Письма в ЭЧАЯ. 2015. Т. 12, № 3(194). С. 590–598

OPTIMIZATION OF CURRENTS IN ITER CORRECTION COILS

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In tokamaks, nonaxisymmetric magnetic field perturbations (error fields) can induce in plasma locked modes and cause disruption. In ITER, the main contributor to error fields is the assembly and manufacturing errors of the magnet system of the machine. To suppress intrinsic error fields and guarantee the expected plasma performance, ITER is provided with the proper correction coils (CC). The paper is related to optimization of CC currents. The optimization takes into account as constraints both CC current capacities and an allowable level of error fields.

В токамаках отклонения неосесимметричного магнитного поля могут индуцировать в закрытые виды плазмы и вызывать сбой. В ITER основными факторами ошибок являются ошибки сборки и изготовления магнитной системы машины. В целях уменьшения исходной погрешности и обеспечения получения ожидаемой плазмы для ITER предоставлена необходимая корректирующая катушка. В работе рассматриваются методы оптимизации потоков корректирующей катушки. Оптимизация включает в себя пропускную способность корректирующей катушки и допустимый уровень исходной погрешности.

PACS: 03.50.De; 41.20.-g

INTRODUCTION

In tokamaks, nonaxisymmetric magnetic field perturbations (error fields) with an amplitude as small as 10^{-4} of the toroidal magnetic field may cause locked modes leading to disruptions [1–5]. In ITER, the main contributor to error fields is the assembly and manufacturing errors of the central solenoid (CS), poloidal (PF) and toroidal field (TF) coils, usually considered as positioning errors in the current centreline (CCL) of the coils. The allowable level of error fields is about several Gauss, on a background of much larger toroidal magnetic fields, 5.3 T.

Three sets of superconducting correction coils (see Fig. 1): six Top CC, six Side CC, six Bottom CC are designed for suppression of intrinsic error fields [6]. Within each set, the toroidally opposed coils are connected electrically in antiseries to provide suppression of error fields modes with the toroidal number $n = 1$. Each set of CC has three independent

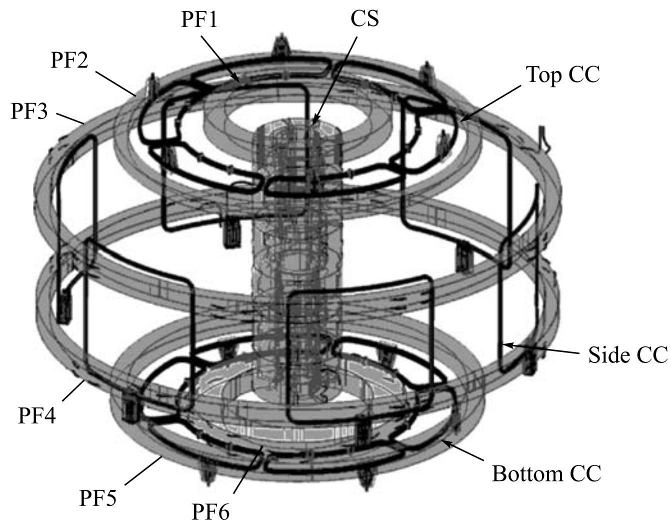

Fig. 1. Layout of correction coils, PF and CS coils

power supplies allowing phase adjustment of correction field modes. Based on the physics requirements and the design considerations, the total current capacities of 320 kAt for the Top, Bottom CC and of 200 kAt for the Side CC are accepted.

The *baseline* set of the coil tolerances [7] is given in the left columns of Tables 1–3. They result in 670 independent degrees of freedom (DOF) in position and shape of the CCL of the tokamak main magnets.

Table 1. **Tolerance on different deviations of the CS coils relative to their ideal positions (mm)**

Type of deviation	Baseline [7]	Increased [8]
CSU3 shift	3	**5**
CSU2 shift	3	**4**
CSU1/L1 shift	3	3
CSL2 shift	3	**4**
CSL3 shift	3	**5**
CSU3 tilt	2	**3**
CSU2 tilt	1.7	**2.5**
CSU1 tilt	1.4	**2**
CSL1 tilt	1.1	**1.5**
CSL2 tilt	0.8	**1**
CSL3 tilt	0.5	0.5
CS stack shift	2	2
CS stack tilt	0	**1**
CSU3 wrapping	1	**2**
CSU2 wrapping	1	**2**
CSU1/L1 wrapping	1	1
CSL2 wrapping	1	**2**
CSL3 wrapping	1	**2**

