BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Second Generation HTS Quadrupole for FRIB

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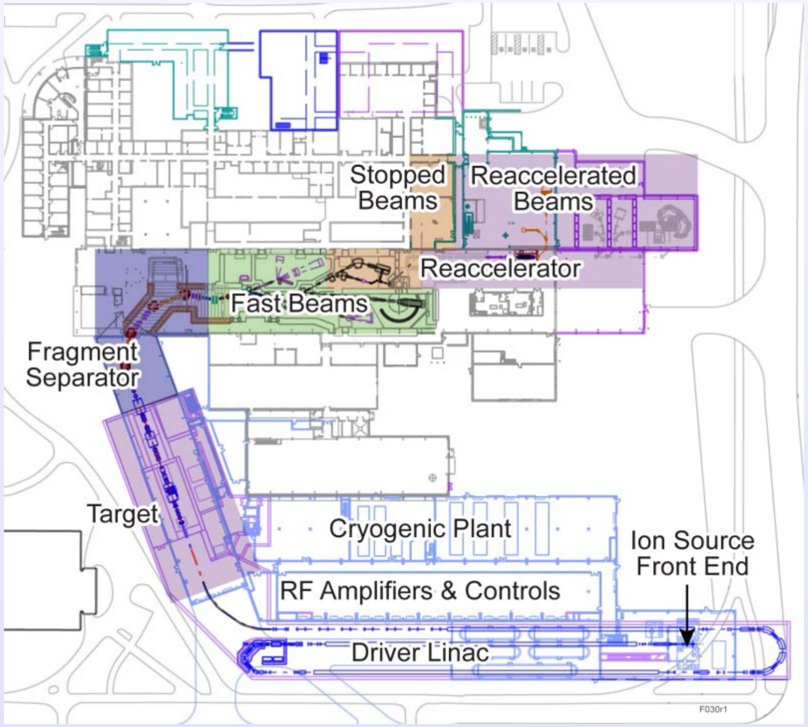
Overview

- What is FRIB ?
- Why HTS Quad ?
- 1st Generation HTS Quad
- 2nd Generation Design, Related Test Results
- Summary

FRIB Facility Concept

- Facility for Rare Isotope Beams (FRIB) will be located at MSU (Michigan State Univeristy)
- FRIB will create rare isotopes for research in intensities not available anywhere today
- Uses existing components of National Superconducting Cyclotron Lab (NSCL)- Fast start of FRIB
- Driver linac with energy of ≥ 200 MeV/amu for all ions, P_{beam} = 400 kW (high beam power)
- BNL is partner with MSU for developing high performance radiation tolerant quad

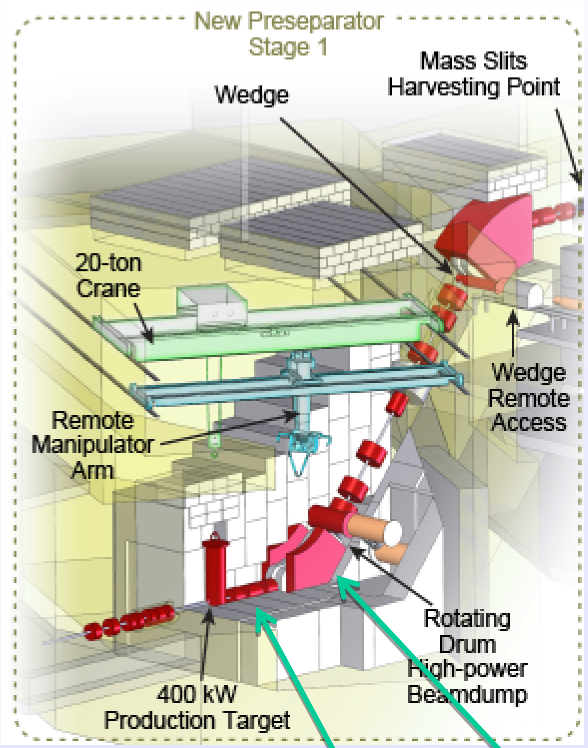


Courtesy: Wilson, MSU

Radiation and Heat Loads in Fragment Separator Magnets

To create intense rare isotopes, 400 kW beam hits the production target.

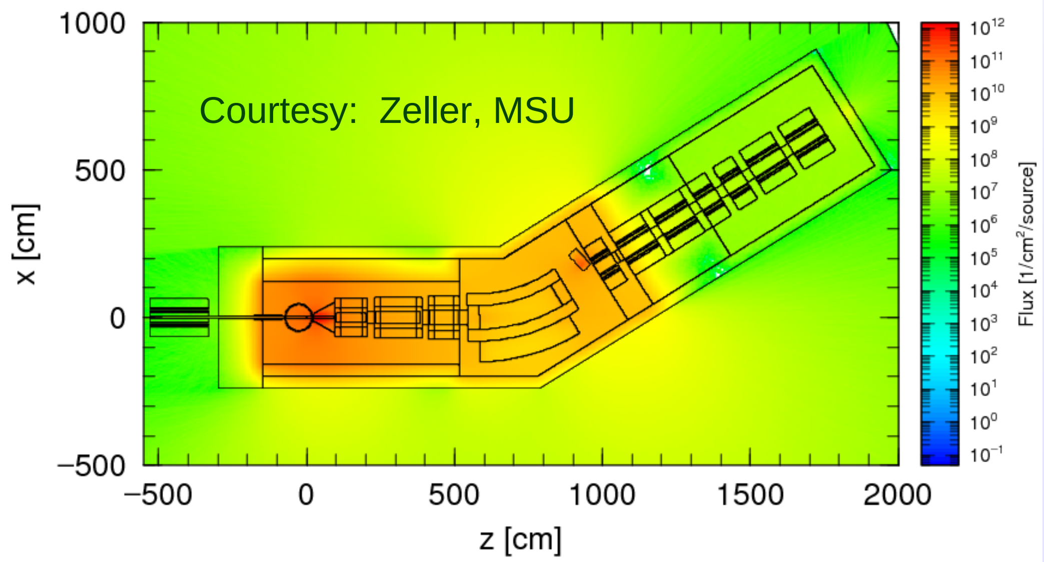
Quadrupoles in Fragment Separator (following that target) are exposed to unprecedented level of radiation and heat loads



Radiation resistant
Pre-separator quads and dipole

Exposure in the first quad itself:

- **Head Load : ~10 kW/m, 15 kW**
- **Fluence : 2.5 x10^{15} n/cm^2 per year**
- **Radiation : ~10 MGy/year**



HTS Magnets in Fragment Separator

Use of HTS magnets in Fragment Separator region over conventional Low Temperature Superconducting magnets is appealing because of :

Technical Benefits:

- HTS provides large temperature margin – HTS can tolerate a large local and global increase in temperature, so are resistant to beam-induced heating

Economic Benefits:

- Removing large heat loads at higher temperature (~50 K) rather than at ~4 K is over an order of magnitude more efficient.

