Development of Radiation Resistant Quadrupoles Based on High Temperature Superconductors for the Fragment Separator

R. Gupta and M.Harrison, Brookhaven National Laboratory
A. Zeller, Michigan State University

Abstract

A very high radiation dose on the quadrupole magnets in RIA's fragment separator makes them as one of the most challenging element in the RIA proposal. To overcome this problem, a new design is proposed that reduces both radiation dose and heat load by an order of magnitude. The proposed warm iron design will use commercially available High Temperature Superconductor (HTS) with stainless steel insulation. HTS are tolerant to large temperature variations and can operate at high (20-30 K) temperature. This paper presents the concept and reports the status of joint work between the Brookhaven National Laboratory and Michigan State University.

Introduction

The magnets in the focusing quadrupole triplet in the Fragment Separator for RIA must meet some of the most demanding requirements in the proposed Rare Isotope Accelerator (RIA). These magnets are exposed to over several orders of magnitude more radiation and energy deposition than typical beam line and accelerator magnets during entire lifetime. This high radiation originates from the fast neutrons ($E > 1$ MeV) coming from the production target. The beam will lose 10-20 % of its energy in the production target, producing several kilowatts of neutrons. A large fraction of these neutrons end up in the cold mass of these magnets. This creates problems both on short and long-term time scales. The proposed design of the fragment separator, optimized for particle acceptance, requires the first quadrupole to operate at a gradient of 32 T/m, with a good field radius of 50 mm in the original beam optics, or 16 T/m for a good field radius of 100 mm in the alternate beam optics. Both designs require the field at the iron yoke and/or conductor to be well over 3 T, and the coil current density to be in the range of 100-150 A/mm^2. These performance specifications are beyond that which can be obtained from conventional magnet technology. Conventional Low Temperature Superconductors (LTS) with standard insulation do not appear viable for both technical and economical reasons because of the large radiation and heat load. Thus, there is no demonstrated technical solution to the baseline requirements based on existing technology.

For short time scales, dumping large amounts of energy in the superconductor will cause the magnet to quench if it exceeds deposition levels of several mJ/g. In addition, the constant dose to the cold mass is approximately 1 W per kilogram, a significant heat load on the refrigerator assuming the temperature rise from the radiation can be controlled sufficiently well to keep the magnet superconducting.

The long-term problem is the destruction of the conductor, the insulation or other components of the magnets. The present lifetime dose of these magnets (12 years) has been (crudely) estimated to be 10^{19} neutrons/cm^2 in the region of 0 to 30 degrees. NbTi has an estimated end of useful life dose of approximately 10^{19} n/cm^2 for reactor spectra neutrons [1] but the higher energy of the RIA spectrum would be expected to reduce this somewhat. Nb3Sn is a little better in this regard. Materials such as iron and copper will absorb about 100 times more radiation before damage occurs. Polyimide insulation such as kapton, traditionally used for superconducting magnets in radiation environments, has been demonstrated to remain viable up to 5 x 10^{15} n/cm^2 [3] but starts to show mechanical deterioration beyond this level [4]. The insulation is therefore the weakest link in a superconducting magnet of standard design [5,6].

Going to radiation resistant magnets that use conventional copper conductor at room temperature results in decreased gradients or decreased apertures in the quadrupoles because the achievable current densities are much lower than in a superconducting version. This means significantly lower acceptances and inefficient use of the beam intensity. Moving the quadrupoles back and adding more shielding also means higher gradients and larger apertures to regain the capture efficiency. Neither of the options is very attractive and are, at best, fallback options.

The desired solution is a superconducting version that is radiation resistant, can absorb significant energy deposition without quenching, and can tolerate a high heat load (i.e. temperature insensitive). All of these design goals are potentially achievable using magnets based on High Temperature Superconductors (HTS) though no complete magnet has been built to date using this technology [7]. HTS magnets can operate at relatively high temperatures and show only a small loss in critical current density for a several degree increase in temperature. In addition, HTS materials do not quench in the accepted sense of the word (a phase transition to the normal state) but rather become more resistive with increasing temperature.

It is desirable to operate the superconductor at the highest possible temperature. Ideally, operation at 77 K would be the best option, but operation at 20 – 40 K would be of great use. The higher enthalpy provides temperature stability and removes significant load from the refrigerator. In addition, the radiation damage at the higher temperatures is lower than at 4 K, so this makes it more attractive. The achievable current density with a BSCCO 2223 tape commercially available today indicates that a maximum operating temperature around 30K might be feasible.

