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# Radiation Resistant HTS Quadrupoles for RIA

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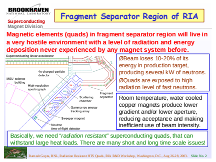
**Extremely high radiation, levels with accumulated doses comparable to those in nuclear reactors than in accelerators, and very high heat loads (~15 kW) make the quadrupole magnets in the fragment separator one of the most challenging elements of the proposed Rare Isotope Accelerator (RIA). Removing large heat loads, protecting the superconducting coils against quenching, the long term survivability of magnet components, and in particular, insulation that can retain its functionality in such a harsh environment, are the major challenges associated with such magnets. A magnet design based on commercially available high temperature superconductor (HTS) and stainless steel tape insulation has been developed. HTS will efficiently remove these large heat loads and stainless steel can tolerate these large radiation doses. Construction of a model magnet has been started with several coils already built and tested. This paper presents the basic magnet design, results of the coil tests, the status and the future plans. In addition, preliminary results of radiation calculations are also presented.**



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**Fragment Separator Region of RIA**

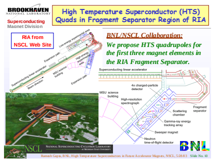
**Magnetic elements (quads) in fragment separator region will live in a very hostile environment with a level of radiation and energy deposition never experienced by any magnet system before.**

- Beam loses 10-20% of its energy in production target, producing several kW of neutrons.
- Quads are exposed to high radiation level of fast neutrons.

Room temperature, water cooled copper magnets produce lower gradient and/or lower aperture, reducing acceptance and making inefficient use of beam intensity.

Basically, we need "*radiation resistant*" superconducting quads, that can withstand large heat loads. There are many short and long time scale issues!

Ramesh Gupta, BNL, Radiation Resistant HTS Quads, RIA R&D Workshop, Washington, D.C., Aug 26-28, 2003. Slide No. 2



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**High Temperature Superconductor (HTS) Quads in Fragment Separator Region of RIA**

RIA from NSCL Web Site

***BNL/NSCL Collaboration:***

*We propose HTS quadrupoles for the first three magnet elements in the RIA Fragment Separator.*

Ramesh Gupta, BNL, High Temperature Superconductors in Future Accelerator Magnets, NSCL, 5/28/03 Slide No. 10

**The Rare Isotope Accelerator is a proposed major facility in United States for research in Nuclear Science. It will produce copious amounts of rare isotopes when a high-energy heavy ion beam hits the target. The Fragment Separator will then select a particular isotope and transport it to an experimental area. For optimal capture efficiency, superconducting magnets are required in at least the first focusing quadrupole triplet of the separator. These magnets are one of the most challenging elements in the RIA proposal, as they are exposed to several orders of magnitude more radiation and energy deposition than typical beam line and accelerator magnets receive during their entire lifetime. The first quadrupole itself is subjected to ~15 kW of energy deposition.**

## What is RIA?

A schematic of the RIA facility is shown in Figure 1. The key to the scientific discovery potential of the facility is its ability to provide the highest-intensity beams of stable heavy ions for the production of rare isotopes. This concept builds on developments in superconducting technology in the U.S. and Europe over the past two decades. RIA's driver accelerator will be a flexible device capable of providing beams from protons to uranium at energies of at least 400 MeV per nucleon, with beam power in excess of 100 kW. With this flexibility, the production reaction can be chosen to optimize the yield of a desired isotope. In comparison to the two main competing in-flight facilities, the Radioactive Ion Beam Factory at RIKEN and the GSI upgrade, RIA has two advantages. First, RIA's capability for post acceleration (not included in either of the other two projects) will allow a wider range of studies and will include the measurement of nuclear reactions at astrophysical energies and the search for new heavy elements with long lifetimes. Second, the acceleration scheme of RIA's primary-beam linac is planned to be 20-fold more efficient than either of the other facilities and, hence, able to deliver significantly more primary-beam power. In comparison to the main ISOL competition, ISAC at TRIUMF, RIA has higher primary-beam power and a more flexible combination of ion sources, which will provide higher intensities and a wider variety of rare isotopes.

