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**Internal Resistive Initiation
Coil Electromagnetics
in the FED/INTOR Baseline Design**

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INTERNAL RESISTIVE INITIATION COIL ELECTROMAGNETICS IN THE FED/INTOR BASELINE DESIGN

by

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ABSTRACT

This study determined some of the electric requirements for radio-frequency nonassisted plasma initiation from normal conducting coils inside tokamak toroidal field coils in the presence of cryostats and other major structures. We also studied the effects of bellows or highly insulated sections. Depending on whether or not insulating sections are used, the field penetration time is 50 to 90 ms, the blip pulse length is 0.15 to 0.19 s, and the power supplied to the blip coils is 400 to 700 MW. Because of its plasma stabilizing effect, a highly conducting vacuum shell is recommended.

INTRODUCTION

This study was made to determine some of the electric requirements for plasma current initiation from internal and normal conducting coils in the presence of cryostats and other major structures. Eddy current losses, induced voltages, and effects of bellows or highly insulating sections are determined.

The induced currents in the Fusion Engineering Device or International Tokamak Reactor (FED/INTOR) structures will be important in the design of the vacuum vessel. This is true in machines now being constructed, and it will be more important for FED/INTOR because of a thicker vacuum vessel, large areas for neutron-shield material, added cooling piping, the great amount of stored energy associated with the plasma current, and increased requirements for maintainability.

Initiation, as well as a major fast disruption with the plasma current vanishing in 20 ms, causes the following.

- Large currents are induced in structures, which by mutual interaction generate forces and torques on adjacent coils and structures. The toroidal induced currents interact with the steady-state vertical or horizontal fields to provide electromagnetic forces. Similarly, radially directed currents induced in the

structures, particularly in the sector end plates, interact with the toroidal field to produce large forces and torques on each segment of the vacuum vessel. If the construction arrangement of the vacuum-vessel segments results in arcs or currents at right angles to the toroidal field, erosion and large forces or torques occur on the segments.

- A voltage is induced in external poloidal coils that can cause damage to insulation. The superconducting coil terminals limit the allowable induced voltage.
- The superconductor operation requires a safe margin between the superconducting state and the normal state. Induced eddy currents increase the required safety margins in the toroidal field (TF) coils. The heat generated by eddy currents in structures at superconducting temperatures increases the cooling requirements.
- If the induced structure currents result in arcs between sectors of the vacuum vessel, erosion, proportional to the transferred electric charge, may result. Damage may be particularly severe in the coolant piping system and may result in an increase in the impurity level in the vacuum vessel. On the

other hand, a vacuum-vessel shell with high conductivity near the plasma may provide a path for the image currents to stabilize the plasma. Conversely, the initiation and control power requirements become more severe in the presence of a high-conductivity shell.

The voltage (100 V for 0.10 s) required for plasma initiation can be obtained by induction from the ohmic heating (OH) poloidal circuit or from a special "blip" coil. A simplified Engineering Test Facility or Internal Tokamak Reactor (ETF/INTOR) study¹ on a similar topic showed the energy supplied to the initiation pulse was 180 MJ when fed through the OH coil versus 40 to 60 MJ when fed through the blip coils. Our study is confined to the latter arrangement. The OH induced voltage will be 5 V/turn with a blip coil; without a blip coil, the required OH driving voltage is 357 V/turn. The blip coil can be installed to couple closely with the plasma so that it need not be superconducting. The induced voltage in the OH and poloidal field (PF) superconducting coils may be less for most coils, because the blip coil couples less to the superconducting coils than to the plasma.

The FED/INTOR baseline design whose linear dimensions are shown in Fig. 1 is the basis of this study. All passive conductors in the structure are effectively thin when compared with the skin depth in a plasma startup pulse. Hence, for pulse analysis, the passive conductors are subdivided only in their long radial or axial dimension.

Table I shows the structural elements and some of their characteristics, including the resistance of each. Those elements whose resistance is varied to determine the effect of including bellows or insulating sections are marked in the table. Circular symmetry and the existence of a magnetic flux normal midplane are always assumed.