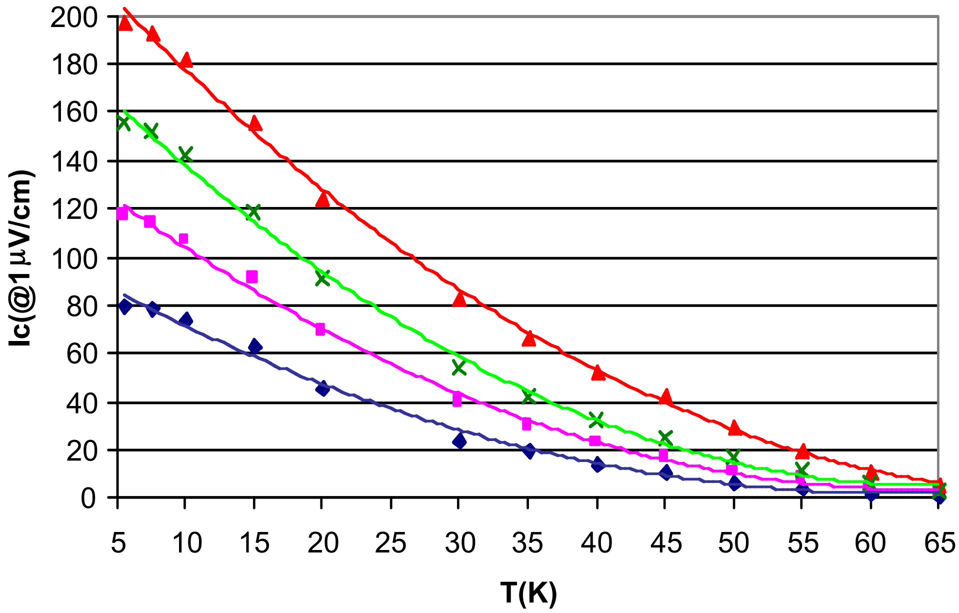


Fig. 1: Ic vs. Temperature for some HTS coils tested at Brookhaven. Operation at 20 K reduces Ic to about 60% of the 4 K value. Note the large spread in the early HTS conductor Ic.

Brookhaven National Laboratory (BNL) has recently successfully tested several HTS R&D magnets and test coils for possible accelerator applications based on BSCCO 2212 wire [7]. Of more relevance to this application, coils using BSCCO 2223 tape have been built and tested as part of an R&D program aimed at developing a next generation 25T NMR facility [8]. The operating current densities in these 2223 tape HTS coils already meet the requirements of the RIA design [9]. A unique and very pertinent feature of these coils is the successful use of stainless steel as the insulation material between turns. This technique was developed to provide a strong mechanical coil package capable of withstanding the large Lorentz forces in a 25T environment, but will also provide a highly radiation resistant coil.

The study of the effect of neutron irradiation on the superconducting properties of the HTS material BSCCO 2223 is very limited. In fact there is only one [2]. In this study the critical temperatures Tc, and currents Ic, at 5K and 80K were determined after a fast neutron (>1 Mev) dose of 3.5 and 7 x 10^{17} n/cm^2 [2]. The effect on Tc was minimal and Ic actually increased by 50% at 3.5 x 10^{17} but then started to decrease to close to its original value at 7 x 10^{17}. There was however a decrease in Ic at higher temperatures and fields. A similar HTS material, YBCO, has been tested and showed similar results with severe Ic degredation at 2 x 10^{19} n/cm^2. The radiation resistance of any superconductor (HTS or LTS) appears to be close to the desired value but given the crudeness of the present estimates one goal of this R&D proposal will be to improve the calculations of expected dose rates and the expected damage due to the RIA neutron energy spectra.

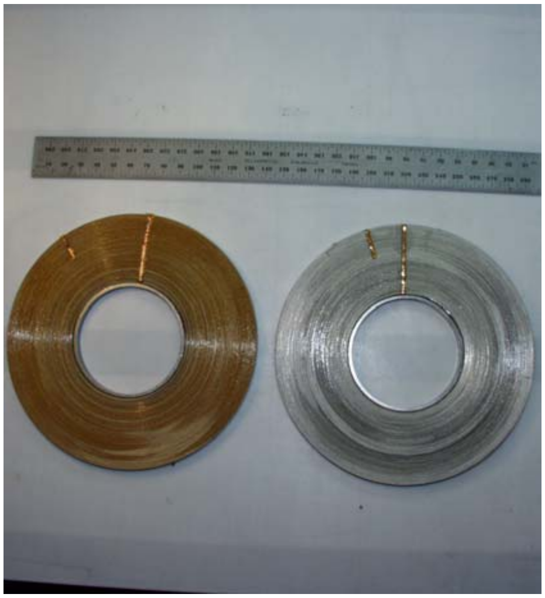


Fig. 2: Two double pancake NMR coils, with conventional kapton insulation on left and stainless steel tape insulation on right.

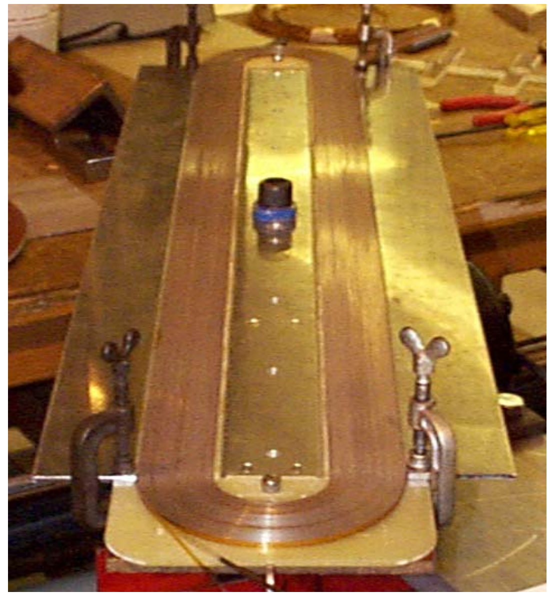


Fig. 3: An HTS test coil for an accelerator magnet. Initial test results prove that the brittle HTS can be successfully handled in building magnets.

