Progress Towards
A High-field HTS Solenoid

Ramesh Gupta
For PBL/BNL Team

Overview

- **High Field HTS Solenoids SBIR**
  - **Fields approaching 35 to 40 T (with multiple proposals)**
  - **Status (including related R&D) 🡐 Focus of this presentation**

- 5 minute overview of HTS magnet R&D at BNL (sharing resources & experience)
  - Several significant programs using ***tens of kilometers of HTS***

- **Summary**

➢ **Note 30 T operational (Palmer, new) means ~35 T design**

SBIR for High Field Solenoids

Collaboration between Particle Beam Lasers (PBL) and BNL:

- A useful collaborative program between PBL & BNL to develop high field superconducting solenoid technology for muon collider

- PBL brings ideas, persons with significant experience and funding through SBIR

- BNL has several ongoing HTS programs with funding from a variety of sources. Synergizing various R&D allows a shot of stated goals within the limited budget permitted by individual SBIR

List of Participants

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

High Field HTS R&D Solenoid for Muon Collider

R. Gupta, M. Anerella, G. Ganetis, A. Ghosh, H. Kirk, R. Palmer, S. Plate, W. Sampson, Y. Shiroyanagi, P. Wanderer
Brookhaven National Laboratory

B. Brandt, D. Cline, A. Garren, J. Kolonko, R. Scanlan, R. Weggel
Particle Beam Lasers

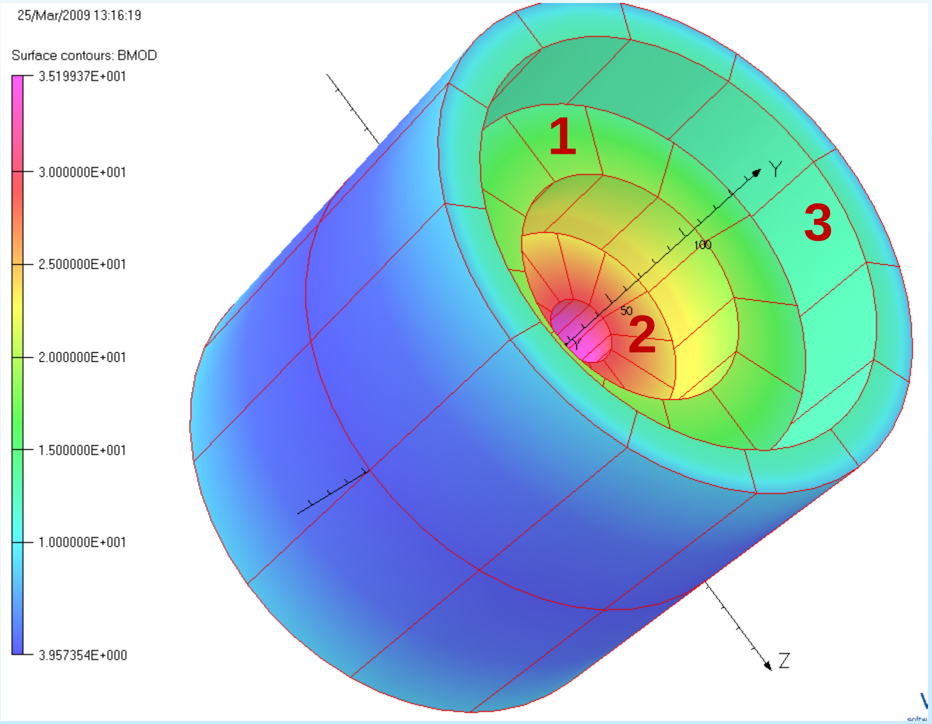
Overall Program Strategy

- There is not enough funding in one SBIR for a 35-40 T solenoid
- However, this could be only be done with a series of SBIR
  - But everyone of these proposals must be attractive in its own right
- There are good technical and other reasons to split the program
  - Large Loretz forces cause large integrated stresses and hence the solenoid needs to be split in several blocks anyway to manage stress accumulation
  - Sequencing also allows lessons learnt from one SBIR to apply to the next

Components of 35-40 T Solenoid

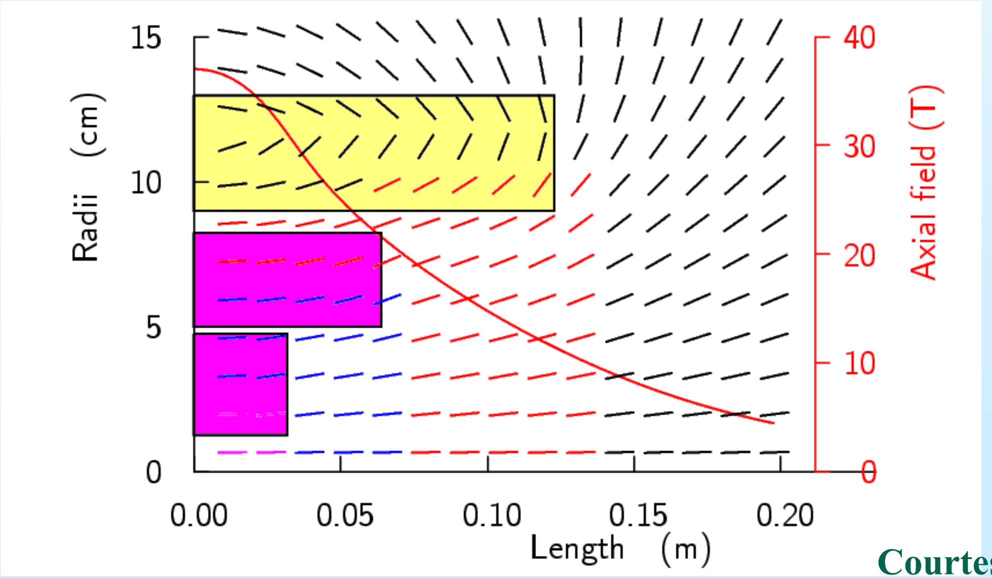
SBIR proposals from PBL:

1. Phase II #1, 08-10 (funded): ~10 T HTS solenoid (middle)
2. Phase II #2, 09-11 (funded): ~12 T HTS (inner)
3. Phase 1, 11-12 (proposal under review): 12-15 T Nb_3Sn (outer)

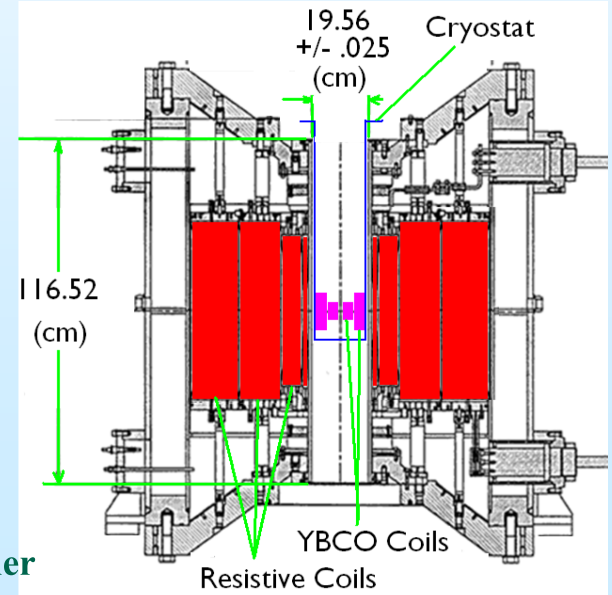


Overall Programmatic Features

- The dimensions of all solenoids have been carefully chosen so that one fits inside the other and the two HTS solenoids (generating 20+ T) fit inside the NHMFL ~19 T resistive solenoid
- As a part of the Phase II SBIR #2, we will test the ~20+ T HTS solenoid in the background field of NHFML ~19 T resistive magnet to test HTS technology at fields approaching 40 T
- Third SBIR (currently a Phase I proposal), would build a Nb_3Sn solenoid with Rutherford cable and will attempt a ~35 T superconducting solenoid and demonstrate the technology



Courtesy: Bob Palmer



Ambitions and Overall Challenges

There are number of major challenges in 35-40 T superconducting solenoid

Each SBIR takes on those challenge one at a time in a sequential manner:

1. ~10 T HTS, 100 mm i.d. HTS solenoid:
   - previous ~10 T HTS solenoid had ~19 mm i.d.; larger aperture =>larger stresses
2. 20+ T all HTS solenoid with new ~12 T HTS insert together with the above
   - this will be the highest field all HTS solenoid ever built
   - when tested in the background field of ~19 T resistive solenoid at NHMFL, HTS will be subjected to unprecedented level of stresses
3. 12-15 T Nb_3Sn outer solenoid to first time build a ~35 T superconducting solenoid
   - this is an attempt to make highest field superconducting solenoid ever built
   - earlier high field Nb_3Sn solenoids have been made with CICC; Rutherford cable will allow much higher current density (and hence compact size, etc.)

