20 T Target Solenoid with HTS Insert

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Overview

- **Target solenoid magnet design overview**
- **Motivation for replacing 6 T Cu solenoid by 6 T HTS insert in 20 T region**
  - Significant reduction in size, stored energy and operating cost with more space for shielding.
- **Relevant high radiation HTS magnet R&D for FRIB at BNL**
  - Magnets subjected to large amount of radiations
  - Radiation damage studies on HTS
  - Energy deposition studies on HTS magnets
- **Relevant high field HTS solenoid R&D at BNL**
  - PBL/BNL 20+T HTS solenoid SBIR for muon collider (~40 T in background field)
  - ~25 T, large aperture HTS SMES
- **Possible benefits from more HTS in lower field region of target solenoid**
  - Use of HTS may significantly reduce the amount of Tungsten shielding
- **Summary**

HTS Insert in Target Solenoid

<u>Presentations describing the proposed work:</u>

- Motivation and conceptual design (this presentation)
  - Ramesh Gupta, BNL

- More detailed design and SBIR proposal (next presentation)
  - Bob Weggel, PBL

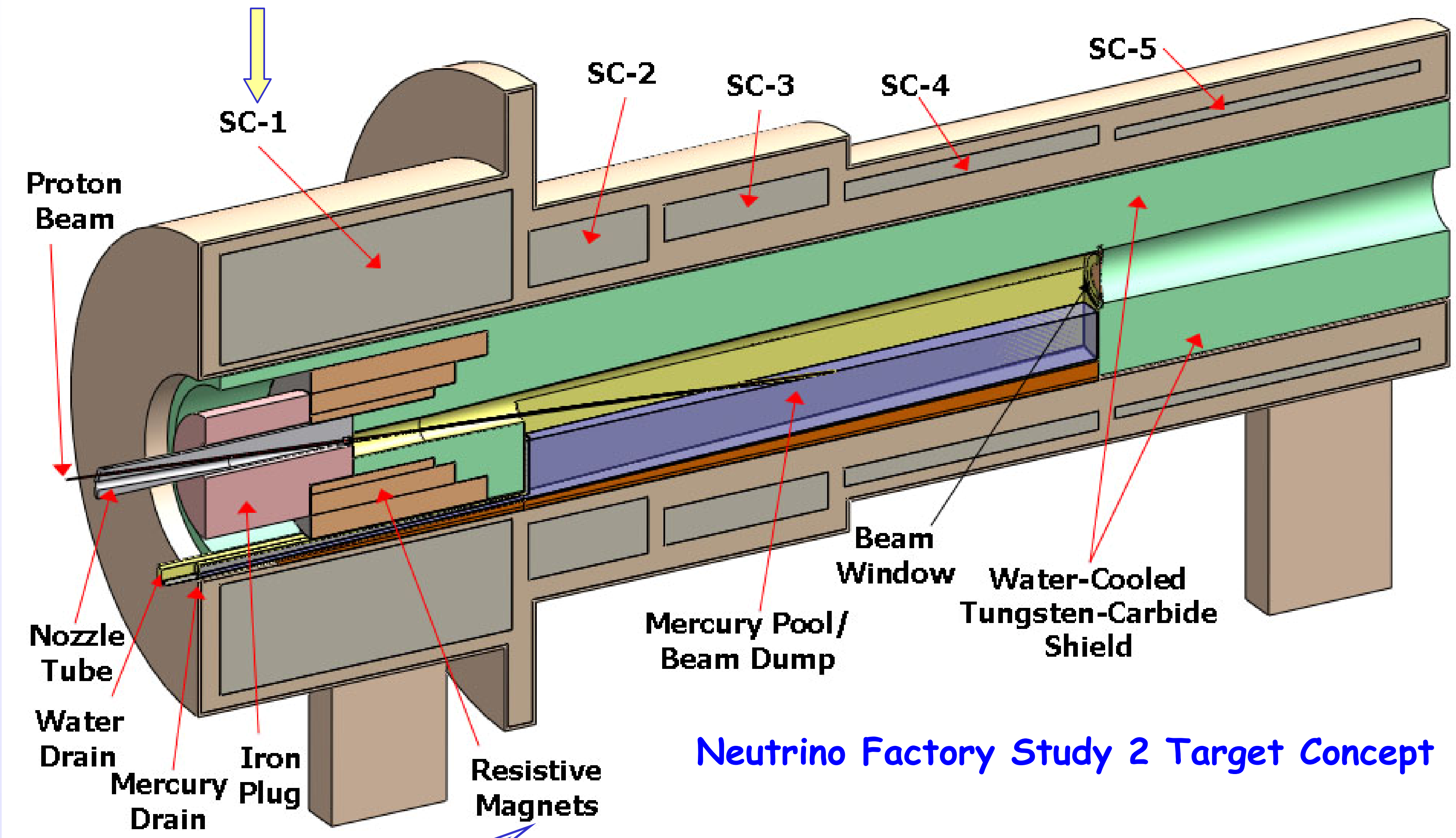
The Key Target Parameters

Proton Driver

- **4 MW Beam Power**
- **5-15 GeV KE (8 GeV is currently favored)**
- **50 Hz NF operation / 15 Hz MC**
- **3 Bunch structure (280 μs total favored) NF (1 bunch MC)**
- **Target System**
- **20-T solenoid magnet**
- **Liquid metal jet**
- **20 m/s flow rate ("new" target every pulse @ 50 Hz)**
- **High-Z (Hg favored)**

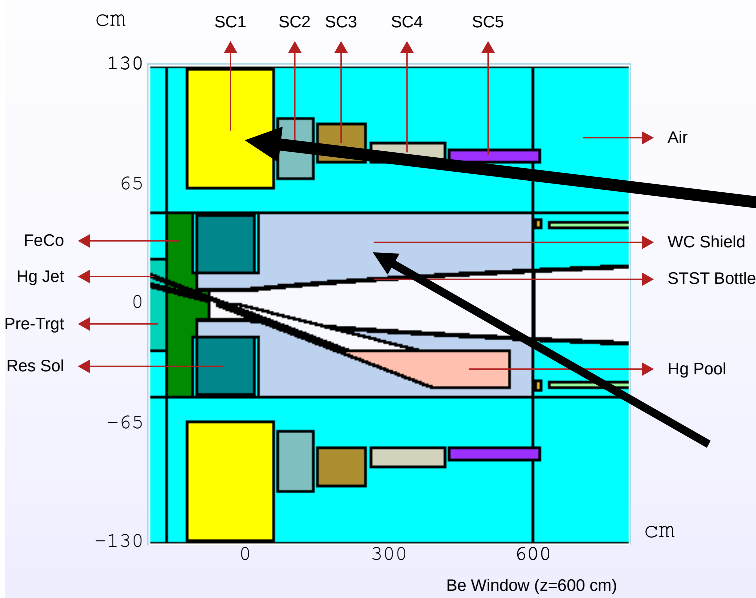
Courtesy: H. Kirk

Cryostat Upstream End



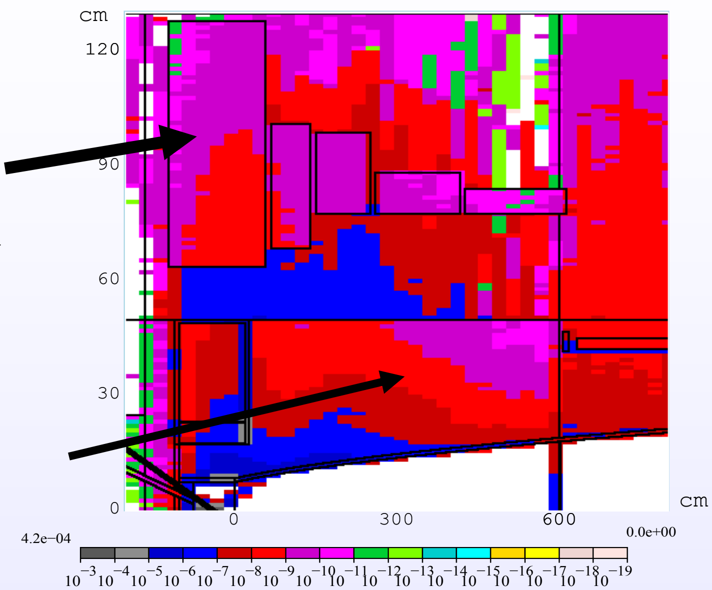
Courtesy: H. Kirk

Front End Challenges Target Shielding



25KW of Energy deposition In SC1

~2.5MW in Shielding



Mitigation Strategies:

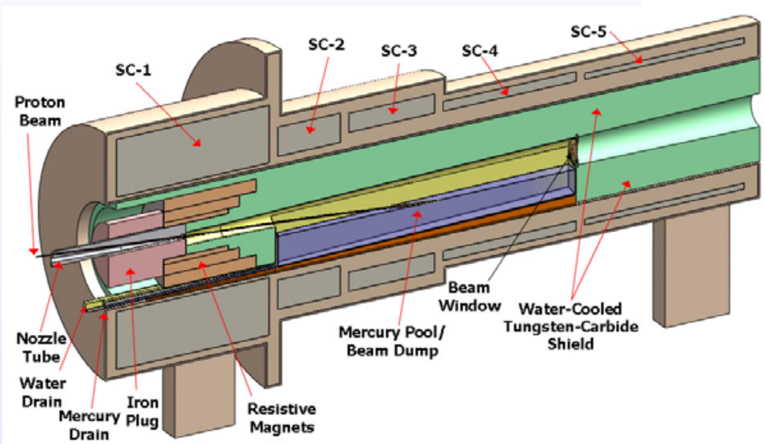
Informal proposal from Gupta before MAP Review

- **Increase SC IDs**
- **Replace Cu Resistive insert with HTS insert**
- **Design and engineer thermal management solution**

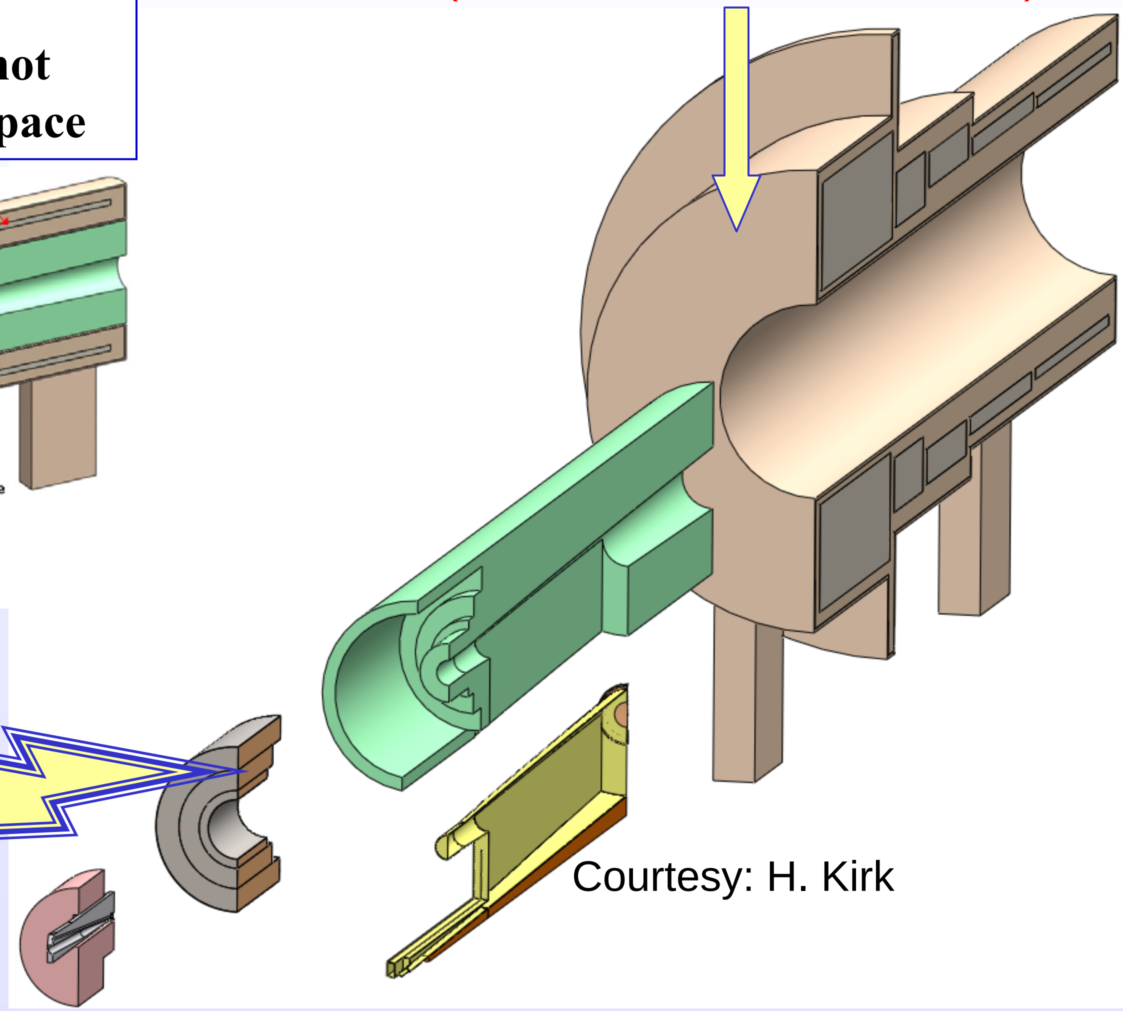
Courtesy: H. Kirk

Upstream Target Exploded View

- **All insertion/extraction from upstream end**
- **Locating & supporting features not shown – will require additional space**



Superconducting Outsert
(conventional NbTi and Nb3Sn)



Courtesy: H. Kirk

Resistive insert
(proposed to be replaced
by HTS insert)

Motivation for Replacing Resistive Copper Insert by HTS Insert

- Copper insert coils permit low current densities (of the order of A/mm^2) and therefore requires large volume. This also means large size of 20T solenoid, including superconducting outer coils. Larger size solenoid becomes expensive and complex due to large stored energy, forces, etc.
- Superconducting insert, allows one to two order of magnitude higher current densities (depending on the details) and therefore makes overall solenoid much smaller with significantly lower stored energy, forces. This means that the overall solenoid may become simpler and cheaper to built.
- Compact insert also allows more space for shielding, etc.
- Only HTS (NOT NbTi or Nb3Sn) allows superconducting option because such high fields (20 T) in such large aperture are only practical with HTS.
- Use of HTS also significantly reduces the operating cost. It was ~9M$ for resistive insert (per Weggel) and is negligible for HTS.

