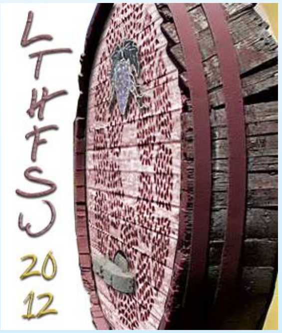
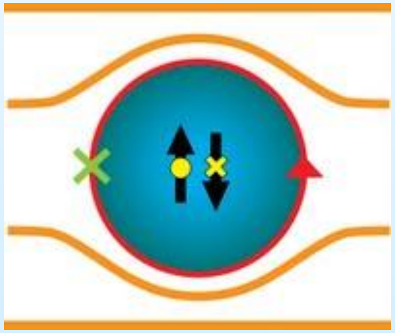
HTS Magnet R&D at BNL





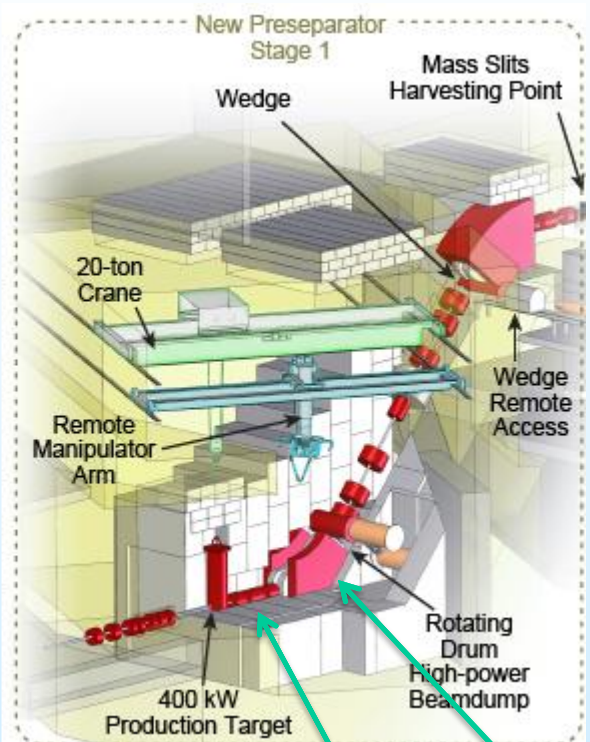
Ramesh Gupta
(on behalf of BNL staff and external collaborators)

HTS Magnet R&D at BNL

- **Accelerator dipole and quadrupole magnet programs**
  - **HTS magnet is now part of the baseline design of a major proposed facility – Facility for Rare Isotope Beams (FRIB)**
    - **This is a significant 1st – perhaps a major milestone**
  - **High field magnets in a hybrid design for LHC upgrade**
    - **New initiatives – primary topic of this presentation**
- **High field solenoid programs**
  - **Separate presentation (later in this session)**

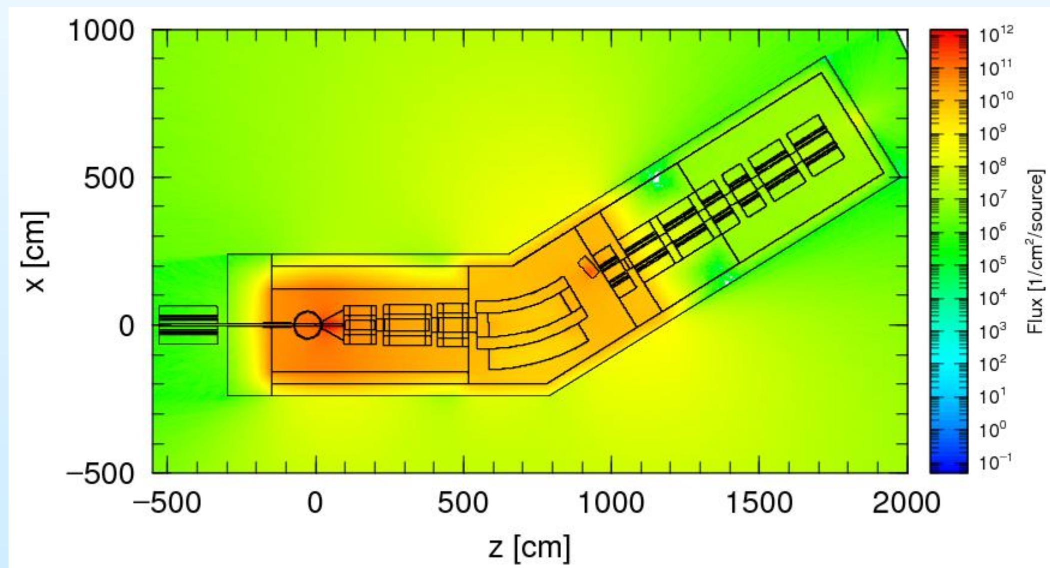
Magnet Requirements for FRIB

Large Radiation and Heat Loads in Fragment Separator Region Magnets



Exposure in the first magnet itself:

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



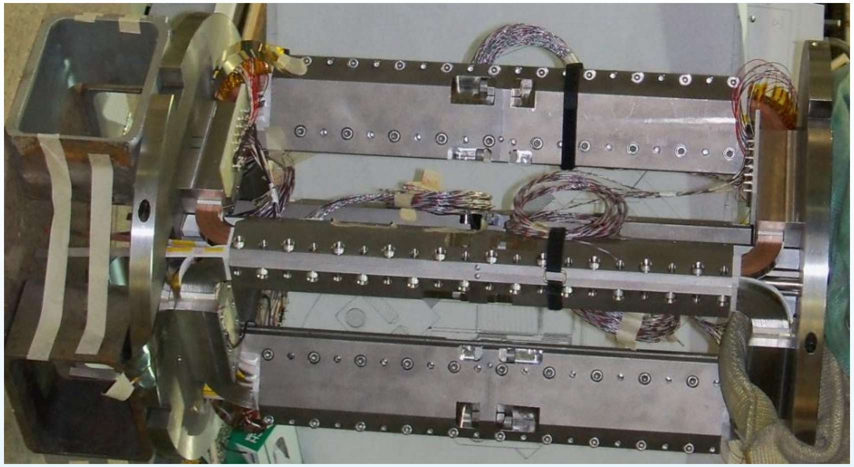
Radiation resistant
Pre-separator quads and dipole