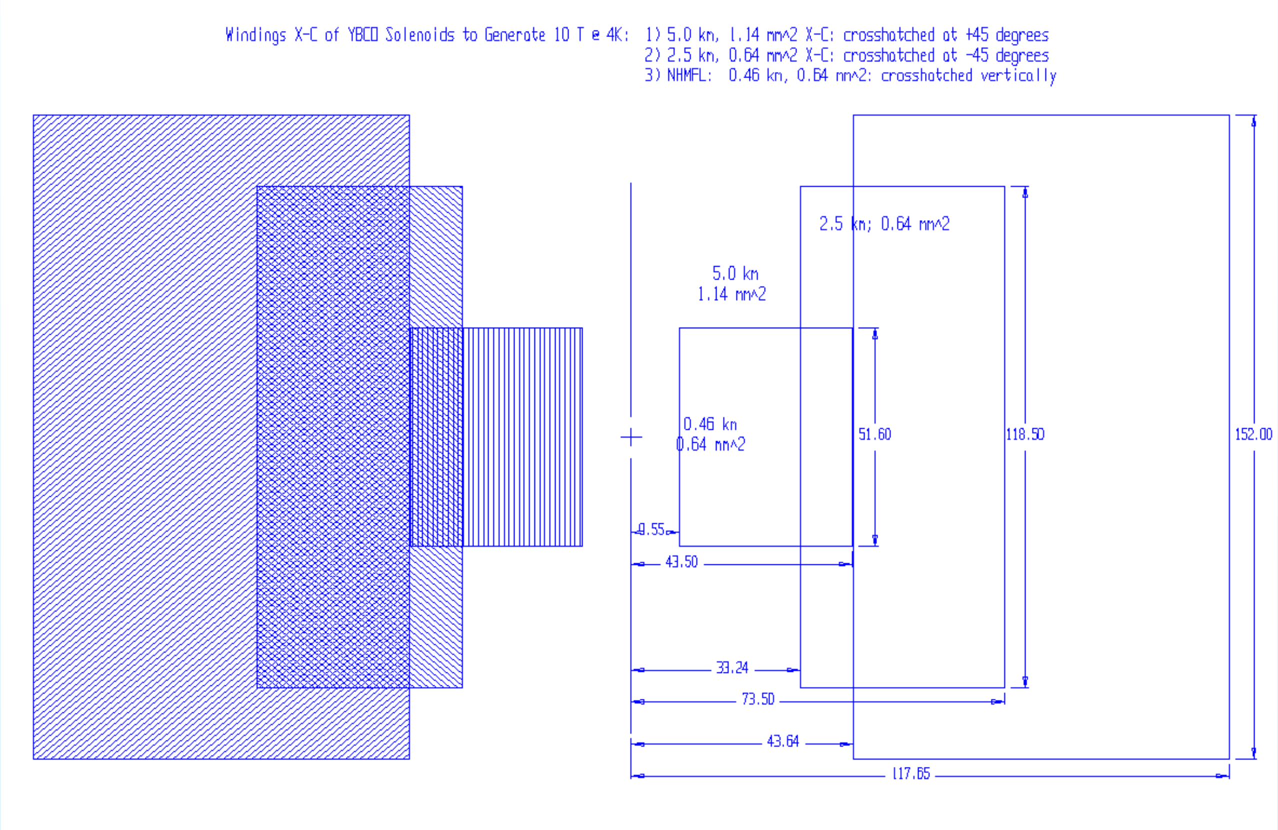
SBIR #1

Design, Progress and Status

HTS Solenoid SBIR #1

Solenoid in original proposal: 10 T@4K and 5 T@33 K with 66.5 mm coil i.d.

- We made this task more ambitious by increasing coil i.d. to 100 mm



Under construction:

Coil o.d. = ~165 mm

Type of coil : Pancake

No. of pancakes: 24

Conductor: 2G HTS from SuperPower

~0.1 mm X 4.2 mm

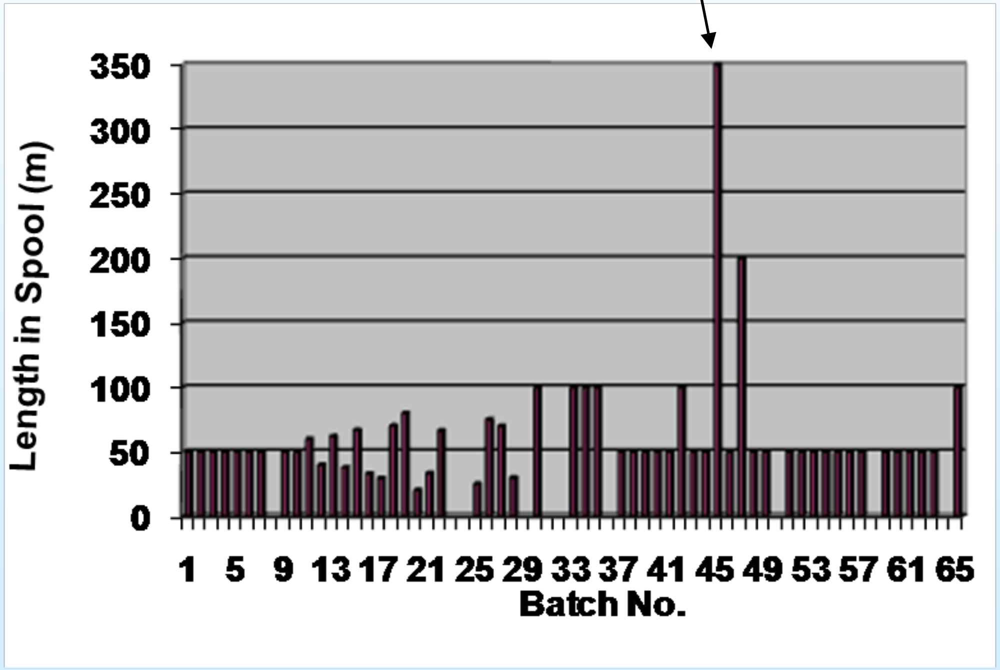
100 meter per pancake

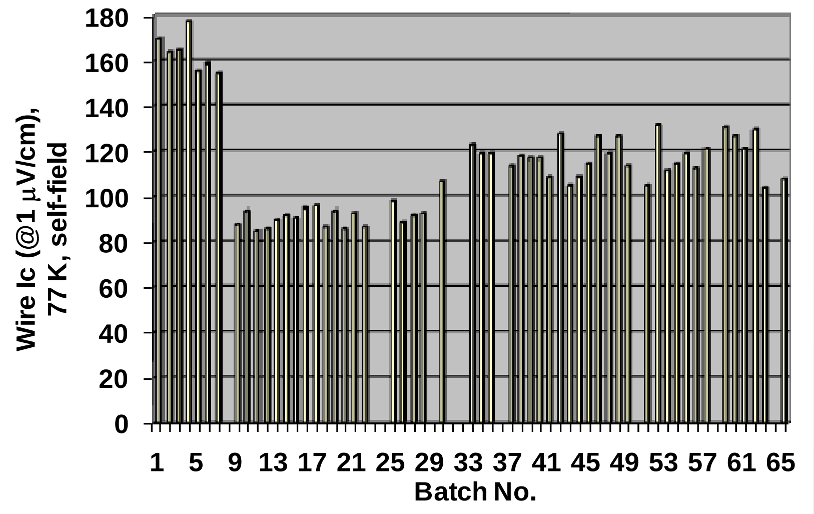
Original Proposal (Courtesy: Bob Weggel)

Conductor Received from SuperPower

Each coil needs 100 meter tape.
One splice allowed in 100 m for cost reasons.

350 m piece length for the price/m of 50 m





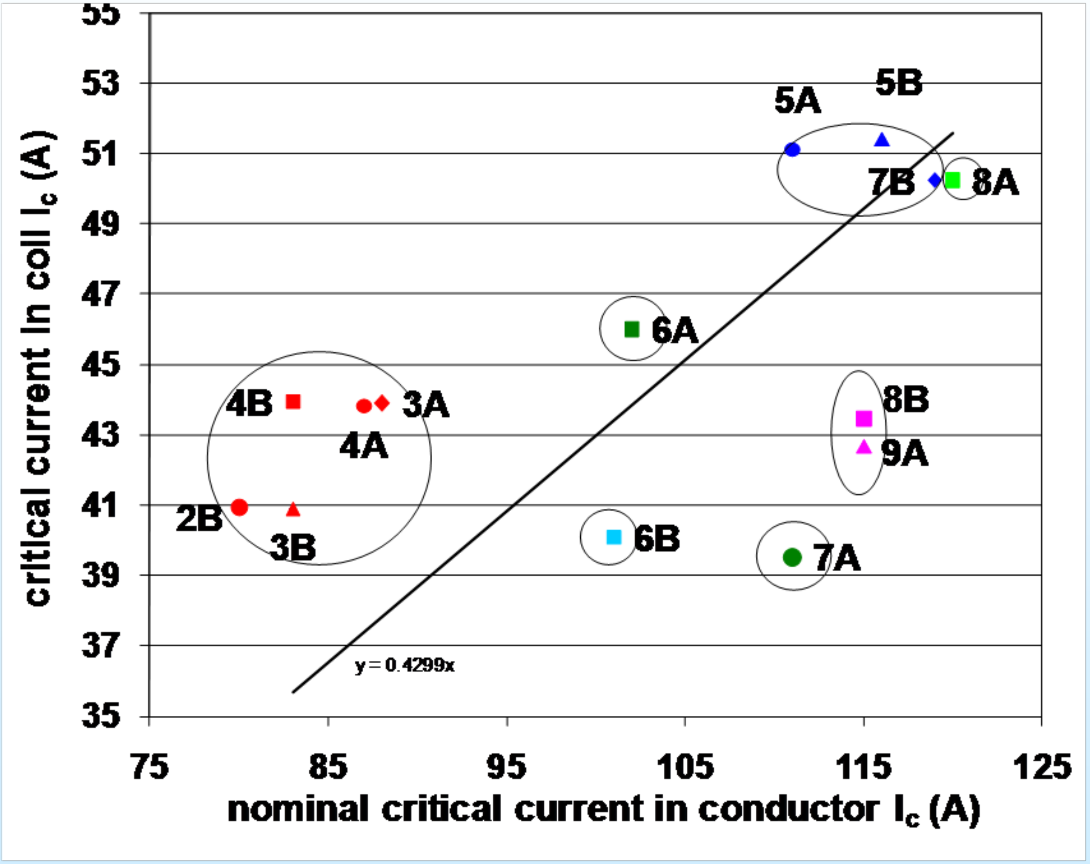
Somewhat different I_c from batch to batch (spec: 100 A)

