# FRIB R&D
# Radiation Resistant Magnets

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# Technical Requirements

**High fields and large apertures require superconducting magnets**

**Magnets in the fragment separator target area that survive the high-radiation environment**

- **Require that magnets live at least 10 years at full power**
- **Require refrigeration loads that can be handled by the cryoplant**
- **Require magnets that facilitate easy replacement**

**Reduced operational costs**

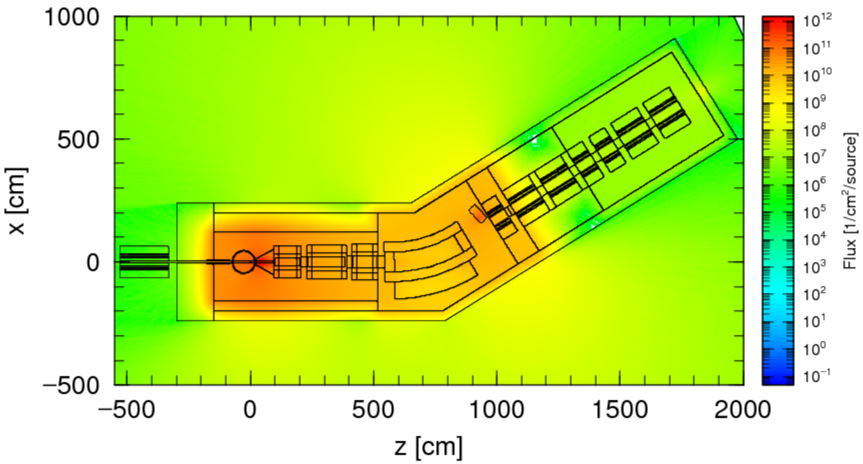
- **No down time for magnet replacement**
- **Higher acceptance reduces experimental times**
- **Robust and resistant to beam-induced quenchs**

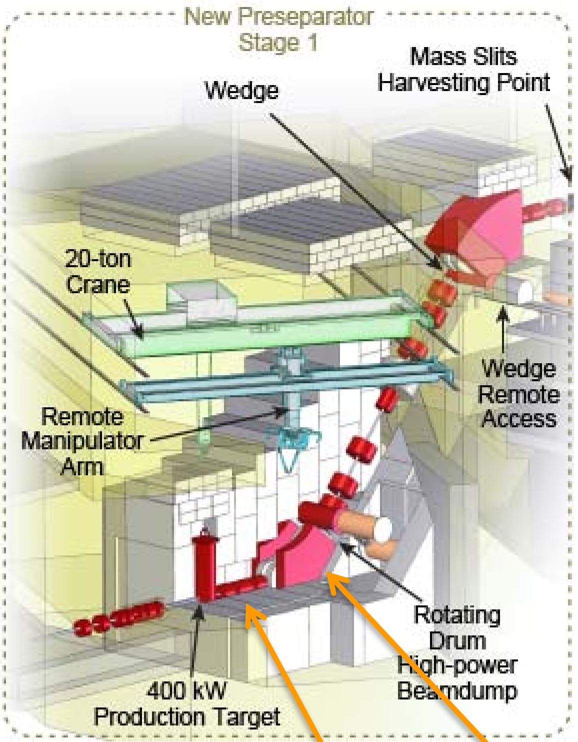
# Scope

## Target area and pre-separator

## Neutron fluence on first quad:

## $2.5 \times 10^{15}$ n/cm$^2$ per year



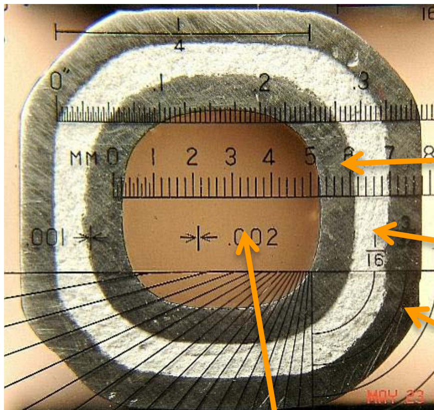

Pre-separator quads and dipole

# Approach

## Risk mitigation

- Four solutions will be evaluated
  - PRIMARY
    - » Radiation resistant magnets using metal-oxide Cable-In-Conduit-Conductor (CICC)
    - » Radiation resistant magnets using High Temperature Superconductors (HTS)
  - SECONDARY – only if Primary fails
    - » Standard A1900-type quads using radiation tolerant epoxy, but with warm iron
  - TERTIARY – only if Primary & Secondary fail
    - » Standard A1900-type quads, but with warm iron and easily replaced
- Down select
  - Efficacy of technical solutions understood and best option chosen
  - Accomplished by 2012 so no impact on TEC schedule

