PRINCETON PLASMA PHYSICS LABORATORY

Memo #971108-PPPL-CKESSEL-01

To: Distribution

Date: November 8, 1997

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Subject: PF Coil Error Fields in NSTX

A first analysis of error fields in NSTX is presented in the following. The error fields ($n \neq 0$, $m > 0$) from shifts and tilts of the PF coils have been examined for PF1-4. The shift is taken to be 0.003 m, and the tilt is taken to be 0.2 degrees. These are values found to be typical on DIII-D from work done by LaHaye[1]. They lead to $n = 1$ error fields. It is found that PF3 provides the largest error fields for shifts and PF4 provides the largest error fields for tilts. The PF coil currents used were $I_{PF1} = -575$ kA, $I_{PF2} = 474$ kA, $I_{PF3} = -565$ kA, and $I_{PF4} = -238$ kA. These were the largest currents found among the equilibria reported in the memo dated 4/3/97 from Pomphrey. The plasma surface used was the $q = 2$ surface from an equilibrium calculated in JSOLVER. The plasma has $I_p = 1.0$ MA, $B_T = 0.3$ T, $R_o = 0.854$ m, $a = 0.679$ m, $\kappa_{edge} = 2.0$, $\delta_{edge} = 0.5$, $q_o = 1.10$, $q_{edge} = 13.7$, $\beta_p = 0.74$, $\beta = 30.5\%$, $\beta_N = 6.0$, and $l_i = 0.48$. The $q = 2$ surface geometry is described by $R = 0.955$ m, $r = 0.489$ m, $\kappa = 1.87$, and $\delta = 0.28$. All the error field components are evaluated at the $q = 2$ surface, NOT at each particular rational flux surface. The PF coil data that was used is given in Table 1.

The 3D magnetic fields are represented by a double Fourier series,

$$B_r(\theta,\phi) = \sum_{n=0}^{N}\sum_{m=0}^{M}\left[B^c_{r_{m,n}} cos(m\bar{\theta} - n\phi) + B^s_{r_{m,n}} sin(m\bar{\theta} - n\phi)\right]$$

where B_r refers to the radial magnetic field pointing normal to the flux surface. The sums are over the number of toroidal and poloidal Fourier harmonics. The $n = 0$ terms are calculated, however they are not error fields. The $B^{c,s}_{r_{m,n}}$ are the Fourier amplitudes, with the value of interest being,

$$B_{r_{m,n}} = \sqrt{(B^c_{r_{m,n}})^2 + (B^s_{r_{m,n}})^2}.$$

It should be noted that the poloidal angle must be chosen correctly to represent the magnetic field line in the true toroidal and shaped surface geometry. Using the straight forward angle in the poloidal plane is only correct for a cylinder. That is why the angle is denoted by $\bar{\theta}$. The procedure used to calculate the error field is 1) determine the correct poloidal angle and generate a grid in (θ_j, ϕ_i) space corresponding to this poloidal angle, 2) calculate the 3D magnetic field at these grid points, 3) calculate the component of the magnetic field normal to the flux surface at the grid points, and 4) solve for the Fourier components from the following relations.

$$B^c_{r_{m,n}} = \frac{2}{N_\phi N_\theta} \sum_{i=1}^{N_\phi} \sum_{j=1}^{N_\theta} B_r(\theta_j, \phi_i) cos(m\bar{\theta}_j - n\phi_i)$$

$$B^s_{r_{m,n}} = \frac{2}{N_\phi N_\theta} \sum_{i=1}^{N_\phi} \sum_{j=1}^{N_\theta} B_r(\theta_j, \phi_i) sin(m\bar{\theta}_j - n\phi_i)$$

Here N_ϕ and N_θ are the number of toroidal and poloidal points, respectively. The values for the error fields are given in Table 2 and 3.

The criteria provided by Kaye, in the 12/18/96 memo, for the critical (2,1) error field that leads to locked modes is given by,

$$B^{crit}_{r_{2,1}} \approx 5.0 \times 10^{-4} \quad (Tesla)$$

which should be compared with a total error field from all sources. The results presented here represent only a possible subset of error field sources. Additional sources would include PF coil ellipticity and bowing. The TF coils also provide a source of field error, which may be significant in NSTX because of the demountable outboard TF leg. Future work will include PF coil ellipticity and bowing, and TF coil misalignments. The error fields from bus work, coil feeds, coil crossovers, and magnetic materials are considered to be small in comparison to coil irregularities. It is not clear how to approach the misalignment of the centerstack. These results must be factored in with feasible engineering tolerances in coil placement and manufacturing.

Another issue that may be important in NSTX error field analysis is the affect of other rational surfaces and the error fields that couple to them. LaHaye[2] has been trying to develop an approach to include the affect of other rational surfaces on the (2,1) surface. He cites two effects, 1) (2,1) error fields created by currents induced at the (1,1) and (3,1) surfaces, and 2) drag from error fields at the (1,1) and (3,1) surfaces would slow the (2,1) as well, leading to a lower critical field for mode-locking. This approach would require that we add the (1,1), (2,1), and (3,1) error fields, with appropriate weights, to determine the actual error field at the (2,1) surface. This feature may be more important in NSTX since the plasma will have many more rational surfaces, than typical tokamaks with $q_{95} \leq 4$, and these rational surfaces are spatially close together for $q \geq 3-4$. The error fields for a given PF coil show a slower fall off with increasing poloidal mode number than was typical for TPX, which is most likely due to the close proximity of the coils to the plasma.

Table 1: NSTX PF Coil Data

PF Coil	I(kA)	R_c(m)	Z_c(m)	ΔR(m)	ΔZ(m)
1	-575.0	0.180	1.448	0.040	0.540
2	474.0	0.790	1.934	0.180	0.068
3	-565.0	1.490	1.634	0.180	0.068
4	-238.0	1.800	0.650	0.100	0.068

Table 2: NSTX Error Fields from 0.003 m PF Coil Shifts (10^{-4} Tesla)

PF Coil	$B_{r_{1,1}}$	$B_{r_{2,1}}$	$B_{r_{3,1}}$	$B_{r_{4,1}}$	$B_{r_{5,1}}$
1	0.138	0.137	0.114	0.082	0.055
2	0.310	0.291	0.224	0.153	0.095
3	0.641	0.570	0.434	0.311	0.194
4	0.205	0.275	0.340	0.323	0.294

Table 3: NSTX Error Fields from 0.2° PF Coil Tilts (10^{-4} Tesla)

PF Coil	$B_{r_{1,1}}$	$B_{r_{2,1}}$	$B_{r_{3,1}}$	$B_{r_{4,1}}$	$B_{r_{5,1}}$
1	0.066	0.059	0.045	0.030	0.018
2	0.129	0.118	0.099	0.078	0.051
3	0.650	0.843	0.736	0.563	0.386
4	1.062	1.039	0.888	0.768	0.667

[1] TPX Physics Design Description, 1993.

[2] R. LaHaye, Physics of Locked Modes in ITER: Error Field Limits, Rotation for Obviation, and Measurements of Error Fields, GA-A22468, 1996.