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SUPERCONDUCTING POLODIAL COILS
FOR
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MASTER

by

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SUPERCONDUCTING POLOIDAL COILS FOR "STARFIRE" COMMERCIAL REACTOR*

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Summary

STARFIRE is considered to be the tenth commercial tokamak power plant. A preliminary design study on its superconducting poloidal coil system is presented. Key features of the design studies are: the elimination of the ohmic heating coil; the trade-off studies of the equilibrium field coil locations; and the development of a conceptual design for the superconducting equilibrium field coils. Described are the 100 kA cryostable conductor design, the coil structure and evaluation of the coil forces.

Introduction

STARFIRE[1] is an assumed steady state operating commercial tokamak based on a continual plasma current mode. The plasma startup, heating and current drive are accomplished by a lower hybrid rf system. This system eliminates the need for ohmic heating coil systems.

STARFIRE Equilibrium Field (EF) coils provide several important functions.[2] Firstly, the EF coils will provide the static equilibrium of the plasma against both the radial and the vertical displacements; secondly, the EF coils will elongate the plasma; thirdly, the EF coils will control the plasma position; fourthly, the EF coils will provide disruptive instability control; and finally, the EF coils will drive the plasma through the current induction. If the EF coils were placed inside the Toroidal Field (TF) coils, there would be tremendous difficulties in coil assembly, disassembly, support, repair and maintenance; as well as in the assembly, disassembly and maintenance of the blanket and shield and the first wall. However, if EF coils were placed outside the TF coils, it is difficult to control plasma position, to generate a sufficiently D-shaped plasma and to control the plasma disruptive instability. Furthermore, EF coils outside the TF coils will require an order of magnitude larger ampere-turns, stored energy and will produce large tipping forces and superimposing fields onto the TF coils. Thus, the location of the EF coils is a key design consideration in the STARFIRE design.

The basic design approach is to locate almost all the EF coils outside of the TF coils; all such EF coils will be superconducting. A limited number of segmented copper coils would be located inside the TF coils but outside of the blanket and shield. These auxiliary coils will be used for control purposes. Although this configuration increases the ampere-turns and the stored energy of the magnet system, the reliability and the maintainability of the EF coil system should be far superior to an inside EF coil system. With this configuration, however, it is important to minimize the TF coil size. For example, equilibrium calculations with EF coils exterior to a toroidal field coil with the outer leg at 16.8 m showed that a total of about 200 MA turns would be required in the EF coils to support plasma with 10 MA current, major radius of 7 m, elongation of 1.6, and beta poloidal β_p of 1. This large EF coil current implies very large local forces on the TF coil and very large stored energy, as well as great positional sensitivity of the plasma to the EF coil currents. When the coil outer leg is moved in to the current design value of $\sim$ 13.5 m, the EF coil current is reduced to around 100 MA-turns, indicating the importance of minimizing the TF coil size.

In STARFIRE, the plasma current normal startup and shutdown period will be of the order of 10 to 60 s and the plasma disruptive shutdown will be of the order of 5 s. Rapid or sudden changes in the plasma position due, for example, to modifications of the current profile by MHD activity, cannot be followed by the external EF coil system without oversizing of the power supplies and difficult constraints on coil manufacture due to the high voltage to be applied to the terminals. It is more practical to employ the internal EF coils for the purpose of plasma control. These coils would be actively controlled and would carry little average current and will thus consume little I^2R losses.

The blanket and shield are segmented toroidally and insulated to facilitate the soak-in of the current fields. In the event of a plasma disruption, large voltages will be generated in the vicinity of the plasma. These voltages will break down the intersegment insulation of the blanket or the control coil insulation unless an alternative path for the current is provided. For STARFIRE a system of toroidal conductors with spark gaps will be designed for this purpose.

