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Disruption-induced poloidal currents in the tokamak wall

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HIGHLIGHTS

- Induction effects during disruptions and rapid transient events in tokamaks.
- Plasma-wall electromagnetic interaction.
- Flux-conserving evolution of plasma equilibrium.
- Poloidal current induced in the vacuum vessel wall in a tokamak.
- Complete analytical derivations and estimates.

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ABSTRACT

The poloidal current induced in the tokamak wall during fast transient events is analytically evaluated. The analysis is based on the electromagnetic relations coupled with plasma equilibrium equations. The derived formulas describe the consequences of both thermal and current quenches. In the final form, they give explicit dependence of the wall current on the plasma pressure and current. A comparison with numerical results of Villone et al. [F. Villone, G. Ramogida, G. Rubinacci, Fusion Eng. Des. 93, 57 (2015)] for IGNITOR is performed. Our analysis confirms the importance of the effects described there. The estimates show that the disruption-induced poloidal currents in the wall should be necessarily taken into account in the studies of disruptions and disruption mitigation in ITER.

1. Introduction

In tokamaks, strong currents are induced in the conducting structures when the plasma discharge disrupts. This results in huge pulsed forces on the vacuum vessel (simply called 'wall'), as observed in JET [1,2]. The level of the related dangers increases for future devices with larger thermal and magnetic energies that can be released during disruptions. This turns into a challenging problem for ITER and, consequently, is receiving attention in fusion research [1–13].

Calculation of the disruption-induced electrodynamic loads ultimately reduces to integration of $\mathbf{j}_w \times \mathbf{B}$, where $\mathbf{j}_w$ is the current density in the wall and $\mathbf{B}$ is the magnetic field. Evaluation of $\mathbf{j}_w$ is always based on various simplifying assumptions because of the complex disruption dynamics. This is an unavoidable reason of significant scatter and uncertainties in the predictions. In addition, the wall itself is also described in a simplified way. For example, in several famous codes used in the disruption studies, the wall is replaced by a set of axisymmetric toroidal filaments, see Refs. [8,13–21] and references therein. Then only toroidal $\mathbf{j}_w$ is allowed, while the poloidal current in the wall is technically forbidden.

Being in practical use for dozens of years, the filament representation of the wall became a customary part of the disruption modelling. It has rather historical than physical roots and seems to be a repairable element, but whether we need an improvement is so far unclear.

The role of the disruption-induced poloidal current in the wall has been recently discussed in Ref. [14], where the DINA and TSC codes have been compared and benchmarked for ITER disruption modelling, and later in the paper [8] devoted to the electromagnetic disruption analysis in IGNITOR with codes MAXFEA and CarMa0NL. In Ref. [14], it was stated that the effect of poloidal eddy current is negligibly small in usual cases (which means without halo cur-

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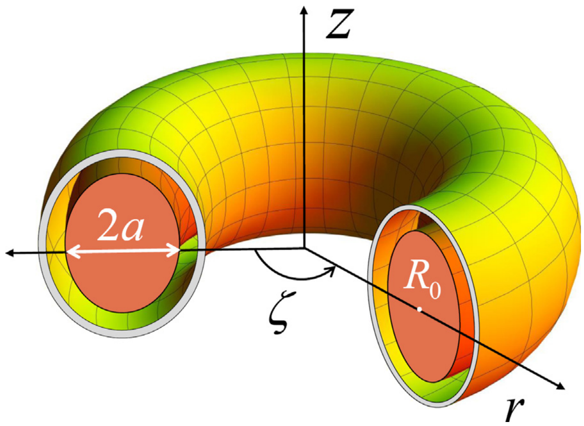

Fig. 1. Geometry of the task and the notation. The plasma of minor radius a and major radius R_0 is separated from the resistive wall by a vacuum gap. (r, ζ, z) are the cylindrical coordinates related to the main symmetry axis of the torus.

rents), compared with toroidal eddy current. In Ref. [8], on the contrary, it was numerically demonstrated that the force density distribution on the wall is appreciably different when the poloidal current is taken into account.

In the latter study, the maximum total poloidal current was found to be of the order of 1 MA on the whole torus (IGNITOR). The fact of generation of such disruption-induced current has been analytically confirmed in Ref. [22] with estimates that produced twice larger value about 2 MA under the conditions specified in Ref. [8]. The strength of the effect in Refs. [8,22] and its authorized neglect in Ref. [14], the qualitative agreement and quantitative discrepancy between Refs. [8] and [22], the importance of the reduction of the disruption forces in ITER [2,10,23–25], all these aspects urge a deeper study of the problem.