Table 2. **Tolerance on different deviations of the PF coils relative to their ideal position and shape (mm)**

Type of deviation	Baseline [7]	Increased [8]
PF coil shift	2	2
PF coil tilt	1	1
PF1 wrapping	1	**2**
PF2 wrapping	1	**3**
PF3 wrapping	1	**4**
PF4 wrapping	1	**4**
PF5 wrapping	1	**3**
PF6 wrapping	1	**2**

Table 3. **Tolerance on different deviations of the TF coils relative to their ideal position and shape (mm)**

Type of deviation	Baseline [7]	Increased [8]
TFC WP radial shift	0.5	0.5
TFC WP side shift	1	1
TFC WP vertical shift	0.5	0.5
TFC WP tilt, around Y-axis	0.5	0.5
TFC WP tilt, around X-, Z-axes	2	2
Points A, B, shift along X-axis	1	1
Points A, B, shift along Y-axis	3	3
Points A, B, shift along Z-axis	1	1
Points C, F, shift along X-axis	2	2
Points C, F, shift along Y-axis	3	3
Points C, F, shift along Z-axis	2	**6**
Points D, E, G, shift along X-axis	2	**6**
Points D, E, G, shift along Y-axis	3	3
Points D, E, G, shift along Z-axis	2	2
TFC case radial shift	2	**3**
TFC case side and vertical shift	2	2
TFC case tilt, around Z-axis	2	2
TFC case tilt, around Y-axis	4	4
TFC case tilt, around X-axis	4	**2**

The TF coil manufacturing and assembly errors come from: 1) winding pack (WP) manufacture, 2) WP insertion in the case, and 3) assembling of eighteen TF coils around the vertical axis of the machine. These errors can be considered separately as follows:

• A set of seven reference points marked by ABCDEFG (Fig. 2) is used for checking position and shape of the CCL of the TF coils with indirect methods. Shifts in X, Y, and Z directions of these points (21 DOF per coil) define the WP errors.

• On insertion of the winding pack in the coil case it may be shifted or tilted as a rigid body (6 DOF per coil).

• The assembly errors are considered to be in the form of rigid body displacement and/or rotation of the TF coil case (6 DOF per coil) around the vertical axis of the machine.

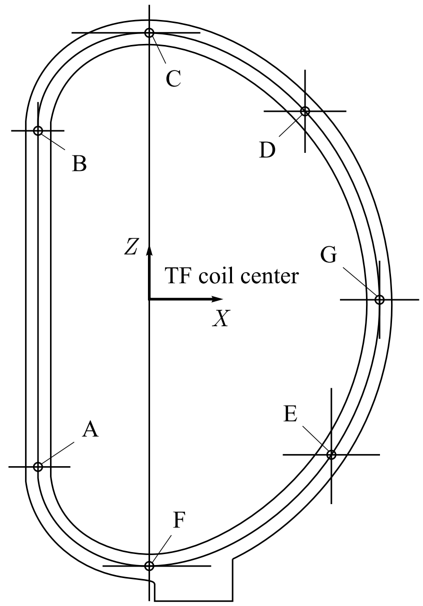

Fig. 2. Locations of the reference points A–G on the TF coil centreline

In the error field analysis, the positioning errors are considered as independent and, therefore, additive. Related error fields caused by given coil tolerances in 670 DOF can be calculated using the Monte Carlo studies.

Taking into account that the tolerances on coil manufacturing and installation may have a trend to increase, the analysis of error fields reported in this paper is based on the set of increased errors in manufacturing and assembly of the coils. This set of *increased* tolerances proposed for the sensitivity study is given in [8] and summarized in the right columns of Tables 1–3.

The analysis of error fields expected from the coils misalignments is statistical and performed commonly in terms of the Fourier harmonics on a given surface in the plasma region [9, 10]. Assessment of the CC currents required for the error fields correction is based on the Fourier transform of the CC correction fields and can be treated as an inverse problem, which, in this case, is ill-conditioned. The problem is solved by using the regularization procedures [11]. *Therefore, in calculations, different currents can be obtained using different vector norms (different optimization criteria).*

CALCULATION MODEL AND APPROACHES

The ITER magnet system is assumed to have several hundreds of DOF defined by the number of possible deviations of the current centrelines of the coils from their ideal positions and shapes. The Monte Carlo calculations enable us to evaluate statistical properties of expected error fields from statistical combinations of individual deviations of coils [12].