Operational Benefits:

- In HTS magnets, the temperature need not be controlled precisely. This makes magnet operation more robust, particularly in light of large heat loads.

Challenges with HTS Magnets

Can HTS tolerate these unprecedented level of radiation and heat loads?

- Yes it can, based on previous and recent R&D (backup slides)

Can HTS be affordable?

- In few special purpose, high impact magnets (as here), conductor cost (including high priced-HTS) is only a fraction of the total R&D cost.
- Moreover, this can be recovered in utility cost over time since HTS at high temperature is much more efficient in removing large heat loads.

Can HTS magnets be reliable ?

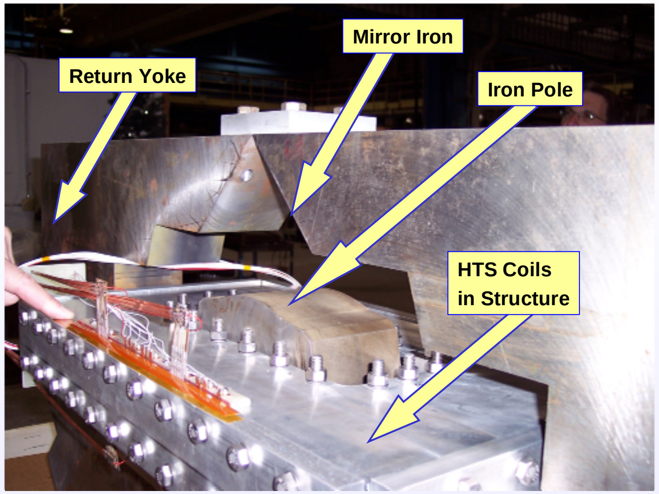
(always a question with a new technology)

- This is a relatively conservative design (specially at 50 K, low current).
- Many R&D HTS coils and magnet structure have been built.

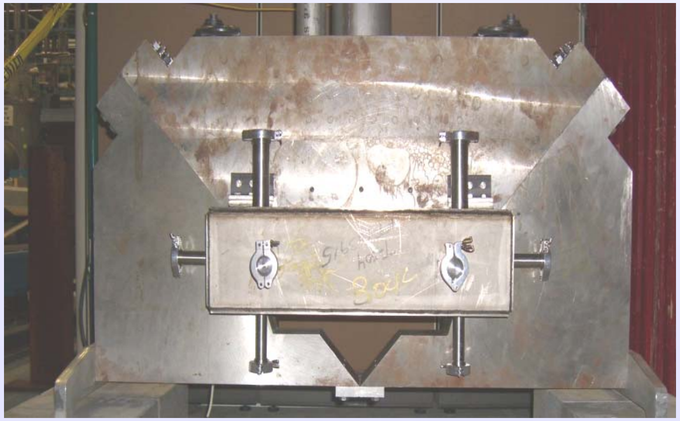
Risk because of new technology; benefit because of a unique enviorment.

First Generation R&D

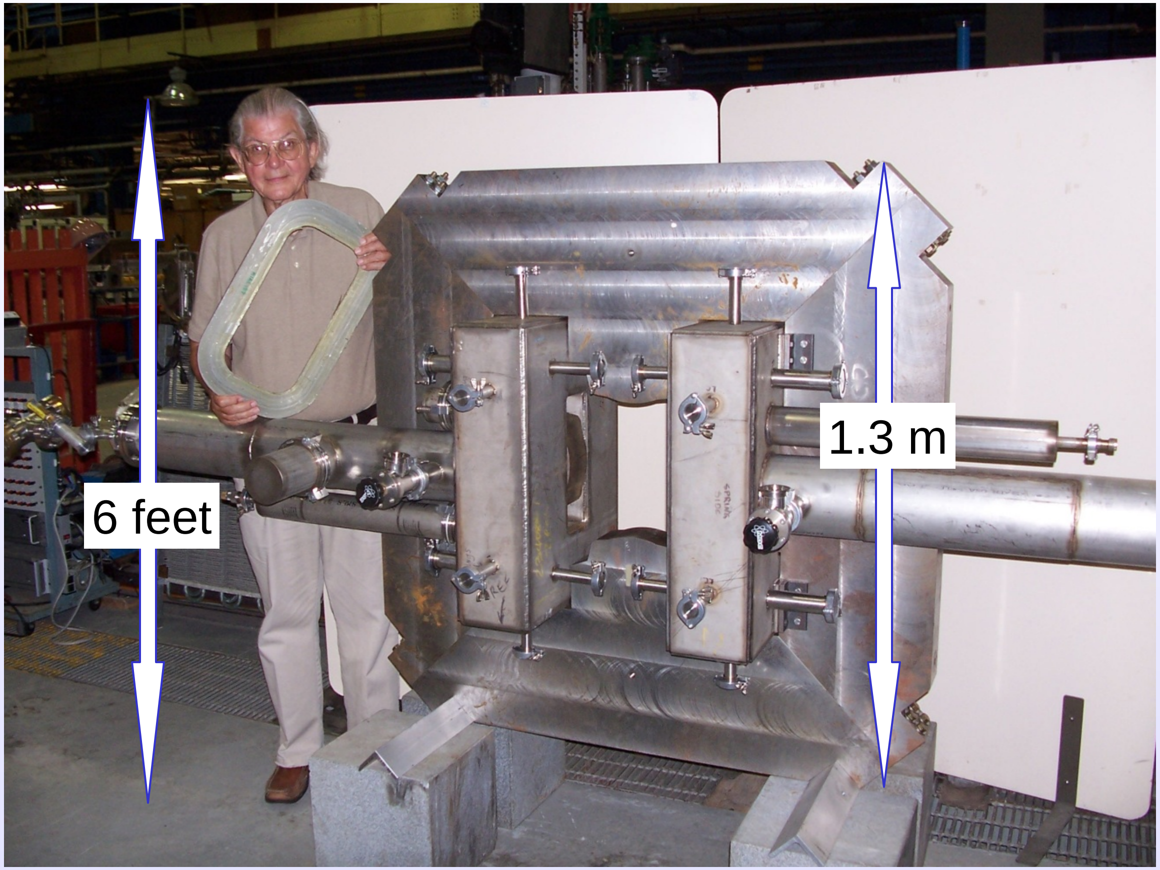
Magnet Structures for FRIB/RIA HTS Quad
(Several R&D structures were built and tested)



