Benefits of moderate 3D fields in Tokamaks - NHTX as an example

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I. INTRODUCTION

Key questions to be resolved for DEMO, and resulting requirements for an experiment to "tame the plasma material interface" have been posed [1], and non-axisymmetric coil systems and their 3D effects identified as important areas for study. Non axisymmetric perturbing fields can provide a variety of beneficial effects in tokamaks. ELM mitigation and RWM feedback stabilization are probably the most familiar. As well, we consider the possibility of using 3D perturbing coils to allow start-up without transformer assist, and to passive stabilization of the vertical instability of elongated tokamaks.

The tokamak configuration we use to test the beneficial effects of 3D fields is the National High Power Advanced Torus Experiment, NHTX [1, 2]. The machine parameters of the "existence proof" design point are $R = 1.0$m, $a = 0.55$m, $\kappa = 2.7 - 3.0$, $B_T = 2.0$T, $I_p = 3.0$MA, $\beta = 10\%$. The baseline rotational transform, ι, varies between $\iota \approx 0.5$ ($q = 2$) at the plasma center and 0.1 ($q = 10$) at the plasma edge. 3D coils are mounted on a vacuum vessel modeled as a vertical cylinder of radius $R_c = 1.90$m, extending between $Z = \pm 0.90$m, joined to a slanted cylinder extending to $R = 1.05$m, $Z = \pm 1,80$m. The candidate 3D coils (see Fig.1) are saddle coils based on the semi-stellarator windings proposed in [3, 4] providing in their simplest connections (currents equal in each leg of all saddles) $n = 5$ "stellarator symmetric" perturbing fields.

II. ELM MITIGATION

Small nonaxisymmetric magnetic perturbations applied to the edge region of tokamaks have been shown to reduce, even eliminate, Type-I ELMs[5]. ITER is planning to install 3D coils for ELM mitigation. An empirical criterion for ELM control is that magnetic islands induced by the perturbation overlap in the outer 5-10% of the plasma minor radius measured in units of normalized poloidal flux. Satisfying the Chirikov Overlap criterion sets a required level of coil current in a given 3D coil set. Low-n perturbing fields penetrate deeper in the plasma than do high-n fields.

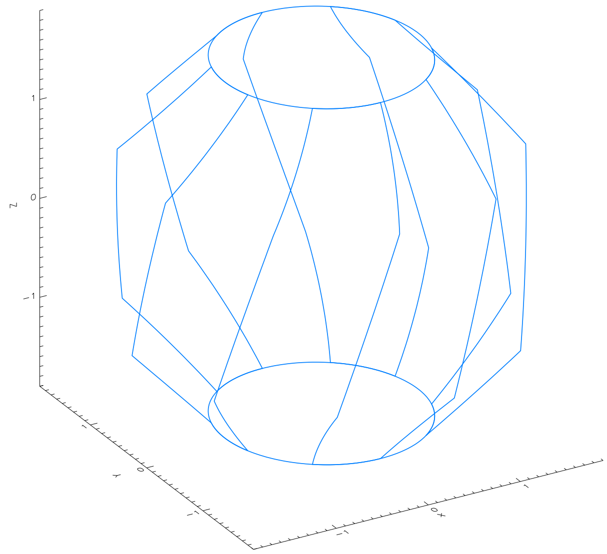

FIG. 1: Candidate n=5 Semi-Stellarator windings for NHTX. Currents in adjacent outboard legs have currents which flow in opposite directions.

Typically, coils used to supply the magnetic perturbations produce penetrating low-n perturbing fields. Degradation of confinement in the plasma interior due to nonaxisymmetric penetrating fields is a concern. In principle, the geometry and currents in the perturbing coils can be optimized to produce quasi-axisymmetric fields, minimizing deleterious effects on transport. In any event, the effect on neoclassical transport can be simply estimated by evaluating the effective helical ripple using code modules that have been applied in the design work for the stellarator NCSX, such as NEO [6].

Using $n = 5$ 3D coils for an NHTX candidate configuration with $I_{3D} = 5.0$kA-turns per saddle coil, a Chirikov parameter in excess of unity at $\rho/a = 0.90$ is achieved. The NEO code was used to evaluate the effective helical ripple. We find $\epsilon_{eff} < 0.05\%$ over the entire plasma region, even for $I_{3D} = 10.0$kA-turns, indicating little departure from axisymmetry. For comparison, ϵ_{eff} for the transport optimized NCSX configuration varies between 0.1% in the core and 1.4% at the edge. In the $1/\nu$ regime, neoclassical transport scales as $\epsilon_{eff}^{3/2}$.

III. PASSIVE STABILIZATION OF THE VERTICAL MODE

In axisymmetry there is no natural tendency for the plasma to center itself in the vacuum vessel. Stellarator fields, however, form a cage surrounding the plasma which inhibits plasma motion. For NCSX, equilibrium calculations showed that quenching either β or the plasma current results in little change in the location of the plasma outer boundary. Stability calculations also showed the plasma is robustly stable to the vertical mode. Morphing the NCSX equilibrium into a perturbed tokamak by decreasing the magnitude of the helical fields has shown that the vertical mode remains stable for rather modest levels of externally produced rotational transform [7, 8].

