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Modelling of transient electromagnetics in Tokamaks during off-normal conditions

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Abstract. — During plasma disruption events in Tokamaks, a considerable amount of magnetic and thermal energy is associated to the transfer of plasma current into eddy and Halo currents. In this paper, a predictive numerical modelling is described concerning plasma-wall interactions during disruptive instabilities. Preliminary results are presented, giving an estimation of heat transfer interaction with electromagnetic phenomena. Eddy currents and heat deposition increase significantly with decreasing disruption time. An estimation of the order of magnitude of Halo currents and associated forces on plasma-facing conducting components is also presented.

1. Introduction.

In a Tokamak-type magnetic fusion device the off-normal conditions (plasma vertical instabilities and disruptions) and the large magnetic fields generate electromagnetic phenomena in transient modes which lead to strong induced currents (Halo and eddy) and large body loads that must be correctly accommodated in the engineering design of the structural components. In particular those to be considered (having the highest inductive coupling with the plasma) are: the in-vessel region (first wall, blanket segments, passive stabilization loops and divertors), the vacuum vessel and the poloidal field coils.

Eddy current phenomena are governed by the quasi-static electromagnetic field equations, based on two of the Maxwell’s equations that are the Ampere’s and Faraday’s induction laws.
and supplemented with constitutive equations between $B$ and $H$, $E$ and $J$, taking different parameters depending on material properties. The « three-current components » computer codes applied in that context (e.g. CARIDI & TRIFOU) have their formulation based on the electric vector potential $T$ and the magnetic field intensity $H$ respectively with the use of edge variable elements. They are used to compute the eddy-current flow, Ohmic power dissipation, induced voltage, transient magnetic field and electromagnetic body forces.

Recent observations in experimental Tokamaks, of great concern for accident prevention, have identified currents flowing from the plasma boundary (Halo) into the vessel wall and other conducting plasma facing components, in cases of loss of vertical plasma position. As far as plasma positional instabilities are concerned, we have set up a first model of an elongated plasma which is translating, rotating, changing shape through a magnetic field. This field may vary in magnitude and direction in space and may also be changing in time. According to Faraday’s induction equation the changing magnetic flux during vertical positional instabilities drives a poloidal-current in the Halo, regardless of the factors responsible for the magnetic flux change. The direction of the induced current may be derived from Lenz’s law. In case of a moving plasma, the force exerted by the external magnetic field on the induced current must oppose the motion of the plasma. When the plasma disrupts after contact with the first wall components, the changing plasma current induces a poloidal current component in the Halo which is in the same direction as during the positional instability, such increasing the total Halo current. The positional and disruptive instabilities are thus actually coupled.

Since the Halo current entering into the first wall components follows a least resistive path, it may also reverse direction, depending on the topology of the first wall components.

In this paper we present preliminary results of two numerical methods which are in the previously described framework.

— An estimation of heat transfer interaction with electromagnetic phenomena during plasma disruptive instabilities. Two different 3D integral finite element methods, implemented into TRIFOU and CARIDDI codes, have been used in order to calculate transient magnetic fields and eddy-currents, considering a simplified TOKAMAK inboard blanket during reference plasma disruptions (the geometrical arrangement is outlined in Sect. 2.3, see also Figs. 1 and 2). Results are presented for different disruption times and quenches of the plasma, playing the role of an external current source. Up to now energy deposition was estimated only from the heat flux contained in the plasma.

— An estimation of the order of magnitude of Halo currents and associated forces on plasma-facing conducting components by means of a lumped parameter model, incorporating also electrical arcing effects.

Finally, from the viewpoint of magnetomechanical design of fusion reactor components, it is desired to establish numerical design methodologies capable to evaluate the impact of the electromagnetic body forces and of the magneto-mechanical-thermal coupling effects.

2. Eddy-current interaction with « Marangoni » flows.

During plasma disruptions in a Tokamak the first wall and blanket components are subject to high heat fluxes, which may cause melting and evaporation.

It has recently been demonstrated that surface tension driven flows (Marangoni flows) are an important mechanism for the depth and the motion of molten layers produced in small-scale laser driven experiments [1]. These experiments were performed in the absence of electromagnetic phenomena and therefore analysed with a simplified hydrodynamic model which does not account for external forces and heat sources due to eddy currents. The basic equations of this model are the continuity equation and the Navier-Stokes & adjusted Fourier equations
for convective heat transfer:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}
\]

\[
\rho \frac{d \vec{v}}{dt} = \vec{F} - \nabla p + \eta \Delta \vec{v} \tag{2}
\]

\[
\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \frac{k}{\rho c_p} \Delta T + \frac{1}{\rho c_p} K \tag{3}
\]

where \( \rho, v, t, p, T, \eta, F, k, c_p, K \) are density, velocity, time, pressure, temperature, viscosity, electromagnetic force density, thermal conductivity, heat capacity and eddy-current power density, referring to molten layers. Distinctive features in the presence of electromagnetic phenomena are seen in the formulation of equations (2) and (3). To model the coupled real process the addition of the electromagnetic force term in the first equation, and the addition of the heat source term in the second equation is still necessary. The numerical procedure for the calculation of the real process is then a combination of the eddy current calculation and the calculation of Marangoni flows. To evaluate the influence of the additional terms for the coupled problem, we consider in this paper the heat sources due to eddy currents and electromagnetic body forces in the conducting structures.

