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A Systematic Approach to Error Field Analysis in ITER

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The locked mode threshold (LMT) in ITER is expected to be more restrictive than in present tokamaks. As a consequence, stringent coil alignment tolerances and comprehensive analysis techniques are being developed to reduce the impact of locked modes on plasma performance. This paper summarizes the analysis approach being used to insure that ITER error fields will be below the expected LMT. Asymmetric error fields from the PF & TF coils are decomposed into helical components on the q=2 surface and are superimposed using a Monte Carlo technique to establish the most probable machine error fields. A constrained, least square technique is used to optimize currents in a superconducting correction coil (CC) system to reduce the statistically expected machine error fields to below the LMT.

I. INTRODUCTION

In existing major tokamak devices, locked mode phenomena can degrade plasma performance and lead to premature discharge termination [1]. Theoretical models and recent tokamak experiments have shown that non-axisymmetric fields (asymmetric error fields) in tokamaks interact with the plasma on rational q surfaces to form magnetic islands [1-4]. Normally formation of these islands is shielded by the natural plasma rotation and by neutral beam induced rotation. However, error fields above a threshold size, referred to as the Locked Mode Threshold (LMT), produce sufficient torque to stop plasma rotation. Mode locking leads to performance loss and ultimately, plasma disruption [5]. As a consequence, asymmetric error field reduction is a major design challenge for ITER [6].

ITER LMT limits are expected to be very restrictive and, accordingly, stringent requirements are being placed on coil manufacturing and assembly tolerances and a wide range of error field sources is being investigated [6,7]. A robust correction coil (CC) system is being designed to compensate for residual machine error fields. In this paper we extend the results of the previous work [6] to include: a more recent estimates of the assembly tolerances, a new Monte Carlo formulation of the statistical problem, and statistical information on phase in the CC optimization.

II. ERROR FIELDS AND ITER LIMITS

Asymmetric error fields are characterized by decomposition of the normal magnetic field component on rational q surfaces (safety factor, q = 1, 2, 3) in terms of poloidal (m) and toroidal (n) helical harmonics. Fourier analysis of these m,n error field components follows from:

$$B_{m,n} = \frac{1}{2\pi^2} \int_{\phi=0}^{\phi=2\pi} \left[\int_{\hat{\theta}=0}^{\hat{\theta}=2\pi} B_\perp\left(\phi,\hat{\theta}\right) e^{i\left(n\phi - m\hat{\theta}\right)} d\hat{\theta} \right] d\phi \;;\; \text{where: } \hat{\theta}(l) = \frac{1}{q} \int_{l_o}^{l} \frac{B_\phi}{R\,B_p} dl \quad . \tag{1}$$

and $B_{m,n}$ is the m,n helical component, ϕ is the toroidal angle, $B_\perp$ is the perpendicular magnetic field and $\hat{\theta}$ is the modified poloidal angle. B_ϕ and B_p are the unperturbed toroidal and poloidal magnetic fields; R is the major radius and l is the poloidal length, with l_o corresponding to $\hat{\theta} = 0$.

Lower order error fields, especially m,n=2,1, are the most troublesome for low q tokamak operation [1–4]. An early study based on scaling of COMPASS-C, DIII-D and JET experiments indicated the ITER LMT for Ohmic operation is: $B_{21} / B_{\phi o} \leq 1 \times 10^{-5} \equiv 1$ Unit ($B_{\phi o}$= 5.7 T) [5]. This is an order of magnitude more stringent than on other large tokamaks. Scaling of more recent experiments in JET and COMPASS-D indicates that the ITER m,n=2,1 may be a much more tolerable $7{\times}10^{-5}$ [8]. The present machine is designed to meet the more stringent 1×10^{-5} requirement and, as such, can be regarded as a conservative design.

Although the 2,1 mode typically is the most dangerous mode, recent experiments have shown that other lower order (m,n) modes, most notably the 1,1 and 3,1, exhibit a drag effect on the q=2 surface. A more general expression including the influence 3 modes, from DIII–D scaling is [5]:

$$\frac{B_{3\mathrm{mode}}}{B_{\phi o}} \equiv \frac{\sqrt{B_{2,1}^2 + 0.8B_{3,1}^2 + 0.2B_{1,1}^2}}{B_{\phi o}} \le 2 \times 10^{-5} \equiv 2\underline{\mathrm{Units}} \tag{2}$$

Recent experiments on JET and COMPASS-D show similar, albeit slightly more complex, multi-mode dependence [9].

