Analysis of Electromagnetic Forces in Tokamak Vacuum Chamber due to Induced Poloidal Current after Thermal Quench

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Abstract—The work is devoted to the analysis of the influence of poloidal current induced in a tokamak vacuum chamber due to change of paramagnetic plasma properties as a result of thermal quench on the magnitude and distribution of electromagnetic forces in a vacuum chamber. The work was performed numerically using the plasma-physics code DINA for conditions of major disruption in the plasma of ITER and T-15MD. A comparison is made of the electromagnetic effect obtained from the toroidal and poloidal currents induced in the vacuum chamber as a result of thermal quench with estimates of the electromagnetic forces due to only toroidal currents. It is shown that the integral radial component of the electromagnetic force in the elements of the vacuum chamber when the poloidal current is taken into account can be much lower than in the case of only the toroidal current induced in the chamber. The paper presents a model for calculating the poloidal current induced in a vacuum chamber first used in the DINA code.

Keywords: tokamak, electromagnetic forces, major disruption, thermal quench, DINA code

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INTRODUCTION

A major disruption in the tokamak plasma begins with a rapid (about 0.1–1 ms) thermal energy emission from it (TQ—Thermal Quench), after which an uncontrolled vertical motion of the plasma (VDE—Vertical Displacement Event) begins, accompanied by a decrease in the plasma current (CQ—Current Quench) due to a sudden increase in the plasma electrical resistance after TQ [1–4].

It is generally accepted that one of the main negative consequences of a major disruption for a tokamak is the generation of electromagnetic forces in the conducting elements of the vacuum chamber, in which, owing to the inductive coupling of the elements of the vacuum chamber with the plasma, the toroidal current component is induced during the CQ process [3, 5]. In this case, the initial phase of the major disruption of TQ preceding the CQ stage was not considered until recently as a stage during which significant electromagnetic loads arise in the chamber [3, 6–8]. However, recent studies have appeared in which it was shown both analytically [9] and numerically [10] that significant toroidal currents are induced in the conductive elements of the vacuum chamber located near the plasma during the TQ process. This is due to the change in the plasma pressure during the TQ process and the corresponding change in the magnetic field inside the plasma. According to estimates [10], the integral electromagnetic force from toroidal currents in the ITER vacuum chamber after TQ can reach a level of ~70 MN, which is comparable with the level of the maximum allowed mechanical loads in the ITER chamber [3, 5].

In addition to toroidal currents, a poloidal current is induced in the vacuum chamber as a result of TQ, during which the plasma becomes paramagnetic with a corresponding rise in the toroidal magnetic flux in it. It compensates for this rise and contributes to the electromagnetic effect on the vacuum chamber. The role of the poloidal current in the wall was analyzed analytically in [11–13] and numerically in [14].

In this work, using the plasma-physics DINA code with a free plasma boundary [15], we obtained the results of a numerical analysis of the electromagnetic effect on the vacuum chamber of the ITER [3] and T-15MD [16] tokamaks due to the toroidal and poloidal currents $\mathbf{j}_w = \mathbf{j}_w^{\text{pol}} + \mathbf{j}_w^{\text{tor}}$ induced during the TQ process:

$$F_w = \int (\mathbf{j}_w \times \mathbf{B}) dV. \quad (1)$$

At the same time, the results of the analysis of electromagnetic effects on the ITER vacuum chamber arising only owing to the toroidal currents induced in the TQ process [10] are reproduced.

In Eq. (1), integration is carried out over the volume of the conducting structure of the vacuum cham-
ber, and \( j_{\text{pol}} \) and \( j_{\text{tor}} \) are the density components of the current induced in the wall in the poloidal and toroidal directions, respectively. The resulting electromagnetic effects are compared with estimates of electromagnetic effects only due to the induced toroidal currents.

