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ELECTROMAGNETIC EFFECTS ON THE FED/INTOR LIMITER*

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ABSTRACT

Electromagnetic effects were among the critical issues of the impurity control system examined in the 1982 FED/INTOR design study. During a plasma disruption, the decaying plasma current induces voltages and currents in the first wall and limiter systems which can produce arcing between limiter segments and large forces and torques on the limiter. The effects of first wall time constant, limiter electrical resistance, and limiter segmentation on the voltages, forces, and torques were studied.

INTRODUCTION

A pumped limiter was one option for impurity control incorporated in the 1982 FED/INTOR design study. Electromagnetic effects on the limiter were among the critical issues examined. During a plasma disruption, the decaying plasma current induces currents and voltages in the first wall and limiter systems. These currents can interact with the poloidal and toroidal fields to produce large forces and torques. The voltages can lead to arcing between segments of the limiter. The objectives of the study were to determine how the forces, torques, and voltages depend on such system parameters as the first wall electromagnetic time constant, the limiter material (particularly its electrical resistivity), and the degree of toroidal segmentation of the limiter. In the study, the system consisted of a double-bladed limiter located below the plasma, an electrically continuous first wall, poloidal field coils with fixed locations and currents, and a plasma current decaying linearly to zero in 20 ms. A computer code¹ has been developed to model the induced currents in the blade and first wall as functions of time.

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MODEL FOR LIMITER AND FIRST WALL

The configuration of the limiter and first wall used in the calculations is shown in Fig. 1. The surface resistance of the first wall is chosen to give a first wall time constant of 0.1 s. For higher or lower time constants, the resistance is adjusted accordingly. The limiter and the first wall are modeled as a series of wire conductors as shown in Figs. 2 and 3. The conductors are shown as circles with area proportional to the self inductance used for the calculations.

Figure 4 shows the locations of the poloidal field coils as circles with areas proportional to the current. The plasma is represented by a single current loop. The limiter is also shown, along with a magnetic flux line which wanders through the system.

Fig. 1 Configuration of First Wall and Limiter

Fig. 2 Position of Wires Used to Model Limiter

Fig. 3 Position of Wires Used to Model First Wall

The voltage acting on all the wire conductors can be written in vector notation as

$$\vec{V}_p + \vec{V}_{IR} + \vec{V}_M = 0 \quad (1)$$

Fig. 4 Position of Poloidal-field Coils, Plasma, and Limiter, with One Flux Line.

where

$\vec{V}_p$ is the vector of voltages induced in conductors by the changing plasma current,

$\vec{V}_{IR}$ is the vector of resistive voltage in the conductors, and

$\vec{V}_M$ is the vector of voltage induced in conductors by changing currents in all the conductors, via the symmetrical inductance matrix M .

The currents in the poloidal field coils are constant and do not induce voltages. The change in the vector of currents $\vec{I}$ between times t and $t + dt$ can be found by solving Eq. (1).

$$\vec{I}(t + dt) - \vec{I}(t) = M^{-1} (\vec{V}_p + \vec{V}_{IR}) dt \quad (2)$$

where M^{-1} is the inverse of M .

This model, in which the first wall and limiter are represented by coaxial circular current loops, does not lend itself to a

treatment of segmentation effects. The first step toward segmentation, a single cut in the limiter, can be modelled by imposing an additional voltage term on the limiter wires only. The voltage is chosen to make the sum of the limiter currents vanish. Resistive voltages near the cut due to radial current flow are neglected.

Those radial currents interact with the toroidal field to produce large vertical forces, of opposite direction on the two sides of the cut. Those forces can be calculated from the current in each limiter wire, the radial displacement of the wire from the central radius of the limiter, and the toroidal field.

