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SUPERCONDUCTING EQUILIBRIUM COIL DESIGN STUDIES FOR THE ARGONNE EXPERIMENTAL POWER REACTOR*

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Summary

As an integral effort in the Argonne Experimental Power Reactor design studies, a scoping-study was made on the equilibrium coil system. Various design options were investigated. The reference design is a superconducting equilibrium field coil system located outside the toroidal field coils for reasons of ease of coil assembly, disassembly, coil support, remote maintenance and the least interference with the assembly and disassembly of the first wall and the blanket and shield. It was also found that there is a large I^2R loss if the coils were made of water-cooled copper. The superconducting equilibrium coil design was developed in considerable detail with the 60,000 A ac superconducting low loss cable design, ac pulsing loss evaluation and the full stabilization examination. The proposed superconductor is NbTi with copper and cupro-nickel as two-component matrix. Finally, the equilibrium field requirements are also discussed.

Introduction

The required equilibrium field for the Argonne Tokamak Experimental Power Reactor (TEPR) is 3 kG. For stability against radial displacement, $|\partial B_{vz}/\partial R|$ must be less than 3.6 G/cm, where B_{vz} is the vertical field component and R is the toroidal radius. For stability against vertical displacement the vertical flux lines must be concave toward the toroidal axis. Furthermore, the equilibrium coils are located so that they are decoupled magnetically from the ohmic heating coil and yet produce a bonus of 37 volt-sec for the plasma, thus reducing the volt-sec requirement for the ohmic heating coils.

Different placements of equilibrium coils were studies. Nuclear heating and refrigeration, radiation damage, coil arrangement, assembly and disassembly and flux diffusion through the laminated blanket and shield have been evaluated for each case. Comments on the advantages and the disadvantages of each design version are made.

The proposed superconducting equilibrium coils is a fast pulsing (~1 sec) high current (~10^5A) and large stored energy magnet. The fast pulsing suggests that the filaments must be small, twist pitch must be short and a three-component composite with a highly resistive barrier of cupro-nickel between filaments must be used. The high current and fine filaments suggest that multiple-strand fully-transposed cable must be used to ensure good current sharing. Because of the large stored energy, the equilibrium coil must be fully stabilized. This means that the strand diameter must be minimized in order to ensure an adequate surface to volume ratio for cooling. With these considerations and based on careful design calculations, a practical high current cable conductor has been designed and the ac pulsing loss evaluated. For comparison, the I^2R loss of a water-cooled copper coil was computed and comparisons made between superconducting coils and the copper coils.

One of the big problems of operating a fast-pulsing large stored energy energy magnet is the cost of the power supply. A flux-return iron yoke will be discussed as a method to reduce the stored energy of the equilibrium coil and thus reduce the power supply size and cost.

Equilibrium Field Requirements

The hoop force generated by a toroidal plasma current ring tends to expand the plasma ring and thus increase the major radius of the plasma. Therefore, a weak field pointed in the vertical direction (called Z direction) is needed so that the interaction of the external vertical field and the toroidal plasma current provides a $J \times B_v$ force inward toward the toroidal axis. The required vertical field B_v must have such a magnitude and curvature that the tokamak equilibrium condition $J \times B_v = \nabla P$ is satisfied. For uniform current density plasma,[1] the required equilibrium holding field is given by

$$B_{eq} = \frac{I_p}{R}\left(\ln 8\frac{R}{a} - 1.25 + \beta_\theta\right) \times 10^{-6}\ (KG) \qquad (1)$$

where I_p is the plasma current in amperes, R is the toroidal radius in meters, a is the plasma radius in meters and β_θ is the ratio of plasma pressure to poloidal field pressure. Note that B_{eq} is the neutral-equilibrium field while B_v is the stable-equilibrium field.

For stability against radial displacement, Greene et al.[2] have shown that the vertical-field component, B_{vz}, must be smaller than the holding field B_{eq} for $R < R_o$ and that B_{vz} must be greater than B_{eq} for $R > R_o$, where R_o is the major radius of the plasma. That is, the condition

$$\left|\frac{\partial B_{vz}}{\partial R}\right| < \left|\frac{\partial B_{eq}}{\partial R}\right| \qquad (2)$$

is needed for stability against radial displacement.

For stability against vertical displacement, Yoshikawa[3] has shown that the required condition is that the vertical-field lines must be concave toward the toroidal axis. That is the condition

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$$\frac{\partial B_{vz}}{\partial R} / B_{vz} < 0 \qquad (3)$$

must be satisfied so that the resulting force tends to center the plasma on the axis $z = 0$. (B_{vR} is the radial component of the vertical field.)