The 3D procedure constitutes a basis for the modelling of Marangoni flows in real situations, incorporating the electromagnetic effects.

Throughout this paper we use SI units, unless otherwise specified.

2.1 FORMULATION OF THE PROBLEM. — The basis of the analysis are the general Maxwell equations in the low frequency approximation:

\[
\nabla + \vec{H} = \vec{J} \tag{4}
\]

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{5}
\]

Equations (4) and (5) are coupled by the constitutive relations:

\[
\vec{B} = \mu \vec{H} \tag{6}
\]

\[
\vec{J} = \sigma \vec{E} \tag{7}
\]

where \( E, H, J \) and \( B \) are the electric and magnetic field intensities, current density and magnetic flux density, respectively. \( \mu \) and \( \sigma \) are the magnetic permeability and electrical conductivity.

2.2 FINITE ELEMENT FORMULATION IN TRIFOU AND CARIDDI. — The computer codes TRIFOU [2] and CARIDDI [3] have been used with a simplified geometric representation of an inboard blanket module, to analyze the effects of eddy currents for reference plasma disruptions.

TRIFOU code uses a finite element method in order to compute the eddy current distribution in 3D, related to a tetrahedric mesh for the domain that includes the conductors, coupled with a boundary integral method outside this domain. For the present application (an inboard blanket slice near the equatorial plane) we have used a 120 node mesh, forming 225 tetrahedra (see Fig. 1), considering two planes of symmetry; only the one fourth of the module has been modelled.

CARIDDI is based on a 3D integral formulation of the eddy current problem, using a current vector potential \( T \). This potential possesses only two scalar components, as the gauge chosen
to ensure its uniqueness is $\mathbf{T} \cdot \mathbf{u} = 0$, where $\mathbf{u}$ is a prescribed vector field [3]. Only the structure under analysis is discretized using eight-node brick elements. For this investigation we have used a 282 node mesh, forming 128 hexahedra. We have considered one plane of symmetry, so half of the specimen has been modelled (see Fig. 2).
2.3 MODELLING OF THE PLASMA. — The geometric arrangement of the plasma and the inboard blanket module is outlined in the following scheme:

![Diagram of plasma and blanket module]

The plasma may be modelled as a single filament with uniform or space varying current density in the poloidal plane [3].

\[ J(r) = J_0 e^{-a(r-R)^2} \]  

(8)

More precisely, using TRIFOU, we consider a filamentous coil, while using CARIDDI the plasma has been represented:

- as a filamentous coil
- cylindrical with a shape factor \( \alpha \) for the current density profile equal to 0
- cylindrical with the above factor \( \alpha \) equal to 3.

The basic plasma parameters are given in table I.

2.4 PLASMA DISRUPTION SIMULATIONS. — The analysis of plasma disruptions was performed on a simplified inboard blanket module of 316 stainless steel. Basic parameters are given in table II.

<table>
<thead>
<tr>
<th>TABLE I: Basic plasma parameters</th>
<th>TABLE II: Parameters for the inboard blanket slice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma major radius, ( R ): 6 m</td>
<td>Dimensions:</td>
</tr>
<tr>
<td>Plasma minor radius, ( r ): 2.15 m</td>
<td>width 117 mm</td>
</tr>
<tr>
<td>Initial plasma current: 22 MA</td>
<td>length 300 mm</td>
</tr>
<tr>
<td>Plasma disruption times: range: 5-50 ms</td>
<td>height 60 mm</td>
</tr>
<tr>
<td>Distance plasma axis-blanket: 2.4 m</td>
<td>Resistivity, ( \eta ):</td>
</tr>
<tr>
<td>Shape parameter, ( \alpha ): 0 and 3</td>
<td>range 0.9 e^{-6}-3 e^{-6} Ohm m</td>
</tr>
<tr>
<td></td>
<td>Plasma-facing panel width: 15 mm</td>
</tr>
</tbody>
</table>

Experimental observations indicate that during a real plasma disruption the current quench phase is preceded by a thermal quench, in which the thermal plasma energy is rapidly lost [4]. The consequent decrease of the plasma pressure results in an increase of the plasma current by about 10% in about 1 ms. In our calculations we have taken account of this current increase during the initial phase of the disruption simulations [5].
2.5 DISCUSSION OF THE RESULTS. — Figures 1 and 2 illustrate the finite element models used for the TRIFOU and CARIDDI runs. The simplified inboard blanket module consists of two regions with different resistivities: $0.9 \times 10^{-6}$ Ohm m for the external box and $3 \times 10^{-6}$ Ohm m for the internal blanket region. Figures 3 and 4 show the eddy current density distributions for the 5 ms disruption, resulting from TRIFOU and CARIDDI respectively. The higher conductivity in the plasma facing panel of the blanket module leads to a concentration of eddy currents in that part.

