High Field HTS Magnets

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HTS Magnet Programs at BNL (1)

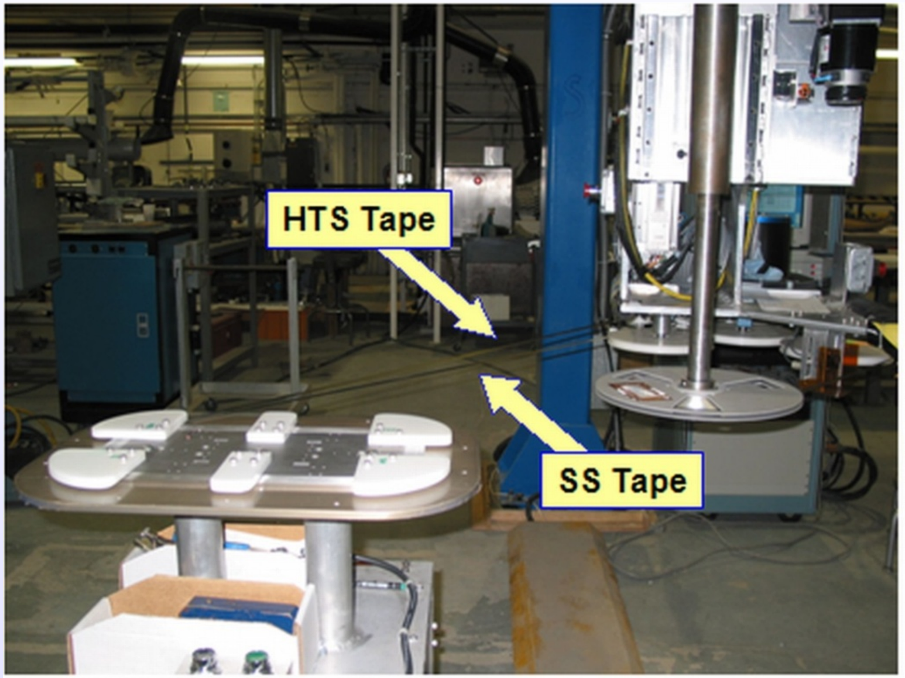
- **BNL has been active in developing HTS technology for well over a decade.**
- **We have used all types of HTS**
  - **Bi2212 (tape and Rutherford cable)**
  - **Bi2223**
  - **MgB_2**
  - **YBCO (Second Generation)**
- **The size of our HTS program is significant. It can be gauged by the amount of HTS coming in. Following are the combined quantities (normalized to the standard 4 mm tape equivalent) for various programs:**
  - **Last 12 months: ~12,000 meter**
  - **Before last 12 month: ~9,000 meter**
  - **Next 24 month (based only on funded programs): >35,000 meter**
- **This experience should help development of future HTS magnets such as those needed for LHC energy upgrade.**

HTS Magnet Programs at BNL (2)

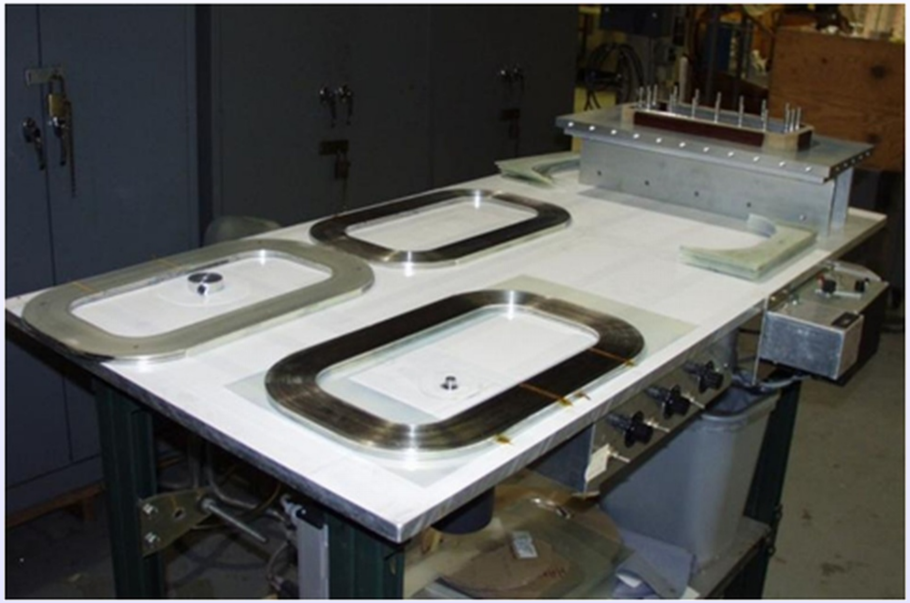
- We have successfully designed, built and tested a large number of HTS coils and magnets:
  - Number of HTS coils built: ~100
  - Number of magnet structures built and tested: ~10
- We are performing HTS magnet R&D on a wide range of programs:
  - High T, low B (several, in house)
  - Medium T, medium B (3 funded programs)
  - Low T, high B (>20 T, 2 funded programs)
- These varieties of programs help each other in developing a wider understanding while efficiently sharing resources
- Next few slides: quick review of selected HTS magnet programs at BNL; then focus on high field HTS magnet R&D

HTS Coils for RIA/FRIB Magnets

- RIA quad is made with 24 coils, each using ~200 meter of HTS.
- This gives a good opportunity to examine the reproducibility in performance.



RIA: Rare Isotope Accelerator

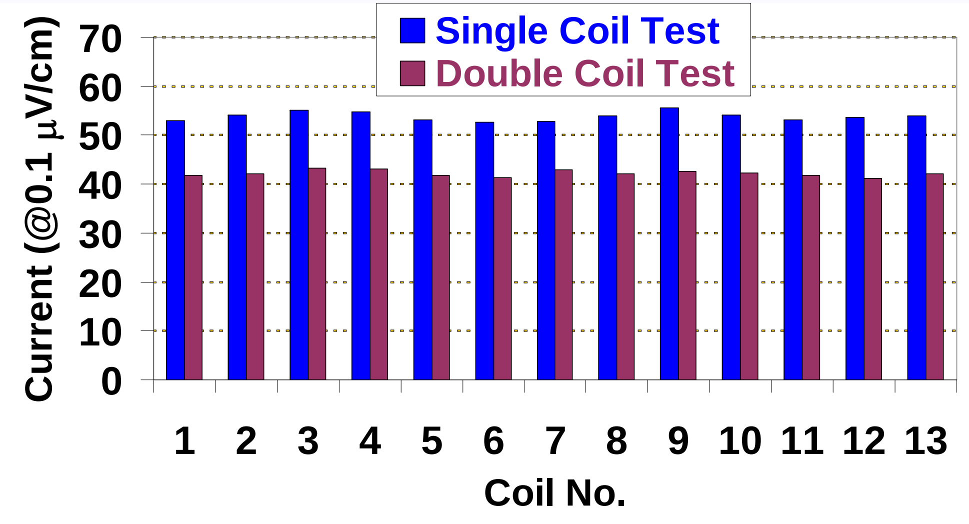


FRIB: Facility for Rare Isotope Beams

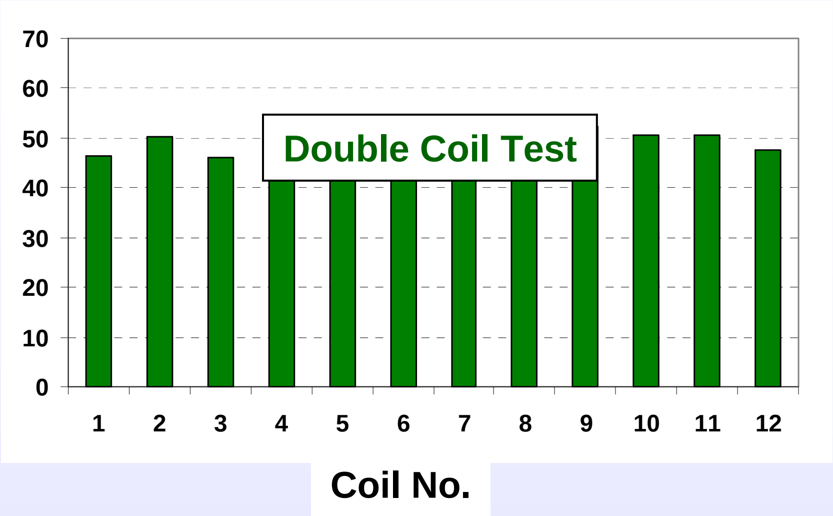
LN_2 (77 K) Test of 25 HTS Coils Made with ASC 1st Generation Conductor

Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1



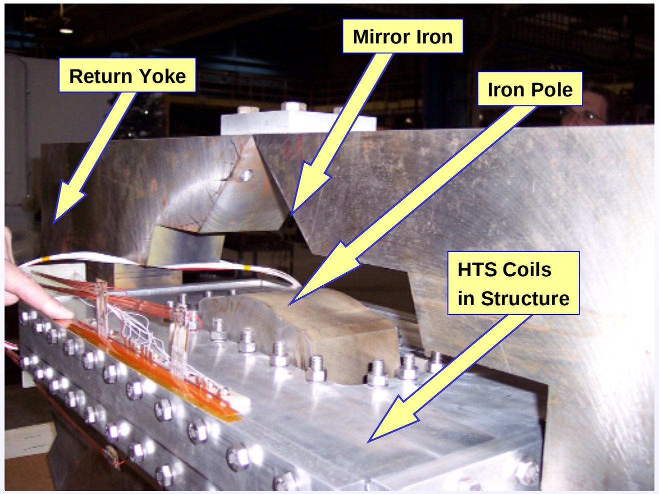
12 coils with HTS tape in year #2



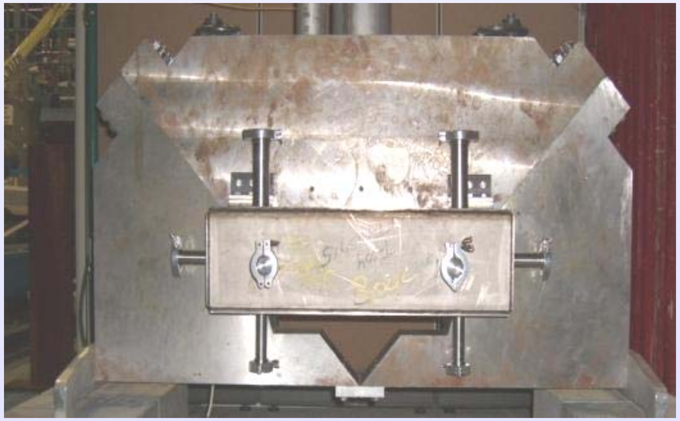
Note: A uniformity in performance of a large number of HTS coils.

It shows that the 1G HTS coil technology has now matured !

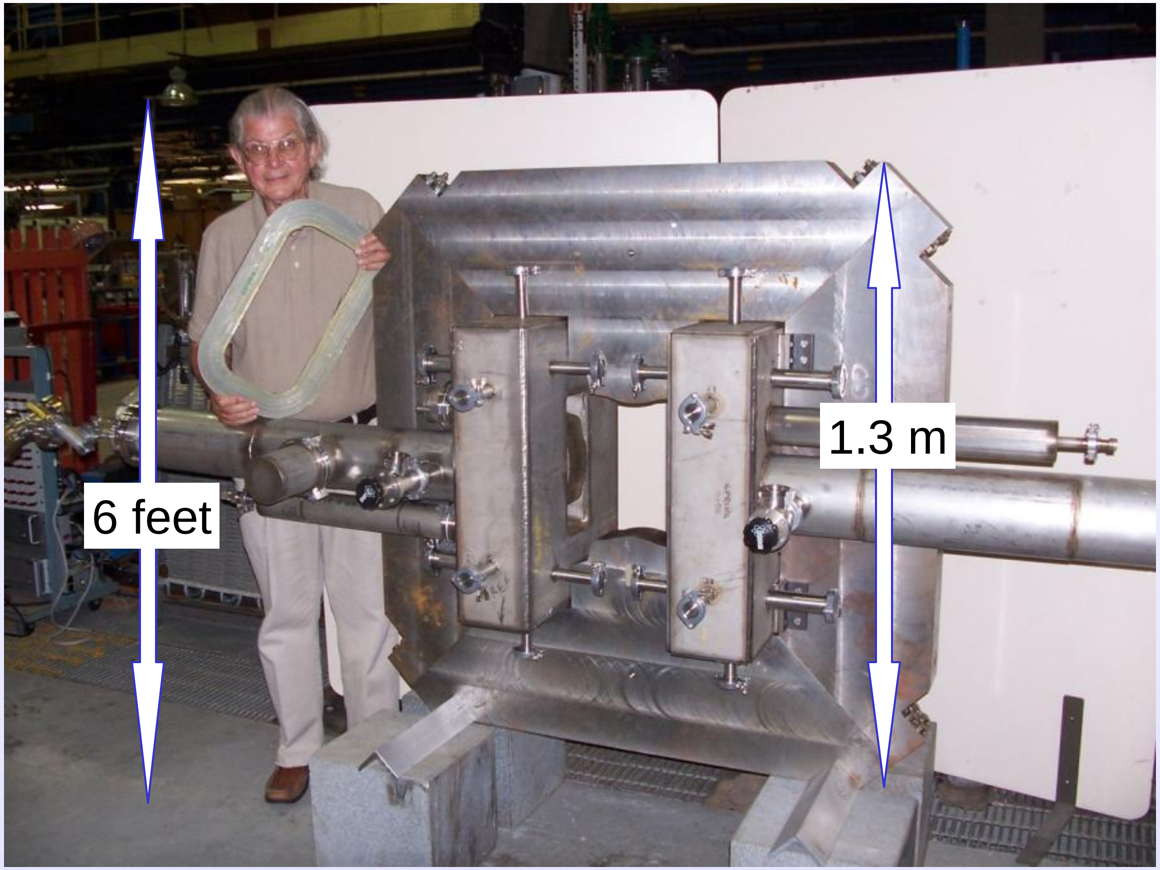
Magnet Structures for FRIB/RIA HTS Quad
(Several R&D structures were built and tested)



