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TOKAMAK FUSION REACTOR START-UP SIMULATION

By

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by

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ABSTRACT

A simulation code TSEC (Time-dependent Spectral Equilibrium Code) has been developed to model the axisymmetric evolution of a tokamak on the resistive (L/R) time scale of the external coils, conductors, or shell. The electromagnetic interaction between the plasma and the external circuit is taken into account in a self-consistent manner. TSEC is Lagrangian and utilizes magnetic flux coordinates with spectral decomposition in the angle variable θ . The plasma is modeled as a finite-size, zero-inertia, finite-pressure fluid which adjusts its position and shape to remain in free-boundary equilibrium consistent with the currents in the external circuits. At the heart of TSEC is a fast method of calculating the self-consistent free-boundary plasma equilibrium at each time step which is based on the minimization of a certain mean-square error.¹

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I. INTRODUCTION

A high temperature tokamak plasma system evolves on many different time scales characterized by different transit times, instability growth rates, and natural response frequencies. This paper describes a simulation model appropriate for describing the evolution of the tokamak plasma over the time scale characterized by the current decay time in the vacuum vessel and the nearby current-carrying external coils. This is the time scale over which the plasma current builds up from zero to a steady-state value and over which the toroidal eddy currents in the vacuum vessel decay. For large tokamaks, this time is in the range of 0.01 to 10.0 seconds.

Since we are considering times much longer than the Alfvén transit time, plasma inertia is unimportant, and we take the plasma to pass through a series of equilibrium states. The external coils and conductors all obey circuit equations so that the free-boundary plasma equilibrium must be consistent with the evolving coil currents at each instant of time. We find it useful to differentiate between (a) the fast time scale $\tau_1 < \tau_{cp}$, and (b) the slow time scale $\tau_2 > \tau_{cp}$, where τ_{cp} is the anomalous plasma current penetration time. An example of time evolution on the fast time scale is the adiabatic compression of a tokamak plasma where applied voltages on the vertical field coils compress the plasma to a smaller major radius. A phenomenon on the slow time scale is the current start-up phase of a tokamak reactor plasma. A comparison between these two will be given later.

The fast time scale modeling of the adiabatic compression of the Tokamak Fusion Test Reactor (TFTR) will be given elsewhere.² Here we shall focus on the slow time scale current start-up phase in reactor plasmas. We take the start-up phase to last for several or tens of the L/R times of the external coils or shell. This way, the increased ohmic-heating flux has sufficient time to

diffuse, and the plasma size will increase and the current will grow in magnitude. Since anomalous flux diffusion takes place, a skin current does not develop at the plasma vacuum interface. Details of the model will be found in Sec. III while the circuit equations are given in Sec. II. In Sec. IV, we present results of the simulation of the current start-up phase in a proposed Fusion Engineering Device (FED) plasma surrounded by a conducting shell. The shell is modeled by a set of twenty-two up-down symmetric passive copper coils. We close in Sec. V with some concluding remarks.

II. CIRCUIT EQUATIONS

Our model of the external circuits and conductors consists of a set of discrete axisymmetric filamentary conductors carrying current in the toroidal direction. If ϕ is the symmetry angle, then the poloidal field in the vacuum can be represented in terms of a flux function as

$$\vec{B}_p = \frac{1}{2\pi} \nabla \phi \times \nabla \chi. \quad (1)$$

The poloidal flux at the i^{th} coil, χ_i , obeys the circuit equation

$$\frac{d\chi_i}{dt} = V_i - r_i I_i; \quad i = 1, \dots, N, \quad (2)$$

which states that χ_i changes only due to resistance r_i in the coil or an applied voltage source V_i which may be part of a feedback control circuit. The value of χ_i in terms of the vacuum Green's function G is

$$\chi_i = L_i I_i - \sum_{j=1}^N I_j \mu_0 G(\vec{x}_i, \vec{x}_j) - \oint \frac{d\vec{x}}{2\pi x_b} G(\vec{x}_b, \vec{x}_i) \frac{\partial \chi(\vec{x}_b)}{\partial n}, \quad (3)$$