Mirror cold iron



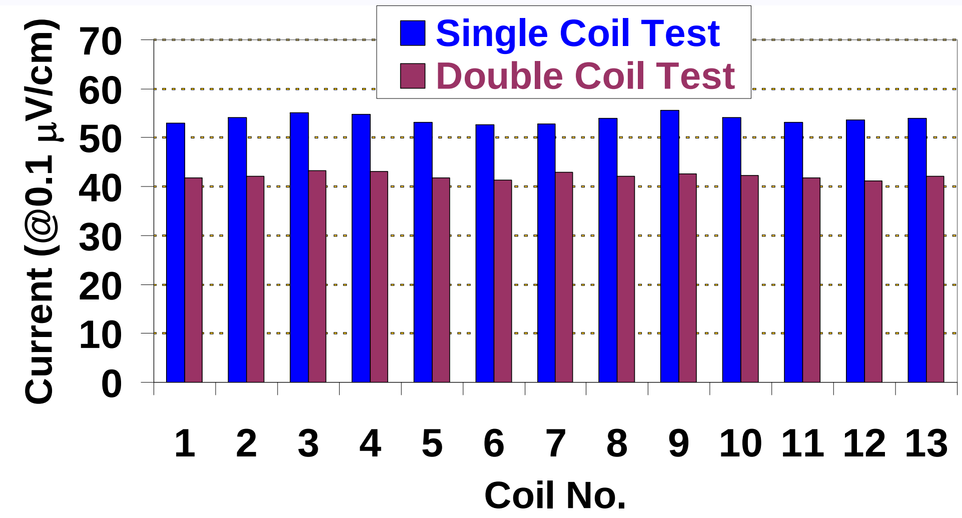
Mirror warm iron



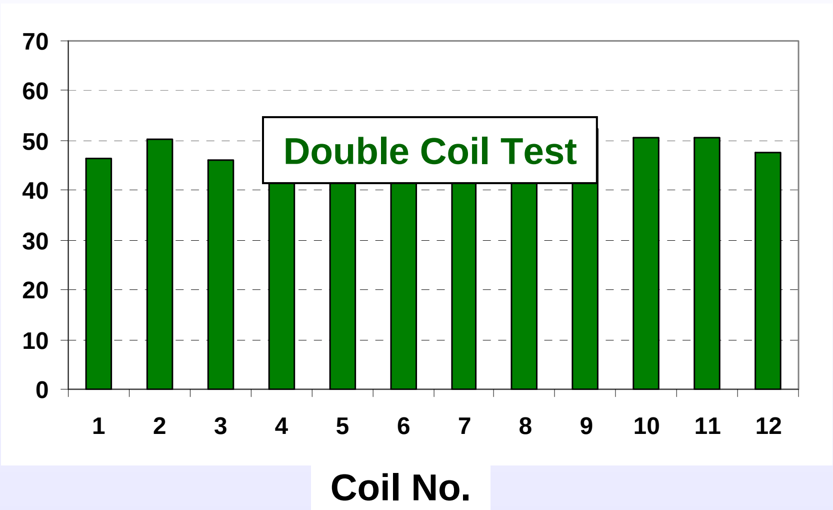
LN_2 (77 K) Test of Coils Made with ASC 1st Generation HTS

Each single coil uses ~200 meter of tape

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.

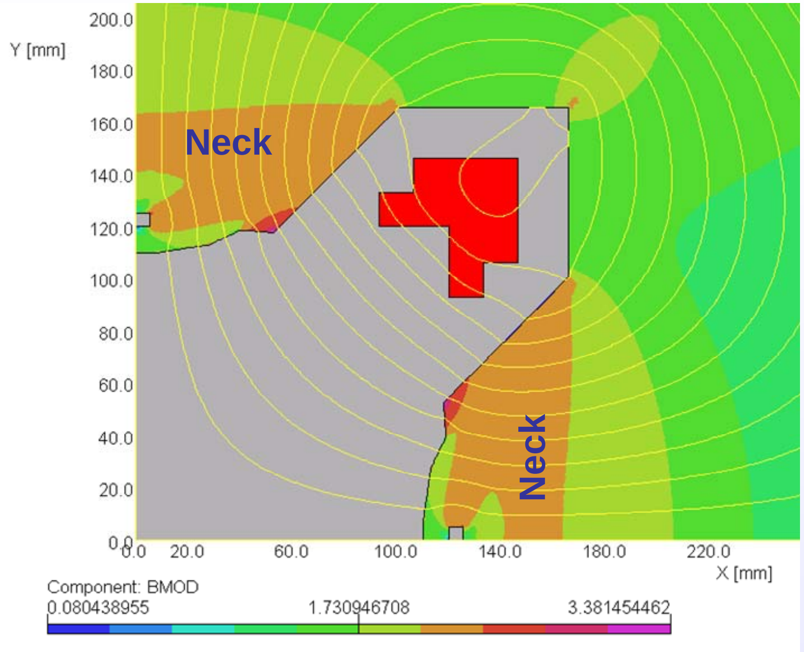
It shows that the HTS coil technology has matured !

Why 2G HTS

- Allow higher gradient at higher operating temperature
  - 15 T/m instead of 10 T/m
  - ~50 K operation rather than ~30 K
- Conductor of the future
  - Projected to be less expensive and have better performance

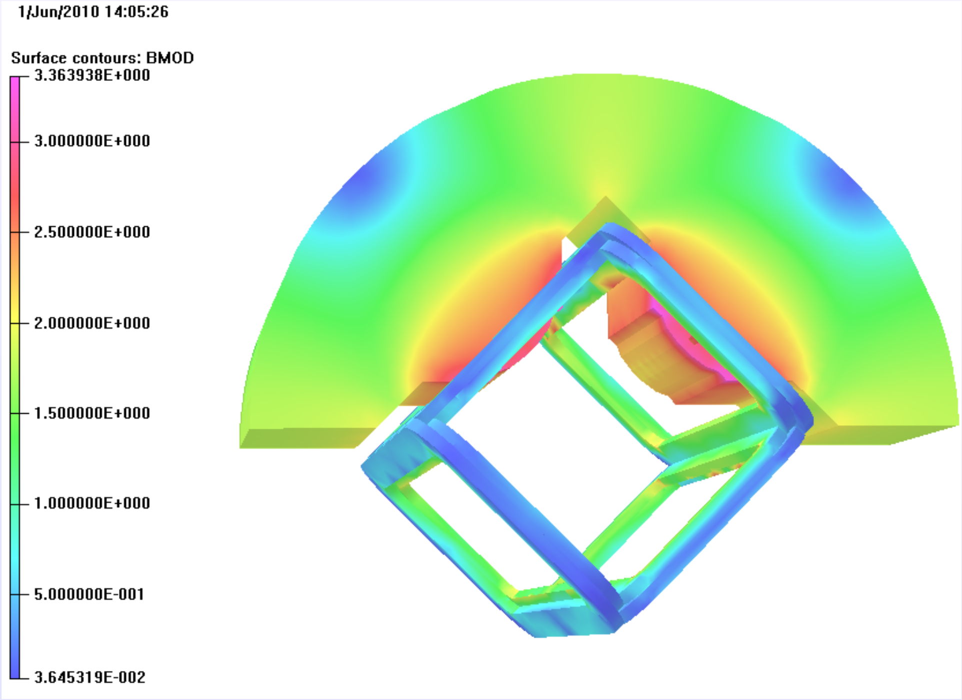
Quick Overview of the Design

Magnetic Design



Uses 12 mm tape rather than 4 mm

- Minimizes the number of coils and joints
- Current is higher (inductance is lower)
- Relative impact of local weak micro-spot less



