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FLEXIBILITY AND ROBUSTNESS CALCULATIONS FOR NCSX

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Introduction

The National Compact Stellarator Experiment (NCSX) will study the physics of low aspect ratio, high β, quasi-axisymmetric stellarators. In order to achieve the scientific goals of the NCSX mission[1], the device must be capable of supporting a wide range of variations in plasma configuration about a reference equilibrium. Numerical experiments are presented which demonstrate this capability.

The NCSX coil-set comprises 18 modular coils, 6 in each of the 3 field periods of the machine. The coils are grouped into 3 independently controlled circuits - one circuit for each distinct coil shape. A novel island-healing algorithm[2] was incorporated in the coil design methodology to ensure good flux surfaces. A supplementary toroidal field coil system can provide a 0.5 T 1/R field in either direction relative to the modular coil field. This provides the capability to vary the external rotational transform at fixed toroidal field. A system of 6 pairs of axisymmetric poloidal field coils is included for additional flexibility, four of which provide low-order axisymmetric multipole fields, and the remaining two provide an ohmic field.

The primary computational tool for the flexibility studies is STELLOPT, a VMEC-based free-boundary optimizer which varies coil currents to generate equilibria with targeted physics properties, such as stability to kink and ballooning modes (conducting wall at infinity) and good quasi-axisymmetry (QA). Essential code modules within STELLOPT include an equilibrium solver (VMEC[3]), stability analysis codes (TERPSICHORE[4] for kink modes, COBRA[5] for ballooning modes), and a QA analyser (NEO[6] which evaluates QA by calculating the effective helical ripple, ε_h).

Plasma performance as β and I_p are varied

Here STELLOPT is used to calculate coil currents which support stable plasmas with good QA as I_p and β are varied from their reference values. Profiles of pressure and current are held fixed, equal to a bootstrap-consistent form (see curves labelled $\alpha = 0.0$

and $\gamma = 0.0$ in Fig. 1) appropriate to the $B_T = 1.7$ T design point (S3) where $I_p = 174$ kA, $\beta = 4.2\%$. For a 5x5 matrix of equally spaced I_p, β values spanning $I_p \in [0, 174$ kA$]$, $\beta \in [0, 4\%]$, STELLOPT successfully produces ε_h-optimized equilibria which are stable to kink and ballooning modes for all I_p, β values, with ε_h varying within a factor of two of the reference ($\varepsilon_h^{ref} = 0.5\%$ at $s \sim (r/a)^2 = 0.5$). In addition, a stable configuration with good quasi-axisymmetry was obtained at $\beta = 6\%$ for $I_p = 174$ kA, $B_T = 1.7$ T and reference profiles of current and pressure. (No attempt has yet been made to find the β-limit for optimized profiles). Modular coil currents vary by less than ±10% over the $I_p - \beta$ plane and the auxiliary TF field variation is less than ± 0.10 T. Using reference profiles, we conclude there is a substantial region of stability with good QA in the I_p - β plane. For these calculations STELLOPT was run in a mode which provides a cost function penalty for instability but no reward for stability margin. Therefore each equilibrium produced in the I_p, β scan is marginally stable (as was verified by freezing the coil currents, increasing β, and noting the appearance of instability). Configurations with a wide range of β-limits can be easily generated by an appropriate choice of the coil currents.

Plasma performance as profiles are varied

We now examine plasma performance when plasma profiles are varied about reference forms at fixed I_p and B_T. A 1-parameter sequence of J.B profiles, labelled by parameter $\alpha \in [0, 1]$, describing the effect of peaking the current profile in the core of the plasma is shown in Fig. 1a. Using the reference p(s) and $I_p = 174$ kA, $B_T = 1.7$ T, STELLOPT finds stable configurations with $\beta \geq 3.0\%$ for $0 \leq \alpha \leq 0.5$, with $\varepsilon_h \leq 0.5\%$ at s = 0.5. Current profiles with finite edge current have also been examined. At $\beta = 5.0\%$ we find stability is maintained as $J.B^{edge}/J.B^{max}$ is raised to 50%! (dashed curve in Fig. 1a). The stability of stellarators to edge currents[7] is in contrast with tokamak behavior and leads to the interesting possibility that H-mode profiles may be beneficial to NCSX.

