Assessment of 3D perturbation of plasma boundary and variation in field lines inclination near outboard first wall caused by non-axisymmetric magnetic fields expected in ITER

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Introduction

Non-axisymmetric perturbations of magnetic fields caused in ITER by the finite number of toroidal field coils (TF ripple), the vacuum vessel ferromagnetic inserts (FI, Fig. 1), reducing the TF ripple [1], and ferromagnetic elements of the test blanket modules (TBM, Fig. 2), as well as the Correction coils [2] (Figs. 3, 4) and edge localized modes (ELM) coils [3] (Fig. 4) lead to deviations of magnetic field lines relative to the ones of the unperturbed (ideal) toroidal magnetic field. This will cause 3D perturbation of the plasma boundary and peaking of the heat loads on the first wall due to an increase in the angle between the first wall and the magnetic field line striking it.

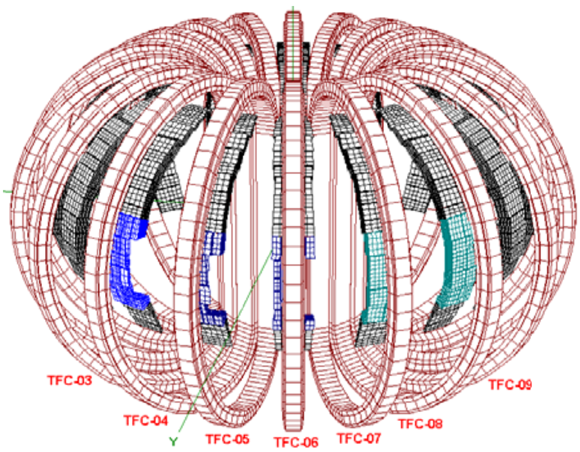

Fig. 1. Magnetic model of Ferromagnetic Inserts.

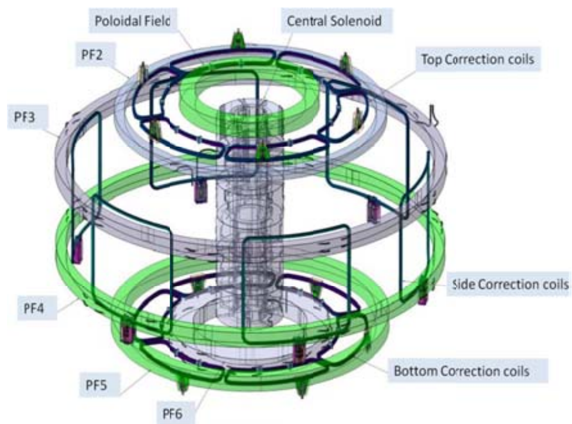

Fig. 3. Error field Correction coils, central solenoid and poloidal field coils

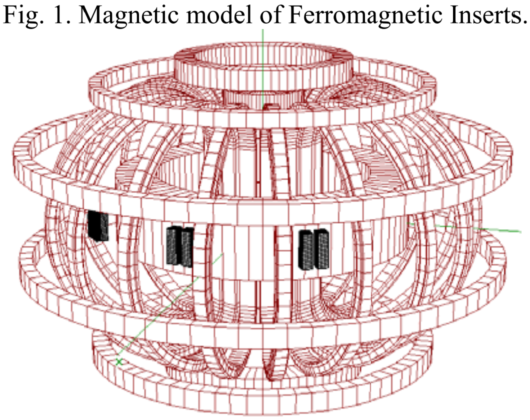

Fig. 2. Magnetic model of six Test Blanket Modules.

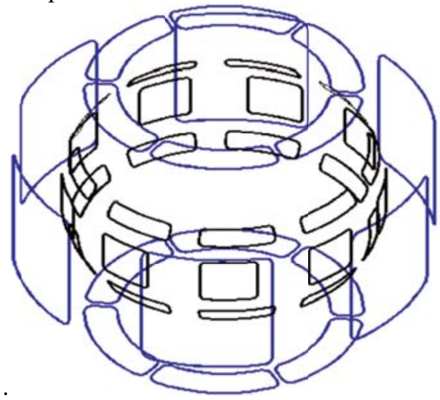

Fig. 4. Error field Correction coils (blue coils) and ELM control coils (black coils)

