REBCO and BSCCO Coils at BNL

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Presenting work of
BNL, PBL, FRIB, Muons, Inc. and SMES Teams

MAP HTS MAGNET WORKSHOP
Fermi National Accelerator Laboratory
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Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

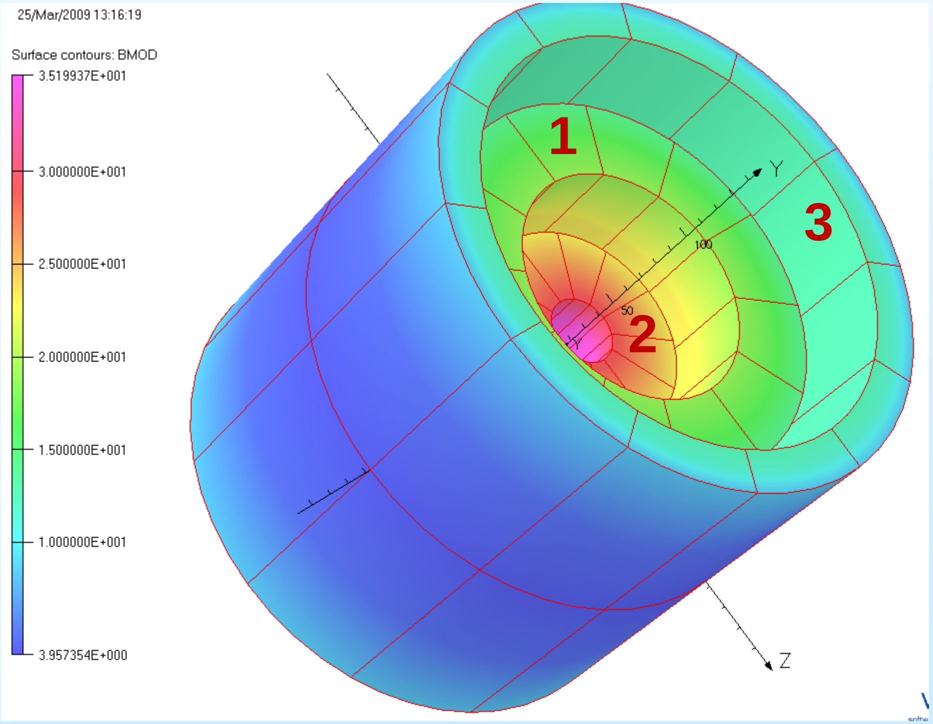
- Overview of the BNL HTS magnet program
  - REBCO and BSCCO coils and conductor
  - 40-50 km HTS (4 mm tape equivalent), 100+ coils, 10+ magnets
  - Emphasis on R&D involving high field or large use of HTS
- Recent progress in high field HTS magnet technology
  - 15+ T in an all HTS magnet
  - protection and survival after quench (or whatever) of a relatively large HTS coil having a significant field and stored energy
- Summary and Recommendations

Ongoing REBCO Programs at BNL

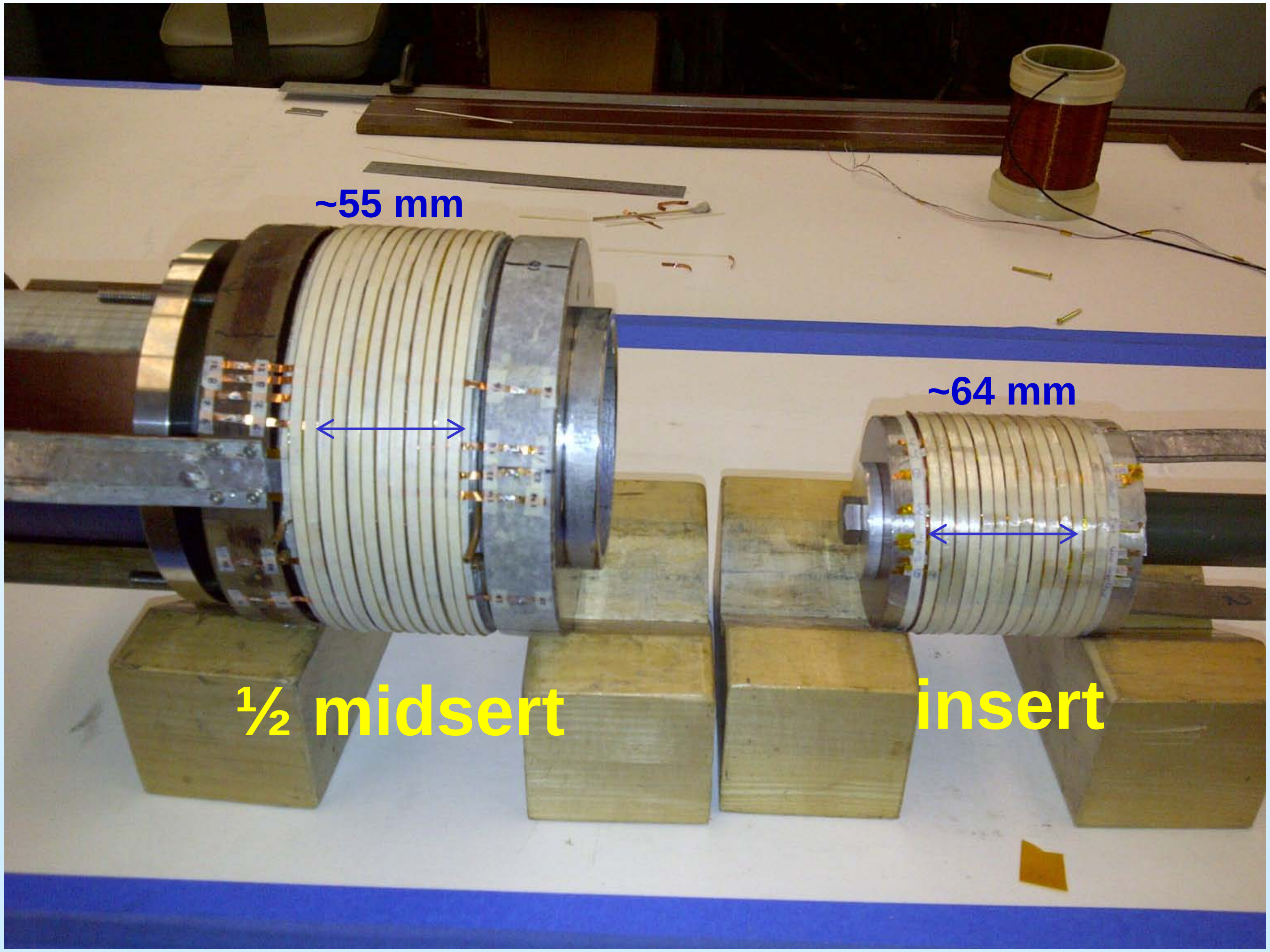
- **MAP high field solenoid SBIR with PBL, Inc.**
- SMES – with ABB & SuperPower
- YBCO conductor testing at high fields – exciting results
- HTS Quad – now a baseline design for FRIB
- Cosine theta coils – PBL SBIR and FRIB funding
- Curved dipole - STTR on FRIB with Muons, Inc.

