Impact of PF and TF Coil Misalignment on Toroidally Asymmetric Plasma Error Fields in TPX*

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ABSTRACT

Error fields from misalignment of the toroidal field (TF) and poloidal field (PF) coils in TPX are presented in terms of the outward normal B-field ($B_\perp$), expanded in poloidal and toroidal harmonics (m, n), on a simulated, D-shaped, plasma flux surface. Results are reported for n=1 toroidal mode number and low poloidal mode numbers, m, and for various displacements of the TF and PF coils. In particular, results are given for the m,n = 2,1 error field which interacts with the q=2 surface to cause locked modes and loss of plasma performance. Based on existing experiments, maximum permissible field errors are 4 G for the 2,1 mode and 8 G for the n=1; m=1,3,4 modes. Results are presented for a rigid shift and rotation of a single TF coil and for a rigid, radial shift of each PF coil.

I. INTRODUCTION

Recent tokamak experiments have shown that small toroidally asymmetric magnetic error fields can have severe impact on plasma performance [1-4]. Theoretical models [4,5] and scaling from experiments [6] indicate that the allowable asymmetric error field decreases with device size. Many existing machines have added error field correction coils to allow plasma operation in error field sensitive regimes, and recently proposed machines like TPX and ITER are being designed with a reasonable understanding of error field constraints. However, the next generation devices are expected to have many non-axisymmetric error field contributors caused by coil shape and assembly errors, asymmetric eddy current paths and dynamic movement associated with cryogenic operation and large stresses. The identification and reduction of error field contributors is a major design task for next generation tokamaks.

Small static non-axisymmetric fields in the plasma caused by external currents resonate at low order rational surfaces (safety factor, q = 1, 2, 3 ...) in the plasma [5]. The most detrimental error field component has been found to be the toroidal harmonic with mode numbers m, n = 2, 1; where m is the poloidal mode number and n is the toroidal mode number. This mode couples with the q= 2 surface which is the location of a strong plasma instability. Diamagnetic drift and tangential neutral beam injection cause plasma rotation which suppresses island formation and growth. Error fields create static magnetic islands near the rational surfaces which apply a torque to slow down the natural plasma rotation. Above critical error fields, these torques are sufficient to stop rotation and islands at resonant surfaces grow. This is typically called a "locked mode", and leads to degradation in plasma performance and, potentially, plasma disruption. Based on extrapolation from existing machines, studies have shown that the critical error field for the 2,1 mode is $B_{\perp 2,1}/B_0 < 0.9 \times 10^{-4}$ for TPX [6]. TPX magnets are being designed to stringent error field constraints and will have error field correction coils to further reduce the fields and allow investigation of the error field phenomena.

II. MODEL

Two models were independently developed to determine the response of coil misalignment on the lower order (m,n) toroidal harmonics in the plasma. The first model, referred to as the “filament model” consists of a general purpose, 3-D filament description of the toroidal field (TF) and poloidal field (PF) coils. The perpendicular error field is determined on a toroidal surface with a uniform distribution of grid points in the poloidal (θ) and toroidal (ϕ) directions. The magnetic output is coupled to a 2-D fast Fourier transform model which decomposes the results into modal harmonics on the toroidal surface. The second model was developed primarily within the OPERA/TOSCA [8] magnetics code and is referred to as the “TOSCA model”. Rectangular cross section straight, arc and solenoid elements with uniform current density are used to represent the coils. Fourier integrals representing the toroidal harmonics are evaluated by numerical integration over the toroidal surface. Results from both models are similar for all cases studied.

The toroidal surface upon which the Fourier decomposition was performed consists of a D-shaped cross section. The shape is defined parameterically in an R, Z coordinate system by [9]:

$$R(\Theta) = R_0 + a \cos\left(\Theta + \delta \sin \Theta\right) \quad , \qquad (1)$$

and,

$$Z(\Theta) = -\kappa \ a \sin \Theta , \qquad (2)$$

where R_0 is the plasma major radius, a is the minor radius, κ is the elongation, and δ is the triangularity. The parameter Θ varies from 0 to 2π and is analytically related to the poloidal angle (θ) used in the Fourier decomposition [9]. For the TPX

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plasma: R_0 = 2.25 m, a = 0.5 m, κ = 1.8, and δ = 0.5 which represents the approximate outer edge of the plasma. Fig. 1 shows the functional shape of this surface based on a 36 by 36 grid used in the filament model of the PF system. Larger numbers of grid points were used in the TF analysis.