Since the very beginning of the ITER design activity, the "3-mode" error field criterion has been used as an allowable level of error fields (the Locked Mode Threshold (LMT) for operation with low plasma density) [5]:

$$\frac{B_{3\text{-mode}}}{B_{t0}} = (0.2B_{1,1}^2 + B_{2,1}^2 + 0.8B_{3,1}^2)^{1/2}. \quad (1)$$

Here, $B_{3\text{-mode}}$ is the weighted averaged amplitude of the $(1,1)$, $(2,1)$, and $(3,1)$ Fourier modes of the component of magnetic field, which is normal to the $q = 2$ magnetic surface of a considered phase of plasma scenario (definition is given in [9]). The nominal toroidal field is $B_{t0} = 5.3$ T at $R_0 = 6.2$ m.

It should be noted, that the second criterion has been also developed for the ITER plasmas on the base of the Ideal Perturbed Equilibrium Code (IPEC) [10], taken into account the ideal-MHD response of plasmas to magnetic perturbations, not considered in the paper.

The start of flattop (SOF) phase of 15MA DT scenario has been used for the analysis as one of the most sensitive to error fields (low plasma density and lack of plasma rotation driven by tangential injection of the neutral beams).

The previous analysis of the CC currents required for the error field correction was rather conservative [12–14]. The CC currents were selected using the statistics of error fields assuming *uniform* distribution of probability of the relative phases of the three harmonics considered. In turn, the maximum CC currents were found to depend strongly on a phase combination of the modes. This means that a confidence level of significance of the CC currents obtained in [12–14] as the maximum for all possible relative phases of the harmonics is higher than the 99.9% confidence level of significance of $B_{3\text{-mode}}$, defined by Eq. (1).

A more optimistic assessment of the required CC currents can be obtained by using a statistics of the CC currents themselves additionally to that of error fields. This requires a calculation of the CC currents for each obtained statistical combination of the individual positioning errors of the coils from a sample of 1,000,000–10,000,000 random trials. Note, that such a statistics is simpler for analysis, because a randomized variable, a current, is one-dimensional.

Such calculations have been carried out. A set of coil *increased* tolerances specified in [8] has been used for the calculations. The coils deviations have been assumed to be uniformly distributed within the tolerance limits given in Tables 1–3. The simulated probability distributions of the amplitudes of the $(1,1)$, $(2,1)$, and $(3,1)$ modes are closed to the Rayleigh distribution.

The maximum amplitude of the "3-mode" error field, expected from misalignments of the TF, CS, and PF coils for the specified set of tolerances, has been estimated as $B_{3\text{-mode}}/B_{t0} = 19.86 \cdot 10^{-5}$ with the 100% probability for 1,000,000 statistical events. Reduction of the "3-mode" error field with the amplitude of $19.86 \cdot 10^{-5}$ to $5 \cdot 10^{-5}$, assuming its amplitude and relative phases of the modes $(1,1)$, $(2,1)$, and $(3,1)$ as *independent* random variables (similar to the approach used in [12–14]), requires 217 kAt in the Top CC, 119 kAt in the Side CC, and 354 kAt in the Bottom CC, if minimizing the root-mean-square norm of currents:

$$||I|| = \left(\sum_{i=1}^{9} I_i^2\right)^{1/2}. \quad (2)$$

As seen, the currents in the Bottom CC exceed their capacity.

Statistical properties of the CC currents required to suppress the error fields to the threshold value are shown in Figs. 3 and 4. In this analysis, the error field amplitudes and the relative phases of the three modes are *not independent* parameters.

The results of optimization shown in Fig. 3, *a–c* correspond to the minimum norm solution using the root-mean-square norm of currents (2). The CC currents required for reduction of $B_{3\text{-mode}}/B_{t0}$ from $19.86\cdot10^{-5}$ to $5\cdot10^{-5}$, with the 99.9% probability, do not exceed 171 kAt in the Top CC, 80 kAt in the Side CC, and 222 kAt in the Bottom CC.

Note, that the upper engineering limits on the CC currents can be included as constraints on optimization of the current values. In particular, the results show a potential possibility of current redistribution among the three sets of CC within their current capacities while meeting the LMT criterion.

