PPPL--1967

NUMERICAL STUDY OF THE MAGNETIC FIELD DIFFUSION

DE83 006549

IN THE

TOROIDAL FIELD COILS OF THE TFTR

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Abstract

The diffusion of the vertical magnetic field through the toroidal field coils is numerically analyzed in TFTR. Two different excitations of the vertical field are assumed whose behavior can be described by either a step function or a ramp function. Using the computer code FEDIFF, the distribution of the eddy currents in the windings and casing of the toroidal field coils, as well as their time behavior, is calculated for these functions. From integration of the eddy current functions over their pulse length, the energy dissipated by them is obtained. Finally, the magnetic field of the eddy currents within the torus is calculated. Based upon this field, which is represented as a function of time and space coordinates, the influence of this diffusion upon the field curvature index is described.

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1. Introduction

In tokamaks the vertical magnetic field, often called equilibrium field (EF), varies with time. Eddy currents are induced when the EF diffuses through a conductor, such as a metal wall or the toroidal field (TF) coils. Because the field from these eddy currents superimposes itself upon the EF, the plasma equilibrium will be perturbed, since the equilibrium is provided by the vertical magnetic field. Consequently, detailed knowledge of the eddy current's evolution is a prerequisite if the control of the plasma equilibrium is to be attempted by feedback.

Additionally, eddy current calculations are needed when the thermal effects must be considered by calculating the dissipated energies.

To summarize, the purpose of this report is to investigate the diffusion of the EF through the TF coils by numerical computation as it relates to the Princeton Tokamak Fusion Test Reactor (TFTR).

2. Method of Calculation

The computer code FEDIFF uses the so called "finite element network method" (FENM)^{1,2} for the numerical calculations. By using this method the metal walls penetrated by the field are divided into rectangular elements of a finite thickness. These elements can be considered as branches of a three-dimensional electrical network. Each element is assigned to one of the directions of a curvilinear orthogonal coordinate system u , v , w . Henceforth these elements will be called u -, v -, or w -plates. Each network branch which is formed from a u -, v -, or w -plate has a resistance R_μ , a self-inductance $L_{\mu\mu}$, and a mutual inductance $L_{\mu\nu}$ which

can be calculated from the geometric structure and the position of the finite elements or the coils. After this all network parameters can be assembled in matrix form resulting in a system of ordinary differential equations for the branch currents (i). From the solution vector (i) of the branch currents one obtains directly the distribution of the eddy currents.

In the final step their magnetic fields are computed which, when superimposed on the exciting field, describes the diffusion process.

2.1 Computational Model of the TFTR

Let us define the numerical model for the EF diffusion mechanism through the TF coils and their casing structure. The EF will be produced by twelve coils which are arranged coaxially with the Z axis and symmetrically with respect to the $Z=0$ plane (Fig. 1). With the EF coils connected in series, their current, i_{EF} , varies with time. The winding direction of the six coils located closest to the Z axis is positive, while that of the rest of the EF coils is negative. An essentially vertical EF field in the plasma region is produced. This field is to penetrate through the twenty TF coils. The position of the two coil systems and the coordinate systems are shown in Fig. 1. The TF coils in which the eddy currents are being induced are now divided into finite elements according to the FENM. Each TF coil consists of two symmetrical pancakes, surrounded by a stainless steel casing. In order to simplify the calculations, the side walls of the casing are neglected (but will be considered in future calculations) so that the casing according to Fig. 1 consists only of an inner and

outer cylinder. By doing this and because of the insulation between the windings, eddy currents will not flow in the w direction. By using this approximation the loss of accuracy of the calculations will not be too great since the surfaces which are surrounded by the eddy current lines in $w=\text{constant}$ planes are much larger than those in the $u=\text{constant}$ planes.