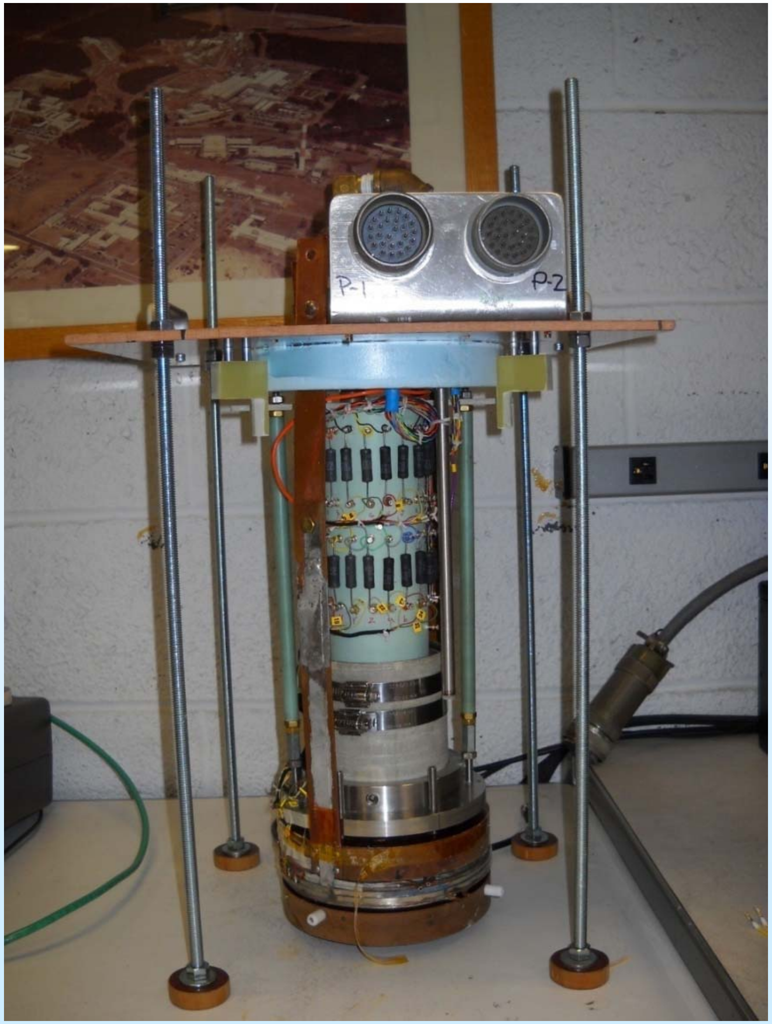
Current Status of the BNL/PBL HTS Solenoid SBIR #1

- 29 coils for 100 mm aperture solenoid have been wound with stainless steel insulation
- All coils have been individually tested at 77 K (24 coils needed for the solenoid)
- This is a significant size HTS R&D program with ~3 km of conductor already consumed
- 24 coils have been selected after they passed all QA requirements, including 77 K test
- With 2.4 km in 24 pancakes, this solenoid is made with over five times than that used in previous SuperPower solenoid
- We should have the test result of completed the solenoid in about six months

"Wire Ic Coil Ic Correlation" and "New Test Setup"

Correlation between 2G Coil Ic and Wire Ic at 77 K



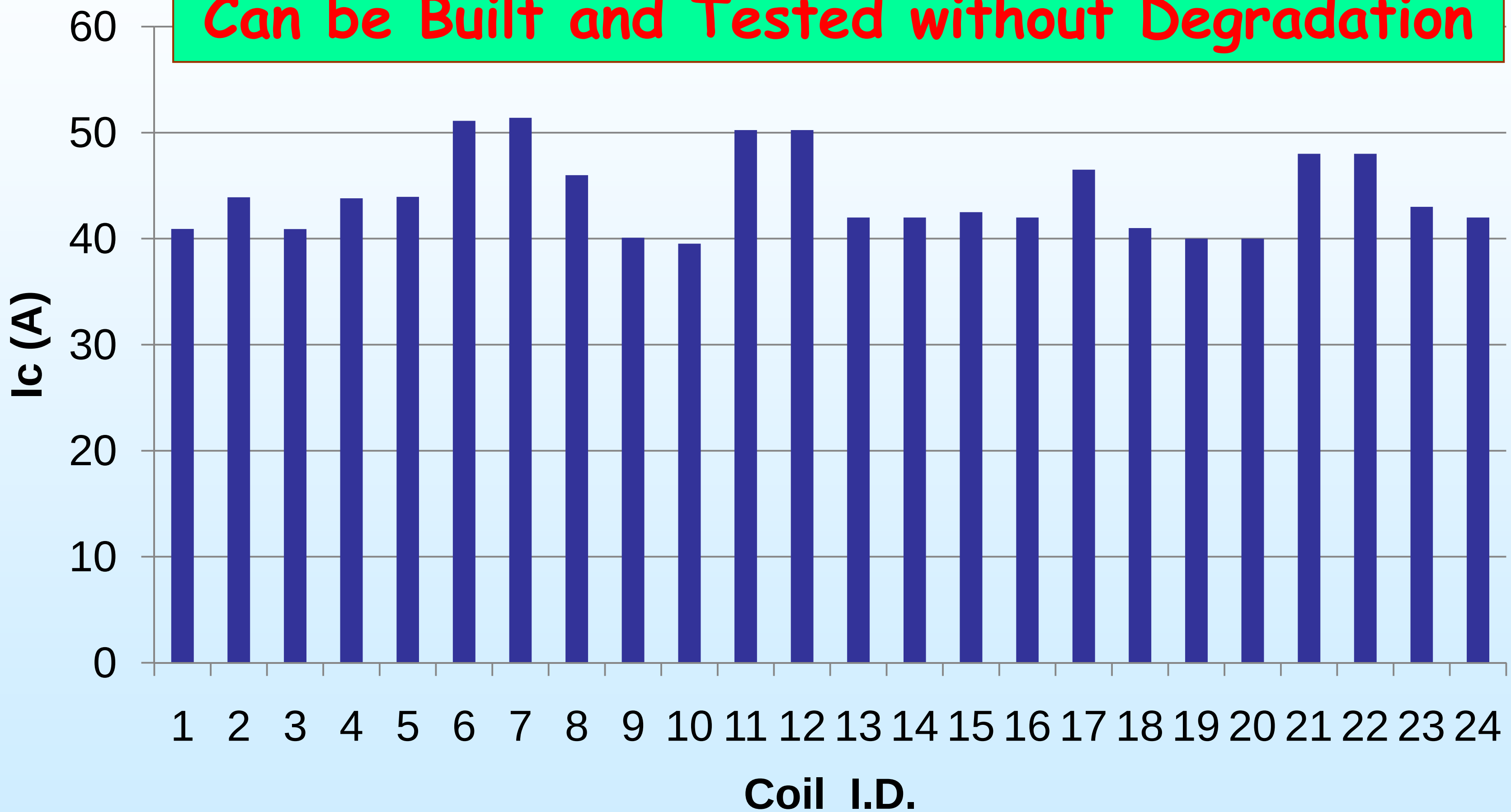


New Test Setup

What will be the correlation at 4 K?