III. ERROR FIELD STATISTICAL FORMULATION

The primary sources of error field in the ITER machine are misalignment of the toroidal and poloidal field coils [6] and the magnitude of these error fields is presented in Ref. 7. Below we statistically superimpose individual coil misalignment errors to predict the residual machine error field. An analytical model which uses a normal (Gaussian) distribution of misalignment errors [6] is compared with a Monte Carlo model which uses a more realistic, uniform distribution of misalignment errors between two fixed limits.

In a statistical formulation, each misalignment error is assumed to be randomly distributed. The PF system has 10 coils each with 4 degrees of freedom (2 orthogonal radial and tilt). For each of the 20 TF coils, eight degrees of freedom are considered independent: 3 rigid displacements, 3 rigid rotations, and two coil deformations associated with radial and axial increases in size. A total of 200 degrees of freedom are used to simulate the combined coil system.

For each coil degree of freedom, and for the machine as a whole, the probability of an m,n component of error field (B_{mn}) lying between B_{min} and B_{max} can be expressed in terms of a probability density function. In the analytic treatment, using a normal distribution of misalignment errors, the distribution function has a Rayleigh form [6]:

$$P\{B_{min} \le B_{mn} \le B_{max}\} = \int_{B_{min}}^{B_{max}} f_{Bmn}(B_{mn})\, dB_{mn}, \quad \text{where :} \quad f_{B_{mn}}\left(B_{mn}\right) = \frac{B_{mn}}{\sigma_{B_{mn}}^2} e^{-\frac{B_{mn}{}^2}{2\sigma_{B_{mn}}^2}} U(B_{mn}) \tag{3}$$

and, σ_{Bmn} is the square root of the sum of the squares of the individual m,n components and U is the unit step function. A similar expression has been developed for the 3-mode formula in Ref. 6. The Monte Carlo technique allows determination of the probability density function f_{Bmn} by numerical summation of all degrees of freedom associated with all coils. A nominal basis function is constructed from all the degrees of freedom in the system. Each element is perturbed based on random number theory and the resultant machine error field computed. The probability density function and its statistics are computed from a summation over a large set of cases.

Figure 1 shows the error field probability density function for a uniform distribution of PF and TF misalignment errors (200 degrees of freedom) based on a 200,000 case Monte Carlo simulation. The point shown on each curve is the 50 cumulative percentile error field and represents, with 50% confidence, the expected machine error field. Table I shows statistics for each distribution and compares results with the analytical normal distribution (Eq. 3). The uniform distribution, Monte Carlo results are 40 to 60% below the analytic, normal distribution results. As with previous studies, the TF–coil is the major contributor to the 3-mode error field through its large m,n = 1,1 component. The PF– and TF–coil contributions to the m,n = 2,1 component are almost equal.

Each m,n component has magnitude and phase and the Monte Carlo technique allows computation of the phase statistics. Figure 2 shows the probability density function associated with the difference in phase between two m,n components (e.g. $\delta\Phi_{21\text{-}11} = \Phi_{21} - \Phi_{11}$). The distribution is

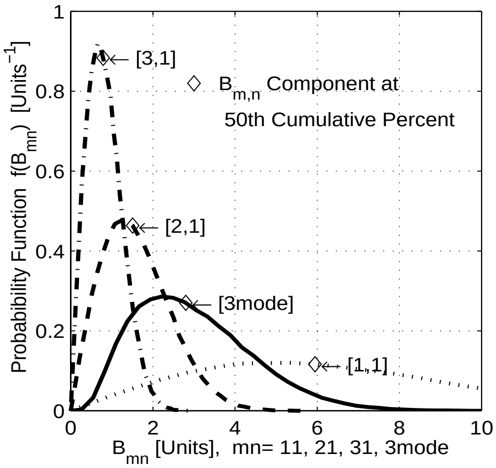

Fig. 1. Probability density function for ITER machine error fields based on a Monte Carlo analysis using uniformly distributed errors.

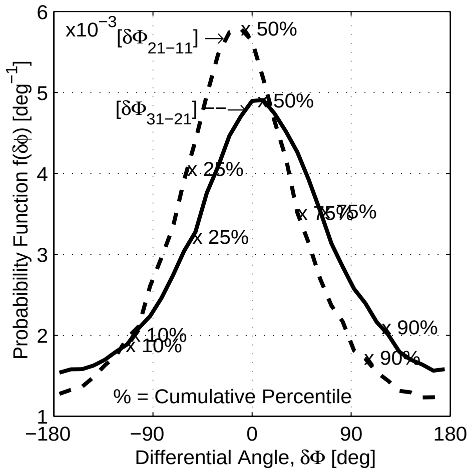

Fig. 2. Differential phase probability density function $\delta\Phi_{21\text{-}11}$ & $\delta\Phi_{31\text{-}21}$ for a uniform distributed error.

shown to be approximately normal with mean very close to zero. The variance is relatively large, indicating the CC must have a wide range of phase capabilities.