In the ANL-TEPR design, we have $I_p = 4.5 \times 10^6$ A, $R_o = 6.25$ meters, $a = 2.1$ meters, and $\beta_\theta = 2.2$. Therefore, the required vertical field at the center of the plasma ring is 2,967 G. Equation (2) says that $\partial B_{vz}/\partial R$ must be less than 3.6 G/cm for radial equilibrium (note that $\partial B_{vz}/\partial R$ must be negative.) Equation (3) simply states that B_{vR} is negative in the +z plane and positive in the -z plane, so that the field lines are concave toward the toroidal axis.

Equilibrium Coil Design Choice

If the equilibrium coil is placed outside the first wall but inside the blanket, the required ampere-turns, power supply and flux diffusion time shift will be minimum. The field interaction with toroidal field coil will also be a minimum, but the assembly, disassembly and repair maintenance of equilibrium coil, blanket and shield, and first wall will be extremely difficult. Because of the high temperature environment and the high neutron flux, it is difficult to design even a conventional copper coil at this position. With the Argonne blanket and shield reference design,[4] we have found that if superconducting coils are placed closer than 25 cm from the first wall, the nuclear heating will result in a refrigerator power greater than the I^2R loss of copper coil and the radiation-induced resistivity of copper stabilizer will be saturated at 3.0×10^{-7} Ω-cm.

If the coils are placed at a distance of 60 cm from the first wall so that excessive refrigeration requirements can be avoided, then the required total ampere-turns is about 7.5×10^6 with half of this serving to decouple the ohmic heating coil. The decoupling coil is placed outside the toroidal coil. The radiation-induced resistivity will be 1.0×10^{-7} Ω-cm and the ac pulsing loss will be about 11,000 J/cycle at 4.2°K. The averaged nuclear heating per cm^3 copper will be 0.8×10^{-3}W. The total nuclear heating of these coils will be about 750 W at 4.2°K. The total heat dissipation will be about 1000 W at 4.2°K. If these coils are made of water-cooled copper instead, the averaged I^2R loss will be about 15 MW provided that the decoupling coils are still superconducting.

The third alternative is to place the equilibrium coil outside the blanket and shield but inside the toroidal field coils. The ampere-turns will be about the same as if they were placed at 60 cm away from the first wall, but the induced resistivity in the copper will be about 2.5×10^{-8} Ω-cm and the nuclear heating will be about 5×10^{-6} W/cm^3 assuming a neutron wall loading of 0.2 MW/m^2 and 1 m thick blanket and shield. Since the equilibrium field coil bundles have large radii and small axial thickness, and thus inherent high peak fields. The proximity of these coils to the inside surface of TF coils results in a large additional pulsed field being superimposed on the TF-coil system, which severely limits the peak field of the TF coil and generates a large eddy-current heating loss. Furthermore, there are large tipping forces exerted on the TF coil.

If the equilibrium coil is located outside the TF coil, the required ampere-turn will be 20×10^6, the ac pulsing loss will be about 27,000 J per cycle at 4.2°K. The radiation induced resistivity is negligibly small and so is the nuclear heating. The coil arrangement is flexible, the coil assembly, disassembly, remote maintenance and control as well as coil support will be simplified tremendously. The disadvantages are larger ampere-turns and stored energy of power supply. If the coils are made of water-cooled copper coil, the averaged power loss will be about 92 MW with 35 seconds between pulses.

For comparisions, it is found that if the equilibrium coils are placed inside the toroidal field coil, there are great difficulties in coil assembly, disassembly, coil support, assembly and disassembly of blanket, shield and first wall, as well as the design of remote control and maintenance. Although the larger ampere turns (~20×10^6) and energy (~ 900 MJ) will be required if the coils are located outside the toroidal coil, these disadvantages are small. Furthermore, we are investigating the possible reduction of power supply stored energy by introducing the flux-return iron yoke outside the TF coil and the equilibrium coil system.

Equilibrium Field-Coil Design

Based on the evaluation of previous design options, equilibrium field requirements, and the final consideration that the equilibrium coils were designed to produce as much volt-sec as possible for the plasma ring, the equilibrium-coil configuration was designed as shown in Fig. 1. The detailed dimensions and magnet characteristics are listed in Table 1.