where x, ϕ, z are cylindrical coordinates

$$\vec{x}_i \equiv (x_i, z_i),$$

$$G(\vec{x}_i, \vec{x}_j) = -(x_i x_j)^{1/2} k^{-1} [(2 - k^2) K(k) - 2E(k)],$$

$$k^2 \equiv 4x_i x_j / [(x_i + x_j)^2 + (z_i - z_j)^2],$$

$K(k)$ and $E(k)$ are the complete elliptic integrals of the first and second kind, respectively, and $\partial\chi(\vec{x}_b)/\partial n$ is the normal derivative of the poloidal flux χ evaluated at the plasma-vacuum boundary $\vec{x}_b$. The subscript b stands for quantities at the boundary, and the line integral in Eq. (3) is taken over this interface. The self-inductance, L_i , of a circular coil with square cross section is given by³

$$L_i = \mu_0 x_i n_i^2 \left\{ \frac{1}{2} \left[1 + \frac{1}{6} \left(\frac{b_i}{2x_i} \right)^2 \right] \left[\ln 8 - 2 \ln \left(\frac{b_i}{2x_i} \right) \right] - 0.84834 + 0.2041 \left(\frac{b_i}{2x_i} \right)^2 \right\}. \quad (4)$$

Here n_i is the number of turns, x_i the mean radius of the turns, and b_i the dimension of the square cross section. In Eq. (3), the first term is due to the self-inductances of the coils, the second term comes from the mutual inductances between the coils, and the last term arises from the coupling between the coils and the plasma.

In the plasma region, the magnetic field has the form

$$\vec{B} = \frac{1}{2\pi} \nabla\phi \times \nabla\chi + R_0 B_0 \hat{g} \nabla\phi. \quad (5)$$

Here R_0 and B_0 are normalization constants, and g is the toroidal field function. In our calculation, g is always normalized to 1 in the vacuum. The spectral representation of $\vec{x} \equiv (x, z)$ in the plasma region is given by [Eq. (13) of Ref. 1]

$$x(\psi, \theta) = x^{0c}(\psi) + (\psi T)^{1/2} E(\psi) \cos \theta + \sum_{m=2}^M \psi^{(m-2)/2} [x^{mc}(\psi) \cos m\theta + x^{ms}(\psi) \sin m\theta] \quad (6a)$$

$$z(\psi, \theta) = z^{0c}(\psi) + (\psi T)^{1/2} E^{-1}(\psi) \sin \theta + (\psi)^{1/2} z^{1c}(\psi) \cos \theta + \sum_{m=2}^M \psi^{(m-2)/2} [\sigma_{a,m} x^{ms}(\psi) \cos m\theta + \sigma_{s,m} x^{mc}(\psi) \sin m\theta] \quad (6b)$$

The scale factor T is introduced so that without loss of generality, the flux label ψ always goes from 0 at the magnetic axis to 1 at the plasma boundary. For a perfectly circular outermost flux surface ($\psi = 1$), we see that $(T)^{1/2}$ is the minor radius. In general, T measures the volume in that a change in T is needed to change the plasma cross-sectional area and hence the plasma volume. The constants $\sigma_{a,m}$ and $\sigma_{s,m}$ are usually set to +1 and -1, respectively. The shape harmonics E , x^{2c} , and x^{3c} are the ellipticity, triangularity, and squareness, respectively. The boundary is given parametrically by

$$\vec{x}_b \equiv (x_b, z_b) = [x(1, \theta), z(1, \theta)] \quad (7)$$

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Interior to the plasma, the shape harmonics are determined from the plasma equilibrium condition that $\nabla p = \mathbf{J} \times \mathbf{B}$. In Ref. 1 we have used a variational principle to show that this is equivalent to the set of ordinary differential equations

$$\langle \hat{J} \hat{G} \rangle = 0 \quad (8)$$

$$\langle (xz_\theta \cos \theta + E^{-2} xx_\theta \sin \theta) \hat{G} \rangle = 0 \quad (9a)$$

$$\langle (-xz_\theta \cos m\theta + \sigma_{s,m} xx_\theta \sin m\theta) \hat{G} \rangle = 0, \quad m = 0, 2, 3, \dots \quad (9b)$$

$$\langle (xx_\theta \cos m\theta) \hat{G} \rangle = 0, \quad m = 0, 1 \quad (9c)$$

$$\langle (-xz_\theta \sin m\theta + \sigma_{a,m} xx_\theta \cos m\theta) \hat{G} \rangle = 0, \quad m = 2, 3, \dots \quad (9d)$$

where G is the Grad-Shafranov operator in the flux coordinates:

$$\begin{aligned} \hat{G} = & 2x_\psi \left\{ \frac{1}{J} \frac{\partial}{\partial \psi} \left[x_\psi \frac{(x^2_\theta + z^2_\theta)}{J} \right] - \frac{1}{J} \frac{\partial}{\partial \theta} \left[x_\psi \frac{(x_\psi x_\theta + z_\psi z_\theta)}{J} \right] \right. \\ & \left. + p' + \frac{q}{x^2} \frac{1}{\langle J/x^2 \rangle} \left[\frac{qx_\psi}{\langle J/x^2 \rangle} \right]_\psi \right\}. \end{aligned} \quad (10)$$