Test Results of 24 Coils at 77K

Proof That A Large Number of 2G HTS Coils Can be Built and Tested without Degradation



Field parallel ~0.5 T; field perpendicular ~0.3 T @40 A

SBIR #2

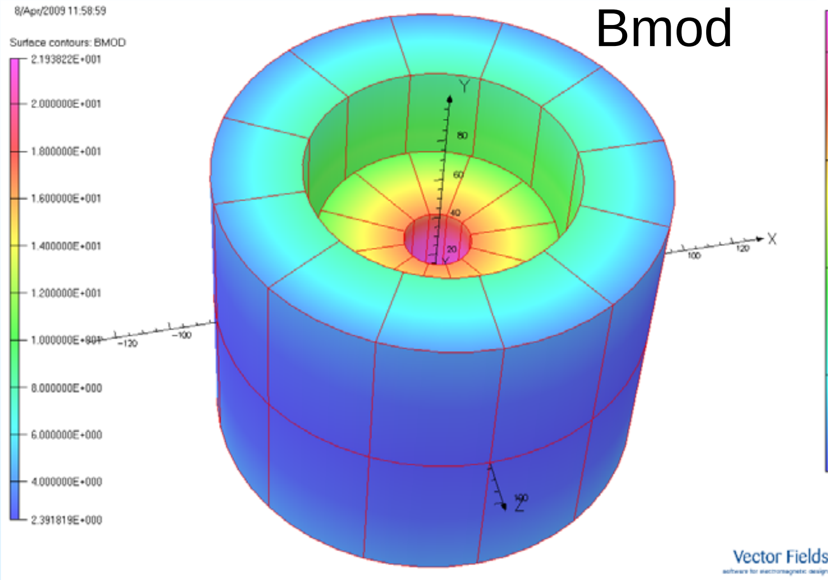
Design, Progress and Status

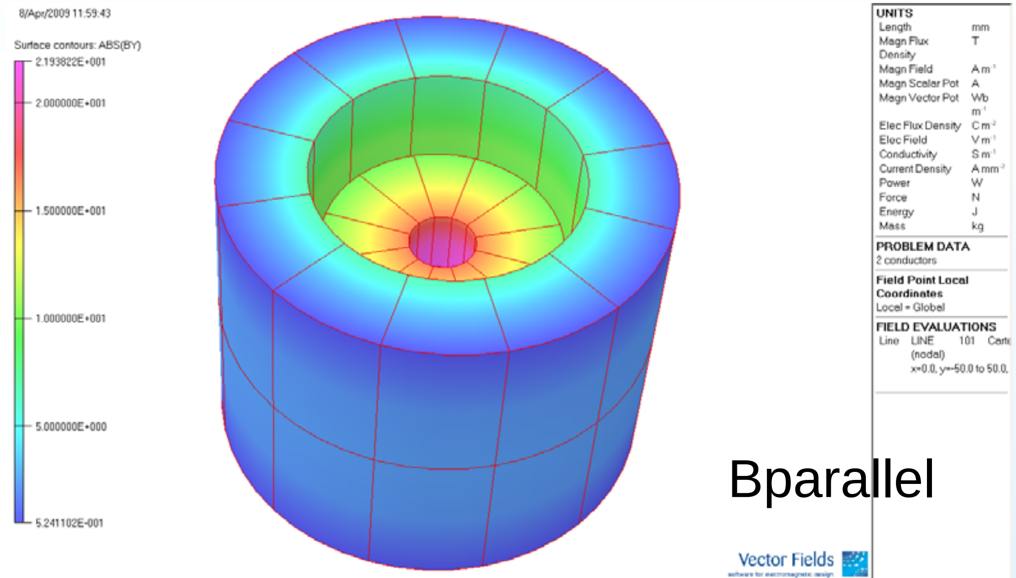
Motivation and Purpose

- Muon collider solenoid will be consisted of several layers
- Each of these layers can be made of different materials
- Use conventional Low Temperature Superconductor (LTS) in outer layer(s)
- Two options for insert:
  - ➢ Resistive (like that used in NHMFL solenoid in Florida)
  - ➢ or HTS (as LTS won't do at 30-40 Tesla fields)
- Resistive insert would consume hundreds of MW power – not practical

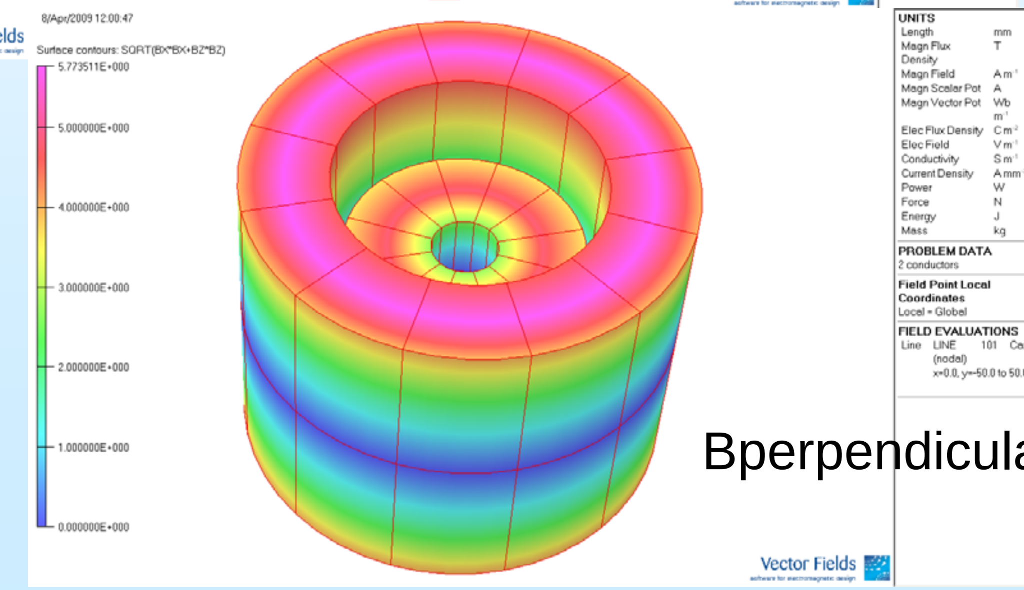
❖ **Development of 20+ T HTS solenoid technology is essential for a 35-40 T muon collider solenoid even while using LTS for outer layer(s)**

YBCO Solenoids





1. First PBL/BNL Phase II SBIR ~10+ T solenoid (i.d. = 100 mm, o.d. = 165 mm, 24 pancakes)
2. Second PBL/BNL Phase II SBIR ~12+ T insert (i.d. = 25 mm, o.d. = 95 mm, twelve pancakes)
3. Together 20+T Field



Current Status of the BNL/PBL HTS Solenoid SBIR #2 (a)

- **Design needs twelve new pancake coils**
- **Each will have i.d. of ~25 mm and o.d. ~95 mm**
- **Each coil will be made with 50 meter of 100 micron thick, ~4.2 mm wide 2G HTS from SuperPower (already received)**
- **There will not be any splice in any coil**

Current Status of the BNL/PBL HTS Solenoid SBIR #2 (b)

Five out of twelve coils have been wound

Two coils have stainless steel insulation and three kapton insulation

- **A solenoid made with four coils will be taken to NHMFL for insert coil test in the background field of ~19T resistive solenoid**

Upcoming Insert Coil Test at NHMFL

- **HTS solenoid test in background field during March 21-25, 2011**
  - PBL Organizer: Ron Scanlan
  - BNL participants: Yuko Shiroyanagi and Piyush Joshi
  - NHMFL point of contact: Huub Weijers

- **A few purpose of these tests**
  - Compare stainless steel and kapton insulation in coils made with HTS tape
  - Examine coil-to-coil splice under large Lorentz forces
  - Examine safe operation under multiple cycles to 250 Amp (or so)
  - Examine influence of varying operating conditions (ramp rate, background field, etc.). Time possible for other experiments

- **A dry run for the 20 T HTS solenoid test (in about a year) to fields approaching 35-40 T in the same background field magnet**

Significant Technical Challenges in High Field HTS Solenoids

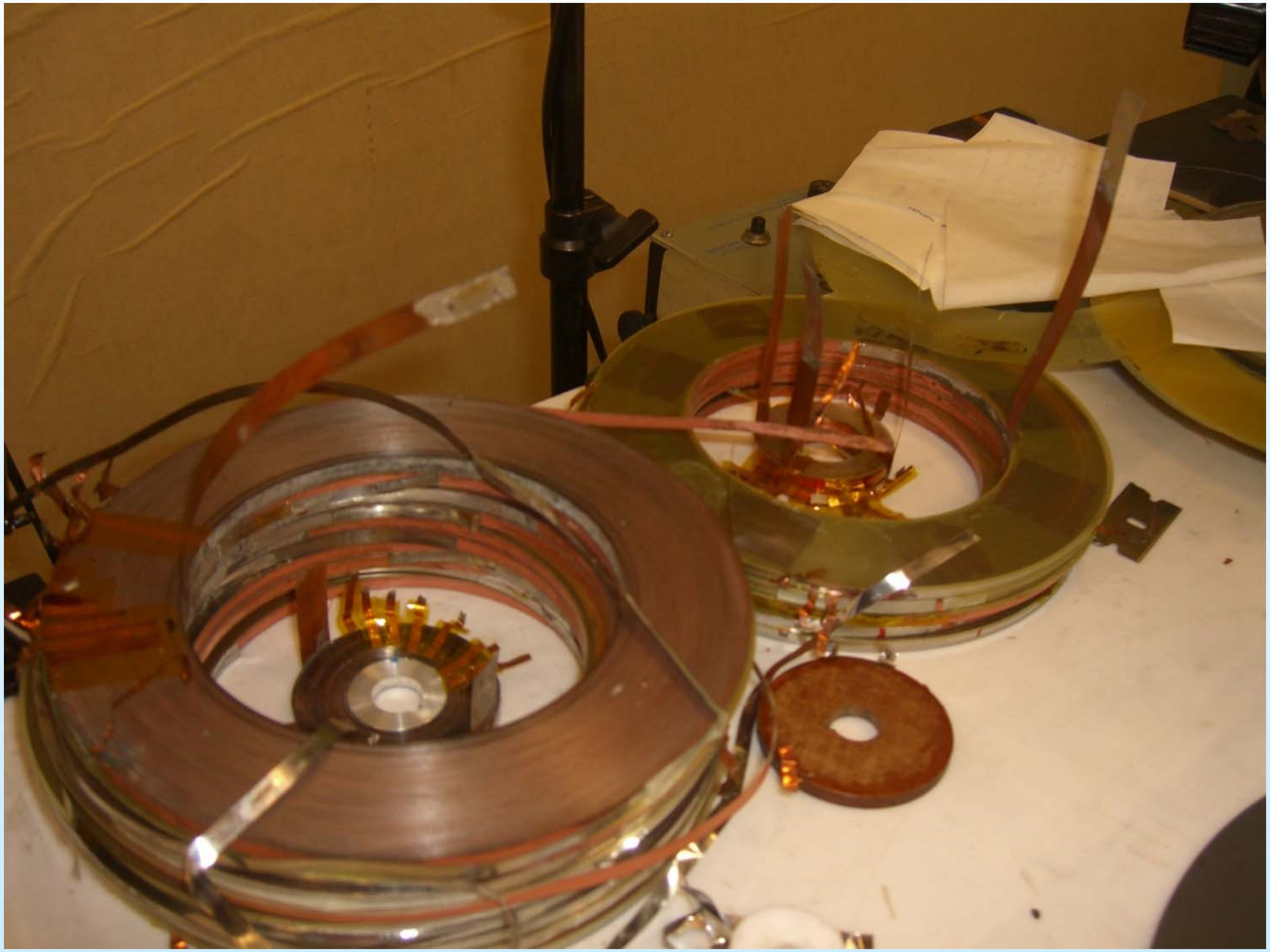
- Length of conductor: Shorter length requires splices within coil (not desired). However, now available in hundreds of meters thus may need few to none.
- Quench protection: by far the biggest challenges - ongoing R&D to deal with it.
- Small imperfections in conductor that turn into significant defects under demanding conditions of high fields: need more improvement in the conductor and/or quench protection system to catch problem earlier.
- Anisotropic magnetic & mechanical properties: Measure and deal in the design
- Large stresses: Segment coils to manage stress
- Remember development of HTS technology is important to muon collider.
- We have devised an experimental R&D approach which has been very successful in many other HTS magnet programs so far. This coupled with good analysis and innovations is perhaps the best way to proceed in limited funding.

