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

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An MSE analysis routine for improved resolution of iota in the core of LHD

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A new MSE analysis routine has been developed for improved spatial resolution in the core of LHD. The routine was developed to reduce the dependency of the analysis on the Pfirsch-Schlüter current in the core. The technique used the change in 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 much smoother and more realistic iota profiles in the core of LHD.

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 iota profile is typically smaller than 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 MSE system on LHD was designed to measure the iota profile on LHD[8,9].

The difficultly of interpreting the MSE results in stellarators is converting 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 LHD and allow an analysis of all of the shots on LHD[11]. Prior analysis, described here[11], had a problem resolving iota in the core of LHD. This paper describes the improved analysis technique that has been developed in order to properly analysis the core MSE data.

In the core of 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 figure 1). The MSE measurement on 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 figure 2). As such a relatively small change in the PS current can have a larger effect than a large change in plasma current on the measurement. As such,

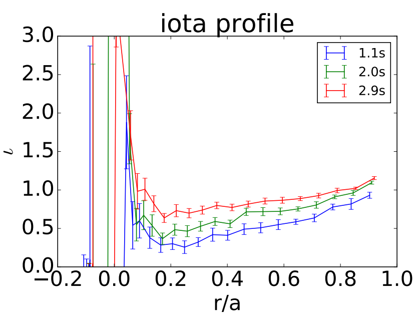

FIG. 1. The old fitting routine often gave unphysical values of the iota profile in the core region due to uncertainties in the PS contribution to the MSE measurement. Beyond r/a values of .3, where the relative contribution of the PS current is smaller, the fitting routine works well and the change in iota with a change in current is recoverable.

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 LHD on the MSE measurements.

II. BACKGROUND

The database of VMEC 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, quadrruple 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 using

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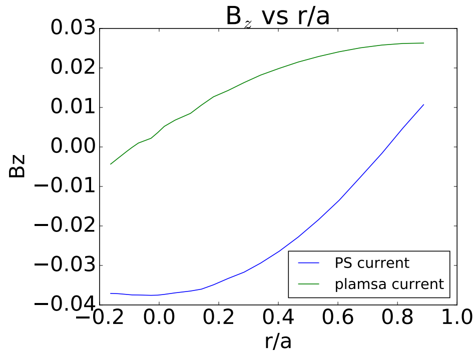

FIG. 2. The profile of B_z along the sightline of the diagnostic is plotted. The plasma current contribution to B_z goes to zero in the core but the slope with respect to flux is nonzero. The PS current current is nonzero in the core but the slope is approximately equal to zero in the core. Therefore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

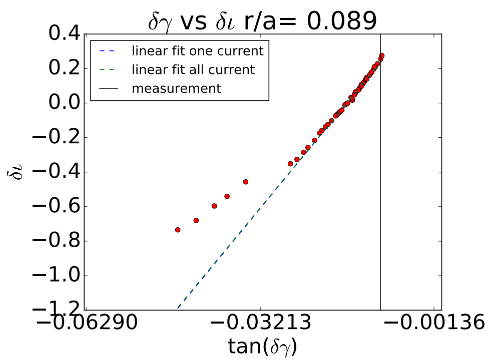

FIG. 3. The VMEC database is used to find the change in polarization angle and iota with a scan of currents and current profiles. The relationship is generally linear, which allows fitting to be done to find the experimental change in iota from a given MSE measurement. The experimentally measured change 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 radii value. The outputted iota value can be seen in figure 1.

the method 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 change in 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 angle and iota data from a scan of plasma current (± 5 kA/T) and current peaking factors to find a linear relationship between the change in polarization angle and iota (as seen in figure 3). The linear fit is then used in conjunction with the experimental change in angle to find the change in iota.

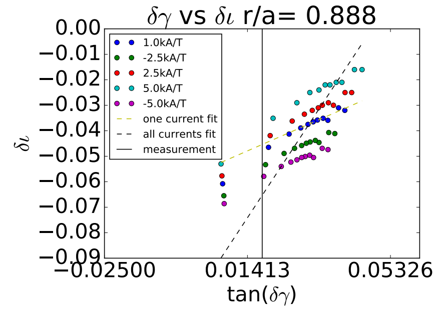

FIG. 4. The old fitting routine takes a linear fit of a scan of currents ($\pm 5kA/T$) and peaking factors. This can lead to problems in the edge where the iota value can be known by the net plasma current and is insensitive to current peaking factor. Near the edge, the different currents have similar dependence of iota on 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.