STELLOPT was run for a sequence of pressure profiles (see Fig. 1b) where the peakedness in the core region, parameterized by $\gamma \in [0, 1]$, was varied. Fixing β at 3.0% and using the reference J.B current profile, the stable range of p(s) is $0 \leq \gamma \leq 0.8$. For this range of profiles, $\varepsilon_h \leq 0.4\%$ at r/a = 0.5. The $\gamma = 1.0$ configuration is stable at $\beta = 2.5\%$. Finite edge pressure gradients were also studied. Using the pedestal profile shown in Fig. 1b, a stable configuration at $\beta = 3.0\%$, with $\varepsilon_h = 0.56\%$ was found.

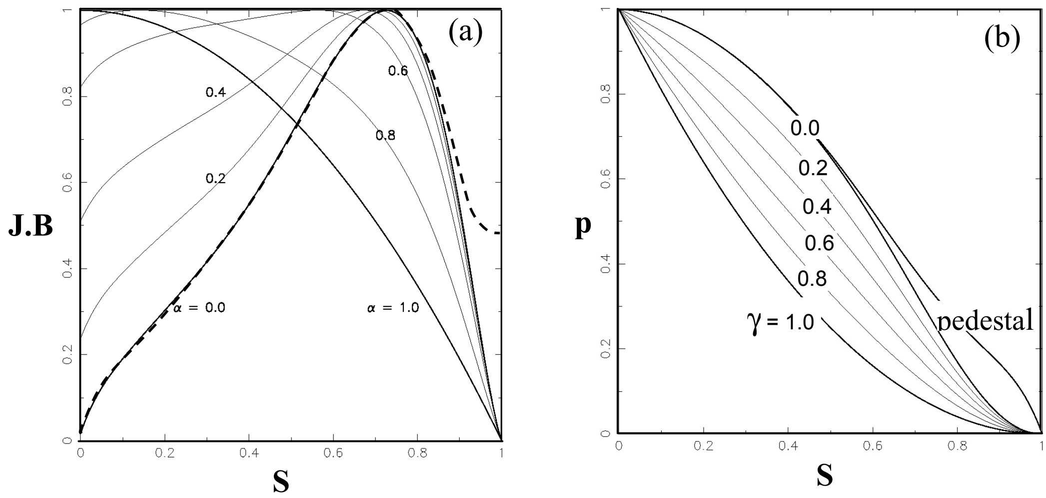

Figure 1: J.B(s) and p(s) profiles used in flexibility studies. $S \sim (r/a)^2$ is normalized toroidal flux.

Control of Quasiaxisymmetry

The ability to generate configurations with good quasi-axisymmetry is an essential requirement of the NCSX design. For a systematic exploration of the role of QA in improving the transport properties of stellarator plasmas, it is necessary to have the ability to control the degree of QA-ness. In this Section we demonstrate this ability, by varying NCSX modular coil currents to induce plasma shape changes that degrade/enhance the QA-ness (measured by the magnitude of the ripple amplitude, ε_h) while maintaining plasma stability to kink and ballooning modes. This ability is shown in Fig. 2 which shows an overlay of plasma boundaries for three configurations, each with I_p = 87.5 kA, β = 2.0%, each with the same (reference) profiles of plasma current and pressure, but each exhibiting quite different degrees of quasi-axisymmetry. The modular coil currents vary by approximately 20% as the QA varies by a factor of ten in this example.

