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HIGH-FIELD, HIGH-CURRENT-DENSITY, STABLE SUPERCONDUCTING MAGNETS FOR FUSION MACHINES*

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ABSTRACT

Designs for large fusion machines require high-performance superconducting magnets to reduce cost or increase machine performance. By employing force-flow cooling, cable-in-conduit conductor configuration, and NbTi superconductor, it is now possible to design superconducting magnets that operate at high fields (8–12 T) with high current densities (5–15 kA/cm^2 over the winding pack) in a stable manner. High current density leads to smaller, lighter, and thus less expensive coils. The force-flow cooling provides confined helium, full conductor insulation, and a rigid winding pack for better load distribution. The cable-in-conduit conductor configuration ensures a high stability margin for the magnet. The NbTi superconductor has reached a good engineering material standard. Its strain-insensitive critical parameters are particularly suitable for complex coil windings of a stellarator machine. The optimization procedure for such a conductor design, developed over the past decade, is summarized here. If desired, a magnet built on the principles outlined in this paper can be extended to a field higher than the design value without degrading its stability by simply lowering the operating temperature below 4.2 K.

INTRODUCTION

High-performance superconducting magnets that run at high current densities and produce high fields are in constant demand in fusion machine design as well as other physics applications. The large next-generation stellarators under design—the Large Helical Device (LHD) [1], Wendelstein VII-X (W VII-X) [2], and the Advanced Toroidal Facility (ATF-II) [3]—all call for a magnetic field on plasma axis of 3–4 T, or a maximum field on the winding of 6–8 T. Current density requirements for both LHD and W VII-X have increased from 2.5 kA/cm^2 to 4 kA/cm^2 over the winding pack in their latest design changes [1,2]. This is because higher current density will lead to a smaller, lighter winding pack and smaller machine. Thus, a less expensive machine or a better performance machine can be realized at a given cost.

The superconducting magnet development efforts over the past decade have led to a conclusion that force-flow cooling magnets based on cable-in-conduit NbTi superconductor will best fulfill these demands. A force-flow-cooled conductor can be fully insulated to provide high-voltage integrity, and the winding can be potted to form a rigid structure. The cable-in-conduit conductor configuration further provides a large cooling surface for the superconducting strands and ensures good stability margin for the coil. NbTi superconductor has proven to be a good engineering material, suitable for large fusion magnets.

FORCE-FLOW COOLING

A force-flow-cooled magnet is built with conductor that has the cooling channel embedded within it or on the perimeter of the winding. Supercritical or two-phase helium is forced through

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the channel for direct or indirect cooling. The conductor outer surface is not wetted with helium for heat transfer. It can be fully wrapped with multiple layers of insulation. Thus, high-voltage integrity (10 kV or more) can be maintained.

The winding of a force-cooled magnet is usually potted in an epoxy compound suitable for cryogenic service. Thus, it forms a rigid structure and limits conductor motion (excessive conductor motion can generate enough heat to quench the coil). The potting also helps to distribute the electromagnetic load throughout the winding and transmit it to an external case. This helps to prevent local stress buildup on the conductor. Force and stress calculations can be performed for potted coils with higher reliability than for pool-boiling coils.

Since the helium is not boiling and is well confined in a force-cooled magnet, its temperature can easily be changed by either the refrigerator or an outside heat exchanger. The heat transfer coefficient stays essentially the same. Thus, a magnet can be operated at higher current and higher field without losing its stability margin by lowering the operating temperature below 4.2 K, provided enough structure has been built into the magnet. Or it can be operated at higher temperatures to save on refrigeration load. This is particularly true with cable-in-conduit conductors, as discussed later. Another advantage that may be worth mentioning is that, for a force-cooled magnet, a relatively small-scale segment test may suffice to extrapolate to a full-size magnet. This makes the R&D program for a large system less expensive and faster to carry out.

CABLE-IN-CONDUIT CONDUCTOR CONFIGURATION

In a superconducting magnet, it is generally believed that conductor motion under electromagnetic forces can generate enough local heating to drive the conductor normal. If the heat is not transferred away by the coolant, the normal zone will grow and the whole magnet will quench. As mentioned above, the potting of a force-cooled magnet can minimize the motion-induced heat source. But the conventional force-cooled conductors do not provide a heat barrier to the superconductor and do not have large enough cooled surfaces. Thus, they do not have good stability margins as a whole.