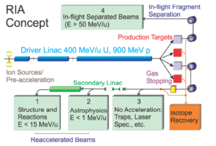


*Figure 1.*
*The heart of the facility is composed of a driver accelerator capable of accelerating every element of the periodic table up to at least 400 MeV/nucleon. Rare isotopes will be produced in a number of dedicated production targets. Upon extraction from the targets, these isotopes can be used at rest for experiments in Area 3, or they can be accelerated to energies below or near the Coulomb barrier and used in Areas 2 and 1, respectively. Isotopes will also be harvested for applications (Isotope recovery). Fast beams of rare isotopes can also be used directly after separation in a high-resolution fragment separator (Area 4). RIA brings together the most powerful known techniques for rare isotope production in a single facility.*

The extraction of exotic nuclei at RIA will employ three methods. In the first, a thick ISOL-type target will be coupled to an ion source and a post accelerator for energies beyond the Coulomb barrier. This method will provide the most intense reaccelerated beams of those elements with chemistry favorable for rapid release. A second target area will utilize a thinner target and a recoil mass separator that can operate in two modes. In one mode, the fast mass separated exotic nuclei will be energy-degraded and then stopped in a gas catcher from which they can be rapidly extracted for reacceleration in the post accelerator. This will provide intense beams of short-lived isotopes or elements that are difficult to obtain from the standard ISOL target. In the second mode of thin-target operation, after mass separation, the ions from the target can be used directly as fast beams for experiments at high energies. In all cases, stopped nuclei can also be used for decay experiments, they can be injected into atom or ion traps, or they can be accelerated to low energies suitable for astrophysics studies.

Expected mass-separated intensities from RIA are shown in Figure 2. Many of these nuclei have never before been available as in-flight or reaccelerated beams. Generally, the intensity of rare isotopes will be more than two orders of magnitude greater than with any existing or planned facility. As shown in the figure, essentially all the nuclei that participate in the various astrophysical processes, such as the rp- and r-processes, will be available for study. The high intensities of rare isotopes will allow a full exploration of the limits of nuclear stability and will provide a wide range of isotopes for each element.

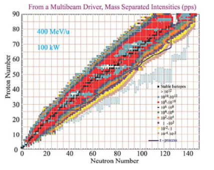
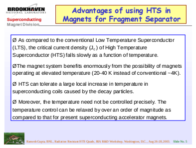


*Figure 2: Estimated yields for RIA in ions per second. The detailed description of how these yields were*



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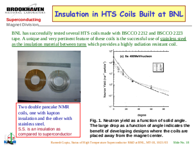
**Advantages of using HTS in Magnets for Fragment Separator**

- As compared to the conventional Low Temperature Superconductor (LTS), the critical current density ($J_c$) of High Temperature Superconductor (HTS) falls slowly as a function of temperature.
- The magnet system benefits enormously from the possibility of magnets operating at elevated temperature (20-40 K instead of conventional ~4K).
- HTS can tolerate a large local increase in temperature in superconducting coils caused by the decay particles.
- Moreover, the temperature need not be controlled precisely. The temperature control can be relaxed by over an order of magnitude as compared to that for present superconducting accelerator magnets.

Ramesh Gupta, BNL, Radiation Resistant HTS Quads, RIA R&D Workshop, Washington, D.C., Aug 26-28, 2003. Slide No. 5



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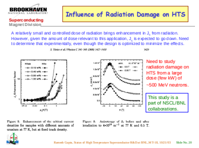
**Insulation in HTS Coils Built at BNL**

BNL has successfully tested several HTS coils made with BSCCO 2212 and BSCCO 2223 tape. A unique and very pertinent feature of these coils is the successful use of stainless steel as the insulation material between turns which provides a highly radiation resistant coil.

Two double pancake NMR coils, one with kapton insulation and the other with stainless steel.
S.S. is an insulation as compared to superconductor

**Fig. 1. Neutron yield as a function of solid angle. The large drop as a function of angle indicates the benefit of developing designs where the coils are placed away from the magnet center.**

Ramesh Gupta, Status of High Temperature Superconductor R&D at BNL, MT-18, 10/21/03 Slide No. 18



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**Influence of Radiation Damage on HTS**

A relatively small and controlled dose of radiation brings enhancement in $J_c$ from radiation. However, given the amount of dose relevant to this application, $J_c$ is expected to go down. Need to determine that experimentally, even though the design is optimized to minimize the effects.

Need to study radiation damage on HTS from a large dose (few kW) of ~500 MeV neutrons.

This study is a part of NSCL/BNL collaborations.

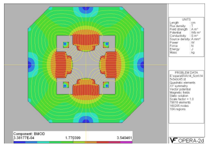
Figure 2. Enhancement of the critical current densities for samples with different amounts of uranium at 77 K, but at fixed track density.

Figure 3. Anisotropy of $J_c$ before and after irradiation to $4{\cdot}10^{15}$ m$^{-2}$ at 77 K and 0.5 T.

