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RADIATION-HARDENED FIELD COILS FOR FMIT QUADRUPOLES*

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Summary

Modern accelerators of the Fusion Materials Irradiation Test (FMIT) class deliver enormous power onto their targets. The high beam currents of such machines produce highly activating radiation fields from beam/target interaction and normal beam losses. The 100-mA deuteron beam from the FMIT accelerator produces a backstreaming fast-neutron flux of 10^{11} n/s-cm^2 near the target. In addition, the neutron contribution from distributed beam spill of 3 μA/m along the rest of the machine prevents the use of epoxy resin potting materials in all magnet field coils above 10-MeV beam energies. Two special techniques for radiation-hardened field coils have been developed at Los Alamos for use on the FMIT accelerator. One technique uses vitreous enamel coatings on the conductors and appears attractive for the drift-tube quadrupoles. Another method uses a thermally efficient two-layer coil design that has solid mineral-insulated (MI) conductors with indirect cooling coils, all bonded together in a lead matrix. Test results are discussed, along with applications of the quadrupoles in the FMIT facility that reduce gamma exposures during maintenance periods.

Introduction

Many accelerators typically operate in pulsed mode and deliver high peak currents for only short periods. No machine today operates at as high an average current as will the FMIT accelerator: 100 mA cw. Some beam inevitably will be lost to the linac structure and to the beam-transport system. Deuteron machines such as the FMIT accelerator are especially activating and are fully capable of destroying radiation-soft materials, such as field-coil epoxies, during its 20-yr lifetime as a neutron factory.

Thus, it is imperative that magnet elements located near the beamline be radiation hardened. In the FMIT accelerator, the radiation-damage problem is twofold. First, normal beam loss in the drift tubes and high-energy beam transport (HEBT) beam tube above 10 MeV will produce neutron and gamma fields that degrade epoxy field-coil plottings severely during the machine's lifetime. The beam loss assumed for the FMIT accelerator is 3 μA/m, based on beam studies and experience with machines such as LAMPF. Russian studies of an FMIT-type facility have assumed a loss model of 10 μA/m,[1] which indicates that, to be safe, conservative designs must be pursued. The second problem facing designers of the FMIT accelerator system is neutron backstreaming from the target caused by deuteron stripping in the lithium. The backstreaming field of fast neutrons is 10^{11} n/s-cm^2 near the target. The last HEBT quadrupoles are located in a shield-wall plug within 2-m of the target. To compound the difficulty, this final quad is built into a steel cask that is removed only with difficulty, using remote manipulators after cutting the field coil conductors, thus destroying the magnet. High reliability is of prime importance, especially for these shield-wall quadrupoles.

Magnets used in the FMIT accelerator therefore fall into four design categories. Below 10 MeV, epoxy-potted field coils will be used, and a number of these have already been built as part of the 5-MeV accelerator program at Los Alamos.[2] From 10-MeV to the full FMIT accelerator output at 35-MeV, radiation-hardened insulations are required; they must adapt well to the drift-tube quads and must operate inside welded shells under soft vacuum. In the HEBT's upstream region, normal, directly cooled, MI conductors can be used conveniently on the large-bore quadrupoles. These conductors have a channel formed in them for direct water-cooling. Beyond the bending magnets, within a few meters of the target, backstreaming neutrons add to those generated by beam loss and cause the field-coil cooling-water to dissociate, thus releasing free oxygen. In directly cooled copper, this free oxygen will form oxides that can cause plugging of the cooling channels and filters. Thus, near the target, indirectly cooled MI conductors will be used. With these conductors, heat is carried across the mineral-insulation barrier to the ground sheath, then conducted through a molded-lead matrix to stainless steel cooling channels imbedded in the lead mold along with the conductors. Free-oxygen release in the stainless steel cooling tubes causes no oxide formation; therefore, this type of coil is extremely resistant to both radiation damage and plugging.

In a development program at Los Alamos, we have found solutions to all four of the above coil-insulation design problems. We have developed epoxy-potted drift-tube quads and the upstream HEBT quadrupoles using directly cooled MI field coils. These units will be operated in the 2-MeV accelerator program. Independently, we also have undertaken the development of vitreous enamel-insulated drift-tube field coils and have built some test coils. Finally, we have built and tested a special coil design, using the lead-impregnated solid-core MI conductors with indirect cooling.

