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HIGH CURRENT SUPERCONDUCTORS FOR TOKAMAK TOROIDAL FIELD COILS*

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W. A. Fietz†

ABSTRACT

Conductors rated at 10,000 A for 8 T and 4.2 K are being purchased for the first large coil segment tests at ORNL. Requirements for these conductors, in addition to the high current rating, are low pulse losses, cryostatic stability, and acceptable mechanical properties. The conductors are required to have losses less than 0.4 W/m under pulsed fields of 0.5 T with a rise time of 1 sec in an ambient 8-T field. Methods of calculating these losses and techniques for verifying the performance by direct measurement are discussed. Conductors stabilized by two different cooling methods, pool boiling and forced helium flow, have been proposed. Analysis of these conductors is presented and a proposed definition and test of stability is discussed. Mechanical property requirements, tensile and compressive, are defined and test methods are discussed.

INTRODUCTION

Although the designs proposed for superconducting tokamak machines differ widely on many technical points, there is general agreement on one item: the operating current in the field coils will be higher than in any of the presently operating superconducting devices for the magnetic fields involved. Experimental devices for the near future are expected to operate at 10,000 to 20,000 A in peak fields of 8 T, while more ambitious projects farther down the road may require conductors rated up to 80,000 A, possibly at even higher magnetic fields.

Nevertheless, operating current is only one of the requirements of the tokamak field coil conductor. A study of the proposed operation of the machines leads to the selection of five basic conductor specification areas. These are operating current, pulsed field loss, stability, mechanical properties, and insulation. The conductor must meet the requirements of each category and still be of a design that can be readily and economically fabricated.

The first step toward the development of these conductors at ORNL will be taken by the large coil segment tests. Conductors for these tests have been specified and requests for quotations have been issued. These specifications are briefly summarized in Table I along with future projections. These bases for these specifications are reviewed and four potential conductors are analyzed in the balance of this paper.

THE SPECIFICATIONS

Operating Current

In the toroidal field coils, the desire for high currents is based on the need to limit voltages during charging and discharging the coil, on the fact that a larger, more robust conductor will usually result in a stiffer winding, and on a need to reduce the labor of coil winding. In the resulting trade-off against higher losses in the current leads, a current of a few tens of thousands of amperes has usually been selected for tokamak designs. In order that the large coil segment tests properly simulate tokamak conductor designs, an operating current of 10,000 A at 8 T and 4.2 K was selected. This choice appears to be the smallest value which will provide a significant increase over present practice and still be in the operating range of tokamak machines.

Pulsed Field Losses

Although the tokamak field coils themselves produce a steady state magnetic field, the plasma is operated intermittently. This operation results in a pulsed magnetic field at the field coil conductor. Reference designs for the Oak Ridge Experimental Power Reactor (EPR) predict that pulsed magnetic fields of about 0.5 T with a rise time on the order of one second will be present at the toroidal field windings with a duty cycle of about 1%. These pulsed fields will have one component parallel to the conductor and one perpendicular to the conductor in a direction outward from the minor axis of the toroid. The orientation of these components is shown in Fig. 1. Losses in the conductor as a result of these fields arise from several sources: eddy currents in the normal conductors, hysteresis losses in the superconductor, and coupling losses between filaments in the composite. Control of these losses requires proper sizing of the normal metal components, an optimum filament diameter, and the proper twist pitch of the individual conductor strand.

Based on refrigeration requirements, a design value for the total average pulse loss from these sources of 12 W/m^3 of conductor at 4.2 K has been chosen. With the 1% duty cycle, this allows a dissipation of 1200 W/m^3 during the pulse. This choice places a limit on the maximum conductor dimension perpendicular to the pulsed field of about 1 mm for a high conductivity matrix superconductor in order to limit normal eddy current losses. In the conductor designs which follow pulse loss consideration is one of the factors that most strongly affect conductor design.

Losses in composite superconductors have been studied extensively[1,2] and may be calculated from the relationships shown in Table II.

For the purpose of estimating total loss in a complex conductor each component is calculated separately. The sum of these contributions is taken as the total loss ignoring interaction effects. In elements of the conductor which contain no superconducting filaments only normal eddy currents are assumed to contribute to the losses.

Minimizing the total loss with respect to the parameter χ_0 gives the relationship $(8Br_0/\lambda J_c) = \chi_0[1 - (1 + \chi_0^2)^{-1/2}]$, which defines the optimum value of χ_0. This value is found to be about 0.35 for the conductors and parameters considered here, corresponding to a twist length of about ten diameters.

