POLOIDAL FIELD POWER SUPPLY IGNITION REQUIREMENTS FOR INESCO PHIBEX TOKAMAKS BY COMPUTER BASED CIRCUIT ANALYSIS

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Summary

The PHIBEX (Physics Ignition and Burn Experiment) tokamaks are small ($R \sim 0.57$ m, $a \sim 0.22$ m), inexpensive, modular, high field, OH and D-T alpha heated machines designed to demonstrate ignition and thermonuclear burn. Ohmic Heating (OH) bias current minimization is critical due to the small allowable size of the central OH coil and the high material stresses. Water cooled copper OH and Vertical Field (VF) coils are considered, as well as conducting and nonconducting first walls. The coupled equations for the OH, VF, plasma, and wall circuits are solved with the plasma current (3.3 MA peak), plasma resistance, and poloidal beta β_p (3.3 peak) as driving functions. The system inductances are calculated with the UT-CEM tokamak inductance code TINDERB. The wall dc resistance is derived. The VF and plasma currents are related by finite element magnetic code analysis and β_p in the plasma inductance expression. OH bias currents (33-39 kA) are determined for several coil configurations and plasma current variations which extend into the burn period. Required OH and VF power supply voltages, currents, powers, and energies are calculated as are coil dissipations. The effects of conducting first walls without flux breaking insulating slits are investigated. Wall currents (to 250 kA), resistive volt-sec, dissipated powers, and temperature rises (to 23 °C) are obtained for several wall resistances. Four designs with nonconducting walls are compared.

Introduction

The recently conceived INESCO PHIBEX (Physics Ignition and Burn Experiment) tokamaks[1,2] are small ($R \sim 57$ cm, $a \sim 22$ cm), inexpensive, modular, high field ($B_T \sim 16$ T) machines, heated Ohmically and by D-T alpha particles. PHIBEX I has a circular plasma cross section, while that of PHIBEX II is elliptical. These tokamaks are intended to demonstrate ignition and controlled thermonuclear burn with low cost and short development time. The required Ohmic Heating (OH) and Vertical Field (VF) coil power supply waveforms are determined by computer calculations for several coil configurations and plasma current variations.

Poloidal Field Coil Design Constraints

The constraints on the central air core OH coil are severe. The coil must be small enough to obtain the required high toroidal field. Its area must be large enough to escape destruction from Joule heating by the required high OH current. It must be cooled to counteract nuclear and Joule heating.

Its conductivity must be high to reduce the power supply voltage. The coil must be strong enough to withstand the pulsed stresses from the OH field (25 T) and current (40 kA). Minimization of the OH bias current is critical to the OH coil design.

The constraints on the peripheral OH coils and the VF coils are less severe. The coils should have large enough area to lower Joule heating and supply voltage. They should be numerous enough for proper coupling to the plasma. But, they should intercept only a minimal amount of the neutron flux required to demonstrate the achievability of efficient power reactor operation.

One PHIBEX I poloidal field coil arrangement[3] is shown in Fig. 1. The 299 turn, H_2O cooled OH coil is made of AMAX-MZC[4] copper alloy with a yield strength of 428-455 MPA and a resistivity $\rho = 2.16 \times 10^{-8}$ Ω-m at 20 °C. The 100 turn, H_2O cooled VF coil is OFHC with an allowable stress of 250 MPA and $\rho = 2.86 \times 10^{-8}$ Ω-m at 192 °C.

