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NUMERICAL SIMULATION OF THE PLASMA CURRENT QUENCH FOLLOWING A DISRUPTIVE ENERGY LOSS

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ABSTRACT

The plasma electromagnetic interaction with poloidal field coils and nearby passive conductor loops during the current quench following a disruptive loss of plasma energy is simulated. By solving a differential/algebraic system consisting of a set of circuit equations (including the plasma circuit) coupled to a plasma energy balance equation and an equilibrium condition, the electromagnetic consequences of an abrupt thermal quench are observed. Limiters on the small and large major radius sides of the plasma are assumed to define the plasma cross section. The presence of good conductors near the plasma and a small initial distance (i.e., 5–10% of the plasma minor radius) between the plasma edge and an inboard limiter are shown to lead to long current decay times. For a plasma with an initial major radius $R_0 = 4.3$ m, aspect ratio $A = 3.6$, and current $I_p = 4.0$ MA, introducing nearby passive conductors lengthens the current decay from milliseconds to hundreds of milliseconds.

1. INTRODUCTION

Disruptions in tokamak plasmas are generally assumed to result from growing tearing modes, leading to magnetic island overlap and enhanced heat conduction.¹ This is usually followed by a loss of plasma position and current through electromagnetic effects and catastrophic interaction with limiters. These two phases may be termed as the thermal quench and current quench, respectively. A model has been developed to explore the basic plasma electromagnetic phenomenon associated with the second phase, that is, the current decay following a plasma disruptive thermal quench.

If the current quench can be prevented in tokamaks, it may be possible to restore plasma confinement without machine shutdown. The ASDEX tokamak² (with a vacuum vessel time constant of 10 ms and efficient feedback on plasma current, position, and density) has demonstrated recovery from sequences of thermal quench and has successfully avoided the usually fast current quench.

Present torus designs are typically influenced by inductive startup requirements and need a relatively high electrical resistance vacuum vessel. Long pulse times in future reactors may permit long startup scenarios and hence lower resistance structures near the plasma. Previous electromagnetic studies on the Fusion Engineering Device (FED)³ suggest that good passive conductors near the plasma increase the current decay phase, protecting first wall surfaces from the effects of a disruption. Results reported in the FED-A study⁴ suggest that a closely fitted ~1-cm-thick copper shell at a radius of 1.1-1.4 times the plasma minor radius would be effective in actually preventing disruptions in low q discharges by limiting the growth time of tearing modes. The avoidance of disruption or the recovery of confinement following a disruption is of great importance in future tokamak devices where the large thermal and magnetic stored energy would potentially damage the machine. A first step in this direction is to obtain quantitative estimates of the effects of nearby conductors in slowing the rate of the current quench.

The plasma electromagnetic interaction with its environment, including poloidal field coils, nearby passive conductors (e.g., a conducting first wall), and limiters, is described by circuit equations, a simplified energy balance, and an equilibrium relationship. The resulting system, including both differential and algebraic equations, is solved by efficient computational methods using state-of-the-art software.

2. EQUATIONS

The model assumes toroidal symmetry and a circular plasma cross section with the plasma size a_p determined by the relative position of the plasma major radius R_p with respect to the limiter location R_L :

$$a_p = \begin{cases} R_p - R_L & R_p \leq R_L + a_c \\ a_c & R_L + a_c < R_p < R_R - a_c \\ R_R - R_p & R_p \geq R_R - a_c \end{cases}, \quad (1)$$

where a_c is the initial plasma minor radius. That is, when the plasma position R_p, Z_p is such that the cross section intersects a limiter, the minor radius a_p is reduced linearly.

Circuit equations for the conductor currents (I_i , $i = 1, \dots, N$) and plasma current (I_p) are

$$\sum_{\substack{j=1 \\ j \neq i}}^N M_{ij} \dot{I}_j + L_i \dot{I}_i + M_{ip} \dot{I}_p + I_p \frac{\partial M_{ip}}{\partial R_p} \dot{R}_p + I_p \frac{\partial M_{ip}}{\partial Z_p} \dot{Z}_p = V_i - \Omega_i I_i, \quad (2)$$