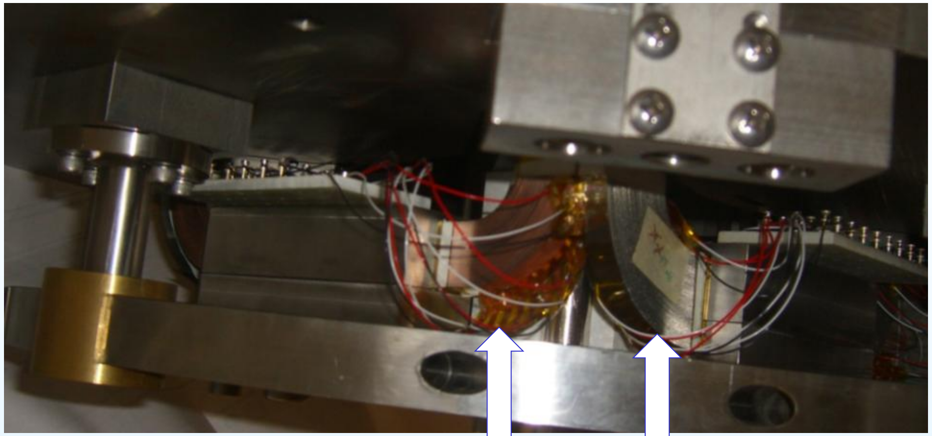
Copper or NbTi Magnets don’t satisfy the requirements

HTS Magnets For FRIB

- **HTS offers a unique solution for challenging environment of FRIB magnets with unprecedented energy and radiation loads.**
- **Because of large thermal margins HTS magnets can operate reliably and can remove large heat loads efficiently at ~40 K.**
- **Radiation damage and energy deposition experiments found that HTS magnets can satisfy the machine requirements.**
- **HTS magnets are now the baseline design for the quadrupole and dipole magnets in the fragment separator region of FRIB.**
- **This means (a) HTS technology is now being relied upon to deliver a solution in a challenging environment and (b) all issues (quench protection, reliable operational, etc.) must be solved.**
- **First generation model was built with over 5 km of 4 mm 1G tape and 2nd generation full size magnet built with 12 mm 2G tape from SuperPower & ASC (over ~9 km equivalent of 4 mm).**