Conceptual Design Development

The maximum field on the coil in superconducting magnets or the pole tip field in the iron pole in superferric magnets must be well over 3 T to produce the required gradient of 32 T/m for a 50 mm good field radius. The two superconducting options that have been considered in the past are shown in Fig. 4 (a typical superconducting and a typical superferric quadrupole).

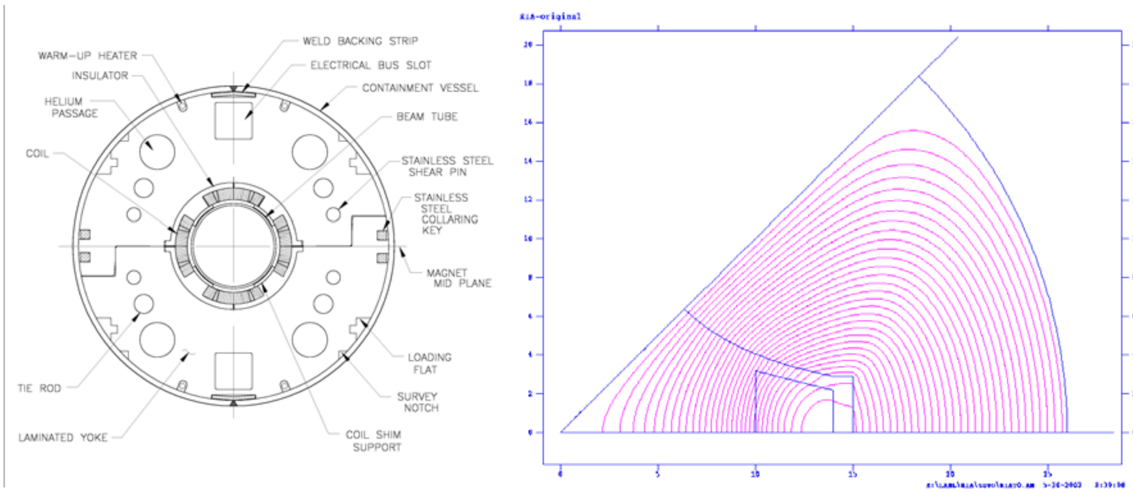


Fig. 4: Conventional superconducting quadrupoles magnet designs (cosine theta on left and superferric on right) that can produce the field gradient required for RIA fragment separator. The coils in both designs are subject to very high radiation dose (estimated to be 10^{19} neutrons/cm^2 in the region of 0 to 30 degrees of solid angle from the target).

To develop an alternate concept, we made a basic evaluation of the source of problems and examined the use of existing technologies to develop a new design where these problems can be significantly mitigated.

The rare isotope beams of various species are created when the proton beam hits the target. In going through the fragment separator region the beam and the neutron intensity peak in the forward solid angle. A typical neutron distribution of neutron yield as a function of solid angle away from the target is shown in Fig. 5. This is for Xenon with 400 Mev/nucleon [11].