This paper is devoted to evaluation of the net poloidal current I_w induced in the tokamak wall during fast transient events. To be specific and indicate the applicability areas and dominant drivers, we can refer to thermal and current quenches, TQ and CQ, that represent two main constituents of the disruptions and the disruption mitigation events. As in Refs. [8,13,14], it is assumed that the evolving plasma remains axially symmetric. First, we derive a general electromagnetic equation for I_w. It somewhat differs from similar equation (2.11) given in Ref. [8] without derivations, which justifies this introductory step in our analysis. Then the flux-conserving evolution of the plasma is considered and the analytical relations for I_w within the large-aspect-ratio tokamak model are presented. These give explicit dependence of I_w on the plasma pressure and current and allow easy estimates that are compared with numerical results of Ref. [8]. Finally, the coupling of the equation for I_w with plasma equilibrium task in a general case is discussed.

2. Formulation of the problem

The standard tokamak configuration is considered here: the toroidal plasma separated from the vacuum vessel (simply called wall) by the vacuum gap, as shown in Fig. 1. This system is assumed axisymmetric. Our interest is the wall reaction on the plasma transition between two states with essentially different pressure and/or current.

In an axially symmetric toroidal configuration, the magnetic field $\mathbf{B}$ subject to $\nabla\cdot\mathbf{B}=0$ can be prescribed by

$$2\pi\mathbf{B} = \nabla\psi\times\nabla\zeta + \mu_0 I\nabla\zeta \tag{1}$$

with $\mu_0=4\pi\times10^{-7}$ H/m the vacuum magnetic permeability (SI units are used here). Accordingly, from the Ampere's law

$$\mu_0\mathbf{j} = \nabla\times\mathbf{B} \tag{2}$$

we have for the current density $\mathbf{j}$:

$$2\pi\boldsymbol{j} = \nabla I\times\nabla\zeta - r^2\nabla\zeta\,\mathrm{div}\frac{\nabla\psi}{\mu_0 r^2}. \tag{3}$$

These definitions imply that I is the poloidal current through the contour $r=const$ at a given z:

$$I(r,z) \equiv \int \mathbf{j}\cdot d\boldsymbol{S}_{pol} = 2\pi\int_0^r \boldsymbol{j}\cdot\boldsymbol{e}_z r dr. \tag{4}$$

Similarly, ψ is the poloidal flux. Hereinafter, (r, ζ, z) are the cylindrical coordinates related to the main axis (ζ is the toroidal angle), see Fig. 1, and $\mathbf{e}_z\equiv\nabla z$.

In our task, all changes are triggered by variations in the plasma, wherein $\mathbf{j}$ is subject to the force-balance equation

$$\nabla p = \mathbf{j}\times\mathbf{B} \tag{5}$$

with p the plasma pressure.

In the plasma-wall gap, $\mathbf{j}=0$ and $I=I_g(t)$ is a time-dependent constant. In the initial stationary state, I_g is the full poloidal current in the toroidal coils:

$$I_g^{eq} = I_{tc}. \tag{6}$$

The plasma evolution during the discharge gives rise to the inductive currents in the wall. Then

$$I_g = I_{tc} + I_w, \tag{7}$$

where I_w is the poloidal current in the wall. This is the unknown that we are going to find as a function of the plasma parameters.

The inductive voltage responsible for the appearance of I_w is determined by the change in the toroidal magnetic flux Φ_w through the tube enclosed by the wall:

$$\oint_w \boldsymbol{E}\cdot d\vec{\ell}_w = -\frac{d\Phi_w}{dt}, \tag{8}$$

which is obtained by integrating the Faraday's law

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}. \tag{9}$$

Here $\mathbf{E}$ is the electric field, t is the time, Φ_w and other relevant toroidal fluxes are defined by

$$\Phi_\alpha \equiv \int_\alpha \mathbf{B}\cdot d\mathbf{S}_\alpha = \frac{1}{2\pi}\int_\alpha \mathbf{B}\cdot\nabla\zeta d\tau = \frac{\mu_0}{4\pi^2}\int_\alpha \frac{I}{r^2}d\tau \tag{10}$$

with α denoting, respectively, the wall (w), plasma (pl) and plasma-wall gap (g). Symbolically, $w=pl+g$ in this and similar cases. The first integral is calculated over the perpendicular ($\zeta=const$) cross-section of the toroidal tube α with $d\boldsymbol{S}_\alpha$ the surface element oriented along $\nabla\zeta$. It is transformed into the volume integral (with $d\tau$ the volume element) by using $\mathbf{B}\cdot\nabla\zeta=\nabla\cdot(\zeta\mathbf{B})$. The last equality in (10) is obtained with the use of (1). The definitions are illustrated by Fig. 2.

The current density in the wall with conductivity σ is described by the Ohm's law:

$$\mathrm{j}_w = \sigma\mathbf{E}. \tag{11}$$

This equation is exploited in deriving a general equation for I_w, but it becomes insignificant for estimating I_w in the ideal-wall limit, which is one of our goals here.