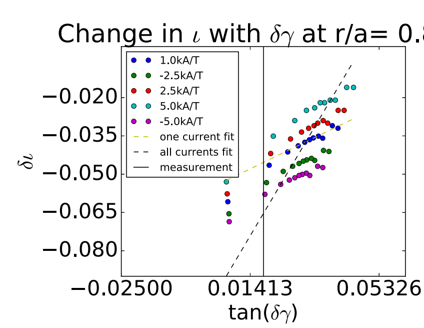

FIG. 4. The old fitting routine takes a linear fit of a scan of currents (±5 kA/T) and peaking factors. This can lead to problems at the edge where the iota value can be known from the net plasma current and is insensitive to the current peaking factor. Near the edge, the different currents have similar dependence of iota on the polarization angle but can have different offsets. This can lead to inaccurate fitting and therefore only the actual plasma current is used in the fitting of the plasma edge.

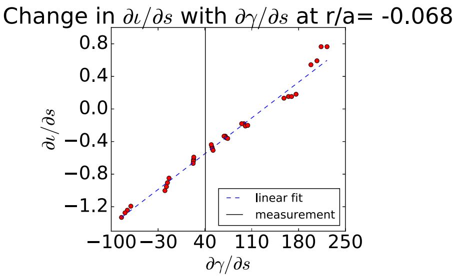

FIG. 5. The VMEC database is used to find the change in the polarization angle and iota with respect to flux. This is calculated for a scan of currents and current profiles and a linear fitting is done to find the experimental change in dι/ds from a given MSE measurement of dγ/ds. The vertical line is the experimentally measured dγ/ds value. The very hollow profiles can have a nonlinear dependency and are therefore ignored in the fitting. The negative r/a value indicates measurements on the inboard side of the device.

and current peaking factors mentioned earlier, linearly fits this data, as seen in Fig. 5. This linear fit is then used with the experimentally measured derivative of the polarization angle with respect to the flux to find the value of diota/ds at a given measurement location, where s is the normalized toroidal flux. By using diota/ds and integrating inward from a location where the iota value is known (for example, at the edge, where the iota value can be known from the plasma current), the iota profile can be calculated with this method. This method has the advantage that the dependency of the PS current has a small radial dependency, so this new method can reduce the effect of the PS current in the core.

The derivative with respect to flux is calculated by applying a linear fit of three points and taking the slope as the derivative, except at the outermost MSE channels where two points are used. Using three points instead of two to find the derivative was found to lead to a smoother fit that was less likely to be affected by an error in a single measurement channel.

There are several difficulties and potential problems with this technique. Unlike the previous analysis method, where the accuracy of each point was independent of the others, an error in one point of the measurement can lead to an error in the whole iota profile due to the integration inwards. If there is one "bad" data point, the slope of the iota profile will keep the proper shape but there can be an offset in iota introduced by the integration. In addition, the uncertainty of the fits is passed down each step of the integration, which can lead to a large uncertainty in the core. This can be seen in Fig. 9, where the error increases throughout the region of integration to its largest values on the innermost points. Another problem arises from the resolution of the VMEC mapping in the core, which will be described in Sec. III B.

In order to avoid the problems of the old and new methods, a hybrid method was developed. The method uses the old method beyond r/a of 0.3, but the new integration method in the core, where there are questions about the validity of the old method. This hybrid method reduces the problem caused by the propagation of errors by reducing the number of points used in the integration, and it also avoids the problem caused by the uncertainty in the PS current in the core of the LHD.

B. Part two: Improved mapping of the VMEC database

Another problem faced in both analysis methods arises from the poor spatial resolution of the VMEC database in the core. This poor resolution leads to a rough inverse mapping of the views onto the VMEC database. This lack of resolution is especially important for the integration method where the flux values of a given view need to be known accurately to find the derivatives and completing the integration used to find the iota profiles.

The VMEC code,[10] which is used to create the database for MSE analysis, creates a radial grid of surfaces equidistant in flux space from each other in its default settings, which were used in this work. This leads the minor radius of the VMEC surfaces to be concentrated on the edge because s = $(r/a)^2$. As such, the interpolation of VMEC near the core of the LHD can be difficult due to a lack of nearby VMEC surfaces. Problems arise in the current interpolation method when the measurement location was at or near the innermost surface (the inner two most surfaces are at $r/a = 0.1$ and 0.14). Depending on the location of the magnetic axis, as many as 5-10 channels can be found inside the innermost flux surface. Increasing the number of surfaces in the VMEC calculations will improve this problem, but a fourfold increase in resolution is needed to reduce the location of the innermost flux surface in half. This process can be increasingly expensive, especially for making a large database of several thousand equilibria.

