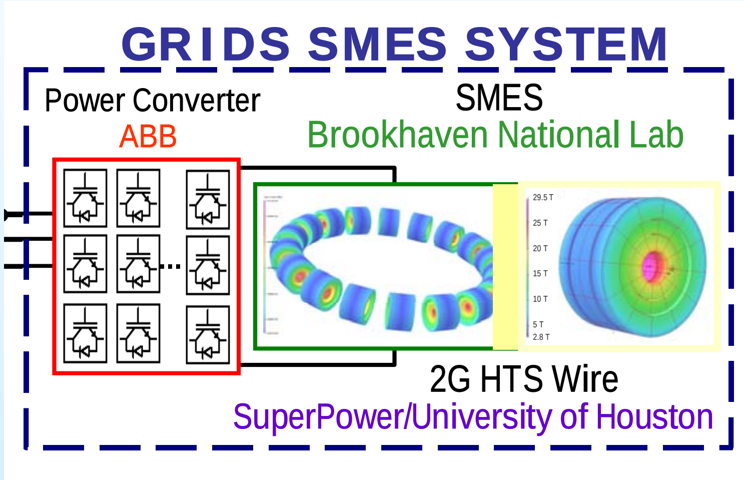
Superconducting
Magnet Division

High Field HTS Magnets

Ramesh Gupta, BNL



HTS Magnet Programs at BNL

- BNL has been active in HTS conductor, coil and magnet R&D for over a decade.
- The level of involvement in HTS R&D may be gauged with the amount of HTS coming in. Net total in all programs (normalized to 4 mm tape):
  - In last one year: ~12,000 meter
  - Before last year: ~9,000 meter
  - Next two years (based only on funded programs): >35,000 meter
- 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
- Magnet R&D at BNL on a wide range of HTS magnet programs:
  - Low B, High T (several, in house)
  - Medium B, medium T (3 funded programs)
  - **High B**, low T (>20 T, 2 funded programs) ←**focus of this presentation**
- These variety of programs help in developing a wider understanding of HTS technology. Sharing of resources (as long as they fit the need of individual program goal) also makes it more cost effective.

Current Status of the Availability of Long Length HTS to Users

Delivery of 12 mm 2G HTS (wide) tape to BNL from SuperPower and ASC for FRIB

(Facility of Rare Isotope Beams)

SuperPower

Length(m)	width(mm)	Thickness(mm)	Ic (A), Min (77 K, self field)
130	12.0	0.089-0.098	285
149	12.0	0.089-0.098	279
144	12.0	0.096-0.101	240
128	12.0	0.096-0.100	274
145	12.0	0.097-0.098	253
100	12.0	0.095-0.097	255
104	12.0	0.094-0.096	255
100	12.0	0.098-0.100	275
Total Conductor		1000	meter

Specified minimum length:

50m ASC; 100m SuperPower (smaller lengths for cost reasons and not for availability reasons)

American Superconductor (double tape)

Length (m)	width(mm)	Thickness(mm)	Ic (A), Min (77 K, self field)	
58	12.0	0.302	522	
72	12.0	0.295	521	
207	12.0	0.302	519	
210	12.0	0.302	519	
60	12.0	0.292	412	
85	12.0	0.29	439	
123	12.0	0.297	410	
		total conductor length=	815	meter
	remaining length to be delivered		185	meter

Length as long as 210 meter

FRIB Coils with Wide 2G HTS

Key programmatic features/plans for conductor and coil for FRIB:

- 12 mm tape is preferred over 4 mm for a variety of reasons
- One coil may use up to ~350 meter; no coil will have more than two splices
- At least one coil will be made without any splice

FRIB test coil and first partially wound coil with 12 mm 2G tape

- *FRIB/RIA has been a consistent source of HTS R&D from last ~5 years*

High Field HTS R&D Programs 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
- Technology development program with short coils
- Other Programs: Open Midplane Dipole, Common Coil Dipole

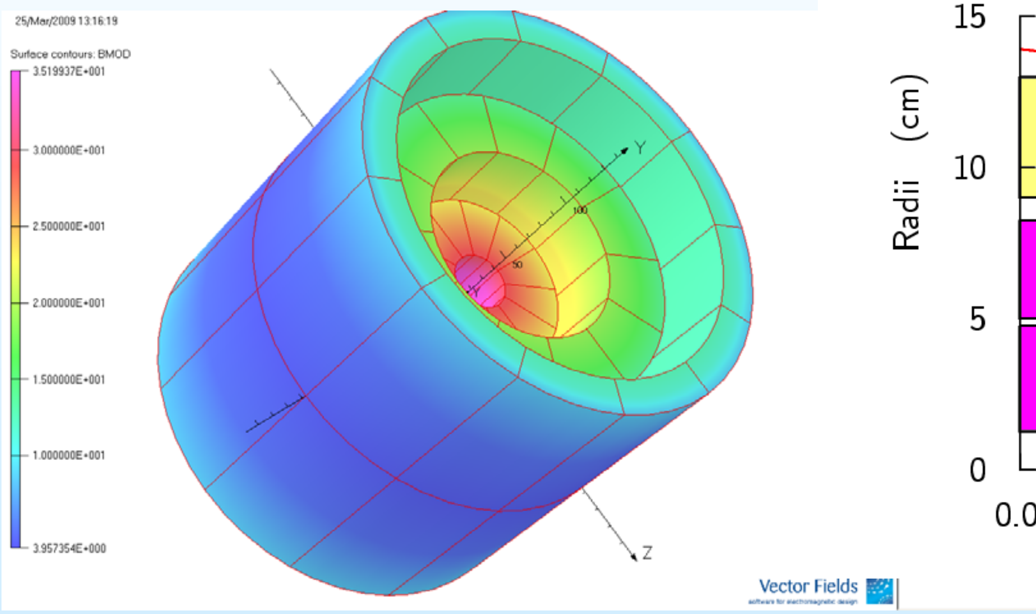
SBIR collaboration with PBL plays a significant role in high field HTS R&D at BNL. Apart from funding, it brings key individuals (e.g., Bob Palmer, Bob Weggel and Ron Scanlan in magnets & Harold Kirk, David Cline and Jim Kolonko in machine physics).