The poloidal angle averaging operator $\langle \rangle$ is defined as

$$\langle A \rangle = \frac{1}{2\pi} \int_0^{2\pi} A \, d\theta.$$

Equations (8) and (10) can be solved for the poloidal flux χ and the shape harmonics if the boundary conditions are given and if the functional forms of

the pressure profile $p(\chi)$ and the safety factor profile $q(\chi)$ are given.

The poloidal flux at the plasma-vacuum boundary is given by

$$\chi(\vec{x}_b) = \sum_{i=1}^N I_i [-\mu_0 G(\vec{x}_b, \vec{x}_i)] + \oint \frac{d\vec{x}_s}{2\pi x_s} [-G(\vec{x}_b, \vec{x}_s)] \frac{\partial \chi(\vec{x}_s)}{\partial n}, \quad (11)$$

where

$$\frac{\partial \chi(\vec{x}_s)}{\partial n} = x'_s [\vec{x}_s(\theta')] \{[(x_\theta^2 + z_\theta^2)^{1/2}/J]\}_s \quad (12)$$

and $\chi' \equiv d\chi/d\psi$. Both subscripts b and s stand for quantities evaluated at the boundary with b corresponding to the angle variable θ and s corresponding to θ' . The Jacobian for the transformation from the cylindrical coordinates (x, ϕ, z) to the flux coordinates (ψ, θ, ϕ) is $J = x(x_\psi z_\theta - x_\theta z_\psi)$, with subscripts ψ and θ denoting partial derivatives. Equations (3) and (11) give the self-consistent interaction between the external circuits and the plasma, and Eq. (2) governs the time evolution of the poloidal fluxes x_i at the coils. Numerically, the boundary is represented by a discrete set of line elements, and the line integrals by discrete sums. Then Eqs. (3) and (11) can be combined into a single matrix equation

$$\vec{F} = \vec{M} \cdot \vec{I}, \quad (13)$$

where $\vec{M}$ is the inductance matrix; $\vec{F}$ is the flux vector containing x_i , $i = 1, 2, \dots, N$, and the fluxes at the discrete line elements, x_b ; and $\vec{I}$ is the current vector containing the coil currents I_i , $i = 1, 2, \dots, N$, and the currents in the discrete line elements, $(\Delta i/2\pi_0 x_s) \partial \chi/\partial n$. At each time step, x_i is advanced in time for each coil:

$$x_i^{n+1} = x_i^n + \Delta t (V_i^n - r_i I_i^n); i = 1, \dots, N. \quad (14)$$

A free-boundary plasma equilibrium consistent with these x_i is calculated at each time step n as described in Ref. 1. During each free-boundary iteration step, the inductance matrix $\vec{M}$ is inverted to obtain the currents I_i . In the calculations we present here, we assume a linear voltage waveform:

$$V_i = V_i^0 (1 + \alpha_i n). \quad (15)$$

For the ohmic-heating (OH) and equilibrium field (EF) coils, the initial voltages V_i^0 , the rate of increase α_i , and the initial currents I_i^0 are given in Table 1 together with the coil locations. The locations of the set of passive copper coils which model the shell are given in Table 2.

III. START-UP MODEL

For our proof-of-principle model, we consider tokamak reactor start-up via an ohmic-heating transformer in the presence of a copper shell. The shell provides an electromagnetic shield protecting the coils, instruments, etc. outside the shell from high voltages in case of a major disruption. We consider a circular shell with a major radius of 4.8 meters and a minor radius of 2.8 meters. The shell is modeled by twenty-two up-down symmetric passive coils as shown in Fig. 1(a). While the ohmic-heating transformer flux is increased, simultaneous variation of the currents in the vertical field coils (EF1 and EF2) is needed to maintain major radius equilibrium. Ideally one would need some sort of a feedback circuit to have precise control of the plasma position. In the calculation to be presented, we simply chose an appropriate value for α_i , $i = \text{EF1, EF2}$, for a given value of α_{OH} as shown in

Table 1. For simplicity, we chose the OH and EF coils to be superconducting; the calculation would proceed exactly the same way if they were coils with finite resistance.