III. IMPROVEMENTS TO THE FITTING ROUTINES

The old analysis technique works well in the mid-radius region ($.3 < r/a < .75$). 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 the polarization angle. Therefore, using a current scan can lead to bad fits as can be seen in figure 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 PS current can greatly effect 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 lead to a large change in iota (see figure 3). This can be problematic, because there is also a change in polarization angle from the PS current. This is primarily due to the shift in the magnetic axis from the PS current. Due to the steep dependency of polarization angle and iota, a small error in the offset from PS current can lead to a very large, unphysical error in iota in the core, as seen in figure 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.

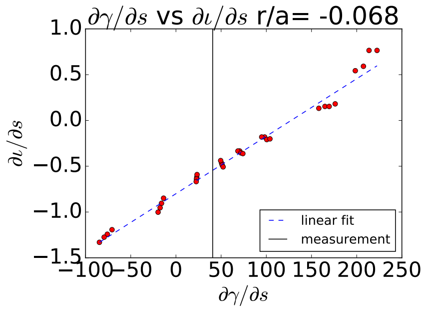

FIG. 5. The VMEC database is used to find the change in polarization angle and iota with respect to flux. This is calculated for a scan of currents and current profiles and a linear fitting is done to find the experimental change in dι/ds from a given MSE measurement of dγ/ds. The vertical line is the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

This method takes the derivative of the polarization angle and iota with respect to flux taken from the database and, using a scan of current and current peaking factors mentioned earlier, linearly fits this data, as seen in figure 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. 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 effected by an error in a single measurement channel.

There are several difficulties and potential problem 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 are passed down each step of the integration, which can lead to a large uncertainty in the core. Another problem arises from the resolution of the VMEC mapping in the core, which will be described in the next section.

In order to avoid the problems of the old and new method, a hybrid method was developed. The method uses the old method beyond r/a of .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 PS current in the core of 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 grid of flux surfaces equidistant in flux space from each other. This leads the r_{eff} of the flux surfaces to be concentrated on the edge because flux= $(r/a)^2$. As such, the interpolation of VMEC near the core of LHD can be difficult due to a lack of nearby flux surfaces. Problems arise in the current interpolation method when the measurement location was at or near the innermost flux surface (the inner two most flux surface are at r/a =.1 and .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 equilibrium.

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

This methods 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 figure 8. The new fitting was used to create figures 3, 4, & 5.

For most of the outer radius there is a very linear dependency found between the change in iota and polarization angle (see figure 3). In some situations the highly peaked or hollow cases give scattered and nonlinear results (see figure 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

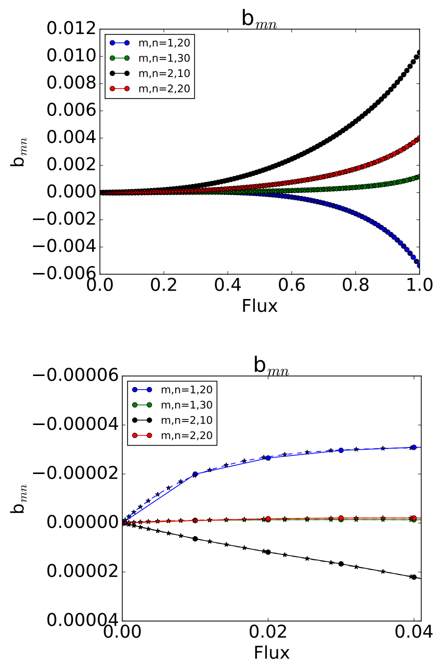

FIG. 6. The mode amplitudes of the VMEC outputs were interpolated in mode spaces using a Chebshev fit staring from equidistant points in flux space to equidistant in r/a space in order to increase the core resolution of the VMEC database. The stars are the interpolated fits while the circles are the original data.

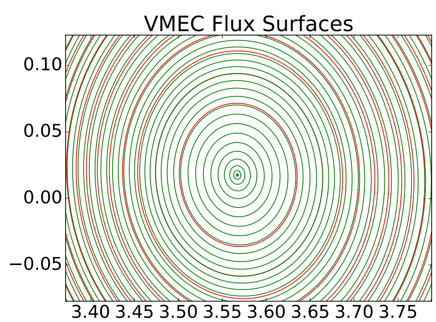

FIG. 7. The change in the flux surfaces with the new mapping are plotted. The new flux surfaces in green have a much finer resolution in the core than the old mapping, in red. The plots show mode amplitudes as a function of flux for the two mappings.