A Fly through the Support R&D

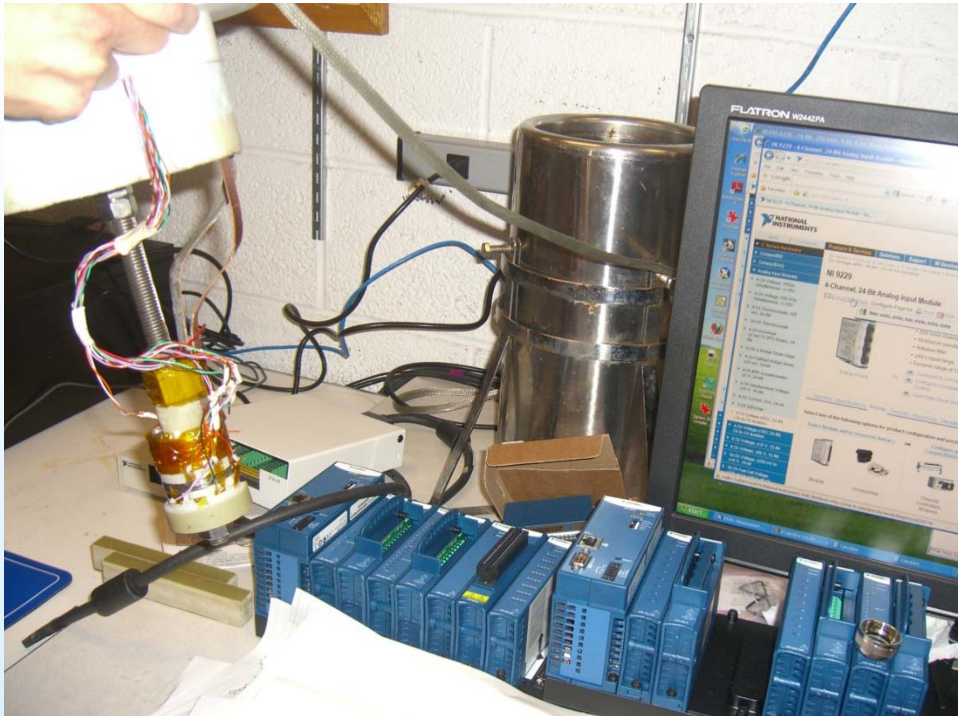
to Develop Essential Technology

Variety of HTS Coils

Large, small, single pancake, circular, double pancake, bi-filar



Experimental R&D with Test Coils (need to build and test many coils)

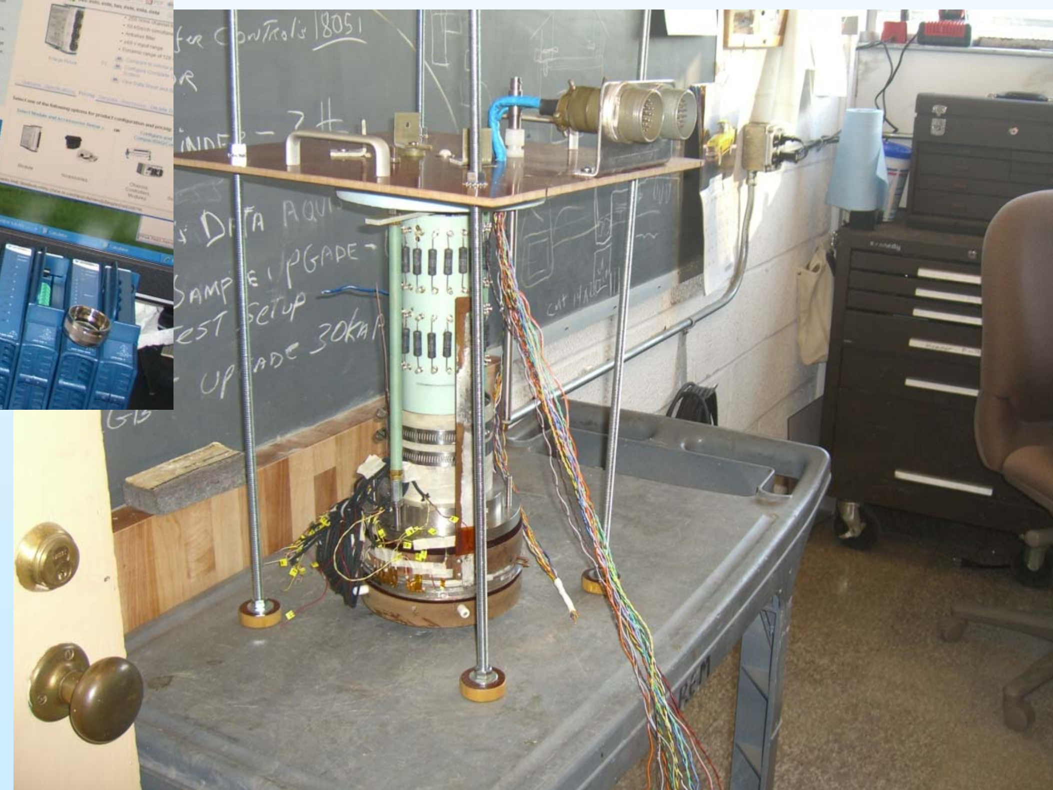


Smallest coils:

use 10 to 100 meters of wire

(can afford to sacrifice some

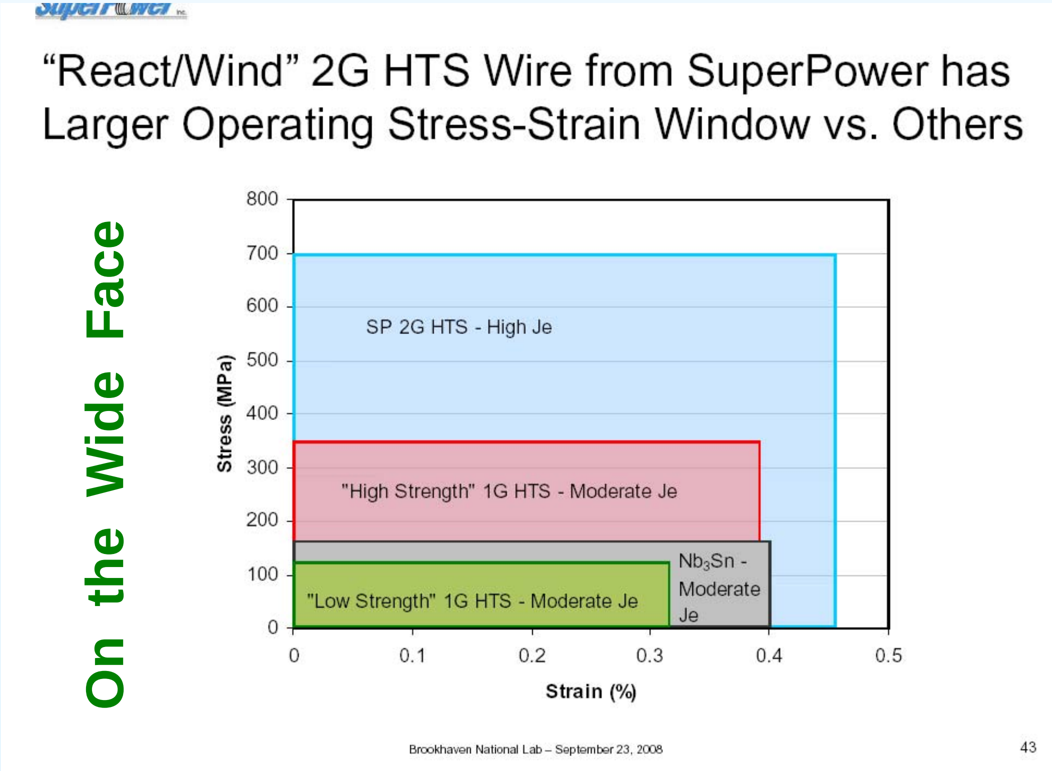
to understand the limit)