Superconducting EF Coils

The locations of the external superconducting equilibrium field coils and the currents in them are determined as follows. First, an MHD equilibrium of the plasma is determined based on the plasma physics requirements of the reactor. Among the equilibrium properties are the plasma current distribution and the poloidal magnetic field in the plasma. Part of the poloidal field is produced by the plasma currents. The remaining part, the external field, must be supplied by the EF coils.

For given locations of the EF coils, the required current in them is determined by making a least squares fit of the field produced by the coils to the desired external field of the MHD equilibrium. Experience has determined that an average error of $\approx$0.3% in matching the desired external field is sufficient to reproduce the plasma physics parameters and the desired plasma boundary. Any additional flexibility in the coil system is used to minimize the stored energy in the EF coil system. This procedure is described in detail along with many examples in Reference 3.

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The optimized design is found by systematically varying the locations of the coils, subject to engineering constraints such as the location of vacuum ducts. For STARFIRE it was found the configuration shown in Fig. 1 was a satisfactory design. Basically, the plasma D shape is formed by pulling the plasma outward with the two upper coil pairs (with current in the same direction as the plasma current) and by pushing in with the other two. The vacuum ducts come out between the two outermost coils, and the space between the two upper coils is left for engineering access. The stored energy of 10.1 GJ could be reduced slightly with more coils. The 98 MAT would, however, increase somewhat more rapidly. The location of the coils is such that moving any of them a short distance (but not inside the non-allowed space) would increase the stored energy.

The vertical field pattern generated by the EF coils is plotted in Fig. 2. The EF coils produce a vertical field of about 0.61 T at plasma center. The field lines concave to the right are required to generate a noncircular plasma. However, the field lines will not provide stability against vertical displacement. The total flux contour contributed by both the superconducting EF coils and the 10.8 MA plasma current is shown in Fig. 3. The plasma obtained has an elongation of 1.60 and a triangularity of 0.5.

Main characteristics of the EF coils are given in Table 1. The EF coils will have a maximum operational current of 200 kA. To reduce spongeness of the high current cable, it is proposed to connect in parallel all coils above the machine midplane with their counterparts below the midplane, thus the operating current of the superconducting cable in each coil will be 100 kA. The EF coils will have 490 turns in each parallel path. The normal charging or discharging voltage for the EF coils is about 9.6 kV to 1.6 kV depending upon the 10 second or one minute ramping time and the turn-to-turn voltage is about 18 to 3 V. The self-stored energy of the EF coils is 10.1 GJ.

The EF coils will be cooled by pool boiling at 4.2 K and 1 atmospheric pressure. Pool boiling is simple, inexpensive, reliable and easy to operate and control.

The superimposing field on the TF coils generated by both the EF coils and the plasma is also shown in Fig. 1. It is seen that the superimposing field will generate fairly large tipping forces on the TF coils as well as impose an order of 1 T additional field margin onto the TF coil winding.

Axial Pressure and Hoop Stress

Table 2 shows the peak field and the computed vertical forces per unit length of each EF coil. It is seen that all coils except Coil No. 2 will have attractive forces toward the midplane. The axial magnetic pressure, P_z, is a function of both axial and radial positions within a coil cross section. The maximum axial magnetic pressure for each coil is also given in Table 2.

Assuming a uniform coil structure, the average hoop stress is the product of the average current density, the mean coil radius and the axial field component averaged over the coil cross section. On the other hand, the average radial magnetic pressure is the product of the average current density, the coil radial thickness and the average axial field component. Both the hoop stress and the radial magnetic pressure for each coil are computed and listed in Table 2. Since the coil mean radius is generally larger than the coil radial thickness, the average loop stress is generally larger than the average radial magnetic pressure. The maximum magnetic pressure is 823 Kg/cm^2 (about 12,000 psi) exerting on Coil No. 4.