Conductor Stability

The stability requirement for the tokamaks toroidal field coils can be simply stated as, "The superconducting coils must not quench under any conceivable operating condition that would not otherwise disable the machine." Methods of achieving a suitable level of confidence in the superconducting coils are not, however, uniquely defined. Stekley,[3] Laverick,[4] and Whetstone[10] set forth the basic ideas of cryostatic stability in boiling liquid helium. They stated that if all the current flows in normal metal,

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the surface heat transfer must be high enough to allow the conductor to return automatically to a superconducting state.

This condition for cryostatic stability can be met by providing enough stabilizing normal metal and conductor surface area with direct cooling by boiling liquid helium. The resulting device has a rather low overall current density, usually around 1000-2000 A/cm^2, and may be too conservatively designed for tokamak use. Higher current density can be obtained by designing for operation below the minimum propagating current.[6,7] Devices designed to these specifications can be operated at an overall current density of 2000-5000 A/cm^2. The main differences between the two criteria for stability are that in the minimum propagating current approach heat transfer along the conductor is taken into account, as are the effects of superconducting properties.

Sources of uncertainty in applying the stability criteria to real devices arise mostly in the heat transfer properties. A detailed analysis of the geometry of the entire device is required to ascertain the surface heat transfer at every point. Since reliable calculations verified by experiment on complex machines are not presently available, considerable uncertainty exists in applying stability criteria to real devices.

The uncertainties of heat transfer can be largely avoided in principle by using supercritical single-phase helium cooling. The most effective method of using the properties of supercritical helium, as proposed by Hoenig and Montgomery,[8] is to place the conductor inside a conduit and force the fluid through at a rate of several grams per second. Overall current densities of 5000 A/cm^2 have been demonstrated in systems that can recover from a completely normal condition in the conductor.

To specify stability under pool boiling conditions for the conductors presently being purchased, the minimum propagating current calculated by the method of Maddock et al.[6] is used, along with the heat transfer curve of Lyons.[9] Stability for forced flow conductors is evaluated using the method of Dresner.[10] The question of what sort of heat input the conductor should be expected to recover from has not yet been resolved. We have arbitrarily chosen a pulse which gives a momentary temperature rise of 20 K in the entire conductor.

Mechanical Properties

The conductor must be capable of withstanding mechanical stresses of three types without adverse effects on device performance. The first of these stresses occurs during the winding and handling of the conductor, presumably at room temperature. The conductor is subjected to bending, twisting, tensile, and compressive forces between the time of its manufacture and the completion of winding of the device. Analysis of these stresses will enable the specification of conductor properties and handling instructions to ensure that the conductor is not damaged. For NbTi conductors the handling will probably not present a problem, but these specifications will be indispensable for the application of Nb_3Sn conductors.

A second crucial stress period for the conductor may occur during cooldown of the device. Analysis of the structure will be necessary to avoid overstressing any of the conductor by differential thermal contraction within the device. Thermal gradients within the winding will be limited by proper instrumentation and controlled cooling of the device. Requirements for cooldown will be prepared prior to ordering conductor for large devices to assess the effects on conductor design.

Finally, the conductor must be designed to withstand the stresses of operating the energized device under any conceivable conditions, including quench. Although the stabilized conductor makes the possibility of quench remote, an event such as loss of coolant might result in a quench which the conductor must withstand without damage.

Mechanical specifications for the conductor must therefore be very carefully considered. They will obviously depend on the overall design of the machine and the anticipated operation. For the first conductors operating under simulated tokamak conditions, three mechanical specifications have been selected: longitudinal tensile stress of 18,000 psi, a lateral compressive stress capability of 4000 psi, and a bending diameter of 0.75 m. Each test is to be performed repeatedly (at least 3 times) on the insulated conductor without resulting in any physical damage or performance degradation.

Insulation

Insulation of tokamak conductors is an area requiring a considerable amount of further study and experiment. The insulation will probably be the component most susceptible to damage by radiation. In addition, the insulation must be abrasion resistant and firmly adherent to the conductor, and its application must be compatible with the conductor component (e.g., curing temperature).

Because of the lack of suitable criteria, the only specification for insulation for the large coil segment tests is a dielectric strength of 250 V between adjacent turns under operating conditions. Probably the insulation scheme used in the large coil segment tests will be a compromise system such as an open helix of epoxy-impregnated fiberglass or other material.

CONDUCTOR DESIGNS

Conductor Types

Although many different classifications of conductors are possible, for this evaluation they are grouped according to the method of cooling (pool boiling or forced-flow) and according to construction (multistrand or monolithic). Within each of these categories further subdivisions may be made according to whether the basic elements are transposed, according to construction of basic elements, etc. Four of these variations are presented in some detail in the following sections. These are pool boiling laminated multistrand, described in Fig. 2 and Table III; pool boiling laminated monolithic, described in Fig. 3 and Table IV; pool boiling transposed multistrand, described in Fig. 4 and Table V; and forced-flow cabled multistrand, described in Fig. 5 and Table VI.