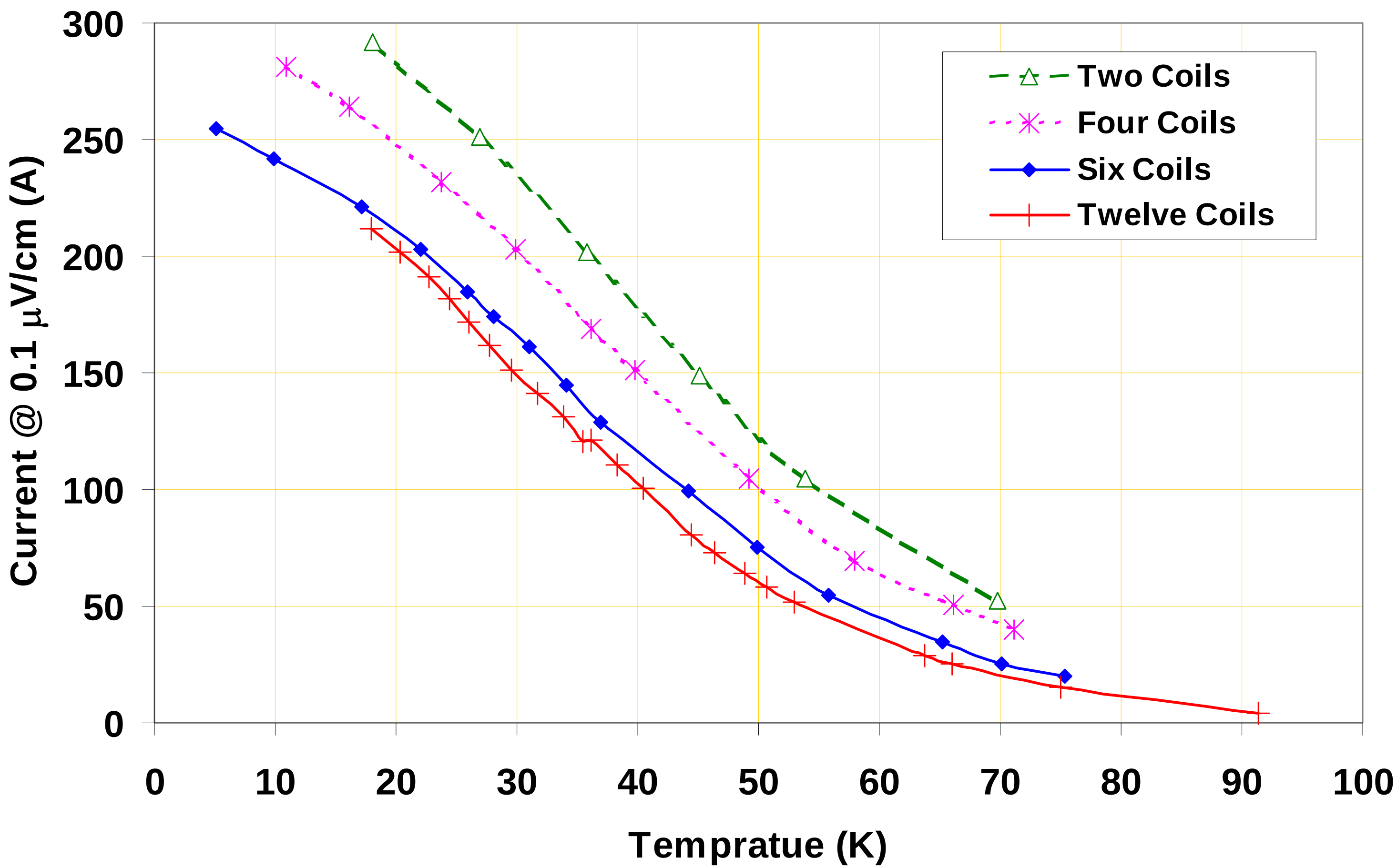
Mirror cold iron



Mirror warm iron



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



Summary of a significant R&D effort.

Measured data obtained from several structures built over a number of years

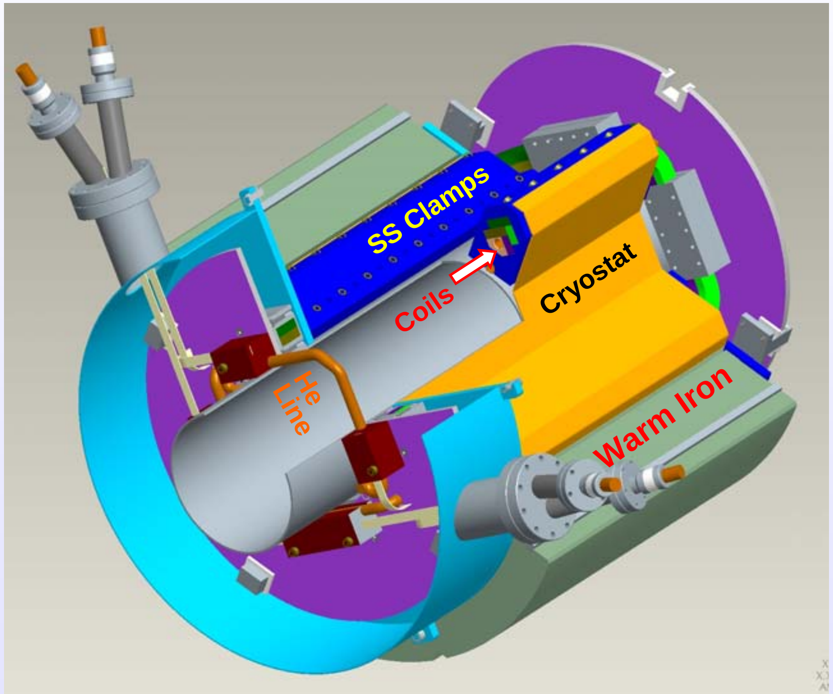
A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

Second Generation HTS Quad for FRIB with 2G (YBCO) HTS

Work on the second generation quad started; coils ready to be wound

9,000 m (4 mm equivalent) 2G HTS was recently acquired

- **Conductor from both US vendors: SuperPower and ASC**



FRIB HTS R&D Quad in cryostat

R&D coil ready to be wound with the 12 mm 2G tape

FRIB R&D : 2G HTS Coils Cooled by Cryo-coolers

Second Generation (2G) racetrack coils cooled by Cryo-coolers

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Superconducting Magnet Division

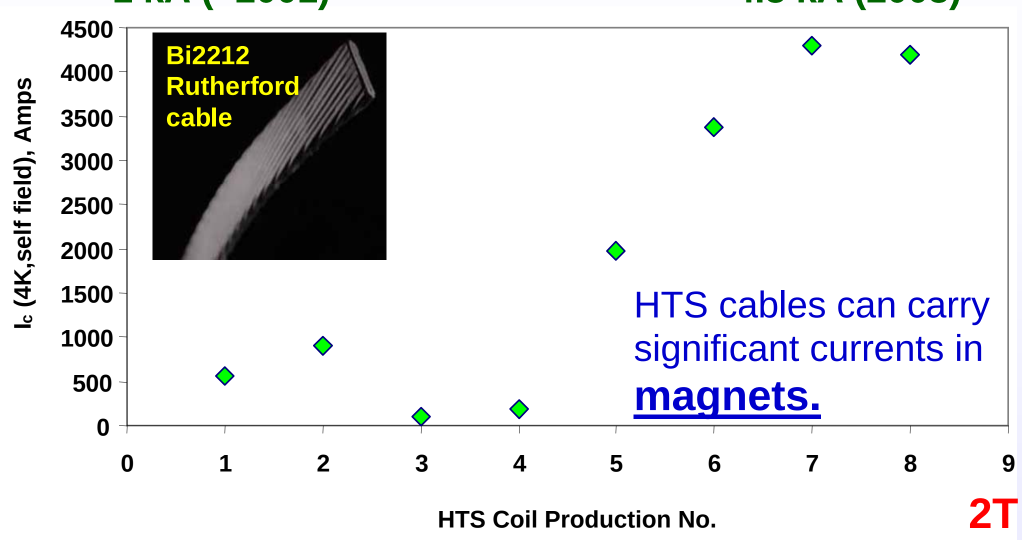
HTS Common Coil Dipole with Bi2212 Rutherford Cable