In our model, the self-consistent flux linkages between the plasma, the driven external coils, and the eddy currents in the conducting shell are incorporated. Furthermore, we assume a constant safety factor (q) profile and a variable toroidal flux within the plasma. These features depart from ideal MHD assumptions and model the internal current profile relaxation processes. In other words, if the current relaxation processes fix the q -profile of a tokamak, then the plasma current will be directly proportional to the toroidal flux contained in the plasma. Because the plasma current must be consistent with the flux linkages involving external coils, the toroidal flux within the plasma, and hence the plasma size, will increase as the current builds up.

The numerical procedure is as follows:

A. $t = 0$ ($n=0$)

(i) Calculate the initial amount of poloidal flux in the plasma, $\Delta\chi$, with g normalized to 1 in the vacuum for a given value of the scale factor T .

(ii) Calculate the initial poloidal flux at plasma/vacuum boundary x_b by minimizing the mean-square error¹

$$\epsilon = \langle [x_b - x(\tilde{x}_b(\theta))]^2 \rangle \quad (16)$$

with respect to x_b yielding

$$x_b = \langle x(\tilde{x}_b(\theta)) \rangle . \quad (17)$$

(iii) Calculate the total magnetic flux linkage at the magnetic axis:

$$x_{MAG} = x_b + \Delta x . \quad (18)$$

For a thermonuclear plasma, resistive dissipation will be negligible at the magnetic axis. Then x_{MAG} is fixed throughout the whole simulation. But x_b and Δx may individually change as the external voltage sources are changed and the plasma current builds up. For a fixed q -profile, the toroidal flux in the plasma is directly proportional to the poloidal flux Δx . In this model, no skin current develops, but instead, the internal poloidal flux Δx varies, and hence, so does the toroidal flux in the plasma.

B. $t > 0$ ($n = 1, 2, \dots$)

The procedure for each time step for $n > 0$ is exactly the same:

(i) Start with a different scale factor T and repeat steps (i) and (ii) in

A.

(ii) Calculate the new total magnetic flux linkage x_T at the axis:

$$x_T = x_b + \Delta x . \quad (19)$$

In general, x_T may not be equal to x_{MAG} , and T has to be adjusted so that they

are equal. We iterate on T as follows:

$$T^{j+1} = T^j - \frac{(x_T^j - x_{MAG}^j)}{x_T^j - x_T^{j-1}} (T^j - T^{j-1}) \quad (20)$$

Note that for each iteration step j, a free-boundary equilibrium calculation has to be made. For completeness, a comparison between the start-up model reported here and the adiabatic compression model to be reported elsewhere is given in Table 3.

IV. RESULTS

The initial equilibrium and profiles are shown in Fig. 1. The plasma minor radius is 1.1 m, $(T^{1/2} = 1.1)$, the volume-averaged beta, $\langle \beta \rangle$, is 0.27%, and the plasma current, I_p , is 2.46 MA. Initially, all the passive shell elements have zero current: $I_i^0 = 0$; $i = 1, \dots, 22$. After 23 time steps with $\Delta t = 50$ ms, a final equilibrium with $(T)^{1/2} = 2.01$ m, $\langle \beta \rangle = 0.2\%$, and $I_p = 14.39$ MA is reached (Fig. 2.). In both Figs. 1 and 2, the current profile j is measured in units of $2\pi\mu_0/B_0$, and the pressure profile p is measured in units of μ_0/B_0^2 . The L/R times of the shell elements vary from 67 ms to 85 ms. Thus the start-up phase is about 13 times the L/R times of the shell elements, and a nearly 5-fold increase in the plasma current is achieved. Values of 5 tesla for B_0 and 4.8 m for R_0 [in Eq. (5)] have been used in the calculation.

The time evolution of the magnetic axis is given in Fig. 3(b), showing that the plasma moved inward; one could fix the plasma position by using a feedback control circuit. The shape harmonics of the boundary, ellipticity (E_b), triangularity (x_b^{2c}), and squareness (x_b^{3c}) evolve in time as shown in Figs. 3(a), (c), and (d), respectively. Here the conventional definition of

ellipticity differs from E_b and is given by $E_{\text{CONV}} = 1/E_b^2$. The time evolutions of $(T)^{1/2}$, I_p , $\langle \beta \rangle$, Δx , and χ_b are shown in Fig. 4 while those of the line current in the OH and EF coil systems are given in Fig. 5. Finally, Fig. 6 shows how the eddy currents in some of the shell elements change in time.