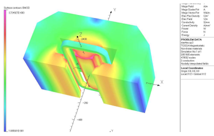
Ramesh Gupta, Status of High Temperature Superconductor R&D at BNL, MT-18, 10/21/03 Slide No. 20

## Current Design

### (14 cm good field radius)



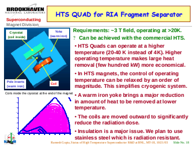
*An OPERA2d model of the 280 mm aperture super-ferric quadrupole design for RIA with field lines and field intensity in coil and iron regions.*



*An OPERA3d model of the 280 mm aperture super-ferric quadrupole design for RIA. Color indicates the field intensity on the surface of coil and iron regions. The above model shows only one symmetric half the complete magnet.*

## An Earlier Design

### (5 cm good field radius)



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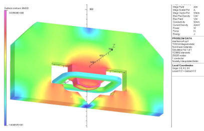
**HTS QUAD for RIA Fragment Separator**

Requirements: ~3 T field, operating at >20K.
? Can be achieved with the commercial HTS.

- HTS Quads can operate at a higher temperature (20-40 K instead of 4K). Higher operating temperature makes large heat removal (few hundred kW) more economical.
- In HTS magnets, the control of operating temperature can be relaxed by an order of magnitude. This simplifies cryogenic system.
- A warm iron yoke brings a major reduction in amount of heat to be removed at lower temperature.
- The coils are moved outward to significantly reduce the radiation dose.
- Insulation is a major issue. We plan to use stainless steel which is radiation resistant.

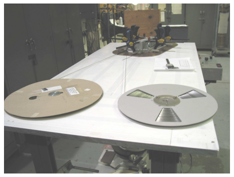
Coils inside the cryostat at the end of the magnet

Ramesh Gupta, Status of High Temperature Superconductor R&D at BNL, MT-18, 10/21/03 Slide No. 18



*An OPERA3d model of the magnetic mirror design. Color indicates the field intensity on the surface of coil and iron regions.*

## Magnet Construction

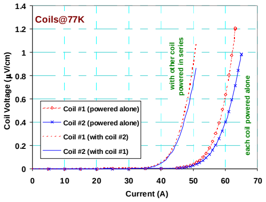


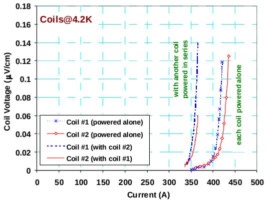
*A coil is being made by co-winding HTS tape (on right) and stainless steel insulating tape (left).*

*A racetrack HTS coil co-wound with stainless steel insulating tape.*

*RIA HTS coil test assembly and test set-up. The coils were tested in liquid nitrogen (simple test set-up for 77 K test) and in liquid helium (4.2 K).*

## Test Results





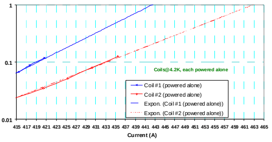


TABLE I
MEASURED CRITICAL CURRENTS (A) IN THE SELF-FIELD OF THE COIL(S)

| | *Coil 1 (alone)* | *Coil 2 (alone)* | *Coil 1 (with coil2)* | *Coil 2 (with coil1)* |
|---|---|---|---|---|
| $I_c$(0.1 µV/cm, 77K) | 53 | 54 | 41.8 | 42.2 |
| $I_c$(1 µV/cm, 77K) | 62 | 65 | 50.5 | 51.5 |
| $I_c$(0.1 µV/cm, 4.2 K) | 419 | 433 | 364 | 372 |
| $I_c$(1 µV/cm, 4.2 K) | 443 | 463 | 384 | 398 |

## Radiation Calculations

**The first quadrupole magnet in the RIA Fragment Separator (FS) is subject to considerable radiation from the production target. The beam will lose 20-50% of 400 kW (maximum beam power) in the production target located directly in front of the first quadrupole, resulting in copious amounts of penetrating radiation directed at this magnet. There is a tungsten shield between the target and the coils. The model calculations show that the tungsten shield is subjected to a heat load of 28 mW/cm³ (total load 3.3 kW), iron 25.3 mW/cm³ (total load 9 kW), and HTS coils 5.1 mW/cm³ (total load 135 W). This clearly shows the benefits of a warm iron design. One major concern is the neutron flux. More data is needed to determine the acceptable dose of high-energy neutrons on HTS coils.**

## Conclusions

**HTS magnets with stainless steel tape insulation offer an efficient solution to the challenges posed by the extremely large radiation and heat loads in RIA. However, this technology has never been used in particle accelerators and hence needs to be demonstrated with a few years of significant R&D effort. If successful, it offers a unique technology for radiation resistant superconducting magnets that can tolerate high heat load loads.**

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