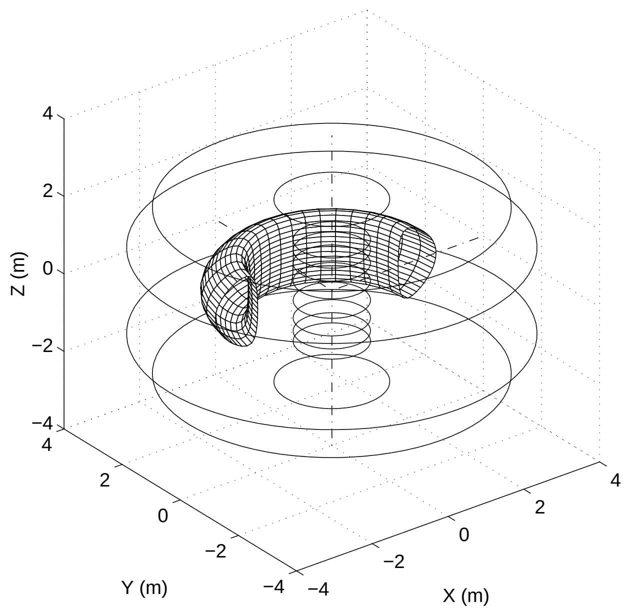

Fig. 1. TPX toroidally symmetric D-surface and PF coil elements used in the filament model for decomposition of the m,n error fields. Half of the 36 x 36 plasma grid is shown.

Limits on low order harmonic terms have been set by the TPX project. Limits are allocated to each sub-system based on an apportionment of the overall machine limits. Values for the TF and PF coil systems are 8% and 32% of the totals, respectively. The total machine limits for n=1 are [9]:

$$\left|\frac{\delta B_{\perp m,1}}{B_0}\right| \begin{array}{l} < 1\times10^{-4};\ \text{for: } m = 2 \\ < 2\times10^{-4};\ \text{for: } m = 1,3,4 \end{array} \quad (3)$$

and, for n=2 are:

$$\left|\frac{\delta B_{\perp m,2}}{B_0}\right| \begin{array}{l} < 2\times10^{-4};\ \text{for: } m = 4 \\ < 4\times10^{-4};\ \text{for: } m = 3,5 \end{array}, \quad (4)$$

where $\delta B_{\perp m,n}$ is the amplitude of the helical m, n Fourier component of the perpendicular field on a toroidal surface and B_0 = 4 T is the toroidal field at the major radius, R_0. These limits correspond to contributions from all sources on the machine.

III. TF COIL ANALYSIS

All 16 coils in the TPX TF system are simulated in the models. In the TOSCA model, each TF coil is modeled as an end-to-end collection of uniform current density rectangular conductors composed of arc's and straight sections. In the filament model, each TF coil is simulated as an array of 560 straight filamentary elements. In order to understand the role of perturbations in the coil locations, a single coil, TF1, is rigidly displaced and the resulting field decomposed into helical harmonics. A radial and vertical displacement of 0.635 cm (1/4 in.) and an angular displacement of 0.1 degree are used to determine characteristic sensitivity to single coil misalignment.

The Fourier components of the perpendicular field for a rigid radial shift of the coil are shown in Fig. 2. The variation in mode magnitude with toroidal mode number, n is shown in Fig. 2(a). The TF ripple is seen at the n=16 position. A sum of the n=16 components for all m yields a 0.15% average TF ripple on the surface which can be compared with a 0.28% peak ripple in the plasma. The effect of the perturbation is seen in the lower mode numbers. Fig. 2(b) shows the variation in mode magnitude with poloidal mode number, m. Table I presents a summary of the results. Radial shifts produce the largest error field. For all cases, the m,n = 1,1 component is largest relative to the limits specified for TPX. The limit imposed by TPX for the m,n=1,1 mode requires that a single coil be held to 0.68 mm radial positional tolerance with all other TF coils in perfect alignment. A preliminary statistical analysis of tolerance build up from all 16 TF coils, each having 6 degrees of freedom, indicates that positional tolerances of ±0.17 mm (±0.007 in.) are required to meet the specified TF coil allowable.