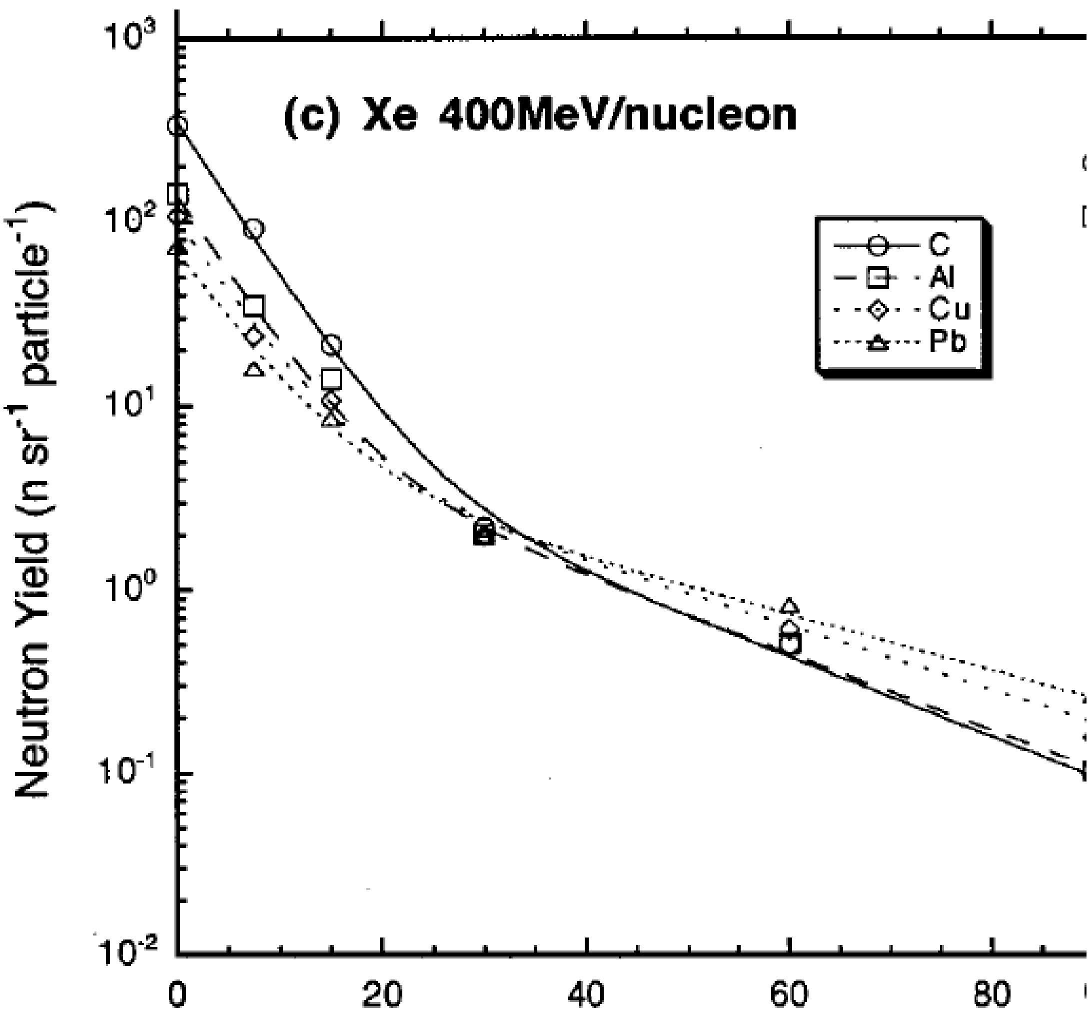


Fig. 5: Neutron yield as a function of solid angle [12]. A large drop as a function of angle indicates the benefit of developing a magnet design where the coils are placed away from the magnet center.

A major problem in the two designs shown in Fig. 4 is that the superconducting coils are subjected to a very high radiation dose. The radiation issue is a long term issue that is associated the lifetime of the magnet because of the degradation in the performance of various components, like superconductor and insulator. In above designs the coils are located at a smaller solid angle as measured from the target. The present lifetime dose of these magnets (12 years) has been (crudely) estimated to be 10^{19} neutrons/cm^2 in the region of 0 to 30 degrees.

Fig. 5 indicates that the radiation dose on the coils decreases rapidly if the coils are moved to a large solid angle. We achieve a reduction by about an order of magnitude by placing the coil outward as shown in Fig. 6. In this superferric magnet design, the magnetic flux is funneled through the iron yoke to obtain a pole tip field that produces the desired gradient of 32 T/m. The iron yoke is at 55 mm.

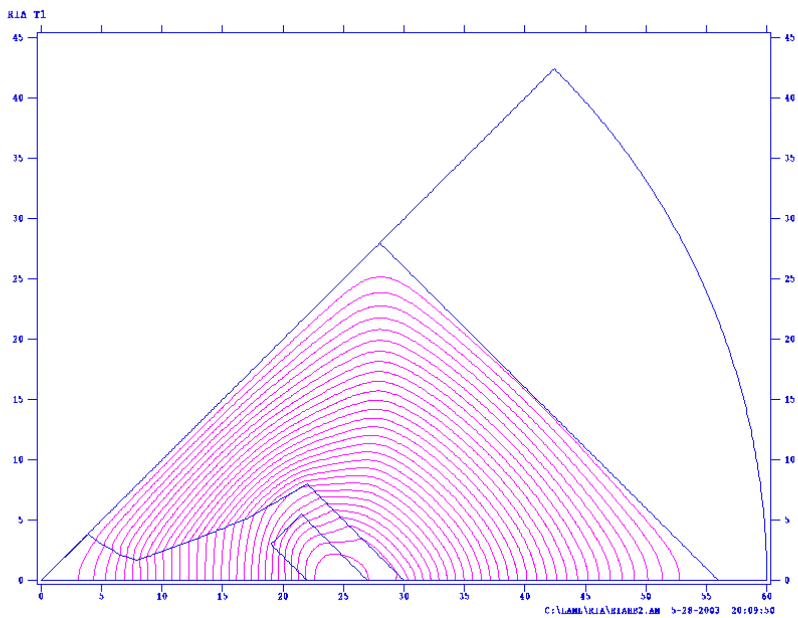


Fig. 6: An octant of the proposed superferric quadrupole design for the RIA fragment separator that produces the required field gradient. The coils are placed away from the magnet center to reduce the radiation dose.