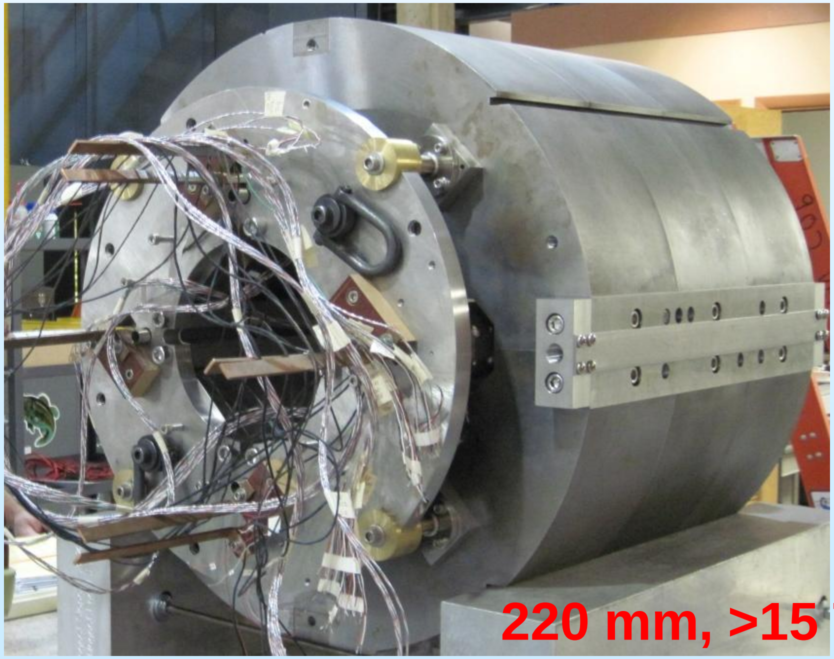
FRIB HTS Quadrupole



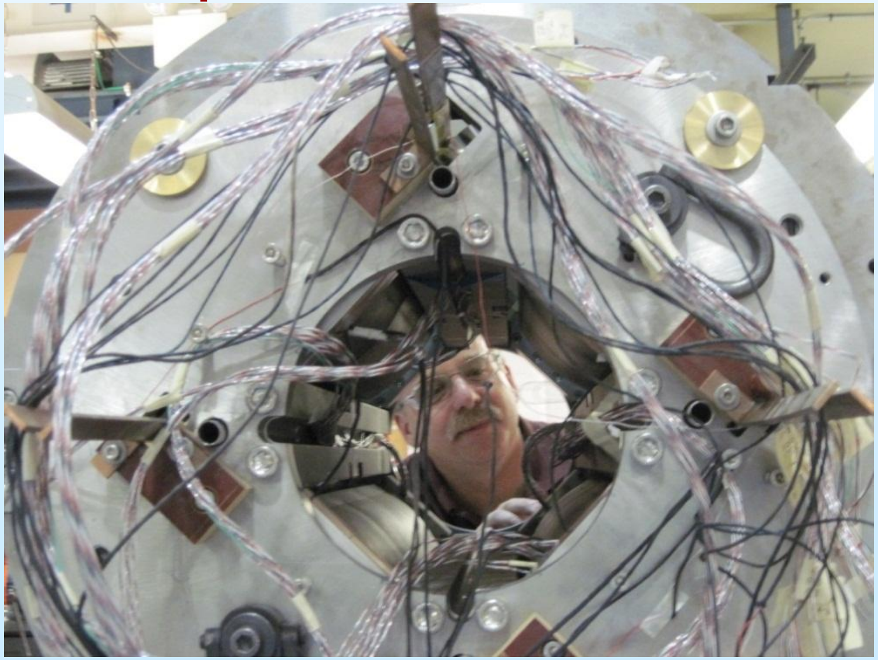


SuperPower

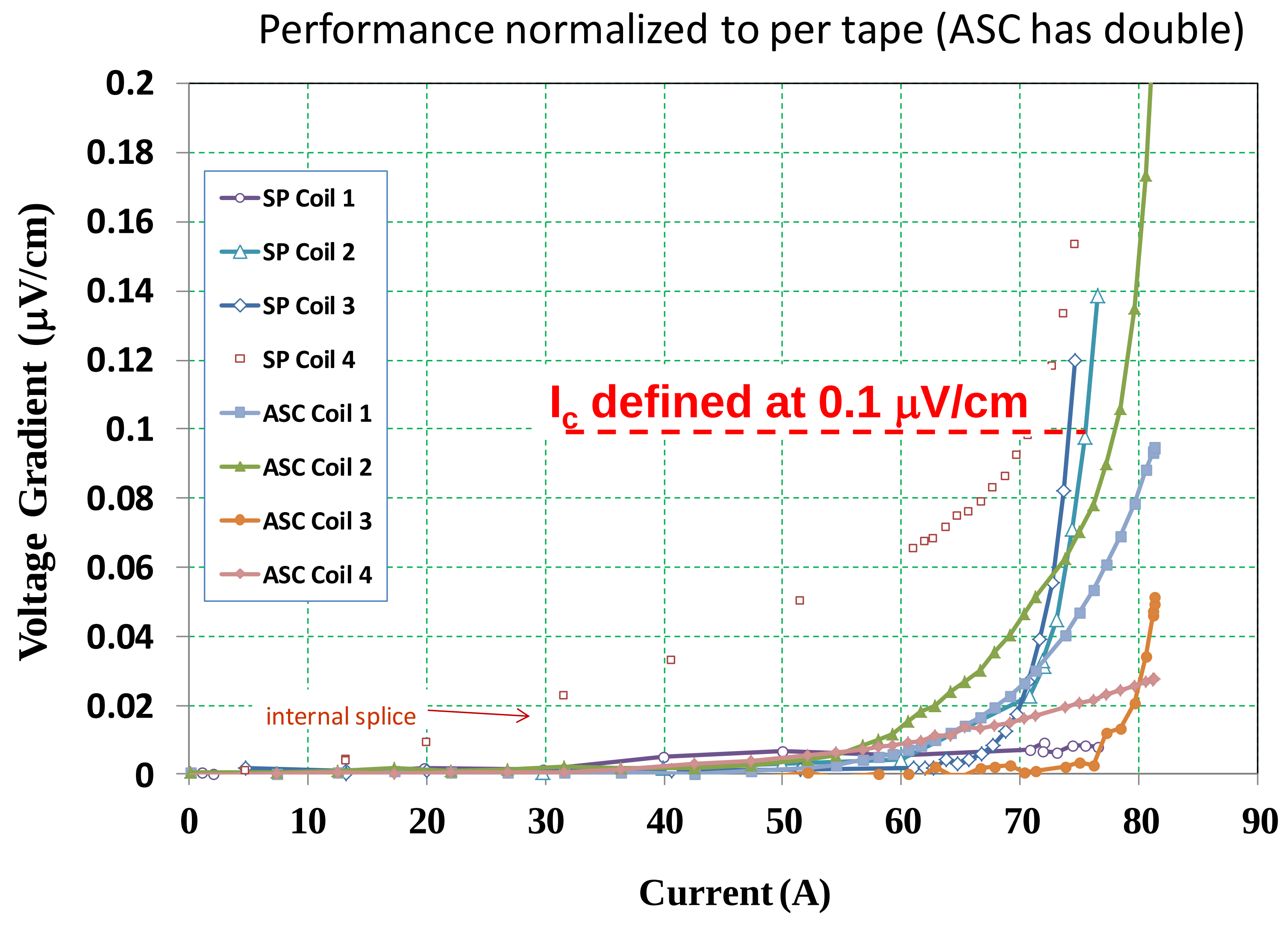
ASC



220 mm, >15 T/m



Coils in FRIB Quad Structure @77 K (made with 2G HTS from SuperPower and ASC)



~330 meter 12 mm used in each of four SuperPower coil and

~215 meter 12mm double tape used in each of four ASC coil

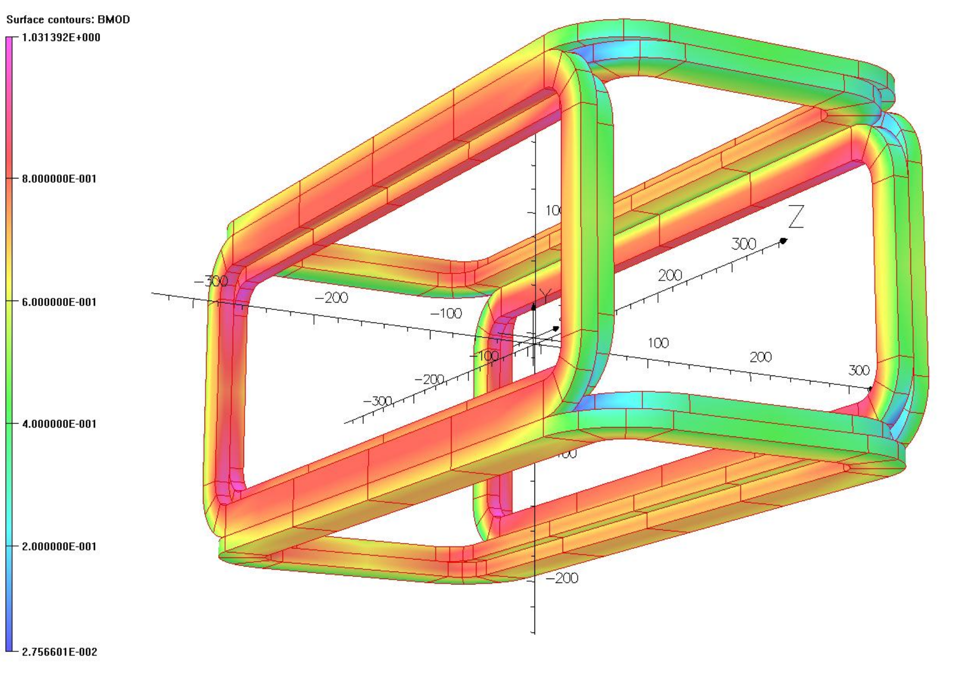
Performance at ~40 K is more relevant

77 K Test in Quadrupole Mode (all eight coils powered)

Currents used in quadrupole mode test at 77 K

SP	ASC
40	69.3
50	86.7
60	104

Field with ASC coils at 200A and SuperPower coils at 115.5 A

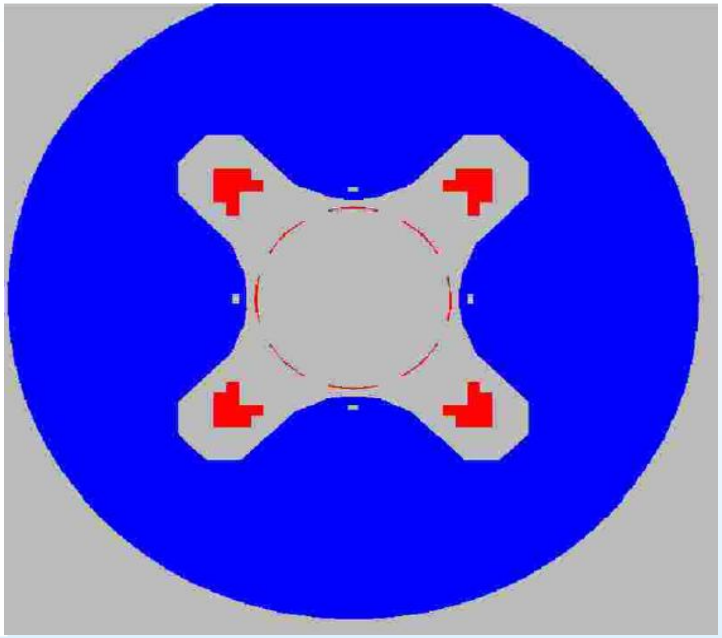


Design: SuperPower coils ~172 A and ASC coils ~300 A (at 40-50 K).