METHOD

By the finite-difference method of the POISSON code, the self- and mutual inductances are computed in the configuration shown in Fig. 1. The self- and mutual inductances lead to a matrix of dimension 48, where all self- and mutual inductances are integrated over both of the tokamak's symmetrical halves, above and below the midplane. To provide an easily understood summary of the 48th-order matrix, we show in Table II the matrix reduced to the 17 elements with generic significance defined in Table I. With the 48 subelements and their

electromagnetic couplings $M_{i,j}$, we write our set of differential equations whose integration is discussed in the text following.

$$\begin{aligned} 0 &= R_1(t) I_1 + L_1 \dot{I}_1 + \sum_{j=2}^{48} M_{1,j} \dot{I}_j \\ 0 &= R_2 I_2 + L_2 \dot{I}_2 + \sum_{j=2}^{48} M_{2,j} \dot{I}_j \\ &\vdots \\ &\vdots \\ &\vdots \end{aligned} \quad (1)$$

$$V_{41} = R_{41} I_{41} + L_{41} \dot{I}_{41} + \sum_{j=41}^{48} M_{41,j} \dot{I}_j$$

$$V_{42} = R_{42} I_{42} + L_{42} \dot{I}_{41} + \sum_{j=42}^{48} M_{42,j} \dot{I}_j$$

$$0 = R_{43} I_{43} + L_{43} \dot{I}_{43} + \sum_{j=43}^{48} M_{43,j} \dot{I}_j$$

$$\begin{aligned} &\vdots \\ &\vdots \\ &\vdots \end{aligned}$$

$$0 = R_{48} I_{48} + L_{48} \dot{I}_{48} + \sum_{j=1}^{47} M_{48,j} \dot{I}_j$$

Some of the resistances R_i are changed as indicated in Table I to account for the high-resistance sections.

The plasma resistance is defined in the time function

$$R_i(t) = \begin{cases} \alpha t^{-1}, & t \leq 0.01 \text{ s} \\ \beta t^{-1.6674}, & t \geq 0.01 \text{ s} \end{cases} \quad (2)$$

where $\alpha = 150 \mu\Omega\text{s}$ and $\beta = 6.94 \mu\Omega\text{s}^{1.6674}$. The loop voltage measured at the plasma surface is a function of the current I_1 and its time derivative, and all three are obtained by integrating the system of Eqs. (1), that is,

$$V_0 = I_1 R_1(t) + L_{\text{int}} \dot{I}_1 \quad (3)$$

where $L_{\text{int}} \approx \mu_0(b/4) = 2.04 \mu\text{H}$ is the internal plasma inductance (b is the major radius). Equation (2) is strongly specialized because it is obtained by fitting one exponential function to the plasma current and another exponential function to the plasma's resistive voltage as

Fig. 1.
Configuration and plasma field of the FED/INTOR baseline design. The labels are defined in Table I.

discussed in Ref. 3 and shown in Fig. 2. In Fig. 2, we added the plots of our approximation, which consist of exponential functions fitted at $t = 0.01$ and 1.0 s. For the time interval $t < 0.01$ s, we used Peng's³ suggested 90-V value for the term $I_1 R_1(t)$. Thus, the current rise is constant, $\dot{I}_1(t) = 0.6$ MA/s. This specialization is used to include the electromagnetic details in the given initiation-scenario calculations. Consequently, the blip voltage V_{41} , V_{42} is determined so that $\dot{I}(t) = 0.6$ MA/s. The artificial constraint $V_{41} = V_{42}$ is applied because there is no assumption on whether one or two blip coils should be used. The number of ampere turns required may thus be found for the blip coil set: all of our computations are based on the single turn coil set.

RESULTS

Figure 3 shows the current in all active coils and the plasma current in Data Case I, that is, for no added resistance (no high-resistance section) when the voltage $V_{41} = V_{42} = 115$ V/turn is applied as a step function. The plasma current rise is delayed by $\tau_d \approx 90$ ms. To overcome a significant part of this delay, one could apply an overvoltage to the system, but the required voltage peak would then be impractical. The delay is caused by slow field penetration, so one may simply delay by τ_d those operations in the initiation scenario that are not coupled to the electromagnetic field, such as the gas injection. The delays τ_d are listed in Table III for five

TABLE I
ACTIVE AND PASSIVE CONDUCTORS

Subelements As Labeled In Fig.1	Element Number	Element Designation	Material	Thickness (cm)	Resistance Above or Below Midplane $2 R_i$ (m Ω)
1	1	Plasma (20 cm rad.)			$R_i(t)$
2, 3, 47, 48	2	Bucking cyl. for TF coils	S.S. ^c	1.0	0.0101
4, 5, 14, 15, 25, 26	3	TF dewar	S.S.	1.0	0.124 ^b
6, 7	4	Spool	S.S.	1.5	0.250
8, 9	5 ^a	Inner wall	S.S.	1.5	0.255
10-13	6	Spool top, shell top	S.S.	1.5, 1.0	0.402
16-20	7 ^a	Plasma shell	S.S.	1.0	0.328
21, 22	8	Graphite	Graphite	2.0	0.685
23, 24	9 ^a	Water pipe	S.S.	1.0	0.936
27-30	10 ^a	Breeder blanket	S.S.	1.0, 0.5	0.879
31, 32	11 ^a	Outer shell	S.S.	1.0	0.940
33	12	OH coil	S.C. ^d	---	0
34	13	EI coil	S.C.	---	0
35-37	14	ED coils	S.C.	---	0
38-40	15	EO coils	S.C.	---	0
41, 42	16	Blip coils	Copper	---	0.00955
43-46	17	OH dewar	S.S.	1.0	0.0286 ^b

^aWe added the resistance, R_{break} , to each pertinent subelement; that is, 0, 1.70, 8.50, 17.0, or 34.0 m Ω in the Data Case I, II, III, IV, or V, respectively, above the midplane, and the same R_{break} to the image element below the midplane.