Figures 1 and 2 indicate that the upper half of a pancake is the smallest symmetrical part of the TF coil system. The structure of the vertical section of a pancake is shown in Fig. 3. In the model each pancake is divided in $MW=3$ layers, one over the other. One is for the copper winding, the other two for the inner and outer cylinder of the casing. Each of these layers will be divided in $MUUP$ u -plates in the u direction and in $MVUP$ v -plates in the v direction (Fig. 4). This determines the number of v -plates to be used. As shown in Fig. 4, one pancake half is being approximated by

$$NP = [MUUP \cdot MVUP + (MUUP + 1) (MVUP - 1)] MW \quad (1)$$

plates or network branches. For $N=20$ TF coils, each with 4 pancake halves, one obtains an eddy current network with

$$NG = 4 \cdot 20 \cdot NP \quad (2)$$

branches consisting, due to the symmetry, of 80 identical partial networks. The transient analysis of the eddy currents can therefore be reduced to a partial network of one pancake half. However this

must be done with consideration of the mutual inductances to all NG branches of the network.² The value of the mutuals diminishes quickly with increasing distance between the network branches. Therefore, in the case of TFTR only the mutuals between the branches of three adjacent coils are to be considered (Fig. 2). The error resulting from this approximation is less than 2% which was demonstrated in a comparative calculation.

Finally, the different boundary conditions from the winding and casing are to be mentioned. In this investigation, the symmetry plane $y=0$ of the TF coil (Fig. 1) is a stream line boundary (s boundary) for the winding while it is an equipotential boundary (e boundary) for the casing. That means the eddy current lines in the winding run parallel to the $y=0$ plane due to the insulation between the pancakes, and in the casing the lines are perpendicular to the $y=0$ plane. Figure 4 shows how these different boundary conditions have to be considered in the arrangement of the u- and v-plates.^{1,2}

3. Numerical Calculations

The TFTR related results presented in Section 4 were obtained with the computer code FEDIFF. (Computations were done on the Cray-1 computer at the MFE Computer Center in Livermore.) FEDIFF generates its results in four principal steps. These steps can be taken in one or several consecutive executions. Figure 5 shows the steps that will execute the following computations.

- Step 1: Compute the inductance and resistance matrices of the TF coils network.
- Step 2: Compute the mutuals between the eddy current network in the TF coils and the EF coils.
- Step 3: Solve the network differential equation system.
- Step 4: Compute magnetic fields from the eddy currents.

3.7 TFTR Input Data

Step 1:

a) Geometric Data for the TF Coils (Fig. 1)

major radius	RG=2.8m
center coordinance	Z=0
radius of the coils	r=1.6745m
coil half width	BH=0.167
radial coil thickness	D=0.375m
radial thickness of the inside casing	DI=0.07m
radial thickness of the outside casing	DA=0.14m
number of coils	NL=20

b) Selected Arrangement of Plates in one Pancake

number of layers	MW=3
number of u-plates in poloidal direction	MUUP=8

number of u-plates in toroidal direction	MVUP=4
number of coils considered for inductance calculation	ID=3
plate thickness in the winding	DP=0.335m
plate thickness in the inside casing	DI=0.07m
plate thickness in the outside casing	DA=0.14m

c) Resistivities

copper	$\zeta_c = 1.72 \cdot 10^{-8} \text{ m}\Omega$
stainless steel	$\zeta_{ss} = 7.7 \cdot 10^{-7} \text{ m}\Omega$

Step 2: Geometric data for the EF coils (Fig. 1),
see handbook version 51A

number of EF coils	NE=12
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Step 3: time increment $\Delta t = 5 \text{ msec}$
time limit $TE = 0.4 \text{ sec}$

a) current in EF coils (step function)

$$i_{EF}(t) = \begin{cases} 0 & \text{for } t \leq 0 \\ 1\text{KA} & \text{for } t \geq 0 \end{cases}$$

b) current in EF coils (ramp profile)

$$i_{EF}(t) = \begin{cases} 500\text{KA/s} \cdot t & \text{for } 0 \leq t \leq 50 \text{ ms} \\ 25\text{KA} & \text{for } 50 \text{ ms} \leq t \leq TE \end{cases}$$

Step 4: grid for the field points:

R coordinate (m)	R = 1.8, 3.8, 0.2
ϕ coordinate (degree)	$\phi = 0.0, 9.0, 3.0$
Z coordinate (m)	Z = 0.0, 0.8, 0.2