Conductor Design and Coil Structure

As an illustration, a 100 kA cable design is shown in Fig. 4. The cable is designed with full cryostability and reasonably low ac losses for the 10 s to 60 s normal charging and discharging purposes. To achieve high reliability, the EF coils must by cryostatically stable. To withstand the dB/dt of about 0.8 T/s during the current swing, individual superconducting strands in the basic cable and the basic cables in the full conductor must be fully transposed. The full conductor was achieved by fully transposing 24 basic cables around a G-10 strip so that the cable will have a height of 2.4 cm by a width of 13.8 cm. Spiral wrapping wetted-wound fiberglass of 3 mm in thickness is employed to band these basic cables together. The fiberglass band will also provide a liquid helium channel of 1 cm in width by 0.3 cm in depth by 13.8 cm in length.

Because of the spongeness of the 100 kA cable, it is important that the EF coil structure must be designed to isolate the electromagnetic forces in both the axial and the radial direction. Figure 5 illustrates such a coil structure using the 100 kA cable. The cable will be loosely fitted into a stainless steel channel with helium cooling and venting slots. The stainless steel channel will support both the axial and the radial electromagnetic forces. Since the cable will be loosely fitted into the channel, the coil body forces could not be accumulated to the cable. The axial coil forces will be bridged through the G-10 plates, which is the support plate for each pancake coil layer. These supporting plates will be machined to have radially outward cooling channels for helium gas venting.

Table I
Characteristics of Superconducting EF Coil

Superconductor/Stabilizer	Nb-Ti/Cu
Stability	Cryostable
Operating Current	200 kA
Cooling	Pool Boiling
Operating Temperature	4.2 K
Average Current Density	About 1400 A/cm^2
Magnetic Field at Plasma Center	0.61 T
Total Ampere Turns	98 x 10^6
Maximum dB/dt (normal operation)	0.8 T/s (10s) to 0.13 T/s (60s)
Self-Stored Energy	10.1 GJ
Power Supply Voltage	9600 V (10s) to 1600 V (60s)
Volt-Second to Plasma*	100
Self Inductance	0.507 H
Mutual Inductance to Plasma	-5.23 x 10^{-4} H

*Plasma self inductance is 12 x 10^{-6} H and its stored energy is about 700 MJ

Table 2
Vertical Forces, Axial Pressure and Hoop Stress

Coil Number		1	2	3	4
Average Current Density (A/cm^2)		1382	1382	1186	1209
Peak Field (T)	without plasma	7.76	7.46	4.30	4.45
	with plasma	6.82	7.80	4.47	4.47
Vertical Force* (10^3 kg/cm)	without plasma	14.93	-4.88	.49	1.31
	with plasma	14.42	-3.95	1.35	.58
Max. Axial Pressure, P_z (kg/cm^2)	without plasma	309.25	134.32	105.05	115.44
	with plasma	299.50	122.11	109.37	111.61
Bz (T)	without plasma	-2.85	2.07	.24	-.46
	with plasma	-2.02	2.42	.40	-.48
Average Hoop Stress, $\bar{\sigma}_t$ (kg/cm^2)	without plasma	607	504	122	785
	with plasma	430	589	208	823
Radial Magnetic Pressure, $\bar{\sigma}_r$ (kg/cm^2)	without plasma	201	233	27	53
	with plasma	142	272	46	56

*Forces pointing toward the STARFIRE midplane are positive. Forces pointing away from the midplane are negative.

References

1. C. C. Baker, S. D. Harkness, D. A. DeFreece, C. A. Trachsel, D. Grauman, J. Kokoszenski, "STARFIRE-Commercial Tokamak Power Plant Overview," This Proceeding.

2. R. Prater, N. Ohyabu, K. Evans, "Poloidal Magnetic Field Coil Considerations for a Commercial Tokamak Reactor," This Proceeding.

3. K. Evans, Jr., D. A. Ehst, P. Messerschmidt, "Equilibrium Field Coil Considerations for Tokamak Reactors," Proceedings of the Third Topical Meeting on the Technology of Controlled Nuclear Fusion, American Nuclear Society Publication CONF-780508, Vol. 2, p. 1084 (1978).

