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HIGH-CURRENT DENSITY COILS FOR HIGH-RADIATION ENVIRONMENTS

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SUMMARY

This paper concentrates on the problems of providing normal (that is, nonsuperconducting) magnet coils for present and short-term-future requirements where significant radiation doses are involved. Projects such as 100-mA deuteron accelerators [1] and bundle diverter coils for TONAMAS [2] are typical of applications where conventional organic insulation limited to 10^{19} rads makes epoxy-based systems unacceptable. Moreover, even in present-day accelerator radiation levels can be high enough to give rise to problems with oxidation of copper conductors if water is used in direct contact with the copper coil. The radiolytic oxygen, being formed in situ, cannot be controlled by external deoxygenation.

An acceptable insulation system for such environments has been described previously [4] and is being employed where radiation is expected to be a problem [4]. Being a compacted magnesium oxide powder, the insulation has the following attributes:

1. Radiation insensitivity - is stable to a dose rate of 10^{17} rads, with a maximum expected life expectancy of 10 years at 1000 rads/hr.
2. Electrical - enabling standard oil-wetted practice to be followed, with all the problems of fused ceramics.
3. Good thermal conductivity - just water at room temperature.
4. High-temperature stability - making the metal components of the coil determine the operational temperature limit, rather than the insulation system as in conventional coils.

Analysis of the remaining constraints on maximum current densities achievable in such a coil construction, using computer codes, leads to coil configurations that operate at higher current densities than are usually found in directly cooled coils. It also becomes clear that the cable can be designed, not necessarily to maximize the "packing factor" by decreasing insulation and sheath thickness, but to optimize the thermal conditions within the coil package. The operating temperature limit is determined by the acceptable oxidation rate of the surface-exposed metal on the coil.

An example of the thermal analysis of one coil configuration is given. The approach taken at Los Alamos to deal with the problems of accessories, temperature sensors for example, which are often as intractable as the coil itself, is outlined.

The problems addressed here, although not of immediate concern to developmental fusion reactors, become of fundamental importance in the construction of commercial fusion reactors.

INTRODUCTION

Coil design for conventional magnet coils is usually directed toward producing a high packing factor, here defined as peak conductor current-carrying cross section (gross coil cross section), while maintaining the total current at a reasonable level for the application. Adding the capability of operating in a high radiation environment, even if it is only after some of these standard concepts, leads to completely different systems, immediately demonstrating a number of restrictions. The coil packages are made of "concrete" [1,2], oxidized aluminum [3], or ceramic insulation [4]. Long-term operation of directly cooled copper conductors in high-radiation levels produces another problem: the formation of copper oxide by radiolytic oxygen, leading to problems in the cooling water circuits [5,6]. This problem may also be related to the copper's operating temperature, but it must be noted that the JAMPF target cell quadrupoles showed no indication of this problem in their early years of operation [7]. It has been reported since beam intensity, and so radiation levels, have risen to their present levels.

The use of indirectly cooled metal coils [8] can avoid the corrosion problem, whatever its source, and the metal technique is particularly well suited to this concept, because of the relatively high thermal conductivity of the insulation (2.36 W/mK) and the copper-jacketed construction that provides a metallic heat path to the cooling sink. This paper describes the design optimization of such a coil. The other advantages of the method may be worth mentioning: less sensitivity to the quality, (or conductivity) of the cooling water, and the absence of electrical insulators in the cooling water system.

COIL DESIGN

An application requiring radiation-hardening of the magnet coil is the beam transport line for the Fusion Materials Irradiation Test (FMIT) [9] accelerator-target, where the final quadrupoles are exposed to not only the estimated 3- μ A/m deuteron spill, but also to back-streaming neutrons from the target [10].

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The magnet cross section chosen is shown in Fig. 1. It provides a compact structure, easily fabricated for 4-fold symmetry, yet can be split readily on the horizontal centerline for remote access to the vacuum system. The coil has two layers of 13.5-mm square solid m.i. cable wound on top of a layer of cooling tubing, which therefore cools the iron parts of the magnet, removing the radiation-deposited heat.

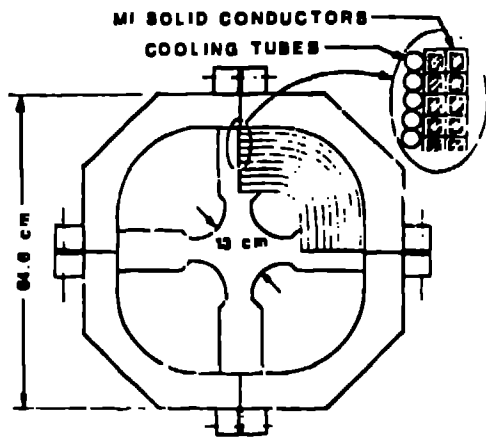


Fig. 1. Magnet cross section showing MI solid conductors and cooling tubes. Dimensions are in centimeters.