$$\begin{aligned} \sum_{j=1}^N M_{pj} \dot{I}_j + L_p \dot{I}_p + \left(I_p \frac{\partial L_p}{\partial R_p} + \sum_{j=1}^N I_j \frac{\partial M_{pj}}{\partial R_p} \right) \dot{R}_p \\ + \sum_{j=1}^N I_j \frac{\partial M_{pj}}{\partial Z_p} \dot{Z}_p = -\Omega_p I_p, \end{aligned} \quad (3)$$

where the resistances Ω_i , voltages V_i , and self and mutual inductances L_i, M_{ij} are given. The inductances M_{pj} and L_p depend on the plasma position and minor radius through Eq. (1). Inductances are computed by the methods described in Ref. 5. The plasma resistance, also influenced by Eq. (1), is given by

$$\Omega_p = 3.276 \times 10^{-9} \frac{Z_{\text{eff}} \ln \Lambda R_p}{a_p^2 T_e^{3/2}},$$

$$T_e = \frac{2}{3} \frac{v_p}{v_p n_e k}, \quad (4)$$

$$\ln \Lambda = 37.82 - \ln \left(\frac{n_e^{1/2}}{T_e} \right),$$

where Z_{eff}, n_e (electron density) are input and v_p is the plasma volume. A simplified energy balance for the total plasma energy w_p is given by

$$\dot{w}_p = - \frac{w_p}{\tau_E} + \Omega_p I_p^2, \quad (5)$$

where the energy confinement time is assumed to be

$$\tau_E = \frac{\lambda}{2} n_e a_p^2 \times 10^{-20}. \quad (6)$$

A scale factor λ in Eq. (6) is used to simulate the magnitude of the thermal quench; that is, it serves to arbitrarily decrease the plasma energy confinement time so the plasma energy will rapidly decrease and the electromagnetic consequences may be observed.

Plasma movement is assumed to take place on the magnetohydrodynamic (MHD) time scale, governed by the equilibrium conditions

$$\sum_{j=1}^N B_Z(R_p, Z_p, R_j, Z_j) I_j = B_V(R_p, a_p, I_p, w_p), \quad (7)$$

$$\sum_{j=1}^N B_R(R_p, Z_p, R_j, Z_j) I_j = 0, \quad (8)$$

where the required externally applied vertical field for MHD equilibrium is given by the Shafranov formula:⁶

$$B_R = \frac{\mu I_p}{4\pi R_p} \left(\ln \frac{8R_p}{a_p} + \beta_p - \frac{\ell_i}{2} - 1 \right), \quad (9)$$

where

$$\beta_p = \frac{8}{3\mu} \left(\frac{w_p}{R_p I_p^2} \right)$$

and the plasma internal inductance for a uniform current distribution is $\ell_i = 1/2$. The functions B_z and B_R give the vertical and radial components, respectively, of the poloidal magnetic field at R_p, Z_p due to unit currents in conductors located at R_j, Z_j . Specifically,

$$B_z = k(R_p R_j)^{-1/2} \left[K(k^2) + \frac{R_j^2 - R_p^2 - (Z_p - Z_j)^2}{(R_j - R_p)^2 + (Z_p - Z_j)^2} E(k^2) \right], \quad (10)$$

$$B_R = k(Z_p - Z_j)^2 \left(\frac{R_p}{R_j} \right)^{1/2} \left[-K(k^2) + \frac{R_j^2 + R_p^2 + (Z_p - Z_j)^2}{(R_j - R_p)^2 + (Z_p - Z_j)^2} E(k^2) \right], \quad (11)$$

where $k^2 = 4R_p R_j / [(R_p + R_j)^2 + (Z_p - Z_j)^2]$ and K and E are elliptic integrals of the first and second kind, respectively.

A further assumption in the present model is that the plasma does not experience the magnetic effect of those coils designated as ohmic heating coils. That is, these coils are inductively linked to the plasma through the circuit equations but do not appear in the calculation of the vertical field at the plasma. Physically, this assumption would be accurate in the case of a decoupled poloidal field system in which trim coils cancel the field of the ohmic heating solenoid at the plasma.