This work is devoted to the analysis of the electromagnetic effects on the conductive structures of the vacuum chamber of the ITER and T-15MD tokamaks as a result of TQ. In much the same way as in [10], the TQ duration for both tokamaks was assumed as \( \tau_{\text{TQ}} = 0.1 \) ms for simplicity of simulation. This value is lower than the value accepted for ITER (of the scale of 1 ms [3]). When solving the problem, the choice of a lower \( \tau_{\text{TQ}} \) value in the calculations does not affect the result of the solution, since the selected value is much lower than the wall resistive time (in the case of ITER, this value is about 300 ms [3, 19]). Thus, the paper presents the results of the simulation of the electromagnetic effect during the TQ stage and the very beginning of the CQ stage (~2 ms in the case of ITER and ~0.6 ms in the case of T-15MD). The total duration of the CQ stage at the disruption in the ITER plasma can vary within 30–150 ms, and in the case of T-15MD, it can vary within 5–20 ms depending on the temperature level after TQ. The effect of the generation of the halo currents during the disruption, which become noticeable only at the end of the CQ stage, is not considered.

**FORMULATION OF THE PROBLEM**

**Disruption in the ITER plasma.** The magnetic configuration of the plasma before the onset of thermal disruption shown in Fig. 1a is the standard plasma configuration of the ITER plasma in the inductive 15 MA deuterium-tritium scenario in the combustion regime of thermonuclear power of 500 MW [17].

The major plasma radius \( R_0 = 6.2 \) m, minor plasma radius \( b = 2 \) m, elongation \( \kappa = 1.7 \), the vacuum toroidal magnetic field at \( R = R_0 \) is \( B_{\text{TO}} = 5.3 \) T and the plasma current is \( J = 15 \) MA [3, 18]. The plasma parameters before the disruption were set as follows: temperature and density profiles were assumed to be parabolic with average values \( n_e^{\text{avr}} = 9.6 \times 10^{19} \) m\(^{-3}\), \( T_e^{\text{avr}} = 9.3 \) keV, and \( T_i^{\text{avr}} = 9.3 \) keV and boundary values \( T_e^{\text{bnd}} = T_i^{\text{bnd}} = 10 \) eV and \( n_e^{\text{bnd}} = 9.55 \times 10^{19} \) m\(^{-3}\). This corresponds to the relative plasma pressure \( \beta_p = 0.62 \) and the internal inductance \( l(3) = 0.72 \).

The thermal disruption, during which \( Jd/dt = 0 \), is simulated by a sudden drop in the electron and ion temperatures to a level of 5 eV [5] over a time \( \tau_{\text{TQ}} = 0.1 \) ms. At the end of the TQ stage, the temperature profiles are taken to be uniform over the cross section as well as the impurity distribution, which provides an effective plasma charge of \( Z_{\text{eff}} = 1.7 \).

**Disruption in the T-15MD plasma.** The magnetic configuration of the T-15MD plasma before the thermal disruption is shown in Fig. 2a. The major plasma radius is \( R_0 = 1.48 \) m, the minor plasma radius is \( b = 0.66 \) m, the elongation \( \kappa = 1.8 \), the vacuum toroidal magnetic field at \( R = R_0 \) is \( B_{\text{TO}} = 2 \) T, and the plasma current is \( J = 2 \) MA. The plasma parameters before the disruption were set as follows: the temperature and density profiles were assumed to be parabolic with the values on the magnetic axis \( T_e^{\text{axis}} = T_i^{\text{axis}} = 5 \) keV, \( n_e^{\text{axis}} = 9.65 \times 10^{19} \) m\(^{-3}\) and boundary values \( T_e^{\text{bnd}} = T_i^{\text{bnd}} = 2 \) eV.
$n_{e}^{\text{end}} = 9.55 \times 10^{19} \text{m}^{-3}$. This corresponds to the relative plasma pressure $\beta_p = 0.65$ and internal inductance $l_i (3) = 0.74$.

The TQ time in the T-15MD plasma disruption model is similar to the TQ time in the ITER plasma disruption model $\tau_{\text{TQ}} = 0.1 \text{ ms}$, and the electron and ion temperature level after TQ is assumed to be 14 eV.