Neglecting the plasma amplification of the external error field, a simplified approach has been used for assessment of these effects. Two parameters have been calculated as functions of the toroidal angle φ: 1) $h(\varphi)$ – the deviation of the perturbed toroidal magnetic field lines in the direction normal to the first wall and 2) $\chi(\varphi)$ – the angle between the perturbed field lines and the axisymmetric model of the first wall. An assessment of these parameters has been performed for the outboard equatorial region (Row 14 of the blanket modules), where non-axisymmetric perturbations of the magnetic field have maximum values. In the analysis of the first wall, the blanket modules are considered as a ring given by the edges with the following coordinates: $R_1 = 8.259$ m, $Z_1 = 1.671$ m for the upper edge (point 1) and $R_2 = 8.383$ m, $Z_2 = 0.623$ m for the lower edge (point 2). The coordinates of the unit poloidal vector $(C_r, C_z) = (0.9931, 0.1175)$ normal to the line between the points 1 and 2 may be found from

$$C_r = \frac{-(Z_2 - Z_1)}{\left((R_2 - R_1)^2 + (Z_2 - Z_1)^2\right)^{1/2}}, \qquad C_z = \frac{R_2 - R_1}{\left((R_2 - R_1)^2 + (Z_2 - Z_1)^2\right)^{1/2}}.$$

Deviation $h(\varphi)$ of the perturbed field line relative to the ideal field line, passing through the point with the coordinates (R, Z, φ), in the direction normal to the first wall can be assessed using the following expressions:

$$h(\varphi) = C_r \Delta r(\varphi) + C_z \Delta z(\varphi), \quad \Delta r(\varphi) = \int_{\varphi_0}^{\varphi} \frac{B_r(R,Z,\varphi')}{B_0(R)} R d\varphi', \quad \Delta z(\varphi) = \int_{\varphi_0}^{\varphi} \frac{B_z(R,Z,\varphi')}{B_0(R)} R d\varphi',$$

where B_r and B_z are radial and vertical components of the perturbed magnetic field, respectively, $B_0(R)$ is the magnetic field corresponding to the "ideal torus" model.

The angle between the perturbed field line, passing through the point with the coordinates (R, Z, φ) and the first wall can be assessed using the expression:

$$\chi(\varphi) = C_r \frac{B_r(R,Z,\varphi)}{B_0(R)} + C_z \frac{B_z(R,Z,\varphi)}{B_0(R)}.$$

The following combinations of sources of 3D magnetic fields have been considered: 1) TF coils with FIs and TBMs magnetized in the nominal or half of the nominal toroidal magnetic field (5.3 T or 2.65 T at $R = 6.2$ m), 2) ELM coils producing $n = 4$ or $n = 3$ magnetic field modes for ELM mitigation with the maximum value of peak current (96 kAturns), 3) TF coils with FIs and TBMs magnetized at 5.3 T in combination with ELM coils having toroidal phase of the currents ($n = 4$ or $n = 3$ modes with peak currents 96 kAturns) producing the largest magnetic perturbation, 4) two opposite Side Correction coils with the maximum current (200 kAturns).

Results

Table 1 shows maximum values of the deviation of the perturbed toroidal magnetic field lines (peak to peak) and the angle between the perturbed field lines and the outboard plasma boundary or the first wall of the blanket module #14.

Table 1

Source of magnetic perturbation	**Outboard plasma boundary**		**First wall of BM #14**	
	$r_{max} - r_{min}$ **cm**	χ_{max} **deg.**	$h_{max} - h_{min}$ **cm**	χ_{max} **deg.**
1) TFC, FI, TBM at 5.3 T	1.3	0.44	2.8	2.3
2) TFC, FI, TBM at 2.65 T	1.4	0.41	4.3	3.6
3) ELM coils (n=4, I_{max} = 96 kAt)	2.8	0.60	3.7	1.0
4) ELM coils (n=3, I_{max} = 96 kAt)	2.8	0.60	3.7	1.0
5) TFC, FI, TBM at 5.3T & ELM coils (n=4)	3.6	1.4	4.5	3.2
6) TFC, FI, TBM at 5.3T & ELM coils (n=3)	3.6	1.4	4.3	3.2
7) Two Side Correction coils (I = 200 kAt)	2.1	0.25	2.5	0.28

As an example, Figs. 5 and 6 show radial and vertical components of the perturbed magnetic field, radial, vertical and normal (h) deviation of the perturbed field line, as well as the angle between the perturbed field and the first wall of the blanket module #14. Fig. 5 corresponds to the source of magnetic perturbation 1) from Table 1. Fig. 6 corresponds to the source of magnetic perturbation 6) from Table 1 (the toroidal phase of the currents in the ELM coils was tuned to produce the maximum value of the magnetic perturbation).