PBL/BNL R&D for MAP

- Ambitious SBIR route to evaluate magnet technology for ~35 T
- Significant demonstrations so far:
  - ➢ **Highest field (>15 T) HTS magnet ever built**
  - ➢ **Large use (1.2 km) of HTS in a high field magnet**



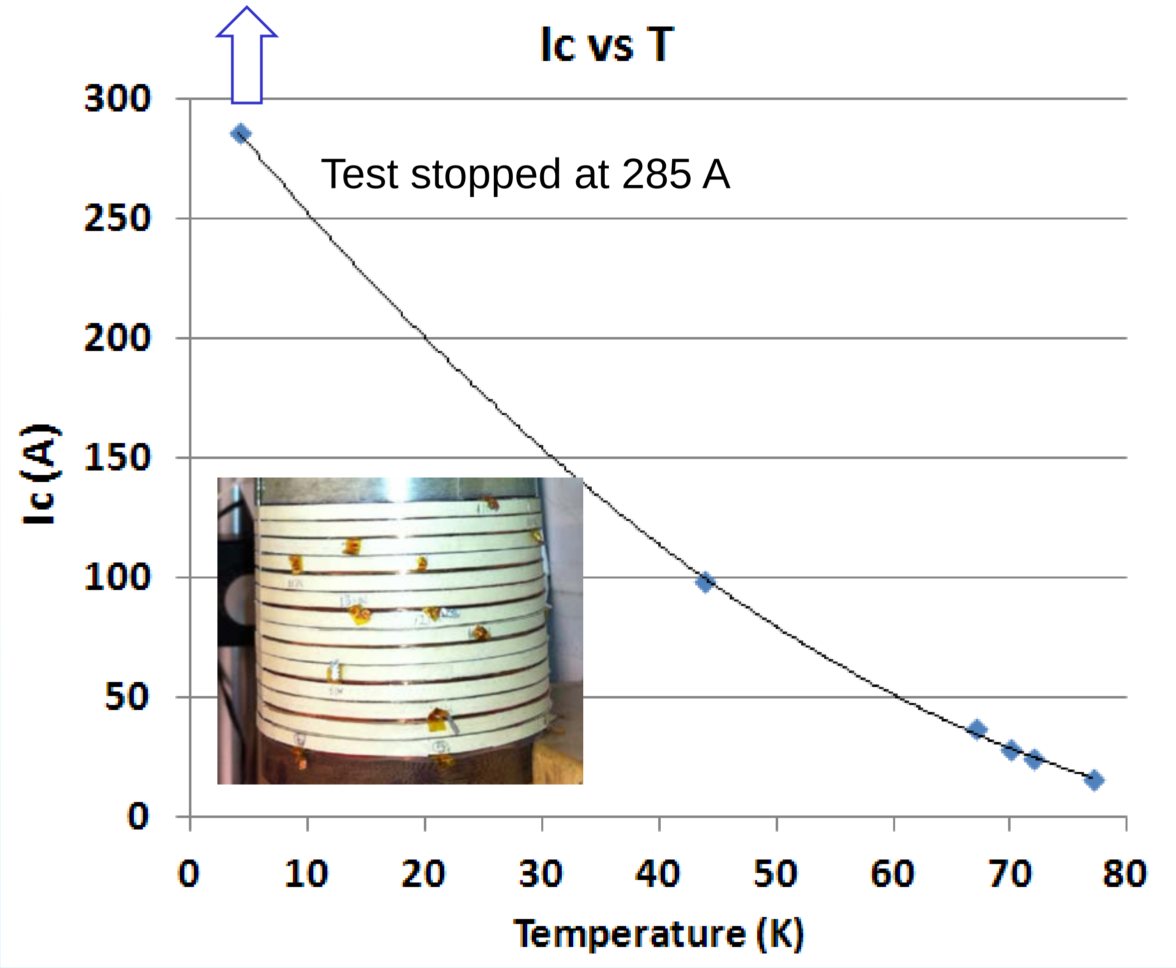
PBL/BNL High Field HTS Solenoids for MAP



Two significant construction and tests

Conductor:
High strength 2G HTS from SuperPower with ~45 μm Copper

High Field HTS Test Results (magnet #1)



24 pancake coils with ~25 mm aperture

PAC2011 paper by Yuko Shiroyanagi, et. al.