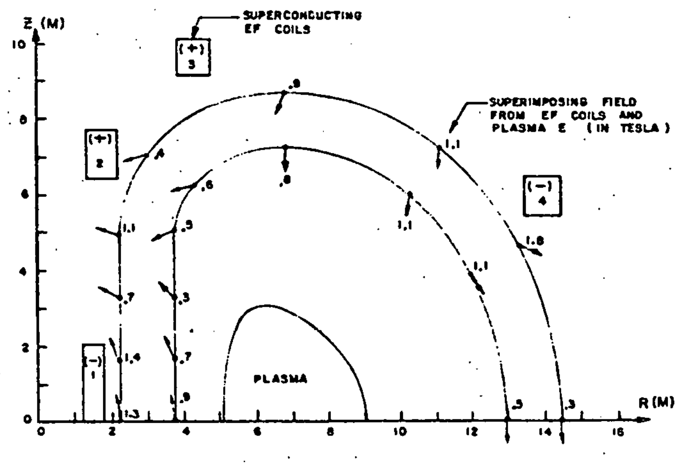

Fig. 1. EF Coils Configuration

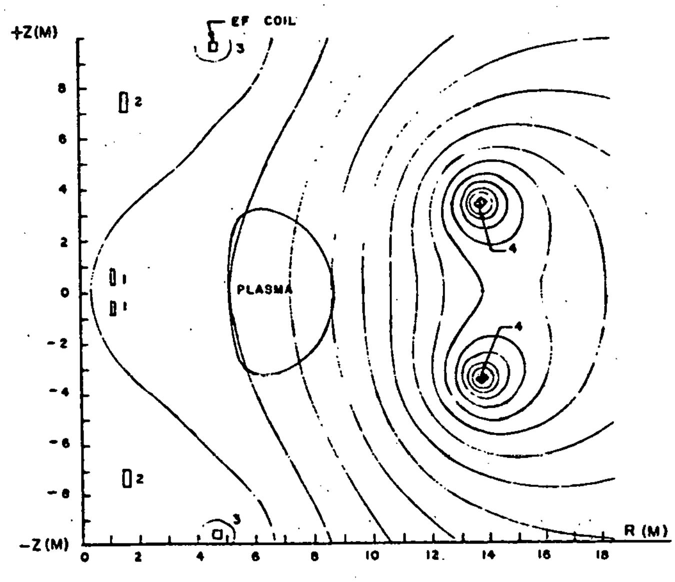

Fig. 2. Equilibrium Field Pattern for Noncircular Plasma

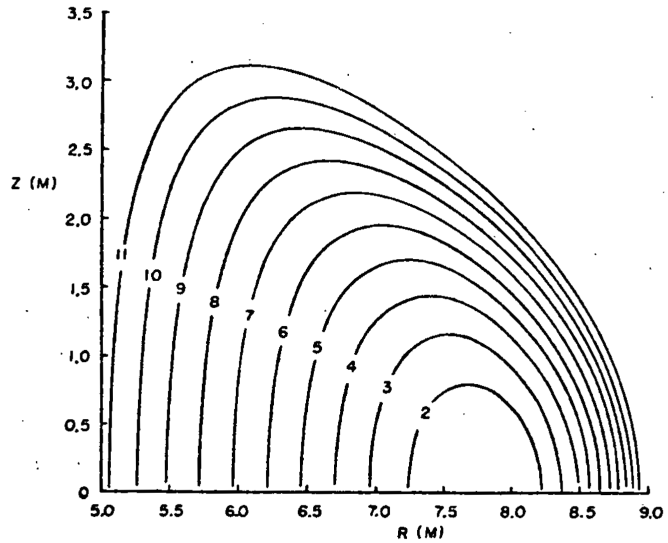