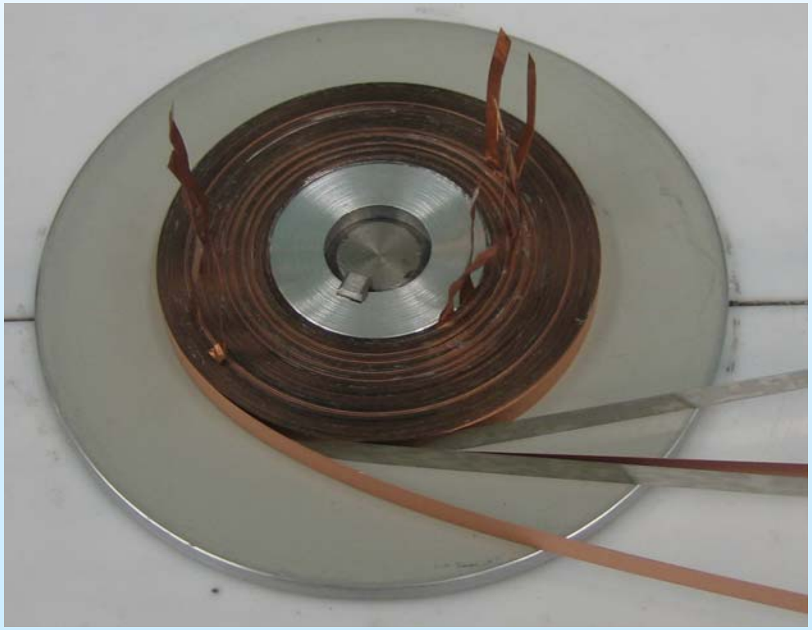
Large coils: use ~100 meters or more wire (test proven theory)

Example: What is the Maximum Allowable Stress on the Conductor?

- 2G HTS from Superpower can tolerate 700 MPa on the wide face of the tape
- However, measured data is not available on narrow face in the coil. Initial guidance given were as low as 25 to 50 Mpa which would be worrisome
- This is a critical number for designing a structure for high field HTS magnets



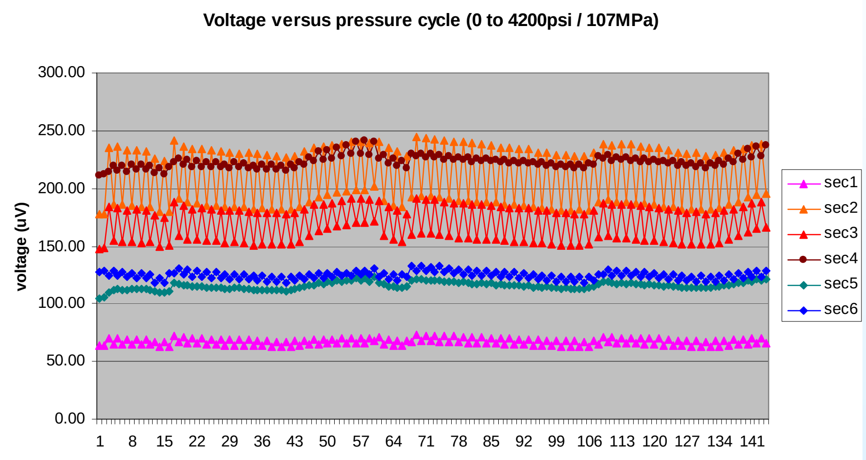
BNL experimental coil

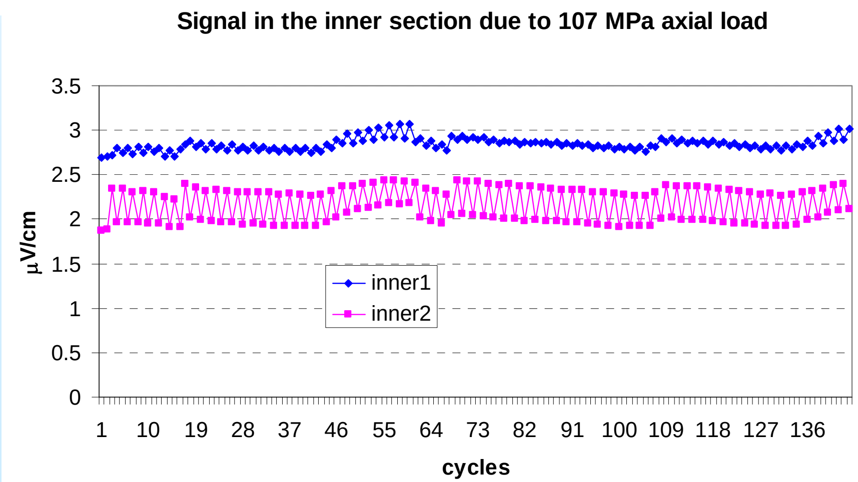


BNL System for in-situ Study of the Influence of Stress on the Narrow Face

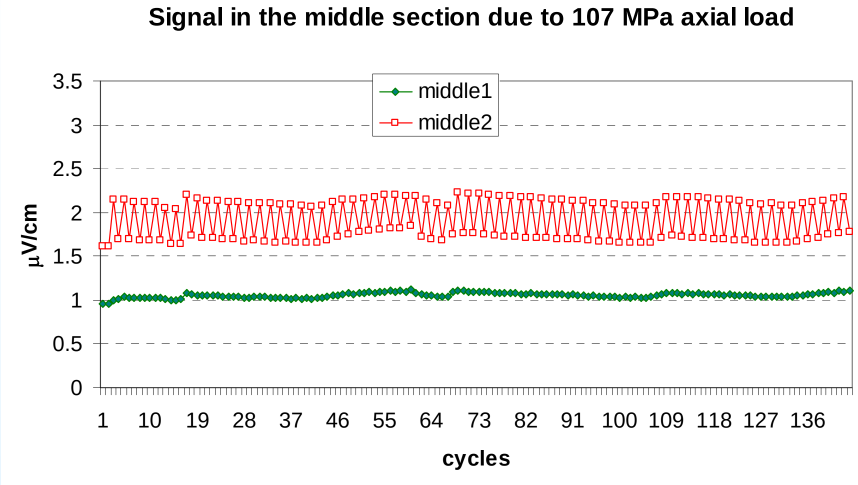
Influence of ~107 MPa Pressure on the Narrow Face of Conductor in 2G HTS Coil

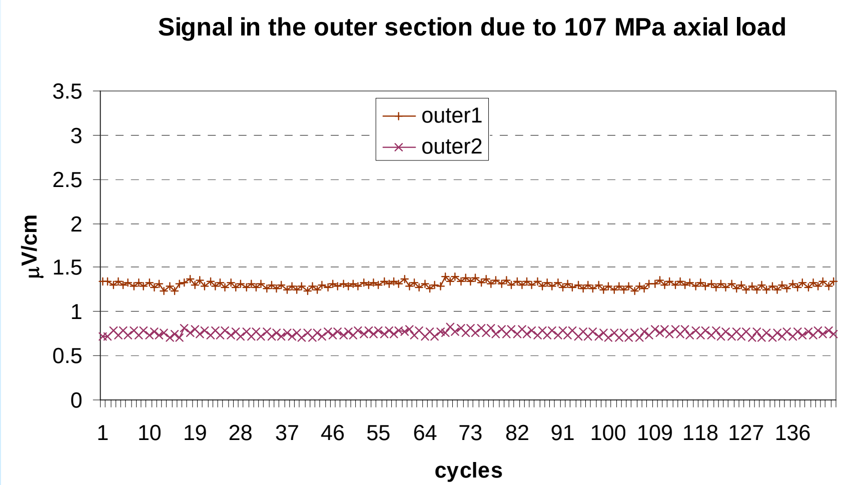
Load ON, Load OFF. Measure change in voltage in every ~1 m long six sections