- **Coils reached over 1/3 of the design current at 77 K itself.**
- **Extrapolation to 40-50 K indicates a significant margin.**

Actual 40 K test is expected in a few months.

HTS Corrector for FRIB



Correctors inside should also be made of HTS for the same reason quad is

Large Aperture Corrector SBIR/STTR Phase I Proposal with Muons, Inc.

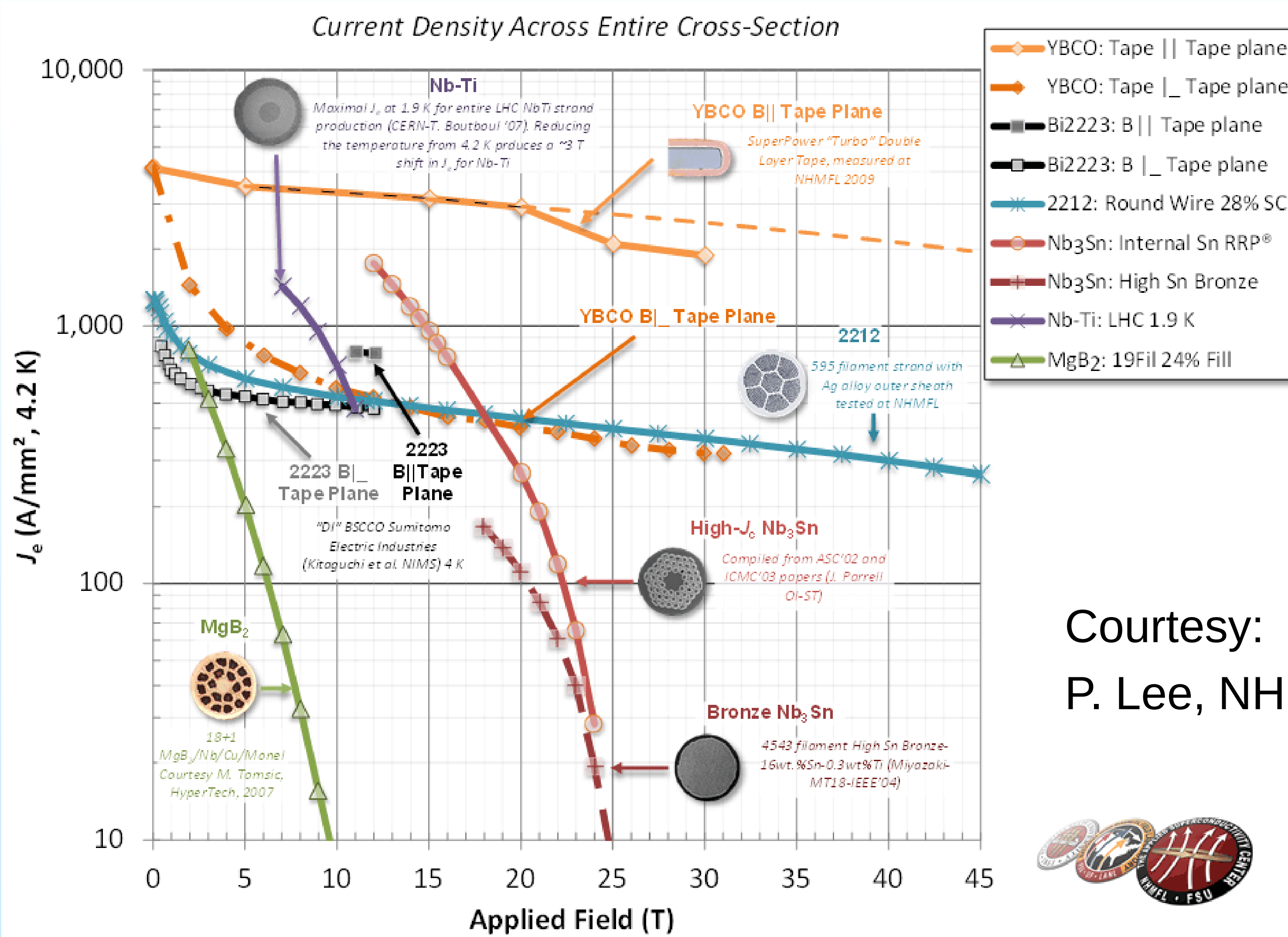
Muons, Inc.

Non-racetrack radiation resistant saddle coil with complex ends

BROOKHAVEN NATIONAL LABORATORY

High Field Dipoles and Quadrupoles for LHC Upgrade and MAP (>20 T)

A Hybrid Design Makes Sense



Courtesy:
P. Lee, NHMFL

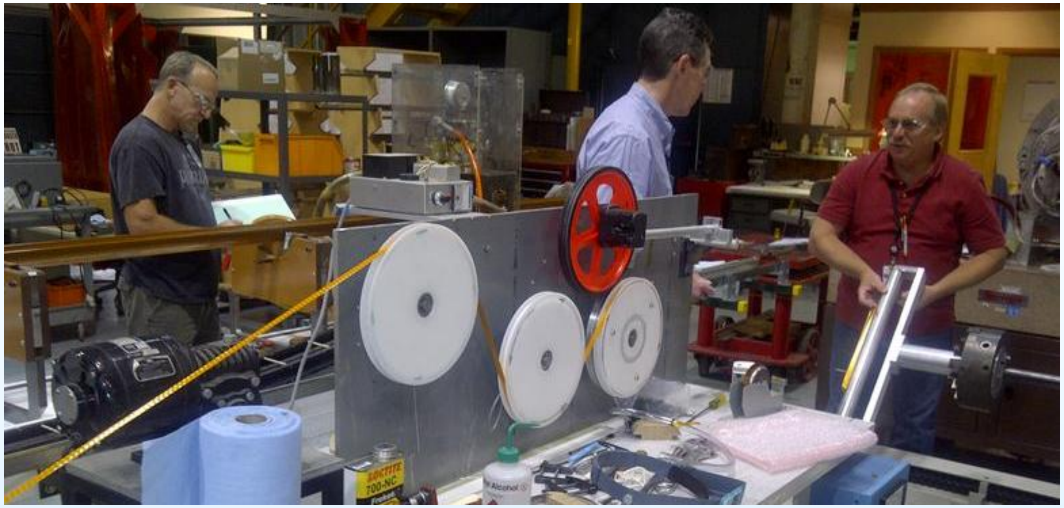
HTS Dipole STTR with PBL (PI: Erich Willen)