# R&D Plan for CICC magnets



Total width = 10 mm

Inner ss316 conduit

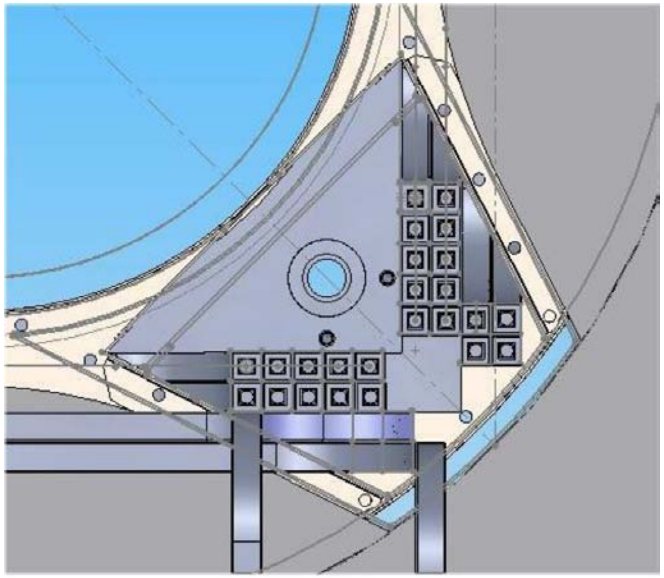
Spinel insulation

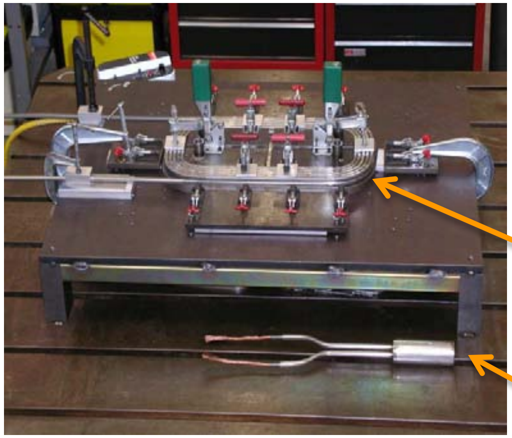
Outer ss316 conduit

60 superconducting wires go here
0.5 mm wire
Cable critical current 15,000 A at 2 T

Turns are welded together – no organic insulation
Lifetime of the magnet is the lifetime of the superconductor

# R&D Plan for CICC magnets






**One Coil Cross Section in Quadrupole.** The coil assembly (small squares and purple stainless steel constraint) is within a cryostat. The remainder of the system, including the magnet iron (gray) and bore (blue) are warm. This allows easy disassembly and replacement in a highly radioactive area by remote handling the MOCICC solution to a radiation-resistant quadrupole.

# R&D Plan for CICC magnets

- Builds on previous work on metal-oxide CICC
  - $Nb_3Sn$ trial pieces operate at 55 $A/mm^2$ at 7 T
  - Dipole operates at 80 $A/mm^2$
  - Building cold-iron quad
    - Two years developing synthetic spinel insulation
    - Long lengths developed
    - Fill factor increased by 50%
- All materials previously demonstrated in accelerator or reactors
- Changes from present demonstration project:
  - Warm iron
  - Higher fields
  - Full size cross section
  - Remote handling optimization
  - Extend technology to dipole
  - Add multipole windings

# R&D Plan for CICC magnets

## R&D Program

– Edited out

## Resources

– Edited out

## Schedule

– Edited out

# R&D Plan for CICC magnets

- **Schedule (by quarter from start)**
- Edited out

# R&D Plan for CICC magnets

## Correlation with TEC activities

- Solution found early enough in enough detail to not affect TEC schedule
- CD-2 is 6 months beyond finish date, so there is time to compare results with competing technologies
- Secondary and tertiary solutions will be cheaper and faster to build than preferred solutions so there will be no delay in CD-4, but will increase operating expenses