IV. PF COIL ANALYSIS

Each PF coil was individually modeled using a solenoid element in the TOSCA analysis and using 80 straight elements in the filament model. Each coil was rigidly shifted 0.635 cm in the radial direction and the modal harmonics calculated. In addition, the outer coils were rigidly rotated about the center to produce a 0.368 cm (1/8 in.) displacement at each edge. A vertical shift (ΔZ) of the coil was not analyzed since it results in an axisymmetric system and produces no error fields. Table II shows results for n=1 and lower order m modes. The n=2 components are essentially zero. The largest component relative to the TPX limits is the m,n=2,1 mode. The project limit imposed on the 2,1 mode requires that the PF7 coil (with 1 MA of current) be held to a 1.38 cm radial positional tolerance with all other PF coils perfectly aligned. When all coils are allowed to move the individual coil requirements will be much more restrictive. However, as specified, the requirements for the PF coils are considerably less restrictive than those for the TF coils.

Fourier contributions from different coils can be linearly superimposed to determine the influence of coil combinations. Each harmonic component is a vector containing magnitude and phase information and vector addition is required. Fig. 3 shows error field variation for a 0.625 cm rigid radial shift of the center solenoid based on superposition of the contributions from coils PF1-4 (upper and lower) and for coil currents based on a nominal plasma equilibrium. The m,n = 2,1 term ($\delta B_{2,1}/B_{\phi o}$) ~ 1.5 x 10^{-4} is largest compared to the TPX specification. Applying the PF system limit to the

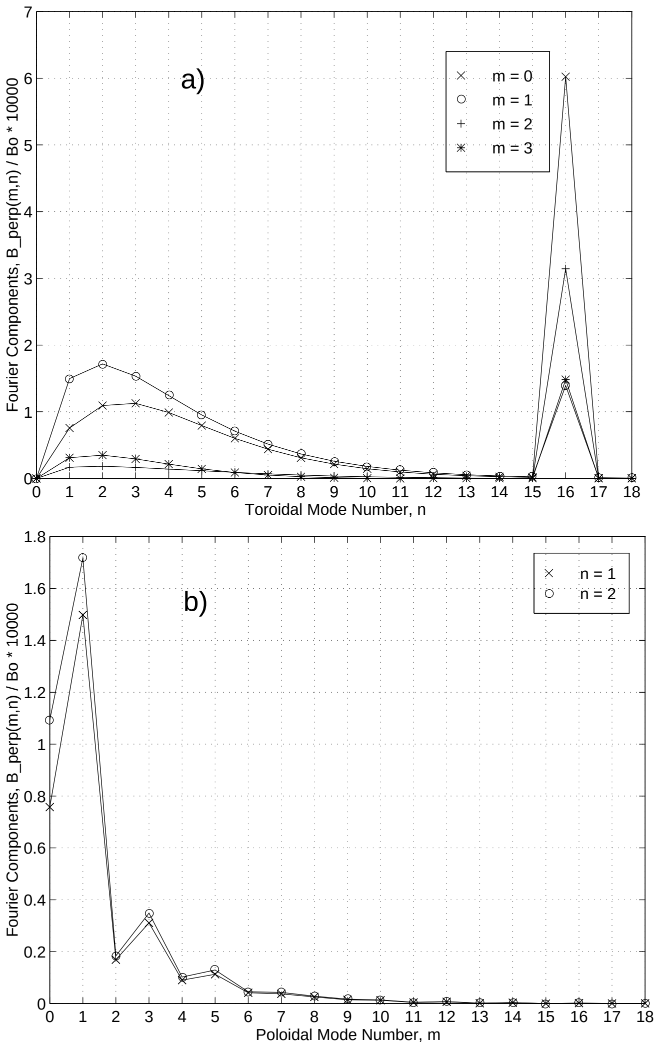

Fig. 2. Amplitude of Fourier components of TPX field error from a 0.635 cm rigid radial shift of a single TF coil: a) variation with toroidal mode number, n; b) variation with poloidal mode number, m. Phase not shown.