Field on axis:
- **over 15 T**

Field on coil:
- **over 16 T**

Real demo of 2G HTS to create high field

Highest field in an all HTS solenoid (previous best SP/NHMFL ~10.4 T)

Overall J_o in coil:
>500 A/mm^2 at 16 T
(despite anisotropy)

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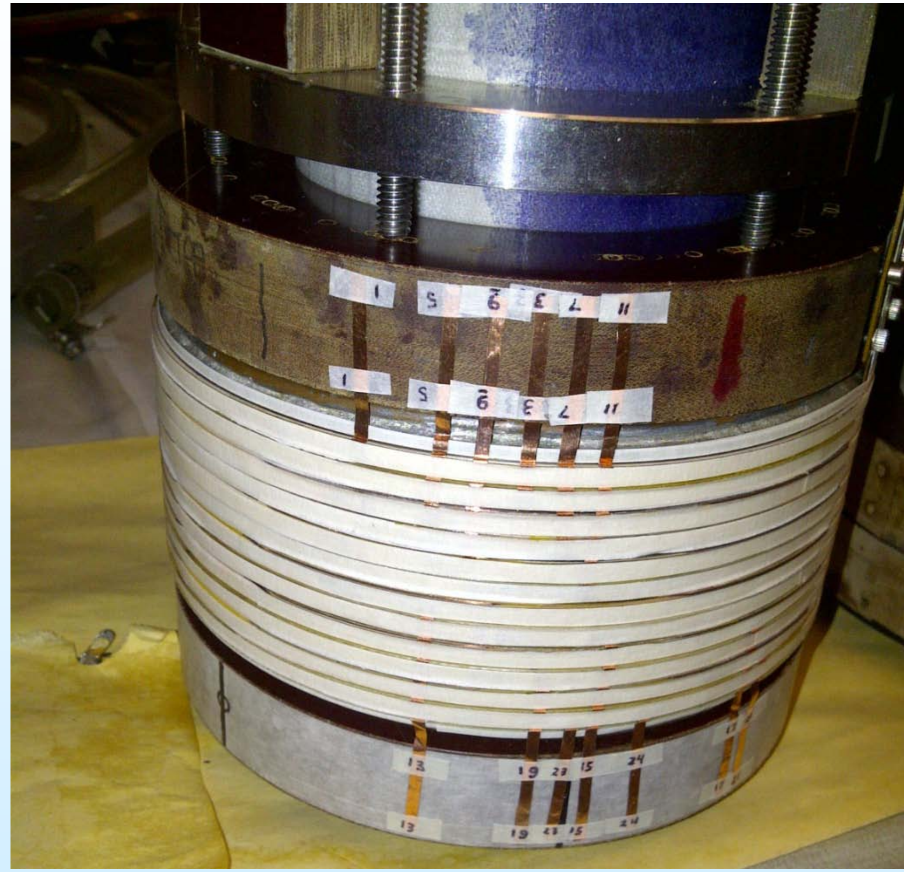
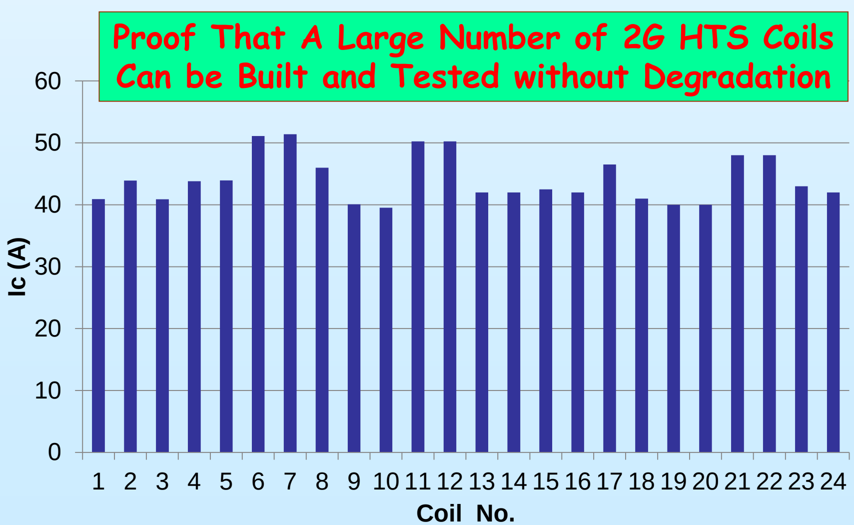
Test Results of ~100 mm HTS Coil (magnet #2 - half length midsert)