**Numerical model.** The calculations of the plasma evolution during the major disruption in the tokamak plasma are executed using the DINA code [15]. The plasma equilibrium at any time is found as a result of solving the axisymmetric 2D Grad–Shafranov equation. The evolution of the toroidal plasma current $J$ is determined by solving the 1D diffusion equation for the poloidal flux [20]

$$\Phi'\Psi' - \Phi\Psi'' = \frac{\mu_0}{\sigma_{||}} (F'J - FJ').$$

(2)

Here $\Phi$ is the toroidal magnetic flux; $\Psi$ is the poloidal magnetic flux; $\Phi'$ and $\Phi''$ are time derivatives of fluxes; $\Psi'$ and $\Psi''$ are derivatives with respect to the radial flow variable $\rho = \sqrt{\Psi_a - \Psi_b} / \sqrt{\Psi_a - \Psi_b}$ ($\Psi_b$ and $\Psi_a$ denote the poloidal flux at the boundary of the plasma and its magnetic axis, respectively); $\sigma_{||}$ is the longitudinal electrical conductivity of the plasma with respect to the magnetic field (the Spitzer formula is used); $\mu_0 = 4\pi \times 10^{-7} \text{ GN/m}$.

A filament model traditionally considered in numerical codes, such as TSC [21], CORSICA [22], and PET [23], is used to calculate toroidal currents in a vacuum chamber in the DINA code. Within such a model, the vacuum chamber is artificially divided into toroidally symmetrical, rectangular-shaped filaments conducting in the toroidal direction. The ITER two-layer vacuum chamber model implemented in the DINA code has 50 filaments in each layer (Fig. 3). Accordingly, the T-15MD single-layer vacuum chamber model has 77 filaments (Fig. 4). The current $I_i (i = 1, ..., N)$ in each filament is determined from the solution to the equation

$$\Psi'_i + \Omega_e I_i = 0.$$ 

(3)

Here, the resistance of the $i$th filament in the toroidal direction is $\Omega_e = 2\pi r_i / (\sigma_{||} S_i)$ under the assumption of a uniform current distribution over the cross section of the element $S_i$ with the center $(r_i, z_i)$. The poloidal flux $\Psi'_i$ on each filament with the inductance $L_i$ can be presented as

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**Fig. 2.** Magnetic configuration of the T-15MD plasma before the start of TQ, time of 0.6 ms (a), and immediately after TQ, time of 0.7 ms (b).
where $M_{ij}$ is the mutual inductance between the $i$th and $j$th filaments, $\Psi^\text{pl}_i$ is the poloidal flux in the $i$th filament from the plasma, and $\Psi^\text{pc}_i$ is the poloidal flux in the $i$th filament from the poloidal coils. Then, instead of Eq. (3), to calculate the toroidal currents in $N$ conductive filaments of the vacuum chamber, it is possible to write the system of contour equations

$$\frac{d}{dt} \left[ L_i I_i + \sum_{j=1}^{N} M_{ij} I_j + \Psi^\text{pl}_i + \Psi^\text{pc}_i \right] + \Omega I_i = 0,$$

where $\Psi^\text{pl}_i$ is not involved owing to the fact that the currents in the poloidal coils do not change during the disruption process.

Points in Figs. 3 and 4 show the centers of the elements, the numbering of which is done in the clockwise direction. It is assumed that $I_i(0) = 0$ as the initial condition for solving the system of Eqs. (5). The total toroidal current induced in the vacuum chamber is defined as $I^\text{tor}_w = \sum_i I_i$, and the electromagnetic force vector from the toroidal current is, respectively,

$$f^\text{tor}_i = j^\text{tor}_i \times B = \frac{I_i}{2\pi r S_i} \nabla (\Psi(r, z_i)).$$

This model is also described in [10].

To calculate the poloidal current in the vacuum chamber $I^\text{pol}_w$, a model is implemented in the DINA code, which is first used to simulate the forces from the generated poloidal current on the vacuum chamber. The model is based on the solution of the contour equation characterizing the balance of the toroidal magnetic flux inside the vacuum chamber:

$$\dot{\Phi}_w + I^\text{pol}_w R_w = 0.$$  

Here $\Phi$ is the flux of the toroidal magnetic field through the area in the poloidal cross section limited by the wall of the chamber; $R_w$ is the resistance of the chamber to the poloidal current; $L_w = \mu_0 \int_0^{s_w} ds$ is the inductance of the chamber in the poloidal direction, where $S_w$ is the poloidal cross section of the chamber. In Eq. (7), the quantity $\Phi_w$ can be written as follows:

$$\Phi_w = \Phi_p + L_w (I^\text{pol}_w - I_{tc}),$$

where $I_{tc}$ is the current in the winding of the toroidal field and $\Phi_p$ is the difference between the toroidal flux inside the plasma volume with the poloidal cross section $S_p$ produced by the poloidal current inside the plasma $F$ and the flux from the sum of the currents in the chamber $I^\text{pol}_w$ and current in the winding of the toroidal magnetic field $I_{TC}$:

$$\Phi_p = \frac{\mu_0}{2\pi S_p} \left\{ \frac{F - (I^\text{pol}_w + I_{tc})}{R} \right\} ds.$$
Here, integration is performed over the poloidal plasma cross section $S_p$. Substituting Eqs. (8) and (9) into Eq. (7) and assuming $dL_w/dt = 0$, we obtain the equation for calculating $I_{w, pol}$, which describes the conservation of the toroidal magnetic flux inside the tokamak chamber:

$$L_w \frac{dI_{w, pol}}{dt} + R_w I_{w, pol} + \frac{d\Phi_p}{dt} + L_w \frac{dI_t}{dt} = 0.$$  \hspace{1cm} (10)

Equation (10) was obtained in [11], in which it was first used to analytically estimate the electromagnetic force in the vacuum chamber due to the induced poloidal current. In [14], Eq. (10) is used to numerically simulate the evolution of electromagnetic loads in the Ignitor tokamak chamber. To solve Eq. (10), we use the initial condition $I_{w, pol}(t_0) = I_{w, pol}^0$. The results of calculations of the evolution of the poloidal current in the tokamak wall were obtained under the assumption $R_w = 0$ and $I_{w, pol}^0 = 0$ and also under the condition $dL_w/dt = 0$. The rationale for the assumption $R_w = 0$ is the need to obtain an estimate of the maximum contribution of the poloidal current generated as a result of TQ to the electromagnetic impact on the conductive elements of the tokamak vacuum chamber. The vector of electromagnetic force from the poloidal current in the $i$th filament of the vacuum chamber is determined accordingly

$$f_{i, pol} = \frac{I_{w, pol}^0}{2\pi r_i} \textbf{e}_{pol} \times \frac{B_{TQ} R_w}{r_i} \textbf{e}_\varphi.$$  \hspace{1cm} (11)

Here $d_i$ is the thickness of the $i$th filament in the radial direction; $\textbf{e}_{pol}$ is the unit vector directed tangentially to the contour of the vacuum chamber; $\textbf{e}_\varphi$ is the unit vector in the toroidal direction.

**CALCULATION RESULTS OF ELECTROMAGNETIC LOAD IN THE ITER AND T-15MD CHAMBER IN THE TQ PROCESS**

Figures 5 and 6 show the evolution of the main parameters of the ITER plasma in the TQ process that begins at the time of 0.6 ms and during the initial stage of CQ.

The plasma shifts in the radial and vertical directions during TQ (see Fig. 6), and then the VDE process begins. As a result of TQ, the plasma shape is slightly deformed (see Figs. 1a, 1b) owing to the increase, first of all, in the plasma elongation.

Figures 7 and 8 show the evolution of the main parameters of the T-15MD plasma during the TQ process, which begins at the time of 0.6 ms. The shape of the T-15MD plasma before TQ and immediately after it is shown in Figs. 2a and 2b.

The thermal energy from the plasma completely disappears during the TQ process as indicated by the rapid drop in $\beta_p$ almost to 0 (see Figs. 5 and 7). First, such a change in the gas kinetic pressure during the TQ process leads to the generation of the toroidal current $I_{w, tor}$ in the vacuum wall, which during the TQ time reaches ~200 kA for the case of ITER (see Fig. 5) and, accordingly, ~80 kA for the case of T-15MD (see Fig. 7).

Secondly, the decrease in $\beta_p$ leads to the increase in the paramagnetic properties of the plasma, which is characterized by the increase in the toroidal magnetic flux $\Phi_p$ inside it. It can be seen in Fig. 9a that TQ in the ITER plasma leads to the increase in the toroidal magnetic flux $\Phi_p$ inside the plasma by ~1.3 Wb. This governs the generation of the poloidal current $I_{w, pol}$ at the level of ~1.2 MA in the vacuum chamber (see Fig. 5). This current is comparable with the estimated wall poloidal current of ~1 MA in the plasma of the Ignitor.
This work presents a comparative analysis of the electromagnetic impact on the vacuum chamber of the ITER and T-15MD tokamaks during the TQ process due to only toroidal currents induced in the chamber (these results for the case of ITER are given in [10]) and their sum with the poloidal currents induced in the chamber.

