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TITLE: HIGH-CURRENT DENSITY COILS FOR HIGH-RADIATION ENVIRONMENTS

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# HIGH-CURRENT DENSITY COILS FOR HIGH-RADIATION ENVIRONMENTS

Alexander Harvey*

## 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 TOKAMAKS [2] are typical of applications where conventional organic insulation limited to $10^{10}$ rads makes epoxy-based systems unacceptable. Moreover, even in present-day accelerator radiation levels can be high enough to give rise to problems with corrosion of copper conductors if water is used in direct contact with the copper [3]. The radiolytic oxygen, being formed in situ, cannot be controlled by external deoxygenators.

An acceptable insulation system for such environments has been described previously [4] and is being employed where radiation is expected to be a problem [5]. Being a compacted magnesia powder, the insulation has these advantages:

1. Radiation insensitivity - [illegible] $10^{10}$ rads, with [illegible] expected [illegible] limit.

2. Flexibility - [illegible] practice to [illegible] allowed, with [illegible] of fired ceramics.

3. Good thermal conductivity - [illegible] 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.

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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 systems, become of fundamental importance in the construction of commercial fusion reactors.

## INTRODUCTION

Coil design for conventional magnet [illegible] is directed toward producing a high packing factor, here defined as the ratio of conductor current-carrying cross section to gross coil cross section, while maintaining the total current at a maximum level for the application. Adding the capability of operating in a high radiation environment, over $10^{10}$ rads, may, after some of these standard concepts, [illegible] of insulation systems immediately, [illegible] ordered, or restricted. The [illegible] "concrete" [1,2], anodized aluminum [illegible] insulation [illegible] [4], [illegible] long-term operation [illegible] copper conductors in high-radiation [illegible] produces another problem: the formation of [illegible] oxide by radiolysis, leading to [illegible] in the cooling water circuits [3,6]. This [illegible] may also be related to the copper's operating temperature, but it must be noted that the LAMPF [illegible] cell quadrupoles showed no indication of this [illegible] in their early years of operation [7]. It has [illegible] since beam intensity, and so radiation levels have risen to their present levels.

The use of indirectly cooled m.i. coils [4,[illegible]] avoid the corrosion problem, whatever its source, [illegible] the m.i. technique is particularly well suited to this concept, because of the relatively high thermal conductivity of the insulation (2.36 W/m•K) 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-μA/m deuteron spill, but also to back-streaming neutrons from the target [10].

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.

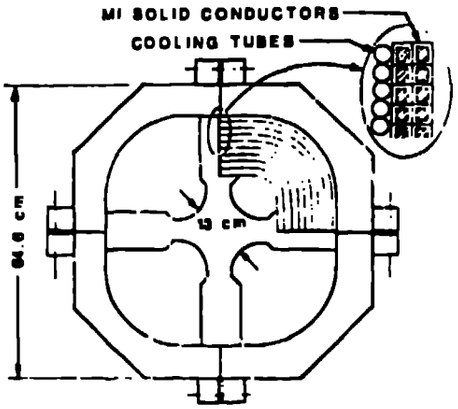



Fig. 1. Mineral-insulated, [illegible] cooled High-Energy Beam Transport (HEBT) [illegible] quadrupole.

In Appendix [illegible], 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 [illegible], the maximum temperature rise is less than [illegible]. For a maximum temperature of [illegible], which is recommended for copper-[illegible] cable [illegible], the current [illegible] 43[illegible] A, giving a current density of [illegible] A/mm². This current density, [illegible] directly cooled conductor, despite the [illegible] factor. A temperature map of the [illegible] is shown in Fig. [illegible].

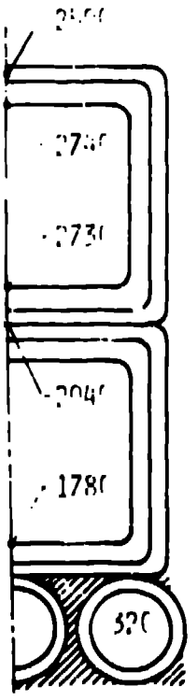



Fig. 2. Temperature map.

## 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, Wc, appears only in the denominator.

2. There will be an optimum value of sheath thickness, ts, for each coil.

3. A minimum insulation thickness, ti, 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 technique.

1. The large cross section will require [illegible] assembly of prefired insulating rings, rather than by Mg powder filling.

