RADIATION RESISTANT MAGNETS FOR THE RIA FRAGMENT SEPARATOR*

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Abstract

The high radiation fields around the production target and the beam dump in the fragment separator at the Rare Isotope Accelerator requires that radiation resistant magnets be used. Because large apertures and high gradients are required for the quadrupoles and similar demanding requirements for the dipole and sextupoles, resistive coils are difficult to justify. The radiation heating of any materials at liquid helium temperatures also requires that superconducting versions of the magnets have low cold-masses. The final optical design has taken the practical magnets limits into account and sizes and fields adjusted to what is believed to be achievable with technology that is possible with sufficient R&D. Designs with higher obtainable current densities and having good radiation tolerances that use superconducting coils are presented, as well as the radiation transport calculations that drive the material parameters.

INTRODUCTION

The Rare Isotope Accelerator (RIA) is a proposed new accelerator capable of delivering 400 kW of heavy ions at the production target of either of two fragment separators (FS) [1]. The FS is designed to separate out rare nuclides from the primary beam and the multitude of secondary fragments. A production rate of one particle per second requires a cleanup by a factor of 10^{14}. To maximize the collection of these rare isotopes, the FS magnets require large apertures and strong magnetic fields. The optical layout is shown in Fig. 1.

Some of the magnets are also exposed to very high radiation doses, mainly from the high-energy neutrons leaving the target or the beam dump. A list of the required magnets is given in Table 1. In Table 1 magnets with descriptions in *italics* are required to be radiation resistant.

RADIATION TRANSPORT

Because radiation resistant magnets are more expensive than standard ones by virtue of the materials used in fabrication, calculations of the radiation doses are required to know which magnets must be radiation tolerant. The Monte Carlo heavy ion-capable transport code PHITS [2] was used to assess the radiation environment.

Calculations were done in conjunction with a project looking at using high-temperature superconductor (HTS) materials for the first quadrupole [3] by two methods: 1) Using simplified geometries (concentric cylinders and coil material pure silver) 2) Using actual geometries and real HTS compositions. Earlier results [4] showed that heat deposition in the iron was so large (~ 15 kW) that any solution had to have iron at room temperature. Since the facility is designed to run beams of essentially every element and the desired rare isotopes are large, the set of beam-target combinations changes the radiation environment. Table 2 lists a small set of probable isotopes of interest and the beam used to maximize the count rate at the end of the FS. It takes into account the acceptance of the FS, as well as the production cross section. This table is important because it gives several cases to allow a determination of the "worst case" in terms of dose to the magnets.

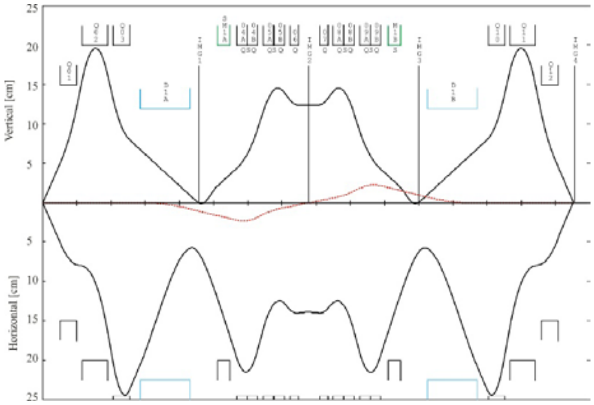

Figure. 1: Beam envelopes for the FS.

Table 1. Optical elements for the FS. Element numbers in *italics* are required to be radiation resistant. Length is optical length and the fields are at the pole radius.

Type	Radius or half-gap (mm)	Field (T)	Length (mm)
Quad *1*,12	150	1.0	1000
Quad *2*,11	200	1.5	1500
Quad *3*, 10	250	1.9	1000
Quad *4*,*5*,8,9	250	1.5	1250
Quad *6*,*7*	250	1.1	500
Dipole *1*,2 (32 degrees)	120	1.9	2940
Sextupole *1*,2	200	0.5	750

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Table 2. Some sample beams of interest.