CONCLUSION

None of the four conductor types analyzed here appears to present any insurmountable difficulties in meeting the specifications for a tokamak toroidal field coil. The selection of a particular design will probably depend on manufacturing cost unless some other conductor feature not covered by these specifications should prove objectionable. For example, current distribution in the laminated conductors might be one such problem. If resistance between elements is moderately low, the conductor would behave like an untwisted filamentary superconductor on a gross scale. Insulating the elements and possibly forcing equal current sharing may be one solution.

Since the pulsed field losses play such a large part in determining the conductor configuration, it

would be worthwhile to re-examine the conductors under more relaxed pulsed field constraints. By a combination of superconductive and normal metal shields it may be possible to attenuate the pulsed field by an order to magnitude. If the resulting conductor can be produced significantly more cheaply, such a scheme may be worth considering.

Review and revision of the conductor specifications and test methods are important parts of the superconducting magnet development program at ORNL. It is hoped that as more experience is obtained the conductor requirements can be stated more concisely without ambiguity and that a set of specific test procedures for evaluating the final product will be prepared.

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TABLE I

LARGE COIL SEGMENT TEST

Current Rating	10,000 A, 8T, 4.2 K
Pulse Losses	0.4 w/m during 0.5 T/S Pulse
Stability	Cryostatic
Mechanical Properties	10,000 psi Tensile 4,000 psi Comp. 0.75 m Bend Diameter
Insulation	250 V Turn/Turn

FUSION DEVICES

Current Rating	20,000 - 30,000 A, 8 - 12 T, 3 - 6 K
Pulse Losses	May Be Relaxed If Shielding Scheme Is Developed
Stability	Cryostatic
Mechanical Properties	Higher Strength Is Desirable
Insulation	Radiation Resistance Is Essential

TABLE II
Relationships for Calculating Pulse Field Loss in Composite Conductors

Perpendicular coupling	$p = \dot{B}^2 r_o^2 / \pi x_o^2$
Perpendicular eddy current	$p = \dot{B}^2 r_o^2 / 4\rho$
Perpendicular hysteresis	$p = 2/3\pi\ \lambda J_c \dot{B} d$
Parallel coupling	$p = \lambda J_c \dot{B} r_o (\sqrt{1 + x_o^2} - 1)/4\pi x_o$
Parallel eddy current	$p = \dot{B}^2 r_o^2 / 8\rho$
Parallel hysteresis	$p = 1/6\ \lambda J_c \dot{B} d$

All values are in W/m^3 if units are used as below:

$\dot{B}$ - Appropriate component of field rate (T/s). For these calculations the parallel and perpendicular components were both taken as equal to 0.35 T/s.

r_o - Equivalent radius of round conductor (m). For rectangular conductors, depending on orientation, various forms have been derived.

ρ - Electrical resistivity perpendicular to the field component (Ω-m).

x_o - $2\pi r_o / t_p$ where t_p is the twist length (dimensionless).

λJ - Overall current density (A/m^2).

d - Filament diameter (m).

TABLE III
Technical Data for Pool Boiling Laminated Multistrand Conductor

Overall Dimensions	10 mm x 34 mm
Element Dimensions (7 total)	10 mm x 1 mm
Element Core (Copper)	8 mm x 1 mm
Composite Strand (8 per element)	1 mm x 1 mm
Copper Strand (14 per element)	1 mm x 1 mm
Spacing between Elements	2 mm Epoxy Fiberglass with channels
Surface Exposed to Bath	40%
Cooled Perimeter	73 mm
Normal Conductor Resistance	2×10^{-6} ohm/M
Dissipation (10KA in Copper)	2700 w/M^2
Current Density in Metal	4.7×10^7 A/M^2
Filament Diameter	5×10^{-5} M
Filaments per Strand	145
Critical Current	12,500 A
Minimum Propagating Current	10,000 A
Pulsed Field Loss	0.28 w/M
Minimum Bend Diameter	0.75 M

TABLE IV
Technical Data for Pool Boiling Laminated Monolithic Conductor

Overall Dimensions	10 mm x 36 mm
Composite Element Dimensions (3 total)	4 mm x 3 mm
Copper Strip (12 total)	1 mm x 10 mm
Spacing between Elements	.08 mm Solder
Cooled Perimeter Equivalent	82 mm
Normal Conductor Resistance	2.6×10^{-6} ohm/m
Dissipation (10KA in Copper)	3150 w/M^2
Current Density in Metal	5×10^7 A/M^2
Filament Diameter	5×10^{-5}
Filaments per Element	2,700
Critical Current	12,500
Minimum Propagating Current	10,000
Pulsed Field Loss	0.30 w/m
Minimum Bend Diameter	0.75 M