- See Bob Weggle next presentation for details; concept here...

HTS Insert Options

Smaller volume of 6T HTS insert (as compared to resistive 6T insert) can be primarily used

1. To reduce the overall size of the solenoid
2. To increase the space for shielding, etc.

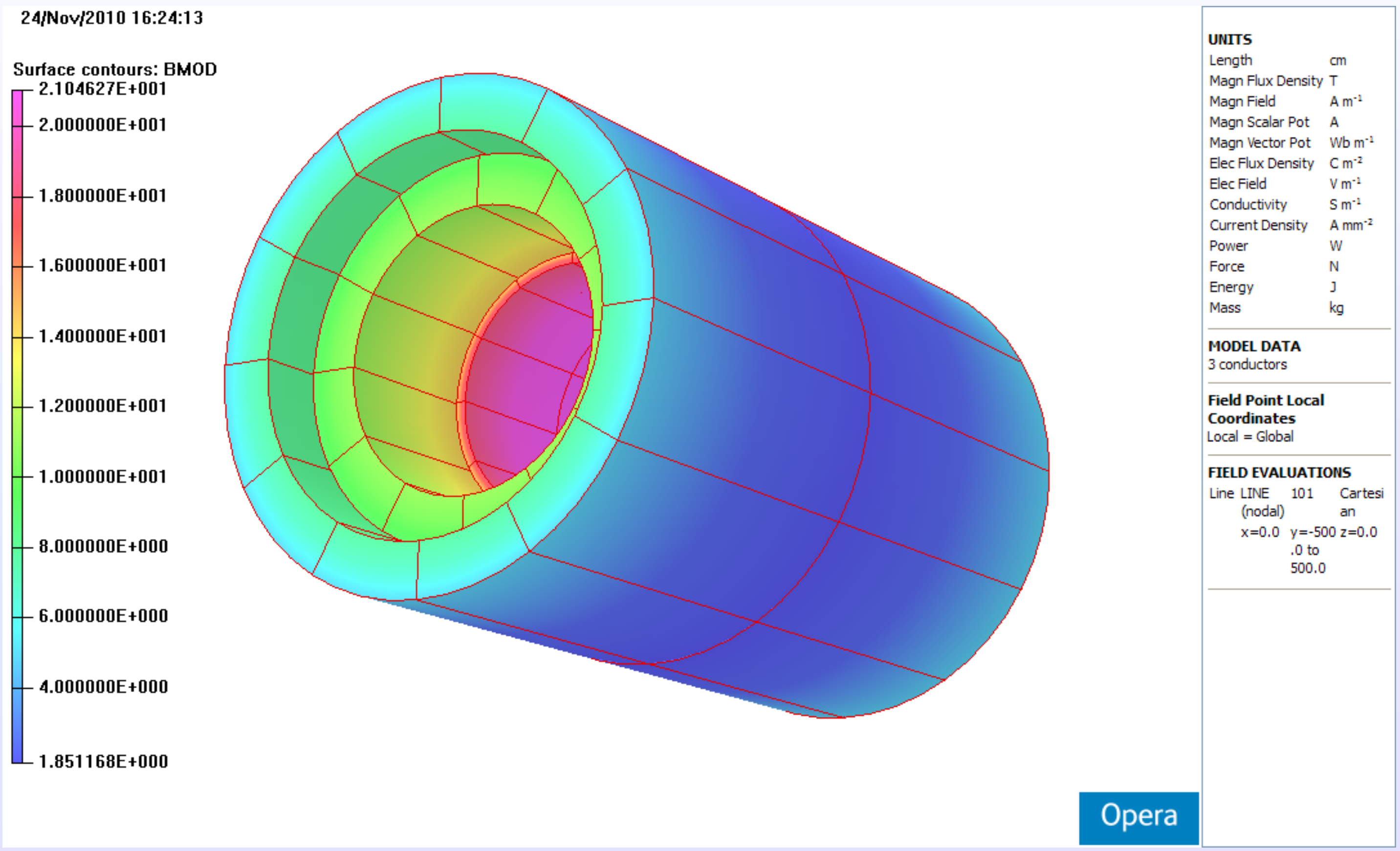
Option 1: Reduce Size

i.r. of HTS coil: 60 cm (slightly more than copper coils)

Je : 125 A/mm^2 (~1/3 of 20 T PBL/BNL HTS solenoid)

i.r of Nb3Sn and NbTi coils get reduced

Je(Nb3Sn): 19 A/mm^2, Je(NbTi): 34 A/mm^2

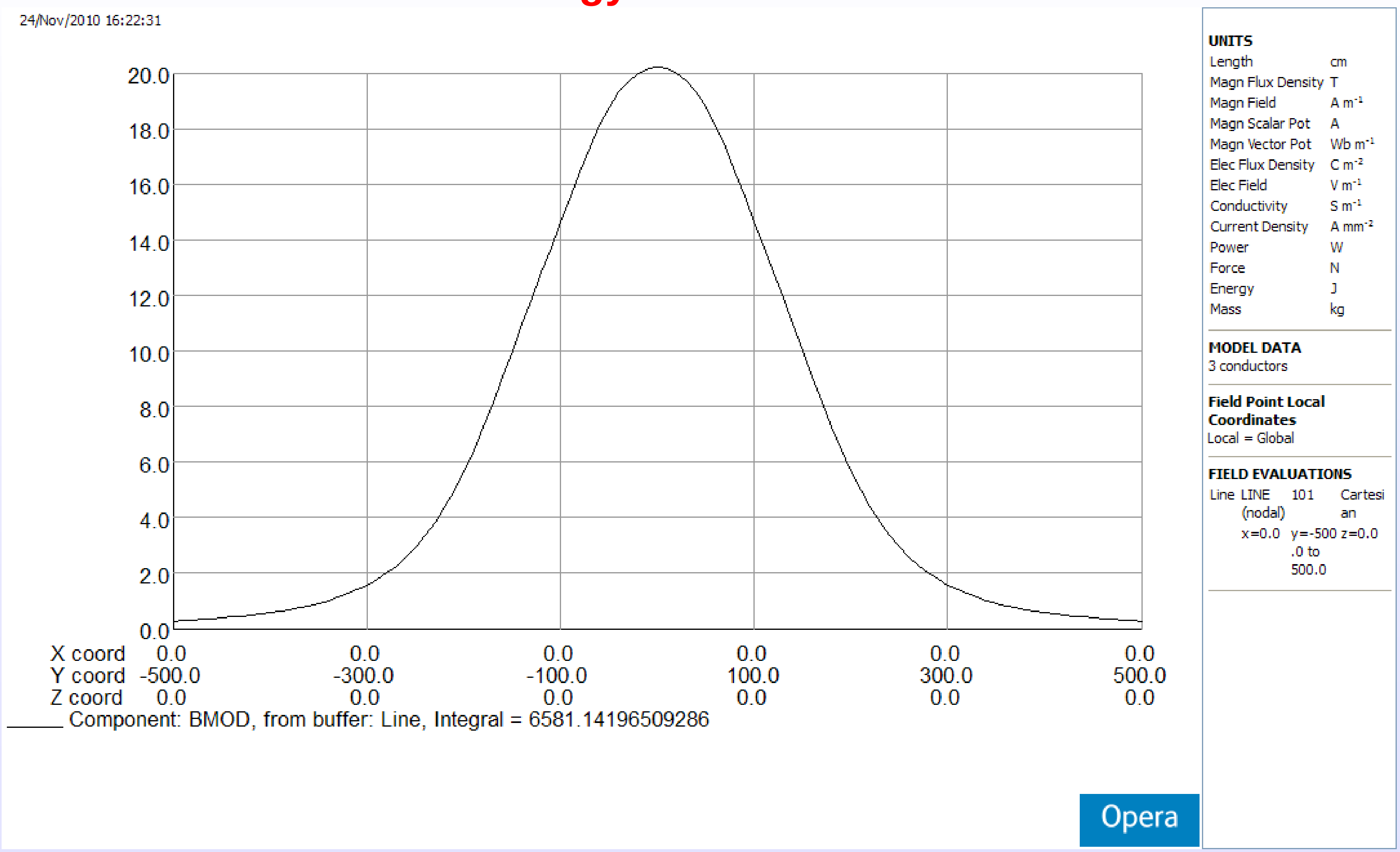


This option primarily Reduces the size of the solenoid (inner radius of HTS coil is only slightly than that of resistive coil)

Outer radius ~1.2 meter

Option 1: Reduce Size

Stored energy: 0.9 GJ

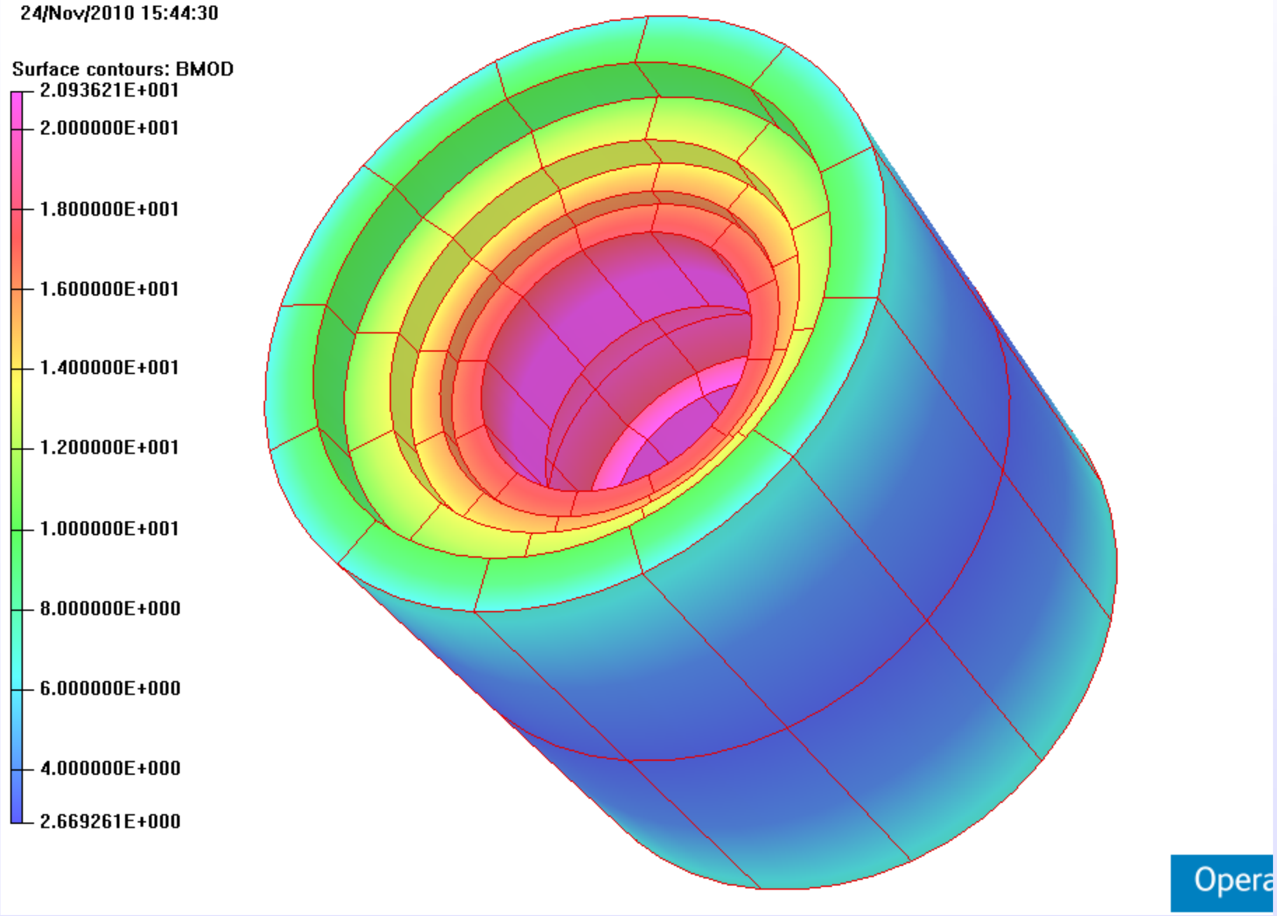


Option 2: Increase Shielding

Nb3Sn and NbTi remains primarily same; HTS coil inner radius increased.