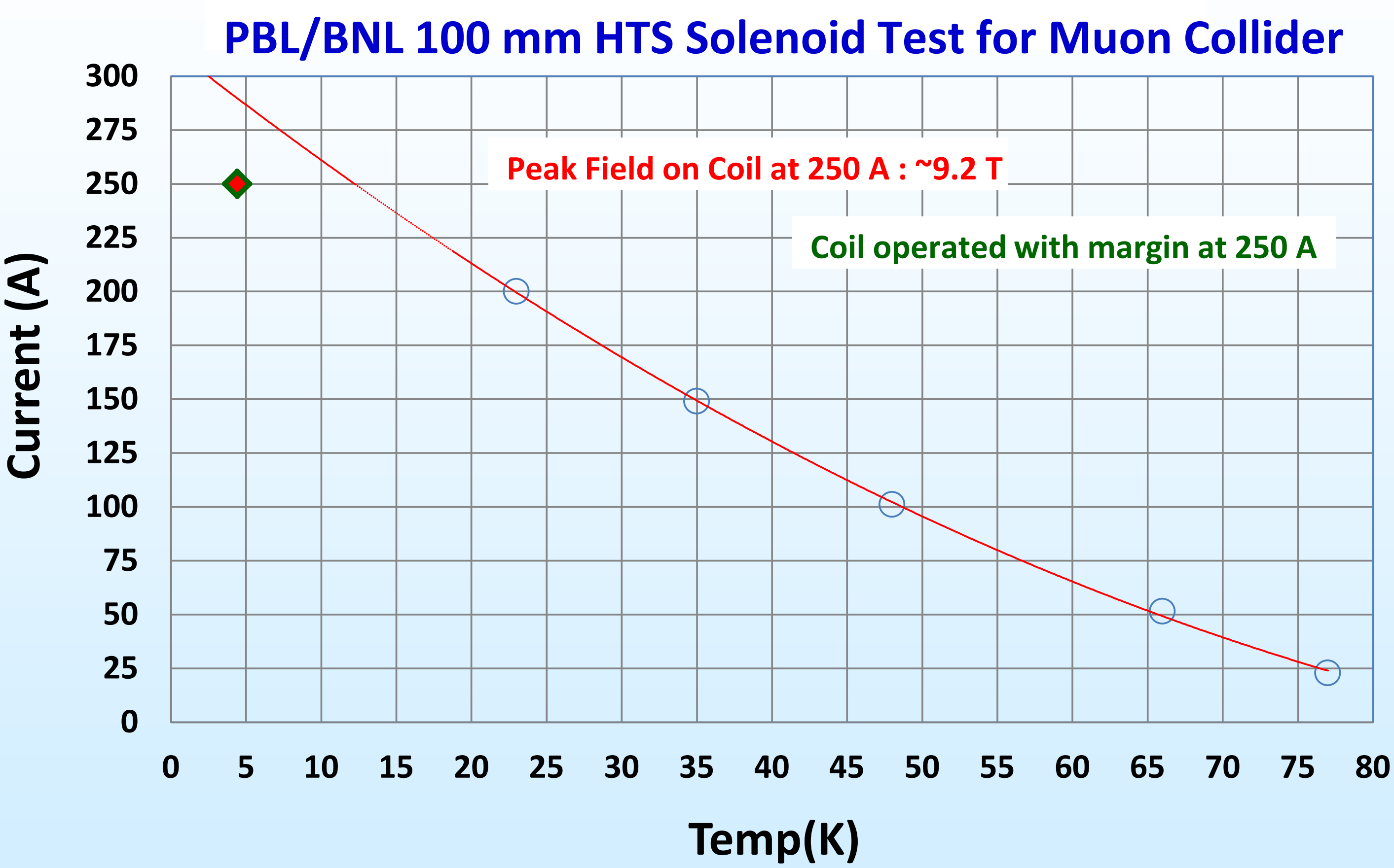


- Intermediate test with 12 pancakes
- Full solenoid will have 24 pancakes

(each coil built with 100 m SP HTS)

Test Results of ½ Midsert Solenoid

Measured Critical Current As a function of Temperature



250 A ==>
6.4 T on axis
9.2 T on coil

Coil could have reached above 10 T, but we decided to hold back to protect our electronics

Status and Future of this Program

- PBL/BNL 25 mm and 100 mm solenoids will be merged together and should be ready for test in a few months
- Expected field: 20-25 T (would be a remarkable result, if it works)
  - Highest field in an all HTS magnet (beating 15+ T just achieved)
  - Would be a major contribution of SBIR/STTR program (thanks)
- Discussion on 20 T background field test of above at NHMFL
- PBL/BNL team waiting for Phase II LTS outsert for ~35 T for MAP
- SuperPower has volunteered for (a) small aperture coil to go inside 20-25 T and (b) end coils with 6 mm tape. That would create 25^{+} T all HTS solenoid, if successful, when combined with above
- **A lot of excitement, a lot of challenges – please join us**

Quench Protection in HTS Magnets

- Protecting high field HTS magnets is a major concern.
- HTS is significantly different from LTS. Things happen slowly (low quench velocities, etc.) which could destroy the coil.
- BNL approach: use different properties of HTS to our advantage – slow progress (longer pre-quench phase) allows more time to act before quench (proper term - run away). This will be the first line of defense to conventional approach with fast acting heaters on the coil (significant progress at NHMFL).
- Challenge is to detect that pre-quench phase fast – small resistive voltage over large noise and inductive voltages. Major progress has been made in this area at BNL.
- But some time with best effort, magnet may quench at high field with large stored energy. We must not only be able to avoid that but must also be able to survive that.
- **We are pleased to report that "the quench protection electronics was able to protect a 100 kJ class HTS coil".**
- Of course, significant more work still remains. But the progress is being made.

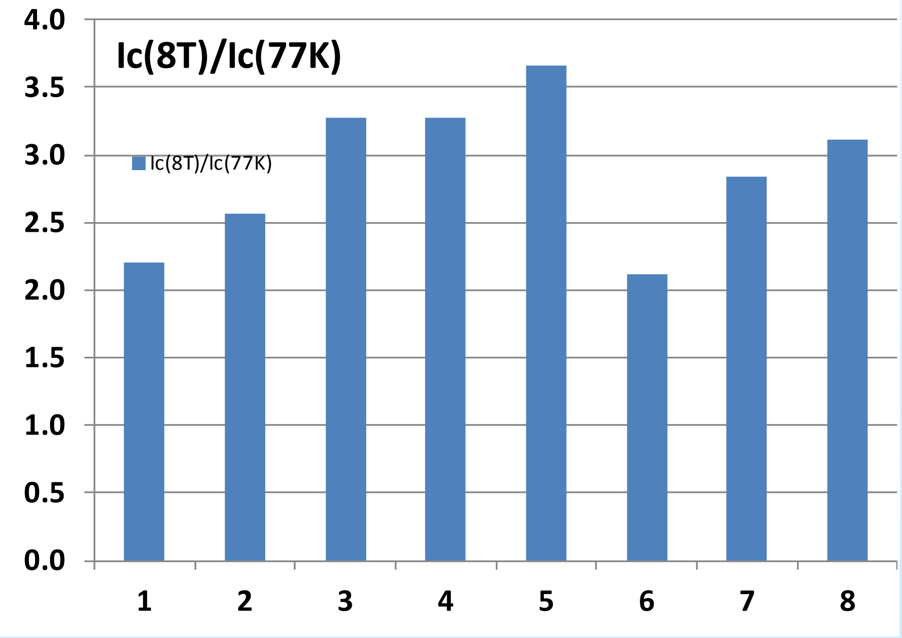
Major Opportunity to Increase High Field Performance of REBCO

- REBCO is highly anisotropic with performance in coil is limited by field perpendicular (or within 20°) value of Ic
- Recent BNL measurements of production samples of SuperPower show that 4K perpendicular field Ic varies as much as 2X

Measurements to be presented in BNL Magnet Division Internal Note MDN-671-39. Arup Ghosh, "Ic Measurements of ReBCO Tapes at 4.2 K in Perpendicular Field.