3. METHOD OF SOLUTION

Equations similar to Eqs. (2), (3), and (7)-(9) have been used to simulate feedback control of plasma position and current in tokamaks.⁷ The typical method of solution is to take the time derivative of the equilibrium expressions (6)-(8) and solve the resulting system as a set of ordinary differential equations (ODEs), given a set of initial values of the dependent variables. The approach used in this study is to treat these equations in their present form, making use of currently available numerical software for solving differential/algebraic equations (DAEs).⁸ This was necessary to accurately include the limiter model [Eq. (1)] since it is a nondifferentiable function. More specifically, Eqs. (1)-(8) are written in the form

$$F(t, y, \dot{y}) = A(t, y)\dot{y} - b(t, y) = 0, \quad (12)$$

where

$$y = (I_1, \dots, I_N, I_p, w_p, R_p, Z_p)^t.$$

Two software packages, LSODI and DASSL, have been used to solve this system of equations. LSODI⁹ was written by A. C. Hindmarsh and J. F. Painter to solve stiff or nonstiff initial value ODEs in the linearly implicit form $A(t, y)\dot{y} = b(t, y)$, where A is a square matrix. This code has the option, however, of solving DAEs of the same form (i.e., where A is singular) if initial values of the derivatives $\dot{y}_0$, as well as function values y_0 , of the dependent variables are supplied (at t_0). The initial derivative vector is required to be consistent with t_0 and y_0 in the sense that $A(t_0, y_0)\dot{y}_0 = b(t_0, y_0)$.

DASSL¹⁰ was written specifically to solve DAE systems of a general form $F(t, y, \dot{y}) = 0$, given the appropriate initial values. DASSL has an option available for approximately $\dot{y}_0$ at the expense of more function evaluations.

Both codes use methods designed for stiff systems of ODEs based on replacing derivatives with backward differentiation formulas and

solving a resulting set of nonlinear equations using a variation of Newton's method. That is, LSODI solves the set of nonlinear equations

$$F\left(t_n, y_n, \frac{y_n - y_{n-1}}{\Delta t_n}\right) = 0 \quad (13)$$

for the value of the vector y_n at t_n . Where LSODI uses the first-order formula (13), DASSL approximates the derivative with backward differentiation formulas of orders one through five, choosing the order as well as the step size Δt_n , depending on the behavior of the solution.

In the solution of Eqs. (1)-(8), an initial derivative vector is obtained by replacing the equilibrium equations in the system with their derivatives to obtain $\tilde{A}y_0 = \tilde{b}$ and then solving for y_0 . The matrix $\tilde{A}$ and vector $\tilde{b}$ are given by

$$\tilde{A} = \begin{bmatrix} L_1 & \dots & M_{1N} & M_{1p} & 0 & I_p \frac{\partial M_{1p}}{\partial R_p} & I_p \frac{\partial M_{1p}}{\partial Z_p} \\ \vdots & & & & & & \\ M_{N1} & L_N & M_{Np} & 0 & I_p \frac{\partial M_{Np}}{\partial R_p} & I_p \frac{\partial M_{Np}}{\partial Z_p} \\ M_{p1} & M_{pN} & L_p & 0 & \frac{\partial}{\partial R_p} \left(L_p I_p + \sum_{j=1}^N M_{pj} I_j \right) & \sum_{j=1}^N I_j \frac{\partial M_{pj}}{\partial Z_p} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ G_1 & G_N & -\frac{\partial B_v}{\partial I_p} & -\frac{\partial B_v}{\partial w_p} & \frac{\partial}{\partial R_p} \left(\sum_{j=1}^N G_j I_j - B_v \right) & \sum_{j=1}^N I_j \frac{\partial H_j}{\partial Z_p} \\ H_1 & H_N & 0 & 0 & \sum_{j=1}^N I_j \frac{\partial H_j}{\partial R_p} & \sum_{j=1}^N I_j \frac{\partial H_j}{\partial Z_p} \end{bmatrix}$$

$$\tilde{b} = \begin{pmatrix} V_1 - \Omega_1 I_1 \\ \vdots \\ V_N - \Omega_N I_N \\ -\Omega_P I_P \\ -w_P/\tau_E + \Omega_P I_P^2 \\ 0 \\ 0 \end{pmatrix}$$

Given similar error criteria, the two codes produced virtually the same solutions to test problems based on this particular set of equations. DASSL, however, used somewhat fewer matrix evaluations and less computer time¹¹ and was adopted for use in generating the results of this study.

A typical configuration and set of solution curves are shown in Figs. 1 and 2. Initial plasma parameters for this case are summarized in Table 1. The poloidal field coil system consists of ohmic heating (GH) coils, equilibrium field (EF) coils, and passive conductors near the plasma. Coil locations, currents, and resistivities are given in Table 2. The inboard limiter position is $R_L = 3.1$ m.