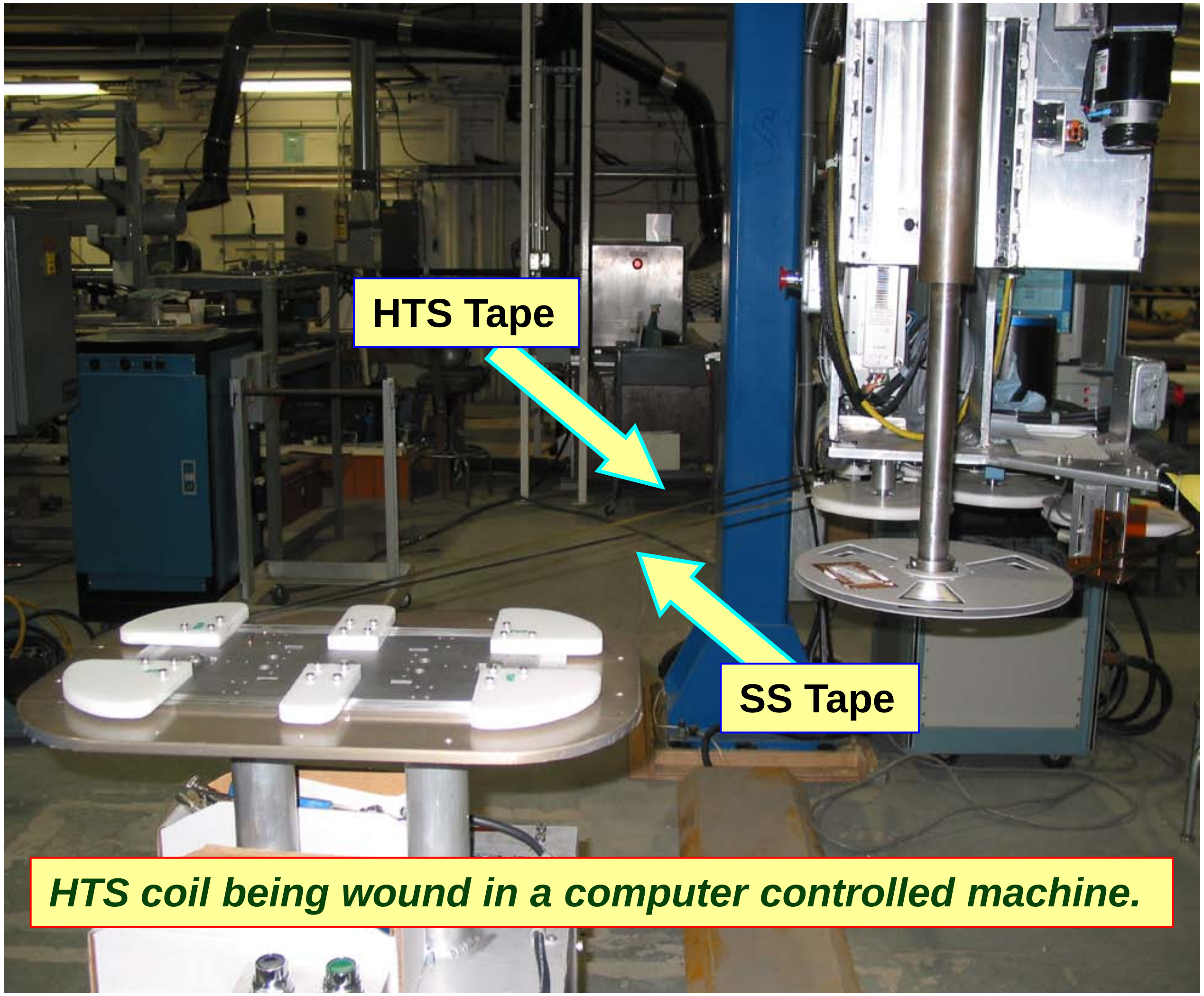
# Summary of CICC Magnet

- **Risk Mitigation**
  - Early failure of superconducting magnets in pre-separator eliminated
  - Magnets will meet aperture and field specifications allowing full acceptance
- **R&D strategy**
  - Demonstrate that full-sized quadrupoles that use metal-oxide insulated CICC fulfill all requirements
  - Demonstrate that full-sized quadrupoles that use HTS fulfill all requirements
  - Show the technologies are extendable to dipoles
  - Show the technologies are consistent with remote handling requirements
- **TEC consequences**
  - R&D completed early enough that CD-2 is not affected
  - Reduce facility costs by reducing down time from failed magnets

