Rotating Wall, the Error-Field Induced Torque and the Problem of the Error Field Shielding in Tokamaks

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Abstract. The electromagnetic torque on the toroidal plasma is calculated analytically. The derivations basically follow the line described in [Pustovitov V.D., Nucl. Fusion **47** (2007) 1583]. The main difference is that the torque is calculated now with account of the resistive wall rotation. The model assumes a thin stationary rotating wall and adopts the cylindrical geometry. The obtained formulas are used for analysis of the error field shielding by a liquid metal wall in tokamaks predicted in a similar model [Zheng L.-J., Kotschenreuther M., Nucl. Fusion **46** (2006) L9] with a conclusion there that a flowing liquid metal wall can prevent resonance amplification of the error field by the plasma near its no-wall stability limit. Our theory does not support this concept. Instead, it gives the expressions for the torque without singularities near the no-wall stability limit, with or without the wall rotation. The reason of the differences is explained, the consequences are discussed and the new predictions are compared with available experimental data. Also the experiments are proposed to model the addressed issues on the existing tokamaks with conventional non-rotating walls.

1. Introduction

The magnetic error field may strongly affect the plasma stability in tokamaks [1]. In the past decade, its important role in destabilizing the resistive wall modes (RWMs) have been discovered and extensively studied in DIII-D experiments [2–6]. It was found that small static asymmetries in the magnetic field can resonantly excite stable RWMs as the plasma approaches marginal stability, leading to enhanced drag on the rotating plasma [2–6]. This resonant response was called ‘error field amplification’ or resonant field amplification (RFA). The discovery of RFA made a breakthrough in the RWM stabilisation. With compensation of the residual non-axisymmetric fields, the duration of the high-pressure discharge was extended to hundreds of times the wall skin time.

In the RWM stability discussions, reduction of the error field level is always mentioned as the crucial precondition [1–8]. The experiments in JET [7] as well as DIII-D have indicated that $m/n = 2/1$ error fields must be kept below $B_{2/1}/B_t = 1-2\times10^{-4}$ in order to avoid strong braking of the rotation when beta is above the no-wall limit [6]. This makes elimination of the error field a difficult task, especially for larger tokamaks (ITER, in particular) where stronger restrictions may apply [1, 6]. Under the circumstances, any idea to ease the requirements on the error field tolerance should be considered with particular attention.

Recently a theory appeared [9, 10] with an extremely promising conclusion that the resonance amplification of the error field in tokamaks can be prevented. The effect was attributed to the metal wall rotating in the poloidal direction and was called shielding of the error field by a liquid metal wall [9, 10]. The conclusion arose from the analysis and comparison of the new expressions [9–11] for the error-field induced torque on the plasma, with and without the wall rotation. It was announced, first, for the case of conventional nonrotating wall, that the static-error-field induced torque has a strong maximum at the no-wall stability limit [9–11]. Second, that the wall rotation eliminates the maximum, which can even be transformed to a minimum, providing thereby dramatic reduction of the error field effects [9, 10].

In both cases the analysis was essentially based on the interpretation of the formulas for the torque expressed through some δW_∞ and δW_b. At the beginning, these quantities were just described as “the energy integrals without a wall and with a perfectly conducting and non-rotating wall” [9], without strict definitions. Later the authors explained that “Their definitions are the same as those introduced in Ref. [1] in the cylinder limit,” which is the comment to Equation (10) in Ref. [11]. The mentioned “Ref. [1]” is the well-known textbook [12] by Freidberg, where δW_∞ and δW_b are given by equations (9.78) and (9.79). For our discussion here the most important is that these equations give real δW_∞ and δW_b. Then the torque found in [9–11] for the conventional wall, instead of being some varying function of the plasma parameters, is identically zero, see equations (20) and (22) in [11], equation (21) in [9], and equations (4) and (6) in [10].