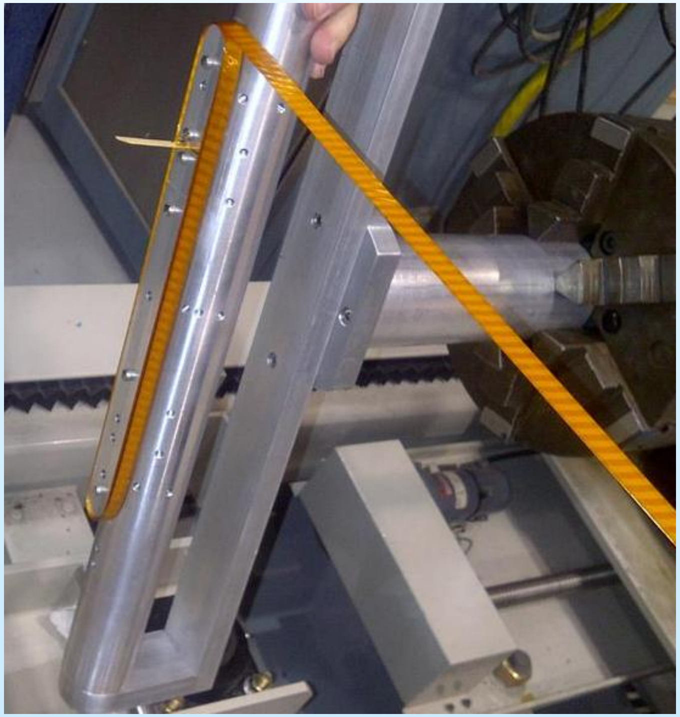
Major Goals of this STTR (Phase I funded):

- Examine cosine theta coils made with 2G HTS tape to coils made with those made with Bi2212 Rutherford cable so that one can compare pros and cons of the two options
- Use widely available 2G HTS tape that can tolerate large stresses, as those expected in very high field magnets
- Demonstrate that cosine theta coil block (with complex saddle coil ends) can be wound without major degradation (verify in Phase I itself with 77 K measurements)
- Evaluate if a cured coil with Kapton-Ci insulation can be made using the techniques similar to those used with NbTi (this would avoid epoxy, which is of concern with 2G coils)
- Measure persistent current induced harmonics (Phase II) to quantify the issue. Expected larger - are they manageable?

Winding of Cos (θ) Coil Block at BNL

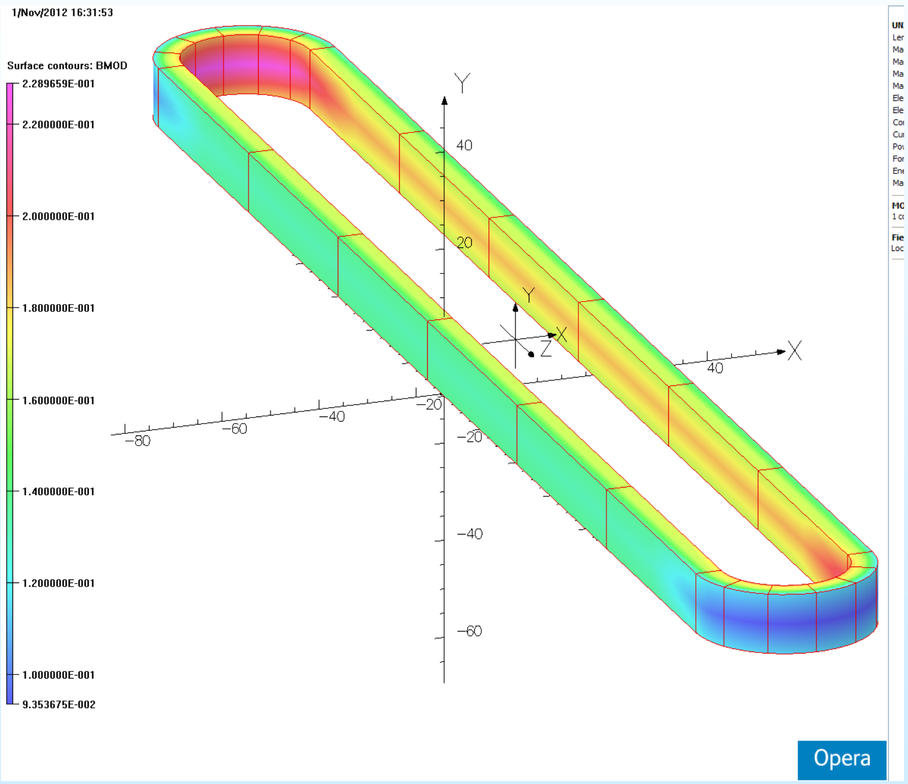
- SuperPower/BNL collaboration on Kapton-Ci insulation on 2G Tape
- BNL proposed and provided Kapton-Ci, SuperPower 12 mm Tape insulated at SuperPower





77 K Phase I Test Results

See Lakshmi's presentation for promising results

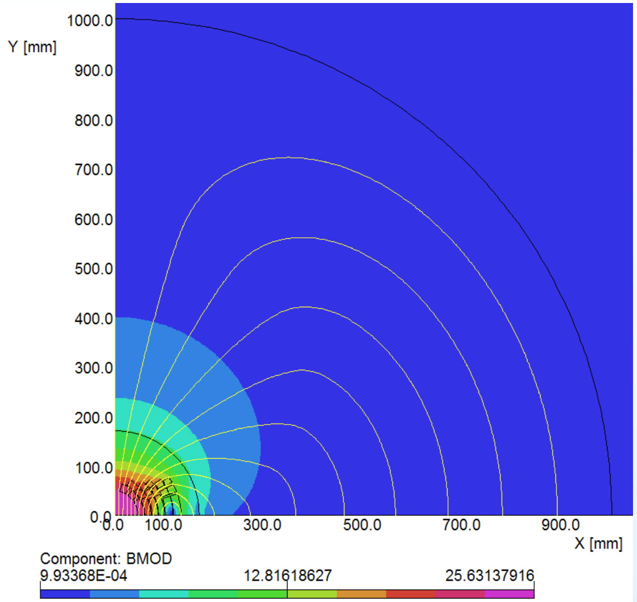


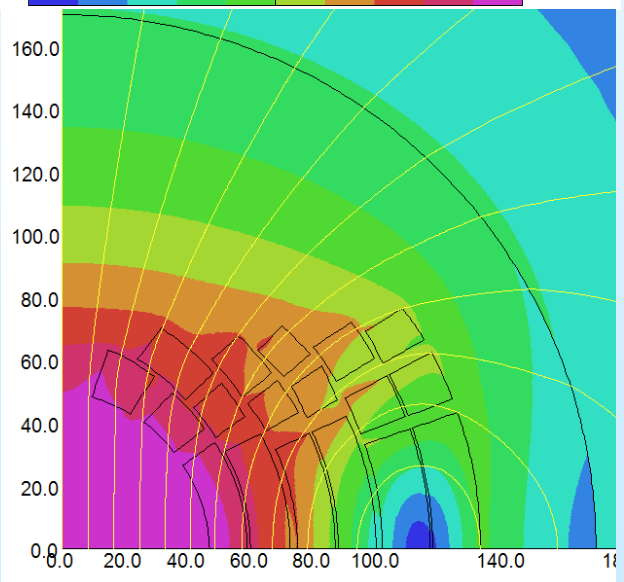
Magnitude of the field at 200 A (coil powered to over 200A @77K)