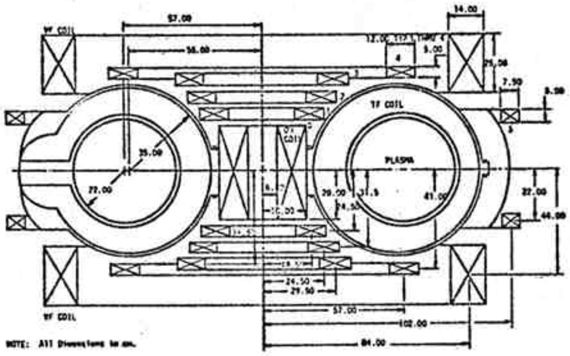

Figure 1 PHIBEX I Coil Arrangement

The Model First Wall

Since the machines operate with a high first wall heat flux (15 MW/m^2), a water cooled, metallic wall without flux breaking insulating slits is desired for high mechanical strength at high temperatures and constructional simplicity. Therefore provision is made for a model conducting wall in the calculations. The wall is a toroidal annulus of circular cross section, centered on the circular plasma. The dc wall current density $J_W = i_W / 2\pi d\,(R - b\cos\theta)$, where i_W is the wall current, R is the major radius, b is the minor radius variable, θ is the azimuthal angle, and $d = (R^2 - a_1^2)^{1/2} - (R^2 - a_2^2)^{1/2}$, with a_1 the inner wall radius and a_2 the outer wall radius. Integration gives the wall resistance $R_W = \rho_W / d$, where ρ_W is the wall resistivity. For $R = 57$ cm, $a_1 = 22.35$ cm, $a_2 = 22.65$ cm, and $\rho_W = 3.578 \times 10^{-8}$ Ω-m for AMAX-MZC at 192 °C, $R_W = 2.776 \times 10^{-5}$ Ω.

The Circuit Problem

The circuit schematic is shown in Figure 2. The plasma current i_P, resistance R_P, and poloidal beta β_p are specified in time from 0-d and 1-d plasma code runs.[5] The time invariant dc inductances are found with the UT-CEM (University of Texas Center for Electromechanics) tokamak inductance code TINDERB.[6] The plasma current is parabolic in minor radius. The plasma size and position are fixed. The VF current $i_{VF} = \alpha(t) i_P$, where α is obtained from the approximate relation[7] for the vertical magnetic field

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$$B_V(T) = i_p \times 10^{-7}[\ln \frac{8R}{a} - 1.5 + \beta_p(t) + 11/12] = Ki_{VF} \quad (2)$$

which assumes negligible ferromagnetic material. K is obtained by finite element magnetic analysis of the VF coil with the UT-CEM code BMAP.[8] The skin effect and variation of resistance with Joule heating are ignored.

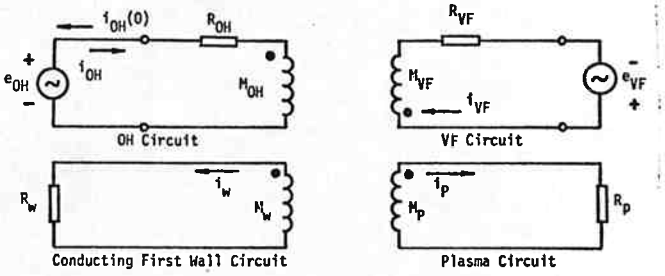

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Figure 2 Electric Circuit Schematic

The voltage loop equations may be written

$$\frac{di_{OH}}{dt} = (C_4 M_{PW} - C_1 M_W)/(M_{OHW} M_{PW} - M_{POH} M_W) \quad (3)$$

$$\frac{di_W}{dt} = (C_4 M_{POH} - C_1 M_{OHW})/(M_{OHW} M_{PW} - M_{POH} M_W) \quad (4)$$

$$C_1 = M_P \frac{di_P}{dt} - M_{PVF} \alpha \frac{di_P}{dt} - M_{PVF} i_P \frac{d\alpha}{dt} + i_P R_P \quad (5)$$

$$C_4 = M_{PW} \frac{di_P}{dt} - M_{VFW} \alpha \frac{di_P}{dt} - M_{VFW}\, i_P \frac{d\alpha}{dt} + i_W R_W \quad (6)$$

$$e_{OH} = M_{OH} \frac{d}{dt} i_{OH} + (M_{OHVF}\alpha - M_{POH}) \frac{di_P}{dt}$$

$$- M_{OHW} \frac{di_W}{dt} + M_{OHVF} i_P \frac{d\alpha}{dt} + i_{OH} R_{OH} \quad (7)$$

$$e_{VF} = M_{OHVF} \frac{di_{OH}}{dt} + (M_{VF}\alpha - M_{PVF}) \frac{di_P}{dt}$$

$$- M_{VFW} \frac{di_W}{dt} + M_{VF} i_P \frac{d2}{dt} + 2 i_P R_{VF} \quad (8)$$

where the Ms are inductances, Rs are resistances, and es are supply voltages.