# Advantages of using HTS in FRIB Magnets
# (Primary Option #2)

- Removing  large heat loads at ~30-50 K (HTS) instead of ~4K (conventional NbTi) is over an order of magnitude more efficient.
- HTS coils can tolerate a large local and global increase in temperature, so are resistant to beam-induced.
- In HTS magnets, the temperature need not be controlled precisely. It can be relaxed by over an order of magnitude as compared to that for the present low temperature superconducting magnets. This simplifies and reduces cost of the cryogenic system while making it more robust.
- Builds on past R&D that determined reliability, thermal capacity and radiation tolerance of HTS in magnets.
- Proposed R&D is to demonstrate a design for current specifications with the $2^{nd}$ generation HTS and proving its radiation tolerance in operating conditions.

# HTS Coil Winding




*HTS coil being wound in a computer controlled machine.*

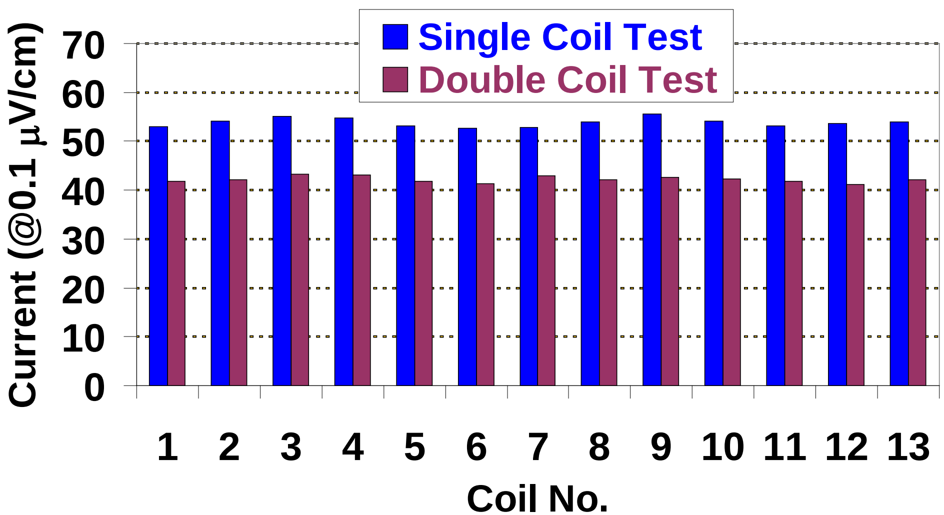
- **Magnet is made of 24 coils, each using ~200 meter of commercially available HTS.**
- **This gives a good opportunity to examine the reproducibility in coil performance.**
- Radiation damage to insulation is a major issue. **<u>Stainless steel tape</u>** serves as an insulator which, being metal, is highly radiation tolerant.

# $LN_2$ (77 K) Test of Coils Made with 1st Generation HTS

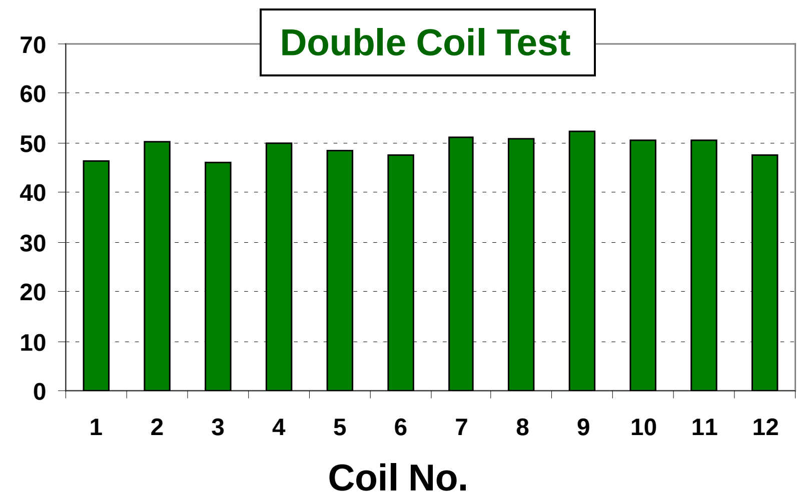
Individual HTS coils were tested at 77K with liquid nitrogen