Fig. 3. — Eddy current density distribution. Disruption time: 5 ms. Calculation with TRIFOU.

Fig. 4. — Eddy current density distribution. Disruption time: 5 ms. Calculation with CARIDDI.
The transient power density due to eddy currents is outlined in figures 5 and 6 (TRIFOU and CARIDDI calculations), as function of the different reference disruption times (5, 10, 20, 50 ms). An improvement of the finite element discretizations, mainly in the corner regions, could reduce the observed difference of about 10%. The values are highest for the hard disruption of 5 ms. Only a small difference is observed in figure 6, if the spatial current distribution in the plasma is taken into account. The peak values increase by about 20%, if the increase of the plasma current during the thermal quench phase is considered (as shown in Fig. 7). An equivalent behaviour is observed for the energy densities in figures 8 and 9.

The spatial distribution of the Ohmic power density along the width of the module is given in figures 10 and 11 for the cases without and with the thermal quench.

The specific power and energy densities in the sensitive plasma facing part of the module are presented in figures 12 and 13 for the most relevant case (thermal quench with 5 ms...
Fig. 7. — Total ohmic power density as a function of time, considering a thermal quench time of 1 ms (current quench time : 5 ms). Calculation with TRIFOU.

Fig. 8. — Time variation of ohmic energy density for different disruption times. Calculation with TRIFOU.

Fig. 9. Total ohmic energy density as a function of time, considering a thermal quench time of 1 ms (current quench time : 5 ms). Calculation with TRIFOU.
Fig. 10. — Ohmic power density along $x$ axis for different disruption times. Calculation with TRIFOU.

Fig. 11. — Ohmic power density along $x$ axis for different disruption times, considering a thermal quench time of 1 ms. Calculation with TRIFOU.

Fig. 12. — Ohmic power density in the plasma facing wall, as a function of time. Thermal quench time: 1 ms, current quench time: 5 ms. Calculation with TRIFOU.
disruption). The peak values are about two times higher in comparison to the overall ones (Figs. 7, 8 and 12, 13).

The temperature increase due to the heat deposition in the plasma facing part may be estimated from an adiabatic power density balance:

\[ \rho c_p \frac{dT}{dt} = J^2(t) \frac{1}{\sigma} \]  

where \( T, J, t, d \) and \( c_p \) are the temperature, eddy current density, time, density and specific heat for the module considered, respectively. For stainless steel the temperature difference amounts to some \( K \). The force density due to the Lorentz force on the circulating eddy currents is outlined in figure 14 for a total magnetic flux density \( B_{\omega 0} \) of 5.1 T. Note that the forces are compressive, directed into the blanket module.


Recent experiments in Tokamaks (DOUBLET-III, JET) regarding plasma stability have identified currents flowing from the plasma boundary (Halo) into the vessel wall and other conducting plasma facing components. These currents result in higher forces on the plasma facing components than expected from existing theoretical models which estimate the inductive current transfer from the plasma to the wall. Forces in the order of several MN are produced due to the interaction of these Halo currents with the toroidal magnetic field [4, 6-9].

Earlier Tokamaks had a plasma cross section of circular shape, but non circular cross sections are considered because higher plasma current and higher beta values are attainable. In case of a vertical positional instability, a very elongated plasma leads to even higher forces on the plasma facing components. To estimate the order of magnitudes of the Halo currents and the associated forces a first theoretical model, based initially on lumped parameters is presented.

3.1 Basic considerations on Halo currents. — We consider a plasma which is translating, rotating, changing shape through a magnetic field. This field may vary in magnitude and direction in space and may also be changing in time. As a result of the motion
Fig. 14. — Force density distribution. Toroidal field : 5 T, poloidal field : 1 T. Thermal quench time : 5 ms, current quench time : 1 ms. Calculation with TRIFOU.

and the magnetic field, every charge in the plasma experiences a force. Specifically a charge $q$ in a plasma element $ds$, which has velocity $v_p$, experiences the force.

$$\bar{F} = q(E_i + \vec{v}_p \times \vec{B})$$

$E_i$ represents the induced electric field which is present when $B$ is changing with time. The instantaneous induced voltage in the loop is defined as the work which the non conservative Lorentz force would do in taking a positive charge one time around the closed loop:

$$V_i = \frac{1}{q} \oint \bar{F} \cdot d\vec{s} = \oint (E_i + \vec{v}_p \times \vec{B}) \cdot d\vec{s} = -\frac{d}{dt} \oint \vec{B} \cdot d\vec{A} \Rightarrow$$

$$V_i \leq B 2 \pi r v_p$$

$r$ is the radius of an equivalent circular cross-section of the plasma. This is Faraday’s law and is valid regardless of the factors responsible for the change in magnetic flux. The direction of the induced current may be derived from Lenz’s law. In case of a moving plasma the force exerted by the external magnetic field on the induced current must opposing the motion of the plasma. Halo currents are thus explained as an inductive phenomenon, based on Maxwell’s induction equation.

