3D Equilibrium Effects due to RMP application on DIII-D*

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The mitigation and suppression of edge localized modes (ELMs) through application of resonant magnetic perturbations (RMPs) in Tokamak plasmas is a well documented phenomenon [1]. Vacuum calculations suggest the formation of edge islands and stochastic regions when RMPs are applied to the axisymmetric equilibria. Self-consistent calculations of the plasma equilibrium with the VMEC [2] and SPEC [3] codes have been performed for an up-down symmetric shot (142603) in DIII-D. In these codes, a self-consistent calculation of the plasma response due to the RMP coils is calculated. The VMEC code globally enforces the constraints of ideal MHD; consequently, a continuously nested family of flux surfaces is enforced throughout the plasma domain. This approach necessarily precludes the observation of islands or field-line chaos. The SPEC code relaxes the constraints of ideal MHD locally, and allows for islands and field line chaos at or near the rational surfaces. Equilibria with finite pressure gradients are approximated by a set of discrete 'ideal-interfaces' at the most irrational flux surfaces and where the strongest pressure gradients are observed. Both the VMEC and SPEC calculations are initialized from EFIT reconstructions of the plasma that are consistent with the experimental pressure and current profiles. A 3D reconstruction using the STELLOPT code, which fits VMEC equilibria to experimental measurements, has also been performed. Comparisons between the equilibria generated by the 3D codes and between STELLOPT and EFIT are presented.

Introduction

Interpretation of the modification of the plasma equilibrium due to resonant magnetic perturbations (RMPs) requires the ability to fit three dimensional equilibria (profiles and synthetic diagnostic response) to experimental measurements. Such a 3D reconstruction capability is provided by the STELLOPT code, previously developed for Stellarator optimization and reconstruction. [4, 5] A double-null (stellarator symmetric) shot was performed on the DIII-D device with applied $n = 3$ RMP (142603). In this shot, the edge localized modes (ELMs) were reduced in size but were not completely suppressed. A 3D reconstruction for this shot is performed using the STELLOPT code. Equilibria are then calculated with the SPEC code and results are presented.

Reconstruction Software

The STELLOPT (STELLarator OPTimizer) code is used in conjunction with the VMEC equilibrium solver to fit equilibrium parameters to experimental measurements. The VMEC code solves for ideal MHD equilibrium under the topological assumption of globally 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 virtual casing [6] in the DIAGNO code. Synthetic Thomson scattering and MSE polarimetry signals are calculated by the STELLOPT code. Reconstructed free boundary VMEC equilibria are then used as an initial condition for the SPEC code. The SPEC code solves for ideal MHD equilibria under the assumption of locally constrained topology. Flux surface topology is enforced at a finite number of surfaces and Beltrami fields are constructed between the surfaces. This necessitates a stepped pressure approximation to a continuous pressure profile, however the number of steps has no limit and thus the code can approximate a continuous pressure gradient.

Parameter	EFIT (2D)	STELLOPT (3D)
Volume (m^{-3})	19.383	19.66
Current (MA)	1.401	1.39
Energy (kJ)	599	525
Beta (%)	1.611%	1.78%
q95	3.772	3.428

Table 1: Comparison of reconstructed equilibria.

The fit of equilibrium parameters is constrained by experimental measurements and quantified in terms of chi-squared

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

Experimental measurements of Thomson scattering, MSE polarimetry, and magnetic diagnostics provide the target constraints. The current profile, pressure profile, total enclosed toroidal flux, and field coil currents, provide the equilibria parameters which are varied by the Levenberg-Marquardt algorithm.

The SPEC code calculates the ideal MHD equilibrium response constraining the magnetic topology locally at a finite number of flux surfaces. These ideal interfaces (flux surfaces) are chosen to exist at highly irrational surfaces and large pressure gradients. Such irrational surfaces are considered to be robust to perturbations, while the existence of large pressure gradients requires flux surface topologies to exist locally in ideal MHD.

Equilibria

A double null shot on DIII-D (142603) was reconstructed utilizing the STELLOPT code coupled to VMEC. The experimental data used to constrain the reconstruction were extracted by averaging over a time window spanning the flattop of the shot ($3250 - 3750\ ms$). The evolution of the reconstruction indicates reductions in chi-squared for all target parameters, despite the total chi-squared being dominated by the pressure profile. The reconstructed 3D equilibria indicates a plasma volume of $19.66\ m^{-3}$, stored energy of $525\ kJ$, and plasma beta of 1.78%. The reconstructed net toroidal current was found to be $1.39\ MA$ with a q_{95} of 3.43. The outboard edge of the plasma indicated a non-axisymmetric variation of $5\ mm$. This displacement was negligible at the boundary where the Thomson chord line intersects the plasma. These values differ from those determined by EFIT 2D reconstruction (Table 1), this is attributed to the choice of a slightly edge toroidal enclosed flux. The EFIT $q_{95} = 3.77$ is larger than in the STELLOPT reconstruction as a bootstrap current model was not included in the 3D reconstruction. Figure 1 shows a plot of the reconstructed pressure profile gradient against the rotational transform. Here we begin to see a correlation between minimums in the electron pressure gradient and low order rational surfaces.