4. Results

4.1 Introductory Remarks

Following are a few brief comments which may be useful in understanding some aspects of magnetic field diffusion. If i_{EF} is the EF coil current with a pulse shape shown in Fig. 6, curve 1, then the resulting eddy current $i_{EC}(t)$ is shown as curve 3. This curve has two distinct branches, which are the current rise and decay phase. The current rise time, T_r , depends on the rise time of the magnetic field excitation and the magnetic coupling, whereas the decay time, T_d , is a function primarily of the time constant τ , that is a composite of all L/R 's in the eddy current network. Of these two characteristic times, T_r and T_d , T_d has the greater practical significance. For this purpose, it is economical to define i_{EF} as a step function (curve 2 in Fig. 6). Then τ can be directly measured from the time function $i_{EC}(t)$, which, in this borderline case, is tangential to curve 4 in Fig. 6. Furthermore, Fig. 6 shows that the maximum of $i_{EC}(t)$ is an absolute maximum when the excitation, i_{EF} , is a step function.

An additional quantity of importance is the shielding parameter in its $t=0+$ definition,

$$F_0 = 1 - B_{EC}/B_{EF} \quad (3)$$

where B_{EC} is the flux density from eddy currents, and B_{EF} the EF flux density. F_0 is a measure of the EF fraction instantly present in the toroidal space behind the shielding structure when the EF is applied as a step function (Fig. 7). Hence, because F_0 is defined at an infinitesimally small positive time, $t=0+$, F_0 is zero in the volume region bounded by a closed metal surface. When $0 < F_0 < 1$, then F_0 may be considered a figure of merit for the degree of shielding if the shielding is incomplete as in the example of the toroidal region partially enclosed by the TF coils.

4.2 Eddy Currents

The eddy current networks have been developed for the selected arrangement and are shown in Figs. 8 and 9 with the branch numbering given there. The network in Fig. 8 (case A) is used on all computations including the TF coil casing. It is advantageous at this point to remember that each network branch has a specific position in the winding or the casing of the TF coils. The size and direction of each branch current can therefore be inferred directly from its respective spatial position in the coil body. This provides the spatial distribution of the eddy currents in the coils, and is derived from the computed branch currents.

The eddy current distribution which was first calculated is shown in Fig. 10. This calculation was made under the assumption that $i_{EF}(t)$ in the EF coils is a step function of $i_0 = 1\text{KA}$.

The eddy current lines for case A and B are given in Fig. 10 as they appear at the time $t=0$. As expected, the eddy currents flow initially only on the surfaces of the coils until they reach the current values as given in Fig. 10. One can recognize in Fig. 10 the different shape of the eddy current lines in winding and casing, as pointed out earlier. In the winding they run tangentially to the plane $y=0$, while in the casing they are perpendicular to it.

4.2.1 The Influence of the Casing on the Diffusion

In order to investigate this influence, the two cases A and B which have been calculated for the step function $i_{EF}(t) = i_0 = 1\text{KA}$ must be compared. The results in Fig. 10 show that in case A the induced currents in the winding are significantly larger than in case B. This result is not surprising, for it demonstrates the expected screening effect of the casing on the winding. The screened eddy currents in the outer cylinder of the casing are greater than those in the inner cylinder. This is because the outer cylinder is closer to the field-generating EF coils than the inner cylinder. The comparison of both cases lends itself to another interesting observation. For this the discussion concerning $t=0$ has to be extended to the entire time scale of the diffusion process. Figure 11 shows the exponential decay of the eddy currents in

case A (numbers on curve represent the branch of the respective network). Analogous to the selection of dominant branch currents in case A, the time behavior of the eddy currents in case B are given in Figs. 12-14 (numbers on curve represent the branch of the respective network). For example, the branch current 31 of Fig. 11 is in the same position within the winding as is the branch current 85 of Fig. 12, etc. In case B the eddy currents in the winding reach their maximum only after they have decayed in the casing, whereas in case A they decay continuously. Due to the considerably higher resistance of the casing as compared to that of the winding, the diffusion through the casing occurs much faster than through the winding (Figs. 12-14). Because of this, the induction in the winding is modified causing the eddy currents to increase. After reaching the maximum, i.e., when the diffusion through the casing is finished, the currents in the winding decay exponentially toward zero.