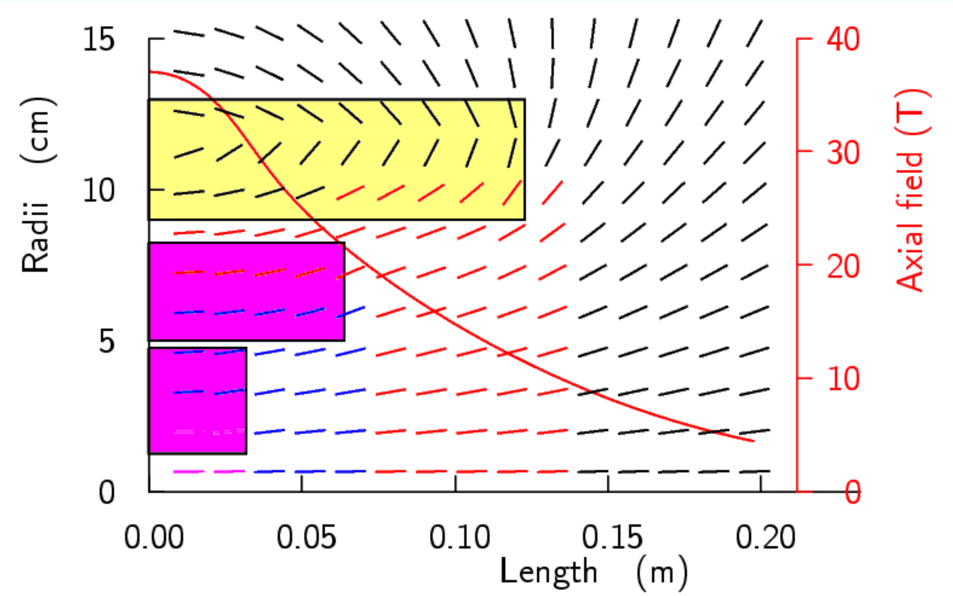
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

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





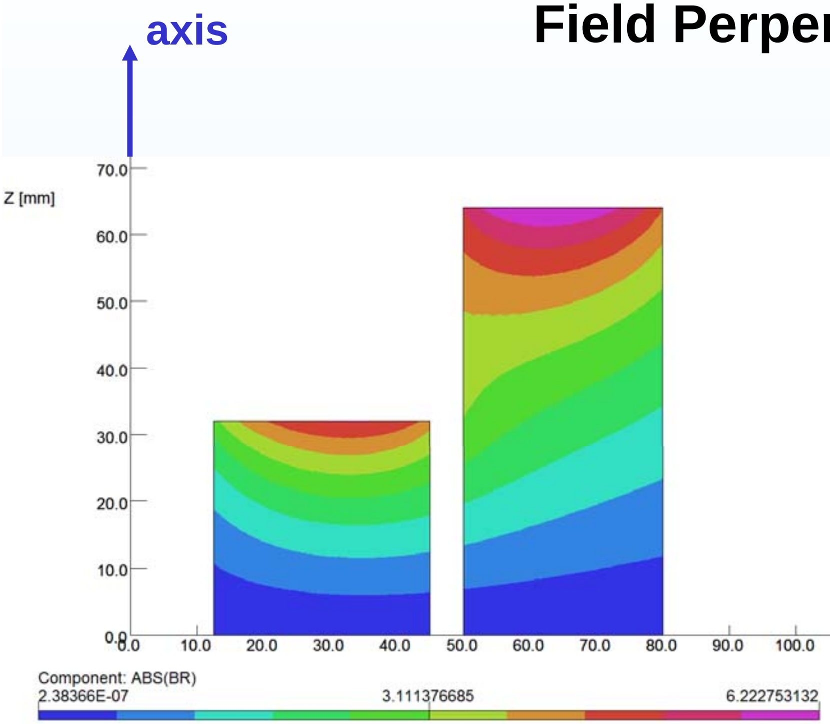
Courtesy: Bob Palmer

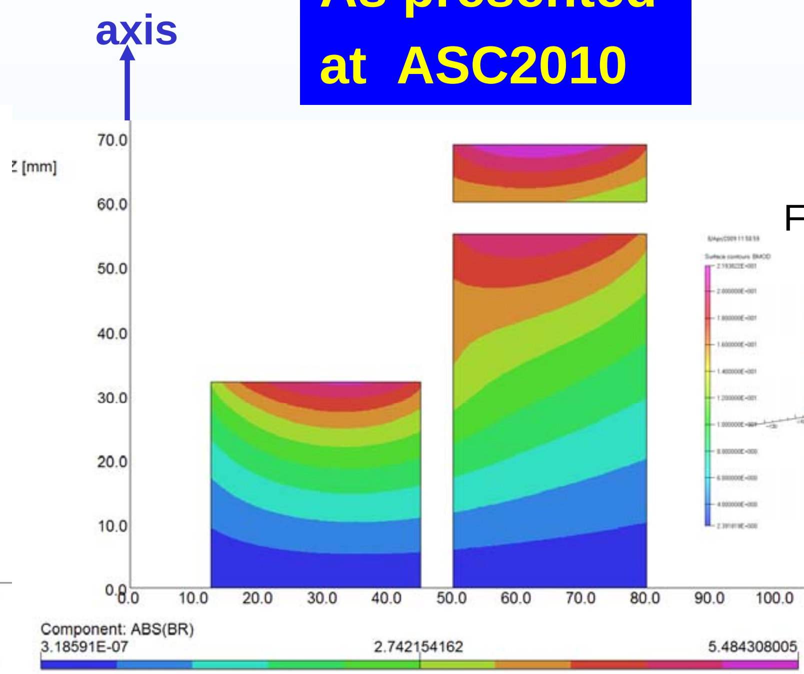
Field magnitude (left) and field lines (right) of the combined magnet using the Nb_3Sn coil (yellow) and the two YBCO coils (magenta)