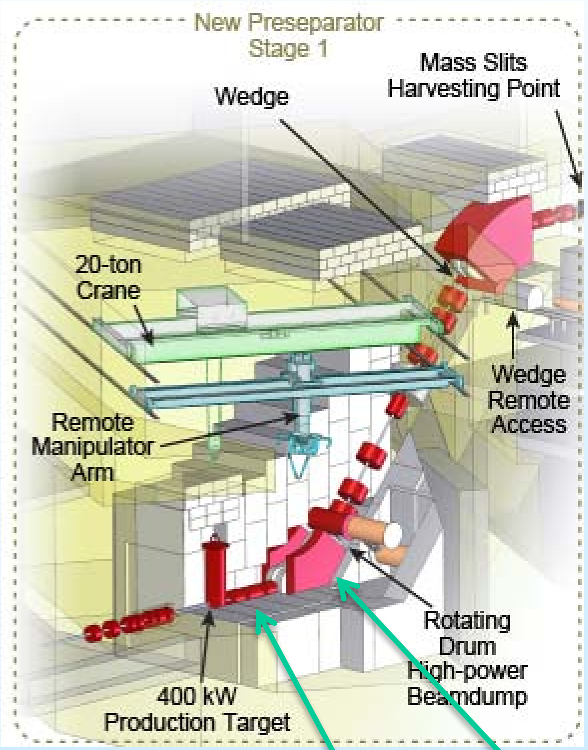
- See afternoon presentation by Selva for analysis (Univ of Houston)
- Once we understand the source, we may find a way to incorporate that in production.
- Here we have an opportunity for increasing effective Ic by a factor of two or more.
- An opportunity for DOE/HEP to support REBCO and get a high impact outcome.

Sample Num	Comments	Tape Width, mm	Ic_Perp(8T)	Ic(77K)	Ic(8T)/Ic(77K)
1	PERP TEST	12	726	330	2.200
2	PERP TEST	12	800	312	2.564
3	PERP TEST	12	1119	341	3.282
4	PERP TEST	12	1324	404	3.277
5	PERP TEST	12	1401	383	3.658
6	PERP TEST	12	773	365	2.118
7	PERP TEST	12	956	337	2.837
8	PERP TEST	12	1369	439	3.118



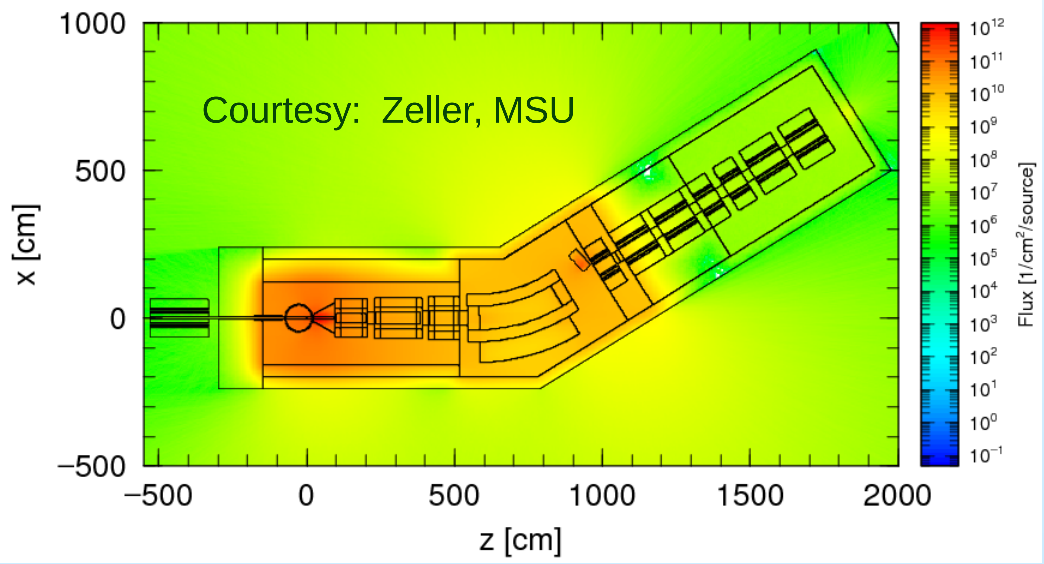
HTS Quadrupole for FRIB

Facility for Rare Isotope Beams (FRIB) is being built in Michigan.
Rare isotopes will be created when 400 kW beam hits the production target.
Magnets will be exposed to unprecedented level of radiation and heat loads.