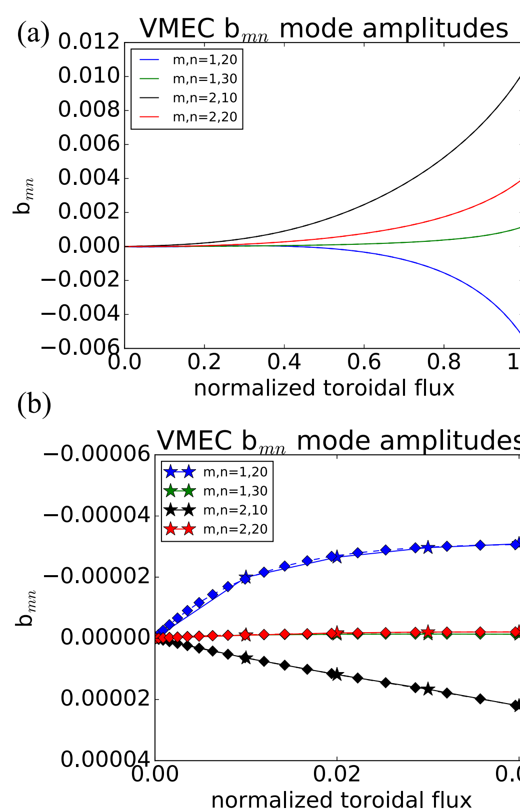

FIG. 6. The plots show mode amplitudes as a function of flux for the two mappings. The mode amplitudes of the VMEC outputs were interpolated in mode spaces using a Chebyshev fit staring from equidistant points in flux space to equidistant in r/a space in order to increase the core resolution of the VMEC database. (b) is a blown up plot of (a) around the magnetic axis. In (b), the stars are the interpolated fits while the diamonds are the original data.

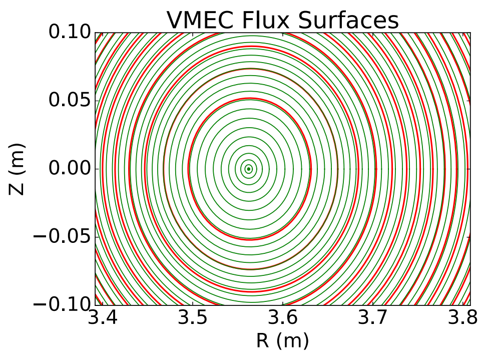

FIG. 7. The change in the flux surfaces with the new mapping is plotted. The new flux surfaces in green have a much finer resolution in the core than the old mapping, in red.

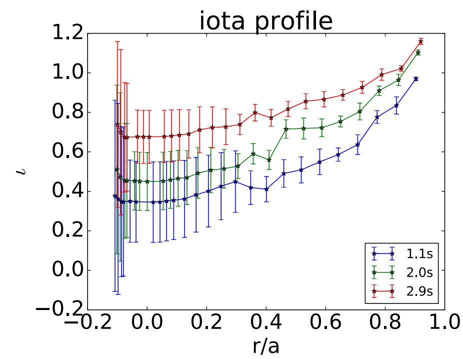

FIG. 9. The iota profile calculated with the new model is plotted for a scan of times in an LHD discharge. This analysis gives a more realistic iota profile compared to the results shown in Fig. 1.

As such, the VMEC output was mapped from flux space to r/a space by interpolating the relevant variables in Fourier space using Chebyshev fits (see Fig. 6). Each mode amplitude as a function of flux was fit, and the values at the new flux surfaces were found. The resulting flux surface shapes can be seen in Fig. 7. This fitting greatly increases the number of surfaces in the core. These new equilibria were then used to create the line of sight database for the MSE system.[9,11]

This method improved core resolution and reduced the scatter in the data used for the fitting in the core which arose due to poor database resolution, as can be seen in Fig. 8. The new fitting was used to create Figs. 3–5.

For most of the outer radii, there is a linear dependency found between the change in the iota and polarization angle (see Fig. 3). In some situations, the highly peaked or hollow cases give scattered and nonlinear results (see Fig. 8), especially near the core. As such, the highly peaked and hollow cases were ignored in the previous analysis. Removing these points can be problematic, however, for plasmas expected to have highly peaked or hollow profiles. The scatter was found to be dependent on the core resolution and the inverse mapping of the MSE views onto the VMEC database. The improvement in core database resolution greatly reduced the scatter of the data in the core as seen in Fig. 8, but nonlinearity was not completely removed for the very hollow current profile configurations.

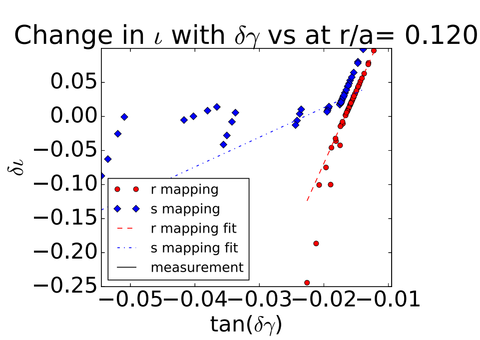

FIG. 8. The change in iota versus change in polarization angle (γ) is plotted for the old mapping in s space and the new mapping in r/a space. The new mapping reduced the scatter of the data in the core, thereby improving the consistency of the MSE modeling data in the core. This leads to more accurate fits in the core.

IV. RESULTS AND FUTURE WORK

In order to test this new model, comparisons were performed between the old and new methods. It was found that the unrealistic iota profiles in the core (see Fig. 1) were eliminated in the core of the LHD with the new mapping and the hybrid model. In Fig. 9, a scan of iota values is plotted as the current in the plasma changes. The iota profile tracks those changes well throughout the whole plasma, unlike before where problems arose in the core.

To conclude, the new analysis technique improves the capability of the MSE system to acquire the iota profile in the core of the LHD by reducing the PS currents' effect on the analysis of the MSE data. This has been accomplished by using the derivative of the polarization angle as a function of flux to find the iota profile in the core.

In the future, changes in the MSE views on the LHD will make measurements on both the inboard and outboard sides possible for most LHD plasmas (for some plasmas with a large shift in axis this is already possible). This will be useful to solve for both the PS and plasma currents simultaneously. It will also reduce the effect of the PS current on the measurement further and allow a better measurement of the PS current in the LHD experiment.

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