Plasma Control for NCSX and Development of Equilibrium Reconstruction for Stellarators[*]

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The NCSX stellarator is a quasi-axisymmetric device under construction at PPPL. Operation and interpretation of experimental results from these devices will require accurate and efficient reconstruction of experimental equilibria and plasma control. The generation of substantial plasma current and the maintenance of kink stability and good quasi-axisymmetry throughout the discharge imposes greater shape control requirements than previous stellarators. In this paper, we discuss the simulation of an entire NCSX discharge, the implications for plasma control, and our work towards designing a set of magnetic diagnostics required to effect the necessary control. We also report recent progress in the development of a new stellarator equilibrium reconstruction tool, V3FIT. V3FIT is based on the widely used VMEC 3D equilibrium code and a 3D generalization of the efficient EFIT response function formalism that is extensively used in tokamak reconstruction.

We take advantage of the quasi-axisymmetry of NCSX plasmas to evolve the pressure profile and poloidal flux in an appropriately defined 2D equivalent tokamak using TRANSP. The energy transport model includes axisymmetric neoclassical diffusivities, a ripple diffusivity to account for the 3D magnetic field, and anomalous diffusivity in the electron and ion channels to make the total confinement time match an empirical scaling, e.g., ITER97L. The plasma current diffusion includes bootstrap current, flux from the Ohmic transformer, and neutral beam current drive. The resulting pressure, p, and flux surface averaged toroidal current density, <J>, profiles are used in 3D, free boundary equilibrium calculations. As the p and <J> profiles evolve, appropriate modular and poloidal field coil currents are calculated using the STELLOPT optimization code in two stages: First, currents are determined which produce a plasma with the same shape as the desired final high β reference configuration. Subsequently, the coil currents (and plasma shape) are adjusted in such a way as to ensure good quasi-axisymmetry and stability properties. A result is shown in Fig, 1. On the left frame the calculated plasma pressure is shown at selected times in the discharge. On the right frame is the transform; the light dashed lines are the profiles after the first stage of optimization, while the heavy lines with stronger shear are the results after the final coil current adjustment to produce the desired physics properties. The change in coil currents is reflected in changes in the boundary shape of the plasma, as shown in Fig.2. This level of shape control is consistent with the degree of control utilized in tokamaks such as DIII-D.

We are presently focused on determining a set of magnetic diagnostics adequate for effecting dynamic control of the plasma shape and equilibrium reconstruction in NCSX. Our criterion

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for sufficiency of the diagnostic set is a demonstrated ability to reconstruct equilibria from a database of VMEC free boundary equilibria that encompasses the range of plasmas that can be produced in the device. A 3D “control surface” (CS) is defined which encloses all plasmas in the database. For each equilibrium a mesh of B_θ values is calculated on the CS. A superset of magnetic diagnostic probes is located outside of the CS in the region between the plasma-facing armor tiles and the coil set. The signals for the diagnostic set are calculated for all equilibria using the magnetic diagnostic tools V3RFUN/V3POST described below. A singular value decomposition eigen-analysis of the influence matrix relating the diagnostic signals to the B_θ distributions indicates which diagnostics are the primary predictors of B_θ. The eigen-function patterns are used to define trial reduced sets of diagnostics, which are then evaluated for their ability to reconstruct the plasma shape and characteristics (e.g., β, l_i).

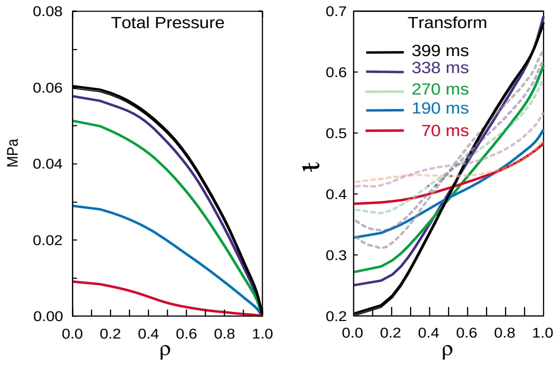

Fig. 1, Plasma pressure and transform profiles from simulation after first and second stages (dashed and solid lines) of optimization.

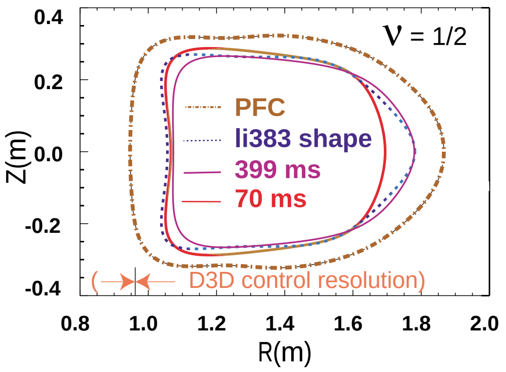

Fig. 2 Changes in boundary shape result from optimization with pressure and current density profiles from simulation.

A key step towards the development of the 3D stellarator equilibrium reconstruction code V3FIT is the generalization of the EFIT response function method to 3D magnetic geometry. This allows the lengthy calculations of the inductance matrix to be pre-computed, stored, and separated from the rapid calculations of magnetic signals. Using the magnetic reciprocity relation, a 3D response function approach has been formulated that allows the plasma contribution to the magnetic flux to be directly related to the plasma current distribution through an integration over the plasma volume [1]. The volume integration can be converted to a surface integration using the virtual casing principle. When the magnetic probes are located close to the plasma boundary, plasma response depends sensitively on the details of the plasma current distribution and it is necessary to use the volume form.

Two computational tools have been developed to efficiently compute 3D magnetic responses to a diagnostic set based on this new approach. V3RFUN computes and stores the diagnostic response functions from the plasma and external coils. V3POST reads the stored response functions and efficiently computes the magnetic response to a diagnostic set for an arbitrary equilibrium. The present approach has been successfully benchmarked against calculations from other less efficient codes. V3RFUN/V3POST are being applied to support design of magnetic diagnostics for NCSX and CTH. Both have been incorporated into the STELLOPT optimization code to provide a prototype 3D reconstruction code to examine various numerical features of the reconstruction process and to guide the development of the optimized V3FIT code. Various linearization schemes to approximate the signal gradients and to speed up the search process based on the efficient 2D EFIT optimization scheme have been formulated and are being tested and optimized using the proto-type reconstruction code.

[1] S.P. Hirshman, *et al.*, Phys. Plasmas **11** (2004) 595.