The OH half bias current is initially estimated from Eq. (9) and then refined by run iteration.

$$|i_{OH}|_{HB} = (M_P i_P - M_{PVF} \alpha i_P + M_{PW} i_W + \int_0^t i_P R_P dt)/2M_{POH} \quad (9)$$

PHIBEX I RESULTS

The circuit equations are numerically integrated on a CDC 6600. Input plasma resistance and beta variations are shown in Figure 3 for ignition at 1.3 sec. The input plasma current is shown in Figure 4, as are the resulting OH and VF currents for a non-conducting wall. The inductances and resistances are given on the figure. The required power supply voltages are shown in Figure 5.

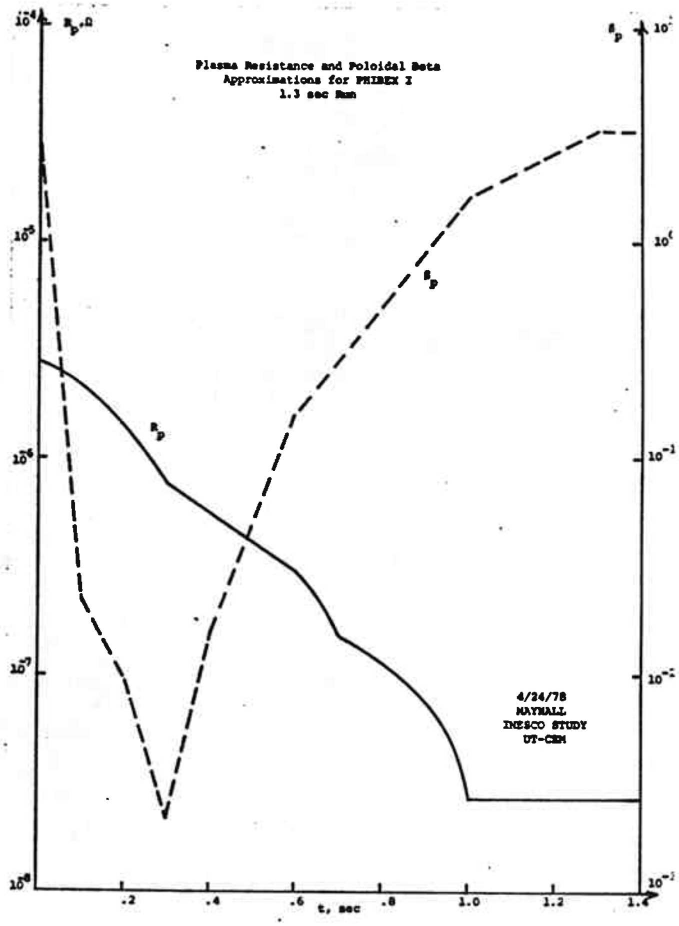

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Figure 3

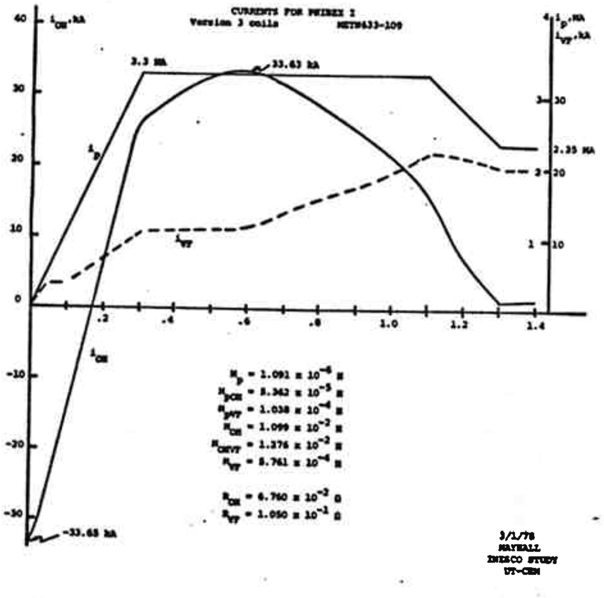

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Figure 4