Getting More Field with Less HTS Tape
Reducing the Perpendicular Component

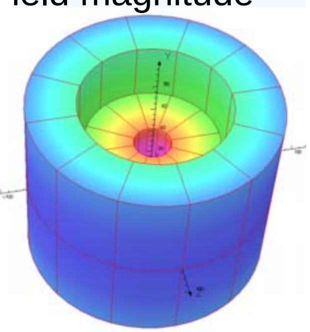
Field Perpendicular

As presented at ASC2010





Field magnitude



Bo: ~22 T

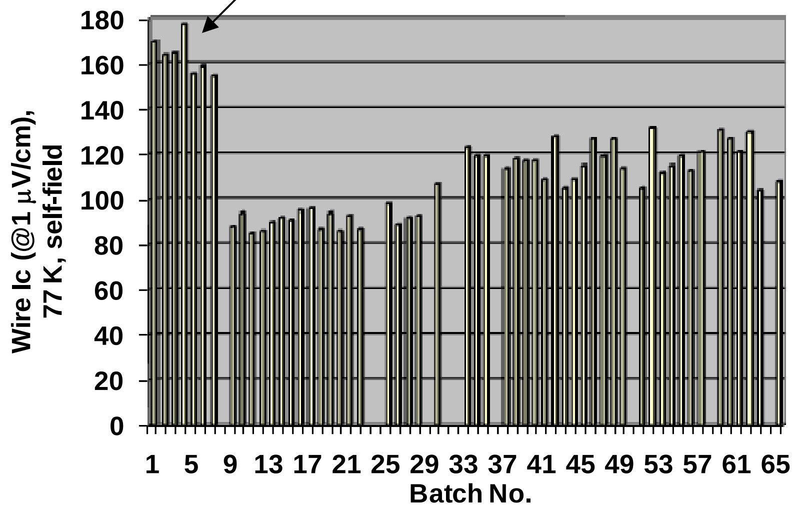
BNL/PBL HTS solenoid (two 2G coils)

5 mm spacer reduces perpendicular component by ~15%

- **We plan to build and test first without spacer and then with spacer**

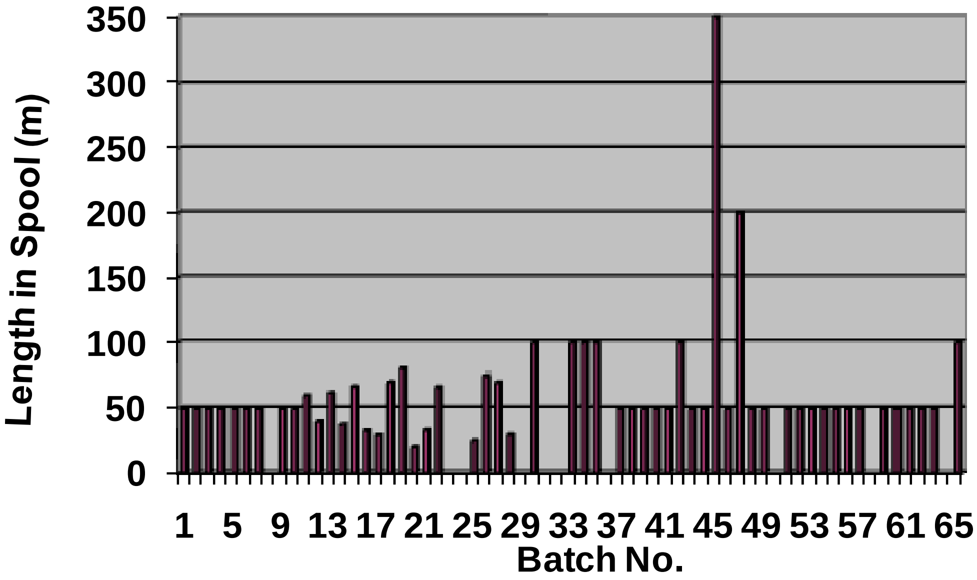
Conductor Received from SuperPower

180 A Ic for the price of 100 A



Somewhat different Ic from batch to batch

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



Each coil needs 50 meter or 100 meter tape.
One splice allowed in 100 m for cost reasons.

2G HTS Coils - Lessons Learnt

We and many other groups have built 2G HTS coils with varying experiences.

- Thermal shocks must be avoided as that may degrade the coil performance

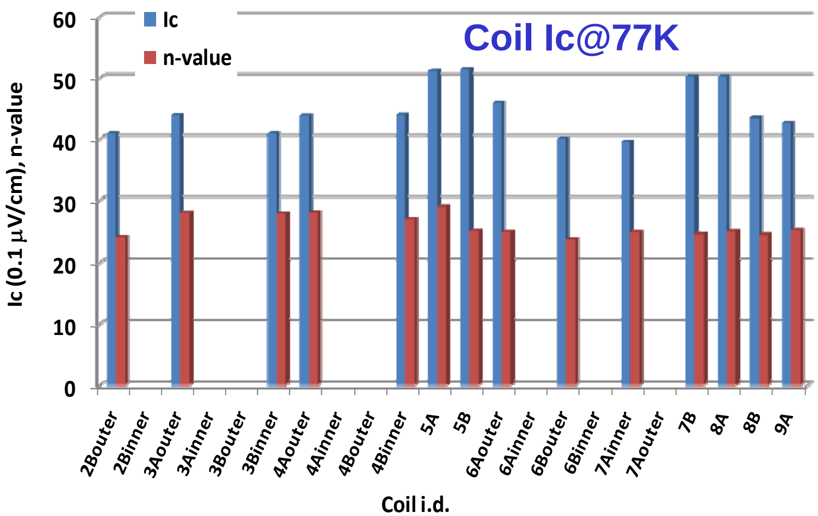
With that precaution, several coils have been built and successfully tested (next slide)

- 2G of today appears to be more sensitive than 1G (got more time to mature)
- One should be able to detect and avoid small local irregularities in the overall tape structure (not just in conductor) which might possibly turn in to defect under the much more demanding circumstances of high field applications