Perpendicular component of the field at top and bottom at 200 A

Initial Plans for Phase II

- Develop an engineering design of cosine theta dipole with Kapton-Ci insulation on 2G HTS tape
- Wind and cure a full 360 degree coil configuration
- Install above coil in a magnet structure
- Carry out the test of this magnet for critical current as a function of temperature (4 K to 77 K)
- Measure field harmonics as a function of current, may be at several temperatures
- Use this experience to develop a magnetic and mechanical design of a hybrid 25 T dipole magnet
- Possible work-plan beyond Phase II – integrate and test above coils in a hybrid magnet structure





HTS Quad SBIR/STTR with PBL (PI: Ron Scanlan)

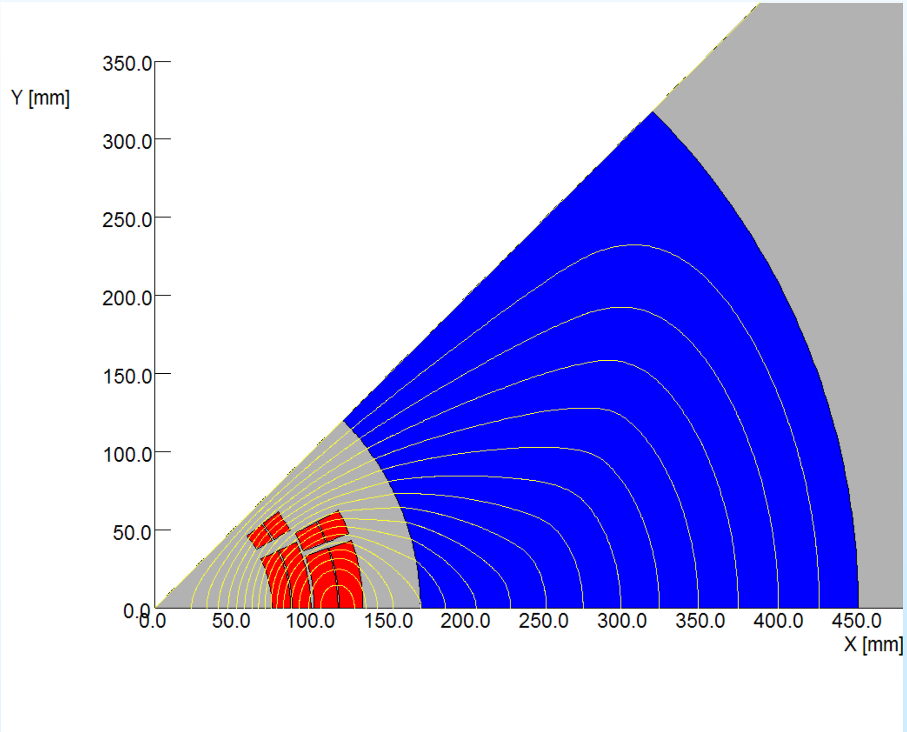
Major Goals of this SBIR/STTR (Phase I applied):

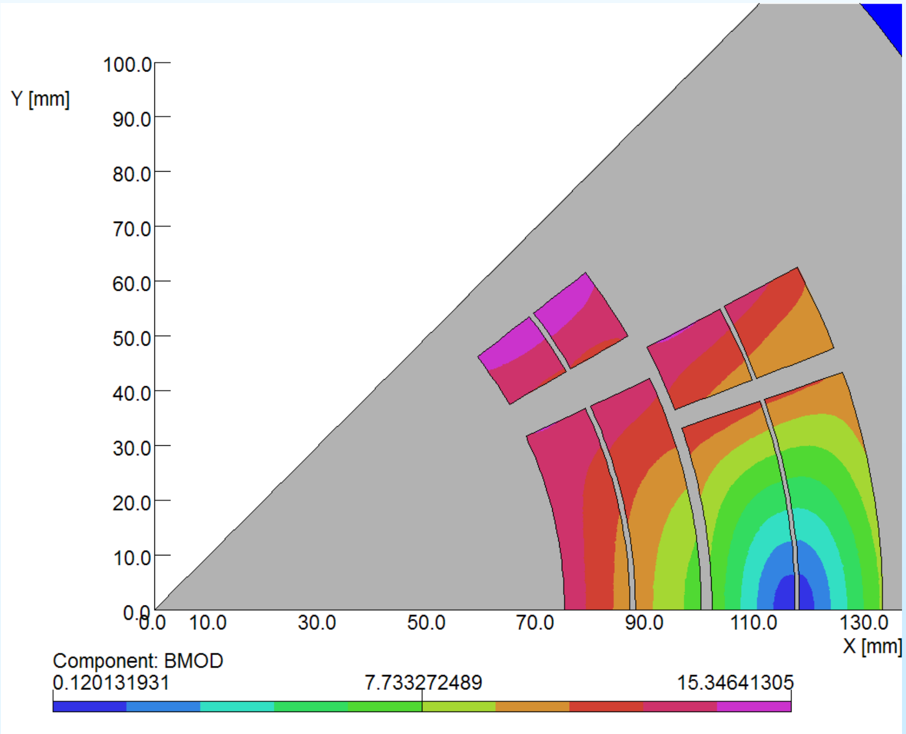
- **Examine both Bi2212 and YBCO with more focus on YBCO.**
- **Optimize geometrical parameters of the ends of saddle coil (key to cosine theta coils made with 2G HTS tape).**
- **Use both simulations & actual winding to vary parameters of cosine theta ends. Optimize design based on these.**
- **Examine the impact of measured magnetization in HTS tape on field errors in quadrupoles.**
- **Examine ways to reduce these field errors.**
- **In RHIC, field errors in IR quads were less critical at low fields and more at high fields. How about in LHC? If so, one may power HTS inner layer primarily at high fields.**
- **What field errors are tolerable in MAP? Less demanding?**
- **Develop a hybrid design (HTS inner layer, LTS outer).**

HTS Quad SBIR/STTR

A Hybrid HTS/LTS Superconductor Design for High-Field-Gradient and/or Large-Aperture Quadrupole Magnets