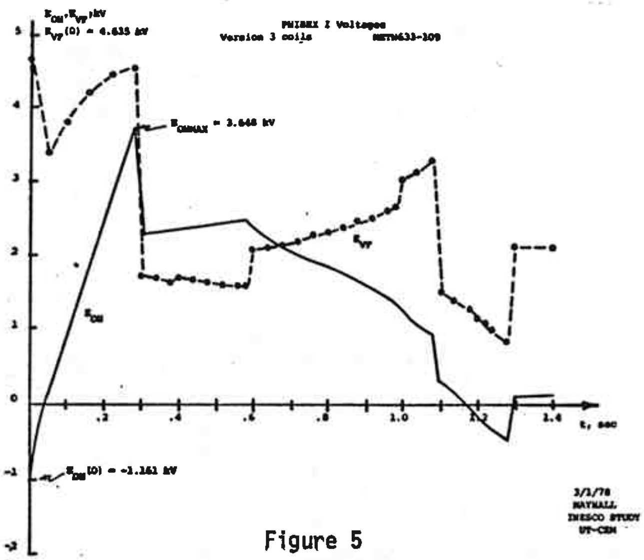

Figure 5

Figure 6 shows the wall current, peak temperature rise, dissipated power, dissipated energy, and resistive volt-sec, when the wall conducts. The wall inductances are $M_{PW} = 7.830 \times 10^{-7}$H, $M_{OHW} = 5.485 \times 10^{-5}$H, $M_{VFW} = 1.087 \times 10^{-4}$H, and $M_W = 8.051 \times 10^{-7}$H. The peak current is 251 kA at 0.2 sec and the temperature rise is 22.6 °C. The OH bias current is increased by 0.9% with the conducting wall. The peak OH power is increased from 101 MW by 8%. The OH energy is increased from 56.3 MJ by 1.7%. Clearly, a more resistive wall is desired. A fivefold increase in wall resistance reduces the peak wall current to 50 kA and the wall temperature rise to 0.9 °C. A stainless steel wall with a forty fold increase in resistance gives a peak current of ∿ 6 kA.