An internally cooled cable-in-conduit conductor configuration was proposed, first by Hoenig [4] of the Massachusetts Institute of Technology (MIT), to increase the stability of a force-cooled magnet. The superconductor is contained in a braided cable of fine strands enclosed in a protective (steel) conduit. Helium, usually supercritical, is forced through the interstices of the cable. The fine division of the conductor into cable form provides large surfaces wetted by the helium. The consequent excellent heat transfer allows a cable-in-conduit conductor to operate stably at quite high current densities.

Engineering Equations for Optimization

Experiments performed on small-scale cable-in-conduit conductors have shown that, because of the tight confinement of helium in the conduit, heat from the conductor induces transient local flow of the helium. This local flow greatly enhances heat transfer from the conductor to the helium. The combination of enhanced heat transfer and the transient conductive heat transfer causes the multiple stability phenomena observed in some cable-in-conduit conductors [5]. The important engineering outcome of these investigations is that there is a limiting current, below which the stability margin of the conductor is very high and is limited only by the available helium enthalpy. The limiting current density over the cable space is found to be [6]

$$J_{\text{lim}} = f\left(F, F_{co}\right)\left[\left(T_c - T_b\right)\rho^{-1}\right]^{1/2} d^{-1}\left(l^2/\tau\right)^{1/15} \tag{1}$$

where $f(F,F_{co})$ is a function of the fraction of conductor in the cable space, F_{co}, and the fraction of copper in the cable, F, T_c is the critical temperature of the superconductor, T_b is the temperature of the helium (bath), ρ is the copper resistivity, d is the diameter of the cable strand, and l and τ are the local heating length and duration. Because of the very small power (1/15), Eq. (1) is insensitive to the uncertain factor l^2/τ.

In addition to stability, protection of a coil when it quenches should be carefully considered. Since a force-cooled magnet can have very good voltage withstand capability, it can be dumped rapidly and prevented from having damaging hot spots. However, the hydraulic length can still be long enough to produce very high helium pressures. The worst case is when the conductor of a whole hydraulic length goes normal all at once. An equation to estimate the ensuing maximum quench pressure, P_{max}, has also been derived and tested experimentally [7]. It has the form

$$P_{\text{max}} = g\left(F, F_{co}\right)\left(\rho^2 J_{cs}^4 l^3 d^{-1}\right)^{0.36} \tag{2}$$

where $g(F,F_{co})$ is another function of F and F_{co}, J_{cs} is the current density over the cable space, and l is now the hydraulic length.

Based on Eqs. (1) and (2) and the available helium enthalpy, one can calculate the stability margin, ΔH, and maximum quench pressure for different values of F and F_{co}. The results can then be plotted as contours of constant ΔH and constant P_{max} in the (F_{co},F) plane. As an example, a NbTi conductor operating at 8 T and 4.0 K, with a current density over the cable space of 20 kA/cm^2, would have the contours shown in Fig. 1. In this figure, the upper boundary of the contours is cut off by $i = 1$, when the operating current would equal the critical current of the conductor. The left boundary is the limiting current density given by Eq. (1). The right boundary is a safe engineering choice of limiting P_{max} to 500 atm. From this plot, one finds that for the given operating conditions a conductor with $F_{co} = 0.8$ (20% void in the cable space) and $F = 0.62$ (Cu/SC = 1.6) would be an optimum choice. Such a conductor operates at 49% of its critical current and has a stability margin of about 100 mJ/cm^3.

Variations

During the studies of cable-in-conduit conductor that led to these scaling equations, it was also found that forced helium flow would push the limiting current to a higher value [6]. However, if a conductor is already in the high-stability regime, the flow has no effect on stability. Thus, helium flow is needed only for steady-state heat removal. In a large magnet with long hydraulic length, the plain cable-in-conduit conductor may present too big a pressure drop to have enough helium flow through the conductor. It is prudent to provide additional cooling paths for a big cable-in-conduit magnet. Figure 2 shows two possible variations to the plain cable-in-conduit configuration. The tube in the conduit variation adds a central cooling tube in the cable space. This is a straightforward modification of the plain configuration. The cable-in-double conduit variation adds another conduit inside the steel conduit. The inner conduit would be more or less