Exposure in the first quad itself:

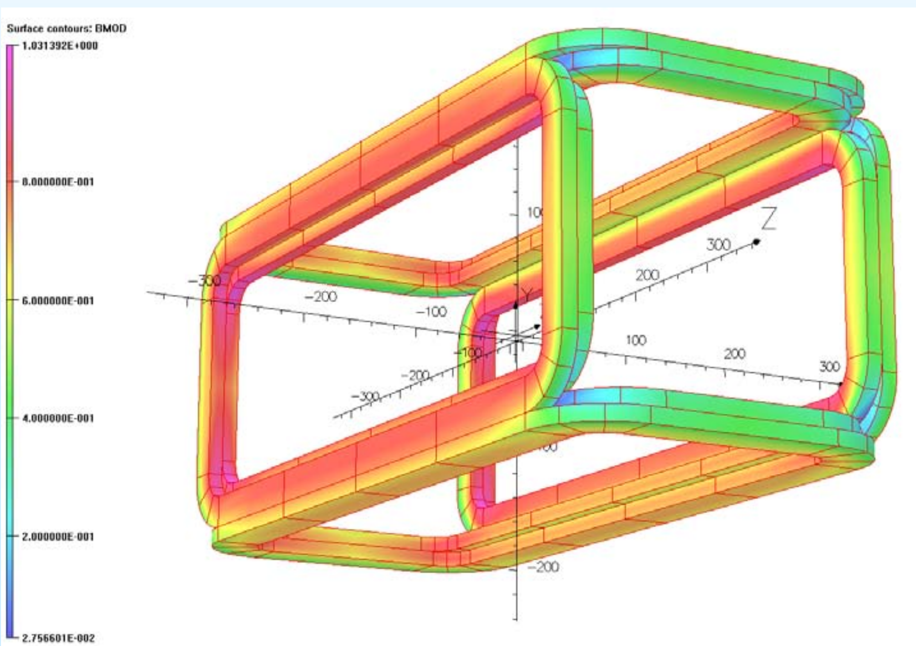
- Head Load : ~10 kW/m, 15 kW
- Fluence : 2.5 x10^{15} n/cm^2 per year
- Radiation : ~10 MGy/year

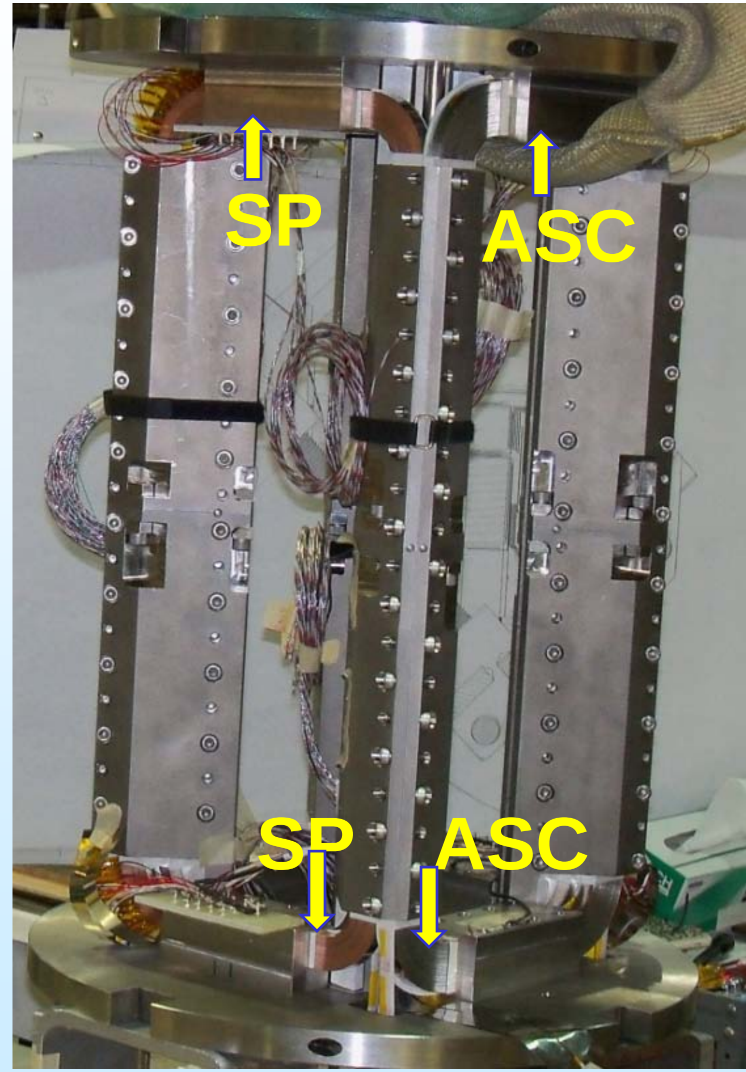


Radiation resistant
Pre-separator quads and dipole

HTS Quadrupole for FRIB (HTS magnet in a real machine)

- HTS quad now is the baseline design
- Eight coils wound with 12 mm REBCO tape (4 with SuperPower and 4 with ASC)
    - Each coil uses ***over 1 km*** equivalent of 4 mm 2G HTS tape (over 9 km total)