In Appendix 2, the heat-flow analysis of the coil is outlined, neglecting temperature-dependent terms in the electrical and thermal conductivity. For the conductor used, and the required current of 4.3 kA, the maximum temperature rise is less than 1°C, for a maximum temperature of 273°C, which is recommended for copper-iron cable [11]. The current density is 4.3 kA/cm², giving a current density of 11.2 A/mm². This current density compares favorably with that directly on the conductor, despite the 4.3 kA peak current. The temperature map of the coil is shown in Fig. 2.

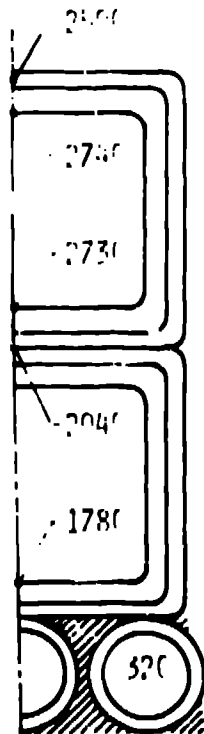


Fig. 2. Temperature map.

FUTURE DEVELOPMENT

The fusion program leads to requirements for coils of much higher current ratings than that described above [12]. Meeting these requirements calls for some changes in m.i. cable technology. Existing cables are made by minor changes in the manufacturing process for conventional m.i. cables; cables for high-power coils will require careful optimization of the cable parameters. Examination of (A-1) in the Appendix shows the following features.

1. The cable should be rectangular, because the conductor width, W_c , appears only in the denominator.
2. There will be an optimum value of sheath thickness, t_s , for each coil.
3. A minimum insulation thickness, t_i , is desirable; the minimum is determined by the voltage standoff required after winding.

The increase in conductor cross section required by the increased current, coupled with the relatively thin sheath, suggests the following changes in fabrication and winding techniques.

1. The large cross section will require the fabrication by assembly of preformed insulator segments, rather than by Mg powder filling.
2. The reduction of cross section of 273°C to 178°C will require a roller system (Turk's head), rather than the drawing through a die.
3. Tension winding of winding the cable to secondary cable fasteners to the magnet will be required. The tension is maintained by winding through a friction device.

CONCLUSIONS

Best to the magnet design of coolant for water-cooled coils. The design includes a flow switch to monitor power if the water flow is inadequate. Flow switches, however, are not very maintenance resistant, are often unreliable, and in multiple-path water circuits, are incapable of detecting the blockage of one circuit.

In the FMI quadrupole described above, there is one water circuit per coil, and the water lines are brought out from the shielded enclosure (cooling the coil electrical leads), so that an individual flow switch per water circuit, in a low-radiation environment, is possible. It is still intended to back this up with an over-temperature switch, as illustrated in Fig. 3, to increase reliability. Thermal analysis of this configuration shows that the temperature difference between switch and conductor is less than 1°C.

When multiple water circuits are connected inside a magnet, the dependence on temperature switches rises, because these switches are the only devices small enough to install. These can be made more effective and reliable by using several switches with an auction-based decision circuit; in Los Alamos two out of three switches determine whether the cooling is adequate. The three switches are from different manufacturers, entirely inorganic, to decrease the possibility of a common failure mode.

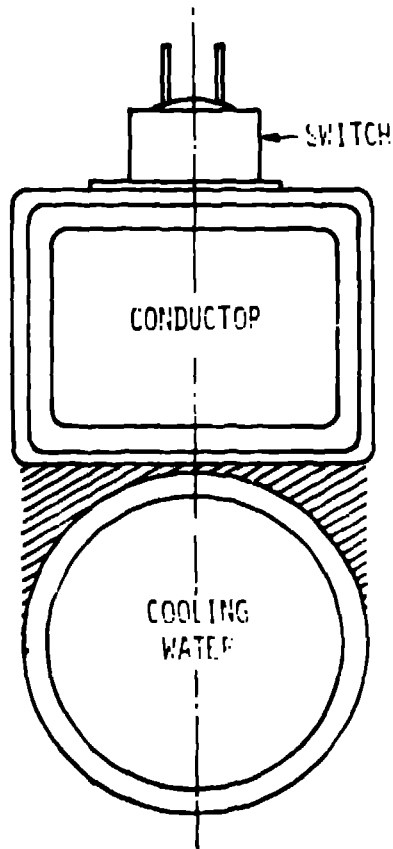


Figure 1. Cross-section of magnet.

with copper conductors. The magnet was operated at 100 kV and 100 mA for 100 hours. The magnet was operated at 100 kV and 100 mA for 100 hours. The magnet was operated at 100 kV and 100 mA for 100 hours.