In Table 1, R_1, R_2, Z_1, and Z_2 represent the inner radius, the outer radius, the initial axial coordinates and the final axial coordinates, respectively. The total conductor length is 727×10^6 ampere-meters. The total ampere-turns is 10×10^6, with half of these ampere-turns serving to magnetically decouple the equilibrium coils from the OH coils. These antimutual inductance coils are coils No. 1, No. 2, and No. 3. These are positioned to generate negligible vertical fields in the negative Z direction everywhere on the Z = 0 axis, thus enabling coil No. 4 and coil No. 5 to produce a useful vertical field. Furthermore, this arrangement increases the volt-sec generated by the equilibrium coils. Finally, these coils produce only small amounts of superimposed field on the TF-coil system. The superpositioned fields, generated by the equilibrium coils, are indicated in Fig. 2. All field calculations were done accurately, using full coil sections rather than filament approximations.

A moderate average current density of 2300 A/cm^2 was chosen for the design calculations. The operational current of 60,000 amperes, resulting in a self inductance of 0.50 H, was chosen with fast pulsing in mind. To drive the equilibrium coils to the operational field strength in one second, the power-supply voltage required is 30.0 kV, neglecting the IR drop if the coils are made of normal conductors. The total stored energy is 900 MJ.

The vertical-field pattern generated by equilibrium coils is plotted in Fig. 3. Also in this figure is B_{eq} defined by Eq. (1). Note that the achieved B_{vz} also satisfied Eq. (2) with $\partial B_{vz}/\partial R$ negative in the plasma region. Therefore, the stability against radial displacement is assured. The concave vertical-field lines are plotted in Fig. 1. Clearly, the condition for stability against vertical displacement is met.

The volt-sec contributed by the equilibrium coils was graphically determined from the data in Fig. 3. The equilibrium coils contribute 37 volt-sec, thus reducing the volt-sec requirements for the OH coils.

Both superconducting and copper equilibrium-coil designs were developed in order that the problems and relative advantages of both options could be examined within the context of the TEPR-design requirements.

Superconducting Equilibrium-Coil Design

Design of 60,000 A AC Superconducting Cables

The equilibrium-field coil operational current is 60,000 A, with a charging time of 1 second and a field excursion of 0 → 37 kG. The fast pulsing suggests that the filaments must be twisted in a short pitch. The requirements for fine filaments suggest that the conductor cannot be made of one strand. Cables of a few strands often result in a poor packing factor, poor mechanical rigidity, and possible shorts between strands. Hence, a composite with a large number of filaments was chosen. Such a composite will have a large diameter. Consequently, a 3-component composite with high-resistive barriers of cupro-nickel between filaments is preferred. On the other hand, the equilibrium-coil system has a large stored energy requiring full stabilization. This means that the composite diameter cannot be too large in order to ensure a large surface-to-volume ratio for cooling.

After careful design calculations to fulfill the cryogenic-stability criterion, a specific superconducting composite, suitable for equilibrium-coil cables was developed as shown in Table 2.

As an illustration of cabling, Fig. 4 shows a practical cabling scheme using a basic group of 8 wires which are twisted and rolled flat into a wide-aspect-ratio strip, two wires high and four wires wide. This strip is then used to form additional transposed groups until a desired current-carrying cable with full transposition is made. It is estimated that a packing factor of ~30% could be achieved for a 60,000A cable, resulting in a cable having an average current density of about $6{,}000\ \mathrm{A/cm^2}$.

AC Loss[5]

The total length of the 61.7A composite is 11.78×10^6 meters. Therefore the total composite volume is $3.33\ \mathrm{m^3}$. With a filament diameter 5μ and a maximum field excursion of 37 KG, the total hysteresis loss over a complete fusion cycle is 11,637J. The matrix loss with $\dot{B} = 37$ KG/sec is 4,353 J. The self-field loss is only 224 J. For a 35-sec cycle time the average power dissipation is about 780 W at 4.2°K, or 233 KW at 300°K.

If the cable tube is a metallic thin-wall tube, the eddy current dissipation during a field swing 0 → B is given approximately by

$$Q_t = \frac{B^2 R^2}{\tau \rho} \quad \mathrm{J/m^3}$$

where R is the tube radius, τ is the duration of field change and ρ is the resistivity of the tubing material. For stainless steel tubing with a 3 cm diameter and a wall thickness of 1.4 mm, the energy dissipation in the tube over a complete fusion cycle is 12,543 J, or 360 W at 4.2°K.

Cryostatic Stability

To examine the stability, the longitudinal resistivity of copper must be used. For 37 kG, $\rho = 2.7 \times 10^{-8}\ \Omega$-cm. Since copper occupies a fraction of 0.570 in the composite, the heat flux h, at 61.7 A is about $0.34\ \mathrm{W/cm^2}$. If the basic group of eight strands were wrapped with a porous binding material, such as Nomex paper, sufficient cooling to achieve cryostatic stability could be achieved.