2. The reduction of cross section should be by roller system (Turk's head), rather than by drawing through a die.

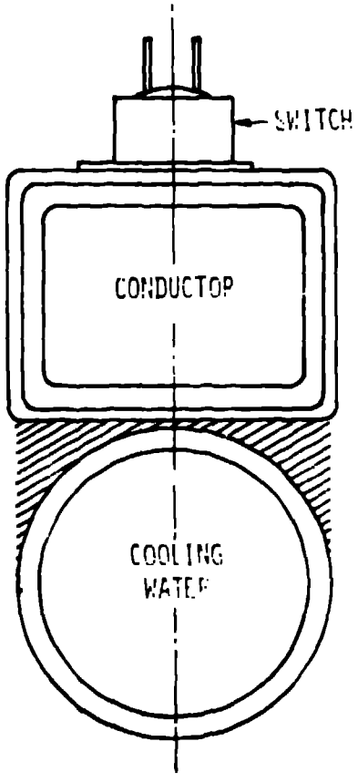
3. Tensioned ring [illegible] winding [illegible] secondary cable fastened to the [illegible] turn is tensioned by running the [illegible] through a friction brake.

## ACCESSORIES

Protection against loss of coolant for water-cooled coils often includes a flow switch [illegible] power if the water flow is inadequate. Flow switches, however, are not very radiation resistant; are often unreliable; and in multiple-path water circuits, are incapable of detecting the blockage of one circuit.

In the FMIT 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 [illegible]°.

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.

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[illegible]

[illegible]

[illegible]


[illegible] M. Mattier, "Mineral-Insulated Magnets," [illegible], Aug. 19[illegible].

[illegible] Stapleton, "Construction of Magnets for Particle Accelerators Using Cementatious Material," RHEL-[illegible], Sept. 19[illegible].

[illegible] M. M. Holland and Joseph Shill, "Radiation Resistant Magnet Coils From Hard Anodized Aluminum Conductor," IEEE Trans. Nucl. Sci., NS-[illegible], Vol. [illegible], pp. 70[illegible], June 19[illegible].

[4] A. Harvey, "Radiation-Hardened Magnets Using Mineral-Insulated Conductors," MT-4 (CONF-720908, pp. 456, 19[illegible].

[5] D. C. Hagerman, Los Alamos Meson Physics Facility, private communication.

[6] A. J. Otter, TRIUMPF, private communication.

[7] A. Harvey, "Experience With the LAMPF Mineral-Insulated Magnets," MT-6, pp. 19[illegible].

[8] D. George, "Magnets With Mineral-Insulated [illegible] at S...N., MT-5, pp. 719, 1975.

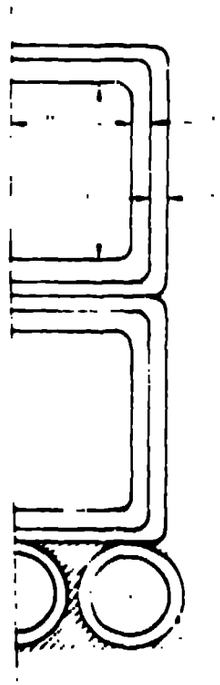
[9] R. A. Jameson, "High-Intensity Deuteron Linear Accelerator (FMIT)," IEEE Trans. Nuc. Sci., NS-26, Vol. 3, pp. 2986, June 1979.

[10] Donald J. Liska, et al., "High-Radiation Zone Design of the FMIT High-Energy Beam Transport," LA-DR-81-770, March 1981.

[11] C. A. Jordan and G. S. Eager, "Mineral-Insulated Metallic-Sheathed Cables," Power Apparatus and Systems, April 1955.

[12] Joel H. Schultz, "Sizing of the Thermal and Electrical Systems for an FEE [illegible] Design with Mi[illegible] Insulation," MIT [illegible] Center, [illegible], December [illegible].


[illegible]



[illegible]

| | | |
|---|---|---|
| Conductor copper height | [illegible] | [illegible] |
| Width | [illegible] | [illegible] |
| Area | [illegible] | [illegible] |
| Electrical resistivity | [illegible] | [illegible] |
| Thermal conductivity | [illegible] | [illegible] |
| Insulation (Mg) thickness | [illegible] | [illegible] |
| Thermal conductivity | [illegible] | [illegible] |
| Sheath (copper) thickness | [illegible] | [illegible] |
| Thermal conductivity | [illegible] | [illegible] |
| Cooling water temperature | [illegible] | [illegible] |

Then per unit length:

Heat produced = $\frac{I^2}{hc \cdot wc}$ 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.

$$= \frac{I^2 \rho}{hcWc} \frac{1.5}{ts \cdot kc} (hc + 2ti + 2ts)$$

$$+ \frac{0.75 \times 0.5}{ts \cdot kc} (hc + 2ts + 2ts) + \frac{ti}{(hc + wc)\,ki}$$

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:

$$[illegible] = [illegible] \frac{[illegible]}{[illegible]} \frac{[illegible]}{[illegible]} [illegible]$$

$$+ [illegible] \frac{[illegible]}{[illegible]} [illegible]$$