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

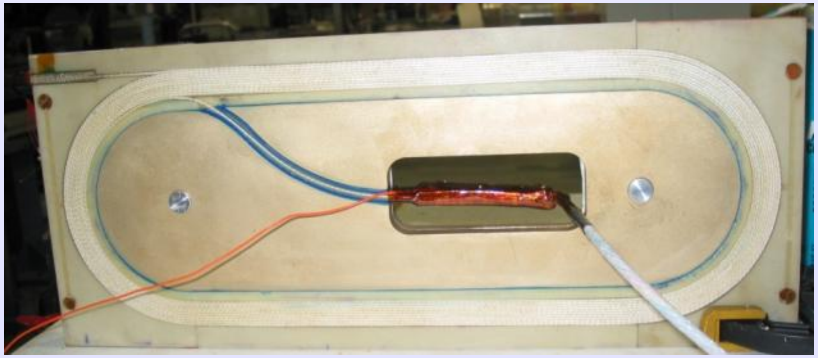
Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	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$_3$Sn	1970	212 [129]	0.66
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb$_3$Sn	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$_3$Sn coils (total 6 coils)	4200	272 [212]	1.84

Earlier coils
<1 kA (~2001)

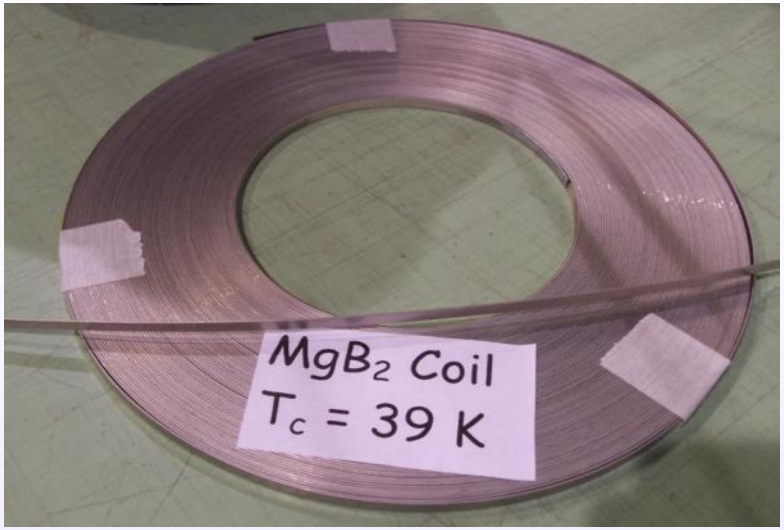
Later coils
4.3 kA (2003)

