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Princeton Plasma Physics Laboratory
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Equilibrium Reconstruction on the Large Helical Device

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Equilibrium reconstruction is commonly applied to axisymmetric toroidal devices. Recent advances in computational power and equilibrium codes have allowed for reconstructions of three-dimensional fields in stellarators and heliotrons. [1] We present the first reconstructions of finite beta discharges in the Large Helical Device (LHD). The plasma boundary and magnetic axis are constrained by the pressure profile from Thomson scattering. This results in a calculation of plasma beta without a-priori assumptions of the equipartition of energy between species. Saddle loop arrays place additional constraints on the equilibrium. These reconstruction utilize STELLOPT, which calls VMEC. The VMEC equilibrium code assumes good nested flux surfaces. Reconstructed magnetic fields are fed into the PIES code which relaxes this constraint allowing for the examination of the effect of islands and stochastic regions on the magnetic measurements.

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Introduction

The three dimensional nature of stellarator equilibria can be reconstructed using the STELLOPT code wherein VMEC [6] is used to solve for the MHD equilibria. Recent advances in computational power have allowed this coupling between the codes to be used for equilibrium reconstructions. Unlike current Tokamak codes (EFIT), STELLOPT can reconstruct systems with 3D fields. This is of relevance to the Tokamak community which utilizes 3D fields (RMPs) to suppress edge localized modes. An understanding of the effects of such fields is manifest relevance to ITER given the high cost of the in-vessel coils. We adapt the techniques utilized on W7-AS [1] to preform reconstructions on the Large Helical Device (LHD). The LHD is a ten period heliotron with superconducting magnets. [2] The device is equipped with various spectral and magnetic diagnostics, including a YAG Thomson scattering system [3] and 24 saddle type flux loops. [4] The Thomson system provides high spatial resolution measurements along the elongated cross-section of the plasma. A segmented Rogowski coil provides the total plasma current and the array of saddle loops provide additional constraints on the equilibrium. Total stored energy is measured by a diamagnetic loop. Reconstructed VMEC equilibria are used to initialize the PIES code which relaxes the good nested flux surface constraint. [5] This allows the formation of islands and stochastic regions, and the evaluation of said regions on the diagnostic response.

Reconstruction Software

The STELLOPT (STELLarator OPTimizer) code is used in conjunction with the VMEC equilibrium solver. The VMEC code solves for plasma equilibria under the assumption of good nested flux surfaces. The STELLOPT code is run in a modified Levenberg-Marquardt mode to search parameter space for a good match between the VMEC equilibrium and experimental data. Synthetic magnetic diagnostics are calculated by a modified form of the DIAGNO code. This modification utilizes a virtual casing principle to represent the plasma response.

In reconstruction mode the STELLOPT code utilizes the pressure profile, toroidal current profile, total enclosed toroidal flux and a pressure scaling factor as independent (free) parameters. The Thompson data, 24 flux loop measurements, stored energy, and total toroidal current become our dependent (target) parameters. The quality of a given fit is measured in terms of chi-squared

$$\chi^2_{total} = \sum_i \frac{\left|x_{i(target)} - x_{i(simulated)}\right|^2}{\sigma_i^2} \qquad (1)$$

where σ is the error bar for a given measurement and x is an experimentally measured value. The pressure profile is varied while the toroidal current profile is held fixed (beam-like profile). The saddle loops lack the sensitivity to the toroidal current profile necessary for reconstruction of the current profile. This necessitates the fixed current profile.

Equilibria

Equilibria were calculated at five distinct times during shot 85384 on the LHD. Equilibria were fit to the Thomson data under the assumption of a fixed toroidal current profile. The equilibria were then optimized to the magnetic diagnostic data along with the Thomson data, total toroidal current, and total stored energy. Figure 1 shows a typical chi-squared evolution during reconstruction. In this figure, the last section indicates almost no sensitivity of the magnetic diagnostics to changes in the current profile.

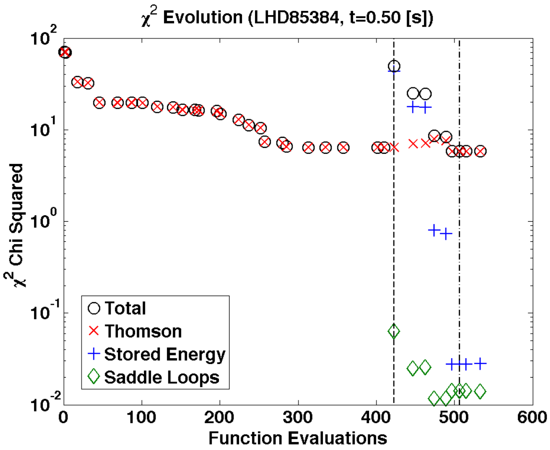

Figure 1: Chi squared evolution for reconstruction. Dashed line indicates the optimization to stored energy and magnetic diagnostics has begun. Dash dotted line indicates optimization of the current profile has begun.