TABLE V
Technical Data for Pool Boiling Transposed Multistrand Conductor

Overall Dimensions	11 mm x 33 mm
Element Dimensions (12 total)	4.5 mm x 4.5 mm
Element Core (Copper)	1.5 mm x 1.5 mm
Composite Strand (4 per Element)	1.5 mm x 1.5 mm
Copper Strand (5 per Element)	1.5 mm x 1.5 mm
Spacing between Layers	2 mm
Cooled Perimeter Equivalent	54 mm
Normal Conductor Resistance	1.7×10^{-6} ohm/M
Dissipation (10 KA in Copper)	3100 w/M^2
Current Density in Metal	3.0×10^7 A/M^2
Filament Diameter	5×10^{-5} M
Filaments per Strand	156
Critical Current	12,500
Minimum Propagating Current	10,000
Pulsed Field Loss	0.22 w/M
Minimum Bend Diameter	0.75 M

TABLE VI
Technical Data for Forced Flow Cabled Multistrand Conductor

Overall Dimensions	20 mm x 20 mm
Composite Strand (127 total)	1.1 mm diam
Copper Strand (254 total)	1.1 mm diam
Surface Exposed to Bath	898 mm
Cooled Perimeter	890 mm
Normal Conductor Resistance	1.2×10^{-6} ohm/M
Dissipation (10KA in Copper)	1.35 W/M^2
Current Density in Metal	3.9×10^7 A/M^2
Filament Diameter	5×10^{-5}
Filaments per Strand	64
Critical Current	12,500 A
Minimum Propagating Current	10,000 A
Pulsed Field Loss	0.2 W/M

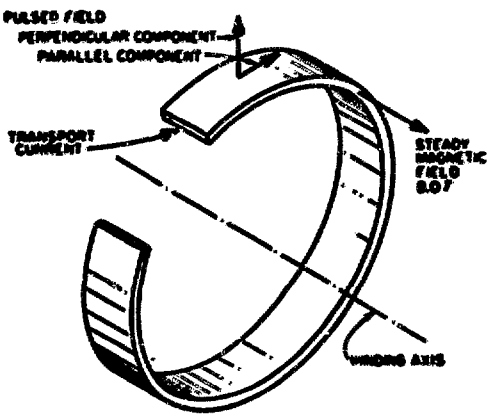

Fig. 1. Pulsed and steady magnetic field components in a tokamak fusion reactor.

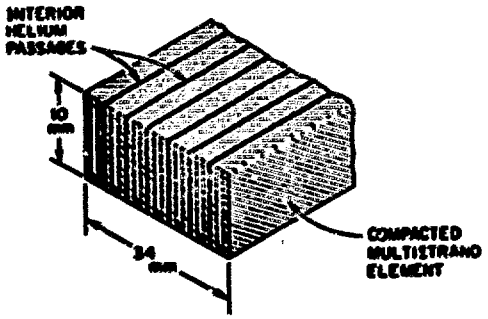

Fig. 2. Pool boiling laminated multistrand conductor.

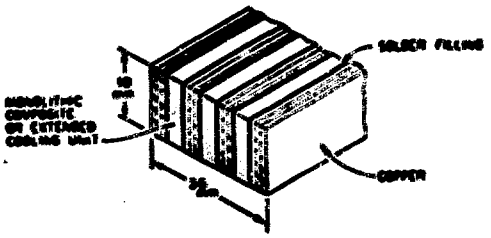

Fig. 3. Pool boiling laminated monolithic conductor.

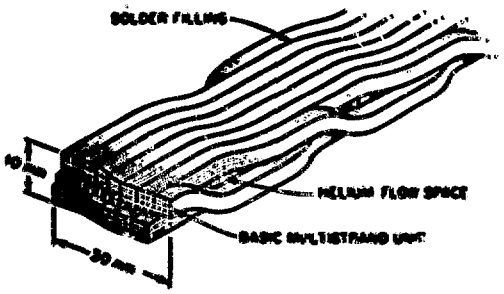

Fig. 4. Pool boiling transposed multistrand conductor.

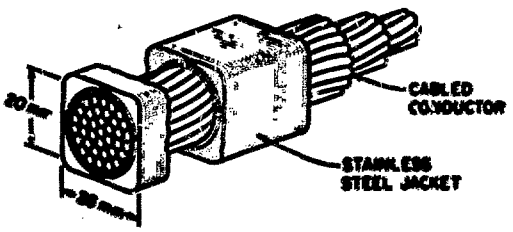

Fig. 5. Forced flow cabled multistrand conductor.