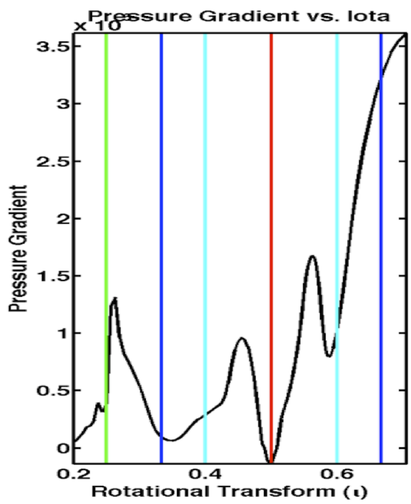

Figure 1: Reconstructed electron pressure gradient plotted against rotational transform. Vertical lines indicate the $q = 4, 3, 5/2, 2, 5/3, 3/2$ surfaces from left to right.

The SPEC code was initialized from the free boundary VMEC equilibria based upon EFIT reconstructed parameters. The SPEC equilibrium has an applied broad poloidal spectrum, $1\ cm$, $n = 3$ boundary perturbation applied. This is slightly larger than the boundary perturbation calculated in VMEC with these EFIT profiles. Flux surface topology is constrained at strongly irrational rotational transform. The steps in the pressure profile are chosen to preserve the area under the reconstructed pressure profile (matching the reconstructed stored energy, Figure 2). The SPEC equilibria indicates the presence of small islands chains at rational surfaces, however no large scale stochasticity is present toward the edge (Figure 3). This result is

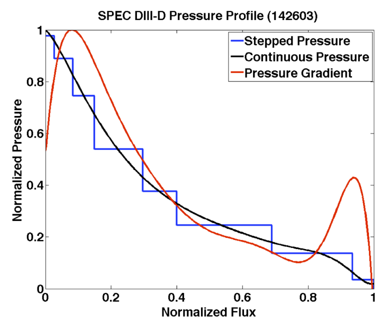

Figure 2: SPEC stepped pressure approximation, where continuous pressure is approximated by a stepped pressure.

consistent with the strong pressure gradient at the edge in H-mode discharges.

Summary

A self-consistent 3D equilibrium reconstruction for a DIII-D double null plasma (142603) with RMP coil energization has been performed. The lack of a bootstrap current model in STELLOPT makes direct comparison with EFIT difficult. The EFIT equilibria profiles were used to calculate free boundary VMEC equilibria. These equilibria were then utilized to initialize the SPEC code. The SPEC code showed small interior island chains but no edge stochasticity due to the relative spacing of edge flux surfaces. Future efforts will focus on the inclusion of additional diagnostics in the reconstruction and implementation of the SPEC code in the STELLOPT code.

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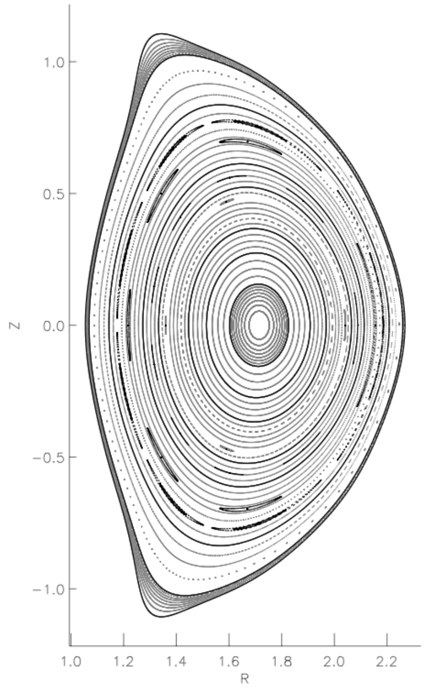

Figure 3: Poincare plot for the SPEC equilibria. Constrained flux surfaces are indicated by dark lines.

References

[1] T.E. Evans et al., Phys. Rev. Lett., **92**, 235003 (2004).

[2] S.P. Hirshman and J.C. Whitson, Phys. Fluids **26**, 12 (1983)

[3] S.R. Hudson, R.L. Dewar, M.J. Hole and M. McGann, Plas. Phys. and Cont. Fusion, **54**, 014005 (2012)

[4] M.C. Zarnstorff, A. Weller, J. Geiger, E. Fredrickson, S. Hudson, J.P. Knauer, A. Reiman, A. Dinklage, G.-Y. Fu, L.P. Ku, D. Monticello, A. Werner, the W7-AS Team and the NBI-Group, Fusion Science and Technology **46**, 1 (2004).

[5] S.A. Lazerson, D. Gates, D. Monticello, H. Neilson, N. Pomphrey, A. Reiman, S. Sakakibara, Y. Suzuki, Proceedings of the 38th EPS Conference on Plasma Physics, (2011).

[6] V.D. Shafranov and L.E. Zakharov, Nucl. Fusion, **12**, 599 (1972).