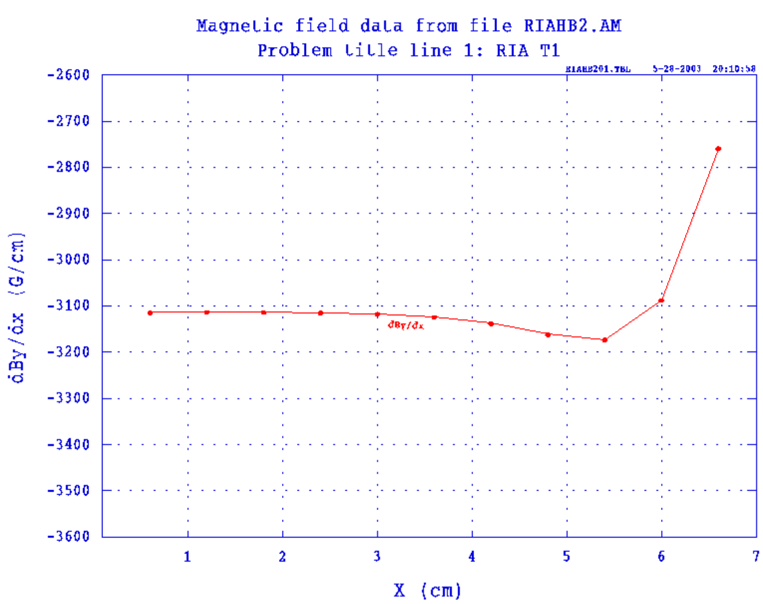
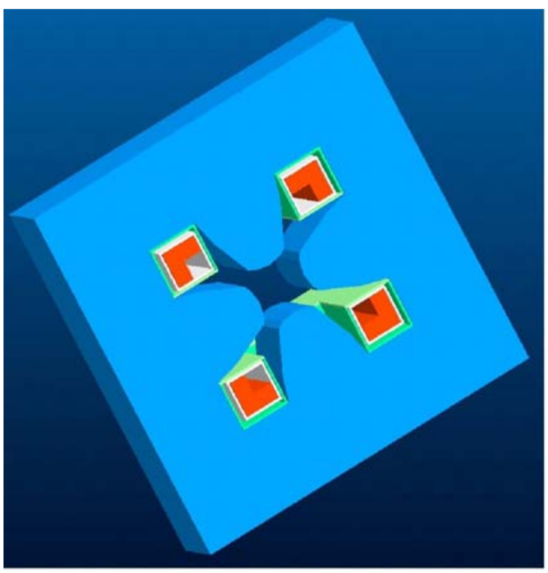


Fig. 7: The field uniformity as seen on the midplane, when the variation of field gradient is plotted as a function of X for the design shown in Fig. 6.

The field uniformity near the maximum field gradient of 32 T/m is shown in Fig. 7. We need to optimize the field quality further, in particular to obtain the desired field uniformity in the entire operating range in the light of large iron saturation.

In addition to the radiation load, there is also a large heat load from various decay particles from the target dumping their energy in the magnets in the fragment separator region. This issue is much more critical for superconducting magnets than for normal water-cooled copper magnets as the superconducting coils lose their superconductivity due to an increase in temperature. Moreover, there is a high cost of removing heat at low temperature.

These problems are significantly mitigated when the coils are made with high temperature superconductors. HTS are an order of magnitude more tolerant to an increase in temperature than the conventional low temperature superconductors. Because of a much higher critical temperature (Tc of NbTi is 9.2 K and of BSCCO2223 is ~90 K), the change in J_c as a function of temperature is much smaller in HTS than in LTS. Moreover, the control of operating temperature can also be reduced by an order of magnitude. In addition, there is also a large saving in operating cost due to the fact that the magnets can be operated at higher temperature (20-40 K instead of ~4K). The cost of removing energy at higher temperatures is significantly lower.



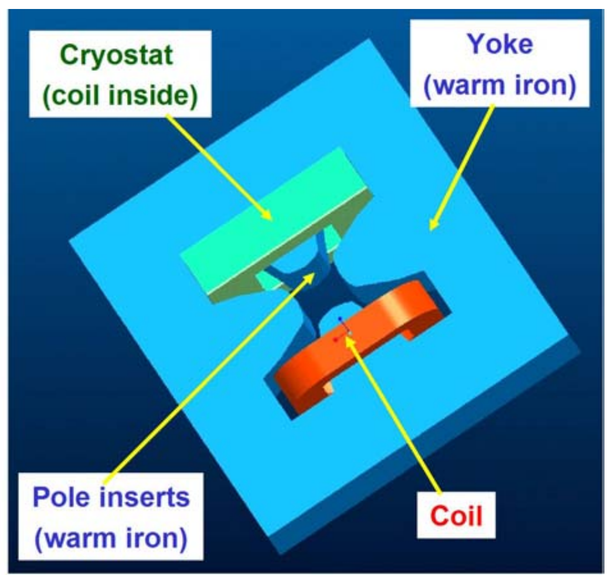


Fig. 8: The proposed warm iron superferric quadrupole design for RIA fragment separator. The two racetrack coils (see right side) are shown in their own cryostat. They produce quadrupole symmetry in the cross section (see left side).