HTS Je is also reduced

As in PBL/BNL SBIR – Bob Weggel (next presentation)

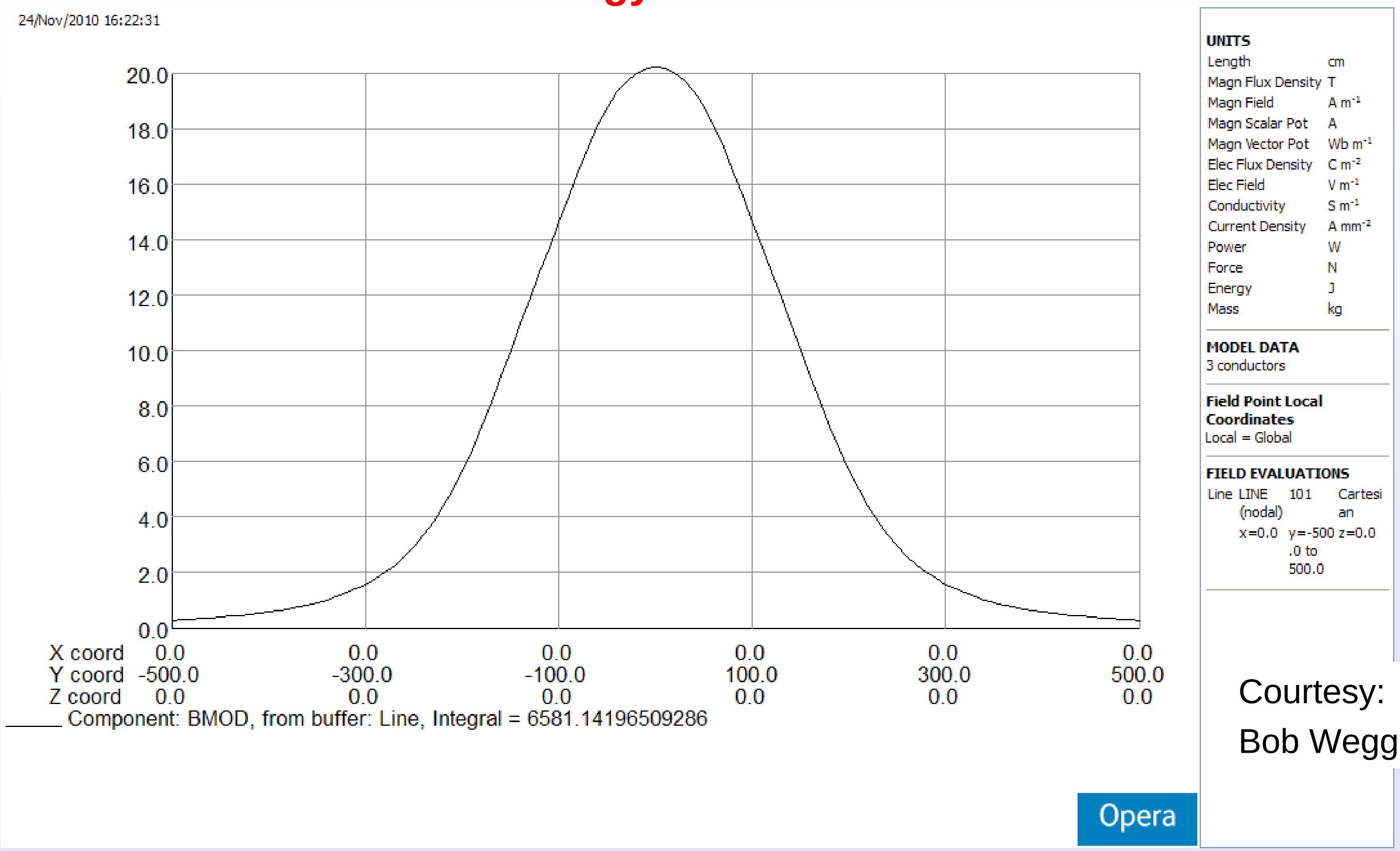


This option primarily gives more space for shielding.

Outer radius
~1.8 meter

Option 2: Increase Shielding

Stored energy: ~3.1 GJ



Courtesy:
Bob Weggel

Technical Challenges for HTS Insert

Insert solenoid target region resides in very high radiation and energy deposition environment.

Can superconducting solenoid tolerate

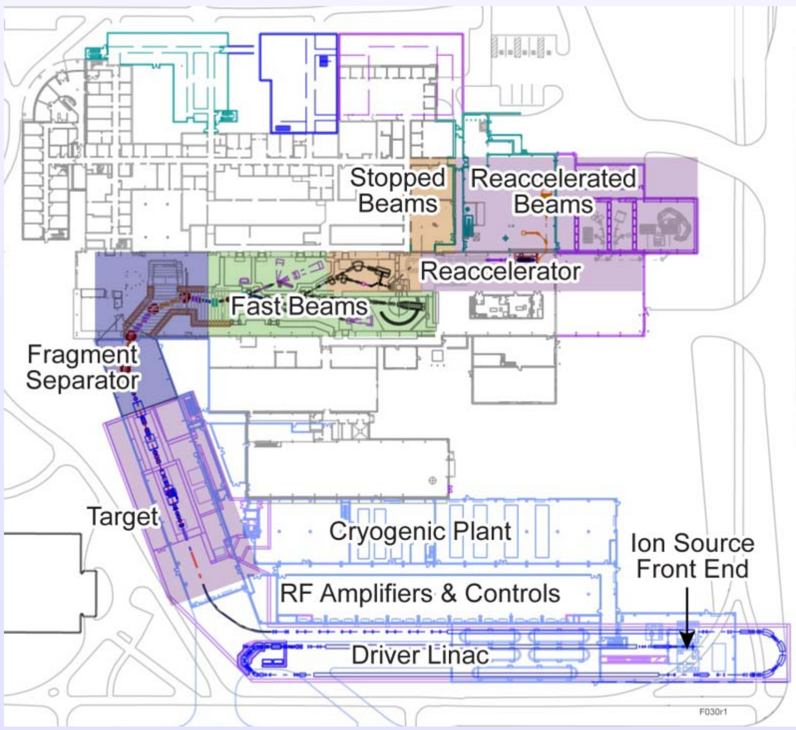
- High radiation (conductor and other components of the magnet)
- Large energy deposition
  - Related FRIB R&D (brief discussion)

Can large aperture high field HTS insert be built

- There is a demonstrated solution with resistive copper insert (present design) at NHMFL. Why not use that
- Motivation are enormous (previous slides) but so are the challenges
  - Related high field solenoid R&D (brief discussion)

FRIB Facility Concept

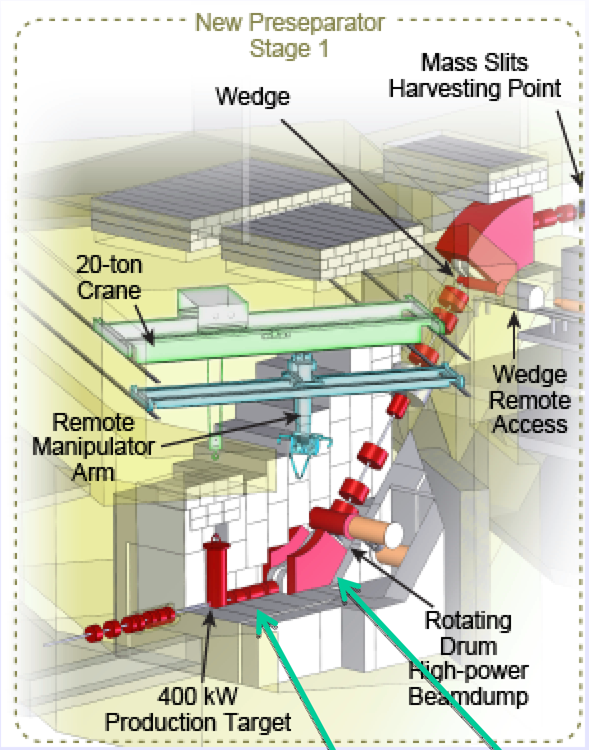
- Facility for Rare Isotope Beams (FRIB) will be located at MSU (Michigan State Univeristy)
- FRIB will create rare isotopes for research in intensities not available anywhere today
- Uses existing components of National Superconducting Cyclotron Lab (NSCL)- Fast start of FRIB
- Driver linac with energy 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

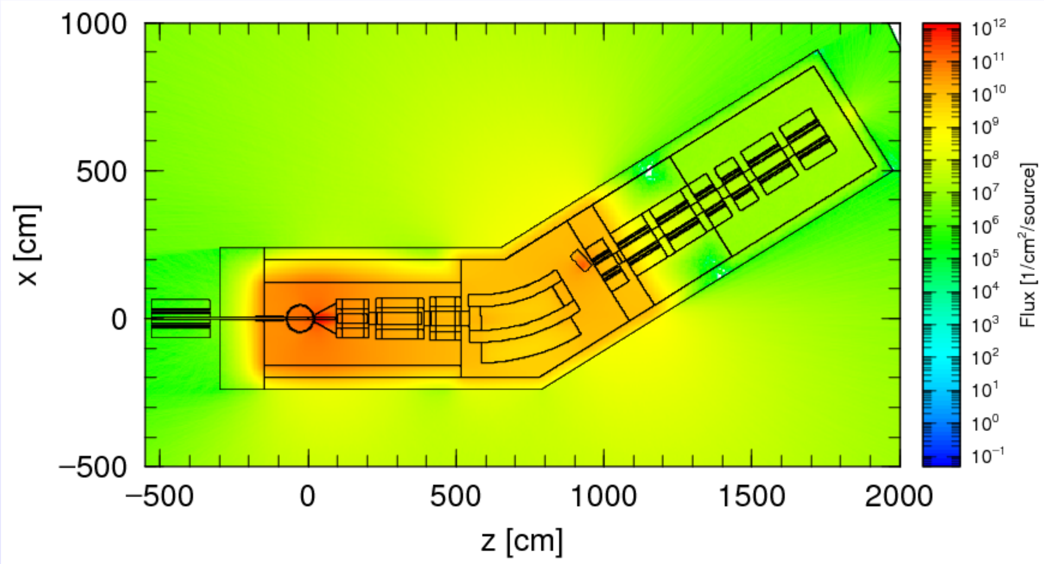
Radiation and Heat Loads in Fragment Separator Magnets

400 kW beam hits the production target. Quadrupoles in Fragment Separator are exposed to large amount of radiation (~20 MGy/year) and large amount of heat loads (~10 kW/m, 15 kW in first quad itself).



Radiation resistant
Pre-separator quads and dipole

Requirement: Quad must survive > 10 years



Neutron fluence on first quad:

2.5 x10^{15} n/cm^2 per year

Courtesy: Zeller, MSU

Radiation Damage Facility @BNL: BLIP

Figure 2. The BLIP facility.

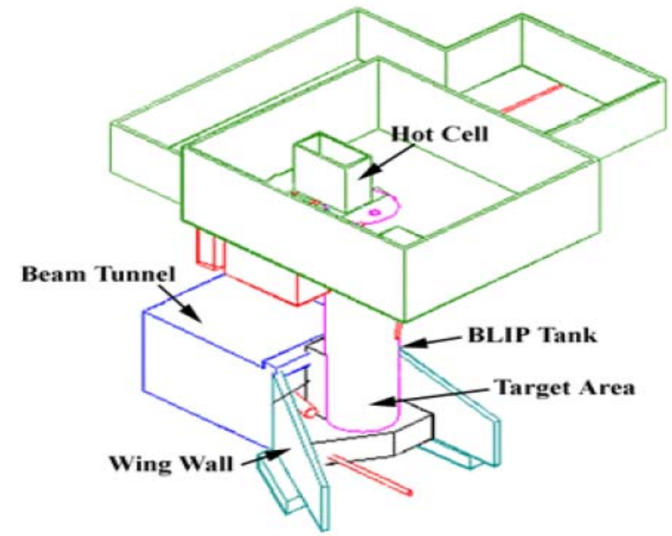


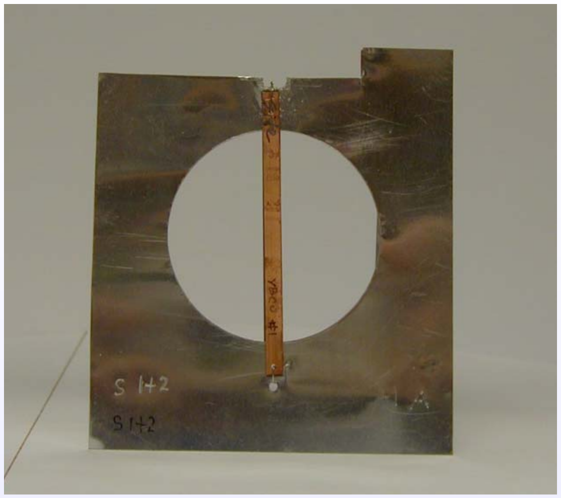
Figure 3. BLIP Beam Tunnel and Target Schematic