Parameter List

Parameter	Value
Pole Radius	110 mm
Design Gradient	15 T/m
Magnetic Length	600 mm
Coil Overall Length	680 mm
Yoke Length	~550 mm
Yoke Outer Diameter	720 mm
Overall Magnet Length(incl. cryo)	~880 mm
Number of Layers	2 per coil
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	26 mm, 39 mm
Number of Turns (nominal)	110, 165
Conductor (2G) width, SuperPower	12.1 mm ± 0.1 mm
Conductor thickness, SuperPower	0.1 mm ± 0.015 mm
Cu stabilizer thickness SuperPower	~0.04 mm
Conductor (2G) width, ASC	12.1 mm ± 0.2 mm
Conductor (2G) thickness, ASC	0.28 mm ± 0.02 mm
Cu stabilizer thickness ASC	~0.1 mm
Stainless Steel Insulation Size	12.4 mm X 0.025 mm
Field parallel @design (maximum)	~1.9 T
Field perpendicular @design (max)	~1.6 T
Minimum I_c @2T, 40 K (spec)	400 A (in any direction)
Minimum I_c @2T, 50 K (expected)	280 A (in any direction)
Nominal Operating Current	~280 A
Stored Energy	37 kJ
Inductance	~1 Henry
Operating Temperature	50 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

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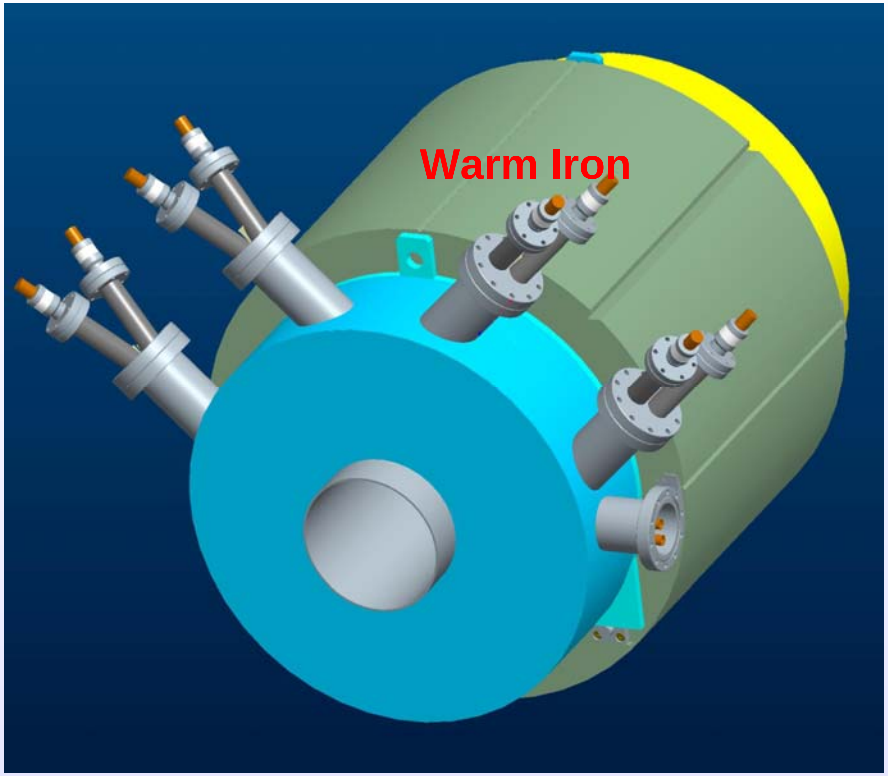
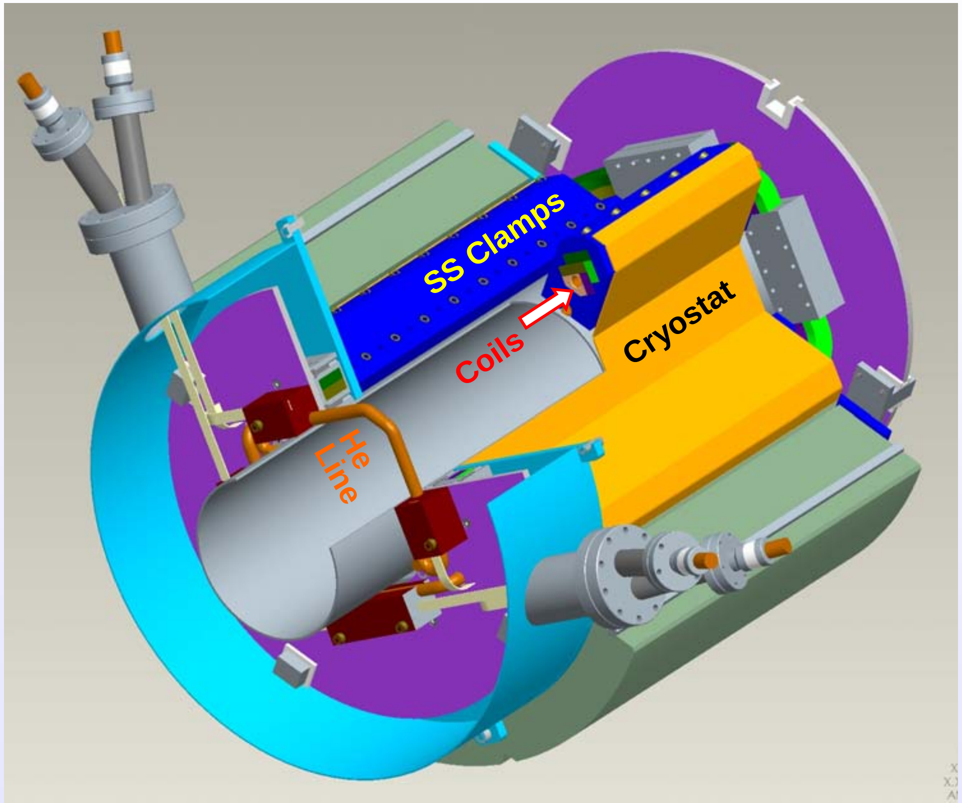
Cryo-mechanical Structure





R&D Magnet in cryo-stat

(allows independent testing of four HTS coils)

Cut-away isometric view of the assembled magnet

(compact cryo design allowed larger space for coils and reduction in pole radius)