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Table 1. Equilibrium Coil System

Coil No.	R_1 (cm)	R_2 (cm)	Z_1 (cm)	Z_2 (cm)	Central Field (Gauss)	Conductor Peak Field (kG)	Coil-Pair Conductor Length (Amp - m)
1	200	230	± 630	± 650	- 261	37	37×10^6
2	230	250	± 630	± 680	- 492	32.5	69×10^6
3	250	270	± 680	± 730	- 287	18	45×10^6
4	726	745	± 640	± 695	2192	32	291×10^6
5	1180	1210	± 362.5	± 390	1732	25	205×10^6

Table 2. Composite Properties

NbTi critical-current density	1.9×10^5 A/cm^2 at 4.2°K, 37 kG
Composite operational current	61.7 A
Composite critical current	123.4 A
Composite diameter	0.6 mm
Composite NbTi packing factor	0.23
Composite composition NbTi:Cu:Cupro-nickel	0.23 : 0.57 : 0.20
Filament diameter	5 μm
Twist pitch	6 mm
Number of filaments in composite	3307
Composite operational current density	2.185×10^4 A/cm^2
Composite critical current density	4.37×10^4 A/cm^2
Composite matrix effective resistivity	10^{-6} Ω-cm

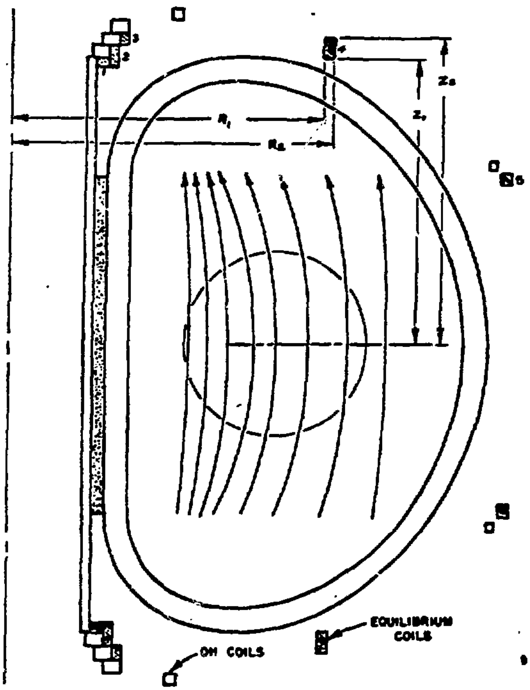

Fig. 1. · Equilibrium Coil and Field Pattern

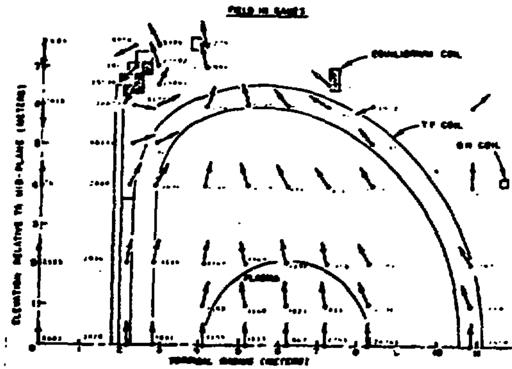

Fig. 2. Field Due to Equilibirum Coil Alone

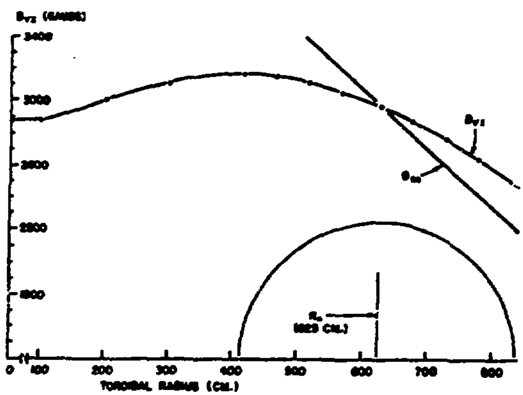

Fig. 3. The Neutral Equilibrium Field B_{eq} and the Stable Vertical Field B_{vz}.

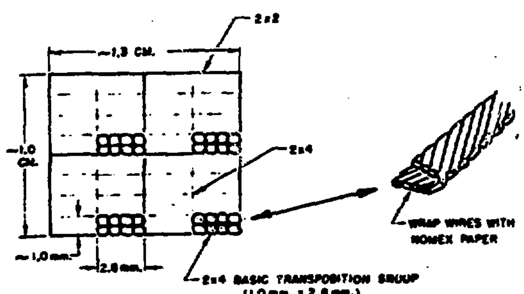

Fig. 4. 15,000 Amp Cable as Illustrated