Figure 10 shows the evolution of the radial and vertical components of the integral electromagnetic load in the vacuum chamber during the initial phase of the development of the major disruption in the ITER plasma, and Fig. 11 shows the radial and vertical components of the electromagnetic load in the T-15MD vacuum chamber. The integral electromagnetic loads in the vacuum chamber are determined in accordance with Eq. (1). Electromagnetic loads on each conductive element of the vacuum chamber are determined using Eqs. (6) and (11).

First of all, it is seen that, both in the case of ITER and in the case of T-15MD, the radial component of the integral electromagnetic force is dominant. In addition, the results of the calculation of the electromagnetic loads from the toroidal and poloidal currents induced in the ITER and T-15MD vacuum chamber show that, firstly, the poloidal current affects the radial component of the electromagnetic force after TQ in the direction of its decrease and, secondly, this effect depends on the level of the toroidal magnetic flux in the vacuum wall at the level of \( \sim 90 \, \text{kA} \) (see Fig. 7).

Tokamak [14]. Correspondingly, TQ in the T-15MD plasma leads to the increase in the toroidal magnetic flux in it by \( \sim 0.05 \, \text{Wb} \) (Fig. 9b) and the generation of the poloidal current in the vacuum wall at the level of \( \sim 90 \, \text{kA} \) (see Fig. 7).
field in the tokamak. The same as, e.g., in the case of the ITER tokamak ($B_{T0} = 5.3$ T), the integral radial component of the electromagnetic force decreases by more than 10 times after TQ: from 70 MN (from the toroidal current) to ~6 MN (from the sum of the toroidal and poloidal currents). In the case of the T-15MD tokamak ($B_{T0} = 2$ T), the effect of the poloidal current on electromagnetic forces as a result of TQ is correspondingly lower. It is seen from the consideration of Figs. 11a and 11b that the decrease in the integral radial component of the electromagnetic force after TQ in the case of T-15MD is ~3 times, i.e., from 1.2 MN from the toroidal current to ~0.4 MN from the sum of the toroidal and poloidal currents. The conclusion about the noticeable effect of the poloidal current induced in the vacuum wall during the TQ process is completely consistent with the results of other studies [11–14]. For example, in [11, 13] it was analytically obtained that taking into account the poloidal current induced in the TQ process in the vacuum tokamak chamber with a round plasma and a large aspect ratio reduces the integral electromagnetic radial force by 2 times compared with the force only from the induced toroidal current. Similar results of comparing the total radial force and the force only from the toroidal current were obtained in [14], in which 3D simulation of the distribution of electromagnetic forces in the vacuum chamber elements of the Ignitor tokamak after the thermal disruption was performed. Moreover, the integral vertical force on the
vacuum chamber from the induced toroidal and poloidal currents is very small (below 0.05 MN).

Figures 12a and 12b show the poloidal distributions of the toroidal current induced in the vacuum chambers of ITER and T-15MD, respectively, immediately after TQ and during the initial phase of CQ. For the ITER vacuum chamber, the distributions are shown for both the inner \((i \leq 50)\) and the outer layers \((51 \leq i \leq 100)\). The index \(i\) determines the number of the conductive filament according to Fig. 3. Accordingly, the index is \(1 \leq i \leq 77\) for the T-15MD vacuum chamber.

Figure 13 shows the evolution of the poloidal distributions of the components of the electromagnetic force calculated using Eqs. (6) and (11) for 2 ms after TQ in the ITER vacuum chamber both from the toroidal current and from the sum of the toroidal and poloidal currents. Figure 14 shows the evolution of such forces in the T-15MD vacuum chamber for 0.6 ms after TQ.

Because of the short duration of the considered time interval after TQ, the poloidal and toroidal magnetic fluxes do not have time to penetrate through the inner layer of the ITER vacuum chamber. Therefore, the toroidal current in the elements of the outer layer of the vacuum chamber is negligible in comparison with the current in the elements of the inner layer of the chamber (see Fig. 12), and the electromagnetic forces from the toroidal current in the elements of the outer layer of the ITER vacuum chamber are also small (see Fig. 13). It is assumed that the induced poloidal current immediately after TQ also flows only through the inner layer of the ITER vacuum chamber.