- This makes initial R&D simpler, faster and cheaper than testing at 4 K

13 Coils made HTS tape in year #1




12 coils with HTS tape in year #2

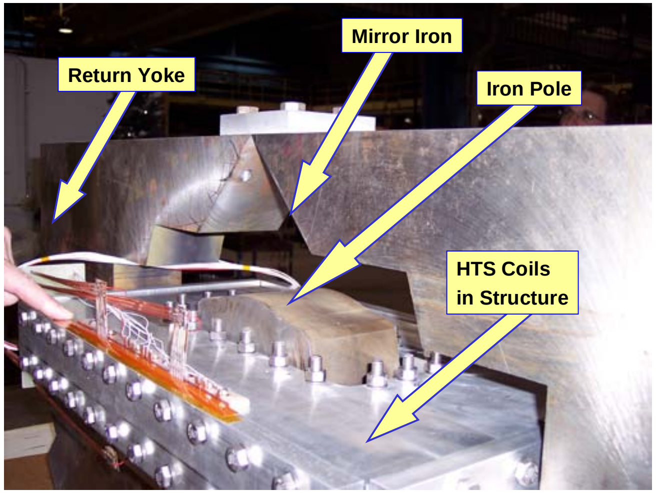



**Note: A uniformity in performance of a large number of HTS coils.**

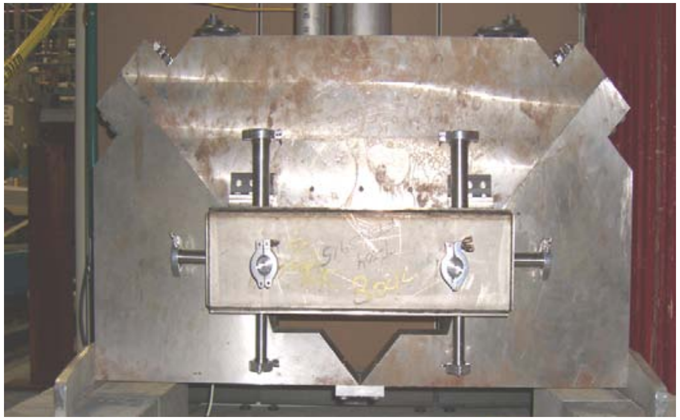
**It shows that the HTS coil technology has matured !**