Fig. 3. Total Flux Contour of STARFIRE

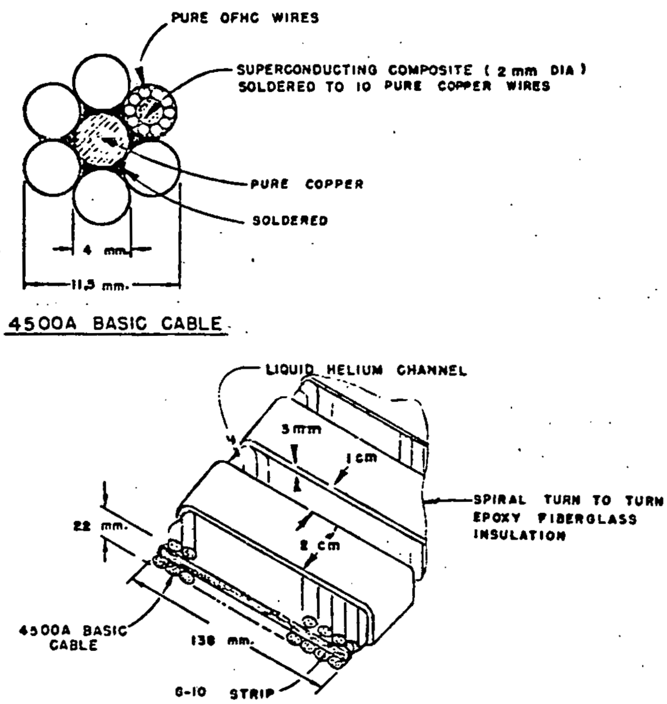

Fig. 4. 100 kA Cryostable Cable Conductor

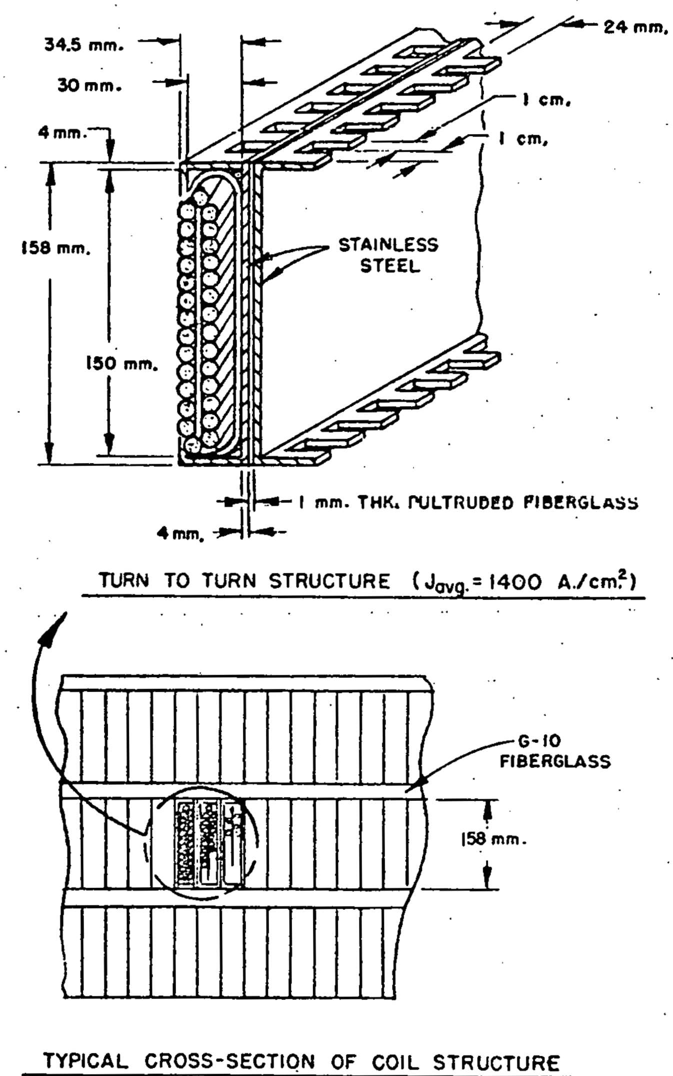

Fig. 5. EF Coil Structure