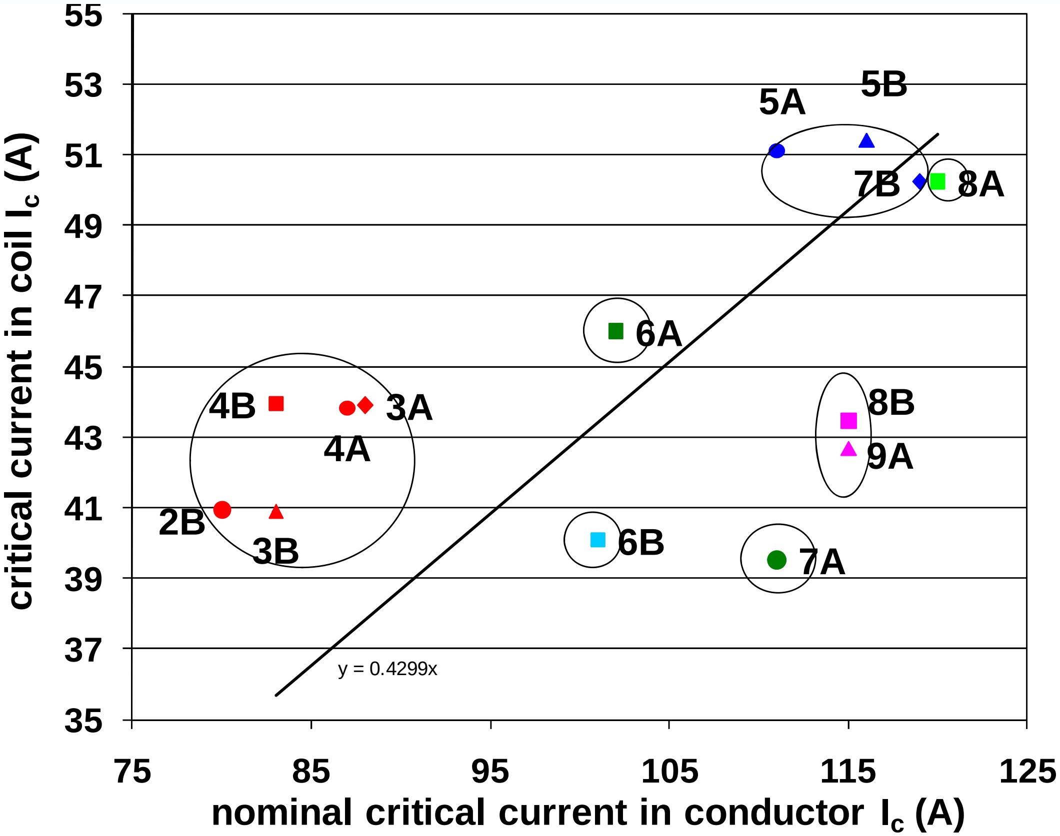
- **Conductor development needs to focus on this now – not just on Ic, Ic, Ic.**

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

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



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



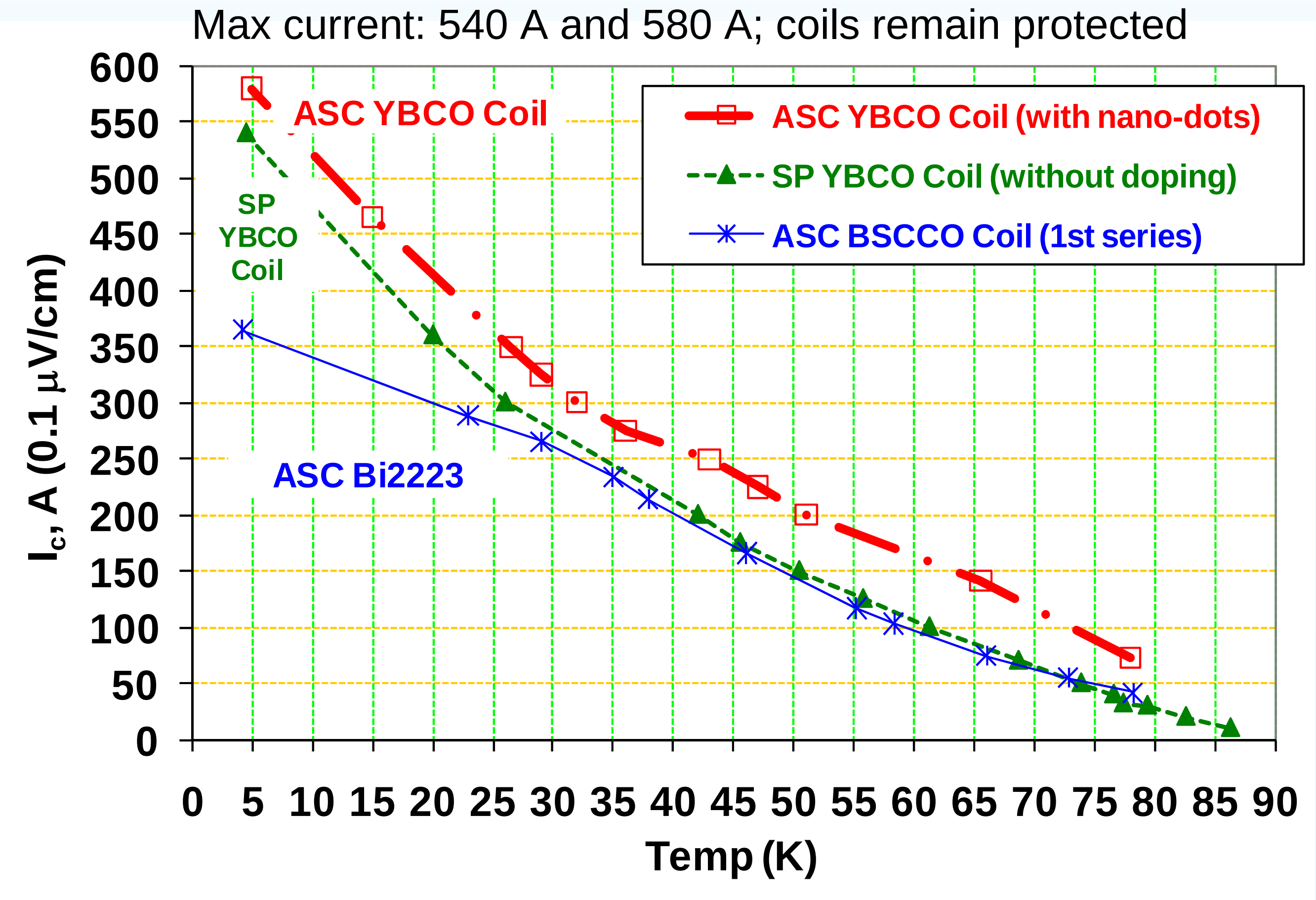
What will it be at 4 K?