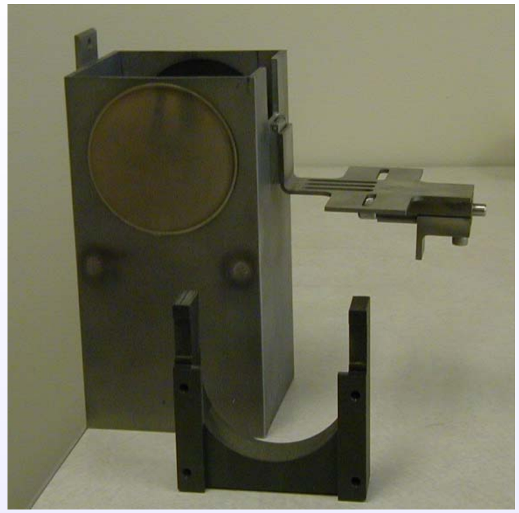
From a BNL Report (11/14/01)

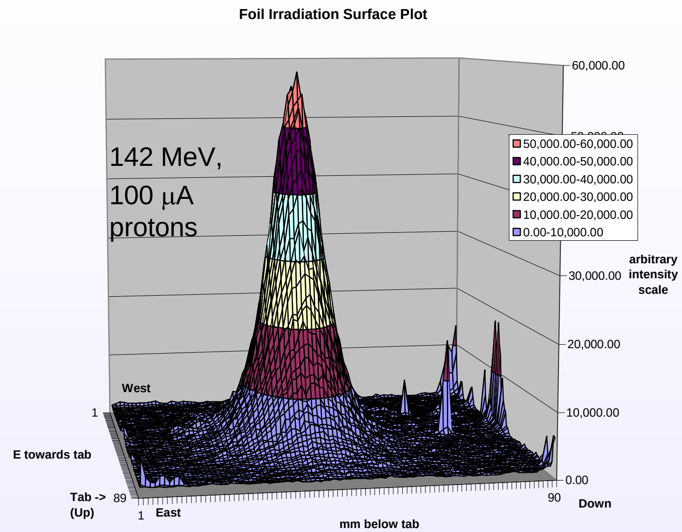
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 µA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

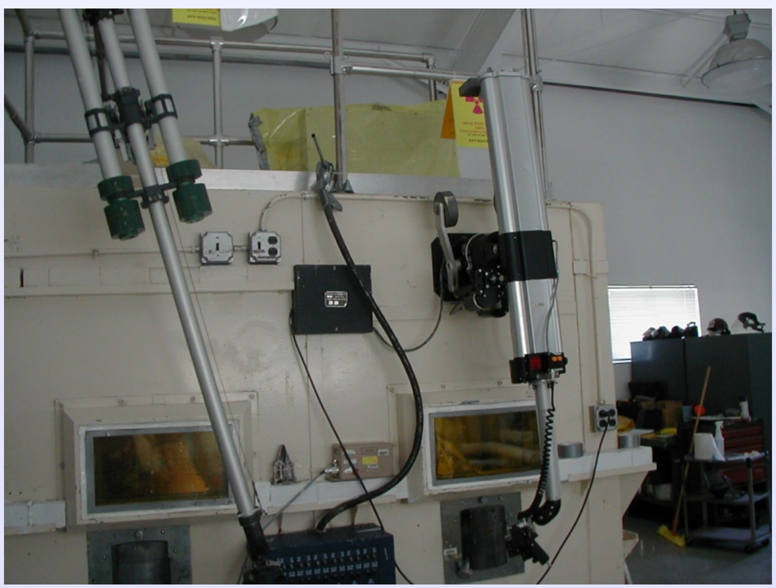
Radiation damage experiments for FRIB were carried out by George Greene, BNL.

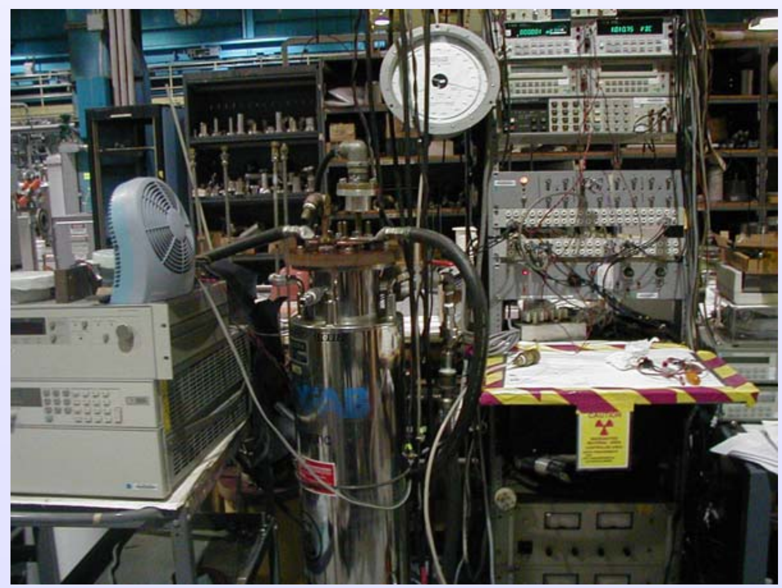
Key Steps in Radiation Damage Experiment











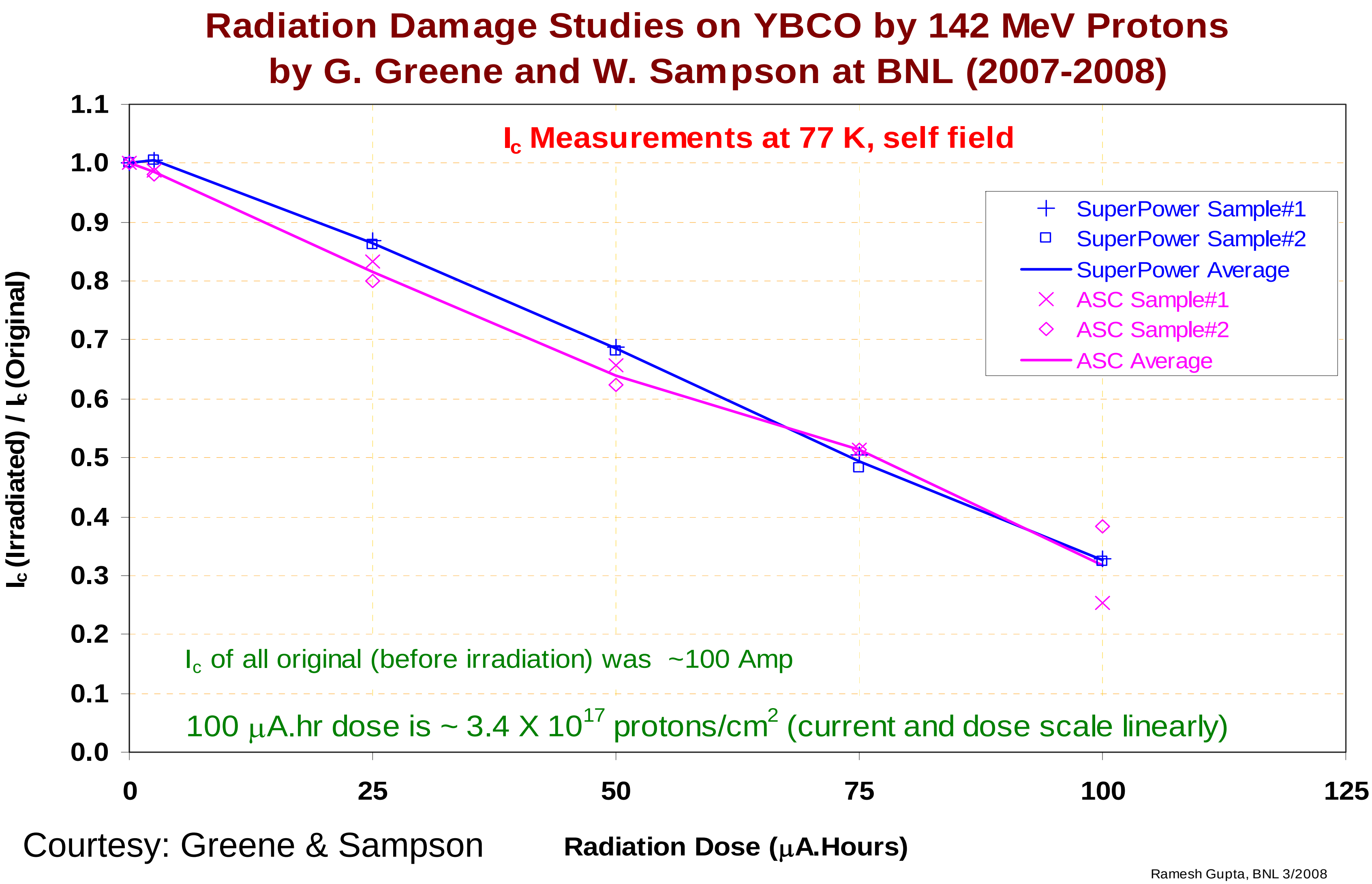
HTS Samples Examined

- Samples of YBCO (from SuperPower and ASC), Bi2223 (from ASC and Sumitomo) and Bi 2212 (from Oxford) were irradiated.

- **We will discuss the test results of YBCO (HTS used in FRIB).**
- Twenty samples were irradiated – 2 each at five doses (10^{16}, 10^{17}, 2 x 10^{17}, 3 x 10^{17} and 4 x 10^{17} protons/cm^2) from both vendors.

- 10^{17} protons/cm^2 (25 μA-hrs integrated dose) is equivalent to over 15 years of FRIB operation (the goal is 10 years).

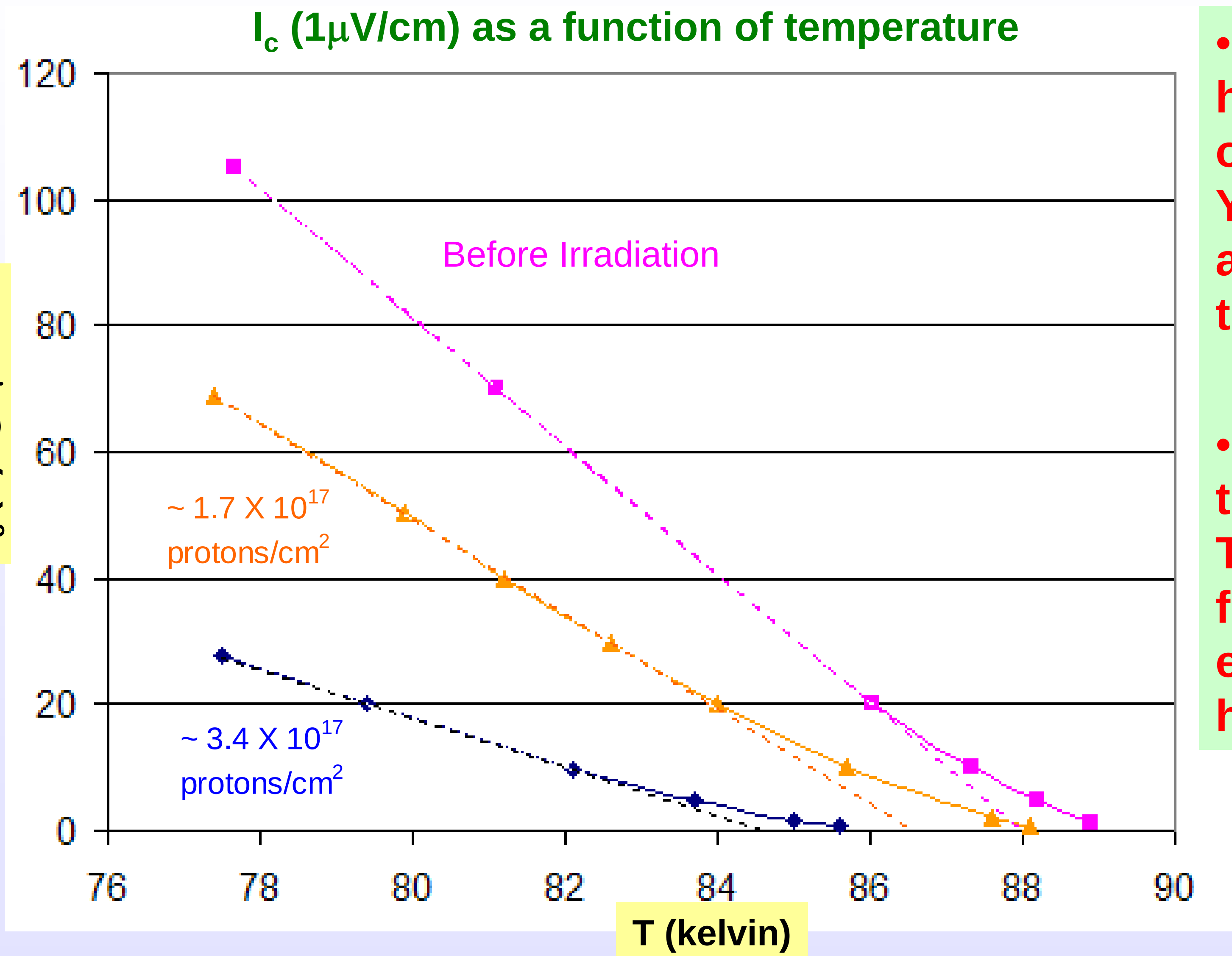
Relative Change in Ic due to Irradiation of SuperPower and ASC Samples



Courtesy: Greene & Sampson

SuperPower and ASC samples show very similar radiation damage at 77 K, self field

Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation

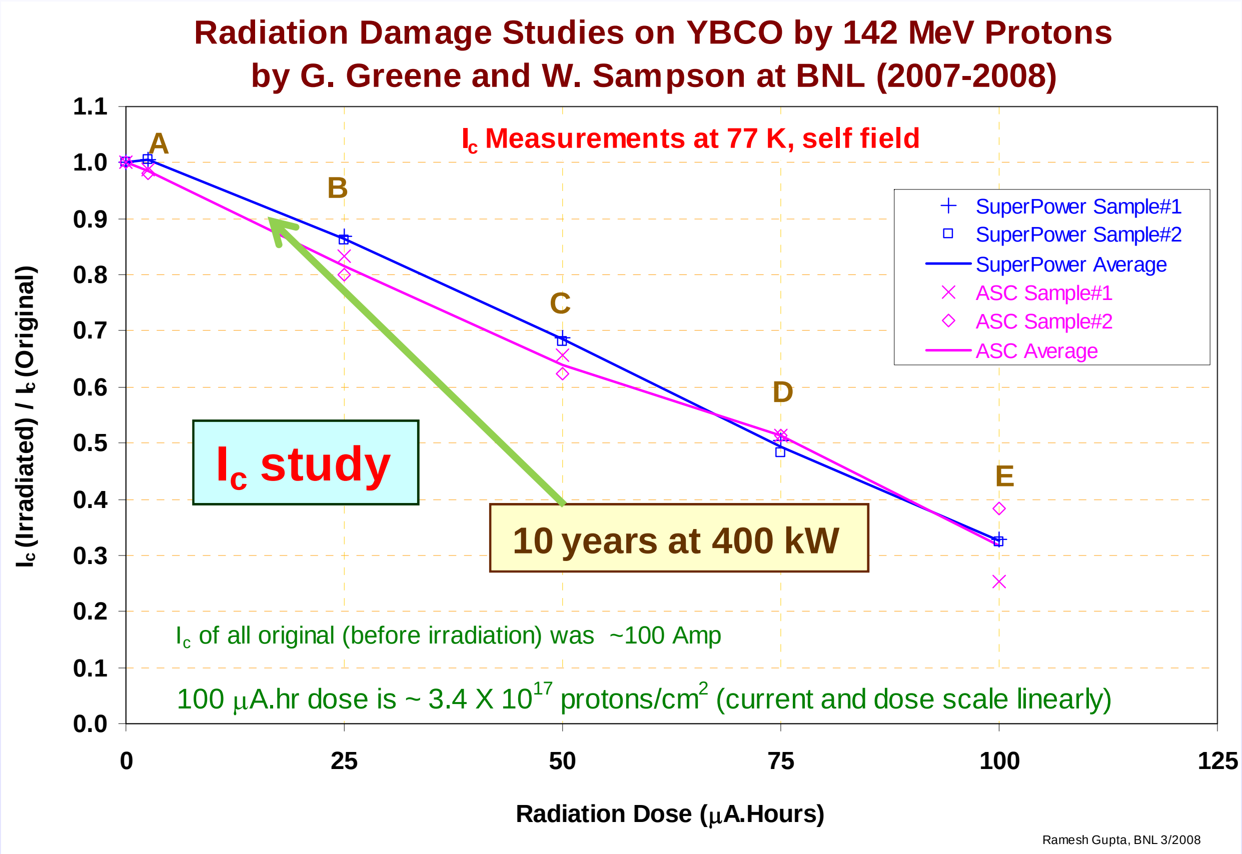


- **Radiation has an impact on the T_c of YBCO, in addition to that on the I_c.**
- **However, the change in Tc is only a few degrees, even at very high doses.**

Courtesy:
G. Greene and W. Sampson

Impact of Irradiation on Magnet

- The maximum radiation dose was 3.4 X 10^{17} protons/sec (100 μA.hr) with an energy of 142 MeV. Displacement per atom (dpa) per proton is ~9.6 X 10^{-20}. (Al Zeller)
- **This gives ~0.033 dpa at 100 μA.hr for the maximum dose.**

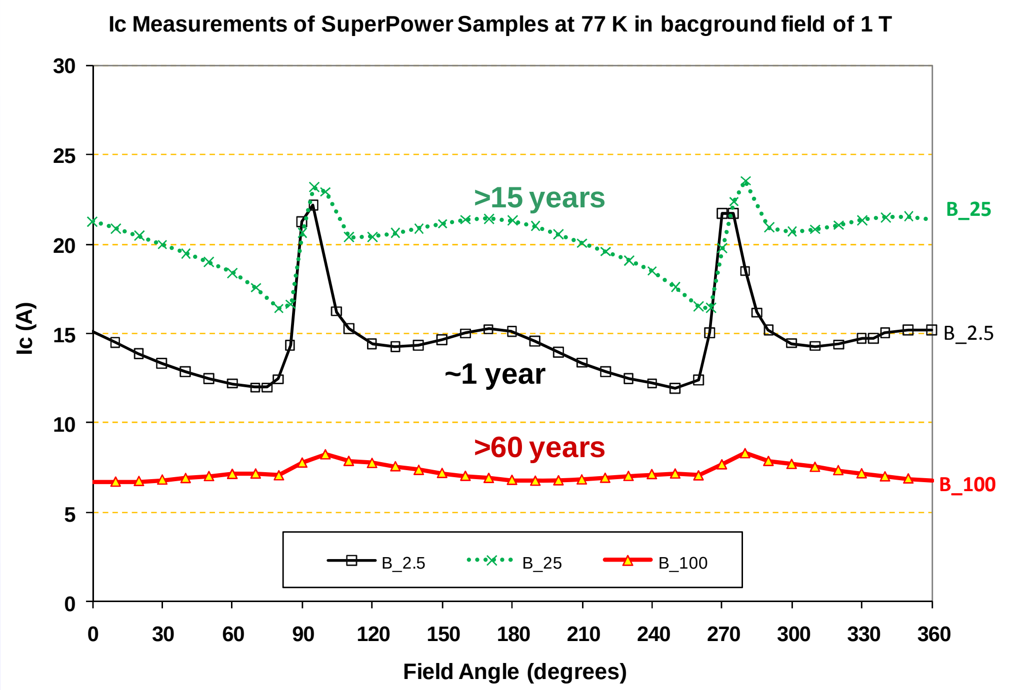


Based on 77 K self field studies:

Reduction in I_c performance of YBCO (from both vendors) is <10% after 10 years of FRIB operation (as per Al Zeller, MSU).

Study of Radiation Damage at 77K in Applied Field

Impact of Radiation in 2G Samples from SuperPower @77K in 1T Applied Field as a Function of Field Angle

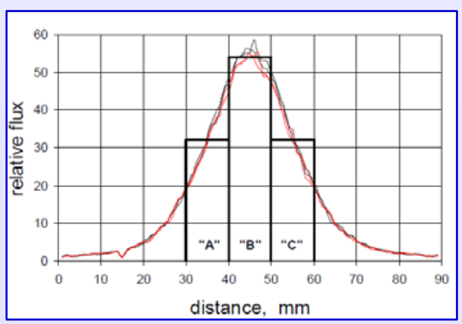


No. of years are estimated based on calculations at MSU

B_25 denotes 25 μA-hrs integrated dose at location B (center position).

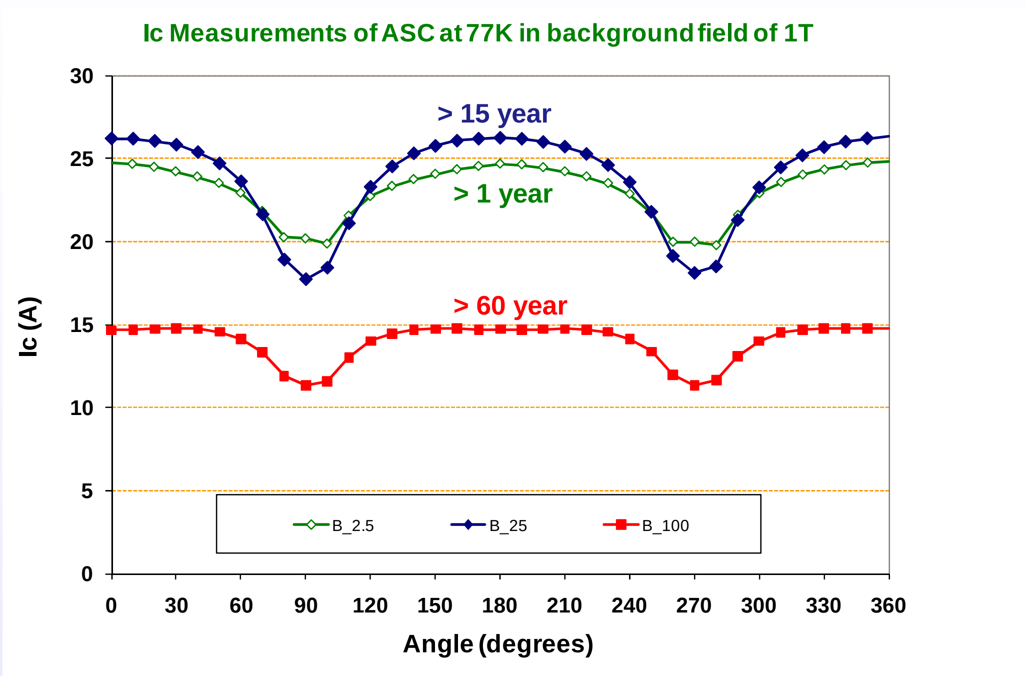
B_2.5 denotes 2.5 μA-hrs and

B_100 denotes 100 μA-hrs.



- Note: A remarkable increase in I_c caused by irradiation from 142 MeV protons.
- 25 indicates 25 μA-hrs integrated dose (10^{17} protons/cm^2) which is equivalent to >15 years of FRIB operation.
- The desired goal was to allow less than 10% damage in 10 years of operation.
- These measurements imply that this HTS from SuperPower tape is acceptable.
- In fact, rather than causing any damage in performance, the radiation seems to improve it based on the measurements at 77K, in 1 T applied field at all field angles.
- Anisotropy is significantly reduced at very high doses.

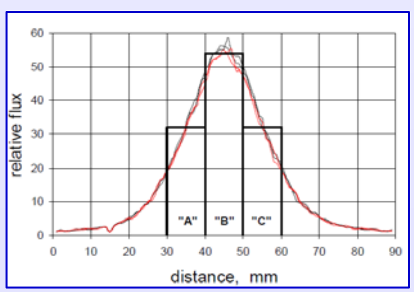
Impact of Radiation Damage in 2G Samples from ASC @77K in 1T Applied Field as a Function of Field Angle



No. of years are estimated based on calculations at MSU

B_25 denotes 25 μA-hrs integrated dose at location B (center position).

B_2.5 denotes 2.5 μA-hrs and B_100 denotes 100 μA-hrs.



- Note: A remarkable change in I_c caused by irradiation from 142 MeV protons.
- 25 indicates 25 μA-hrs integrated dose (10^{17} protons/cm^2) which is equivalent to >15 years of FRIB operation.
- The desired goal was to allow less than 10% damage in 10 years of operation.
- These measurements imply that this HTS from ASC is acceptable for FRIB.
- Initially there is an increase in the maximum value of Ic and decrease in the minimum based on the measurements at 77K, in 1 T applied field at all field angles.
- Anisotropy is increased initially but then reduced at very high doses.