RESULTS

The results in the four following subsections show how the forces, torques, and voltages in the limiter vary with toroidal segmentation, first wall time constant, and resistivity of limiter material. In each of these subsections, three forces and one torque are considered. F_R is the radial force per unit length of limiter due to interaction of the induced toroidal current with the vertical component of poloidal field. F_z is the vertical force per unit length of limiter due to interaction of the induced toroidal current with the radial component of poloidal field. (The poloidal field is the sum of the fields from the PF coils, the plasma current, and the induced currents themselves.) τ is the torque per unit length of limiter, about an axis in the toroidal direction, resulting from F_R and F_z . F_{cut} is the vertical force of interaction between the toroidal field and the radial currents which flow wherever the limiter has a poloidal cut. Results are discussed in more detail elsewhere.²

Effects of Electrical Discontinuities

Four cases have been analyzed:

- 1) A continuous copper toroidal limiter, ignoring effects from the first wall.
- 2) A toroidal limiter with a single poloidal cut.
- 3) A continuous toroidal limiter including the first wall with 100 ms time constant.
- 4) A toroidal limiter with a single poloidal cut including the first wall.

Table 1 summarizes the peak forces for these four cases. Figures 5 and 6 illustrate how the cut and first wall change the time variation of the forces. As expected, the limiter without a cut and without a first wall exhibits the highest forces, which peak at the end of the plasma current quench. The peak forces are reduced by a factor of between three and ten when a single cut is made in the limiter. The first wall eliminates the sharp transients in forces associated with the plasma current quench. The peak forces are then observed at longer times (~ 200 ms) which are associated with the longer current decay times of the first wall. The first wall and a single cut in the limiter provide substantial protection from mechanical forces.

The force of interaction between the toroidal magnetic field and the radial currents at the cut also are reduced by the conducting first wall. With a non-conducting first wall, the force peaks at 20 ms, the end of the plasma current disruption. At that time the vertical force on each side of the cut is 3.50 MN. The conducting first wall

Table 1. Summary of Induced Force Calculations

	Peak Radial Force (N/m)	Peak Vertical Force (N/m)	Peak Torque (Nm/m)	Peak Vertical Force on Cut (MN)
Limiter with No Cut	820,000	500,000	200,000	0
Limiter with Cut	120,000	40,000	85,000	3.50
Limiter with No Cut and First Wall	500,000	260,000	110,000	0
Limiter with Cut and First Wall	21,000	14,000	12,000	1.18

Fig. 5 Induced Torque and Forces on Limiter, Without First Wall and Without Cut in Limiter

Fig. 6 Induced Torque and Forces on Limiter with a Single Cut, for First Wall with Time Constant 100 ms.

reduces the currents in the limiter, and reduces the force at 20 ms to 0.78 MN. However, as the current in the first wall decays, with a 100 ms time constant, the current in the limiter is driven higher; the

vertical force on each side of the cut peaks at 75 ms, at a value of 1.18 MN.

As described above, segmentation effects cannot be calculated with the co-axial ring model. It is possible, however, to give a physical argument to estimate the forces on a segmented limiter on the basis of the forces on a limiter with a single cut and the increased resistance of current paths in a segmented limiter.

The resistance of the radial current path at the cut is neglected in the above calculations with a single cut, surely a good approximation because the radial width of the limiter is small relative to its circumferential length. If the number of segments is increased until the radial width and length are equal (about 24 segments), the resistance of the radial and azimuthal paths are equal and the current is roughly halved. If the number of segments is further increased, the resistance of the radial current paths become dominant, and the current varies inversely with the number of segments. For 72 segments, six per TF coil, the current and vertical force should have one-third of its value with 24 segments. To be conservative, the value of one-half was used instead. With 72 segments, support against resulting torque about a radial axis is manageable.

Variation of Force With First Wall Time Constant

A series of computations was performed for a copper ($\rho = 0.017 \mu\Omega\text{m}$) limiter with a single poloidal cut. Time constants of $\tau = 0, 10, 30, 100,$ and 1000 ms were used. The resulting peak values of $F_R, F_Z, N,$ and F_{cut} are shown in Fig. 7.