Radiation-Hardened Drift-Tube Quads

The FMIT accelerator contains 42 drift-tube quadrupoles that operate above 10-MeV and must be radiation hardened. The linac quads operate in a soft vacuum (10^{-2} torr) and are sealed inside the drift-tube bodies. Once inside, they cannot be repaired without destroying the drift tube. If a failure occurs, a new drift tube most probably will be installed. A radiation-resistant insulation for the conductors is required, along with a concrete-like bonding material to provide support and flexure restraint for the conductors. The method developed at Los Alamos for the radiation-hardened FMIT drift-tube quads is as follows:

- The field coil conductor is wrapped in thin-gauge aluminum to act as a spacer, much in the same way as glass tape is commonly used in coil winding.
- The conductor then is wound around a coil form to produce the desired field-coil configuration.
- The field coil with aluminum wrap then is annealed to relax the conductor in a tightly coiled configuration, but with a uniform spacing around all conductors.
- The aluminum is dissolved away in an alkaline (caustic soda) solution leaving the gap free.

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Finally the coil is coated with a vitreous enamel and then potted in a refractory ceramic cement.

A test coil manufactured in this way is shown in Fig. 1. The enamel coating is noncorrosive and insulating; whereas, the ceramic concrete serves as a solid supporting medium for the enameled coil. The resulting coil is rugged and adaptable to high radiation environments. This type of coil will be used in FMIT.

A test coil was potted using the same coil form as the "A-type" field coils in the low-energy, rad-soft section of the linac. This was a finished rad-hard coil, mechanically interchangeable with any of the existing rad-soft coils. It was cycled repeatedly to 1000 A (5.8-kW coil dissipation) at rated cooling flow to see if thermal stresses caused cracking of the concrete body. No structural or electrical faults of any kind occurred. This gives us complete confidence that this rad-hard field-coil design is fully qualified for the FMIT drift tubes.

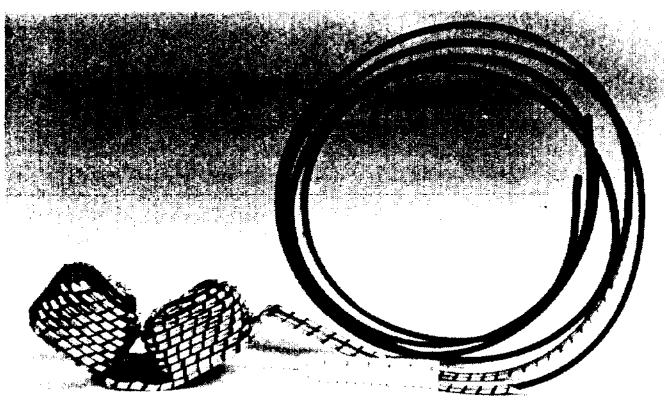
HEBT Quadrupoles

There are two types of HEBT quadrupoles required in the FMIT accelerator: 25- and 30-cm effective length units. Heavy beam damage, lithium contamination including Be^7, and high levels of activation are possible in the HEBT beam tubes; therefore, all the quads are designed to open clamshell fashion for replacement of beam tube sections. The standard HEBT quad design (Fig. 2) allows the top half-section of each magnet, its field coils, and the remote termination panels attached to the top-section field coils to be removed as a unit, thus exposing the beam tube and permitting replacement. Multiple dowels assure accurate reassembly of the quads on the prealigned and anchored bottom-half sections that rest on structurally stiff carriages.

All HEBT quad field coils are built as two-layer assemblies wrapped in a 90° saddle coil. This is an easy coil to wrap, and the thin profile nests neatly into the quad yoke, an important feature in the tightly packaged FMIT HEBT. The conductors are single length (30 to 40 m) with no joints. All water and electrical fittings are made outside the shield wall on the termination panels.

Nine 25-cm quads are required, and these are located in the upstream HEBT, away from the target. A directly cooled MI conductor is used on these units for radiation hardening. Three of the 25-cm quads have been built already and have qualified as part of the FMIT prototype program; they use standard MI techniques.