Nuclide of interest	Beam	Energy loss in target
^{122}Zr	^{136}Xe 500 MeV/u	150 kW
^{22}C	^{48}Ca 350 MeV/u	89.2 kW
^{200}W	^{238}U 400 MeV/u	102 kW

HTS Single Magnet Calculations

The model used for the PHITS calculation for the HTS-based quad is shown in Fig. 2. A heavy metal shadow shield is placed in front of the coils provides a factor of three reduction of the deposited dose in the front edge of the coil. Fig. 3 shows the absorbed doses in the coils for the three cases given in Table 2 as a function of distance along the beam path. The magnetic field in the quad was set to the proper value, but since the majority of the dose comes from neutrons, this does not have much effect for this quad. It will, however, change the doses in subsequent magnets because charged particles of all magnetic rigidities are produced and transported through the fields. From the calculations we see that the uranium beam case is a factor of two less severe than the other two. All calculations have been normalized to 400 kW beam power. The scatter in the points is the result of a relatively small number of events, but calculational times are long, so only an average value is used for interpretation. The peak energy deposition is about 10 mW/cm^3. With an average density of 10 g/cm^3, this gives a dose rate of 1 Gy/s and with 10^7 seconds per year operation, a yearly dose of 10 MGy. For comparison, the magnets in the Neutrino Factory front end (1 MW protons) will receive a calculated yearly peak dose of 1 MGy [5]. For coils other than HTS, changing to copper or standard superconductors, such as NbTi or Nb$_3$Sn, doesn't change the results much, since the densities are about the same.

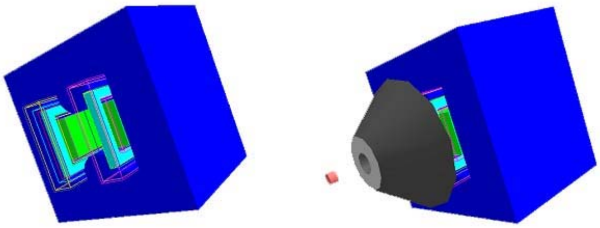

Figure 2: Model of the first quad for PHITS. The wire frames are the cryostat and supports. Small cylinder on the left is the target. The cone is a tungsten shadow shield.

HTS Multiple Magnet Calculations

The FS will be underground, surrounded by shielding, so calculations that include this are required to fully assess the absorbed dose for every magnet. However, including the actual coils and coil support structure results in very long computational times and is not justified because most of the dose comes from simple geometry. Therefore the magnets were modeled as concentric cylinders of coil, air and iron. Actual coil material was used, however. The results are shown in Fig. 4, which shows the FS vault from the target to the ninth quadrupole. A steel shell surrounds the whole system. This produces a low energy sea of neutrons that essentially doubles the dose to the coils. The results for the first three quads are shown in Fig. 5. Two important results are apparent: The dose to the first quad is a factor of two higher (compare with Fig. 3) and the peak doses in the second and third quads only decreases by a factor of two from the preceding quad. One would expect that the preceding quad would reduce the dose by a factor of 100, and the total heat load is reduced, but not the peak dose. Because the lifetime of the magnet is set by the peak dose, rather than the total dose, this means that whatever technology is required for the first quad is also required for the next two. The dipole and quadrupoles beyond it

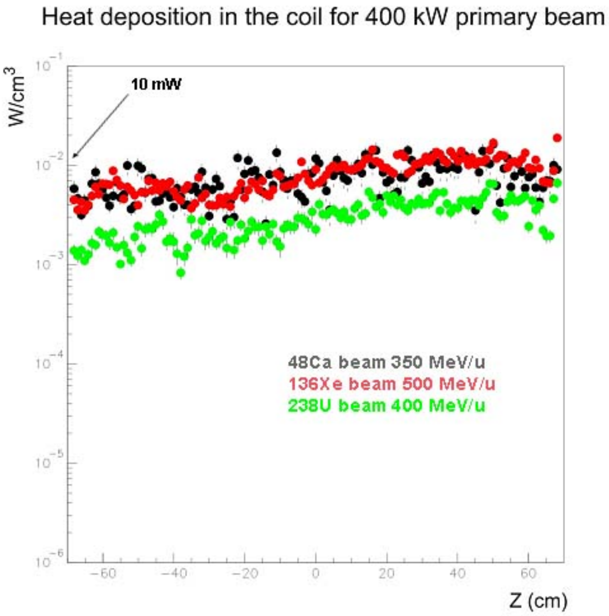

Figure 3: Heat deposition from the cases given in Table 2.

