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High Radiation Designs for Magnets in DT Fusion Reactors*

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***Abstract*—A novel magnet design strategy allows normal conductor resistive coils to operate in intense radiation zones of a DT fusion reactor. Solid insulation is replaced by a combination of highly resistive solid metal and flowing liquid or gaseous coolant behaving as a lossy insulator. Unwanted effects include increased heat dissipation and additional stray magnetic fields, but these can be managed to acceptable levels through optimization .**

Keywords—magnet design, radiation, fusion

I. Introduction

In comparison to normal conducting resistive magnets, superconducting magnets have the obvious advantage of low power consumption. Since at constant magnetic field the power density in the windings of similar resistive magnets of different sizes varies inversely with size, it follows that sufficiently small superconducting magnets can sustain a stronger steady magnetic field than resistive magnets of the same size.

There are situations where it is not practical to use superconducting magnets. In deuterium-tritium (DT) fusion reactors, cryogenic superconducting magnet windings must be protected by an adequate thickness of radiation shielding. In locations where there is not enough space for shielding, it may still be possible to use normal resistive metal conductors since they need no cryogenic cooling, they conduct current well during irradiation and they function until badly damaged by atomic displacements. On the other hand, the solid insulation materials conventionally used in resistive magnet windings are vulnerable to radiation, although some less so than others.

Solid insulation performs two different functions in magnet windings. It blocks leakage currents between conductors, and it transmits forces without significant deformation. Ionizing radiation creates free ion and electron charges causing temporary loss of an insulator's high resistivity. If leakage current then flows in solid insulation, damage can occur quickly with heating. Even without heating, damage still occurs gradually as chemical and microstructure changes accumulate. Either way, the solid insulator eventually fails.

The situation with fluids is different. With no solid structure to damage, many fluids are compatible with intense radiation. For instance, helium is chemically unaffected while water slightly dissociates into hydrogen and oxygen but these are easily recombined so that no permanent damage results. Helium and water are both excellent coolants if rapidly flowing. Helium and pure water have high electrical resistivities in the absence of irradiation. For instance, the resistivity of helium gas is essentially infinite unless it breaks down. Deionized water's resistivity is 10^{13} times the resistivity of copper, drinking water is 10^{9} times copper, while ocean saltwater is 10^{7} times copper.

These resistivities are high enough to serve as good insulators in many applications, although the resistivities decline further when irradiation is producing charge carriers in the fluids. However, charge recombination also occurs and becomes complete as the coolant fluid flows outside the radiation zone to be cooled in a heat exchanger. It is expected that either rapidly flowing helium or water coolant would retain a minimum electrical resistivity considerably greater than the resistivity of any metal while being irradiated anywhere in a DT fusion reactor.

Therefore, either of these two coolant fluids or some other candidates could be used as lossy insulators in fusion reactors. Lossy implies that some leakage current would flow so it is essential that adverse effects of that current remain small. The electric field must be small enough and the flow fast enough to avoid electrical breakdown. Electric fields driving the fluid's leakage currents should be nearly axisymmetric in order to avoid departures from magnetic axisymmetry in the plasma. Also, irradiation of the coolant should not greatly increase a magnet's power consumption during the irradiation.

However, fluids cannot resist sustained mechanical stresses so a different approach involving structural bracing using radiation-resistant solid materials is needed to accommodate the forces. The bracing strategy advocated here starts with rearranging and reshaping the conductor layout to reduce the net force on each conductor so that a minimal amount of solid bracing can be used. Since bracing material will bridge between different conductor voltages it is important to limit the leakage current flowing through bracing. Therefore the bracing cross section should be limited consistent with net forces and any other mission constraints. Thus it is important to choose bracing material that is strong and has a high

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resistivity. Candidate resistive bracing materials include type 316 stainless steel with 44 times copper's resistivity, inconel-718 with 73 times copper's resistivity, and alloy Ti-6Al-4V with 100 times copper's resistivity. It may alternatively be possible to brace using graphite whose resistivity is strongly anisotropic, varying from approximately 150 to 300 times copper's resistivity in directions parallel to the graphite's basal plane and to orders of magnitude more resistivity in the direction perpendicular to that plane. The bracing strategy also includes positioning the bracing material so that the currents flowing through the bracing will together contribute only axisymmetric magnetic field perturbations to the plasma region.