- **A possible topic of collaboration**

Low Temp High Current Test of FRIB Coils(1)

During the initial FRIB R&D period, coils with 2G HTS from ASC (~0.4 mm X 0.3 mm) and SuperPower (0.4 mm X 0.1 mm) were built and tested

Coil built with 4mm 2G HTS purchased ~3 years ago

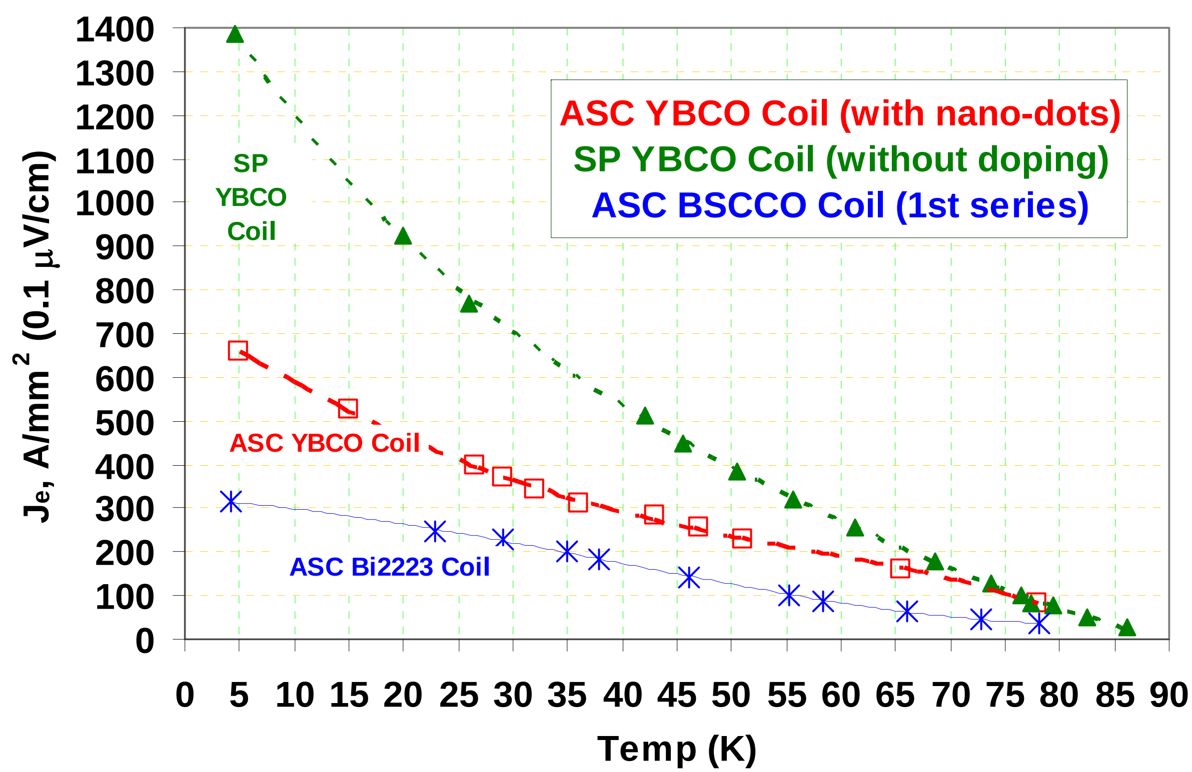


BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Low Temp High Current Test of FRIB Coils(2)

Tape width: ~ 4 mm

Copper thickness: SuperPower ~ 0.045 mm; ASC ~ 0.1 mm



Protection considerations:

If coils to go normal (quench, thermal runaway, etc.):

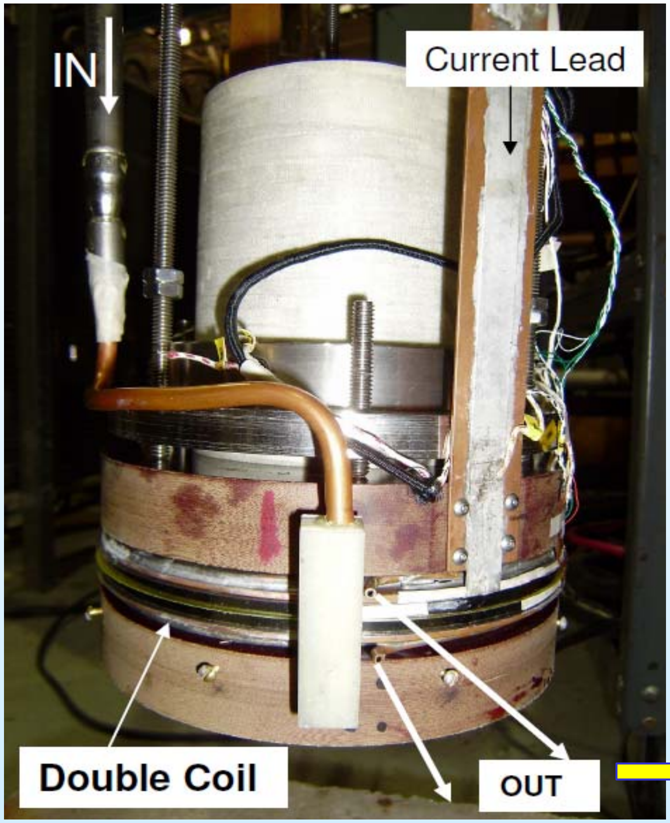
- Copper current density in ASC coil : ~1500 A/mm^2
- Copper current density in SuperPower coil : ~3000 A/mm^2