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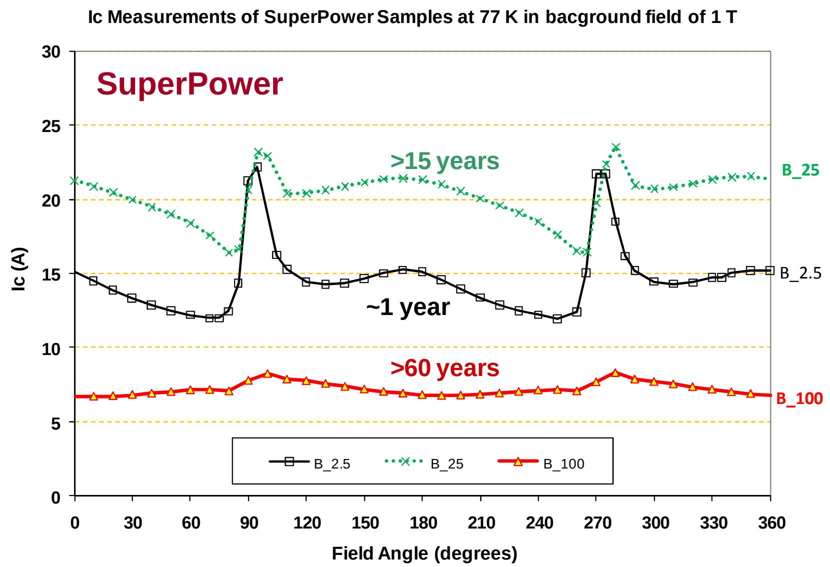
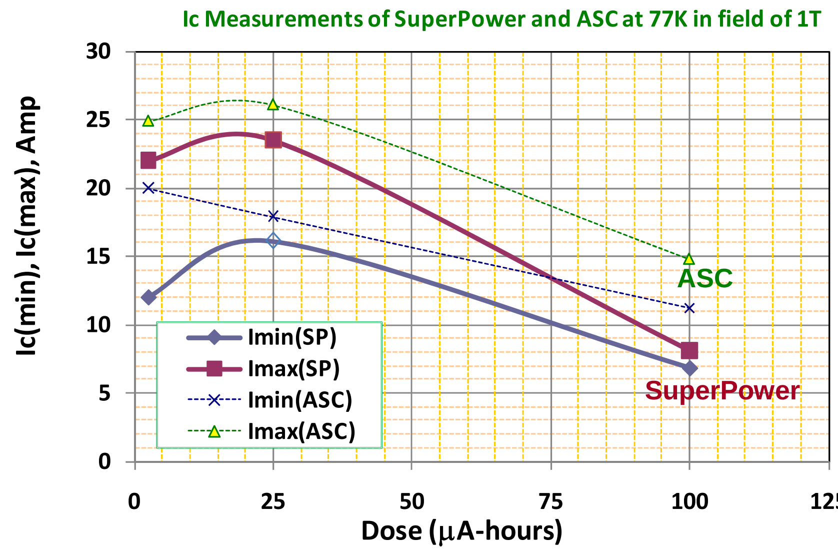
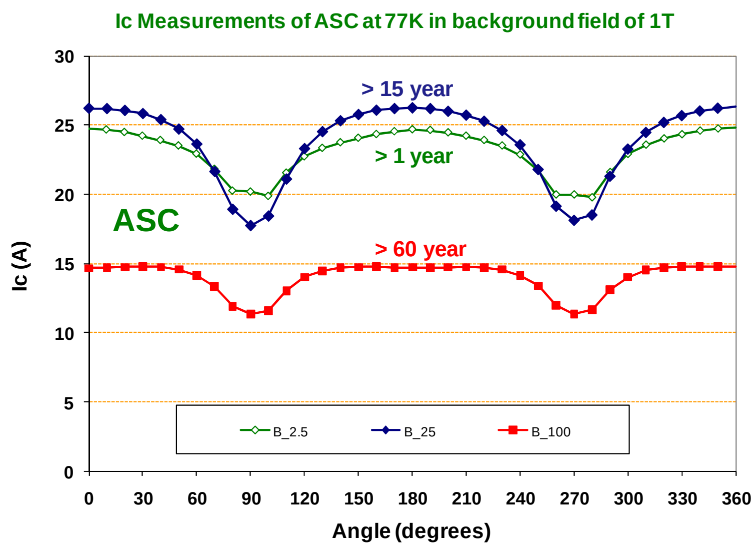
Superconducting Magnet Division

Comparison of 2G from SuperPower and ASC @77K in 1 T Applied Field from 142 MeV Proton irradiation





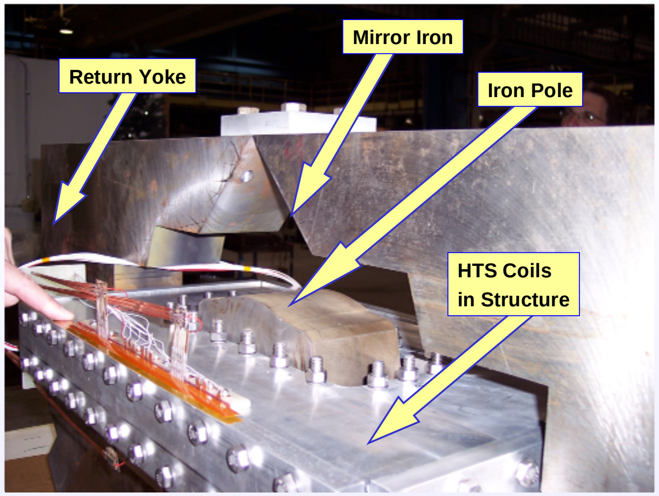
Minimum and maximum values of I_c are obtained from the graphs on the right



- Initially there is an increase in the maximum value of I_C in both samples (see maximum value of each curve).
- In case of SuperPower, both minimum and maximum value increases.
- In ASC, anisotropy initially increases.
- However, after a very large irradiation, samples from both SuperPower and ASC become more isotropic and there is less damage in ASC samples than in SuperPower samples.

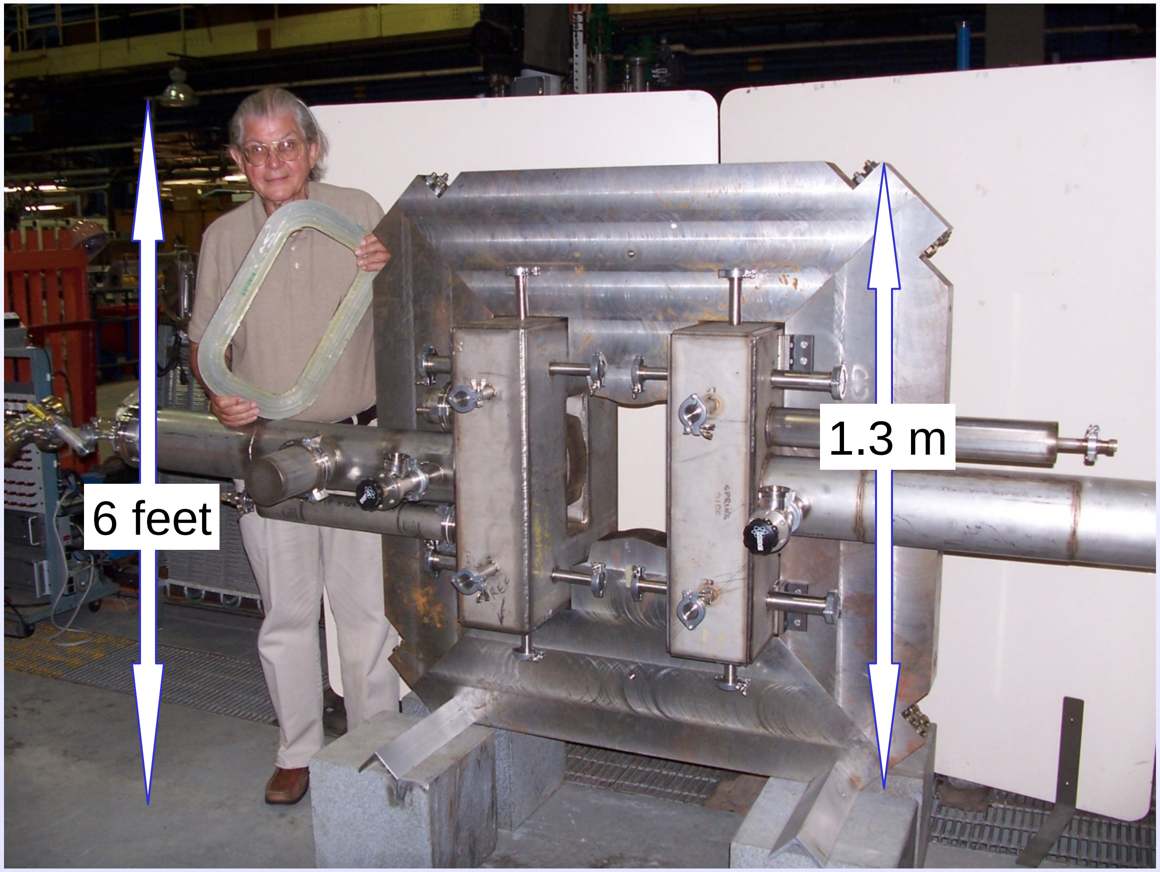
Study of Energy Deposition Studies in FRIB Magnet

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



Mirror cold iron

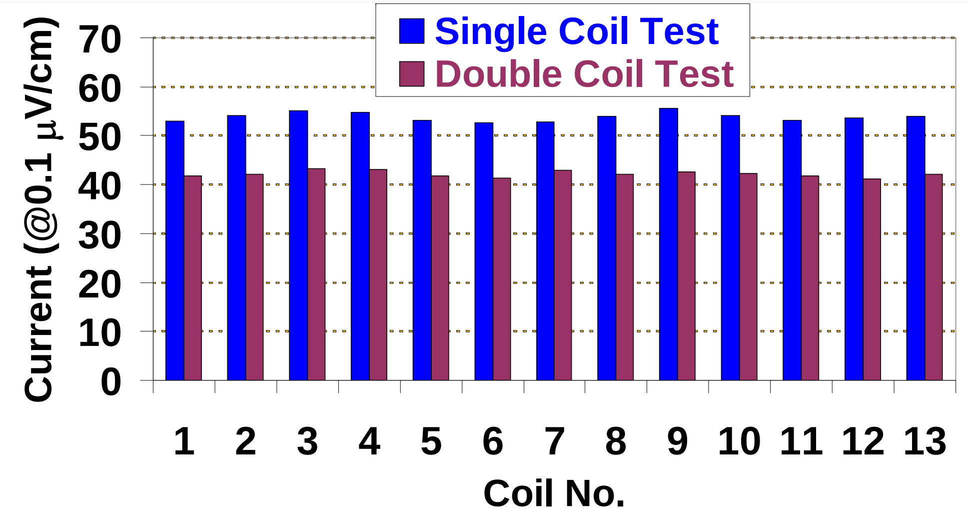
Mirror warm iron



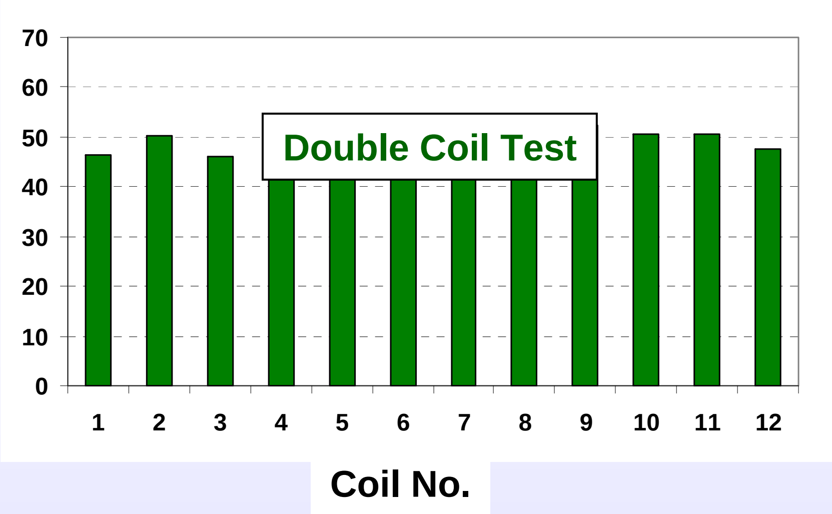
LN_2 (77 K) Test of Coils Made with ASC 1st Generation HTS

Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1



12 coils with HTS tape in year #2

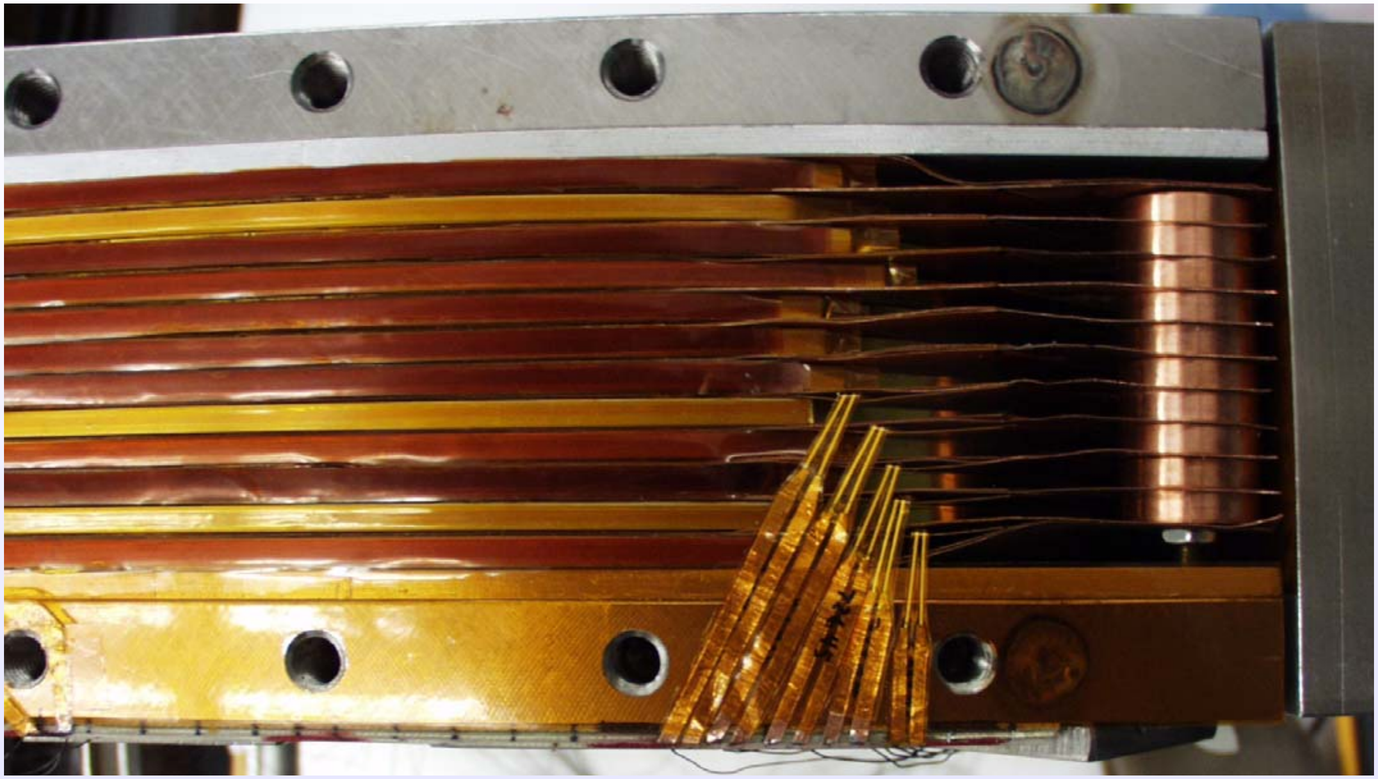


Note: A uniformity in performance of a large number of HTS coils.