A significant reduction in heat load is further achieved by adopting a warm iron design. A preliminary engineering concept of this warm design is shown in Fig. 8. In earlier designs (see for example those shown in Fig. 4), the entire volume where the energy was dumped was cold. The warm iron design reduces the heat to be removed by reducing the cold volume. Moreover, since the coils are placed outward, the cold volume is at a higher solid angle where the energy deposition is also lower. The initial estimates indicate that the heat load on cold coil volume is a few hundred watts and on the iron is ~15 kW. These estimate show the large benefit of a warm iron design over a cold iron design. In a cold iron all heat (15 kW + few hundred watts) would have to be removed as against only a few hundred watts in the proposed warm iron design.

This warm iron approach, however, places a significant challenge on the cryostat and magnet design. The cryostat must be compact and the magnetic design (coil and iron volume) must be carefully examined to obtain the required field gradient. The iron between the two coil poles becomes a bottleneck for flux lines.

The proposed magnet is based on a simple racetrack coil made with HTS tape. To simplify the coil winding and to reduce the cold volume in the magnet ends, we adopt a symmetric two coil design that has quadrupole symmetry in the 2-d cross section and dipole symmetry in the ends. The ends of the simple racetrack coils remain outside the beam tube because of the fact that the coil has been moved sufficiently outward in the magnet cross section to minimize the radiation dose. This configuration, however, creates axial fields in the two ends. These fields cancel each other. This feature, to be verified with beam physicists, should be acceptable for beam line magnets.

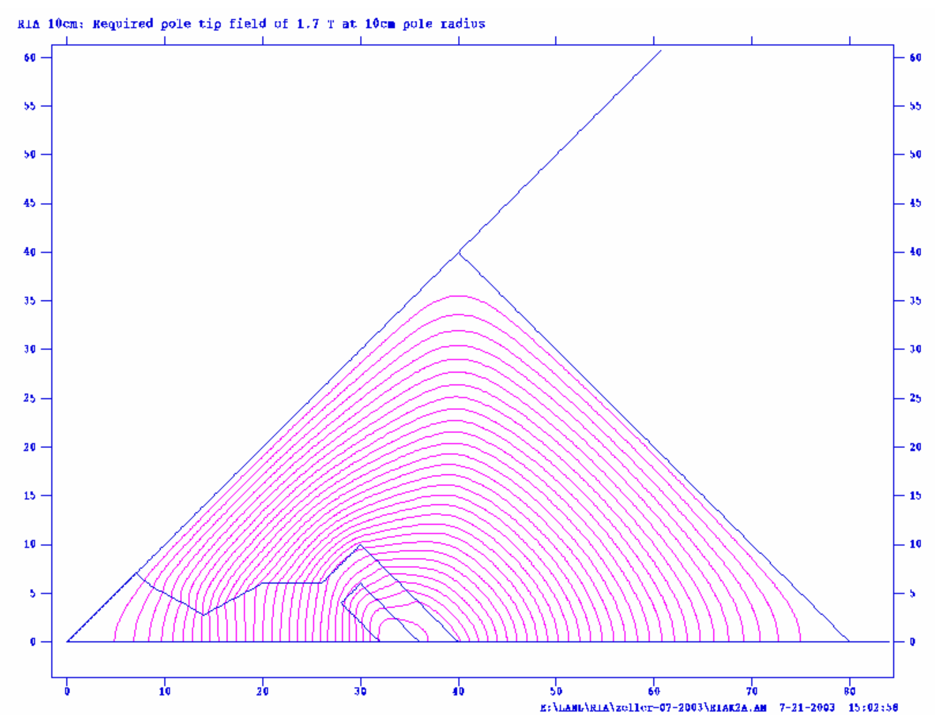


Fig. 9: An octant of the alternate superferric quadrupole design for the RIA fragment separator that produces a field gradient of 16 T/m for a good field radius of 100 mm. The coils are placed away from the magnet center to reduce the radiation dose.

An alternate beam optics design requires the field gradient to be 16 T/m for a good field radius of 100 mm. A magnetic design for these parameters is shown in Fig. 9. The field gradient on the X-axis is shown in Fig. 10.