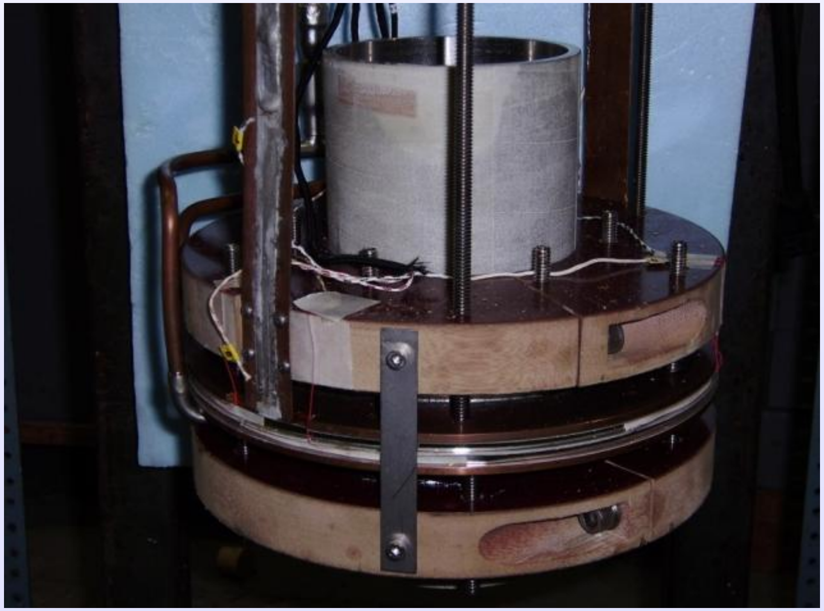


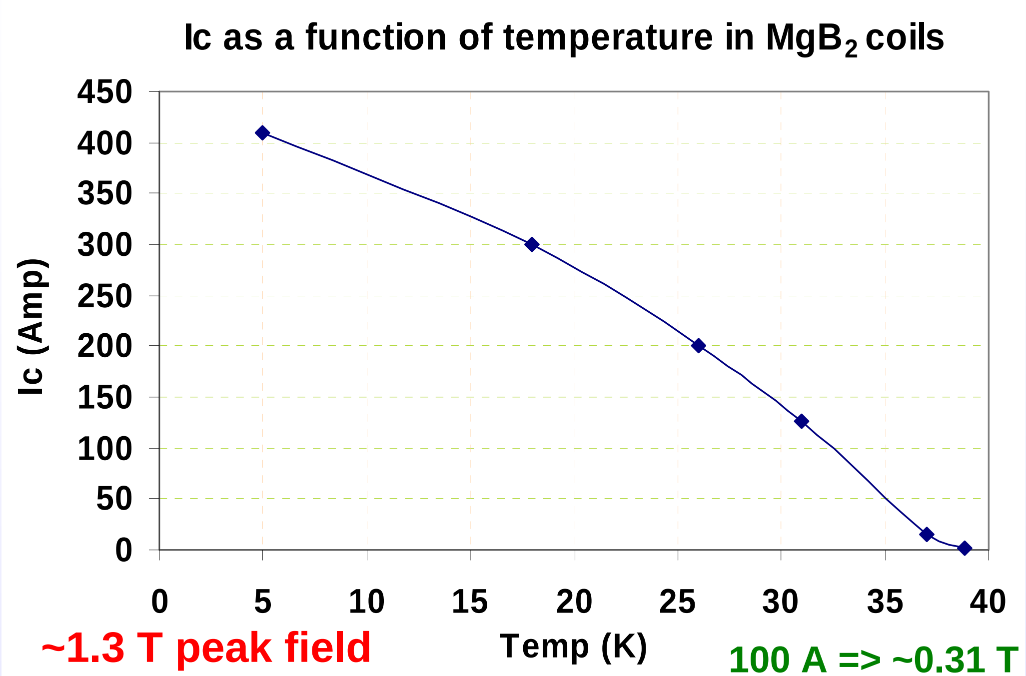
Racetrack HTS coil with Bi2212



MgB_2 Solenoid made with Conductor from COLUMBUS SUPERCONDUCTORS SpA







~1.3 T peak field

100 A => ~0.31 T

MgB_2 Solenoid with a double pancake coil

Coil i.d. = 100 mm

Coil o.d. = 200 mm

# of Turns = 80

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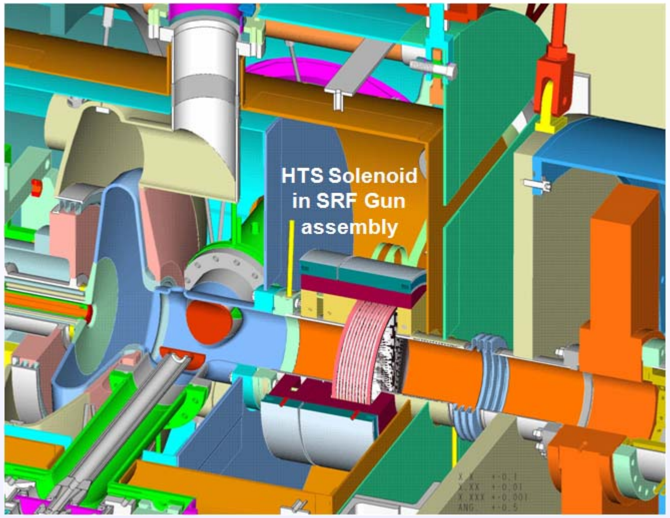
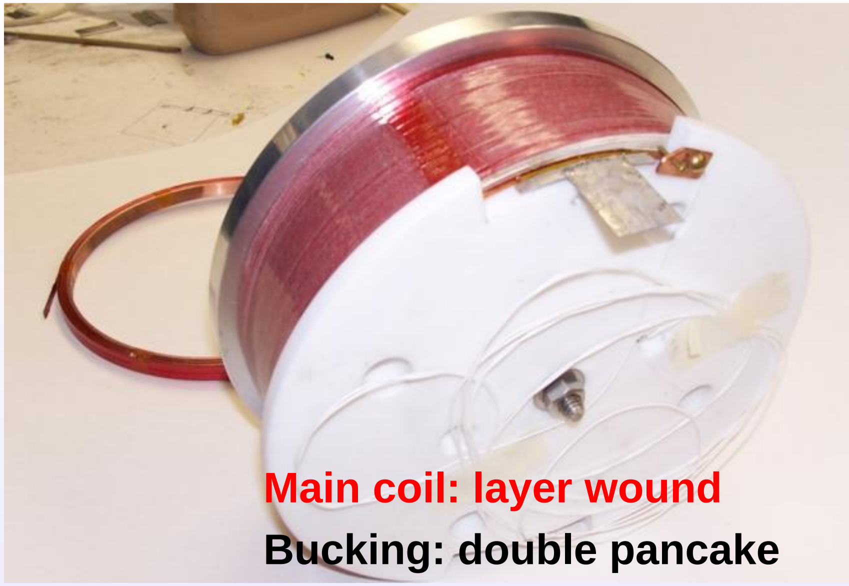
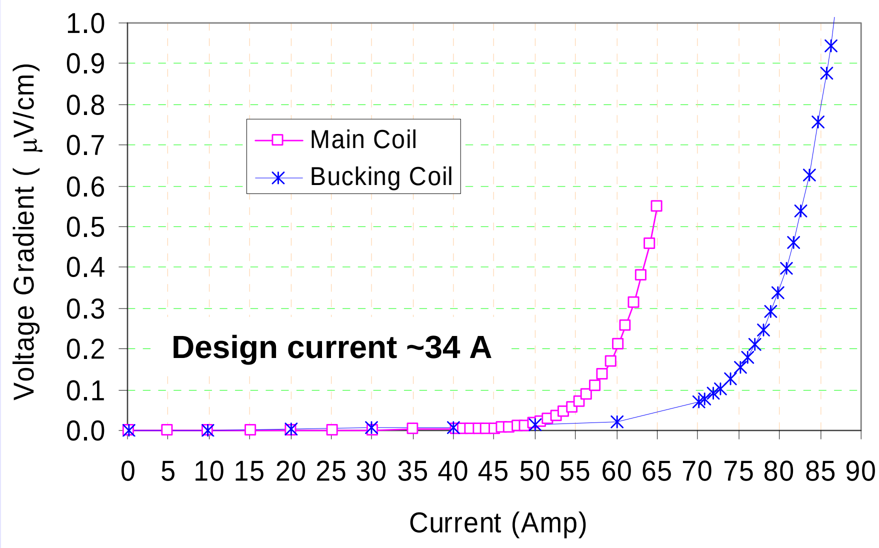
HTS Solenoid for the Energy Recovery Linac (ERL) at BNL

- HTS solenoid provides a unique technical solution.
- It is placed in cold to warm transition region (~20 K)







R&D For High Field HTS Magnets

Two major high field HTS magnet programs:

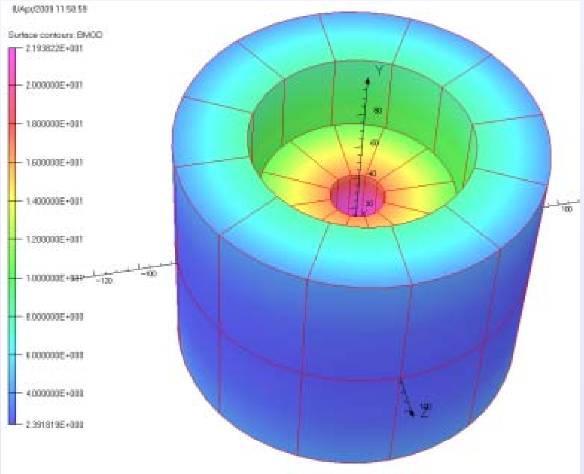
- 20^+ T HTS solenoid for a muon collider
- 25^+ T HTS solenoid for a Superconducting Magnetic Energy Storage (SMES) system

Both are based on 2G HTS from SuperPower.

- An all HTS solenoid is much more challenging than a short insert coil test because of the direction of field and the forces involved.

High Field HTS Solenoid for Muon Collider (SBIR with PBL)

- **Muon collider needs very high field solenoids (~40 T) for ionization cooling. Such high field (20 T or above) s.c. magnets are only practical with HTS.**
- **Component of the programs : (1) ~100 mm, ~10 T solenoid outer solenoid and (2) 25 mm ~12 T inner solenoid (3) Create 20+T field by combing the two in one all HTS solenoid.**
- Subsequent possibilities: High field insert coil test at NHFML and Nb3Sn outer

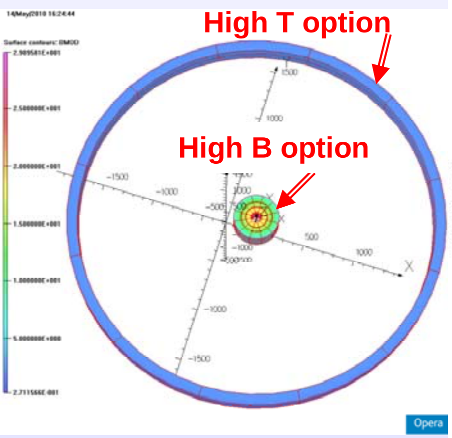


A number of HTS coils have been built and successfully tested at BNL for high field solenoid research program

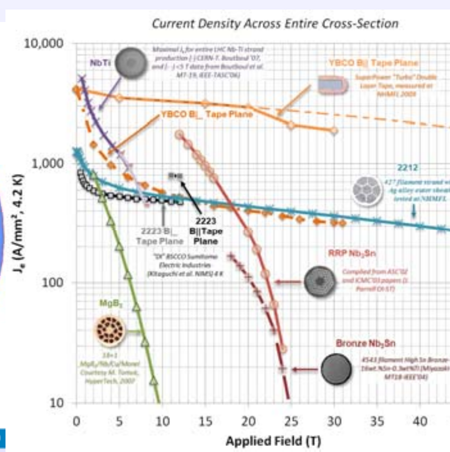
Inner and outer HTS solenoid should create >20 T

Superconducting Magnetic Energy Storage (SMES) System

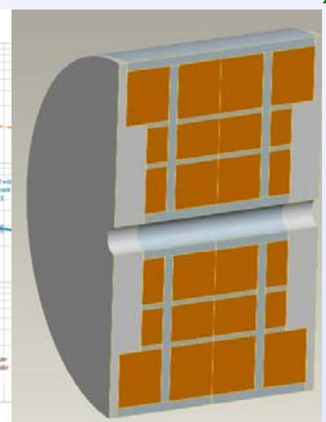
- BNL, along with its research partners, SuperPower (conductor) and ABB (power electronics), received ARPA-E funding for developing HTS SMES (5.25M$).
- HTS with high (very high) field option is used in high energy density (E α B^2) option which minimizes the cost as the conductor (not cryogenics) dominates the cost.
- There are many technical issues to be addressed as such high field 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 !!!**