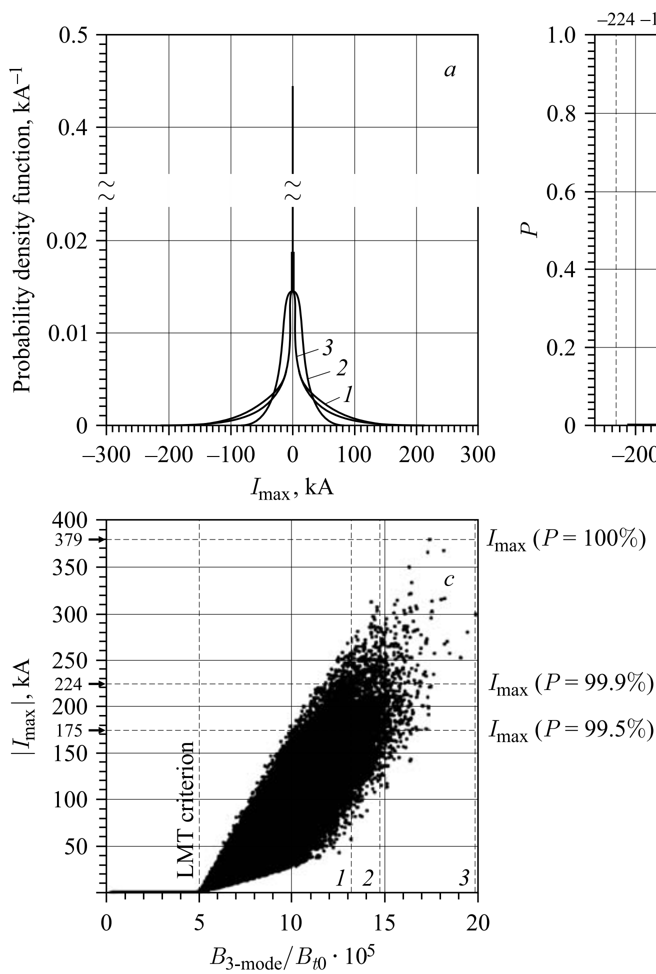

Fig. 3. Probability distributions of the CC currents (*a*), integrated probability of required currents (*b*), and required currents in the Bottom CC (*c*). *1* — Top CC; *2* — Side CC; *3* — Bottom CC. SOF conditions, 670 DOF, *increased tolerances*, 1,000,000 statistical events. Root-mean-square norm (2)