The latter problems have already been discussed in [13]. In [13], the electromagnetic torque on the toroidal plasma was derived in other physical variables. This was done for the “conventional” case with a nonrotating wall, and the result was compared with that of [9–11]. It was shown, in particular, that the conclusions on the torque strong peaking at the no-wall stability limit [9–11] were unjustified because of the wrong identification of δW_∞ and δW_b introduced there as just symbols replacing other unknowns. This must certainly affect the conclusions [9, 10] for the other case, with a liquid wall. To clarify the latter issue, here we perform a study similar to [13], but now assume that the wall may rotate.

2. The model and definitions

We consider the problem using the model and results described earlier for the standard case with a nonrotating wall [13]. Briefly, we assume a cylindrical model with plasma of radius r_{pl} surrounded by the symmetric resistive wall at $r = r_w$, treated as a magnetically thin shell S_w. The approach is based on the Maxwell equations

$$\operatorname{rot}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \operatorname{div}\mathbf{B} = 0, \quad \operatorname{rot}\mathbf{B} = \mu_0 \mathbf{j}, \tag{1}$$

and Ohm’s law for the wall, which is, for the case of interest,

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V}\times\mathbf{B}). \tag{2}$$

Here $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields, respectively, $\mu_0 = 4\pi\cdot 10^{-7}$ H/m is the vacuum permeability, $\mathbf{j}$ is the current density in the rotating wall, σ is its conductivity (in vacuum $\sigma = 0$), and $\mathbf{V}$ is the wall rotation velocity, which is the only new element here compared to the analysis with $\mathbf{V} = 0$ in [13]. We will apply these equations to the region outside the plasma with natural boundary conditions at the interfaces and at the infinity. The plasma enters the problem through the boundary conditions at the plasma surface S_{pl}.

The magnetic field can be described as

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{b}, \tag{3}$$

where $\mathbf{B}_0$ is the equilibrium magnetic field and $\mathbf{b}$ the perturbation. Equations (1)–(2) then yield

$$\frac{\partial \mathbf{b}}{\partial t} - \operatorname{rot}(\mathbf{V}\times\mathbf{b}) = \nabla^2 \frac{\mathbf{b}}{\mu_0\sigma}. \tag{4}$$

This equation has been used to study the wall rotation effect on RWM, see [14] and references therein. Here we consider the uniform wall rotation in both the poloidal and toroidal directions and $\sigma = \text{const}$. In [9, 10], for simplicity, the liquid metal velocity was assumed to be purely in the poloidal direction. Also, $\partial \mathbf{b}/\partial t$ was disregarded there, while here it will play a role.

We have to calculate the toroidal electromagnetic torque exerted on the plasma, which is

$$T \equiv \int R\mathbf{e}_\zeta \cdot (\mathbf{j} \times \mathbf{B}) dV , \tag{5}$$

where R is the radial coordinate, $\mathbf{e}_\zeta$ is the unit vector along $\nabla\zeta$ with ζ the toroidal angle, and integration is performed over the plasma, but can be extended to larger volume because a vacuum region with $\mathbf{j} = 0$ does not contribute to T. With $\mu_0 \mathbf{j} = \text{rot}\,\mathbf{B}$ this can be reduced to the integral over the axisymmetric surface S_{as} in the vacuum:

$$T = \frac{1}{\mu_0} \int_{S_{as}} RB_\zeta \mathbf{B} \cdot d\mathbf{S} = \frac{1}{\mu_0} \int_{S_{as}} Rb_\zeta \mathbf{b} \cdot d\mathbf{S} . \tag{6}$$

This is a general result with $\mathbf{b} = \nabla\varphi$ in the vacuum. Dependence of T on the plasma and wall properties comes when the equation $\nabla^2 \varphi = 0$ is solved with proper boundary conditions at S_{pl} and S_w. In our case the conditions at the wall are specified by equation (4).