Simulating the effect of the thermal phase of a disruption by setting $\lambda = 0.005$, there is a sharp decrease in the plasma energy over the first 12-15 ms. During this time, there is a 35-cm decrease in major radius and a 600-kA reduction in plasma current [Fig. 2(a)] as eddy currents [Fig. 2(b)] are being induced to oppose these changes. This initial phase is followed by a 200-ms interval during which current and plasma position decrease linearly. Finally, there is evidence of a total plasma current quench shortly after 212 ms, although DASSL reaches a point where it cannot satisfy the given error criteria as $a_p \rightarrow 0$.

Table 1. Initial plasma parameters

	Symbol	Units	Value
Major radius	R_p	m	4.3
Minor radius	a_p	m	1.2
Plasma current	I_p	MA	4.0
Plasma temperature	T_e	keV	10.0
Vertical field	B_v	T	0.28

Table 2. Locations and size of conductor

R (m)	Z (m)	a (m)	b (m)	I (MA)	ρ (Ω -m)	Type
9.5	± 4.0	0.4	0.4	2.67	0.01	EF
1.2	± 1.0	0.4	1.0	10.0	0.01	OH
2.8	0.0	0.1	0.1	0.0	20.0	passive conductors
5.8	0.0	0.1	0.1	0.0	2.0	
4.3	1.5	0.1	0.1	0.0	20.0	
4.3	-1.5	0.1	0.1	0.0	2.0	

4. RESULTS

For the same initial plasma parameters, EF, and OH coils as in Tables 1 and 2 but with no passive conductors, the duration of the current quench decreases as λ is reduced. Here, λ is a scale factor in the equation for the energy confinement time, defined in Eq. (6), controlling the rate of the plasma energy quench. Assuming the plasma is initially in contact with the inboard limiter, the effect of changing λ from 0.001 to 0.015 is to extend the current quench time from less than 1 ms to 9 ms, as shown in Fig. 3.

Passive conductors near the plasma, such as a conducting first wall, have the effect of delaying the current quench following a disruption through the induction of eddy currents in a direction such that the rate of current decrease is opposed. The current decay then depends on the position and resistance of the conducting elements. The effect of conductor resistivity ρ is shown by including the passive conductors of Table 2 with uniform resistivity (but differing in resistance due to their position) and obtaining solutions for various values of ρ . Again, the initial plasma is in contact with an inboard limiter, and the disruption is simulated by a value of $\lambda = 0.005$. Figure 4 shows the current decay curves for $\rho \geq 1.6 \Omega\text{-m}$. For $\rho = 1.6 \Omega\text{-m}$, the plasma current decay that occurred in 3 ms with no passive conductors near the plasma is extended to greater than 140 ms.

The impact of varying the inboard limiter radial position R_L in the plasma/limiter interaction model [Eq. (1)] is shown in Fig. 5. With some nonzero distance between the initial plasma and the inboard limiter, the plasma current tends to increase prior to contact with the limiter. During this time, the minor radius remains constant, but the energy loss causes a decrease in the aspect ratio, i.e., a compression of the plasma column. As shown in Fig. 5, where $\lambda = 0.005$, this initial distance between the plasma and limiter extends the current quench time.

By moving the passive conductors closer to the plasma, the mutual coupling is improved, and the resistance in the outboard conductors lowered, resulting in a longer plasma current decay time. Characterizing the constant distance from the plasma center to the passive

conductors of Table 2 by a_w , the effect of decreasing a_w is shown in Fig. 6. Here, $\lambda = 0.005$ and there is initially a 10-cm distance between the initial plasma edge and the inboard limiter. As shown in Fig. 6, a 60-cm decrease in a_w implies a greater than 30% increase in the current quench time.

Conductors near the plasma on the outboard side are important in extending the current decay. In Fig. 7, a configuration with the same plasma initial conditions and passive conductors as used in Tables 1 and 2, but with $\rho = 1.6 \times 10^{-6} \Omega\text{-m}$ in the passive conductors, is compared to configurations with the inboard and outboard conductors omitted. The configuration including the outboard passive conductor is clearly the most effective in slowing the current quench, and the configuration without an outboard conductor is least effective.