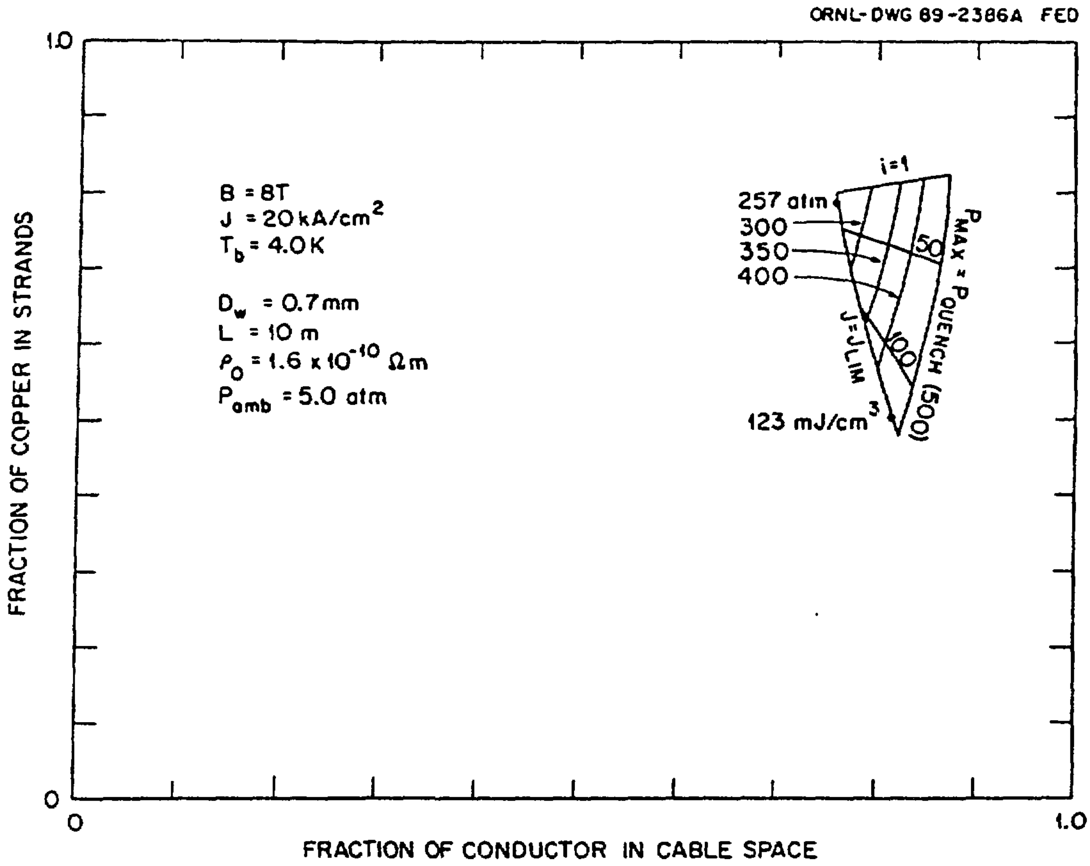

FIG. 1. Contour plots of stability margins and maximum quench pressures for a NbTi cable-in-conduit conductor operating at 8 T and 4.0 K with J_a = 20 kA/cm².

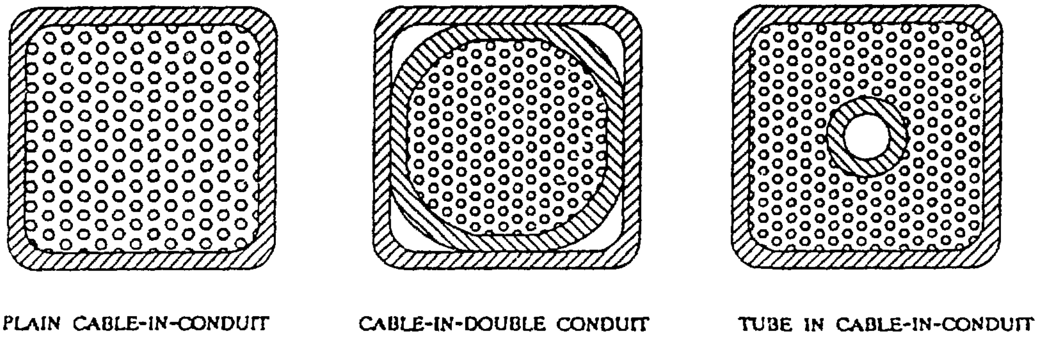

FIG. 2. Possible variations from the plain cable-in-conduit conductor configuration.

round and create additional, larger cooling channels between the two conduits. The inner conduit can be made of a material, such as copper, that would aid in the quench protection of the coil. It would also serve as an additional thermal barrier for the friction heating generated between the conductors and as a magnetic barrier for field perturbations.