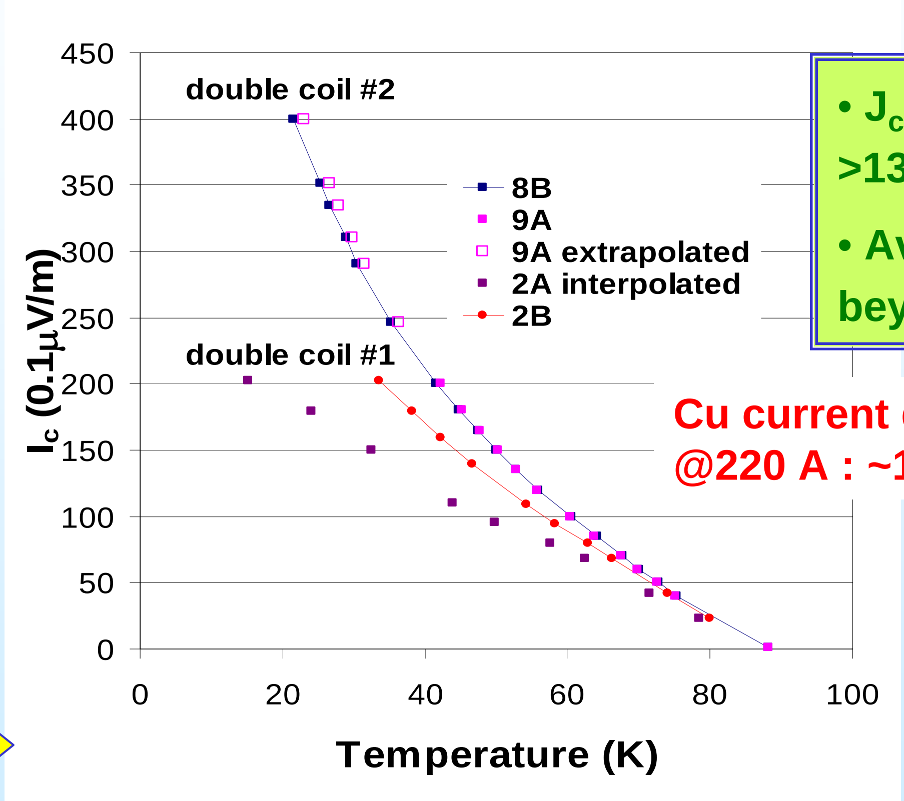
These numbers are really amazing ...

- *May be too demanding for protection and should be avoided in real applications.*

Low Temperature, High Current Tests of BNL/PBL Coils

Note: ~10 T or ~20 T design needs only 220 A with SuperPower Tape





- J_{cu}@250A >1300 A/mm^2
- Avoid testing beyond 250 A?

Cu current density @220 A : ~1200 A/mm^2

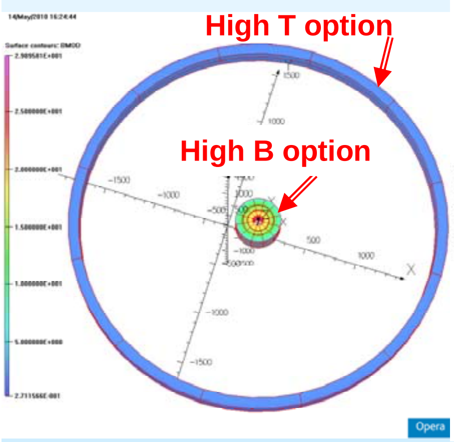
- Are these high current tests too demanding in terms of protection?
- Were we too lucky or spoiled by FRIB in testing coils to > 500 A?
- Do we need more copper for protection for very high currents?

BROOKHAVEN NATIONAL LABORATORY

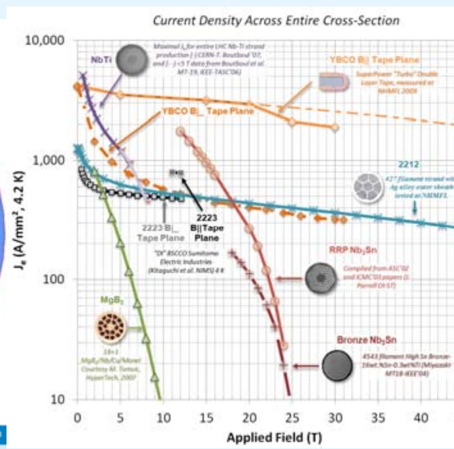
Superconducting Magnet Division

Superconducting Magnetic Energy Storage (SMES) System

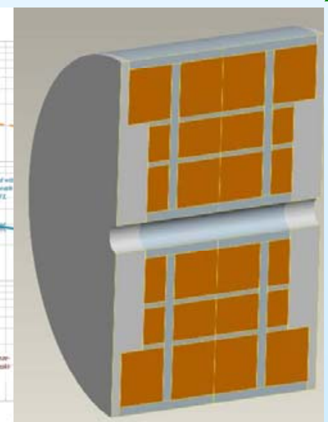
- BNL, along with its research partners, SuperPower (conductor) and ABB (power electronics), received ARPA-E funding for developing HTS SMES (5.25M$).
- HTS with high (very high) field option is used in high energy density (E α B^2) option which minimizes the cost as the conductor (not cryogenics) dominates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



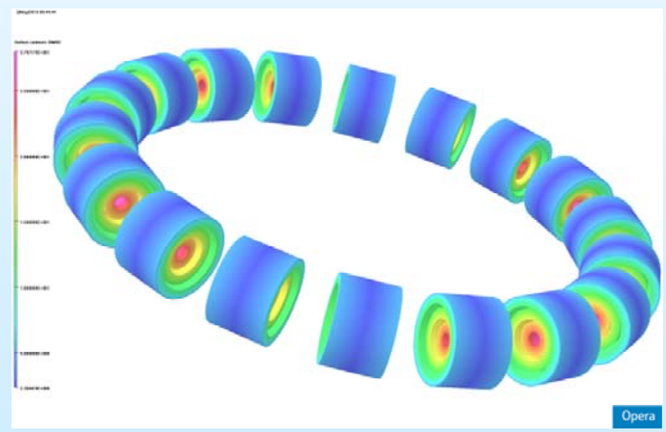
High field option reduces high conductor cost



HTS allows large current densities at high field.