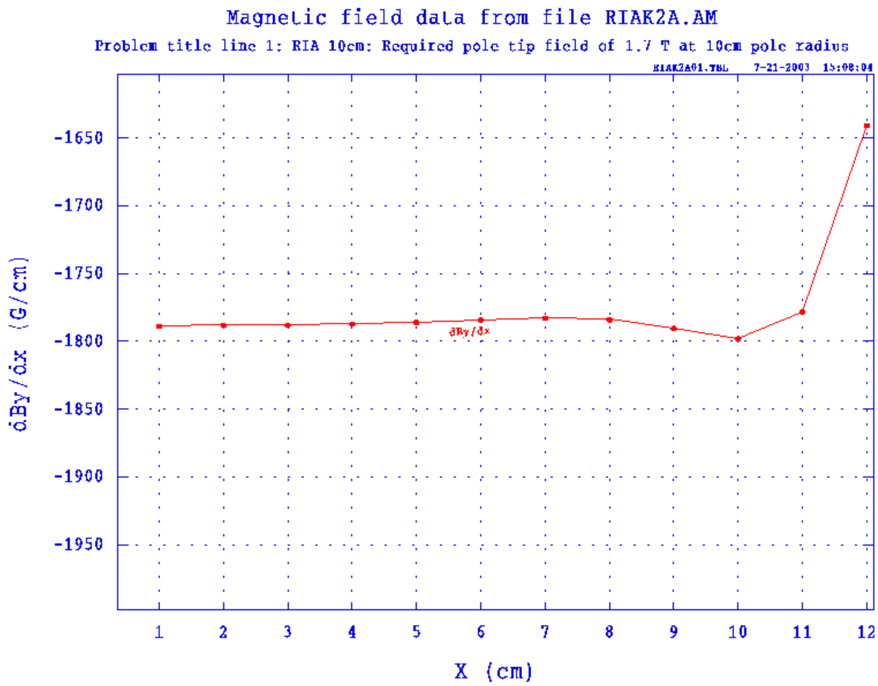
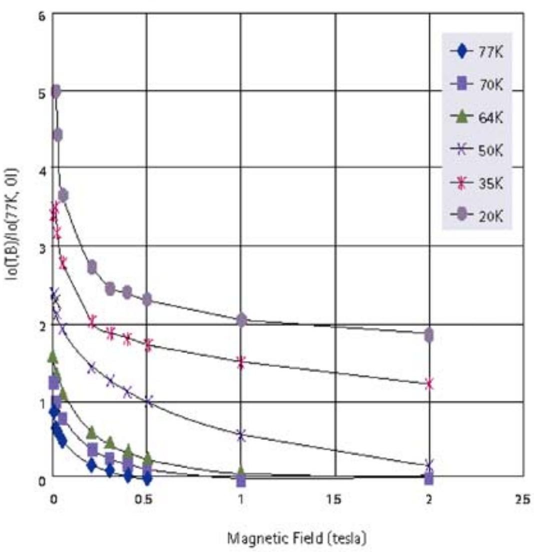


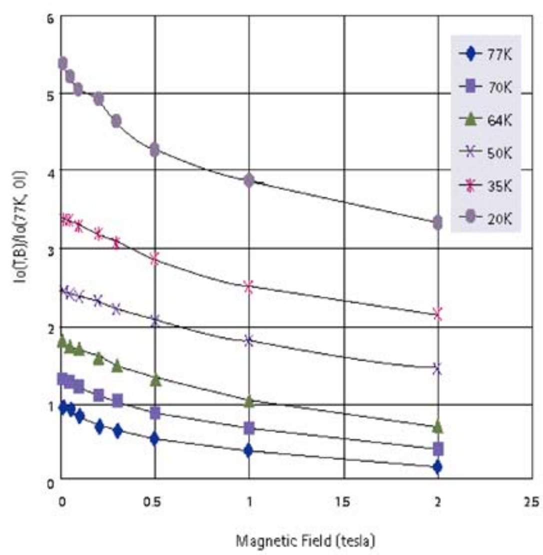
Fig. 10: The field uniformity on the midplane, when the variation of field gradient is plotted as a function of X for the design shown in Fig. 9.

The two preliminary designs (shown in Fig. 7 and Fig. 9) assume a critical current density (the current density till which a material retain its superconductivity) in the range of 100-150 A/mm^2. After years of R&D, these current densities are now available in commercially produced HTS tapes [12]. However the critical current density of HTS tape depends strongly on the direction of applied field. See Fig. 11 for BSCCO 2223 tapes from American Superconductor. The difference between the field perpendicular and the field parallel value is larger at higher operating temperature. This becomes a new and important consideration that is specific to optimizing magnetic designs that use HTS tape. The difference between the field parallel critical current is higher for higher operating temperature. This may limit the magnet to operate below a temperature of ~30 K.

HTS Properties



Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field perpendicular to the tape surface.



Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field parallel to the tape surface.

American Superconductor™
REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY™

Two Technology Drive
Westborough, MA 01581-1727
Ph: 508.836.4200
Fax: 507.836.4714
website: www.amsuper.com

American Superconductor Europe GmbH
Rathausstraße 7
41564 Kaarst, Germany
Ph: 49.2131.766051
Fax: 49.2131.668734

All specifications subject to change without notice from American Superconductor.