The helium in the additional cooling channel and the (possible) copper in the additional conduit (or tube) would probably not aid in the stability margin of the conductor. Thus, the current density used in optimization studies such as those shown in Fig. 1 should refer to that over the cable space only. The current density over the conductor would be lowered by adding the conduits and any additional cooling channel cross sections. The current density over the winding would further be reduced by adding insulation thickness and packing factor. Depending on the conductor size, configuration, shape, and voltage withstand requirement, the current density over the winding could be 35–65% of that over the cable space.

NbTi SUPERCONDUCTOR

The field requirement of 8 T or less on the winding of the next-generation stellarator machine is well within the capability of NbTi superconductor. This material has reached an engineering standard such that all coils built with NbTi in the Large Coil Task operated to 9 T [8]. This superconductor is also preferable for the complex and non-planar helical or modular winding of a stellarator. The strain-sensitive Nb_3Sn superconductor is more liable to damage in such a complex winding.

Even if a field as high as 10–12 T is required, NbTi can still be used by lowering the helium temperature. Optimization studies similar to those discussed in Eqs. (1) and (2) can also be done with superfluid helium [9]. The limiting current density is replaced by a Kapitza limit. Contour plots of stability margin and maximum pressure for a NbTi cable-in-conduit conductor operating at 10 T and 1.8 K with current density of 30 kA/cm^2 are shown in Fig. 3. It is clear from such a plot that higher stability margin, higher field, or higher current density can be achieved with 1.8 K superfluid helium.

CONCLUSION

On the basis of superconducting magnet development efforts over the past decade, it can be shown that by employing force-flow cooling, cable-in-conduit conductor configuration, and NbTi superconductor, a superconducting magnet system can be built to operate at high fields (8–12 T) and high current densities (5–15 kA/cm^2 over the winding pack) in a stable manner. It would thus lead to a less expensive and higher performance next-generation stellarator machine.

It should, however, be pointed out that the database for such coils is still very sparse. A NbTi cable-in-conduit coil [10] was built and tested at Oak Ridge National Laboratory (ORNL) to 7.7 T at 4.2 K and 8.1 T at 3.9 K. It never quenched spontaneously, although the stability margin was measured to be less than 50 mJ/cm^3 above 7 T. Some Nb_3Sn pancakes were built and tested to 12 T by Hoenig of MIT [11]. The largest cable-in-conduit coil built to date is the Nb_3Sn coil built by Westinghouse for the Large Coil Task. The test results showed that it performed well and in good agreement with the small-scale experiments as far as the cable-in-conduit stability properties were concerned.

Finally, in addition to the need for a larger database, a few remaining unresolved issues should be addressed. The cable form of this type of conductor is subjected to strand motion and severe stress at the point of contact under electromagnetic load. It is not clear how much cyclic loading it could take before fatigue would start to degrade the conductor performance. Normal-zone propagation in a cable-in-conduit conductor has not been investigated carefully, and its behavior under different operating conditions is not clear. Systematic studies of this issue may shed light on what the real maximum quench pressure is and on whether the ensuing helium expulsion can be used for quench detection.