Basic structure of a single SMES Unit

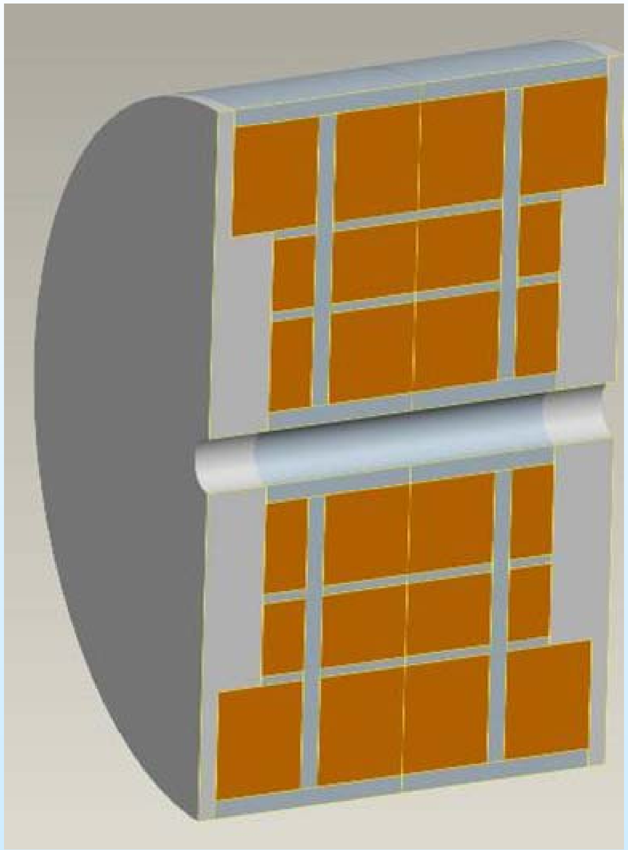


Number of units in a SMES system

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

Current Preliminary Design

Stated explicitly in the proposal: High Risk High Reward

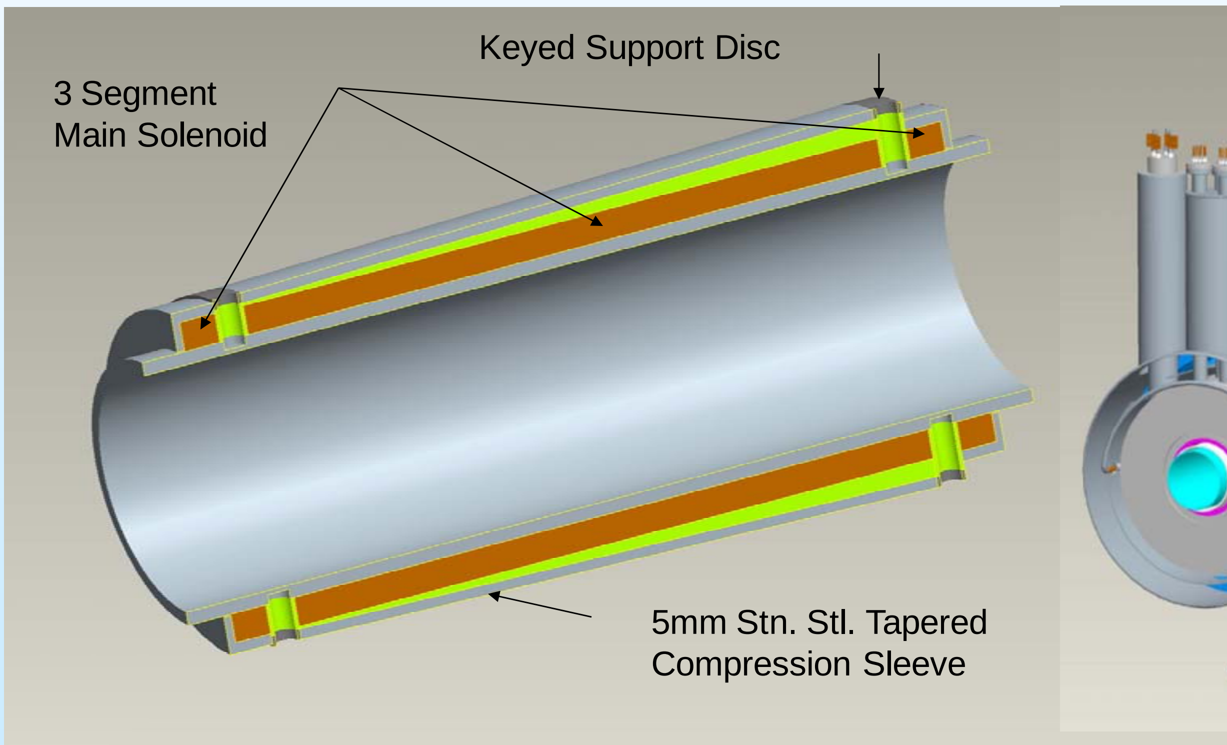


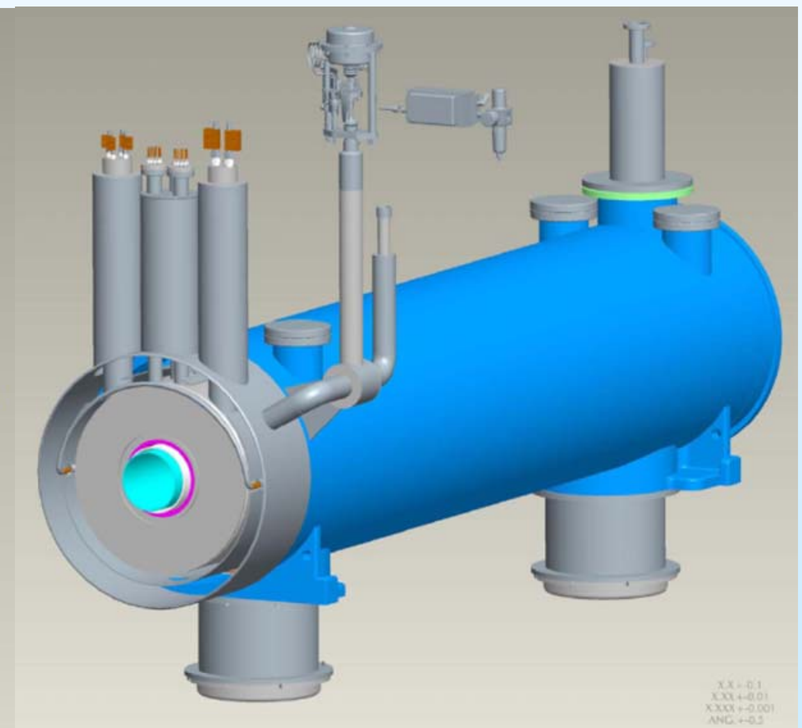
- Field: ~25 T
- Inner Diameter : ~100 mm
- Outer Diameter: ~324 mm
- Length: ~400 mm
- Conductor: YBCO 12 mm wide
- Current at Design Field: ~600 A
- Stored Energy: 2.5 MJ
- Inductance: ~13 H
- Conductor: ~9 km (plus spare)

Magnet needs intermediate support structure to manage stress build-up

Support Structure in BNL NbTi Solenoid

- BNL is building ~7.7 T, 200 mm NbTi Solenoid for internal application
- A novel support structure is being designed and built for managing hoop stress and also large local axial stresses in the ends
- That concept may be useful in SMES & other high field solenoid applications