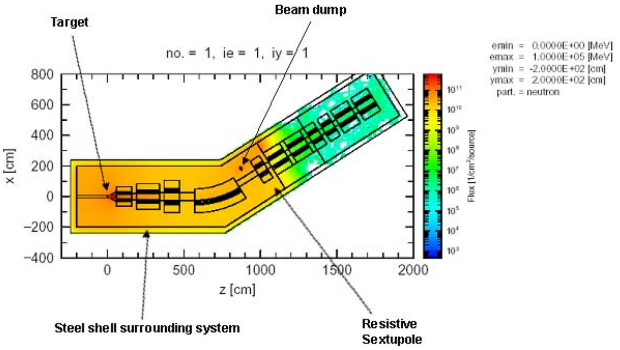

Figure 4: First part of the FS with a ^{48}Ca beam on the target showing the neutron flux.

have not been evaluated. The sextupole is located very close to the beam dump and will need to be resistive to keep heat loads manageable.

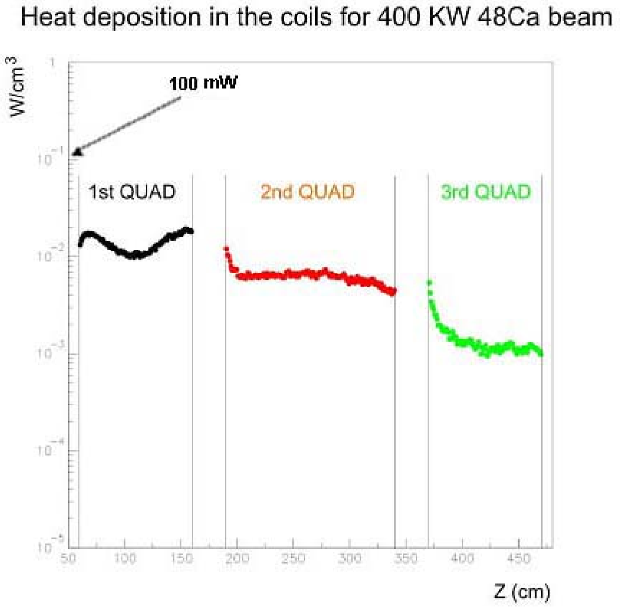

Figure 5: Coil heat deposition in the first three quads.

MAGNET TECHNOLOGY

There are several possible options for fabricating the required radiation resistant quadrupoles. The oldest known is to use metal-oxide insulated copper conductor [6]. The problems with this approach are the low achievable current density and the cooling problems. The low current density and a required high gradient result in a very large magnet, high power operation and many connections. Additionally, the conductor is not cheap.

Using HTS materials for the coil [3] has two advantages that make this an attractive option. The coils can be operated at 20-30 K, with the factor of ten increase in heat capacity compared to operation at 4 K. Additionally, stainless steel can be used for insulation instead of radiation sensitive organics or brittle inorganics. The big unknown is the radiation sensitivity. This question will be answered this summer by irradiating samples for testing. The material is expensive, as well.

In the event that HTS materials cannot be used, then other coil fabrication technologies can be used. Some of these have been described previously [7], but can briefly be summarized as using inorganic insulation. Two likely candidates are internally anodized aluminum Cable-In-Conduit-Conductor (CICC) and metal-oxide insulated CICC. Example of both of these conductors have been fabricated and tested.

A comparison of the different approaches for fabricating the first quad are summarized in Table 3. The quad has the gradient and optical parameters given in Table 1 and the iron length is the one required to give the correct effective length. The minimum mass solution, cold iron, is given for comparison, but is unacceptable because of the neutron-heating load to the cryogenic system. Note the HTS coil cost only includes the conductor costs, and costs for the CICC case is uncertain because only R&D quantities have ever been fabricated. It's likely that CICC costs will be comparable to HTS costs.

Table 3. Comparison for several construction methods for the radiation resistant first quad in the FS. Warm iron. 8 T/m gradient.

Case	**Current density (A/mm^2)**	**Power (kW)**	**Iron (ton)**	**Coil (ton)**	**Coil cost (M$)**
Resistive	2	160	38	7	1
HTS	50	-	10	0.25	0.3
CICC	20	-	20	?	?
Cold iron	35	-	2.5	0.25	0.1

DISCUSSION

The use of superconducting technology for the RIA FS is very desirable, in large part, because lower gradients or smaller apertures would limit acceptance and decrease the device's utility. There are several options, presented above, that indicate the technology is available, as long as the majority of the material is at room temperature. The lifetimes seem acceptable, although the heat loads, 150-300 W are still high even if only the coils and their support structures are cold. Using HTS materials reduces the effective heat load by a factor of ten, so is a very attractive option.

Studies of the remaining magnets are underway.

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