Twelve 30-cm quads are required in the downstream HEBT along the path of neutrons backstreaming from the target. These units use the lead-potted, indirectly cooled, solid-core MI conductors and must be extremely radiation resistant. Two of these units are used in the shield-wall plug near the target. A test coil using this technique has been constructed and tested. A nickel cooling coil with 4.6-mm id was used instead of the 7.7-mm id stainless steel coil intended for FMIT. Also, 50-50 Pb-Sn solder was used instead of pure lead as the potting material. The conductor outer dimensions were 13.5-mm square. The current carrying conductor was 10.2-mm square insulated from the hermetically sealed copper sheath by 0.8-mm MgO. The coil was a simple two-layer pancake with the same cross section as that intended for FMIT. It is shown in Fig. 3 along with some of the test results. The tight packaging of the conductors and the thin profile of the coil improves cooling and allows for dramatic increases in current density. The coil was tested to 2100 A, resulting in a current density of 2034 A/cm^2. At this point the calculated average conductor temperature was 305°C. When the measured sheath temperature reached 149°C the



(a)

(b)

Fig. 1. Radiation-hardened drift tube quad field coil. (a) Aluminum-wrapped conductors. (b) Vitreous enameled and potted field coil.

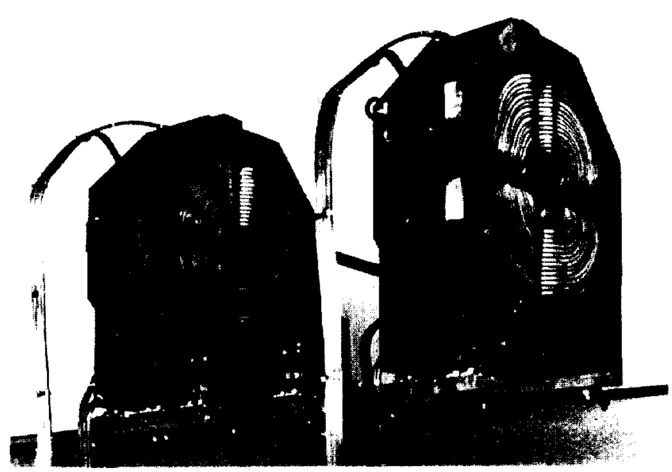


Fig. 2. Standardized FMIT quadrupole design.

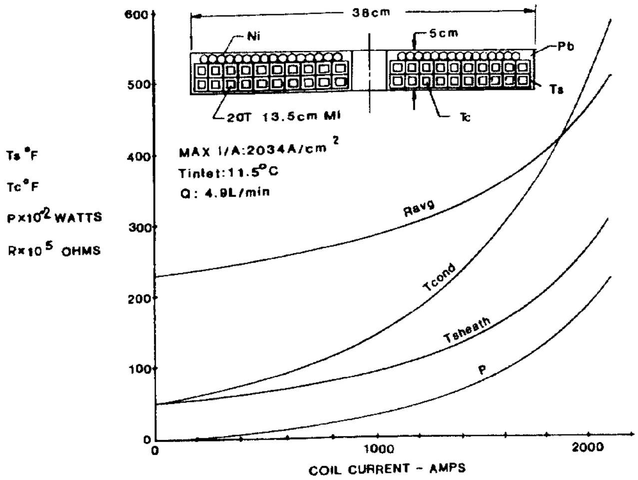


Fig. 3. Test results on lead-impregnated, thin profile field coil.

test was terminated before melting the solder. However, cooling water ΔT was still only 60°C. In FMIT, a maximum current density of only 775 A/cm^2 is required. In the test coil this was achieved at an average conductor temperature of 42°C and a water ΔT of 5°C.

These test results are so encouraging that the decision has been finalized to build the FMIT field coils in the manner described, thus the 30-cm quadrupole design has been completed.

Quadrupole Applications in FMIT

In addition to radiation hardening of the various quadrupoles in the FMIT accelerator, attention has been paid to the gamma fields that are emitted by the copper coils and yoke steel during maintenance periods. To reduce these gamma fluxes, each HEBT quad is designed to present flat faces on all surfaces so that 5-cm-thick slabs of lead can be attached. These lead slabs, in addition to the lead potting used on the 30-cm units, will significantly reduce radiation doses to personnel during maintenance by effectively shielding the hot spots along the beamline. Furthermore, the HEBT design is modularized with three or four magnets on each structurally stiff carriage. The weight limit on each carriage is 10 tons; therefore, the carriages are loaded with lead for maximum gamma shielding within the overall weight limit.

A similar approach is used in the drift-tube bodies where lead cylinders are attached to the bore tubes before welding the drift tube shut. This additional lead inside the drift tubes greatly reduces gamma radiation from the heavy steel and copper quadrupoles.

References

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