V. CONCLUDING REMARKS

We have presented a model to simulate the current start-up phase of a tokamak reactor plasma. This time scale is short compared to the flux diffusion time on the magnetic axis, but long compared to the anomalous current penetration time. Thus the poloidal flux value on the magnetic axis remains fixed while the amount of poloidal flux within the plasma increases. Our model of a fixed q -profile and a variable toroidal flux with no surface current allows for the growth of the plasma current as the ohmic-heating transformer flux is increased. Using this model, we have shown that it is feasible to start up ohmically a tokamak plasma which is surrounded by a thick conducting shell without breaks. Since the conducting shell will, in general, have near zero current in both the initial and the final current flat-top stage, its presence will not compromise the volt-sec swing delivered to the plasma, although it will ohmically dissipate transformer energy and set a lower limit on the plasma current build-up time.

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Table 1

Locations, initial voltages, and line current for the ohmic-heating (OH) coils, the outboard (EF1), and the inboard (EF2) equilibrium field coils. Each coil is superconducting with ten turns, and $b_1 = 0.05$ m. Up-down symmetry is assumed.

i	I_i	V_i	α_i	x	z
	(A)	(volts)		(m)	(m)
OH	110000.	-3000.	0.10	1.0	0.295
				1.0	0.590
				1.0	0.880
				1.0	1.180
				1.0	1.475
				1.0	1.770
				1.0	2.065
				1.0	2.360
				1.0	2.655
EF1	-32000.	-750.	0.49	8.60	1.70
				8.60	3.40
				6.0	3.80
EF2	110000.	-250.	0.08	3.0	3.60

TABLE 2.

Locations of passive copper coils for the shell. Up-down symmetry is assumed, and $I_1^0 = 0$, $b_1 = 0.05$ m.

i	x	z
1	7.50459	0.72469
2	7.22487	1.4
3	6.77990	1.9799
4	6.2	2.42487
5	5.52469	2.70459
6	4.8	2.8
7	4.07531	2.70459
8	3.4	2.42487
9	2.8201	1.9799
10	2.37513	1.4
11	2.09541	0.72469

TABLE 3

Comparison Between Start-up and Adiabatic Compression Models

Start-up	Adiabatic Compression
1. $\tau > \tau_{cp}$	1. $\tau < \tau_{cp}$
2. Ideal MHD Eqs. valid at hot plasma center only.	2. Ideal MHD Eqs. valid everywhere
3. q-profile assumed to be fixed function of $(\chi - \chi_{MAG})/\nabla\chi$ (deviates from MHD assumptions).	3. q-profile remains fixed function of χ (MHD invariant)
4. Anomalous current penetration destroys surface current while keeping q_{edge} fixed.	4. Surface current develops to conserve flux.
5. χ_{MAG} fixed ($\chi_{MAG} = \chi_b + \Delta\chi$)	5. χ_{MAG} fixed
6. $\Delta\chi$ varies	6. $\Delta\chi$ fixed
7. χ_b varies	7. χ_b fixed
8. Volume varies	8. Volume decreases

FIGURE CAPTIONS

- FIG. 1 (a) Initial plasma equilibrium with $(T)^{1/2} = 1.1$ m, $\langle \beta \rangle = 0.27\%$, and $I_p = 2.46$ MA, (b) safety-factor profile, (c) current profile, and (d) pressure profile.
- FIG. 2 (a) Final plasma equilibrium with $(T)^{1/2} = 2.01$ m, $\langle \beta \rangle = 0.2\%$, and $I_p = 14.39$ MA, (b) safety-factor profile, (c) current profile, and (d) pressure profile.
- FIG. 3 Time evolution of (a) boundary ellipticity E_b , (b) magnetic axis, (c) boundary triangularity, and (d) boundary squareness.
- FIG. 4 Time evolution of (a) square-root of the scale factor T , (b) plasma current I_p , (c) volume-averaged beta $\langle \beta \rangle$, (d) amount of poloidal flux in the plasma $\Delta\chi$, and (e) poloidal flux value at the boundary χ_b .
- FIG. 5 Time evolution of the line currents in (a) ohmic-heating coils, (b) outboard equilibrium field coils, and (c) inboard equilibrium field coils.
- FIG. 6 Time evolution of eddy currents in some of the passive shell elements.

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Fig. 1

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Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

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