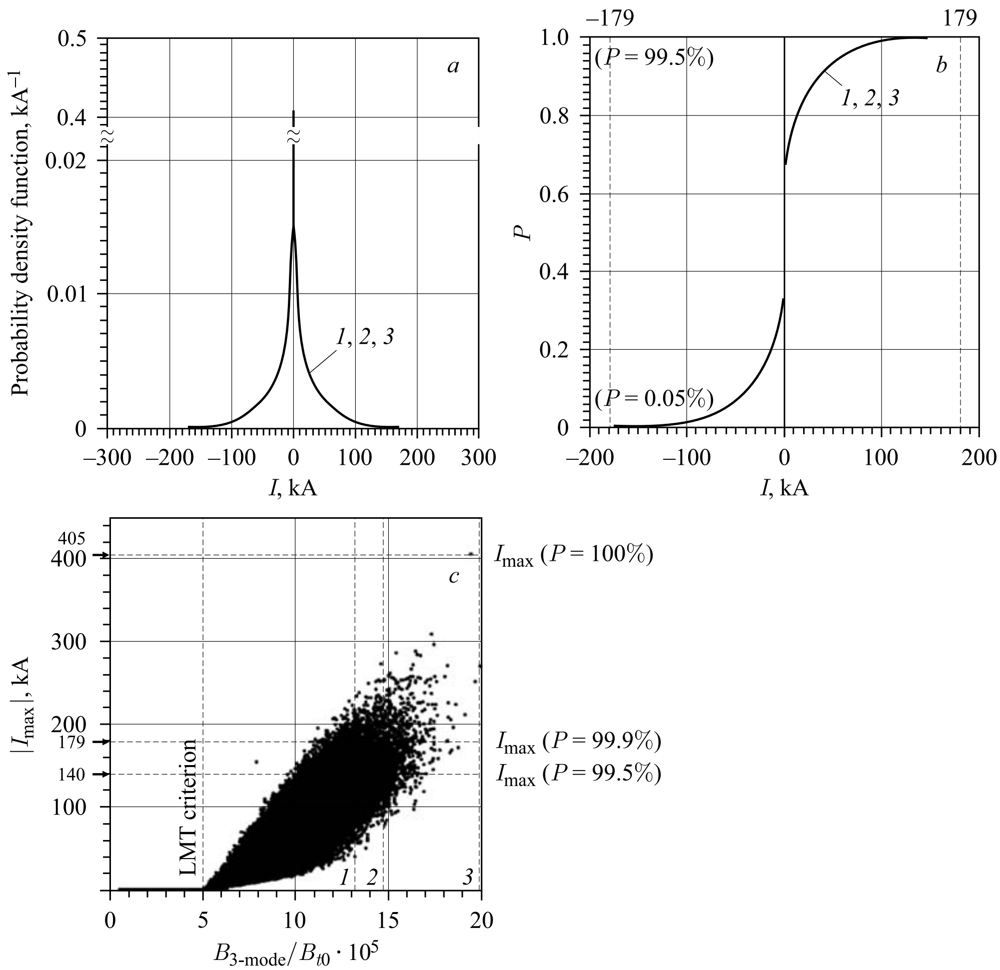

Fig. 4. Probability distributions of the CC currents (*a*), integrated probability of required currents (*b*), and required currents in the Bottom CC (*c*). *1* — Top CC; *2* — Side CC; *3* — Bottom CC. SOF conditions, 670 DOF, *increased tolerances*, 1,000,000 statistical events. Norm of the lowest of a set of maximum currents (3)

The results of optimization shown in Fig. 4, *a–c* correspond to the minimum norm solution using the vector norm of the lowest of a set of maximum current values:

$$||I|| = \max_i |I_i|. \tag{3}$$

However, in this case, 179 kAt will require in *all* CC. As seen, the maximal CC currents retain constant with increasing the volume of random samples from 1,000,000 to 10,000,000 statistical events, that demonstrates a reliability of the statistical estimates of the CC currents. The maximum value of the “3-mode” error field slightly increases from $19.86 \cdot 10^{-5}$ at 1,000,000 events to $20.82 \cdot 10^{-5}$ at 10,000,000 events.

For comparison, the currents required in the Bottom CC for error field correction with the 99.9% confidence assuming the *baseline* set of the coil tolerances [7] (Tables 1–3) were given in [14]. The maximum amplitude of the "3-mode" error field, expected from misalignments of the TF, CS, and PF coils for the specified set of tolerances, has been estimated as $B_{3\text{-mode}}/B_{t0} = 12.56 \cdot 10^{-5}$ with the 99.9% probability for 1,000,000 statistical events. With the confidence of 99.9%, these error fields can be corrected to $5 \cdot 10^{-5}$ with the currents within 132 kAt in the Top CC, 60 kAt in the Side CC, and 164 kAt in the Bottom CC, if the optimization criterion (2) is used. Using the optimization criterion (3), similar correction can be performed within 130 kAt currents. However, in this case, 130 kAt will require in all CC. The CC currents required for reduction of $B_{3\text{-mode}}/B_{t0}$ from $19.86 \cdot 10^{-5}$ (1,000,000 events) to $5 \cdot 10^{-5}$, with the 99.9% probability, do not exceed 179 kAt in all correction coils.

CONCLUSION

The study of the error fields expected from the TF, CS, and PF coil misalignments, as well as the analysis of the currents in CC required for the error fields reduction below the "3-mode" criterion, have been performed on the basis of the Monte Carlo simulations.

The transition from the error field statistics to that of the CC currents allows us to improve the accuracy of probabilistic analysis of the currents required for the error field correction.

The following results were obtained for the baseline set of the coil tolerances [7] and with the set of increased tolerances [8] for the 15MA plasma at the SOF.

Baseline Set of Tolerances. With the probability of 99.9%, the amplitude of the "3-mode" error field, expected from coil misalignments, is less than $12.56 \cdot 10^{-5}$. With the confidence of 99.9%, the error field can be corrected to $5 \cdot 10^{-5}$ by the currents within 132 kAt in the Top CC, 60 kAt in the Side CC, and 164 kAt in the Bottom CC, if the optimization criterion (2) is used. Using the optimization criterion (3), similar correction can be performed by the currents in all coils within 130 kAt. However, in this case, 130 kAt will require in all CC.

Set of Increased Tolerances. With the probability of 99.9%, the amplitude of the "3-mode" error field, expected from coil misalignments, is less than $13.06 \cdot 10^{-5}$. With the confidence of 99.9%, this error field can be corrected to $5 \cdot 10^{-5}$ with the currents within 171 kAt in the Top CC, 80 kAt in the Side CC, and 222 kAt in the Bottom CC, if the optimization criterion (2) is used. Using the optimization criterion (3), similar correction can be performed by the currents in all coils within 179 kAt. However, in this case, 179 kAt will require in all CC.

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