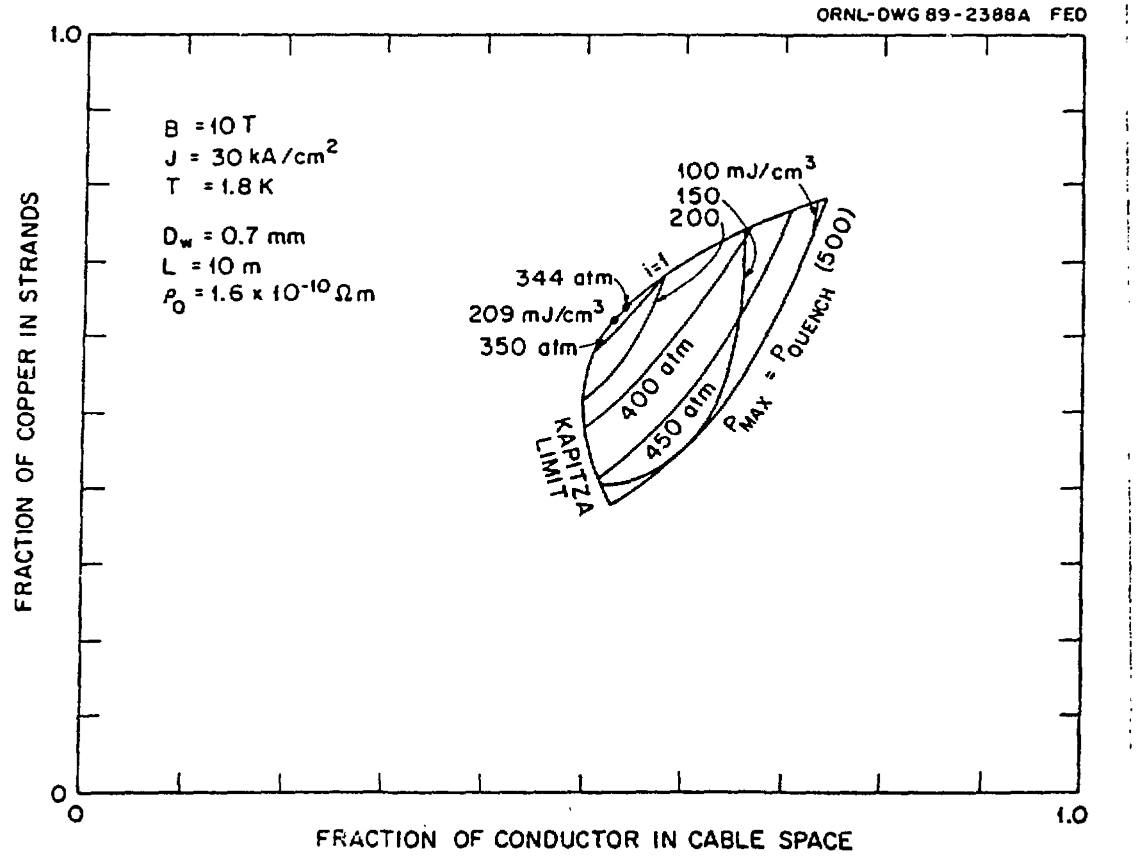

FIG. 3. Contour plots of stability margins and maximum quench pressures for a NbTi cable-in-conduit conductor operating in 1.8 K superfluid helium at 10 T with J_a = 30 kA/cm^2.

REFERENCES

[1] IIYOSHI, A., et al., Recent status of the Large Helical Device project," paper O4-1 presented at this workshop; MOTOJIMA, O., et al., Recent design considerations for the Large Helical Device," paper O4-2 presented at this workshop.

[2] WOBIG, H., et al., The Wendelstein VII-X project, paper O4-4 presented at this workshop.

[3] LYON, J.F., et al., Overview of the ATF program," paper O1-2 presented at this workshop.

[4] HOENIG, M.O., MONTGOMERY, D.B., IEEE Trans. Magn. MAG-11 (1975) 569.

[5] LUE, J.W., MILLER, J.R., DRESNER,L., J. Appl. Phys. 51 (1980) 772.

[6] DRESNER, L., IEEE Trans. Magn. MAG-17 (1981) 753; LUE, J.W., MILLER, J.R., IEEE Trans. Magn. MAG-17 (1981) 757.

[7] MILLER, J.R., DRESNER, L., LUE, J.W., SHEN, S.S., Yeh, H.T., in Proc. 8th Int. Cryogenic Engineering Conf. (Genova, 1980) (RIZZUTO, C., Ed.), IPC Science and Technology Press, Surrey (1980) 321.

[8] BEARD, D.S., KLOSE, W., SHIMAMOTO, S., VÉCSEY, G. (Eds), Fusion Eng. Des. 7 (1988) 1.

[9] DRESNER, L., IEEE Trans. Magn. MAG-23 (1987) 918.

[10] MILLER, J.R., LUE, J.W., BROWN, R.L., KENNEY, W.J., IEEE Trans. Magn. MAG-17 (1981) 2250.

[11] HOENIG, M.O., STEEVES, M.M., IEEE Trans. Magn. MAG-21 (1985) 1052.