3.2 ELECTRODYNAMIC MODEL. — In order to obtain information on the order of magnitude of the Halo currents a first model has been set up, referring to experimental evidence from JET and DOUBLET-III, where plasma facing components (pfc) were broken during vertical plasma dislocations. It assumes that pfc rupture and accelerate in the magnetic field due to the action of the Lorentz force. The effect of electrical arcing in the pfc is incorporated [10]. The
Halo current induced by the magnetic flux change during positional instabilities is given by:

\[ I \frac{dL}{dt} + L \frac{dI}{dt} + RI + nV_{arc} = - \frac{d\Phi}{dt} \] (12)

The force on the pfc equals that of the Lorentz force and gravity:

\[ \frac{dv}{dt} = \frac{BI\ell}{m} - g \] (13)

where \( \Phi \) is the magnetic flux, \( L \) the inductance, \( R \) the resistance, \( \ell \) the length of the current path in the pfc; \( m \) the accelerated pfc mass, \( g \) the gravity acceleration, \( v \) the pfc velocity, \( V_{arc} \) the arc voltage and \( n \) the number of generated arcs. The equations are coupled due to the current time dependence during the acceleration of the pfc.

3.3 NUMERICAL CALCULATIONS. — The input parameters of the model are based on ITER design data (elongated elliptical plasma cross-section):

- plasma toroidal radius, \( R_p = 6 \) m;
- plasma minor radius, \( a = 2.15 \) m;
- plasma major radius, \( b = 3.61 \) m;
- toroidal magnetic flux density, \( B = 7 \) T;
- plasma vertical displacement velocity, \( v_p = 75 \) m/s.

It is also assumed that a rectangular piece of pfc is ruptured having:

- cross section, \( 1 \) e\(^{-4}\) m\(^2\);
- length, \( \ell = 1 \) m;
- electrical resistivity at 293 K, is \( 0.3 \) e\(^{-6}\) Ohm m;
- density, \( 7 \) 700 kg/m\(^3\).

The inductance of the plasma is calculated from [11]:

\[ L = \frac{1}{2} \mu_0 R_p \left( 2 \ln \frac{b}{a} + \ell_i \right) \] (14)

with \( \ell_i = 0.25 \).

From the above equations we deduce:

\[ \frac{dL}{dt} = 4 \pi . 10^{-7} R_p \frac{1}{b} v_p . \] (15)

The numerical integration of the coupled equations (12) and (13) has been performed using SIL, a simulation language [12]. A variable order, variable step size implicit Runge-Kutta method was applied. With a relative accuracy requirement of \( 10^{-4} \), the running time on a M28 Olivetti PC was about 1.5 s per case.

3.4 DISCUSSION OF THE RESULTS. — Figures 15 to 18 show the time variation of the Halo currents as a function of different parameters. Although the approaches are preliminary and entirely on the macroscopic level the following conclusions can be drawn.

Halo currents are in the MA range, reaching the maximum values in a few ms. Their interactions with the time constant toroidal field will generate forces in the order of MN. If plasma stability cannot be assured, a major structural failure is possible to occur.

From figure 15 we can conclude that the influence of resistivity is pronounced. The influence of the inductance is presented in figure 16. In the case of large skin effects the maximum value of Halo current is rapidly reached. Both figures indicate the necessity of further research into the microscopic properties of the plasma.
Figure 15. — Time variation of Halo currents as a function of loop resistance.

Figure 16. — Time variation of Halo currents as a function of plasma inductance.

Figure 17 shows the time variation of the Halo currents as a function of the plasma displacement velocity. Finally, from figure 18, we can point out that the Halo currents are relatively insensitive to the arc voltage. This can be explained by the fact that the energy dissipation in the arc is low during the outlined time scale, while the Halo currents are derived from an energy balance equation.

4. Conclusion.

In this paper we have presented a transient electromagnetics modelling and calculations for two actual issues in relation to plasma wall interaction from eddy and Halo currents. We have calculated the eddy currents in plasma facing components as well as the associated heat deposition. Both values increase significantly with decreasing disruption time, whereas the related temperature difference is not pronounced. In the experiments on surface tension flows