# Magnet Structures for FRIB/RIA HTS Quad

**(step by step R&D program with several tests along the way – build and learn)**



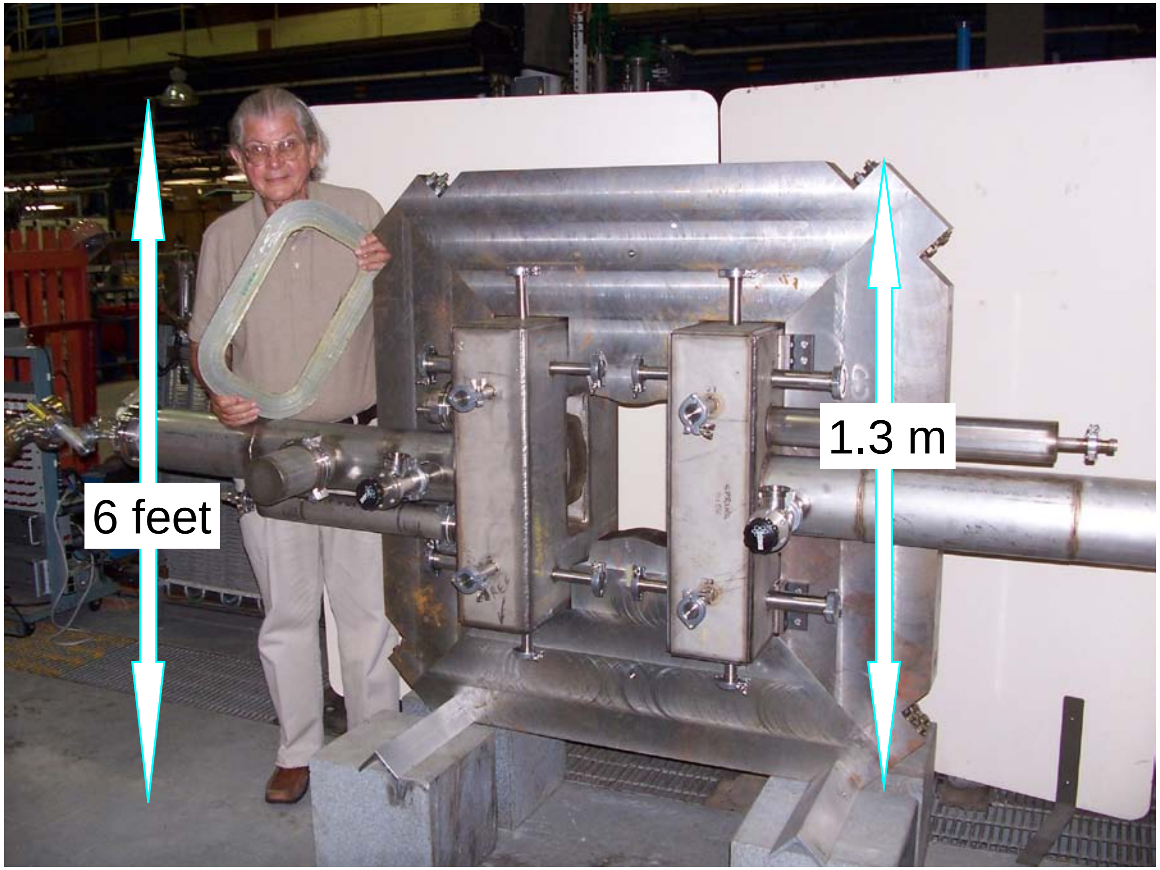

Mirror cold iron



Mirror warm iron

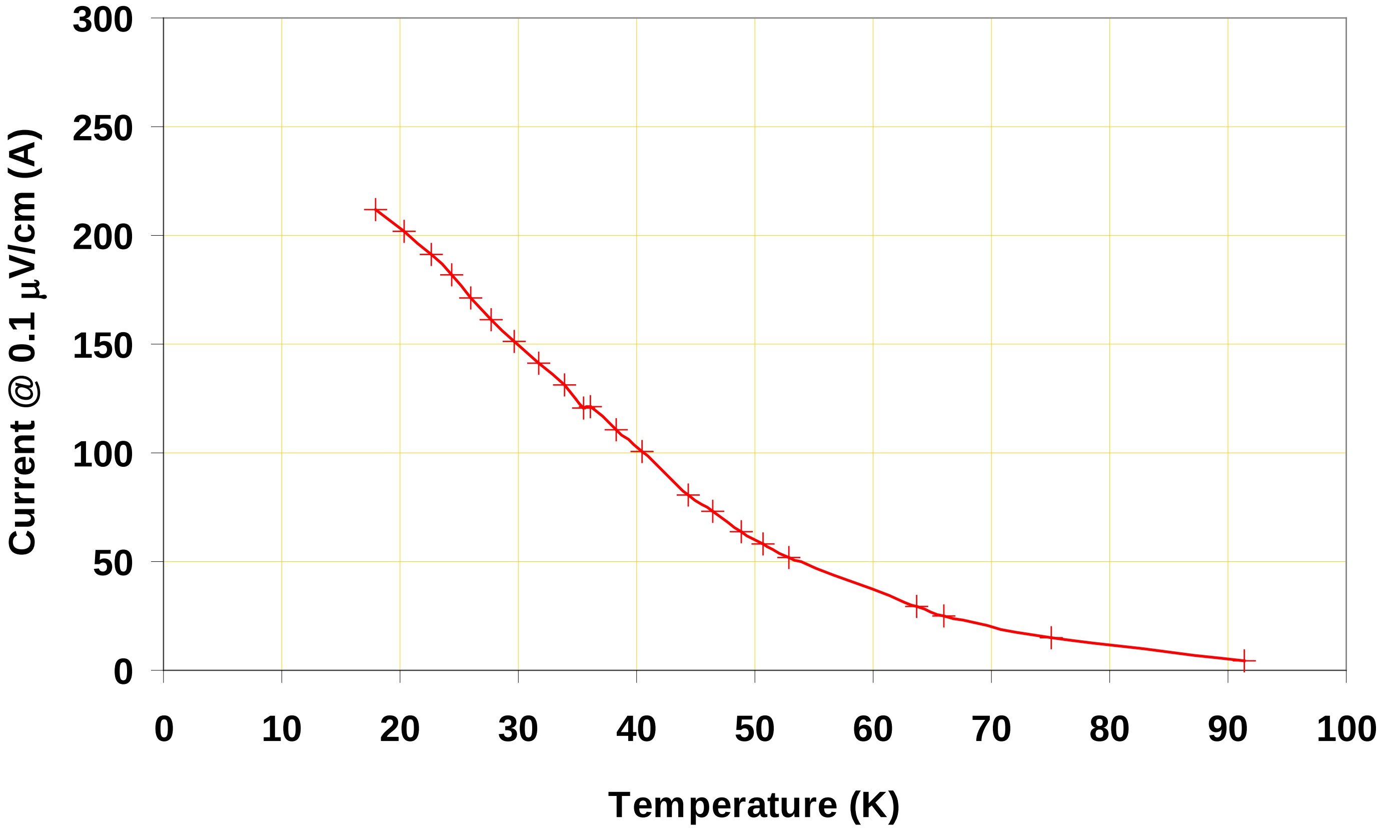
## A warm iron, 2 coil quad design

(to minimize radiation load)




We told you that it was a big aperture magnet