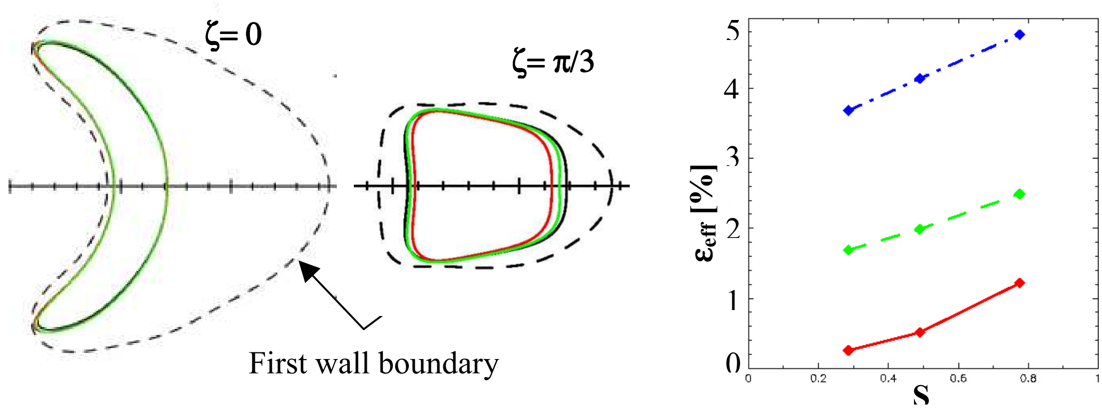

Figure 2: Boundary shapes generated by different modular coil currents for 3 stable onfigurations with $\varepsilon_{eff}(s = 0.5)$ differing by a factor of 10.

Control of iota profile

The ability to change the external transform provides a useful control feature in NCSX. Control of ι(s) can be used to test the importance of avoiding low-order rational surfaces in the plasma region; evaluating the role of shear on neoclassical tearing modes; is useful for mapping stability boundaries; and will be useful for establishing controlled conditions for transport experiments. Using reference profiles of pressure and current and <u>fixed</u> reference S3 values of β, I_p and B_T (for which the axis and edge values of iota are ι(0) = 0.40, ι(1) = 0.65) substantial changes $\Delta\iota(s) \in [-0.2, +0.1]$ at constant shear can be accommodated while keeping the shear constant. Similarly, the shear, measured by ∫ = $(\iota_{max} - \iota(0))$ can be changed in the range 0.23 0.53. Figure 3a,b shows ι(s) profiles for the constant shear and variable shear scans at constant β, I_p and B_T. In conjuction with the variation in iota profiles obtained by varying I_p and β at constant B_T, shown in Fig 3c, the range of iota profiles accessible to NCSX is very broad.

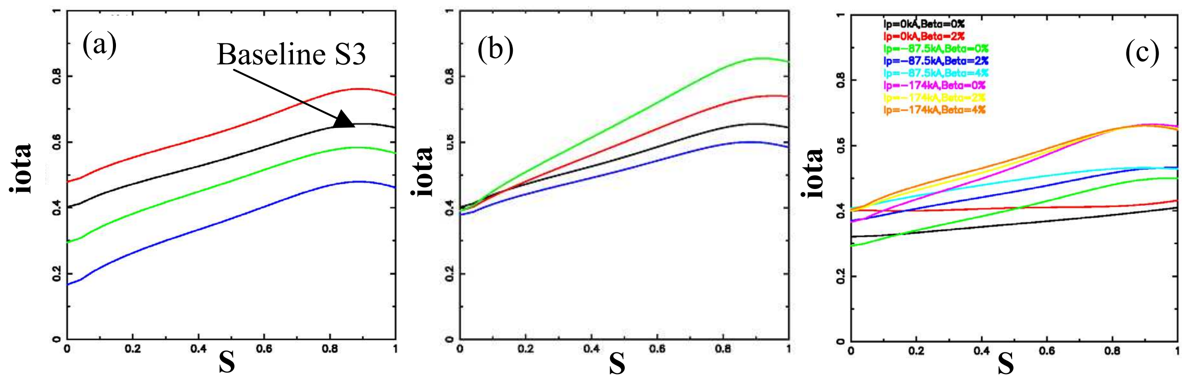

Figure 3a,b: Range of iota variation achieved by varying coil currents at fixed I_p and B_T. 3c: Range of iota profiles obtained by varying I_p and β at constant B_T.

Acknowledgements

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