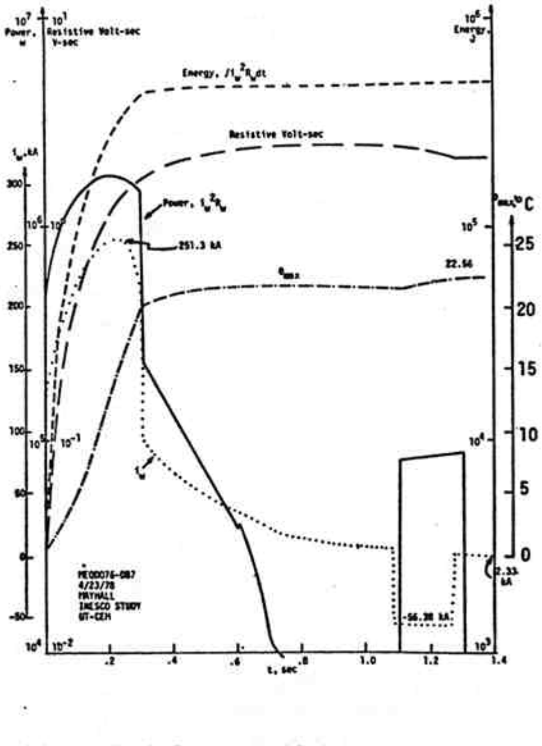

Figure 6 PHIBEX I Wall Quantities

PHIBEX II RESULTS

The poloidal field power supply requirements are estimated in an approximate manner by using an equivalent area plasma of circular cross section in the inductance calculations. The inductances are $M_P = 1.091 \times 10^{-6}$H, $M_{POH} = 5.352 \times 10^{-2}$H, $M_{PVF} = 9.839 \times 10^{-5}$H, $M_{OH} = 1.155 \times 10^{-2}$H, $M_{OHVF} = 1.232 \times 10^{-2}$H, and $M_{VF} = 5.487 \times 10^{-2}$H. Additionally, $R_{OH} = 7.040 \times 10^{-2}\Omega$ and $R_{VF} = 0.1027\ \Omega$. These results are very similar to those for PHIBEX I.

Comparison of PHIBEX I and II Results With a Nonconducting Wall

Peak quantities from 2 PHIBEX I runs and 2 PHIBEX II runs are shown in Table 1. The time (1.3 or 1.9 sec) indicates the time of ignition. For the same ignition time, II requires slightly lower OH bias currents, but slightly higher VF currents. II requires slightly higher peak supply voltages and considerably (∿35%) higher peak VF powers. II requires about 10 MJ more poloidal energy.

Table 1

COMPARISON OF PEAK QUANTITIES FOR THE FOUR RUNS WITHOUT THE CONDUCTING WALL

	Half Bias I_{OH}(kA)	I_{VF}max (kA)	e_{OHmax}(kV)	e_{VFmax}(kV)
PHIBEX I, 1.3 sec Run	33.65	22.12	3.648	4.635
PHIBEX II, 1.3 sec Run	32.95	25.26	3.967	4.945
PHIBEX I, 1.9 sec Run	38.59	22.12	3.432	4.635
PHIBEX II, 1.9 sec Run	37.94	25.26	3.458	4.945

	$e_{OH}i_{OHmax}$,MW	$e_{VF}i_{VFmax}$,MW	$\int e_{OH}i_{OH}dt$,MJ	$\int e_{VF}i_{VF}dt$,MJ
PHIBEX I, 1.3 sec Run	101.0	70.22	56.29	42.65
PHIBEX II, 1.3 sec Run	100.4	93.64	54.45	53.98
PHIBEX I, 1.9 sec Run	108.0	73.44	115.6	54.55
PHIBEX II, 1.9 sec Run	109.0	93.63	112.9	68.75

	$i_{OH}^2R_{OH}$max,MW	$i_{VF}^2R_{VF}$max,MW	$\int i_{OH}^2R_{OH}dt$,MJ	$\int i_{VF}^2R_{VF}dt$,MJ
PHIBEX I, 1.3 sec Run	76.55	51.39	52.19	33.31
PHIBEX II, 1.3 sec Run	76.46	65.52	50.37	42.47
PHIBEX I, 1.9 sec Run	100.7	51.36	109.9	43.37
PHIBEX II, 1.9 sec Run	101.4	65.52	107.4	55.29

	TOTAL POLOIDAL ENERGY SUPPLIED, MJ	TOTAL POLOIDAL ENERGY DISSIPATED, MJ
PHIBEX I, 1.3 sec Run	98.94	85.50
PHIBEX II, 1.3 sec Run	108.4	92.84
PHIBEX I, 1.9 sec Run	170.2	153.2
PHIBEX II, 1.9 sec Run	181.7	162.7

Conclusions

The resistance of the metallic first wall should be increased to decrease the induced wall current. This could be done by reducing the thickness, using a more resistive material, increasing the wall length, introducing high resistance zones, or breaking the wall with insulating sections.

The 1.3 sec ignition runs require OH biases of ∿ 34 kA and VF currents of 22-25 kA. OH voltages of 3.5-5 kV are required, as are poloidal energies of

~105 MJ. The 1.9 sec ignition runs require OH biases of ~ 39 kA and the same range of VF current as for 1.3 sec. OH voltages of ~3.5 kV and poloidal energies of ~175 MJ are required.

Acknowledgement

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