4.2.2 The Profile of the Excitation Current

In the previous calculations it was always assumed that the time behavior of the excitation current, $i_{EF}(t)$, in the EF coils is a step function. For case B we shall demonstrate how the time behavior of the eddy currents changes if $i_{EF}(t)$ assumes the profile of a ramp. A ramp profile is a more realistic excitation than step function and has the following form:

$$i_{EF}(t) = \begin{cases} 500 \text{ KA/s.t for } 0 \leq t \leq 50 \text{ msec} \\ i_o = 25 \text{ KA for } t \geq 50 \text{ msec} \end{cases} \quad (4)$$

The time behavior of the eddy currents for this ramp is shown in Figs. 15 and 16. The numbers on the curves indicate again, as shown in Figs. 12 and 14, the branch number of the network according to Fig. 9. The most significant result can be seen in a comparison of the corresponding curves of Figs. 12 and 15 and Figs. 14 and 16, respectively. It is shown here that the maxima of the eddy currents have decreased to 85% in the winding and to 9% in the casing. This can be explained as follows: The rise time $T_r = 50 \text{ msec}$ of the current $i_{EF}(t)$ is much smaller than the time constant $\tau_w = 120 \text{ msec}$ of the winding but much greater than the time constant $\tau_c = 10 \text{ msec}$ of the casing.

4.3 The Dissipated Energy of the Eddy Currents

The dissipated energy of the eddy currents in the TF coils during the diffusion is calculated. The following equations pertaining to the network are being used:

$$(P) = (i_b)^T (R_b) (i_b), \quad (5)$$

$$(w) = \int_0^{te} (P) dt \quad (6)$$

with

(i_b) , $(i_b)^T$ the vector, respectively the transformed vector of the branch currents,

(R_b) the resistance matrix,

(P) the vector of the dissipative powers,

(w) the vector of the dissipative energies.

For n_b branches of the network all matrices have the dimension n_b . In case B, Eq. (6) is being numerically integrated over the pulse length of $t_e = 0.4$ sec. By this time all eddy currents are negligible. This integration is performed for both kinds of excitations where the steady state value of each current is $i_0 = 25$ KA. The results are given in Table 1.

TABLE 1 Dissipated Energy in a TF Coil

	<u>Step Function</u>	<u>Ramp Function</u>
a) Winding	$W_w = 31.1$ kJ	$W_w = 26.96$ kJ
b) Inside Casing	$W_{ic} = 27.0$ kJ	$W_{ic} = 2.0$ kJ
c) Outside Casing	$W_{oc} = 63.05$ kJ	$W_{oc} = 6.56$ kJ
TOTAL	$W = 121.15$ kJ	$W = 35.52$ kJ

4.4 The Magnetic Field of the Eddy Currents

In the final step, the influence of the diffusion on the EF in the torus will be investigated. In order to do this, it is necessary to analyze the magnetic field of the eddy currents (EC field) with reference to its temporal behavior and its spatial distribution. This analysis is being done for both excitations of the EF coils as defined in Section 3.1.

- a) Excitation current $i_{EF}(t)$ as step function - The EC field in the center of the plasma column ($R = 2.8$ m, $\phi = 0$, $Z = 0$) resulting from this excitation is represented in Fig. 17. Here curve 1 represents the EC field versus time in Case A and curve 2 the EC field in Case B. The two distinct branches of curve 2 demonstrate clearly the sequential development of field diffusion through the winding and casing. The steep part of the curve describes the diffusion through the casing and the gently declining one is through the winding. After the diffusion through the casing is finished, curve 2 and 1 are united. The temporal behavior of the diffusion process can be characterized by the time constants. The time constants τ_w and τ_c for winding and casing, which are derived from these curves, are:

Case A, $\tau_w = 120$ msec

Case B, $= \begin{cases} \tau_c = 10 \text{ msec} \\ \tau_w = 120 \text{ msec} \end{cases}$

These curves also serve for calculating the value F_0 , (Eq. 3) at the time $t=0$. The fraction F_0 is the prompt field penetration into the torus, and accordingly amounts to:

Case A, $F_0 = 94.7\%$

Case B, $F_0 = 88.6\%$

Because of the relatively large gaps between the TF coils, the value F_0 must naturally be relatively large.