In the following, three examples of high radiation magnet designs are presented on a purely conceptual level. The first example is an all-metal, multiturn central TF conductor system for a low aspect ratio tokamak, the second is an all-metal Ohmic Heating solenoid, and the third is an all-metal PF coil intended to operate inside a vacuum vessel adjacent to a DT fusioning plasma.

II. Conceptual Designs

A. Multiturn Central TF System

In a DT fusion reactor using the low aspect ratio Spherical Torus (ST) tokamak plasma configuration, there is not enough space for adequate radiation shielding of the TF magnet within the small central region inboard from the plasma. A conventional multiturn layout for the central region would use wedge-shaped turns wrapped in solid insulation and wedged against each other to produce hoop compression which counters magnetic centering forces. However, this scheme would fail in an ST since the insulation between wedge-shaped turns would short out due to intense radiation. This has led ST advocates to propose normal conductor resistive single-turn TF designs in order to avoid using vulnerable solid insulation. Unfortunately such single-turn TF designs would need extremely large currents at low voltage for which the DC power supply technology does not exist. If developed, such an ultra-high current power supply would also need to be physically co-located with the ST to avoid devastating power transmission losses.

The multiturn central TF magnet conductor system for STs proposed here does not use solid insulation. Instead, each of its central TF conductor turns is shaped as a vertically oriented pipe. Multiple turns are configured as pipes of different diameters nested inside each other and aligned concentrically about the ST's symmetry axis. Fig.1 includes an elevation section view through the vertical symmetry axis and a plan section view on the horizontal midplane. Flowing coolant (blue) fills the space between the nested conductors and in addition fills volumes beyond innermost and outermost turns. This configuration is chosen so that magnetic TF self-forces are balanced within each conductor turn by hoop compression without involving solid insulation. The net magnetic force vector on each central TF turn is identically zero, while net torques which depend on the radial field profile are typically small.

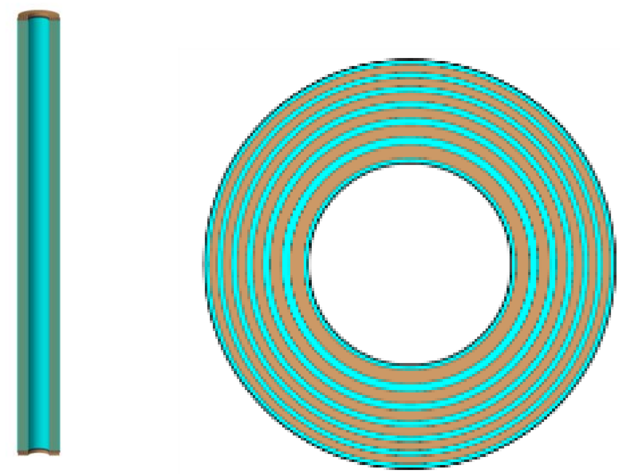

Fig.1. Central TF System Elevation and Plan Sections through Center

This configuration requires engineering development of annular plug assemblies as depicted in Fig.2. Plug assemblies located at the central TF's top and bottom serve three purposes. They structurally connect pipes together as bracing, they contain the pressurized coolant, and they provide a mounting location for external coolant hose fittings. Because the net magnetic force on each TF turn is zero the plug assembly's required strength is limited. However, the plug assembly material should have high resistivity to limit leakage currents. It should be noted that radiation is reduced at upper and lower ends of the central TF so plug designs may have options.

Electrical return currents from the central TF are split among multiple outer legs in order to avoid magnetic field ripple. Fig.3 schematically depicts the circuit through one of several identical outer legs. Current through each central pipe-shaped TF turn flows vertically through demountable joints into conducting rings in upper and lower umbrella structures, then to connected insulated conductors which run radially within the umbrellas and are associated with each outer leg. Each outer leg interconnects turns between upper and lower umbrellas but their connections are advanced between top and bottom in order to connect the central TF turns in series. Each outer leg has its own separate power supply connection so that the total current flowing through each central TF turn is further divided among the parallel-connected outer leg supplies.