It is important to determine whether appropriately designed saddle coils on the top and low field side of a tokamak can produce helical fields which result in complete passive stabilization of the vertical mode, and if so, whether these fields are sufficiently quasi-axisymmetric to avoid deleterious effects on the plasma transport. Numerical MHD stability calculations are needed to adequately study this issue, and these are at their beginning stages for NHTX. In the absence of results from these calculations, we can resort to analytical δW calculations [9] for a large aspect ratio plasma. These show that the vertical mode can be stabilized by a simple set of parallelogram-shaped coils placed above and below the torus . This allows more highly elongated plasmas without loss of control of the vertical mode or conversely should give enhanced vertical stability and resistance to non-linear VDE's at planned elongations.

The nonaxisymmetric field allows stabilization of the vertical mode for a vertically elongated plasma because it can produce an effective averaged B_R component of the magnetic field which is independent of B_Z. If the plasma is displaced slightly in the vertical direction, the sign of the resulting force is determined by the sign of $\partial B_R/\partial Z$. For an axisymmetric externally generated vacuum field, $\nabla \times \mathbf{B} = 0$ relates this to the sign of $\partial B_Z/\partial R$, which is in turn determined by the sign of the quadrupole field. A quadrupole field that increases the vertical elongation produces a destabilizing change in $\partial B_R/\partial Z$. Allowing the magnetic field to be nonaxisymmetric decouples $\partial B_R/\partial z$ from $\partial B_Z/\partial R$. To stabilize the vertical mode, we add a nonaxisymmetric field whose appropriately averaged value of $\partial B_R/\partial Z$ in the plasma is stabilizing.

This physical picture suggests a nonlinear stabilization of the vertical mode even in the presence of linear instability, and possible suppression of vertical displacement events (VDEs). The nonaxisymmetric coils produce an effective averaged B_R which increases exponentially as a function of Z, so that the restoring force $\partial B_R/\partial Z$ increases exponentially for finite vertical excursions of the plasma. We estimate that the magnitude of the non-axisymmetric field must be roughly 10% that

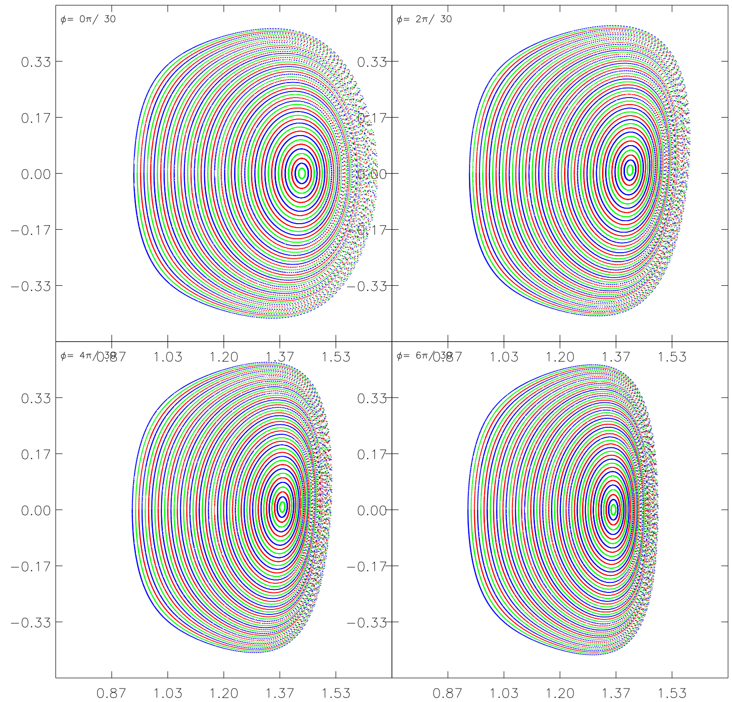

FIG. 2: Vacuum magnetic surfaces for NHTX produced by candidate n=5 coils. Rotational transform on axis = 0.025

of the toroidal field to provide significant stabilization.

IV. VACUUM SURFACES FOR TRANSFORMER-LESS STARTUP

Relatively weak helical fields can ease the startup of a tokamak or spherical torus. The passing electrons that carry the net plasma current are well confined if the product of the electron gyroradius ρ_e divided by the radius of the plasma a and the aspect ratio, A is smaller than the rotational transform $\iota > (\rho_e/a)A$. The electron gyroradius of electrons of temperature T_e in keV, which are in a magnetic field B in Tesla, is $\rho_e = 1.07 \times 10^{-4}(T_e^{1/2}/B)$ in meters, so only a tiny transform is required for confinement. When passing electrons are confined, wave heating can create a fully ionized plasma, which would allow any available induction drive to be used with essentially 100% efficiency or external current drive to slowly ramp up the current.

Numerical field line following in fields produced by the candidate $n = 5$ coils show good flux surfaces in a toroidal region with minor radius in excess of 20cm and rotational transform at the vacuum magnetic axis of 0.025. The ratio of current in the 3D coils to the current-turns in the TF coils is approximately 6%. With tweaking of the vacuum configuration, it appears likely that 100keV electrons can be confined.

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