Test Results on Related R&D

2G HTS Coil for RIA/FRIB

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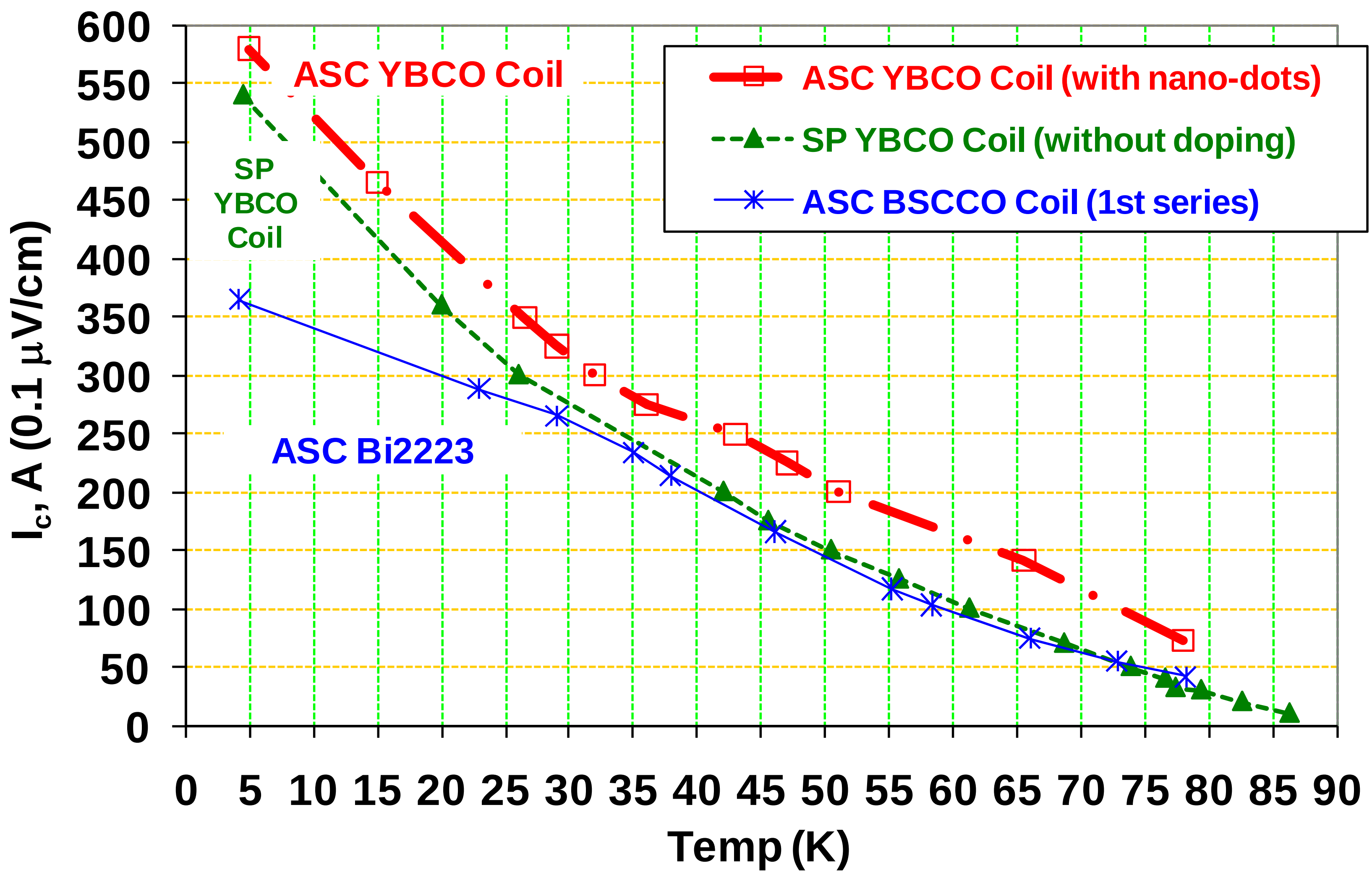
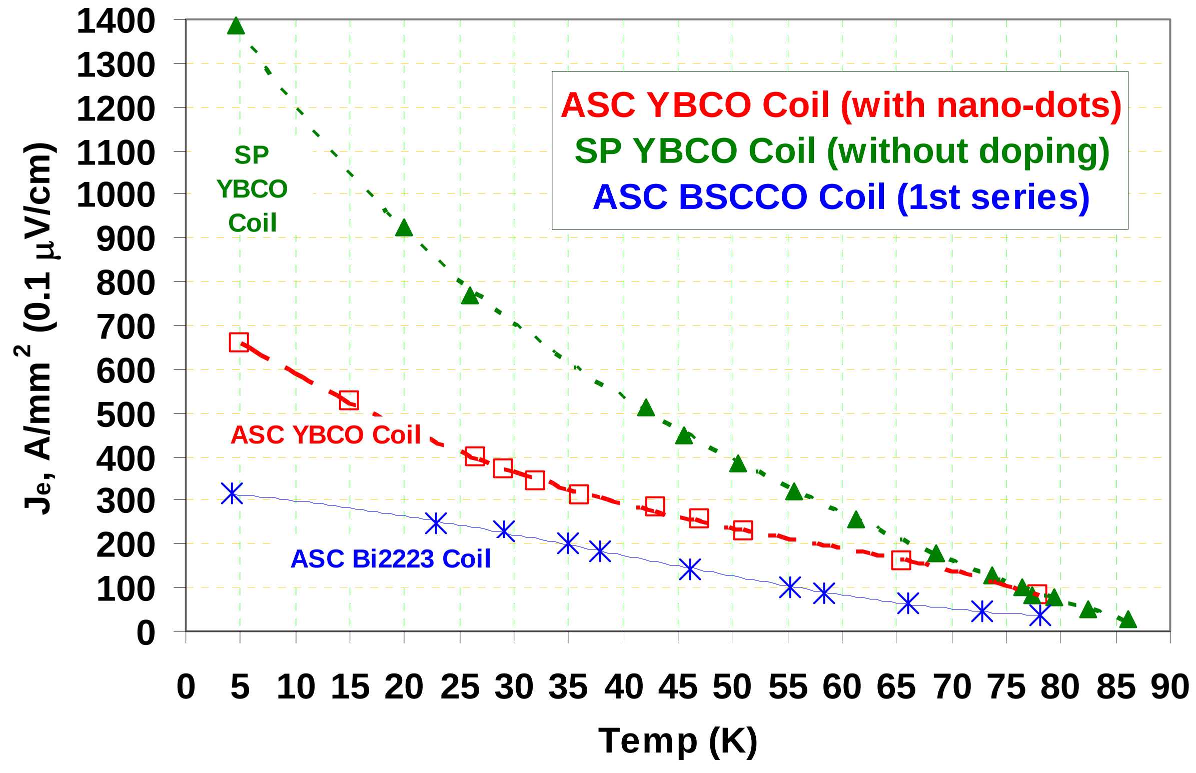
2G HTS FRIB Coil Test Results