As can be seen from Table 1, the maximum variation of the heat flux incidence angle for the outboard first wall can be up to 3.6º. This leads to an increase of the wall heating. A preliminary study of this effect has shown that the increased heat loads are within the first wall design limit [4].

Conclusions

The studies performed have shown that: 1) the peak to peak perturbation of the outboard plasma boundary during operation of the ELM coils can be up to 3.6 cm (plasma amplification of the external error fields can increase this value) and 2) the variation in the toroidal field line inclination to the outboard first wall can be up to 3.6º.

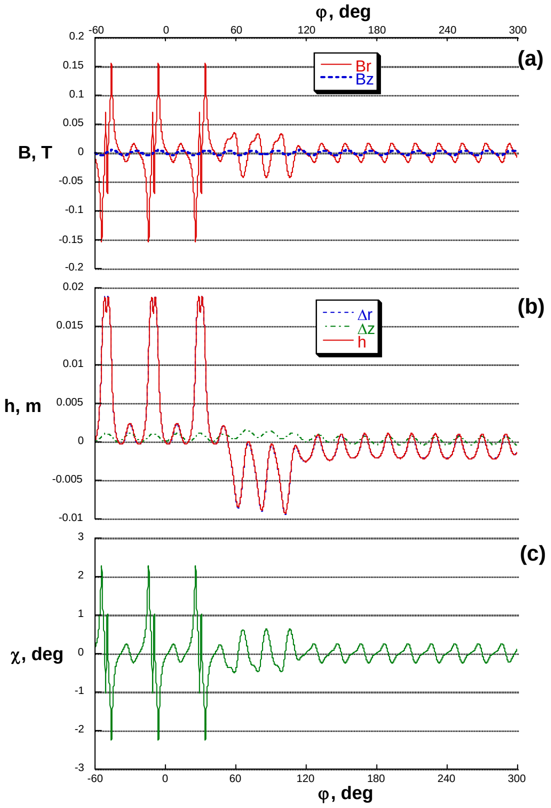

Fig. 5. Radial (B_r) and vertical (B_z) components of the perturbed magnetic field (a), radial (Δr), vertical (Δz) and normal (h) deviation of the perturbed field line (b), as well as angle (χ) between the perturbed field and the first wall of BM #14 calculated assuming TF coils with FIs and TBMs magnetized in the nominal toroidal magnetic field (5.3 T at $R = 6.2$ m).

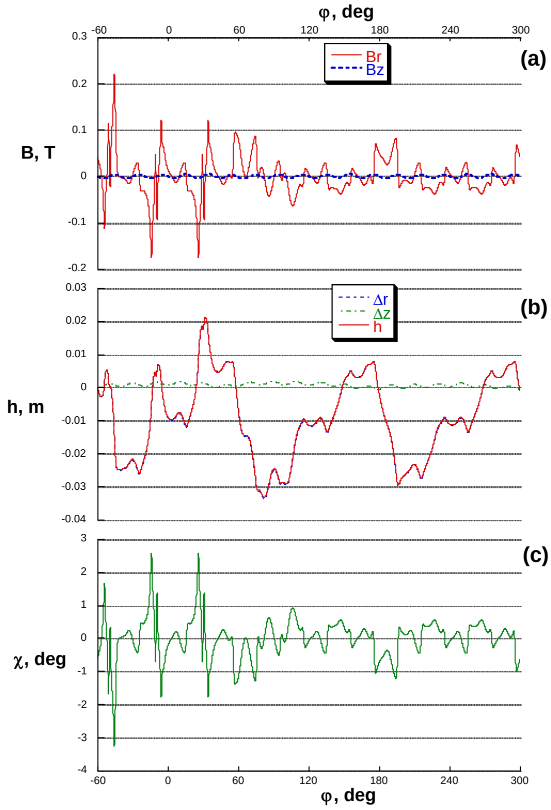

Fig. 6. Radial (B_r) and vertical (B_z) components of the perturbed magnetic field (a), radial (Δr), vertical (Δz) and normal (h) deviation of the perturbed field line (b), as well as angle (χ) between the perturbed field and the first wall of BM #14 calculated assuming TF coils with FIs and TBMs magnetized at 5.3 T in combination with ELM coils having toroidal phase of the currents producing the largest magnetic perturbation ($n = 3$ mode with peak currents 96 kAturns).

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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