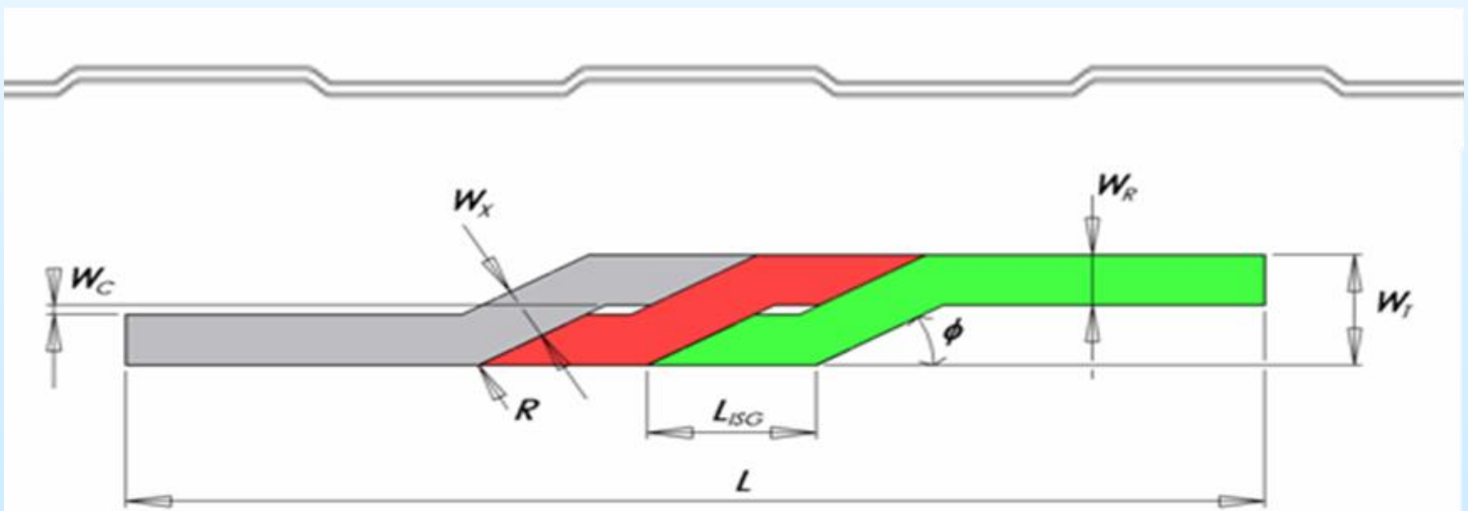
Example: YBCO+Nb_3Sn design for 180 T/m, 150 mm aperture quad for LHC high luminosity upgrade (HL-LHC)





Roebel Cable Common Coil Dipole SBIR/STTR with HyperTech and OSU

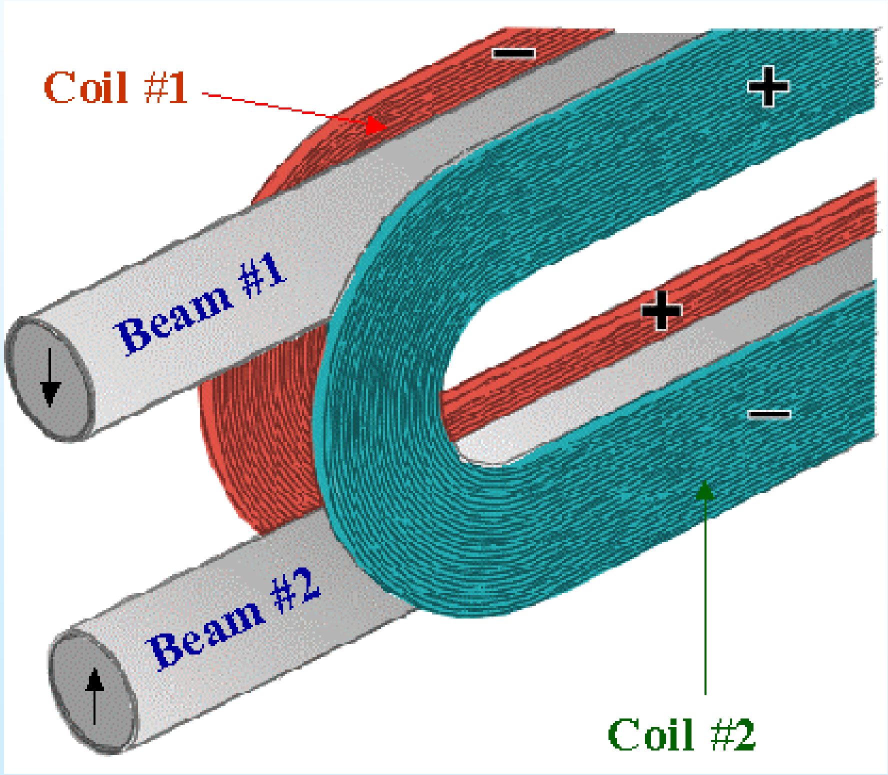
Roebel cable is attractive for accelerator magnets as it offers a possibility of 10⁺ kA. Beside helping in quench protection, it reduces magnetization.

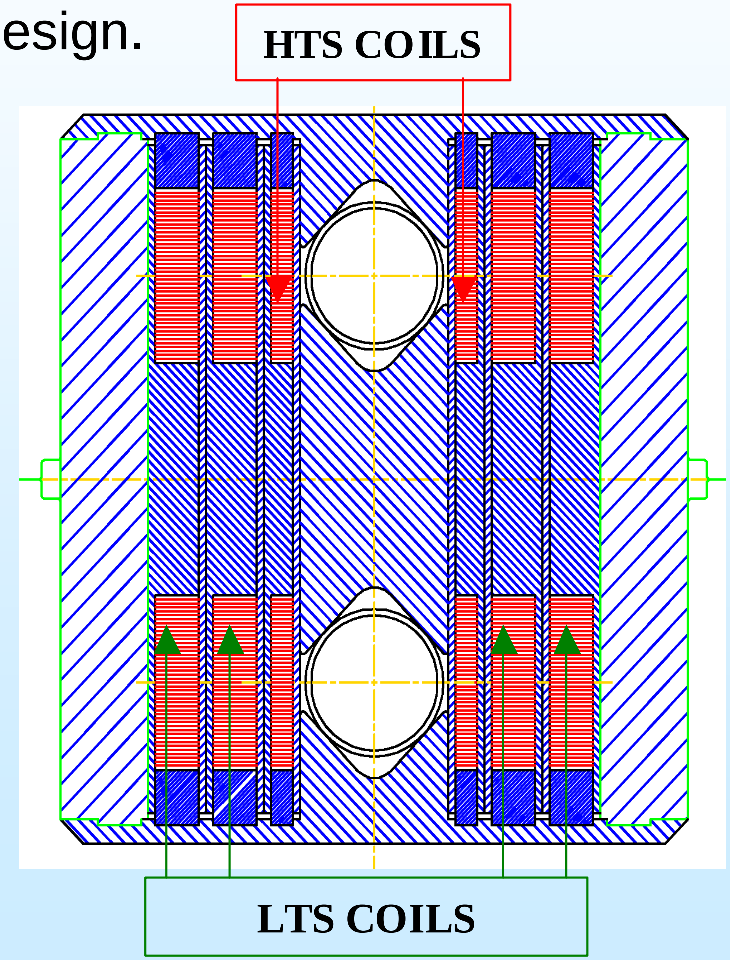


A Roebel cable (top), and schematic of assembly (bottom)