Table I
TPX error field magnitude from a rigid displacement of a single TF coil

Case	(n=1)	$\lvert\delta B_{\perp m,1}/B_o\rvert \bullet 10^4$
	m	
TF1	1	1.498
ΔR= 0.635 cm	2	0.169
I= 2.81 MA	3	0.311
	4	0.090
TF1	1	0.089
ΔΦ= 0.1 deg.	2	0.0043
I= 2.81 MA	3	0.014
	4	0.0075
TF1	1	0.353
ΔZ= 0.635 cm	2	0.088
I= 2.81 MA	3	0.085
	4	0.008

Table II
TPX coil error field magnitude from a rigid PF coil shift.

COIL	(n=1)	$\lvert\delta B_{\perp m,1}/B_o\rvert \bullet 10^4$	
Displac. Type:		Radial	Tilt
Displacement:		0.635 cm	0.635 cm
	m		
PF1U	1	0.257	
R= 0.8101 m	2	0.333	
Z= 0.2514 m	3	0.164	
I= 1.0 MA	4	0.049	
PF2U	1	0.308	
R= 0.8101 m	2	0.261	
Z= 0.7064 m	3	0.120	
I= 1.0 MA	4	0.077	
PF3U	1	0.291	
R= 0.8101 m	2	0.217	
Z= 1.0420 m	3	0.117	
I= 1.0 MA	4	0.074	
PF4U	1	0.245	
R= 0.8101 m	2	0.173	
Z= 1.3058 m	3	0.108	
I= 1.0 MA	4	0.066	
PF5U	1	0.159	0.047
R= 1.213 m	2	0.093	0.035
Z=2.350 m	3	0.064	0.022
I= 1.0 MA	4	0.037	0.011
PF6U	1	0.237	0.096
R= 3.758 m	2	0.139	0.088
Z= 2.144 m	3	0.068	0.046
I= 1.0 MA	4	0.020	0.015
PF7U	1	0.215	0.160
R= 4.297 m	2	0.147	0.116
Z= 1.113 m	3	0.068	0.044
I= 1.0 MA	4	0.038	0.014

solenoid alone results in a tolerance constraint of 1.4 mm on the radial location of the solenoid. Table III shows the results for the central solenoid shift and for a rigid shift of all PF coils relative to the plasma. The latter case would represent a PF/TF system misalignment.

V. DISCUSSION

Error fields must be controlled on an overall machine basis and the statistical nature of the error field buildup must be taken into consideration when allocating error field limits among sub-components. As an example, the TF coil contributes primarily to the m,n=1,1 mode; the contribution to the 2,1 mode is a factor of 4 lower. The PF coil solenoid contributes primarily to the 2,1 mode and the 1,1 contribution is a factor of 3 lower. In essence, these two systems are close