It shows that the HTS coil technology has matured !

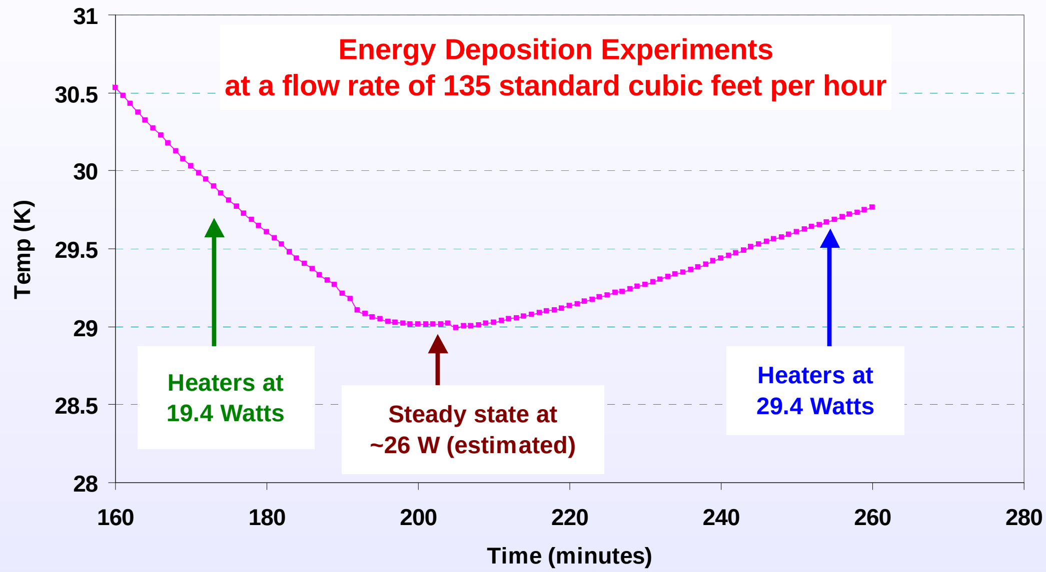
Energy Deposition Studies in FRIB HTS Quad

Stainless steel tape heaters between coils for energy deposition experiments



Energy Deposition Experiment During Cool-down at a Constant Helium Flow-rate

All heaters between HTS coils were turned on while the magnet was cooling down with a helium flow rate of 135 standard cubic feet (SCF)

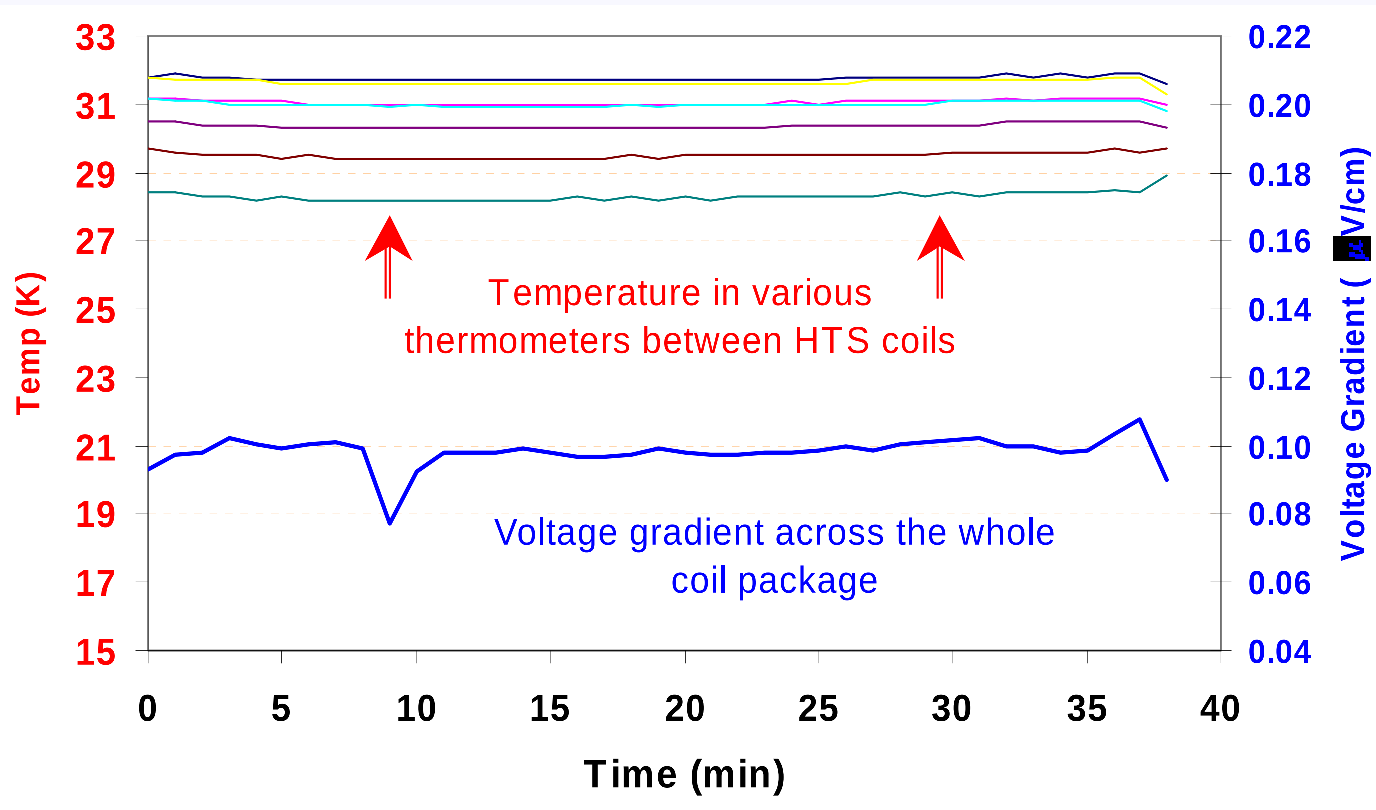


- **Temperature continued to decrease when total power in all heaters was kept at 19.4 W**
- **Temperature started to increase slowly when heater was increased to 29.4 W**
- **Computed heat load for steady state : ~26 Watts**
    - **i.e., expect a constant temperature of 29 K with 26 W at 135 SCF flow rate.**

Note: HTS coil remained superconducting during these tests when operated somewhat below the critical surface.

Simulated Energy Deposition Experiment at the Operating Condition (Environment)

Goal is to demonstrate that the magnet can operate in a stable fashion at the expected heat loads (5mW/cm^3 or 5kW/m^3 or 25 W on 12 short HTS coils) at the design temperature (~30 K) with some margin on current (@140 A, design current is 125 A).



Voltage spikes are related to the noise

Stable operation for ~40 minutes

- **We use 0.1 μV/cm as the definition of I_c.**
- **Temperature differences may be partly real and partly calibration mis-match.**
- **As such HTS can tolerate such temp variations with small margin.**

Summary of High Field Solenoid Program at BNL

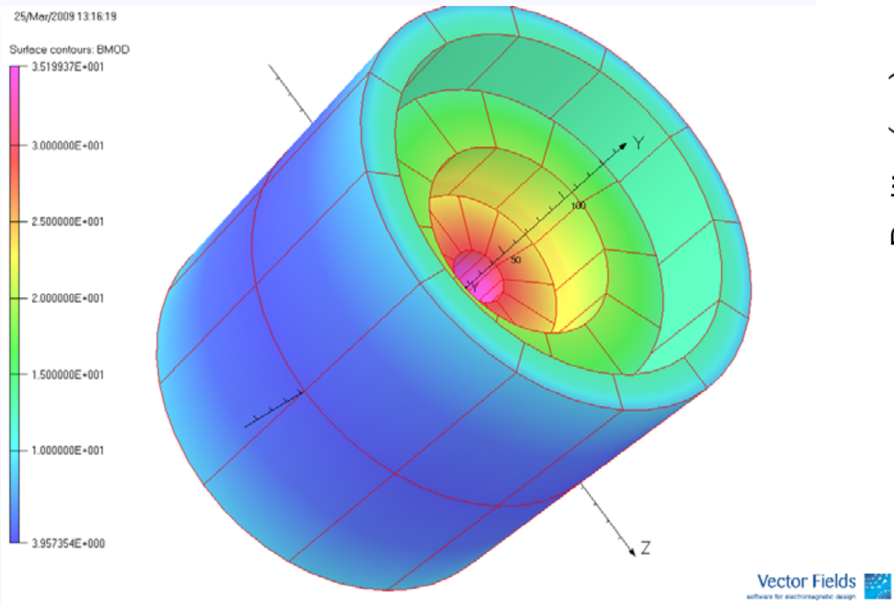
High Field HTS R&D at BNL

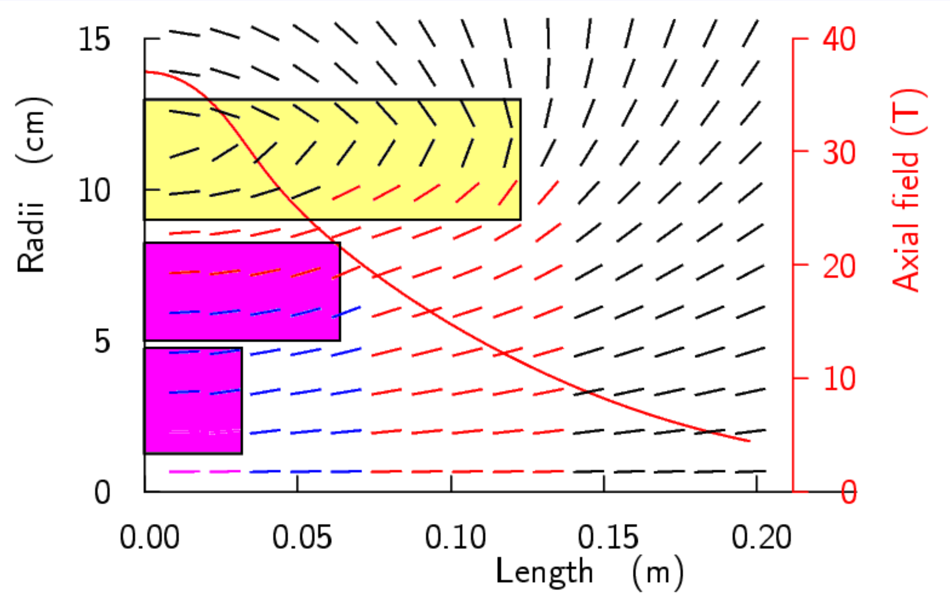
- PBL/BNL 20+T HTS solenoid (already a funded program through 2 SBIR)
  - Plus, this as insert coil test at NHMFL to test for field approaching 40 T
  - Plus, Nb3Sn high current density SBIR for ~35 T

- SMES ABB/BNL/SuperPower 25+ T all HTS large aperture solenoid

PBL/BNL High Field Solenoid

1. ~12 T HTS insert solenoid (i.d. = 25 mm, o.d. = 95 mm, L = 114 mm) – Phase II
2. ~10 T HTS solenoid (i.d. = 100 mm, o.d. = 165 mm, L = 128 mm) – Phase II
3. ~15 T Nb_3Sn outsert (i.d. = 180 mm, o.d. = 215 mm, L = 200 mm) – Phase I proposal