# RIA HTS Mirror Model Test Results
## (operation over a large temperature range)




A few degree increase in temperature makes a negligible impact on the performance

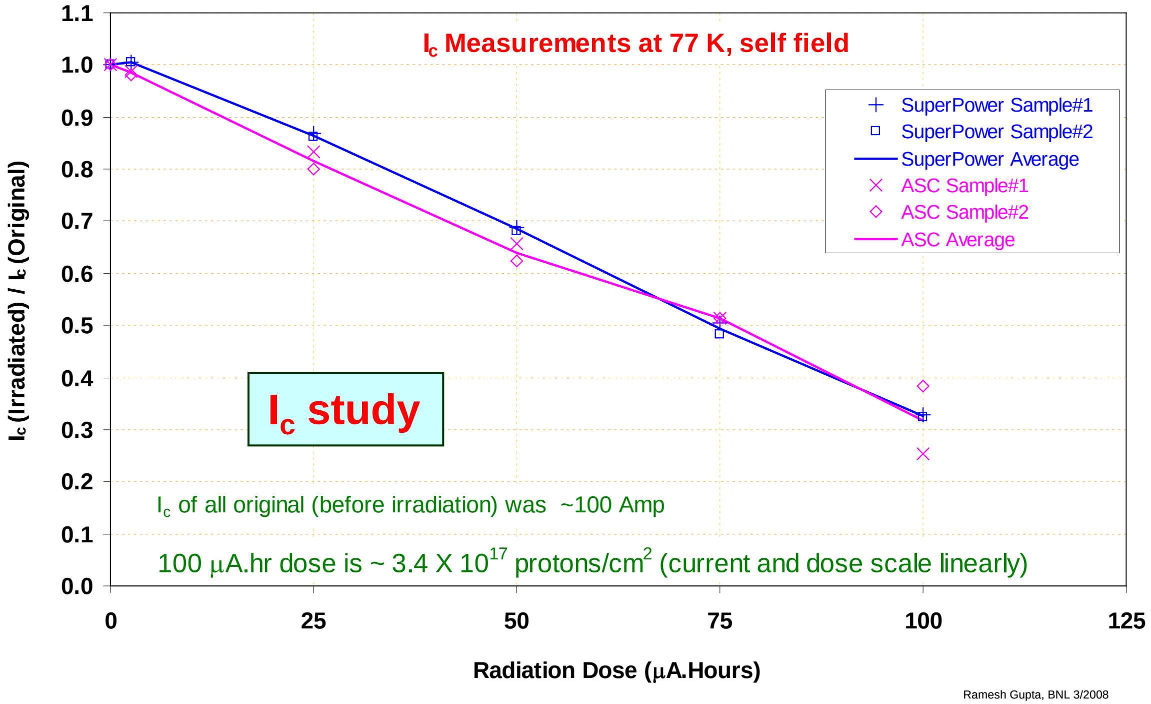
***If future machine studies or upgrade or operational experience requires higher gradient, then that can be achieved by operating at somewhat lower temperature.***