3. Mode equation in the cylindrical approximation

In the cylindrical model with

$$\mathbf{V} = V_\theta \mathbf{e}_\theta + V_z \mathbf{e}_z \tag{7}$$

and $\text{div}\mathbf{V} = 0$ equation (4) gives for the radial component of $\mathbf{b}$ in the wall:

$$\frac{\partial b_r}{\partial t} + \mathbf{V} \cdot \nabla b_r = \mathbf{e}_r \cdot \nabla^2 \frac{\mathbf{b}}{\mu_0 \sigma} . \tag{8}$$

Here we use the cylindrical coordinates $r, \theta, z = R_0 \zeta$ (ζ stays for the toroidal angle, and $2\pi R_0$ for the length of the system).

In terms of harmonics $b_r = \sum b_{mn}(r,t) \exp(im\theta - in\zeta)$ equation (8) is reduced, in the thin wall approximation, to

$$\tau_w \left(\partial B_{mn} / \partial t + i\mathbf{k} \cdot \mathbf{V} B_{mn} \right) = \Gamma_m^0 B_{mn}^{wall} . \tag{9}$$

Here $B_{mn} = b_{mn}(r_w)$, r_w is the minor radius of the wall, B_{mn}^{wall} is the part of B_{mn} produced by the currents in the wall, $\tau_w = \mu_0 \sigma r_w d$ is the 'wall time' with d being the thickness of the wall, Γ_m^0 is a constant approximated for the low-m modes by $\Gamma_m^0 \approx -2M$ with $M = |m|$, and $\mathbf{k} \equiv \nabla(m\theta - n\zeta)$. Finally, equation (9) can be cast in the compact form

$$\tau_w \frac{\partial B_{mn}}{\partial t} = G_m B_{mn} - \Gamma_m^0 B_{mn}^{ext} , \tag{10}$$

where

$$G_m \equiv \Gamma_m - i\mathbf{k} \cdot \mathbf{V} \tau_w = \tau_w \left(\gamma_0 + in\Omega_{Ds} \right) \tag{11}$$

and

$$\Omega_{Ds} \equiv \Omega_0 - \mathbf{k} \cdot \mathbf{V} / n . \tag{12}$$

Here the plasma response to the external perturbation is described by the ratio $B_{mn}^{out} / B_{mn} = \Gamma_m / \Gamma_m^0$ with $\Gamma_m = \tau_w \left(\gamma_0 + in\Omega_0 \right)$ a complex quantity (with real γ_0 and Ω_0)

depending on the equilibrium plasma parameters. Here $B_{mn}^{out} = B_{mn} - B_{mn}^{pl}$ is the part of B_{mn} due to the currents outside the plasma, which includes the contributions from the wall and all the currents behind the wall: $B_{mn}^{out} = B_{mn}^{wall} + B_{mn}^{ext}$. Accordingly, B_{mn}^{pl} is the contribution from the plasma. The error field is a part of B_{mn}^{ext}, and the other part can be due to the currents in the active correction coils. Here we assume no currents in the plasma-wall vacuum gap.

The model with $\mathbf{V} = 0$ and its applications for the linear plasma response are described in [15–17]. The linear perturbation theory, the same geometry and the thin wall approximation was also used in [9–11]. Therefore, our approach is quite adequate, though the derivations here and in [9–11] are essentially different.

The plasma affects the mode equation (10) through Γ_m, the part of G_m in (11), which is directly related to rb'_{mn}/b_{mn} at the outer side of the plasma surface S_{pl}. Precisely, this follows from

$$\frac{rb'_{mn}}{b_{mn}} = -(M+1) - \frac{2M\Gamma_m x^{2M}}{2M + \Gamma_m(1-x^{2M})} \tag{13}$$

for the plasma-wall vacuum gap, where the prime means the radial derivative, and $x = r/r_w$. If there is no surface current at S_{pl}, which should be the case for slow motions of real plasma, the quantity on the left hand side of (13) must be the same at the both sides of S_{pl}. This couples the constant Γ_m to the inner solution for $\mathbf{b}$. For more detail see [15–17].