Common Coil Dipole with Roebel Cable

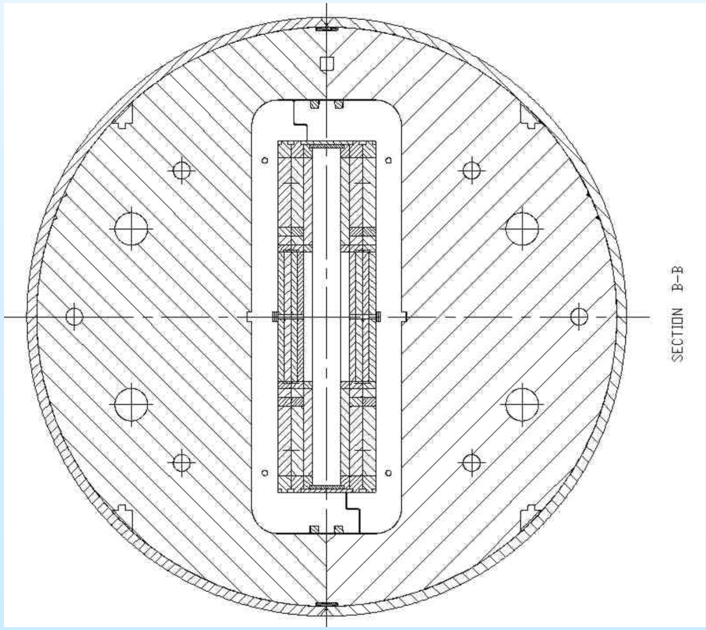
- Due to large bend radius and modular structure, common coil design is particularly attractive for Roebel cable in a hybrid magnet structure.
- BNL has significant experience with this design. It has built Nb_3Sn, 2212 cable and HTS tape magnets based on this design.

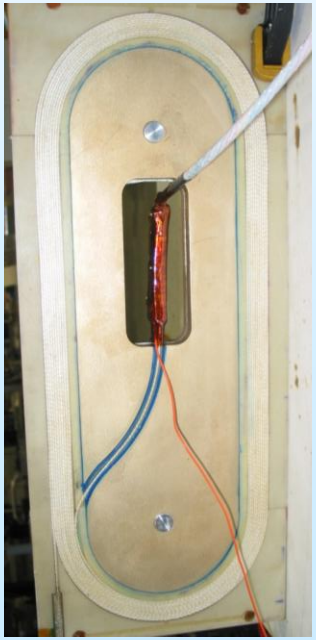




Existing Common Coil Dipole at BNL for Roebel Cable Dipole Magnet SBIR/STTR

- BNL has built a unique 10^{+} T Nb_3Sn common coil dipole with large open space available for HTS racetrack coil becoming a part of the hybrid magnet.
- High current Roebel cable coil built under this SBIR/STTR will be married to this magnet to develop and demonstrate a hybrid (HTS+LTS) high field dipole.
- The plan is for Hypertech to manufacture the coil and BNL to design, build and test the magnet.



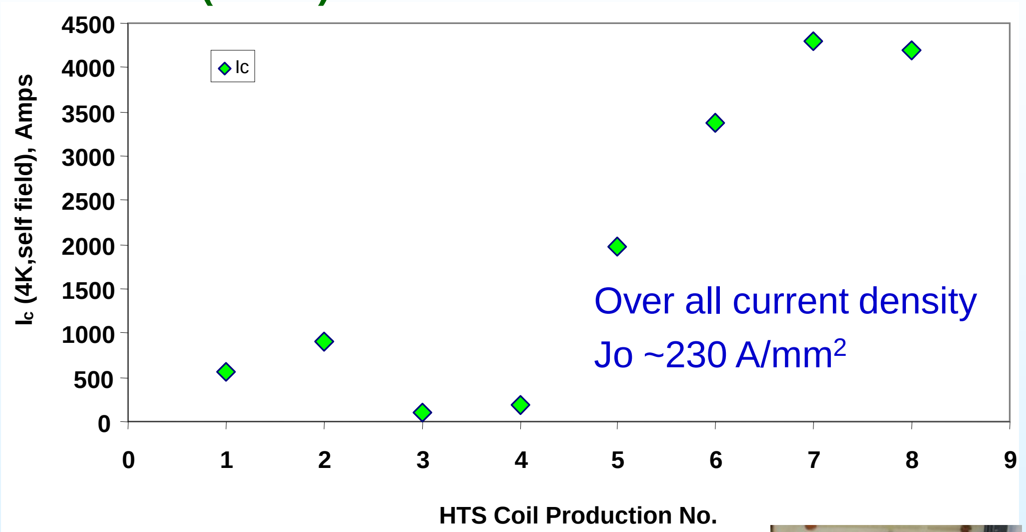


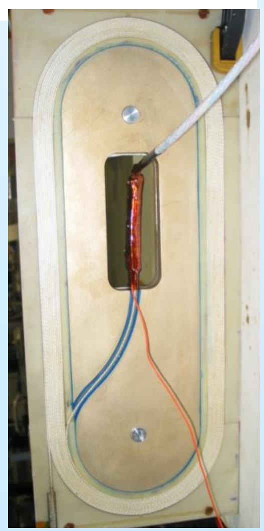
High current 2212 coil

Missed Opportunities

Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)





Noteworthy Demonstrations:

- High current coils with Bi2212 Rutherford cable.
- HTS and Nb_3Sn magnets.

Incomplete Tasks:

- A Hybrid magnet with two together
- Measurements of field harmonics at 4K in Bi2212 coil (done @77K)
- Measurements of mechanical properties of 2212 coil

Missed Opportunities:

- Coils inadvertently disappeared as scrap material, perhaps because they were not used for a long time.
- Missed significant demonstrations and answers to technical questions.

Conductor Needs and Magnet Summary

- Viability of significant use of HTS in accelerator magnets would depend on the reduction in cost, improvement in in-field I_c, better mechanical properties, longer lengths and smaller variations in I_c.
- HTS is a unique conductor. It allows magnets to operate at high temperatures, at high fields and in large heat load environments.
- HTS is now now the baseline design of the critical FRIB magnets.
- There is a significant potential of HTS facilitating very high field superconducting magnets - never thought practical before.
- BNL has a wide ranging program to develop HTS technology.
- At this stage, one must allow different options to evolve and determine experimentally which approach offers the best solution in an individual case rather than pre-determining one early on.
- A variety of projects offer a useful synergy in sharing resources. However, a base program will help in filling the important gaps.