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 $\beta$, quasi-axisymmetric stellarators. In order to achieve the scientific goals of the NCSX mission\textsuperscript{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\textsuperscript{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\textsuperscript{3}), stability analysis codes (TERPSICHERE\textsuperscript{4} for kink modes, COBRA\textsuperscript{5} for ballooning modes), and a QA analyser (NEO\textsuperscript{6} which evaluates QA by calculating the effective helical ripple, $\varepsilon_h$).

**Plasma performance as $\beta$ and $I_p$ are varied**

Here STELLOPT is used to calculate coil currents which support stable plasmas with good QA as $I_p$ and $\beta$ 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 $I_p$, $\beta$ values spanning $I_p \in [0, 174 \ kA]$, $\beta \in [0, 4\%]$, STELLOPT successfully produces $\varepsilon_h$-optimized equilibria which are stable to kink and ballooning modes for all $I_p$, $\beta$ values, with $\varepsilon_h$ 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 $\beta$-limit for optimized profiles). Modular coil currents vary by less than $\pm 10\%$ over the $I_p - \beta$ plane and the auxiliary TF field variation is less than $\pm 0.10 \ T$. Using reference profiles, we conclude there is a substantial region of stability with good QA in the $I_p - \beta$ 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 $I_p$, $\beta$ scan is marginally stable (as was verified by freezing the coil currents, increasing $\beta$, and noting the appearance of instability). Configurations with a wide range of $\beta$-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 $\beta$ 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 $\gamma = 0.5$. 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.
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, $\varepsilon_h$) 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, $\beta = 2.0\%$, 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.
Control of iota profile

The ability to change the external transform provides a useful control feature in NCSX. Control of τ(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 fixed reference S3 values of β, I_p and B_T (for which the axis and edge values of iota are τ(0) = 0.40, τ(1) = 0.65) substantial changes Δτ(s) ∈ [-0.2, +0.1] at constant shear can be accommodated while keeping the shear constant. Similarly, the shear, measured by \( \sigma = (t_{\text{max}} - t(0)) \) can be changed in the range 0.23 ≤ 0.53. Figure 3a,b shows τ(s) profiles for the constant shear and variable shear scans at constant β, I_p and B_T. In conjunction 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.](image)

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References