Henceforth we will only discuss Case B which is the more realistic case. Figures 18-21 show the EC field by using different forms of representations.³ These curves represent the maximum EC field ($t=0$) in the plasma region.

- b) Excitation current $i_{EF}(t)$ with ramp profile - In Section 4.2.2 it was shown how the curve profile of $i_{EF}(t)$ determines size and time behavior of the eddy currents. Consequently, this must also have an effect on the EC field. In Fig. 22 is shown the time behavior of the EC field in the center of the plasma column if $i_{EF}(t)$ has a ramp profile. For this excitation the flux density B of the EC field achieves only $\approx 50\%$ of the B value which was obtained in the case of the step function. It is obvious that the effect of the casing on the diffusion mechanism has been considerably diminished, while that of the winding has been almost maintained. The reason for this has already been discussed in Section 4.2.2. Analogously to

Section a) above, the spatial distribution of the EC field is shown again in various parameter representations (Figs. 23-27). (By comparing the curve representations, the different pulse height in step and ramp functions is to be considered.)

4.5 Total Magnetic Field in the Torus

The magnetic flux density $\vec{B}_i$ of the resulting field in the torus is achieved by superimposing the flux densities $\vec{B}_{EF}$ and $\vec{B}_{EC}$ of the EF and the EC field. This results in:

$$\vec{B}_i = \vec{B}_{EF} + \vec{B}_{EC}, \quad (7)$$

where $\vec{B}_{EF}$ is the flux density of the undisturbed field. For the two excitations discussed above, the components B_{zi} and B_{ri} of the flux density $\vec{B}_i$ are shown in Figs. 28 and 29 as they relate to the EF. The curves in Figs. 28 and 29 show the field $\vec{B}_i$ in the torus at the time of the maximal EC field. The excitation of the EF results from a step function (curve 1) and from a ramp function with a rise time of 50 msec, (curve 2). Since the components of $\vec{B}_{EF}$ and $\vec{B}_{EC}$ are in opposite directions, a reduction of $\vec{B}_i$ results in the torus compared to the undisturbed case.

4.6 The Field Curvature Index

In order to achieve a stable equilibrium in magnetically confined plasma, the vertical field must have certain characteristics. In short, a stability configuration has to be created. Whether a field configuration fulfills this demand can be determined by the so-called field index

$$n = -\frac{R}{B} \cdot \frac{\partial B}{\partial R} \quad (8)$$

As can be seen in Eq. (8), the field index n is a measure for the curvature of the field lines. The condition of stability of the equilibrium position of the plasma column relative to vertical and horizontal displacements can be written as⁴

$$0 < n < 1.5 \quad (9)$$

Now we will show the influence the field diffusion has on n . In doing so, $n = f(R)$ has been calculated along the midplane $Z=0$. This is shown once with (curves 2) the field diffusion included and once without (curves 1), (Figs. 30 and 31).⁵ The curves of Fig. 30 were calculated for a step function and those of Fig. 31 for a ramp function of the excitation current. In both cases it is shown that under consideration of the field diffusion, n can also assume negative values. This results in a curvature of the field lines in opposite directions.

5. Final Remarks

Concerning the accuracy of the FENM, it is important to point out that:

- a) In a comparison between measured and calculated results, there are deviations of less than $\pm 5\%$. This study was conducted within the framework of the ZEPHYR designs.⁶

- b) In comparative calculations with increasing numbers of finite elements, converging results were achieved.

In the calculations presented here the error certainly will be smaller than 10%. In this are included errors which were caused by the FENM, errors which result from the chosen approximation (number of finite elements), and numerical errors.