Low Temp Performance of FRIB Coils (R&D during technology development period)



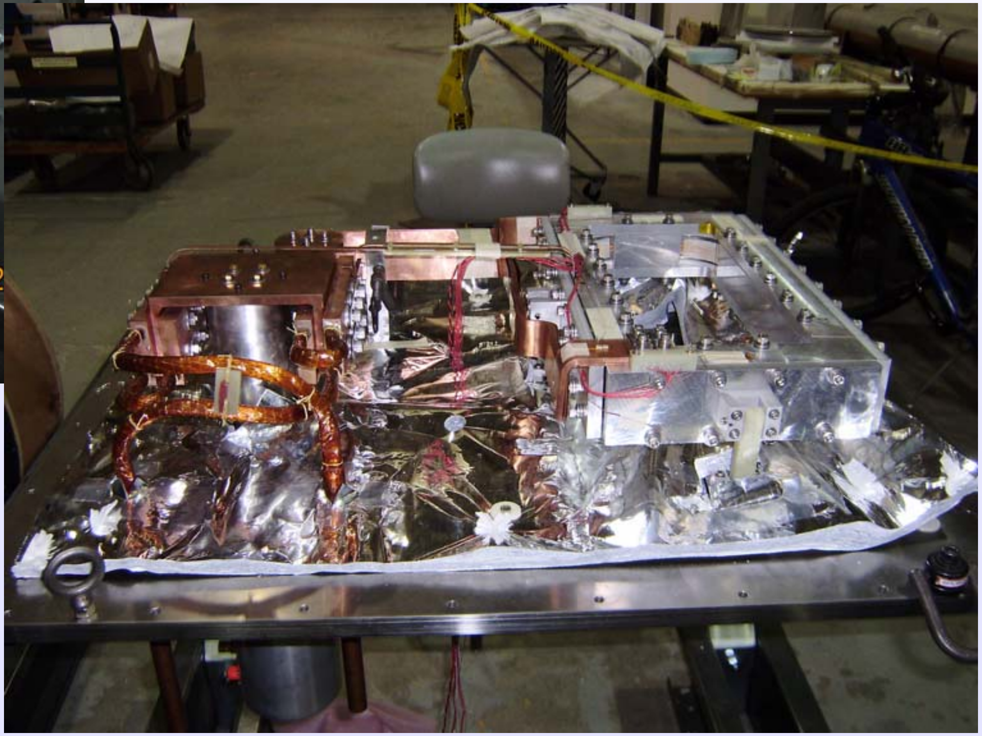
If coils to go normal (quench, thermal runaway, protection):

- Copper current density: ~1500 A/mm^2 (ASC); ~3000 A/mm^2 (SuperPower)

FRIB magnet design is much more conservative (no risk, large margin in real machine):

- ***Copper current density is much lower: ~300 A/mm^2 (ASC) or ~700 A/mm^2*** **(*SP*)**
- ***Reliability is much higher and protection is much simpler***
- ***Still, an advanced quench detection and protection R&D is underway.***

Other FRIB/RIA R&D



Coils previously made under separate R&D funding are ready for testing with cryo-coolers

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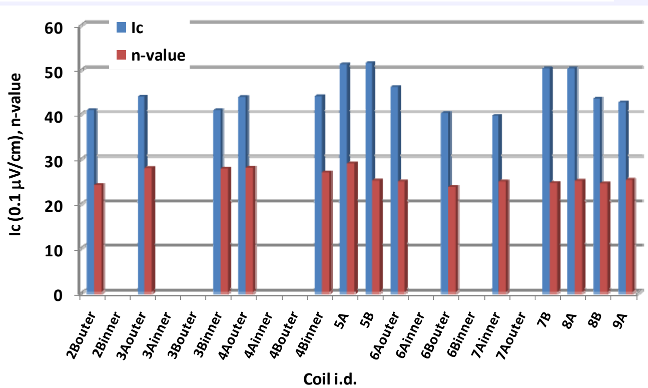
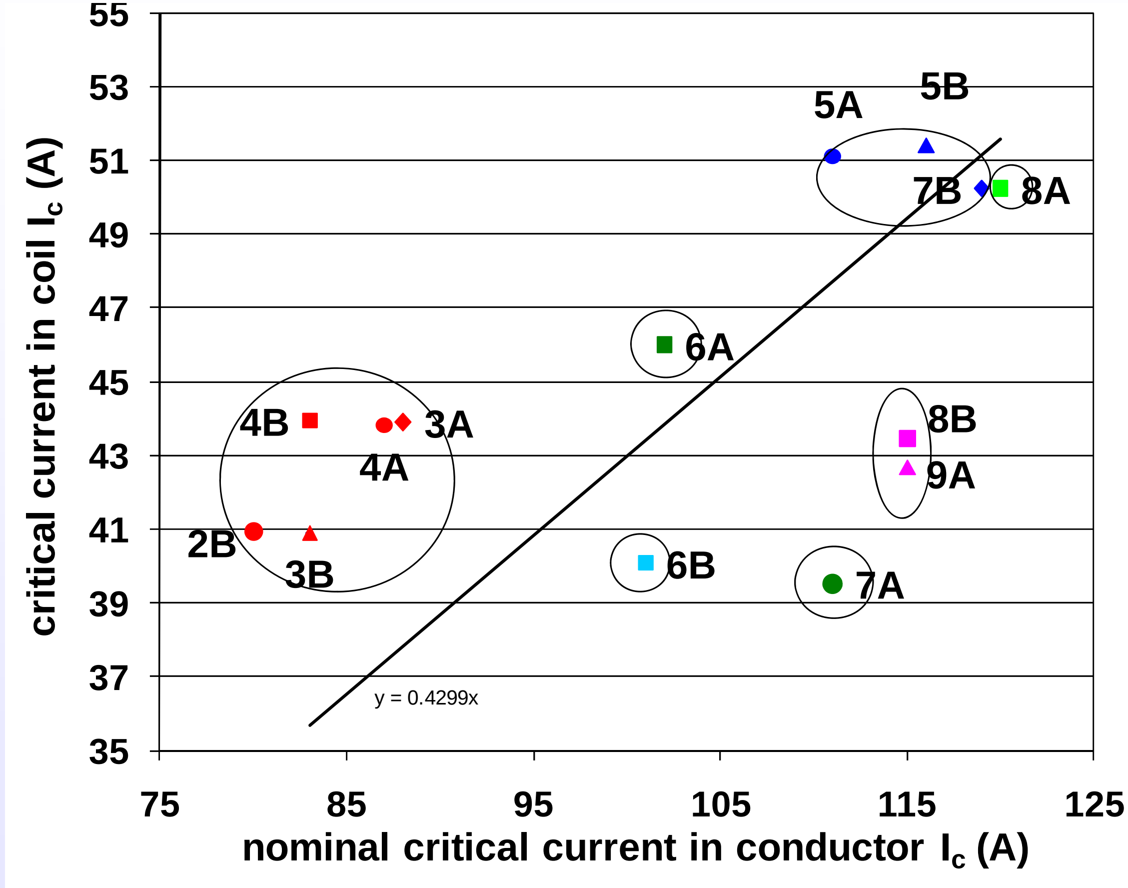
Related R&D : Correlation between 2G Coil I_c and Wire I_c at 77 K

2G HTS solenoid coils build under a different program





For real magnet application, it is important to measure scaling and correlation in a large number of coils made of long length wire – not just small wire.