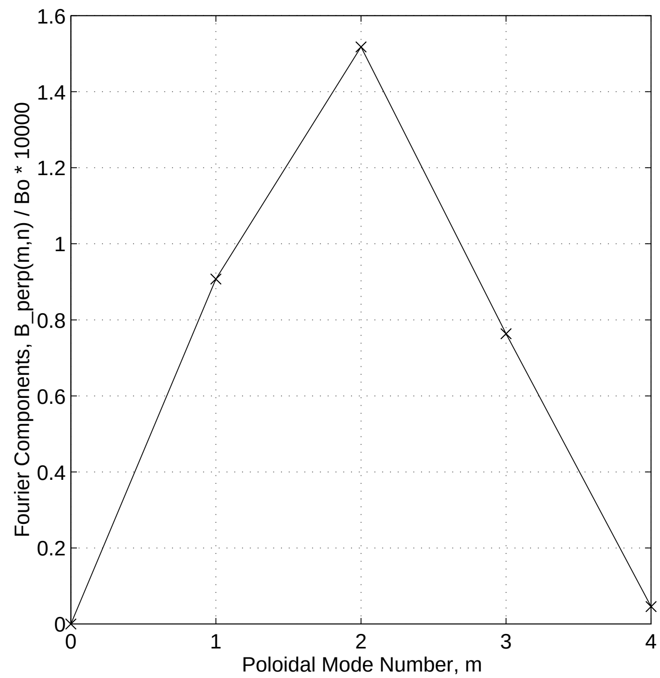

Fig. 3. Amplitude of Fourier components of TPX field error from a 0.635 cm rigid radial shift of the central PF solenoid for n=1 and nominal PF coil currents. Phase not shown.

Table III
TPX coil error field magnitude from a rigid radial displacement of the center solenoid and the PF coil system.

Case	(n=1)	$\lvert \delta B_{\perp m,1}/B_o \rvert \bullet 10^4$
ΔR = 0.635 cm	m	
Center Solenoid	1	0.892
PF1-4	2	1.472
(upper & lower)	3	0.727
	4	0.058
All PF Coils	1	1.894
	2	1.780
	3	0.324
	4	0.170

to orthogonal and constraints imposed using a simple apportionment of machine errors are overly restrictive. If the TF coil is the major contributor to the 1,1 mode and the other systems contribute only a small amount then the TF coil allocation for the 1,1 mode could be close to 100%. In allocating sub-system limits, a systematic analysis of all error field contributors must be performed to account for statistical interactions between systems. The above method, in a linearized sense, forms a basis for this type of analysis.

VI. CONCLUSIONS

Non-axisymmetric error field limits required to minimize the formation of locked modes in the TPX plasma severely restrict coil positional tolerances. As specified, the limits are most severe for the TF coil. Radial position requirements in the sub-millimeter range will be required to meet the error field specification. The TF coil contributes primarily to the m,n=1,1 mode with smaller contributions to the 2,1 mode. Statistical study of the error field build up indicates that tolerances of 0.17 mm will be required to meet TPX TF coil error field specification without the use of error field correction coils. The PF coils tolerances are primarily controlled by the 2,1 mode limit. Based on the present allocation of error field limits, the PF coil tolerances requirements are less restrictive than the TF coil requirements. A study of the statistical nature of error field components on the overall machine should lead to a new partitioning of error field limits and a relaxing of the overall constraints for individual systems.

REFERENCES

[1] J.T. Scoville, R.J. La Haye, A.G. Kellman, T.H. Osborne, R.D. Stambaugh, E.J. Strait, T.S. Taylor, *Nucl. Fusion* **31**, 875 (1991).

[2] A.W. Morris, P.G. Carolan, T.C. Hender, and T.N. Todd, *Phys. Fluids B* **4**, p. 413, 1992.

[3] G.M. Fishpool, D.J. Campbell, R. Fitzpatrick, P.S. Haynes, “A locked mode associated with low density in JET,” Proce. of International Atomic Energy Agency Meeting on Avoidance and Control of Tokamak Disruptions, September 10–12, 1991, p 84.

[4] R.J. La Haye, R. Fitzpatrick, T.C. Hender, A.W. Morris, J.T. Scoville, and T.N. Todd, “Critical error fields for locked mode instability in tokamaks,” *Phys. Fluids B* **4**, p. 2098, 1992.

[5] R. Fitzpatrick and T.C. Hender, “The interactions of resonant magnetic perturbations with rotating plasmas,” *Phys. Fluids B* **3**, p. 644, 1991.

[6] R.J. La Haye, “Limits on m=2, n=1 error field induced locked mode instability in TPX with typical sources of poloidal field coil error fields and a prototype correction coil, C-Coil,” General Atomics Report GA-A21167, 1992.

[7] OPERA/TOSCA Reference Manual, Vector Fields Limited, Oxford England, 1994.

[8] S.C. Jardin, “Updated TPX field error criterion,” TPX Memo 93-950405-PPPL-SJardin-01, April, 5, 1995, also, G.H. Neilson and S.C. Jardin, TPX General Requirements Document Engineering Change #37, March 31, 1995.