Thus, within the model, the perturbation amplitude B_{mn} is described by (10) where the wall rotation enters through the coefficient G_m only, while γ_0 and Ω_0 are the unknown characteristics of the plasma. We need (10) to relate B_{mn} to the error field amplitude when $\mathbf{V} \neq 0$, which is a step to calculating the error-field induced electromagnetic torque on the plasma. In further estimates we assume Γ_m independent of $\mathbf{V}$, B_{mn} and B_{mn}^{ext}, which is a natural requirement in the linear plasma response model with rb'_{mn}/b_{mn} inside the plasma determined by the plasma parameters only.

4. The electromagnetic torque

In the cylindrical approximation, expression (6) is reduced to [13]

$$T = \sum_{m\geq 0, n>0} T_{mn} \tag{14}$$

with

$$T_{mn} = -4i\frac{n}{M}V_w \frac{B_{mn}^{*}B_{mn}^{out} - c.c.}{\mu_0}, \tag{15}$$

where $V_w = 2\pi^2 R_0 r_w^2$ is the volume enclosed by the toroidal wall, both the star and *c.c.* denote the complex conjugate. These formulas were derived in [13] without restrictions on the time dependence and nature of the magnetic perturbation produced by the currents that flow outside the plasma. Therefore we can apply them for the tokamak with a rotating wall.

With $B_{mn}^{out}/B_{mn} = \Gamma_m/\Gamma_m^0$ and $\Gamma_m = \tau_w(\gamma_0 + in\Omega_0)$ equation (15) will give us

$$T_{mn} = 8\frac{n}{M}V_w\Gamma_m^0\frac{\left|B_{mn}^{out}\right|^2}{\mu_0}\frac{n\Omega_0}{\tau_w(\gamma_0^2+n^2\Omega_0^2)} \tag{16}$$

or, in terms of B_{mn},

$$T_{mn} = 8\frac{n}{M}V_w\frac{\left|B_{mn}\right|^2}{\mu_0}\frac{n\Omega_0\tau_w}{\Gamma_m^0}\,. \tag{17}$$

Here the wall rotation affects the amplitudes B_{mn}^{out} and B_{mn}, while other quantities do not depend on the wall rotation velocity $\mathbf{V}$.

In [9–11] the torque was calculated for the stationary state with $\partial B_{mn}/\partial t = 0$. Then for the nonrotating wall we have $B_m^{wall} = 0$, and (16) becomes the torque due to the static error field with B_{mn}^{out} representing the amplitude of this field. However, with a rotating wall, the steady state values B_{mn}^{out} and B_{mn} contain a contribution from the wall, $B_m^{wall} \neq 0$ given by (9). In this case equation (10) yields, when $\partial B_{mn}/\partial t = 0$,

$$B_{mn}/B_{mn}^{ext} = \Gamma_m^0/G_m\,, \tag{18}$$

and the torque expression (17) is reduced to

$$T_{mn} = 8\frac{n}{M}V_w\Gamma_m^0\frac{\left|B_{mn}^{ext}\right|^2}{\mu_0}\frac{n\Omega_0}{\tau_w(\gamma_0^2+n^2\Omega_{Ds}^2)}\,, \tag{19}$$

where Ω_{Ds} is defined by (12). The final formula gives us the torque due to the static error field, calculated for the state with $\partial B_{mn}/\partial t = 0$. This is the same quantity that was discussed in [9] and [10], though expressed in other physical variables. The latter circumstance greatly facilitates interpretation of the result since all the symbols here are defined and have clear meaning.

5. Discussion

The wall rotation affects the torque (19) through Ω_{Ds} only. For fixed B_{mn}^{ext}, γ_0 and Ω_0, which means comparison at similar conditions with only $\mathbf{V}$ varying, the ratio of the torques (19) with and without the wall rotation is

$$\frac{with}{without} = \frac{\gamma_0^2+n^2\Omega_0^2}{\gamma_0^2+(n\Omega_0-\mathbf{k}\cdot\mathbf{V})^2}\,. \tag{20}$$

To make this ratio small, one needs the wall rotation much faster than the natural rotation of the mode at $\mathbf{V}=0$, $|\mathbf{k}\cdot\mathbf{V}| >> |n\Omega_0|$, and in addition $|\mathbf{k}\cdot\mathbf{V}| >> |\gamma_0|$. These conditions could not be obtained in [9, 10] where the torque was expressed through some δW_∞ and δW_b without their physical or mathematical identification.