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 figure 8, but the nonlinearity was not completely removed for the very hollow current profile configurations.

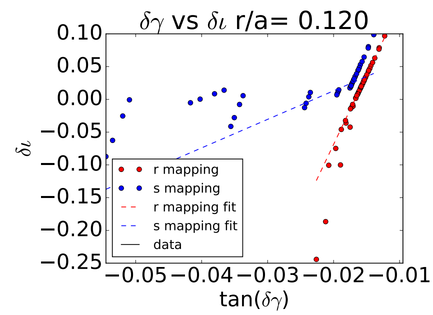

FIG. 8. The new mapping improved the consistency of the MSE modeling data in the core, which leads to a more accurate fit.

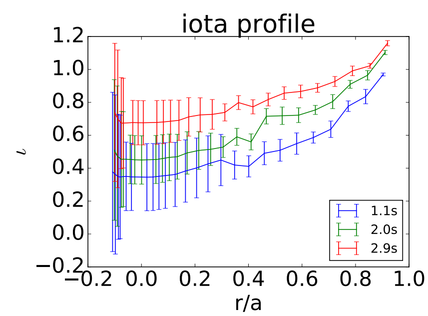

FIG. 9. The iota profile calculated with new model are plotted for a scan of times in an LHD discharge. This analysis gives a more realistic iota profile compared to the results shown in figure 1.

IV. RESULTS AND FUTURE WORK

In order to test this new model, comparisons were made with between the old and new methods. It was found that the unrealistic iota profiles in the core (see figure 1) were eliminated in the core of LHD with the new mapping and the hybrid model. In figure 9, a scan of iota values are 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 capacity of the MSE system to acquire the iota profile in the core of LHD by reducing the PS currents effect on the analysis of the MSE data. This accomplished by using the derivative of polarization angle as a function of flux to find the iota profile in the core.

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

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[1] F. M. Levinton, R. J. Fonck, G. M. Gammel, R. Kaita, H. W. Kugel, E. T. Powell, and D. W. Roberts, Phys. Rev. Lett. **63**, 2060 (1989).

[2] F. Levinton, G. M. Gammel, R. Kaita, H. W. Kugel, and D. W. Roberts, Rev. Sci. Instrum. **61**, 2914 (1990).

[3] D. Wrblewski and L. L. Lao, Review of Scientific Instruments **63**, 5140 (1992), http://dx.doi.org/10.1063/1.1143463.

[4] F. M. Levinton, Review of Scientific Instruments **63**, 5157 (1992), http://dx.doi.org/10.1063/1.1143466.

[5] E. Mazzucato, S. H. Batha, M. Beer, M. Bell, R. E. Bell, R. V. Budny, C. Bush, T. S. Hahm, G. W. Hammett, F. M. Levinton, R. Nazikian, H. Park, G. Rewoldt, G. L. Schmidt, E. J. Synakowski, W. M. Tang, G. Taylor, and M. C. Zarnstorff, Phys. Rev. Lett. **77**, 3145 (1996).

[6] R. Brakel and the W7-AS Team, Nuclear Fusion **42**, 903 (2002).

[7] Y. Feng, F. Sardei, P. Grigull, K. McCormick, J. Kisslinger, and D. Reiter, 30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg **27A** (July 7-11 2003).

[8] K. Ida, M. Yoshinuma, K. Y. Watanabe, T. Kobuchi, and K. Nagaoka, Review of Scientific Instruments **76**, 053505 (2005), http://dx.doi.org/10.1063/1.1898943.

[9] K. Ida, M. Yoshinuma, C. Suzuki, T. Kobuchi, K. Y. Watanab, and L. E. Group, Fusion Science and Technology **58**, 383 (2010).

[10] S. P. Hirshman and J. C. Whitson, The Physics of Fluids **26**, 3553 (1983), http://aip.scitation.org/doi/pdf/10.1063/1.864116.

[11] C. Suzuki, K. Ida, Y. Suzuki, M. Yoshida, M. Emoto, and M. Yokoyama, Plasma Physics and Controlled Fusion **55**, 014016 (2013).