The poloidal distribution of the electromagnetic force has a cosine shape, in which the upper \((10 \leq i \leq 16)\)
Fig. 12. Poloidal distribution of the toroidal current induced in the ITER vacuum chamber: (—) 0.7; (—) 1.7; (——) 2.6 ms (figures from [10]) (a) and in the T-15MD vacuum chamber: (—) 0.8; (—) 1.1; (——) 1.4 ms (b).

Fig. 13. Poloidal distribution of radial forces on the elements of the ITER vacuum chamber from the toroidal current (a) and the poloidal distribution of the vertical forces on the elements of the ITER vacuum chamber from the toroidal and poloidal currents (b) at various times for 2 ms after TQ: (—) 0.7; (—) 1.7; (——) 2.6 ms.

Fig. 14. Poloidal distribution of the radial forces on the elements of the T-15MD vacuum chamber from the toroidal current (a) and the poloidal distribution of the vertical forces on the elements of the T-15MD vacuum chamber from the toroidal and poloidal currents (b) at different times for 0.6 ms after TQ: (—) 0.8; (—) 1.1; (——) 1.4 ms.
and lower ($36 \leq i \leq 42$) parts of the ITER vacuum chamber experience the least electromagnetic impact from the toroidal currents (see Fig. 12), since these parts are the most distant from the center of the plasma and the smallest currents are induced in them (see Fig. 13). A similar phenomenon is observed with respect to the poloidal distribution of electromagnetic impact from the toroidal currents on the elements of the T-15MD tokamak vacuum chamber (see Fig. 14): the elements $30 \leq i \leq 36$ and $62 \leq i \leq 71$ experience the least electromagnetic influence from the toroidal currents. The maximum effect of the radial force $F_r$ is observed at the outer part of the vacuum chamber of both tokamaks. The vertical force $F_z$ is also maximal at the outer part of the chamber, but its magnitude is much lower.

Figures 15 and 16 show the evolution of the distribution of electromagnetic forces after TQ and during the initial stage of CQ on the wall of the vacuum chamber of, respectively, the ITER and T-15MD tokamaks from the toroidal current (see Figs. 15a and 16a) and from the sum of toroidal and poloidal currents (see Figs. 15b and 16b). The forces are determined using Eqs. (6) and (11). It is seen that the vector of the electromagnetic load taking into account the poloidal current $I_{w}^{\text{tor}}$ becomes directed mainly into the chamber at each point of the poloidal bypass of the chamber.

CONCLUSIONS

Using the plasma-physics DINA code, a numerical analysis of the influence of the poloidal current induced in the tokamak vacuum chamber owing to a change in the paramagnetic properties of the plasma as a result of thermal disruption on the magnitude and
distribution of electromagnetic forces in the vacuum chamber of the ITER and T-15MD tokamaks has been performed. The comparison of the electromagnetic impact on the vacuum chamber of the toroidal current induced in it with the variant of the impact of the sum of the induced toroidal and poloidal currents shows a significant effect of the latter on the dominant radial component of the electromagnetic force. In this case, the effect increases with the growth of the toroidal magnetic field in the tokamak. It was found that, when considering the disruption in the ITER plasma in the scenario with a plasma current of 15 MA \( (B_{T0} = 5.3 \text{ T}) \), the radial component of the integral electromagnetic force after the thermal disruption decreases by more than 10 times if the poloidal current induced in the vacuum chamber is taken into account. In this case, the vector of the electromagnetic load becomes directed into the chamber at each point of the poloidal bypass. In the case of the T-15MD tokamak \( (B_{T0} = 2 \text{ T}) \), the decrease in the electromagnetic load taking into account the poloidal current induced as a result of the thermal disruption is lower by a factor of \(~3\). This is explained by the lower toroidal magnetic field in the T-15MD tokamak compared to that in the ITER tokamak. The obtained results confirm the conclusions of earlier works [11–14] about the role of the poloidal current in the magnitude of the electromagnetic load on the vacuum wall, but significantly differ quantitatively from them. According to the results of our work, the radial force on the vacuum chamber when taking into account the poloidal current in it decreases by 10 times, while according to the results of [12] this decrease is much lower, by 2 times.

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CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest.

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