Lesson learnt :

Coils worked very well but for coil I_c one can not just depend on wire I_c yet.

Conductor Related Discussion

• HTS has been available for over a decade but with 77 K, self field spec only.

• To build magnets for real machine, we need to specify conductor performance in field and at operating temperature

Simple spec for FRIB: I_c(2T, 40 K) > 400 A - irrespective of the field direction

>> To minimize measurements, vendors wanted limited angles – agreed.

• This (vendors willing to sell conductor at in field spec) may be considered a contribution of FRIB to HTS magnet technology in general.

• Previous slide showed the importance of placing such specifications.

Summary

- HTS offers a unique magnet solution for challenging fragment separator environment of FRIB.
- 2G HTS allows a better technical solution.
- Lower operating current, wider tape (~12 mm) allows a conservative solution for protection with low current density in copper (as low as ~300 A/mm^2).
- With modest R&D, this could be the first application of HTS magnet in real machine.

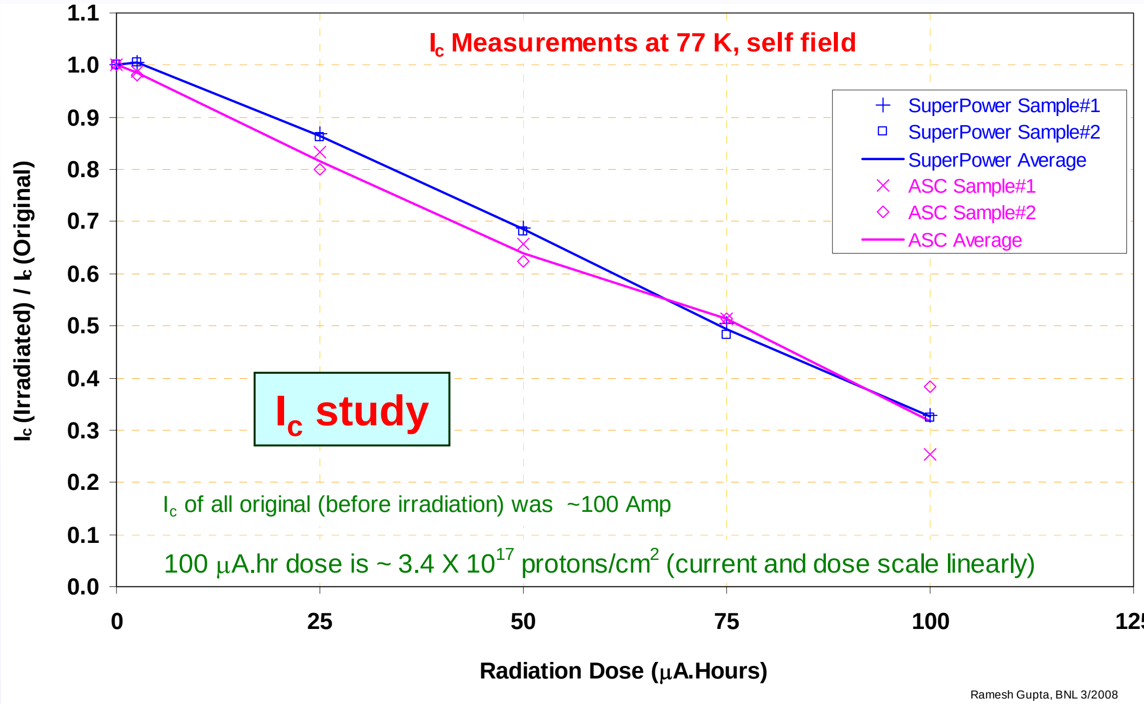
Backup Slides

Radiation Damage Studies of YBCO (HTS) at BNL

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 !

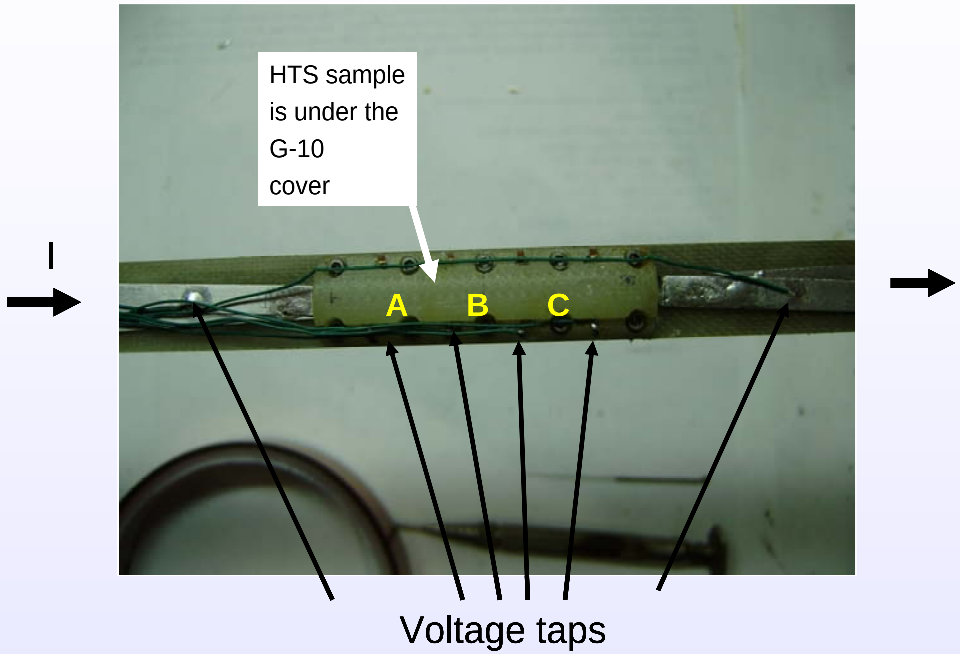
igure 2. The BLIP facility.