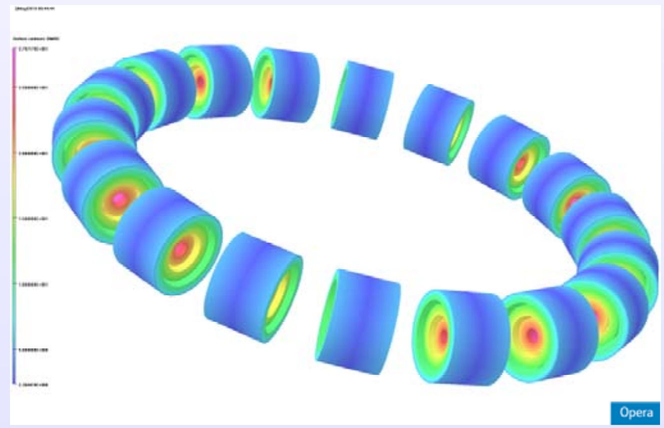


High field option reduces high conductor cost



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

Status of Low Temperature, High Field R&D at BNL

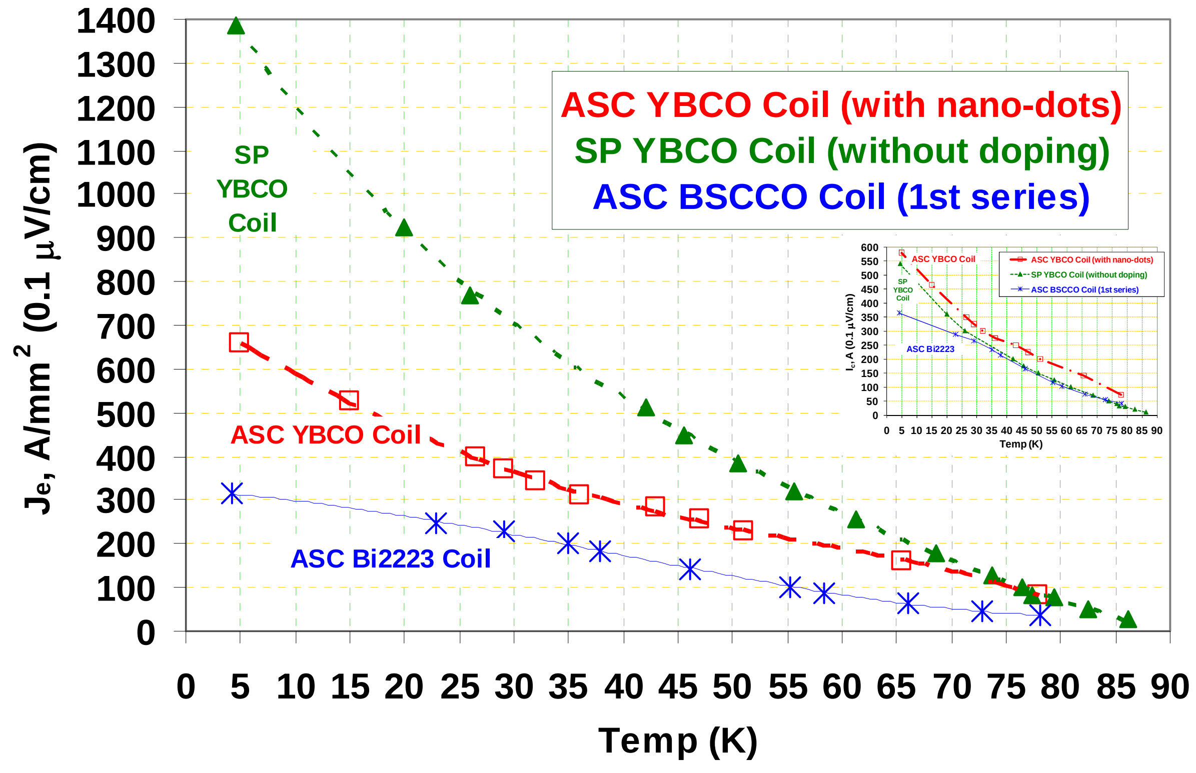
- **25 coils have been made each with ~100 m second generation HTS**

  (in addition to several 2G short coils and a large number of 1G longer coils)

- **19 of them are solenoidal coils and 6 are racetrack coils**

- **Some of these coils have been tested as a function of temperature**
  - **See next few slides**

Performance of Racetrack Coils (measured as a function of temperature)



Cu thickness: SuperPower ~ 0.045 mm; ASC ~ 0.1 mm (width = 4 mm)

If coils go normal (quench, thermal runaway):

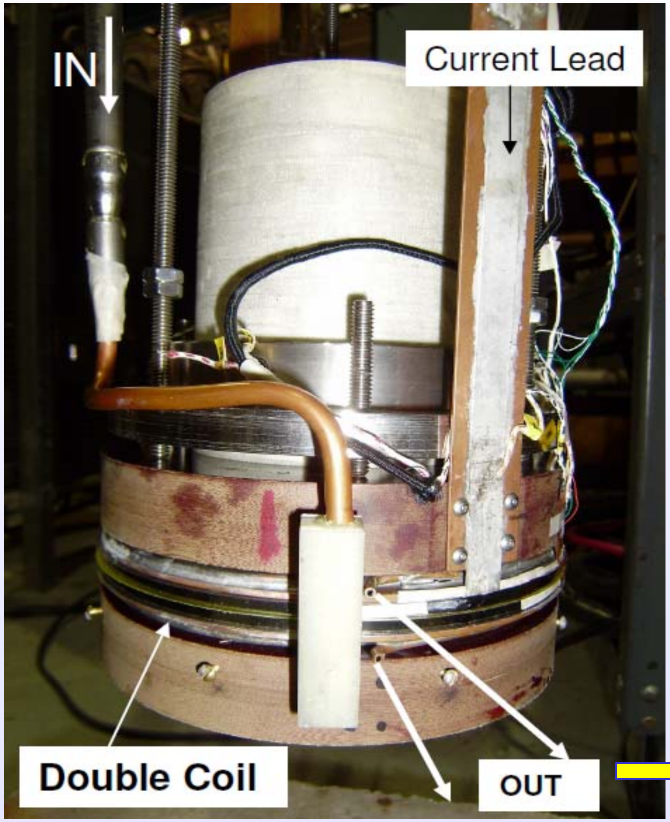
- **Current density in copper: ~1500 A/mm^2 (ASC); ~3000 A/mm^2 (SuperPower)**

These current densities are amazing ...

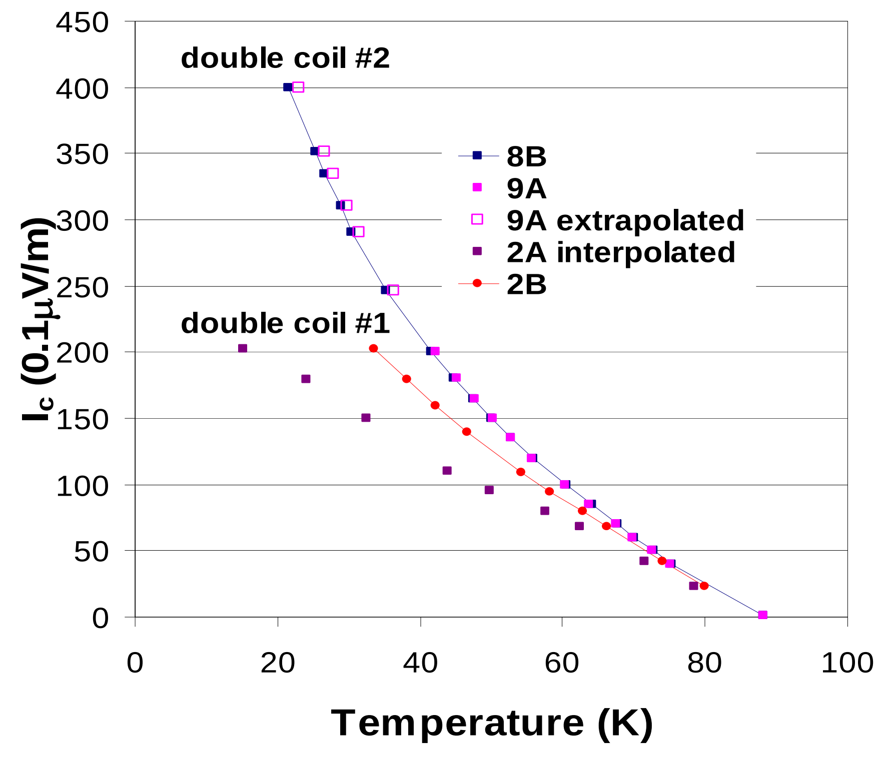
- ***May be too demanding for protection and should be avoided in real applications.***
  - **However, such tests are OK and are even desirable during R&D phase.**