The dashed straight line in Fig. 7 shows the slope for a hypothetical force which varies inversely with the square root of τ . The three quantities $F_R, N,$ and F_{cut} have roughly the same behavior. The plasma current decay time is 20 ms for $\tau \ll 20$ ms. The force is largely independent of τ . The decrease of force with increasing τ is strongest for $\tau \sim 20$ ms. Finally, for $\tau \gg 20$ ms, the force decreases more weakly with increasing τ . The values of F_{cut} were divided by ten to fit them onto the same graph.

Fig. 7 Variation of Forces and Torques on the Limiter with First Wall Time Constant

Variation of Force With Limiter Resistivity

Computations were performed for a limiter with a single cut and a first wall time constant of 100 ms. The three computations differed only in limiter resistivity: values of $\rho = 0.017$ (copper), 0.07 (Cu-Be), and 0.32 (V-15Cr-5Ti) $\mu\Omega\text{m}$ were used. The resulting peak values of F_R , F_Z , N , and F_{cut} are shown in Fig. 8.

All four curves show roughly the slope of the dashed line, which represents a hypothetical force varying inversely as the square root of the resistivity. The values of N have been divided by ten, and those of F_{cut} by 1000, so that all forces could appear in the same graph but not overlap in a confusing way.

Induced Voltages Between Limiter Segments

As shown in Table 1, segmenting the limiter greatly reduces the induced forces and torques acting upon it, by reducing the circulating current from 2.8 MA (for $\tau = 0$ ms) or 1.7 MA (for $\tau = 100$ ms) to zero. Concern has been expressed that the voltage induced by plasma disruptions may lead to arcing between limiter segments. There is considerable uncertainty about how large the voltage between segments can be and still avoid damage

Fig. 8 Variation of Forces and Torque on the Limiter with Limiter Resistivity

from arcing, with values between 20 V and 200 V suggested. It is prudent to use the 20 V value if possible.

In the computations for a limiter with a single cut, the zero net current condition is imposed by finding the electrical potential which reduces the circulating current to zero. For a limiter with a single cut, this potential represents the voltage across the cut. For a limiter with n segments and n cuts, the voltage across each cut is given approximately by dividing the potential by n . This approximation is quite good; the voltage is scarcely influenced by the current flowing in the limiter.

Table 2 shows the variation of the voltage with first wall time constant and with limiter resistivity. Values are computed for a single cut and estimated for one cut per toroidal field (TF) coil and for six cuts per TF coil. The variation with time constant is seen to be similar to the variation of force with time constant: virtual independence for $\tau \ll 20$ ms, rapid decrease with increasing τ for $\tau \sim 20$ ms, and slow (inverse square root) decrease for $\tau \gg 20$ ms. For $\tau = 100$ ms and 72 segments, the voltage is below 10 V.

Table 2. Induced Voltages Between Limiter Segments

First Wall Time Constant τ (ms)	Limiter Resistivity ρ ($\mu\Omega$ m)	Voltage Across Cut (V)		
		1 cut	12 cuts	72 cuts
0	0.017	2100	175	29
10	0.017	1860	155	26
100	0.017	450	38	6.2
1000	0.017	144	12	2.0
100	0.017	450	37.5	6.2
100	0.07	462	38.5	6.4
100	0.32	467	38.9	6.5

CONCLUSIONS

Several conclusions have been drawn from these studies.

- 1) The electrical response of the limiter is sensitive to the electrical behavior of the first wall and cannot be studied independently from it.
- 2) For a first wall time constant of 100 ms, and a limiter segmented into 72 pieces, the forces, torques, and voltages are manageable.
- 3) For a shorter first wall time constant or fewer segments, electromagnetic considerations will be significant in the design of the limiter.
- 4) There is a characteristic variation of limiter forces and voltage with first wall time constant τ , with virtual independence of τ when τ is small compared with the plasma current decay time constant $\tau_0 = 20$ ms, rapid decrease with increasing τ when $\tau \sim \tau_0$, and inverse square root decrease with τ when $\tau \gg \tau_0$.

- 5) Induced forces and torques vary inversely with the square root of limiter resistivity; voltages are virtually independent of limiter resistivity.

- 6) In light of the importance of segmentation effects, an analysis which treats segmentation more adequately is required.

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