~0.5% reversible change in Ic





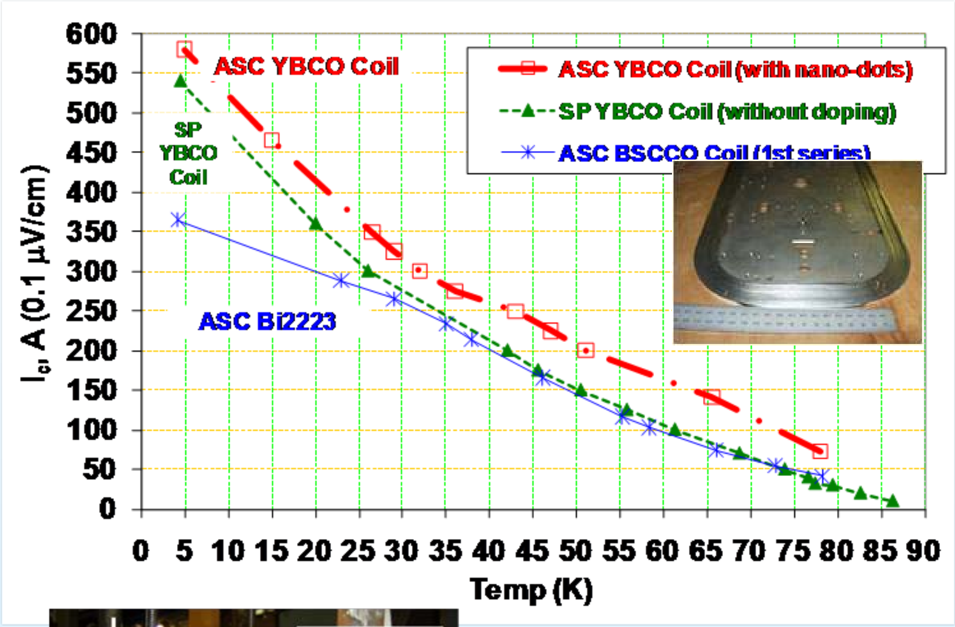
Answer: At least 100 MPa load may be acceptable on narrow face

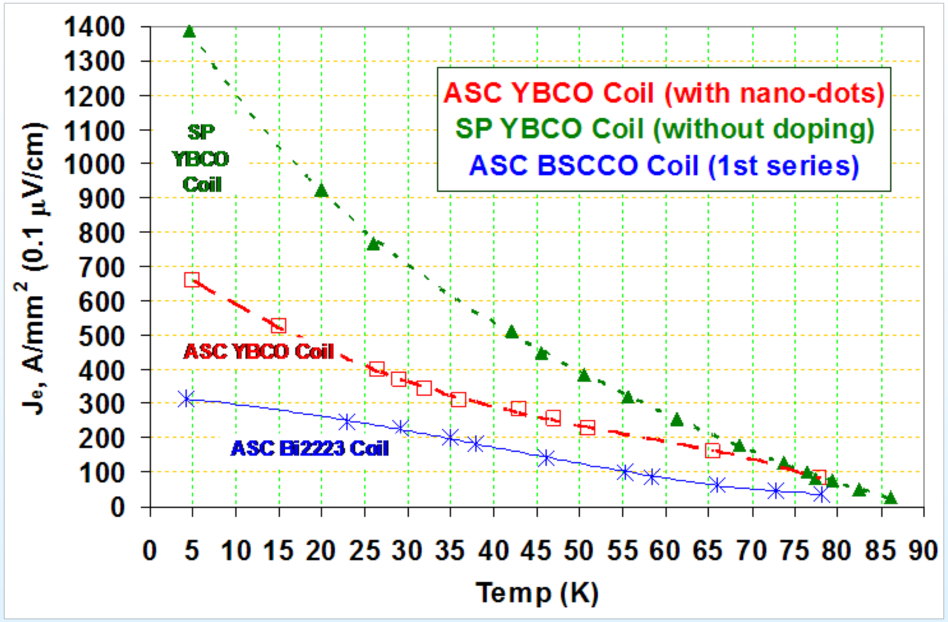
Quench Protection in HTS Magnets

- Quench protection of HTS coils (particularly at 4 K where current densities are high) is considered to be a major challenge in light of low quench velocities
- To overcome these challenges, an advanced quench protection system with fast electronics (to detect quench fast) and low noise (to detect small resistive signal over noise). Modern data acquisition and processing system is being developed to dump energy out fast
- Large number of voltage taps to detect quench in small sections

- Basic system is developed and tested at 77 K
- Next step: increase # of channels and test with coils at 4K
- Will do extensive experimental studies with small coils

Quench Protection Studies in FRIB 2G HTS Coils and Plan in HTS Solenoid





- In FRIB R&D program, 2G HTS coils were made with ~100 m of conductor from ASC and SuperPower.
- Coils survived with copper current density: ~1500 A/mm^2 (ASC); ~3000 A/mm^2 (SuperPower)
- *This is too aggressive for protection and surprising that worked. In some coils, we have seen degradation/damage earlier*
- *In HTS solenoid we will keep Cu current density ~1000 A/mm^2*

Other Significant ongoing

HTS R&D Programs at BNL

Superconducting Magnetic Energy Storage (SMES) Options with HTS

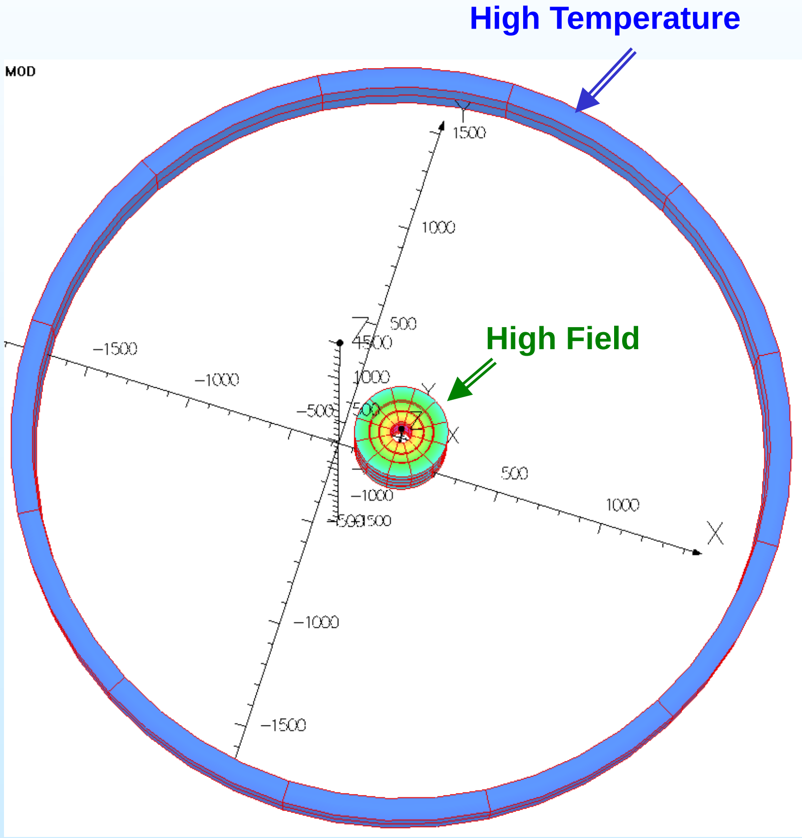
- arpa-e invited proposals on energy storage system under stimulus package
- It required demonstration of certain parameters within the funding limitations

Two options for HTS:

1. **High Temperature (~65 K) Option:**
   Saves on cryogenics (Field ~2.5 T)
2. **High Field (~25 T) Option:**
   Saves on Conductor (Temp. ~4 K)

Our analysis on HTS option:

Conductor cost dominates the cryogenic cost by an order of magnitude (both in demo device and in large application



Our proposal: Bring it in play with an aggressive choice:

- ➢ **Go for ultra high fields 24 – 30 T : only possible with HTS**

Superconducting Magnetic Energy Storage (SMES)

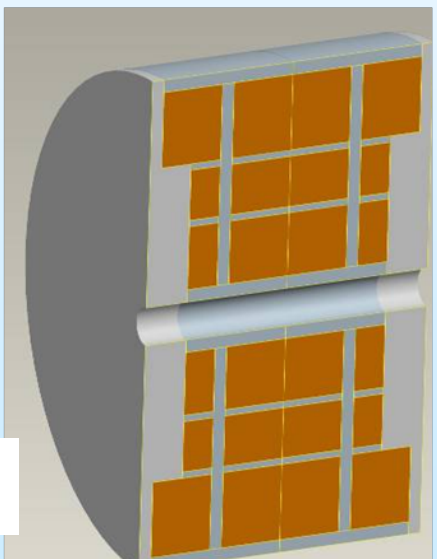
HTS solenoid with high energy density (E α B^2) reduces the system cost

arpa-e specifically asked for "high risk high reward" proposals!