ASC/HTS-FS-0003-02 October 1999

Fig. 11: Critical current density as a function of applied field in BSCCO2223 tapes from American Superconductor when the field is perpendicular and the field is parallel to the tape surface. The stated critical current at 77 K in zero (self) field, I_c(77 K, 0T), is over 115 A. This gives an engineering current density (J_e) of over 135 A/mm^2 for this tape with an overall nominal width of 4.1 mm and nominal thickness of 0.21 mm

Review of Radiation Damage Measurements

RIA presents a hostile environment for magnets because of the high level of radiation. Even though we have significantly reduced the magnitude of radiation on the superconducting coils by moving them outward, it is important to have experimental data available on the extent of damage or degradation caused by the type and level of radiation present. All literature surveyed so far show a small increases in critical current density (see Fig. 12) for irradiated tapes. However, both the type and the magnitude of the radiation were controlled and the doses were orders of magnitude lower than those present in RIA. We expect HTS to lose part of its critical current density to become lower when it is irradiated with RIA type radiation. Therefore, to make further evaluation, dedicated measurements of radiation damage on HTS needs to be performed.

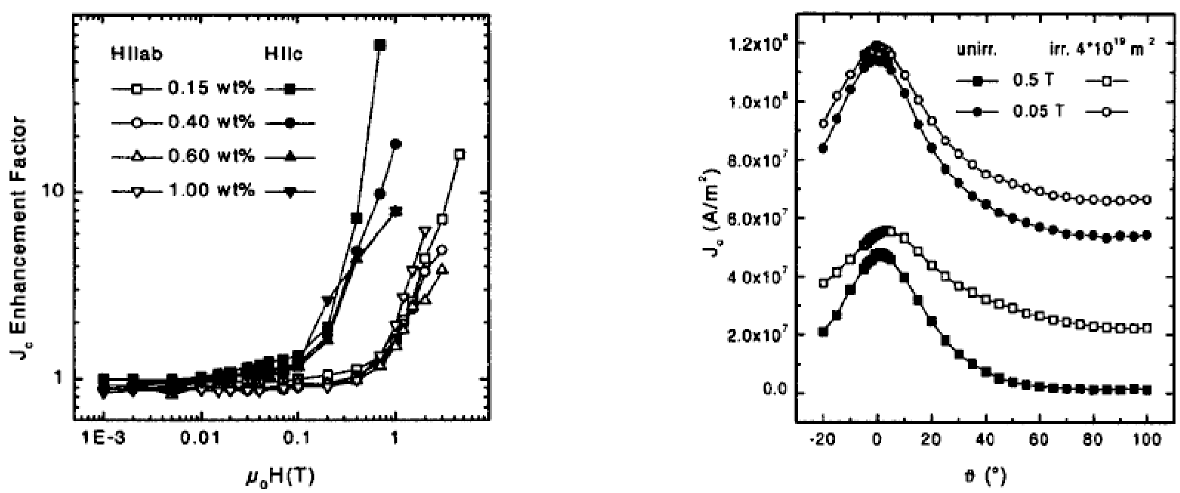


Fig. 12: The influence of controlled irradiation on BSCCO tape [12]. These measurements show an improvement in conductor performance since the critical current density and critical field increase (see figure on the left) and the anisotropy decreases (see figure on the right) after the irradiation. However, the critical current density is expected to decreases when the radiation levels are as high as that in RIA.

Summary

The proposed design significantly reduces the radiation dose and heat deposition on superconducting coils. HTS coils can tolerate a large increase in temperature. In addition, the control in operating temperature can be significantly relaxed. Moreover, the HTS magnets can operate 20-30 kelvin instead of 4.2 kelvin where the heat removal efficiency is significantly better. The use of stainless steel tape as insulator removes the problem associated with the radiation damage of the insulator. The proposed warm iron design minimizes the cold volume and hence the amount of heat to be removed at lower temperature. The design is based on HTS tape that is commercially available today. However, the details of magnet designs and technologies are yet to be developed and the radiation damage issues on HTS and other components needs to be examined.

References

1) *M.Akamatsu et al. Advances in Superconductivity. V, pg 439 (1992).*

2) *H.Kupfer et al. IEEE trans. On Magnetism. 25, pg 2303. (1989).*

3) *www.Dupont.com/kapton/general/radresistance*

4) *LHC Note 348.*

5) *M.E. Sawan and P.L. Walstrom, Fusion Technology (10) 741.*

6) *A.F. Zeller, Radiation Resistant Magnets R&D for Fragment Separation, this workshop.*

7) *R. Gupta, et al., R&D for Accelerator Magnets with React and Wind High Temperature Superconductors, IEEE Trans. Applied Superconductivity 12, pp 75-80 (2002).*

8) *W. Sampson, reference on NMR coils or Internal Communication.*

9) *R. Gupta, High Temperature Superconductors in Accelerator Magnets, Seminar at the National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan on May 28, 2003.*

10) *R. Gupta, et al., Status of High Temperature Superconductor R&D at BNL to be presented at the 18th International Conference on Magnet Technology (MT-18) at Morioka, Japan, October 20-24, 2003.*

11) *S. Tonies, et al., Influence of Neutron Irradiation on the Superconducting Properties of BiSCCO-tapes containing different amount of uranium, Physica C, 341-348 (2000), pp 1427-1430.*

12) *American Superconductor, Fact Sheet of High Strength Wire, ASC/HTS-FS-0003-02, October 1999.*