IV. CORRECTION COIL SYSTEM

A robust set of correction coils is being implemented in the ITER design to reduce the residual machine error field below the LMT. The system is shown in Fig. 3 and is composed of three poloidally distributed sets of superconducting coils designated: Top, Side and Bottom. Each set contains 2 independent currents which allows correction of magnitude and phase of m,n= 1,1, 2,1, and 3,1. The CC current limits for the Top, Side and Bottom coil sets are: 45, 150 and 240 kA.

As in previous studies, a non-linear, least square constrained minimization procedure is utilized to optimize the performance of the overall correction coil system [6]. Fig. 4 shows the maximum magnitude of normalized 3-mode error field which can be reduced to 2×10^{-5} for various differential phase associated with the residual machine error field. In the optimization one or more of the coils are at their respective current limits. The design point represents the statistically

Table I Expected machine error fields from superposition of coil misalignment errors.

Magnitude [Units $= 10^{-5}$]	$\frac{B_{11}}{B_{\phi o}}$		$\frac{B_{21}}{B_{\phi o}}$		$\frac{B_{31}}{B_{\phi o}}$		$\frac{B_{3\text{-mode}}}{B_{\phi o}}$	
distribution:	normal	uniform	normal	uniform	normal	uniform	normal	uniform
ITER LMT Limit			1				2	
50th Percentile:								
PF alone	3.00	1.77	1.89	1.11	1.19	0.70	2.84	1.07
TF alone	9.81	5.67	1.78	1.03	0.64	0.37	4.97	2.59
PF & TF	10.3	5.94	2.60	1.51	1.35	0.79	5.82	2.80
99.9th Percentile:								
PF alone	9.47	5.09	5.96	3.28	3.75	2.04	6.41	2.46
TF alone	31.0	17.8	5.62	3.20	2.0	1.16	14.1	8.02
PF & TF	32.4	18.8	8.19	4.65	4.26	2.39	15.0	8.49

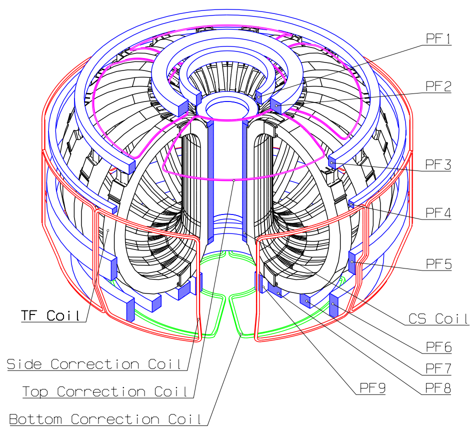

Fig. 3. ITER geometry showing major coil systems including the three CC sets: Top, Side and Bottom.

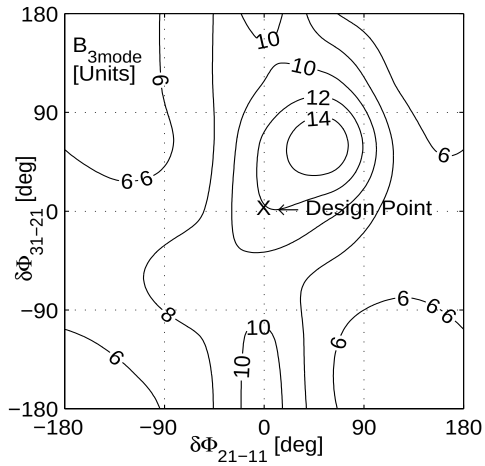

Fig. 4. 3-mode error field magnitude, B_{mn}, which can be corrected to below the LMT by the CC's for different machine error field phase.

expected phase and the CC is capable of reducing approximately 12×10^{-5} of this phase spectra to below the LMT. This compares with the statistically expected, (50%), value of 2.8×10^{-5} and is 30% above the 99.9 percentile value of 8.5×10^{-5} . Currents required in the Top, Side and Bottom coils are 20, 145 and 240 kA-t, respectively.

V. CONCLUSIONS

Asymmetric error field limits in ITER have been established based on scaling of the LMT from present experiments. The ITER LMT limit is more restrictive than in present machines. Accordingly, great attention is being devoted toward identifying and reducing potential error field sources. PF and TF coil misalignment errors are expected to be the largest error field sources. Based on a statistical combination, their 3-mode level is expected to be approximately 3×10^{-5}. The CC system is capable of reducing almost 12×10^{-5} of error field with the statistically expected phase to below the LMT. This capability exceeds the statistically expected 99.9 th percentile level of error field.

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