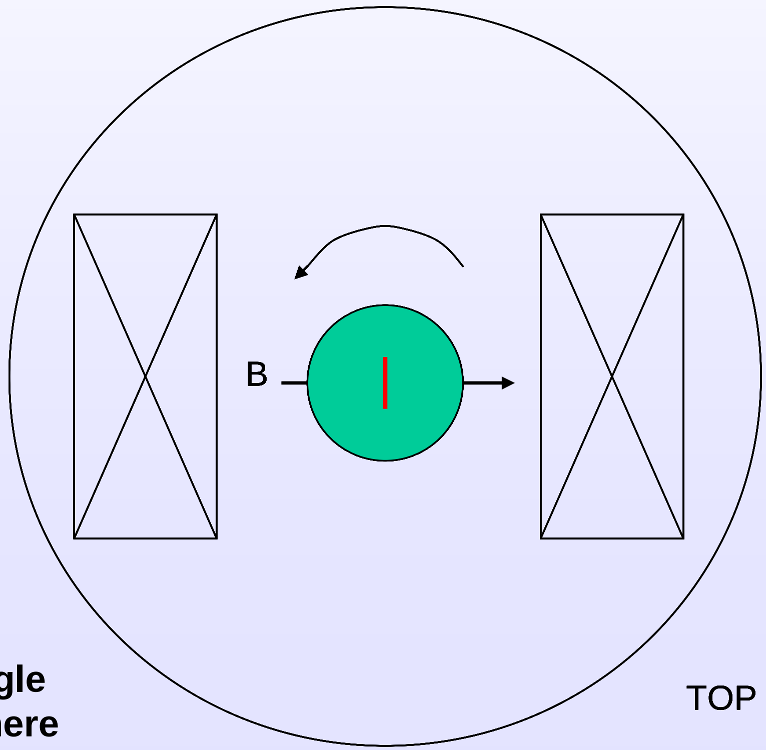
Bottom line – YBCO is robust against radiation damage:

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

Measured Angular Dependence in ASC Samples at 77K (liquid nitrogen) in Various Applied Field

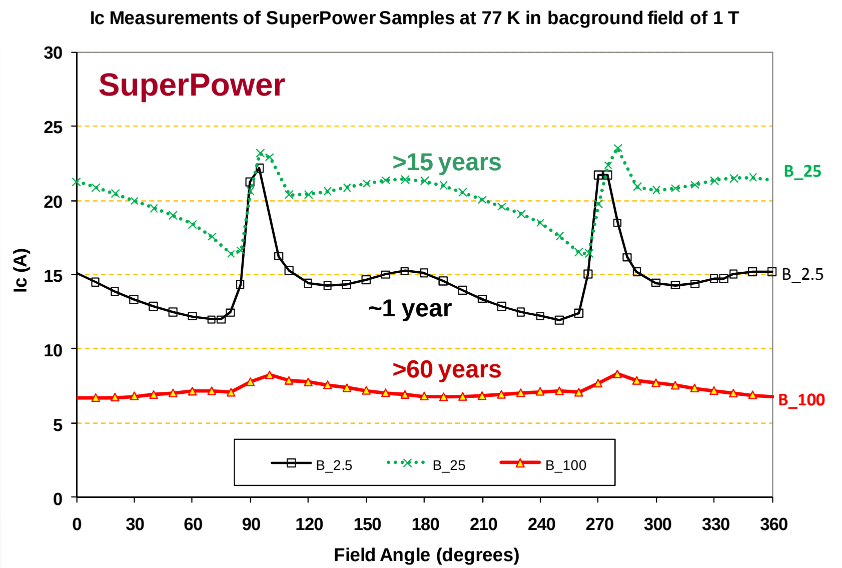


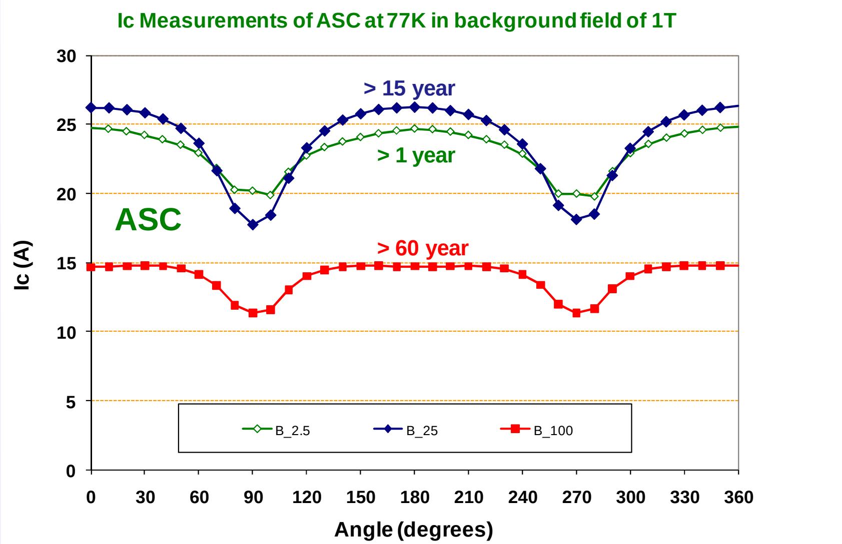
Field is measured with respect to c-axis (see below on right)



Field angle is zero here

Radiation Damage Studies in 2G HTS samples from SuperPower and ASC (@77K in 1 T Applied Field)





- In HTS, I_c is anisotropic with respect to field; radiation changes that anisotropy.
- There is a significant difference in the change in anisotropy between SuperPower and HTS samples.
- In some cases, rather than damage, there is an initial increase in performance.
- However, after a very large irradiation, samples from both SuperPower and ASC become more isotropic.
- Bottom line, HTS seems to survive FRIB radiation (Zeller, Ronningen, MSU) .
- Next step: studies at 40-50 K and 2-3 T.

Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

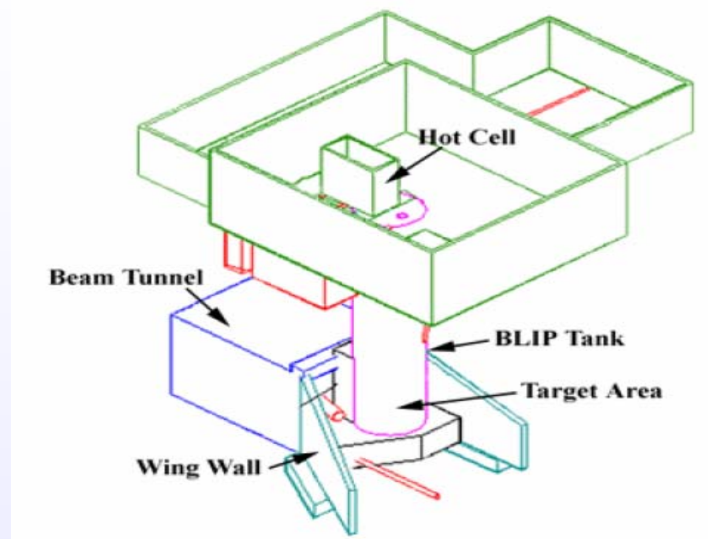


Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 µA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.