# Radiation Damage Studies of YBCO (HTS) at BNL
# (Earlier experiments were performed by Al Zeller at LBL)

Note: The following doses are order of magnitude more than what would be in FRIB

- Radiation damage studies at this level has never been done before !

igure 2. The BLIP facility.



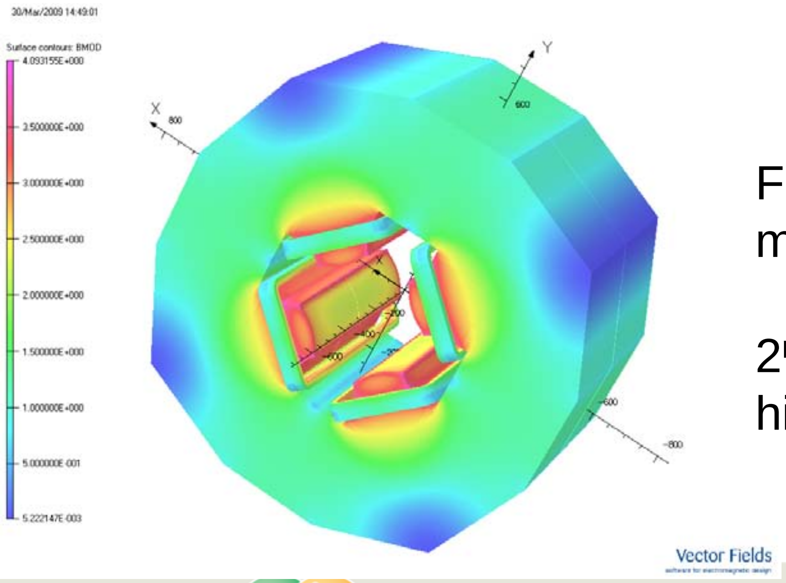

**Bottom line – YBCO is robust against radiation damage:**

- **Negligible impact on FRIB performance even after 10 years (Al Zeller, MSU).**

# Second Generation R&D Program (with proposed funding)

**Second generation magnet design responds to**

- Higher gradient requirements (~15 T/meter instead of  ~10 T/meter)
- Shorter magnetic length (first quad 0.6 meter instead of 1 meter)
- Discontinuation of manufacturing of 1st generation HTS (a corporate decision because 2nd generation HTS is projected to be cheaper)
- 2nd generation HTS also allows a more efficient removal of large heat loads at ~50 K rather than ~30 K in magnets with the 1st generation




For higher gradient performance and shorter magnetic length, 2 coil design is no longer viable.

2nd generation HTS allows magnets to operate at higher temperatures with higher heat leaks

# Overall Cost and Schedule of HTS Magnet R&D

## Resources

- Edited out

## High Level Schedule (major milestones by quarter from start)

Edited out

# Summary of HTS Magnet R&D

- 1$^{st}$ generation program (with previous funding)
  - A consistently good performance of large number of coils in several magnet structures proved that HTS has now matured to a viable magnet technology
  - Energy deposition experiments proved that large heat loads can be removed at elevated temperatures (significant impact on the cost and robustness of the operation)
  - Early radiation damage experiments indicates only a minor degradation in performance
- R&D strategy with proposed funding
  - Demonstrate that full-sized 2$^{nd}$ generation HTS quads, operating at even higher temperature (~50 K instead of ~30 K) fulfill all requirements
  - Demonstrate that HTS is radiation tolerant in actual operating conditions
  - Show the technologies are consistent with remote handling requirements
- TEC consequences
  - R&D completed early enough that CD-2 is not affected
  - Reduce facility construction and operating costs while providing a superior technical solution over resistive magnets with lower gradient (means reduce acceptance)