8 HTS coils in support structure

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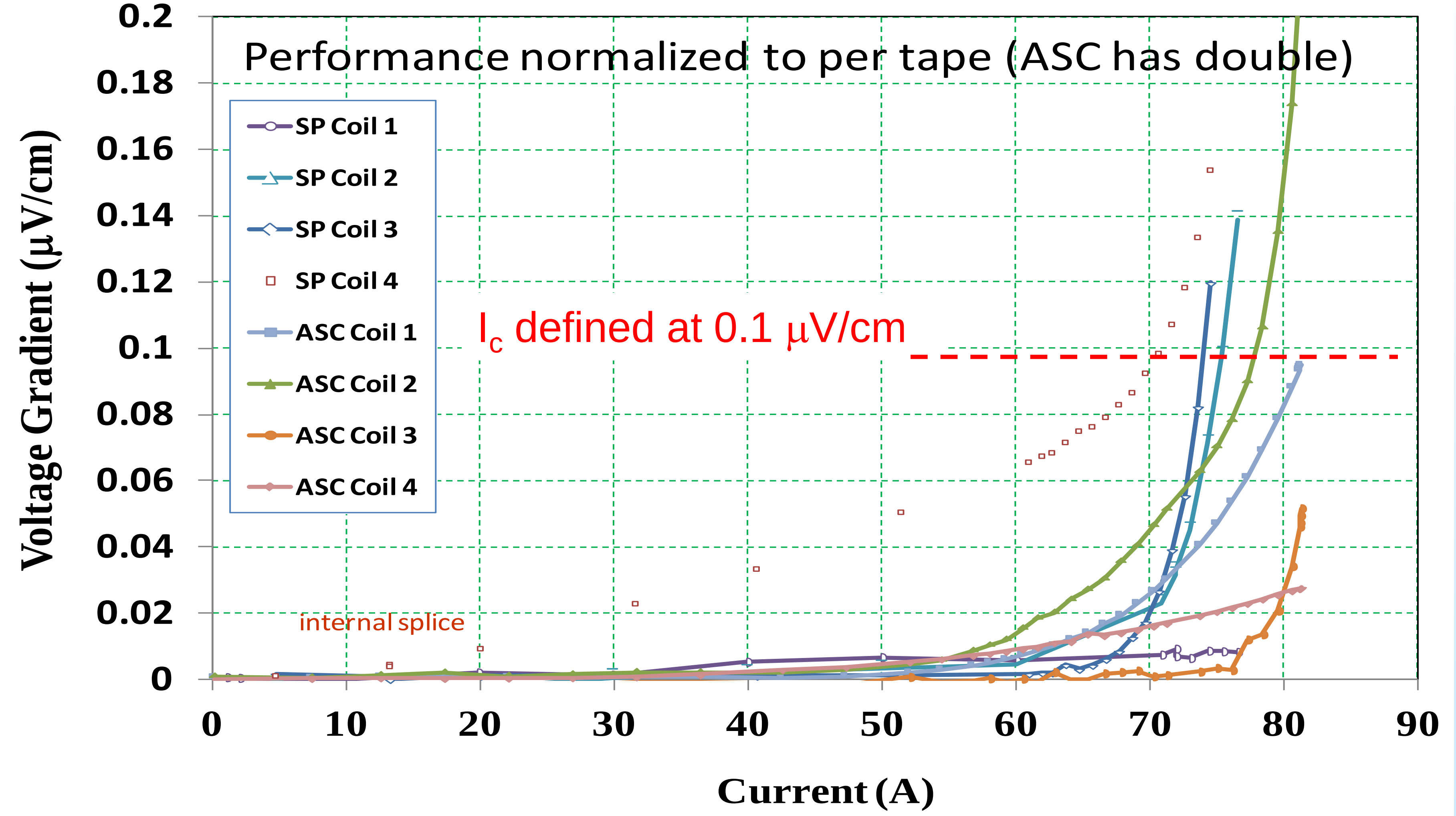
Coils in FRIB Quad Structure @77 K (made with 2G HTS from SuperPower and ASC)

Demonstration of large (9 km of 4 mm equivalent) successful use of HTS tape



Cos θ Magnet with REBCO Tape

Two start-up programs with small but important seed funding:

- DOE/HEP Phase I STTR with PBL (Kapton, small aperture)
- DOE/NP FRIB funding for corrector FRIB (SS tape, large aperture)

Major challenges with tape:

- Ends
- Magnetization

An early cosine θ coil made with Nb_3Sn tape (Sampson)

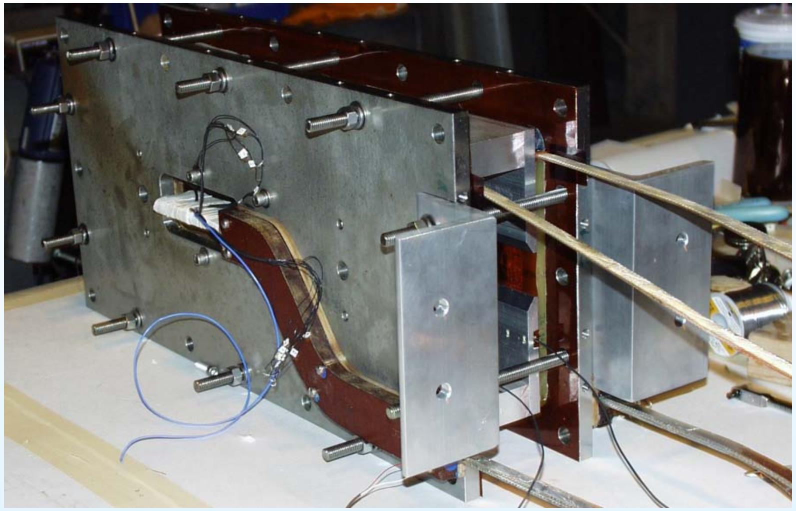
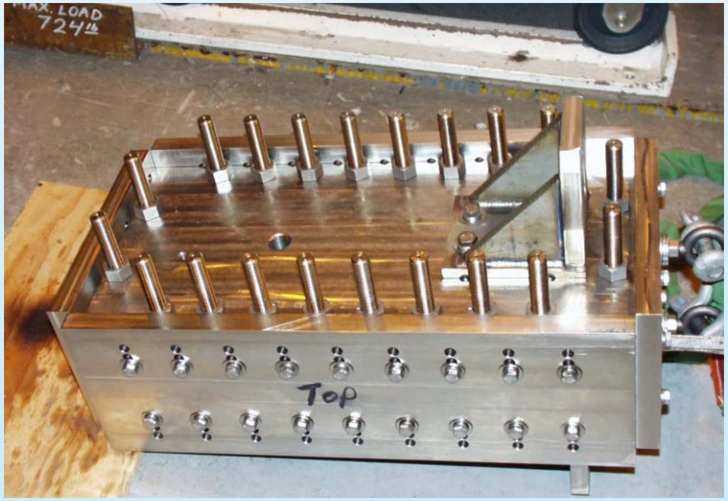
BSCCO Coil Programs at BNL