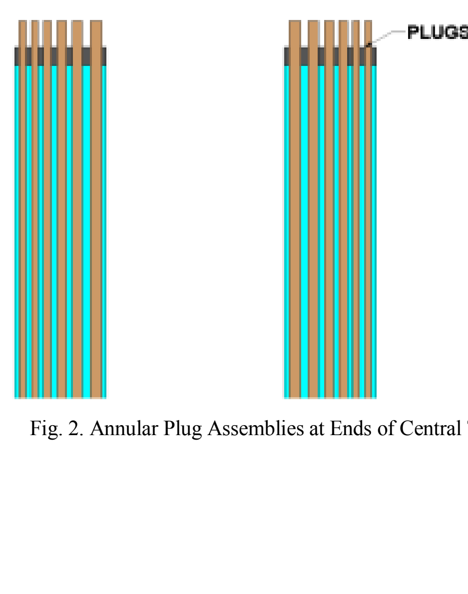

Fig. 2. Annular Plug Assemblies at Ends of Central TF Conductors

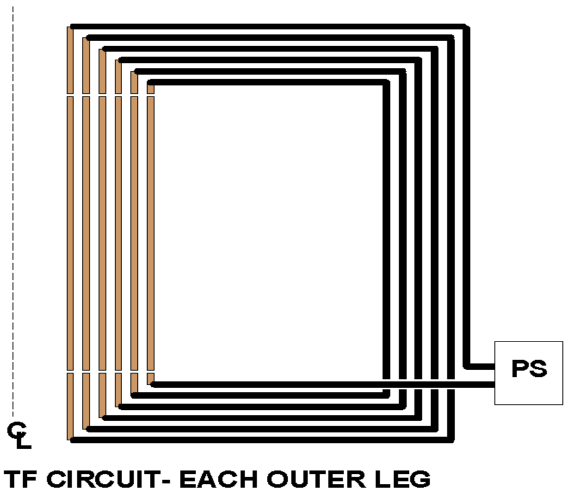

Fig. 3. Schematic of One TF Outer Leg Circuit.

B. All-Metal OH Solenoid

A second high radiation magnet concept is the all-metal solenoid without any solid insulation depicted in Fig.4. As with the previous example, the design motivation is the lack of space within low aspect ratio tokamaks for adequate radiation shielding. Advocates have therefore assumed noninductive plasma startup is essential. However, the all-metal solenoid design proposed here may provide some help from induction for plasma startup and may also provide an ability to better regulate fast variations in plasma current.

Alternating strips of dissimilar metals are helically wound between single-metal end-rings, then rigidly joined together forming a “barberpole” cylindrical conducting assembly. Not shown in Fig. 4 are a braced pressure membrane confining coolant fluid, external coolant fittings, leads which also support, and lead penetrations.

The principle of solenoid operation without insulation is the barberpole’s tilted resistive anisotropy which causes some current to flow azimuthally around the cylinder in response to an axial applied voltage. As with conventional solenoids, magnetic flux is produced, but the barberpole dissipates more power for the same flux by a multiplying factor M>1.

Fig. 4. All-Metal Barberpole Solenoid

To analyze the barberpole, first consider infinitely long narrow alternating strips of two different metals labeled 1 and 2, arranged in a plane running in a direction, B, and joined to each other at their edges. Strip widths are respectively w_1 and w_2, resistivities are η_1 and η_2, strip thicknesses t_1 and t_2.

A lineal current density K_B (amperes per meter) flowing in the B direction splits between the parallel strips so the B component of electric field is related through Ohm's law as:

$$K_B = E_B\left(\frac{w_1 t_1}{(w_1+w_2)\eta_1}+\frac{w_2 t_2}{(w_1+w_2)\eta_2}\right) \tag{1}$$

In the perpendicular A direction, strips alternate in series so the relation there is

$$E_A = K_A\left(\frac{\eta_1 w_1}{t_1(w_1+w_2)}+\frac{\eta_2 w_2}{t_2(w_1+w_2)}\right) \tag{2}$$

Defining fractional widths as

$$f_1 \equiv \frac{w_1}{w_1+w_2};\, f_2 \equiv \frac{w_2}{w_1+w_2} \tag{3}$$

and further defining

$$a = \frac{1}{\left(\frac{\eta_1 f_1}{t_1}+\frac{\eta_2 f_2}{t_2}\right)};\quad b = \left(\frac{f_1 t_1}{\eta_1}+\frac{f_2 t_2}{\eta_2}\right) \tag{4}$$