Though equations (19) and (20) allow the torque reduction due to the proper rotation of the wall, they do not support the main conclusion of [9] that the flowing liquid metal wall can prevent resonance amplification of the error field by the plasma near its no-wall stability limit. First, there is no resonance in (19) near the no-wall limit, since the latter must correspond to some negative γ_0 here, if we consider typical rotationally stabilized discharges in DIII-D [2–6] with the stability boundary ($\gamma_0 = 0$) essentially above the no-wall limit.

Meanwhile, the "no-wall resonance" in [9–11] was attributed to vanishing denominator in the expression similar to (19) (which could be equivalent to formal $\Gamma_m \to 0$). In more detail this was discussed earlier in [13]. Second, the ratio (20) shows that the wall rotation can work in both ways, decreasing or increasing the torque, which was not noticed in [9, 10].

It follows from (20) that, contrary to the dramatic reduction declared in [9, 10], the wall rotation can also provide an increase of the torque when

$$(n\Omega_0 - \mathbf{k}\cdot\mathbf{V})^2 < n^2\Omega_0^2 . \tag{21}$$

This increase can be quite large with $\mathbf{k}\cdot\mathbf{V} = n\Omega_0$ at $n^2\Omega_0^2 >> \gamma_0^2$. Mathematically, this has the same origin as the peak discovered for $\mathbf{V} = 0$ in [9–11] and discussed in [13]: it comes from asymptotic behavior of (19) like $1/x$ at $x \to 0$. However, within the model, any singularity must be treated with care. Unlimited increase of the torque (19) simply indicates that the steady-state assumption $\partial B_{mn}/\partial t = 0$ is not longer valid.

Discussion of (20) will be incomplete without this reminder: equation (19) was obtained for a steady state with $\partial B_{mn}/\partial t = 0$. The preceding equation (17), valid for arbitrary $B_{mn}(t)$, shows that the torque peaking, which is a fundamental result of the new theory [9–11], is only possible with a strong growth of $\Omega_0 |B_{mn}|^2$. The statement that "the reduced rotation further enhances the strength of the braking torque" [9], where the "reduced rotation" implies smaller Ω_0, would then require, for the peaking discovered in [9–11], a singular-like growth of $|B_{mn}|^2$ at some intermediate β below the RWM stability limit β^{RWM} when $\mathbf{V} = 0$. And "shielding of the error field by a liquid metal wall" [9] means complete elimination of this peak at finite $\mathbf{V}$.

However, the experiments on DIII-D, including [2] and [3] mentioned in [9–11] and other [4–6] with more information on the RFA effect, have never shown the peaking of $|B_{mn}|$ at some $\beta < \beta^{RWM}$, when plasma is stable, with subsequent theoretically predicted [9–11] drop of $|B_{mn}|$ at larger β. The same is true for RFA experiments in JET [7] and NSTX [8]. In other words, when β crosses the no-wall limit $\beta^{no-wall}$, $\Omega_0 |B_{mn}|^2$ remains a regular quantity, without sharp peaking at $\beta = \beta^{no-wall}$ and strong reduction behind this point.

6. Experimental application and testing

The DIII-D is a tokamak with a conventional wall, but some results from DIII-D can be a perfect illustration of the effects related to the liquid rotating wall.

To extend the narrow limits of the original problem, we should wonder what physics is involved here. In the combination "rotating wall + static error field" the essential element is the relative motion of the metal wall and the magnetic field. But this can also be realized if we apply a rotating magnetic field while keeping the metal in natural rest.