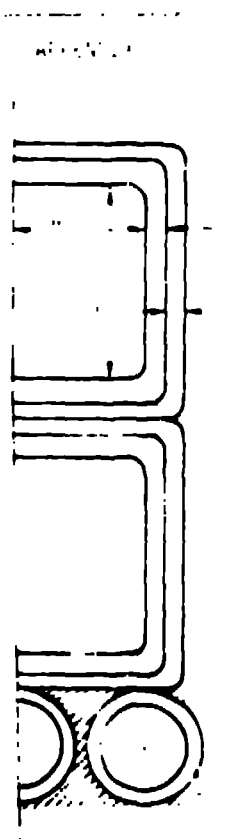
with mineral-insulated conductors.

operated at 100 kV and 100 mA for 100 hours. The magnet was operated at 100 kV and 100 mA for 100 hours. The magnet was operated at 100 kV and 100 mA for 100 hours.

with copper

- [1] G. A. Eager and M. Mattson, "Mineral-Insulated Magnets," *IEEE Trans. Nucl. Sci.*, pp. 1975, 1975.
- [2] K. E. Shollen and G. Stapleton, "Construction of Magnets for the Los Alamos Linear Accelerator using Comptonium Material," *Radiation*, Sept. 1960.
- [3] M. M. Holland and Joseph Hill, "Radiation-Resistant Magnets Made from Hard Anodized Aluminum Conductor," *IEEE Trans. Nucl. Sci.*, NS-10, Vol. 5, pp. 708, June 1973.
- [4] A. Harvey, "Radiation-Hardened Magnets Using Mineral-Insulated Conductors," *MIT-4 (CONF-720908)*, pp. 456, 1972.
- [5] D. C. Hagerman, Los Alamos Meson Physics Facility, private communication.
- [6] A. J. Utter, TRIUMF, private communication.
- [7] A. Harvey, "Experience With the LAMPF Mineral-Insulated Magnets," *MIT-6*, pp. 1972.

- [8] G. George, "Magnets With Mineral-Insulated Conductors at S.L.N., *MIT-5*, pp. 719, 1975.
- [9] P. A. Jameson, "High-Intensity Deuteron Linear Accelerator (FMIT)," *IEEE Trans. Nucl. Sci.*, NS-26, Vol. 3, pp. 2906, June 1979.
- [10] Donald J. Liska, et al., "High-Radiation Tube Design of the FMIT High-Energy Beam Transport," *LA-59-R1-770*, March 1981.
- [11] G. A. Jordan and G. S. Eager, "Mineral-Insulated Metallic-Sheathed Cables," *Power Apparatus and Systems*, April 1955.
- [12] Joel M. Schultz, "Sizing of the Energy and Electrical Systems for an FCC Ring Accelerator Design with MI Insulation," *MIT-10*, Los Alamos Center, LA-59-R1-770, December 1981.



Conductor copper height	h	1.00
width	w	0.50
Area	$h \times w$	0.50
Electrical conductivity	σ	10^8
Thermal conductivity	k	10^4
Insulation (Mg) thickness	t	0.10
Thermal conductivity	k_i	10^2
Sheath (copper) thickness	t_s	0.05
Thermal conductivity	k_s	10^4
Cooling water temperature	T_w	300

Then per unit length:

$$\text{Heat produced} = \frac{I^2}{hcw} \text{ per conductor.}$$

Temperature rise of upper conductor = average temperature of sheath + rise in insulation

= upper temperature rise of lower sheath + 1/2 temperature rise in upper sheath + rise in insulation.

$$= \frac{I^2 R}{h C W C} \frac{1.5}{15 \cdot K C} (t_{LC} + 2t_i + t_{LS}) + \frac{0.75 \times 1.5}{15 \cdot K C} (t_{LC} + t_{LS} + t_{LS}) + \frac{I^2 R}{(t_{LC} + W C K)}$$

Therefore, the temperature of the upper conductor (which will not differ much from that of the top sheath surface) on which we probably want to set an upper limit, becomes:

$$= \frac{I^2 R}{h C W C} \frac{1.5}{15 \cdot K C} (t_{LC} + 2t_i + t_{LS}) + \frac{0.75 \times 1.5}{15 \cdot K C} (t_{LC} + t_{LS} + t_{LS}) + \frac{I^2 R}{(t_{LC} + W C K)}$$