Recent Low Temperature Solenoid Coil Test Results

10 T and 20 T designs need only 220 A with SuperPower Tape



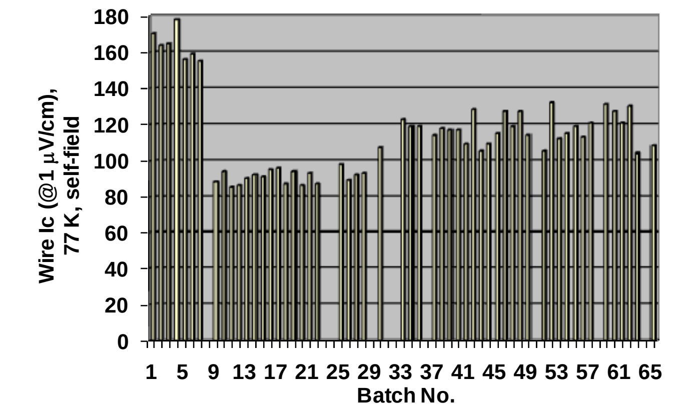
Cu current density @220 A : ~1200 A/mm²



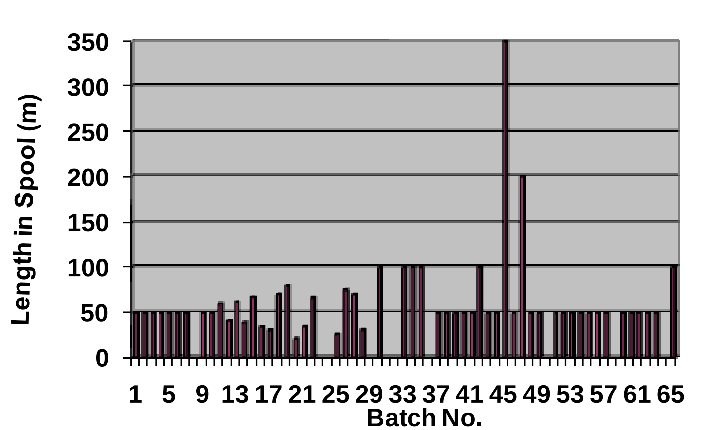
These high current tests may be too demanding for protection...
Were we too lucky or spoiled by earlier racetrack coil tests?

Conductor and Coil Performance

2G HTS WIRE

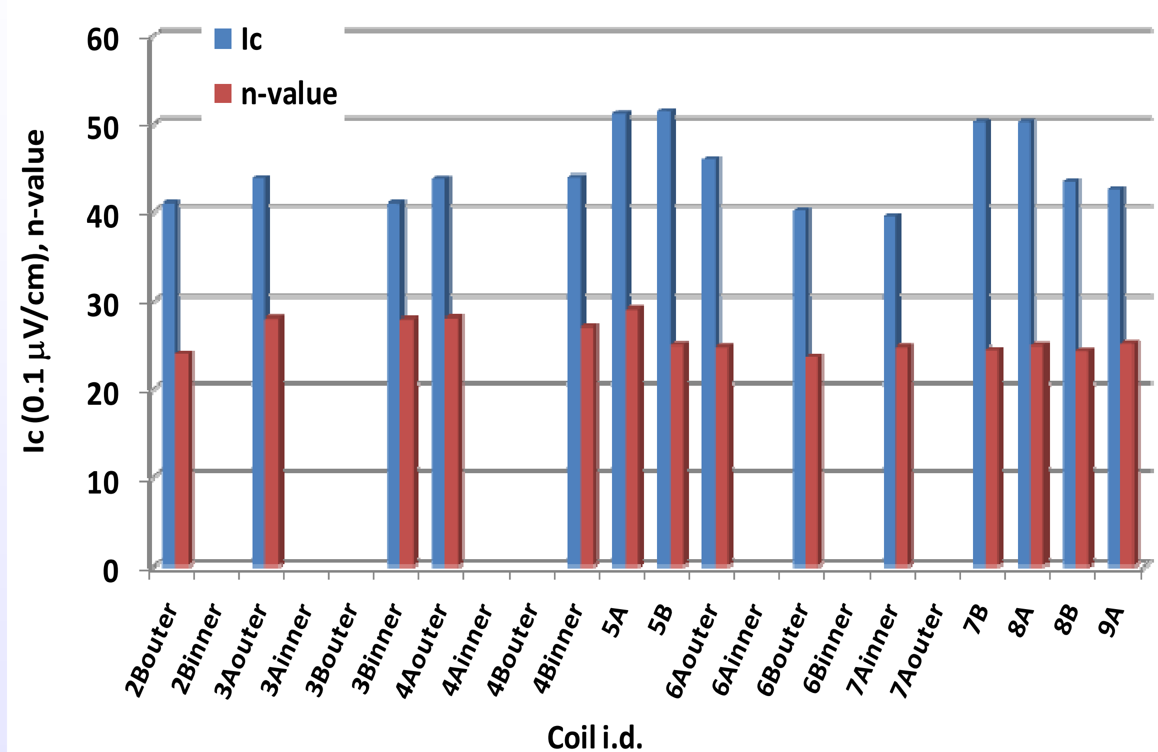


Wire was delivered in several batches. Somewhat different Ic from batch to batch.



Each coil needs 100 meter tape. One splice per coil was allowed for cost reasons.