Figure 8 shows the effect of poloidal asymmetry in the passive conductors by omitting the upper conductor ($R = 4.3 \text{ m}$, $Z = 1.5 \text{ m}$) from the configuration of Table 2. With the same disruption condition ($\lambda = 0.005$), the initial plasma movement is inward due to the decrease in β_p , but eddy currents in the same direction as the plasma current induced in the passive conductor below the midplane also cause a downward motion. Finally, as the plasma current decays, the larger induced current in the inboard conductor has an attractive effect, and the direction of plasma motion is toward the midplane.

In a further application, it was observed that in a smaller plasma of lower temperature ($R_p = 1.0 \text{ m}$, $a_p = 0.2 \text{ m}$, $I_p = 0.2 \text{ MA}$, $T_e = 1 \text{ keV}$, $\lambda = 0.01$), a set of conductor initial conditions could be found (Table 3) such that the plasma current would decay with no change in minor radius through limiter interaction. That is, with a 10-cm distance between the limiter and the initial inboard edge of the plasma, a current quench ($\sim 7 \text{ ms}$) takes place on essentially the L/R time of the plasma. Here the plasma column first moves inward, although not enough to contact the limiter, and then begins moving outward toward the end of the simulation (Fig. 9). This result indicates the possibility of a low beta plasma quenching under certain conditions in the center or outboard side of the chamber.

Table 3. Conductor locations for simulation of Fig. 9

R (m)	Z (m)	a (m)	b (m)	I (kA)	ρ (m)
1.50	± 0.15	0.05	0.05	43.0	2.0
0.25	± 0.15	0.05	0.10	100.0	2.0
0.65	± 0.15	0.03	0.03	0.0	150.0
1.35	± 0.15	0.03	0.03	0.0	2.0

5. CONCLUSIONS

The electromagnetic impact of a plasma major disruption on the components of a tokamak device is strongly related to the eddy current time constants of conductors near the plasma. Passive conductors, such as a highly conducting first wall, can greatly extend the current decay time. The presence of good passive conductors in torus designs would also influence the plasma inductive startup requirements, but the possibility of long startup and pulse times in future reactors may make such designs appear feasible.

In this work, the electromagnetic consequences of a disruptive energy loss are modelled with a differential/algebraic system of equations that includes circuit equations for the plasma and conductors, an energy balance equation, an equilibrium condition determining the plasma position, and an assumed plasma/limiter relationship defining the size of the plasma as a function of time. Results indicate that the current decay time following a disruptive loss of plasma energy can be extended by factors of 10 to 10^2 by (1) positioning passive conductors (e.g., a conducting first wall) near the plasma; (2) extending the time constant of these conductors; and (3) detaching the plasma from an inboard limiter (e.g., with a poloidal divertor). The study shows that conductors on the outboard side of the plasma are most effective in slowing the current quench.

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FIGURE CAPTIONS

Fig. 1. Initial plasma size and conductor geometry. The dashed lines are contours of constant poloidal flux created by the EF coils and passive conductors.

Fig. 2(a). Typical solution curves showing the time dependent behavior of the plasma current I_p , major radius R_p , vertical position Z_p , and plasma energy w_p . Also included are the plasma minor radius a_p and equilibrium vertical field B_v .

Fig. 2(b). Typical solution curves showing the time dependent behavior of the passive conductor currents.

Fig. 3. Plasma current quench, in a configuration with no passive conductors, for various values of λ .

Fig. 4. Plasma current quench for various values of passive conductor resistivity $\rho(\Omega\text{-m})$.

Fig. 5(a). As the major radius decreases, the plasma current increases prior to contact with the limiter, as shown here for various limiter positions R_L .

Fig. 5(b). Plasma current quench for various limiter positions.

Fig. 6. Plasma current quench for different distances between plasma and passive conductors a_w .

Fig. 7. Current quench for different passive conductor configurations.

Fig. 8. Plasma position and size relative to conductors at various times during the current quench in an asymmetric configuration.

Fig. 9. Solution curves for major radius, vertical field, and plasma current in a simulation with no limiter contact (no change in minor radius).

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Fig. 1

Fig. 2(a)

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Fig. 2(b)

Fig. 3

Fig. 4

Fig. 5(a)

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Fig. 5(b)

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Fig. 6

Fig. 7

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Fig. 8

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Fig. 9

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