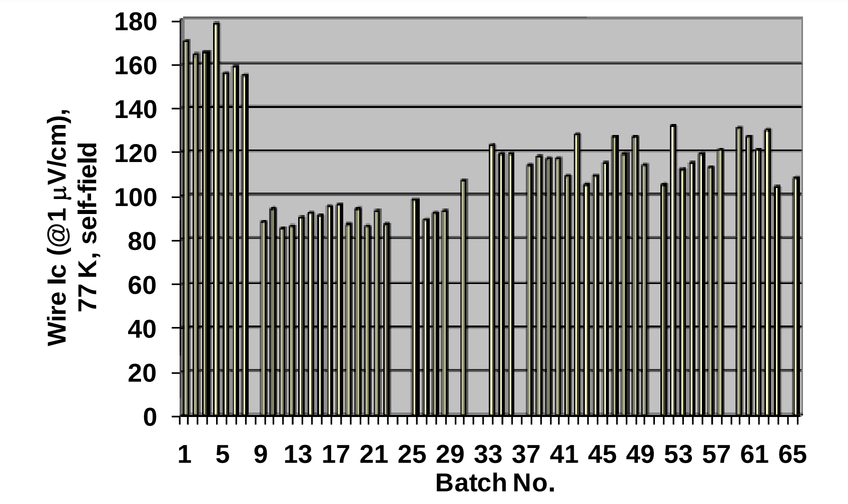


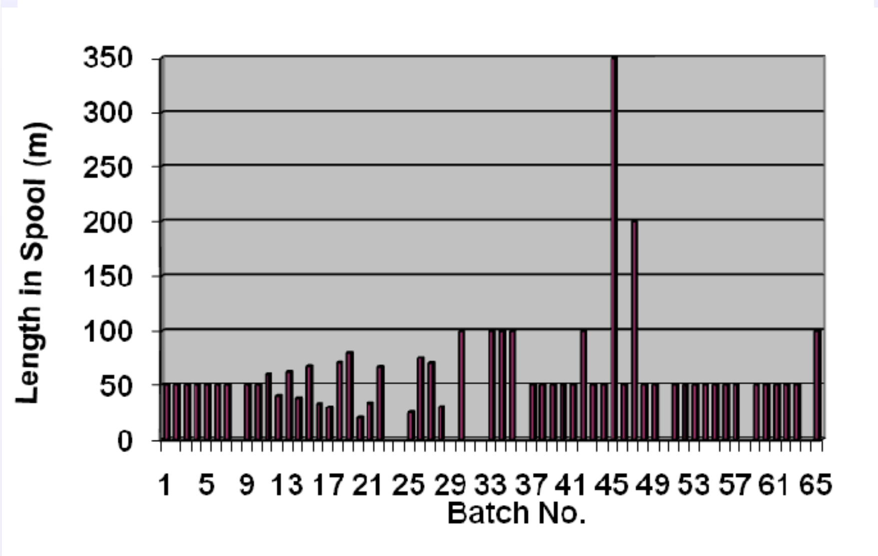
Courtesy: Bob Palmer

Field magnitude (left) and field lines (right) of the combined magnet using the Nb_3Sn coil (yellow) and the two YBCO coils (magenta)

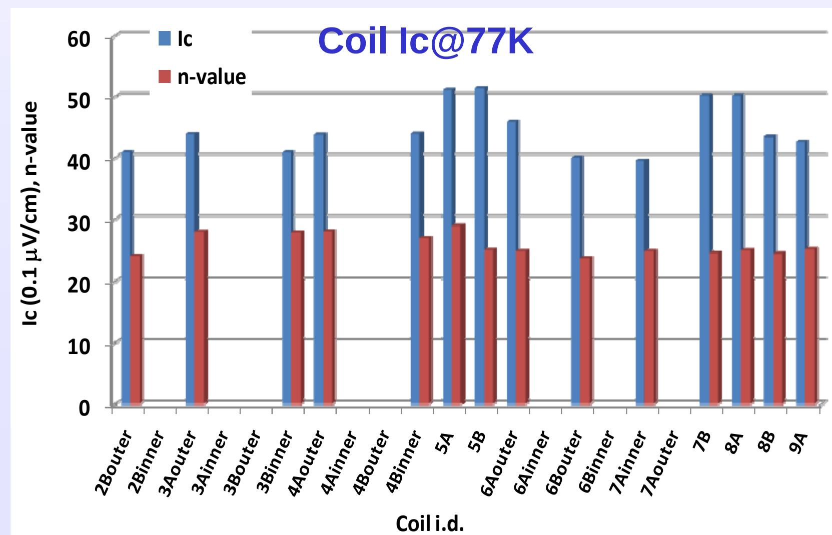
A Large Number of HTS Coils Built

Ic and length of wires delivered



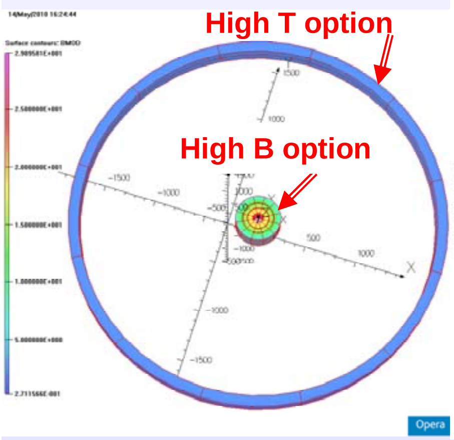


Twenty-one 100 mm i.d. coils, each using 100 meter 2G HTS built for PBL/BNL solenoid

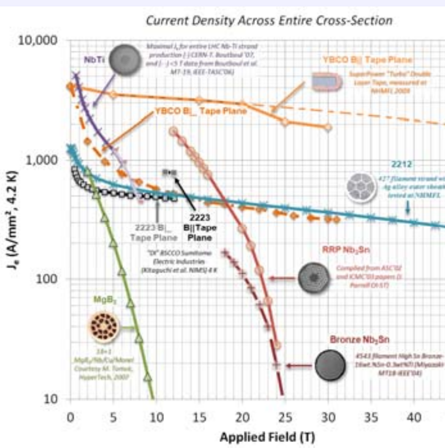


Superconducting Magnetic Energy Storage (SMES) System

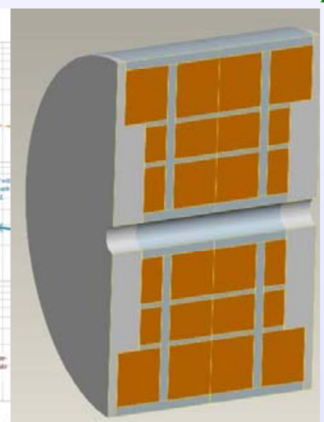
- BNL, along with its research partners, SuperPower (conductor) and ABB (power electronics), received ARPA-E funding for developing HTS SMES (5.25M$).
- HTS with high (very high) field option is used in high energy density (E α B^2) option which minimizes the cost as the conductor (not cryogenics) dominates the cost.
- There are many technical issues to be addressed as such high field (25 T or more), large aperture (100 mm or more) HTS magnets have never been built before.
- **ARPA-E specifically called for "high risk high reward" proposals:**
  - **37 proposals were selected out of ~3,700 submitted !!!**



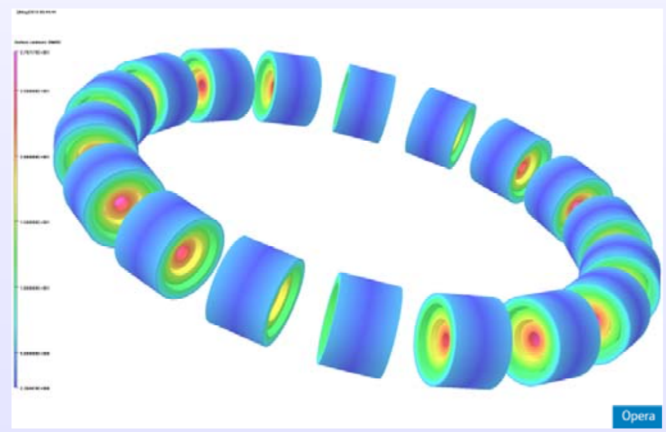
High field option reduces high conductor cost



HTS allows large current densities at high field.



Basic structure of a single SMES Unit



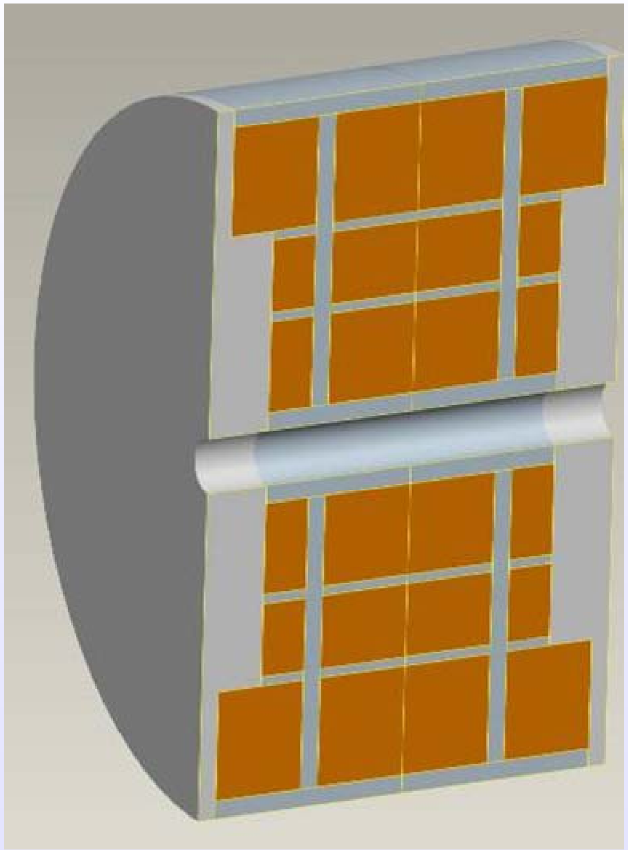
Number of units in a SMES system

Preliminary Design Parameters: ~25 T, 100 mm, 2.5 MJ, 12 mm YBCO

Brookhaven National Laboratory
Superconducting Magnet Division

Current Preliminary Design

Stated explicitly in the proposal: High Risk High Reward

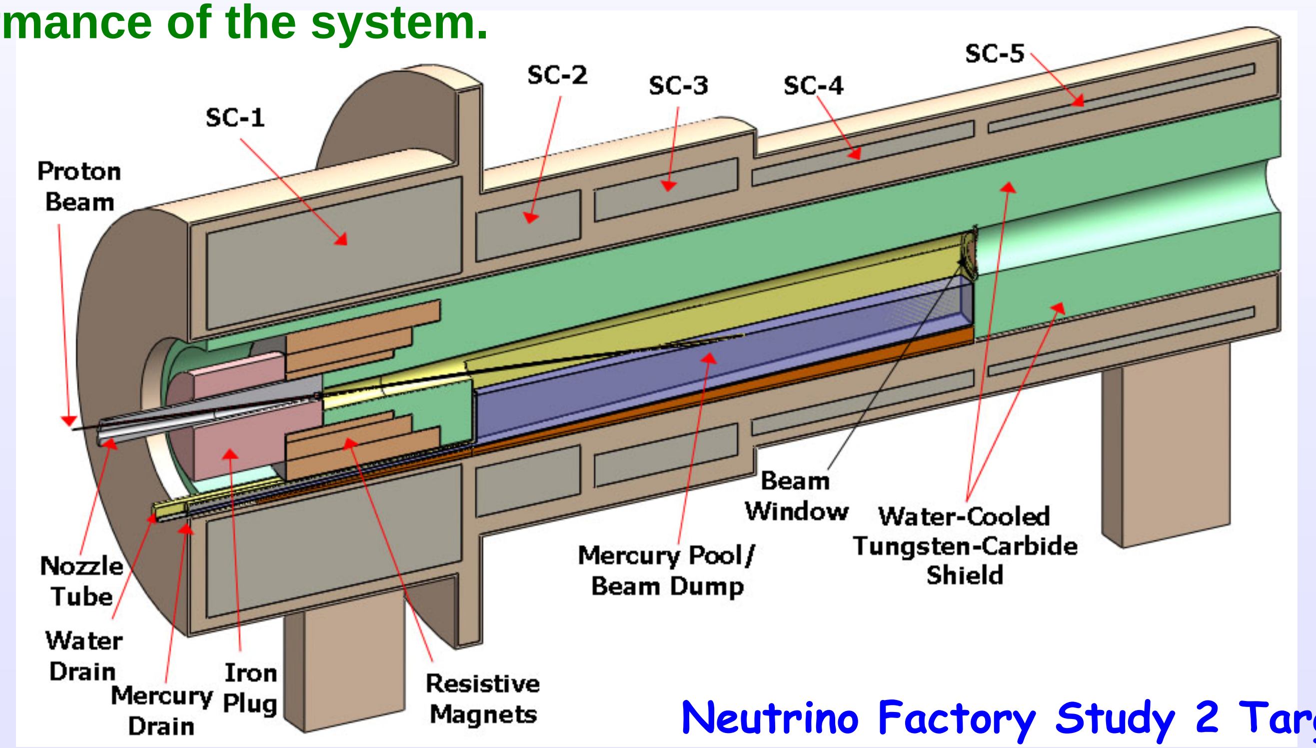


- Field: ~25 T
- Inner Diameter : ~100 mm
- Outer Diameter: ~324 mm
- Length: ~400 mm
- Conductor: YBCO 12 mm wide
- Current at Design Field: ~600 A
- Stored Energy: 2.5 MJ
- Inductance: ~13 H
- Conductor: ~9 km (plus spare)

Magnet needs intermediate support structure to manage stress build-up

Possible Benefit of Replacing Some LTS Coils by HTS Coils

- HTS can tolerate an order of magnitude more heat loads than LTS also can operate with an order of magnitude more temperature variation within the coil.
- Consider using HTS for SC-2 to SC-5 also (either partially or fully).
- That can reduce the amount of Tungsten shield and i.d./size of those solenoids.
- It may be worthwhile studying the impact of this on the overall cost, robustness and performance of the system.



Neutrino Factory Study 2 Target Concept

Summary

- Replacing 6 T Cu solenoid by 6 T HTS insert in 20 T region should bring a significant reduction in size, stored energy and operating cost and/or may provide more space for shielding.
- HTS magnet R&D for FRIB provides a useful background on the radiation damage and energy deposition on the HTS insert.
- High field HTS solenoid R&D on PBL/BNL 20+T HTS solenoid and ~25 T large aperture SMES will provide a useful background on high field magnet technology.
- Use of HTS may provide additional benefits in lower field region of target solenoid