Generally the FENM should be advantageous for diffusion calculations in geometrically complicated devices without iron. By this method, in contrast to the finite difference procedures, only the conductor volume and not the entire space must be modeled. The existing interactions between the finite elements can be ascertained simply by the mutuals. Thus, in the final analysis, storage demand in the computer and CPU time are considerably reduced.

6. References

- ¹U.R. Christensen, Time Varying Eddy Currents on a Conducting Surface in 3-D using a Network Mesh Method, Princeton Plasma Physics Laboratory Report PPPL-1516, 1979.

- ²H. Preis, Die Finite - Element - Netzwerkmethode für dreidimensionale Wirbelstromberechnungen in Experimenten zur kontrollierten Kernfusion. Archiv für Elektrotechnik 65, 233-239 (1982).

- ³H.F. Vogel and H. Preis, Study on Diffusion of the Vertical Magnetic Field in the Toroidal Stabilizing Shell of the ZT-40 Reversed Field Pinch Device. Los Alamos National Laboratory Report (to be published).

- ⁴V.S. Mukhovatov and V.D. Shafranov, Plasma Equilibrium in a Tokamak. Nucl. Fusion 11, (1971).

- ⁵M. Pelovitz, MPLOT - A General Calcomp Drafting Routine, Princeton Plasma Physics Laboratory Report PPPL-TM-314, 1978.

- ⁶N. Gottardi, F. Mast, H. Preis, and R. Sub, Diffusion of the Vertical Field into the Tape-Wound Magnet, Max-Planck-Inst. für Plasmaphysik, IPP-Report 1/189, 1981.

7. Acknowledgements

My special thanks go to U.R. Christensen for the many stimulating and valuable discussions which we had in connection with this report.

This work was supported in part by the U.S. Department of Energy Contract Number DE-AC02-76-CHO-3073 and in part by the Max-Planck-Institute für Plasmaphysik, Garching, Germany.

8. Figure Captions

FIG. 1 Arrangement of the TF and EF coils in the TFTR.

FIG. 2 Arrangement of u-plates in the TF coils.

FIG. 3 Model for calculating the TF coils and casing.

FIG. 4 Modeling of the TF coils: (a) winding, (b) casing. Flattening of the poloidal shape of an upper pancake half. Direction arrows of the u- and v-plates are directed in poloidal and toroidal direction.

FIG. 5 Flow diagram of the 3-d field diffusion code FEDIFF.

FIG. 6 Principle time behavior of the induced eddy currents.

FIG. 7 Principle behavior of the diffusion process.

FIG. 8 Case A: Eddy current network of the upper half of the pancake winding.

FIG. 9 Case B: Eddy current network of the upper half of the pancake winding and casing.

FIG. 10 Top view of the TF pancake coil. Eddy current distribution in the first moment from a $i_{EF}(t) = i_0 = 1\text{KA}$ external excitation.

FIG. 11 Case A: Time behavior of the eddy currents in the TF coil windings for a $i_{EF}(t) = 1\text{KA}$ step function excitation. Curves numbered in accordance with Fig. 8.

FIG. 12 Case B: Time behavior of the eddy currents in the TF coil windings for a $i_{EF}(t) = 1\text{KA}$ step function excitation. Curves numbered in accordance with Fig. 9.

FIG. 13 Case B: Time behavior of the eddy currents in the TF coil inside casings for a $i_{EF}(t) = 1\text{KA}$ step function excitation. Curves numbered in accordance with Fig. 9.

FIG. 14 Case B: Time behavior of the eddy currents in the TF coil outside casings for a $i_{EF}(t) = 1\text{KA}$ step function excitation. Curves numbered in accordance with Fig. 9.

FIG. 15 Case B: Time behavior of the eddy currents in the TF coil windings when a $i_{EF}(t)$ pulse (height 25KA, rise time 50 msec) is applied. Curves numbered in accordance with Fig. 9.

FIG. 16 Case B: Time behavior of the eddy currents in the TF coil outside casings when a $i_{EF}(t)$ pulse (height 25KA, rise time 50 msec) is applied. Curves numbered in accordance with Fig. 9.