Then Ohm's law is written as:

$$\begin{bmatrix} K_A \\ K_B \end{bmatrix} = \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}\begin{bmatrix} E_A \\ E_B \end{bmatrix} \tag{5}$$

The coordinate system is next rotated through tilt angle θ.

$$\begin{bmatrix} E_z \\ E_\varphi \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} E_A \\ E_B \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} K_z \\ K_\varphi \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} K_A \\ K_B \end{bmatrix} \tag{7}$$

Therefore,

$$\begin{bmatrix} K_z \\ K_\varphi \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} E_z \\ E_\varphi \end{bmatrix}$$

$$= \begin{bmatrix} (a\cos^2\theta + b\sin^2\theta) & (b-a)\sin\theta\cos\theta \\ (b-a)\sin\theta\cos\theta & (b\cos^2\theta + a\sin^2\theta) \end{bmatrix}\begin{bmatrix} E_z \\ E_\varphi \end{bmatrix} \tag{8}$$

The average azimuthal electric field is zero so an axial electric field causes an azimuthal current as follows:

$$\begin{bmatrix} K_z \\ K_\varphi \end{bmatrix} = \begin{bmatrix} (a\cos^2\theta + b\sin^2\theta) \\ (b-a)\sin\theta\cos\theta \end{bmatrix} E_z \tag{9}$$

Further analysis relates the barberpole power multiplier M to the design parameters as summarized by Eq. 10.

$$M = \frac{\left(\tan^2\theta\sqrt{\left(f_1 + \frac{1}{q}f_2\right)} + \sqrt{\frac{1}{(f_1 + qf_2)}}\right)^2}{\left(\left(f_1 + \frac{1}{q}f_2\right) - \frac{1}{(f_1 + qf_2)}\right)^2 \tan^2\theta} \quad \text{where} \quad q \equiv \frac{\eta_2 t_1}{\eta_1 t_2} \tag{10}$$

Thus, power inefficiency factor M depends on three parameters: the tilt angle θ, the width fraction f_1 and the resistivity ratio divided by the thickness ratio, q. It is appropriate to choose design parameters to minimize M. However, M monotonically decreases as q is increased, so q should be chosen as large as feasible. The situation is different for f_1 and θ, which minimize M at values within their possible ranges. It is easy to show for any q and f_1 values that the tilt angle parameter optimizes as the arctan of a fourth root of a function of f_1 and q as summarized by Eq. 11.

$$\theta_{opt} = \tan^{-1}\left(\frac{1}{\sqrt[4]{1 + f_1(1 - f_1)\frac{(q-1)^2}{q}}}\right) \tag{11}$$

Using this tilt angle prescription the Fig. 5 contour plot shows θ_{opt} and the resulting M_{opt} vs f_1 and q. Further purely numerical optimization of f_1 to minimize M yields the final design prescriptions for f_1 and θ optimized over all (f_1, θ) combinations. These are summarized in Fig. 6. Using Fig. 6 prescriptions the final optimized performance as a function of q value is summarized in Fig. 7.