- **Bi2212 magnet program with Nb3Sn Dipole for high field testing**
- Other BSCCO programs (not to be discussed here)
  - Bi2223 Tape Common Coil Program
  - Bi2223 Quadrupole for Rare Isotope Accelerator (RIA)
  - Bi2223 Solenoid for ERL at BNL
  - Bi2223 Solenoid for Superconducting electron gun

Main Features of BNL Bi2212 Program

- Rutherford cable
- React and Wind (R&W) conductor friendly common coil design
- Many coils successfully built and tested with significant conductor
- Produced highest current Bi2212 coil (still a record)
- Also built Nb_3Sn dipole (highest field R&W Nb_3Sn dipole) to allow easy high field insert coil testing with unique design

Magnet Structures for Bi-2212

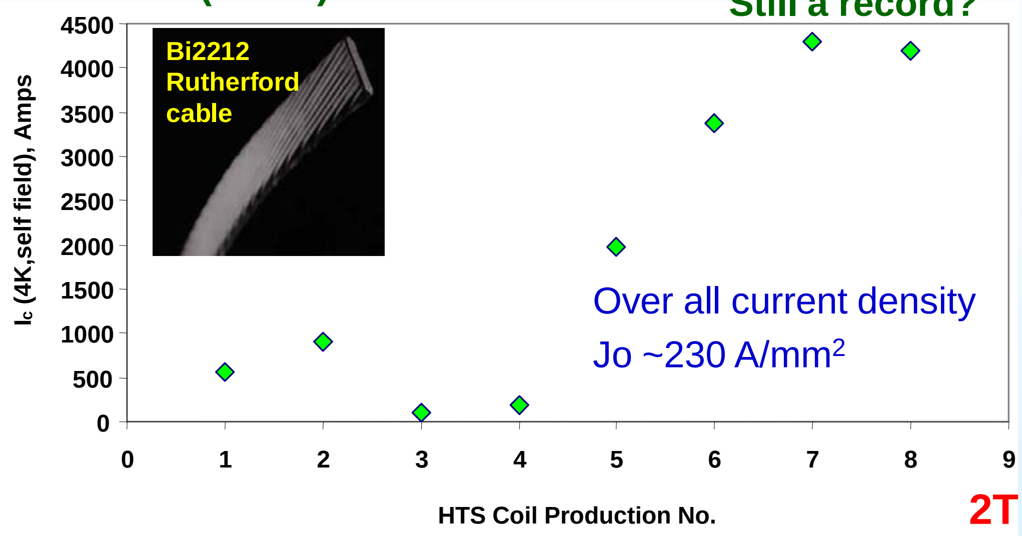
HTS Common Coil Dipole with Bi2212 Rutherford Cable

8 Coils and 5 Magnets built at BNL with Rutherford Bi2212 Cable

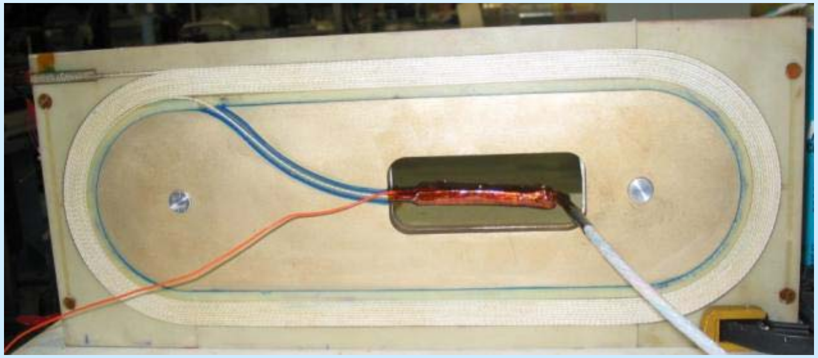
Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand)	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag	74 mm spacing Common coil	182	177 [80]	0.045
CC012 DCC008	0.81 mm wire, 18 strands	Hybrid Design 1 HTS, 2 Nb_3Sn	1970	212 [129]	0.66
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb_3Sn	3370	215 [143]	0.95
CC026 DCC014	0.81 mm wire, 30 strands	Hybrid Common Coil Design	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands	2 HTS, 4 Nb_3Sn coils (total 6 coils)	4200	272 [212]	1.84

Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)
Still a record?



Racetrack HTS coil with Bi2212



SUMMARY

- Significant progress has been made in HTS magnet technology as demonstrated by large use of variety of HTS (ReBCO, Bi223 and Bi2212) in a number of R&D coils and magnets for several projects
- HTS has already been demonstrated as a high field superconductor (over 15 T in an all HTS magnet). Significant experiments are planned in next six months aiming 20+ T
- Recent high field measurements in production conductor plus other progress indicates still more potential for ReBCO
- Early results in quench protection are encouraging
- There are still many issues. However, the need of many future projects (including MAP) and impressive results obtained so far clearly shows need for more interest and support from DOE/HEP.

Recommendations

- There are several focused HTS R&D projects which have been useful but they do not provide funding for systematic R&D. Such R&D would increase the scientific understanding and benefit all projects. There is an urgent need for DOE/HEP to provide supplemental funding to leverage those ongoing projects.
- There is a need to support both conductors –(ReBCO and Bi2212) as each may be good for different applications. It seems that for MAP solenoid ReBCO is the preferred conductor and for field quality applications Bi2212.
- In recent past, DOE/HEP has supported Bi2212 significantly over ReBCO perhaps because ReBCO gets its supported from elsewhere.
- However, most other support has not been for developing HTS as a high field conductor. A reasonable funding and a good collaboration between industry and research institutions may bring a significant improvements to the benefit of MAP.