^bRoom temperature value.

^cStainless steel.

^dSuperconductor.

data cases. In the following equation, τ_d is assumed to be compensated by the operation. Hence, $t - \tau_d$ is substituted for t in Eq. (2), thus

$$R_i(t) = \begin{cases} 150 \Omega, & t - \tau_d \leq 10^{-6} \text{ s} \\ \alpha (t - \tau_d)^{-1}, & 10^{-6} \geq t - \tau_d \geq 0.01 \text{ s} \\ \beta (t - \tau_d)^{-1.6674}, & t - \tau_d \geq 0.01 \text{ s} \end{cases} \quad (4)$$

Figures 4 and 5 show the resulting currents and voltages for Data Case I. Figures 6 and 7 show the resulting

currents and voltages for Data Case IV, where two voltages are given in each plasma-voltage graph. The plots labeled "V-plasma" are for the plasma voltage V_p in Eq. (3), and "V-circuit-1" is given by

$$I_1 R_i(t) + L_1 \dot{I}_1, \quad (5)$$

which is the electromotance (EMF), except for the sign. All other voltages similarly plotted are the respective EMFs. A summary of the blip voltage V_b , the sum I_b of

TABLE II
COUPLING COEFFICIENTS AND SELF INDUCTANCES

Coupling Coefficients

Circuit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000																
2	0.118	1.000															
3	0.237	0.307	1.000														
4	0.207	0.433	0.461	1.000													
5	0.215	0.419	0.455	0.813	1.000												
6	0.266	0.267	0.577	0.355	0.367	1.000											
7	0.483	0.302	0.492	0.534	0.555	0.562	1.000										
8	0.274	0.304	0.386	0.579	0.603	0.368	0.676	1.000									
9	0.553	0.178	0.378	0.299	0.310	0.455	0.745	0.392	1.000								
10	0.526	0.148	0.344	0.245	0.255	0.398	0.680	0.320	0.744	1.000							
11	0.473	0.145	0.366	0.236	0.245	0.417	0.637	0.305	0.688	0.782	1.000						
12	0.282	0.133	0.427	0.198	0.206	0.535	0.465	0.247	0.466	0.465	0.523	1.000					
13	0.377	0.122	0.333	0.196	0.203	0.371	0.519	0.252	0.556	0.622	0.754	0.489	1.000				
14	0.075	0.637	0.200	0.265	0.257	0.183	0.190	0.186	0.114	0.095	0.093	0.088	0.079	1.000			
15	0.113	0.205	0.455	0.137	0.140	0.345	0.223	0.141	0.189	0.173	0.187	0.235	0.172	0.154	1.000		
16	0.150	0.093	0.541	0.118	0.123	0.341	0.254	0.141	0.244	0.242	0.273	0.338	0.262	0.064	0.329	1.000	
17	0.199	0.261	0.492	0.276	0.282	0.659	0.400	0.264	0.333	0.302	0.323	0.446	0.292	0.220	0.302	0.309	1.000

Self Inductances
(μH)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
32.5	11.4	100.7	14.0	14.8	90.5	141.7	26.2	54.6	74.5	72.5	17.8	23.8	2.9	39.5	70.2	33.5

Fig. 2.

Reference time behavior with no radio-frequency (rf) assist during current rise.

magnetomotances taken over all blip coils above and below the midplane, and the blip energy for a blip pulse length $\tau_b = \tau_d + 0.1$ s is listed in Table IV, where I_b and W_b are the magnetomotance and energy-loss values at $t = \tau_b$. The blip voltage V_b is the free variable chosen so the plasma current $I_1 \approx 60$ kA at $t = \tau_b$, which corresponds to the desired $\dot{I}_1 = 0.6$ MA/s. For Data Case I, the energy losses and the volt seconds at $t = \tau_b$ are listed in Table V for the elements of Table I and Fig. 1. The energy balance is satisfied within an error margin of <1 kJ, which is 10^{-5} of the total system energy, consistent with the programmed numerical error.