Assume that the correction coils produce the rotating (m,n) perturbation with

$$\delta B_{mn}^{ext} = b_{mn}^{os} \exp(P_m \tau) , \tag{22}$$

where $\tau \equiv t/\tau_w$, $P_m = in\omega\tau_w$, and ω is the toroidal rotation frequency of the applied field. If such a field is switched on at $t=0$, equation (10) with constant G_m gives for $t>0$:

$$\delta B_{mn} = B_{mn}^0 \exp(G_m\tau) - \Gamma_m^0 b_{mn}^{os} \frac{\exp(G_m\tau) - \exp(P_m\tau)}{G_m - P_m}, \tag{23}$$

where δB_{mn} is the time-varying part of B_{mn}, and B_{mn}^0 is the integration constant. For a stable plasma with $\gamma_0 < 0$, after a transient phase ($|\gamma_0|t >> 1$) this will evolve to

$$\delta B_{mn} = A_{os} b_{mn}^{os} \exp(in\omega t), \tag{24}$$

where A_{os} describes the 'amplification' of the oscillating external perturbation δB_m^{ext}:

$$A_{os} = \frac{\Gamma_m^0}{G_m - in\omega\tau_w}. \tag{25}$$

Then in the steady state described by (24), we have from (17)

$$T_{mn} = 8\frac{n}{M} V_w \Gamma_m^0 \frac{|b_{mn}^{os}|^2}{\mu_0} \frac{n\Omega_0}{\tau_w[\gamma_0^2 + n^2(\Omega_0 - \mathbf{k}\cdot\mathbf{V}/n - \omega)^2]}. \tag{26}$$

This expression incorporates both the wall rotation and the rotation of the applied magnetic perturbation. It shows that they produce exactly the same effects, which allows to use the available experimental data for analysis of the anticipated RFA with the wall rotation.

The amplification of the resonant rotating perturbation was studied on the tokamaks DIII-D [4, 5] and NSTX [8]. The linear plasma response to the applied perturbation and the transition to (24) were observed, and the amplitude and phase of δB_{mn} have been measured. The experimental results in Figure 10 in [4], Figure 6 in [5] and Figure 2 in [8] demonstrate a typical resonant curve that corresponds to [16]

$$|A_{os}| = \frac{|\Gamma_m^0|}{\tau_w\sqrt{\gamma_0^2 + n^2(\Omega_0 - \omega)^2}}, \tag{27}$$

which is a consequence of (25) at $\mathbf{V}=0$. Equations (25) and (26) show that the same dependence must be expected from the wall rotation. The singular-like peak described in [9–11] and similar infinite RFA predicted earlier [18] are, mathematically, reproduced in (27) as an asymptotic at $\omega = \Omega_0$ and $\gamma_0 \to 0$. With such γ_0, however, we step much behind the applicability limits of (24) and (27). Instead we should use the solutions (17) and (23).

7. Conclusions

The conclusion [10] that "the presence of a liquid metal wall causes a dramatic difference" by producing the "shielding of the error field" [9, 10] is not confirmed by our analysis. There is a difference, but not such dramatic as elimination of the resonances, strongly emphasized in [9, 10]. Within the model, there is a natural Doppler shift effect which may either decrease or increase the RFA, depending on the wall rotation velocity $\mathbf{V}$. However, for a plasma stable against the RWMs the model does not allow severe peaking of the torque such as shown in Fig. 1 in [9] and Figs. 1 and 2 in [10], even if the most pessimistic estimate (19) will be used. With or without the wall rotation, for stable or unstable plasmas, the electromagnetic torque on the plasma is proportional to $\Omega_0|B_{mn}|^2$, as described by (17). In the RFA experiments [2–8] this quantity behaves regularly, without singularities. This also points against [9, 10].

The derived equations show that the rotating wall effect on RFA can be modeled and experimentally studied in the existing tokamaks with a conventional solid nonrotating wall. This can be done by applying the rotating perturbations using the technique developed on the tokamaks DIII-D [4, 5] and NSTX [8]. Actually, the information already obtained in the RFA experiments [4, 5, 8] can be used for testing the results and conclusions presented here and in [13]. Qualitative agreement seems evident, and, if necessary, more detailed description can be done by using the full toroidal equations [17] for RFA.

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