The pressure profile is matched to the various diagnostics during the reconstruction. An order of magnitude drop in the total chi-squared is observed. A good fit to the data is characterized by a normalized chi-squared less than one, which is also observed. The plasma boundary also matches the Thomson data well. The chi-squared for the stored energy drops nearly two orders of magnitude during the optimization. Stored energy dropped from ~ 238 [kJ] to ~ 146 [kJ], with a target value of ~ 143 [kJ] in this example. The reconstructed magnetic signals fell to within $\sim 6\%$ their targeted values (the majority of which were within $\sim 3\%$ of their targeted value). This reduction in the magnetic diagnostics signal chi-squared is attributed to a reduction in the pressure scaling factor applied to the Thomson data. Results suggests that integral quantities (over the plasma volume) such as stored energy and magnetic diagnostic signals are more sensitive to single parameters than profile variation. Sensitivity studies on the LHD saddle loops show a weak sensitivity to current profile variation. It is unlikely that given the saddle loops alone, the toroidal current profile can be properly constrained.

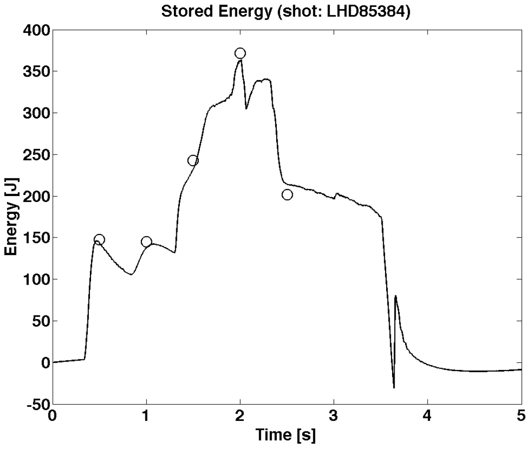

Figure 2: Plot of the stored energy for shot 85384. Circles indicate reconstructed equilibria values of stored energy. The peak value of stored energy at $t \sim 2.0$ $[s]$ equates to a volume averaged plasma beta of 1.28%.

The reconstructed profiles and equilibria are then used to initialize the a run of the PIES code. The NMORPH code is utilized to calculate a set of PIES background coordinates given the VMEC equilibrium. Initial results from the PIES code shows the formation of islands (Figure 3). Comparison with the Thomson data indicates the presence of finite pressure gradients in these islands and stochastic regions. Additional work is underway to better constrain the PIES equilibrium to the Thomson data.

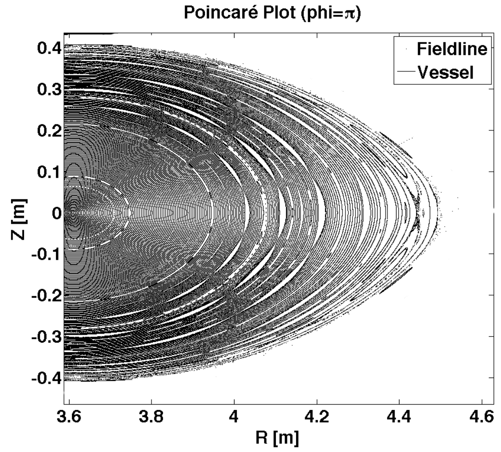

Figure 3: Poincaré plot produced by PIES for LHD. Islands are clearly present in regions of finite pressure gradients.

Summary

The first 3D equilibrium reconstructions on the LHD were conducted using the STELLOPT code. Reconstructed equilibria of plasma betas up to 1.2% showed strong matching to the diagnostic signals. The ability to reconstruct non-axisymmetric equilibria is of great importance to the fusion community. The manifestly 3D nature of stellarators demand 3D codes for reconstruction. Axisymmetric systems have also been found to benefit from the application of 3D fields in order to suppress edge localized modes. Existing Tokamak codes cannot be utilized for these purposes. Additionally, the ability to preform reconstructions provides an additional benchmarking capability between codes which calculate equilibria with islands and stochastic regions (HINT2 [7], PIES, SIESTA [8]). These tools allow for a reconstruction capability with islands and stochastic regions.

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