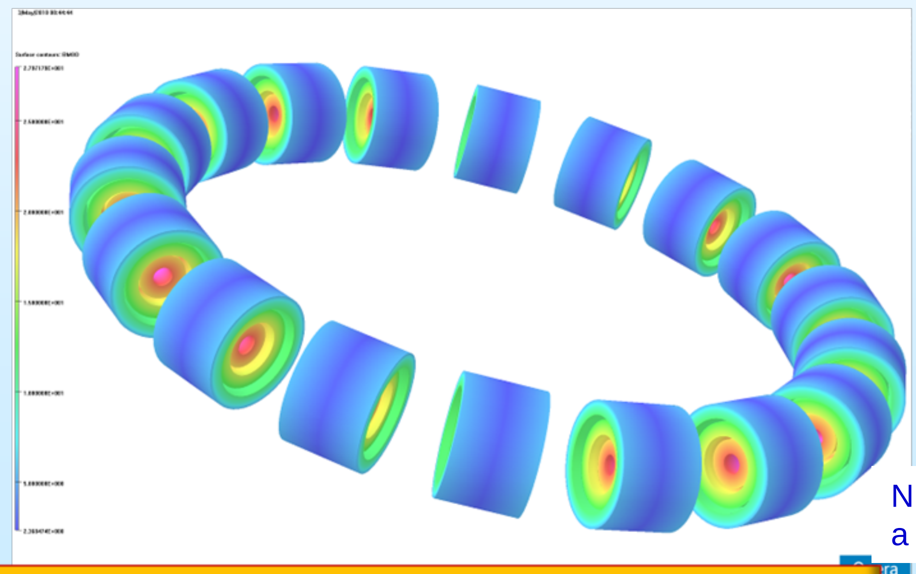
- **37 were selected out of ~3,700 proposals submitted !!!**

this one was the third largest in this announcement with 5.25M$

Participants: ABB, USA (Lead), SuperPower (Schenectady and Houston), and BNL (Material Science and Magnet Division)



Basic structure of a single Unit

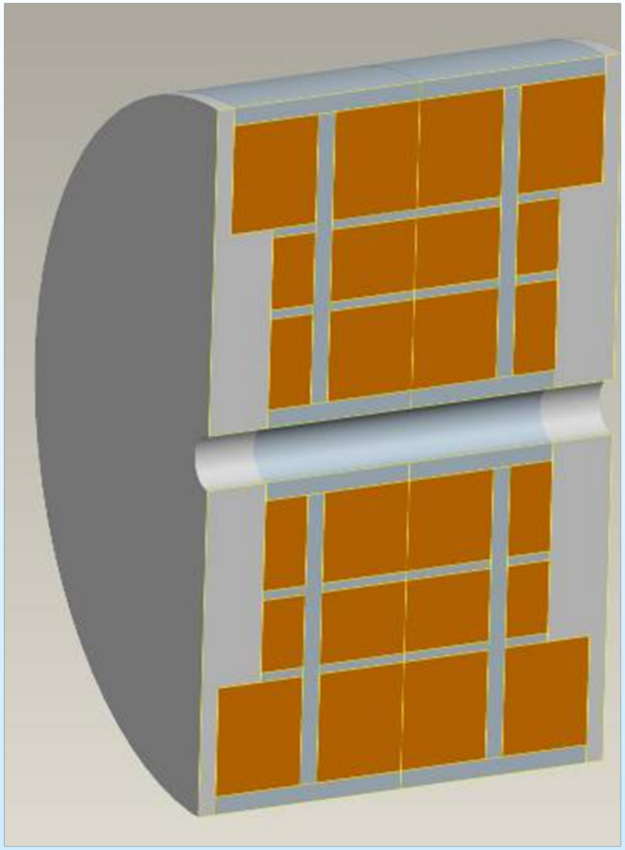


Number of units in a SMES system

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

Current Preliminary Design

- For BNL Magnet Division, it is a follow up on the current R&D under SBIR
- For MAP, it is very relevant to developing high field HTS solenoid technology



- Field: ~24 T
- Inner Diameter : ~100 mm
- Conductor: YBCO 12 mm wide
- Stored Energy: 2.5 MJ
- Conductor: ~9 km (plus spare)

~900k$ funding to magnet division, in addition to 1M$ worth of conductor

- **Plus additional significant funding to improve conductor and reduce cost**

Magnet needs intermediate support structure to manage stress build-up

- Steve Kahn of Muons, Inc. is participating in this effort

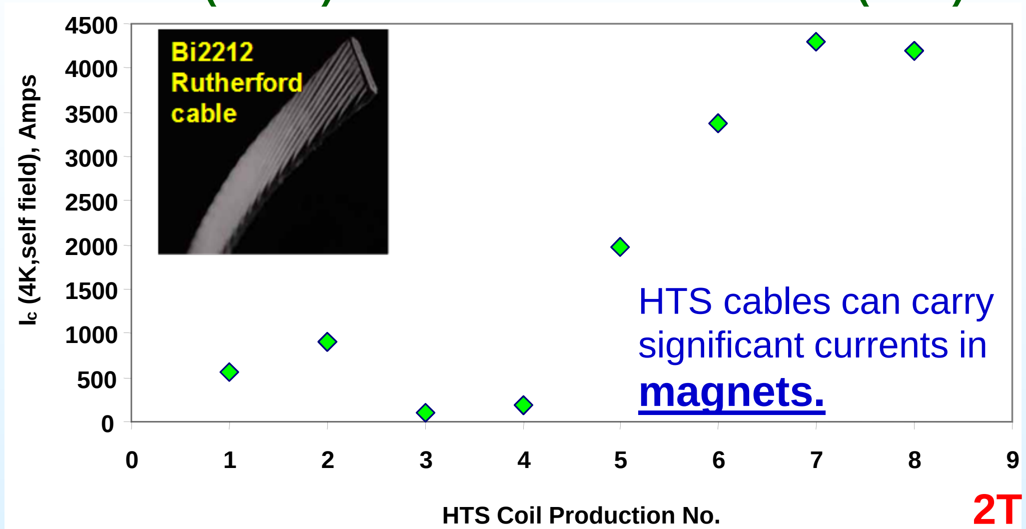
HTS Common Coil Dipole with Bi2212 Rutherford Cable

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

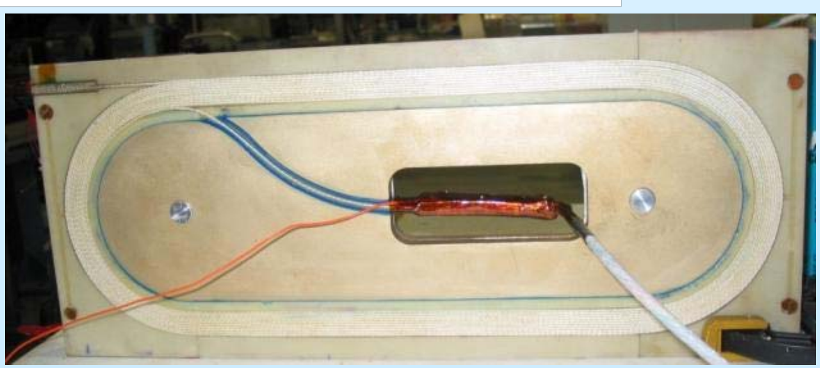
Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	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)



Racetrack HTS coil with Bi2212



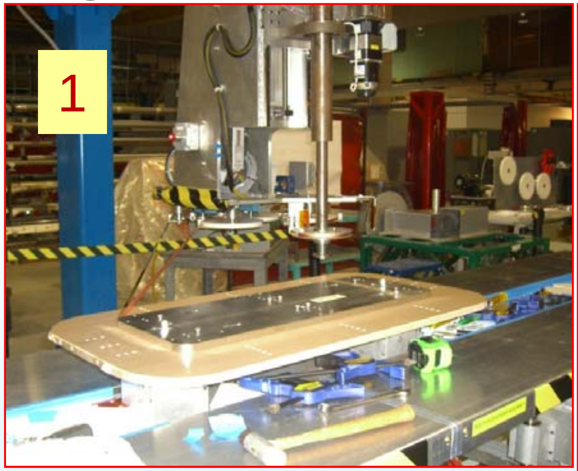
HTS Quadrupole for Facility for Rare Isotope Beams (FRIB)

Will create rare isotopes in quantities not available anywhere

- Site: Michigan State University

- Major source of funding for HTS magnet R&D at BNL

Significant FRIB HTS Coils



- FRIB coils are being made with significant HTS
  - Each coil uses ***over 1 km*** equivalent of standard 4 mm tape
- 6 of 8 coils (4 with 2G HTS from SuperPower and 4 with ASC) are made, 3 tested at 77 K
- One coil is made without any splice (average 1)
- Unique opportunity to test large 2G HTS coils

HTS Magnet Programs at BNL

- **BNL has been active in HTS magnet R&D for well over a decade**
- **The level of involvement may be gauged with the amount of HTS coming in. Net total in all programs (normalized to 4 mm tape):**
  - **Obtained so far: ~20,000 meter**
  - **Next two years (based on funded programs): ~35,000 meter**
- **Successfully designed, built and tested a large number of coils and magnets:**
  - **Number of HTS coils built: ~100**
  - **Number of HTS magnet structures built and tested: ~10**
- **HTS Magnet R&D at BNL on a wide range of operating conditions:**
  - **Low B, High T (several in house, built and tested)**
  - **Medium B, medium T (3 funded programs)**
  - **High B, low T (>20 T, 2 funded programs)**

This is an order of magnitude more than in any such lab in the world

More Information for General Audience

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

http://www.bnl.gov/magnets/staff/gupta/

High Temperature Superconducting Magnets

Revolutionizing Next Generation Accelerators and Other Applications

Ramesh Gupta
Superconducting Magnet Division

466th Brookhaven Lecture
February 16th, 2011

http://www.bnl.gov/magnets/staff/gupta/

Summary

Significant progress towards a high field HTS solenoid with PBL/BNL SBIR

- 24 coils needed for outer solenoid for SBIR#1 have been successfully tested
- 5 of 12 coils needed for SBIR#2 have been wound
- Getting ready for first insert coil test at NHMFL
- Expect periodic results with final outcome in about a year
- Real shot at testing ~35 T solenoid – imagine where we would be without

- MAP and HTS R&D programs at BNL Magnet Division
  - BNL has an unparalleled HTS R&D program with many significant results
  - It may be in the interest of MAP management to have BNL magnet division directly in the overall programming – imagine where we would be without

- PBL and BNL make a great team.
- We are looking forward to continuing this exciting and challenging R&D and making a difference with an experimental program involving demo magnets