The 1.5-GJ loss in the TF cryostat is a conspicuous value, indicating a disadvantage of the high-voltage initiation method with no radio-frequency (rf) assist. By adding an external coil set, strongly coupled to the TF cryostat, it may be possible to impress a current in opposition to the blip field. Such a coil addition might be particularly effective in conjunction with blip coils with improved plasma coupling. Plasma coupling can be achieved when the blip coils are moved radially outward within their present (r, ϕ) plane (flux plot in Fig. 1).

BLIP COIL ESTIMATE

For Data Case I, four single blip coils, each built with 62 turns of a 20-kA copper conductor with 50-A/mm^2

current density, would be ≈ 10 cm in the axial and 60 cm in the radial direction. Two coils would be mounted above the midplane, approximately as shown for coils 41 and 42 in Fig. 1; the two remaining coils would be used for the image below the midplane. If constant current (4.83 MA) is assumed for 0.2 s, the temperature rise from converting the joule loss to residual heat would be 3 K in the coils. The voltage per coil would be 8.5 kV, requiring a supplied peak power of 700 MW for 0.19 s. At the end of the blip, the blip coils would be shorted. For this condition, we extended to 4 s some of the computations corresponding to Fig. 4, using the OH and external field coils as the drivers. This verified that the blip coil current is reversed and continued to increase in the negative direction. Opening the blip circuits at the current zero would thus provide a useful operating procedure. The time from the start of the blip pulse to current zero is ≈ 0.55 s. The joule loss over the 0.55 s equals approximately that for the 4.83 MA over 0.2 s we used for estimating the coil temperature rise (that is, 3 K).

This coil design is not optimized in any way and is given only to convey an idea of the general size of the blip circuit. Presumably, fewer turns would be selected to facilitate fabrication and maintenance.

CONCLUSIONS

Based on our results, we concluded that a blip coil should be provided for nonassisted initiation, and the blip coil should be large enough to provide for the delay caused by the vacuum vessel without insulating break. However, we do not know whether limiter impurity control will require more than 115 V for initiation with no assist. Before detailed preconceptual design is begun, the possibility of assisted initiation should be considered and the high-voltage blip eliminated if possible. Designing a well-conducting liner of the vacuum vessel or a uniform current path between adjacent segments of the vacuum vessel is practical and allows satisfactory initiation. The plasma initiation pulse requires less power and energy than those required for the plasma control circuit, as discussed in Ref. 4.

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Fig. 3.

Currents in Data Case I, 125-V applied external voltage step, zero delay. The tangent on the plasma current defines τ_d .

TABLE III

ELECTROMAGNETIC DELAY TIME

Data Case	Added Resistance In Each Half-Space With Respect To Midplane (m Ω)	Delay τ_d (s)
I	0	0.090
II	1.70	0.083
III	8.50	0.072
IV	17.5	0.056
V	34.0	0.050

TABLE IV

BLIP VALUES

Data Case	τ_b (s)	V_b (V/t)	I_b (MA/t)	W_b (MJ)
I	0.190	137	4.83	68.8
II	0.183	124	4.16	52.2
III	0.172	122	3.89	44.8
IV	0.156	122	3.55	37.5
V	0.150	122	3.45	34.9

Fig. 4.
Active-coil and plasma currents for Data Case I, 137-V applied voltage step.

Fig. 5.

Data Case I active-coil and plasma electromotances (EMFs) and plasma voltage. For the two blip coils, 137-V applied external voltage step is plotted.

Fig. 6.
Active-coil and plasma currents for Data Case IV, 122-V applied voltage step.

Fig. 7.

Data Case IV active-coil and plasma electromotances (EMFs) and plasma voltage. For the two blip coils, 122-V applied external voltage step is plotted.

TABLE V
ENERGY LOSSES AND VOLT SECONDS AT $t = \tau_b$

Element Number	Element Designation	Loss (kJ)	Resistive Vs (Wb)	Inductive Vs (Wb)
1	Plasma (20 cm rad.)	17.4	1.75	1.20
2	Bucking cylinder	199	2.03	0.818
3	TF cryostat	1486	16.56	2.59
4	Spool	327	4.40	0.672
5	Inner wall	374	4.73	0.753
6	Spool top, shell top	4.52×10^3	34.1	5.07
7	Plasma shell	408	15.4	1.69
8	Graphite	21.1	4.69	0.0948
9	Water pipe	153	6.11	1.040
10	Breeder blanket	145	11.9	1.43
11	Outer shell	361	10.0	1.61
12	OH Coil	0	0	0.808
13	EI coil	0	0	0.183
14	ED coils	0	0	4.01
15	EO coils	0	0	10.9
16	Blip coils	8.28×10^3	- 4.74	-55.9
17	OH cryostat	8.99	0.496	0.0492

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