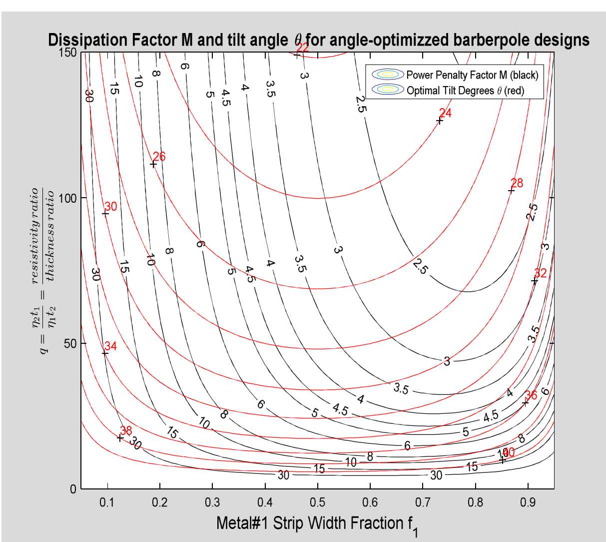

Fig. 5. Best Tilt Angle and Resulting Performance M vs. f_1 and q

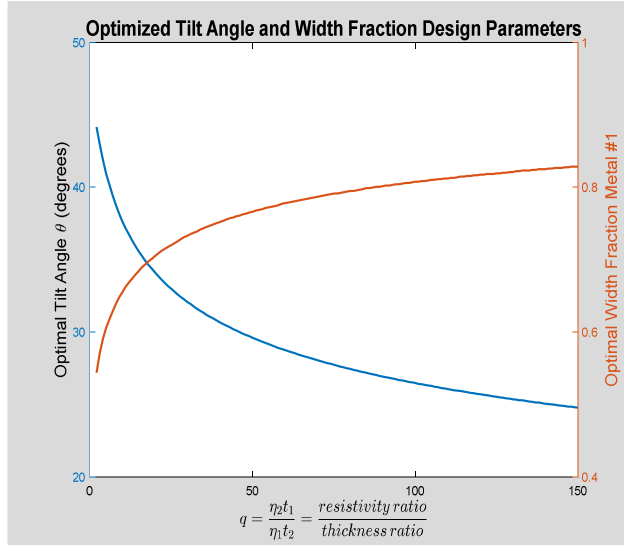

Fig. 6. Optimal Prescriptions for θ and f_1

For example, Fig. 7 shows that using copper with stainless steel M_{opt} =3 can be achieved in a constant thickness assembly and that M_{opt} =2 can be achieved with other metals using a constant thickness. Even lower factors can be achieved using stepped thicknesses of metals with a large resistivity ratio. This demonstrates that the barberpole concept can generate startup flux without insulation within feasible power limits.

Two special cases of the barberpole design concept should be noted. First, a single-metal design is possible by simply cutting a helical groove in a conducting pipe, although it would be difficult to achieve a low M value without compromising structural strength. Second, helical conductor windings placed inside of and soldered to a thin-walled high resistivity metal pipe could work as well as an assembly of joined strips.

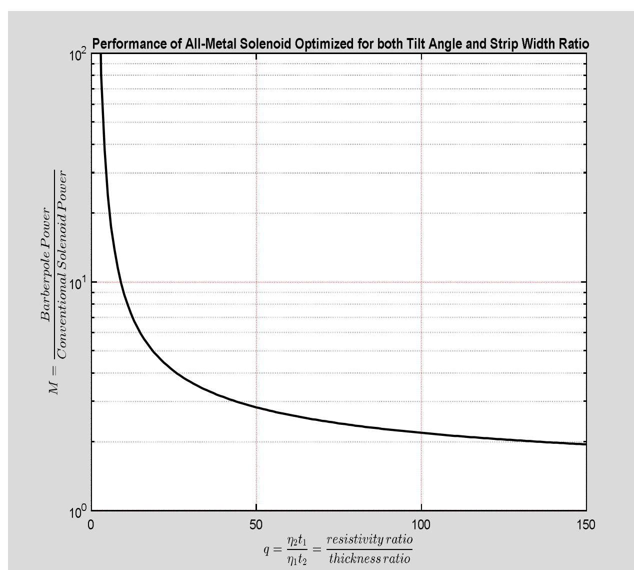

Fig. 7. Optimized Dissipation Factor M_{opt}

C. *Internal PF Coil*

The final design concept is a high radiation PF coil without solid insulation intended to operate within a DT fusion tokamak vacuum vessel. Two all-metal barberpole solenoids with identical heights but opposite helicities and different radii are constructed. One is nested inside of the other, then the two are radially connected at one end. External leads are attached to the other end. The entire assembly is surrounded by a pressure membrane to contain coolant with penetrations and resistive bracing between the all-metal windings and the membrane. While this design would require more power and a supply of coolant, its proximity to the plasma offers shaping advantages.

III. CONCUSION

High radiation magnet design strategies can allow coil operation within the intense radiation zones of a DT fusion reactor. This is not a panacea since power dissipation exceeds that of conventional resistive coils. However, it is expected that these design concepts would be useful in high-payoff niche applications such as providing a close-in plasma shaping capability and providing multiturn TF and plasma startup magnetic flux capabilities for ST-based DT fusion reactors.

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