FIG. 17 Time behavior of the EC field component B_z when a $i_{EF}(t) = 1\text{KA}$ step function is applied. Field point: $R = 2.8\text{m}$; $\phi = 0$, $Z=0$. Case A curve 1; Case B curve 2.

FIG. 18 Case B: EC field component B_z versus radius R at time $t=0$ when a $i_{EF}(t) = 1\text{KA}$ step function is applied. Field points: $\phi=0$; parameter Z is in meters.

FIG. 19 Case B: EC field component B_R versus radius R at time $t=0$ when a $i_{EF}(t) = 1\text{KA}$ step function is applied. Field points: $\phi=0$; parameter Z is in meters.

FIG. 20 Case B: EC field component B_z versus toroidal angle ϕ at time $t=0$, when a $i_{EF}(t) = 1\text{KA}$ step function is applied. Field points: $Z=0$; parameter R is in meters.

FIG. 21 Case B: EC field component B_R versus toroidal angle ϕ at time $t=0$ when a $i_{EF}(t) = 1\text{KA}$ step function is applied. Field points: $Z=0.8\text{m}$; parameter R is in meters.

FIG. 22 Case B: Time behavior of the EC field component B_z , when a $i_{EF}(t)$ pulse (height 25KA , rise time 50 msec) is applied. Field points: $R=2.8\text{m}$; $\phi=0$; parameter Z is in meters.

FIG. 23 Case B: EC field component B_z versus radius R , when a $I_{EF}(t)$ pulse (height 25KA , rise time 50 msec) is applied. Field points: $\phi=0$; $Z=0$. Parameter is the time in seconds.

FIG. 24 Case B: EC field component B_z versus radius R at the time $t=50\text{ msec}$, when a $i_{EC}(t)$ pulse (height 25KA , rise time 50 msec) is applied. Field points: $\phi=0$; parameter Z is in meters.

FIG. 25 Case B: EC field component B_R versus radius R at the time $t=50$ msec, when a $i_{EF}(t)$ pulse (height 25KA, rise time 50 msec) is applied. Field points: $\phi=0$; parameter Z is in meters.

FIG. 26 Case B: EC field component B_z versus toroidal field angle ϕ at the time $t=50$ msec, when a $i_{EF}(t)$ pulse (height 25KA, rise time 50 msec) is applied. Field points: $Z=0$; parameter R is in meters.

FIG. 27 Case B: EC field component B_R versus Z at the time $t=50$ msec, when a $i_{EF}(t)$ pulse (height 25KA, rise time 50 msec) is applied. Field points: $R=2.8m$; parameter ϕ is in degrees.

FIG. 28 Case B: Component B_{z1} related to the undisturbed field B_{zEF} of the total magnetic field B_1 in the torus versus radius R at the time of maximal fields. Curve 1, excitation by a step function. Curve 2, excitation by a ramp function with a rise time of 50 msec.

FIG. 29 Case B: Component B_{R1} related to the undisturbed field B_{REF} of the total magnetic field B_1 in the torus versus Z at the time of maximal fields. Curve 1, excitation by a step function. Curve 2, excitation by a ramp function with a rise time of 50 msec.

FIG. 30 Case B: Index of curvature of the EC field lines versus the midplane distance R at the time $t=0$ when a step function ($i_{EF}(t)$) is applied. Curve 1, without consideration of the field diffusion. Curve 2, with consideration of the field diffusion.

FIG. 31 Case B: Index of curvature of the EC field lines versus the midplane distance R at the time $t=50$ msec when a $i_{EF}(t)$ pulse (height 25KA, rise time 50 msec) is applied. Curve 1, without consideration of the field diffusion. Curve 2, with consideration of the field diffusion.

#82E0204

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

#82E0185

#82E0219

Fig. 7

Fig. 8

#82E0191

Fig. 9

#82E0186

(a) Winding Without Casing

(b) Winding With Casing

Fig. 10

Fig. 11

#82E0201

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

82E0213

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28

Fig. 29

Fig. 30

Fig. 31