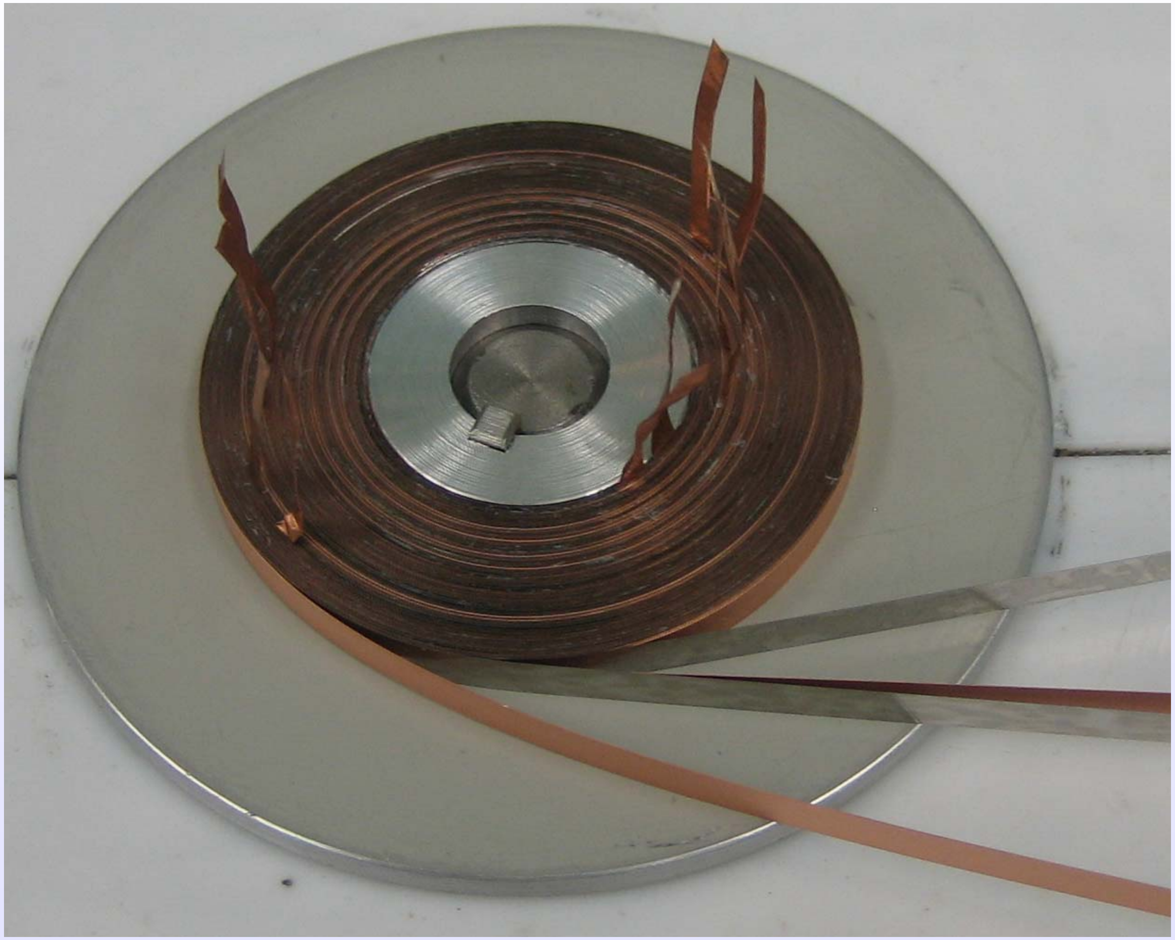
2G HTS SOLENOID COILS (19 similar built so far)



LN_2 Testing

To develop technology, it is important to build and systematically test a large number of coils.

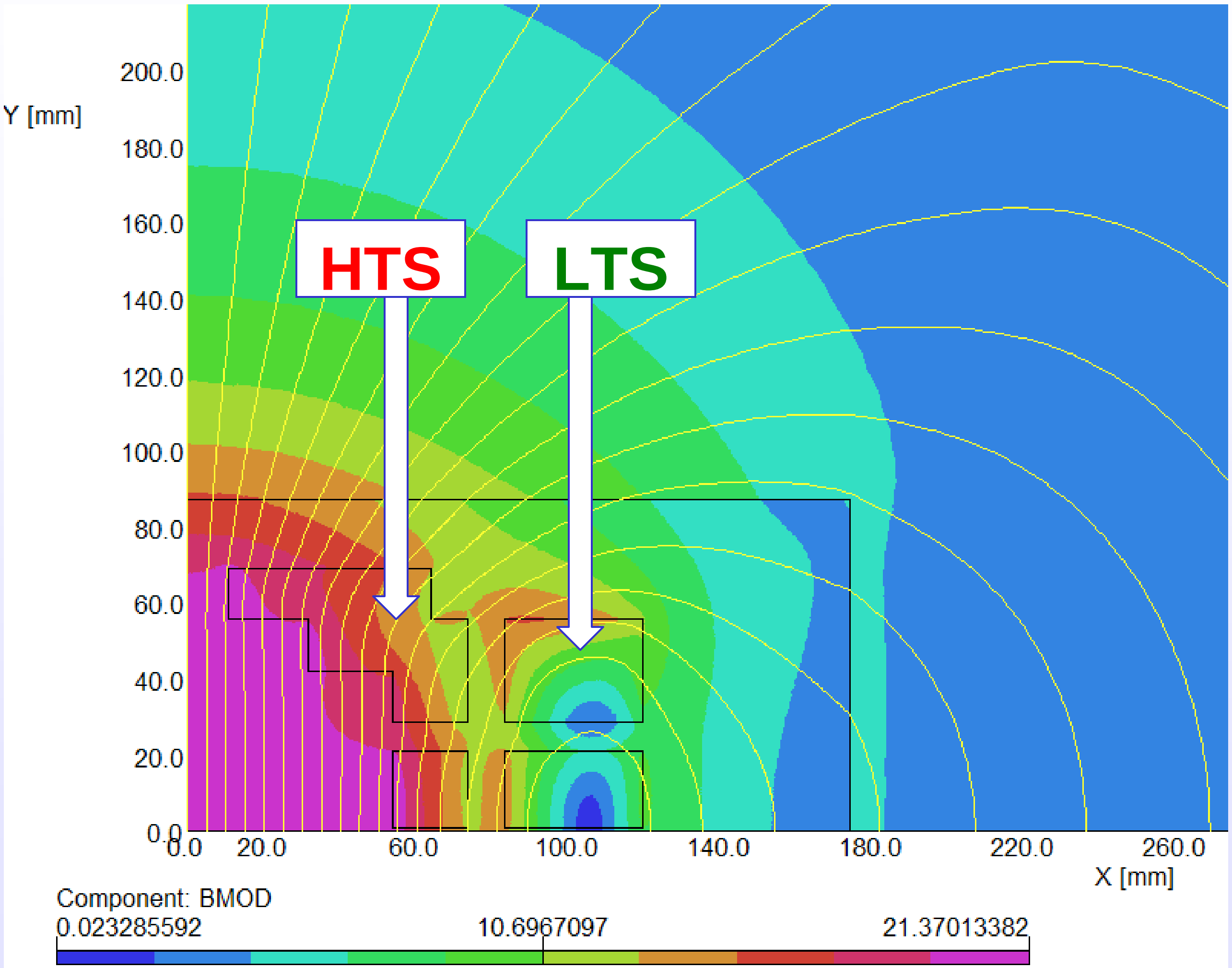
Experimental HTS Short Coil R&D Program to Help Develop Technology



Some critical issues:

- **Quench protection**
- **Stress on the narrow face**

Conceptual 20 T Hybrid (HTS+LTS) Design for LHC Energy Upgrade Dipole



Possible options for HTS:

- **Bi2212 Rutherford cable**
- **Roebel Cable**
- **Wider 2G tape (study magnetization)**

Possible options for LTS:

- **Nb_3Sn (React and Wind or Wind & React)**
- **NbTi (if field is dropped enough - cost analysis?)**

Examine all options at the initial stage and adjust options depending on the progress in the field.

PAC 2011 Papers on HTS from BNL

Wide range of HTS R&D activities will be presented through the following papers at PAC2011:

1. Engineering Design of HTS Quadrupole for FRIB – Cozzolino, et al.
2. Design, Construction and test of Cryogen-free HTS Coil Structure – Hocker, et al.
3. Influence of Proton Irradiation on Second Generation HTS in Presence of Magnetic Field – Siroyanagi, et al.
4. Measurements of the Effect of Axial Stress on YBCO Coils – Sampson, et al.
5. Open Midplane Dipole for Muon Collider – Gupta, et al.
6. Design Construction and Test Results of HTS Solenoid for ERL – Gupta, et al.
7. HTS Magnets for Accelerator and Other Applications – Gupta
8. Quench Protection Studies in HTS with Small Coils – Shiroyanagi, et al.

SUMMARY

Highlight of BNL HTS Magnet R&D Program:

- 50-60 km (4 mm tape) by 2012 and 20-30 T all HTS magnets
- An unprecedented and challenging opportunity to develop HTS magnet technology

LHC Energy Upgrade Proposal:

- Use of HTS is must for magnets 20 T or above
- Looking forward to contributing to LHC upgrade (indirectly or directly) with our significant magnet HTS R&D program