Basic HTS Coil R&D

HTS coil and magnet R&D is in initial stages. For high field applications, a basic R&D program is needed to answer fundamental questions, such as:

- How much stress can conductor tolerate on narrow face?
- How much copper is required?
- What's the best approach and right conductor and coil parameters for quench protection?

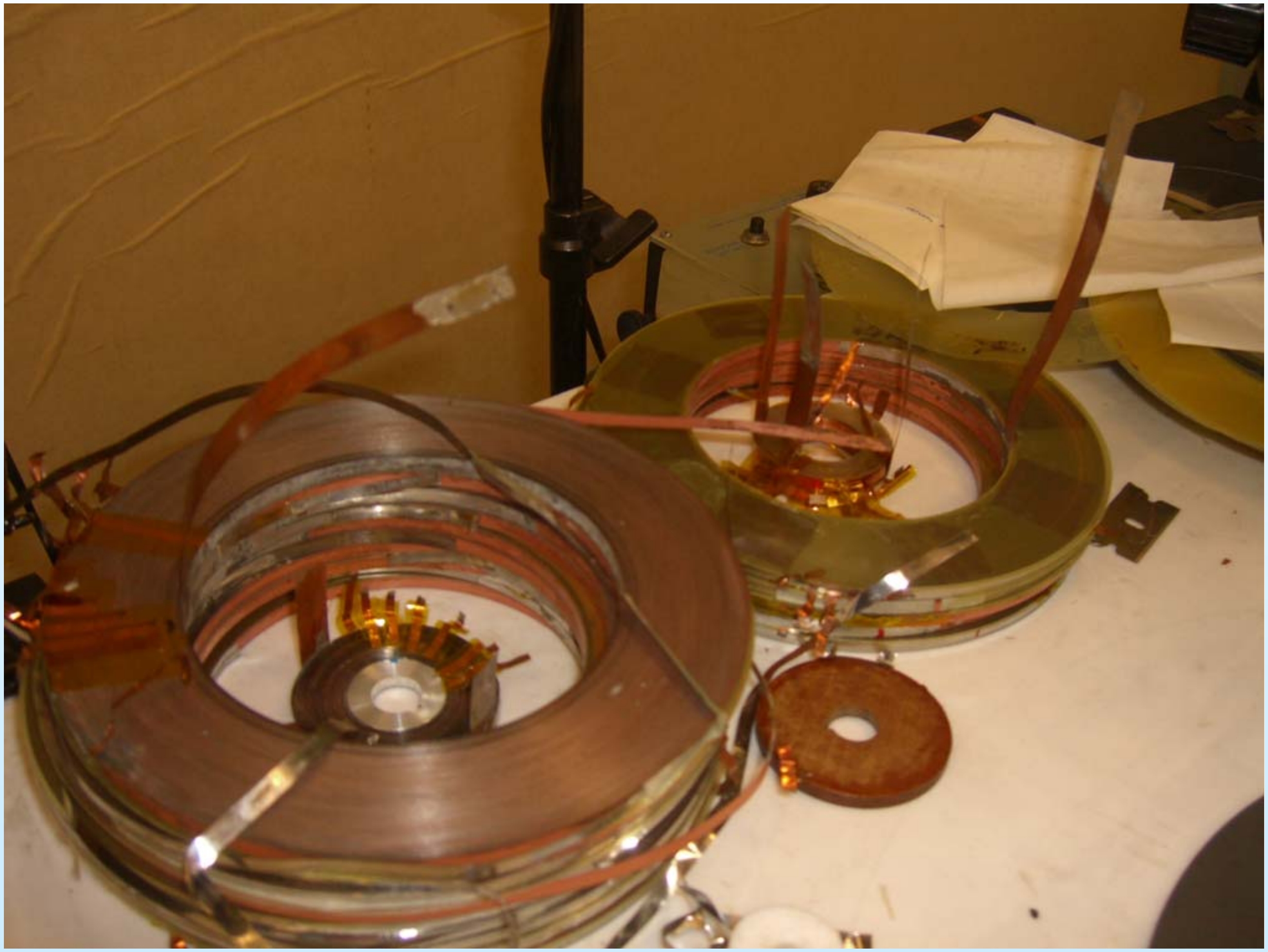
BNL has launched a systematic, small HTS coil R&D program to experimentally answer these technology/engineering questions.

With over a decade of experience with a variety of HTS conductor, coil and magnets, it is the most experienced laboratory to carry out such a program which is critical to DOE/HEP for the development of high field HTS magnets

BNL HTS magnet R&D is not directly funded by HEP base program. We are trying to manage it at low cost by pooling resources; but there are limitations.

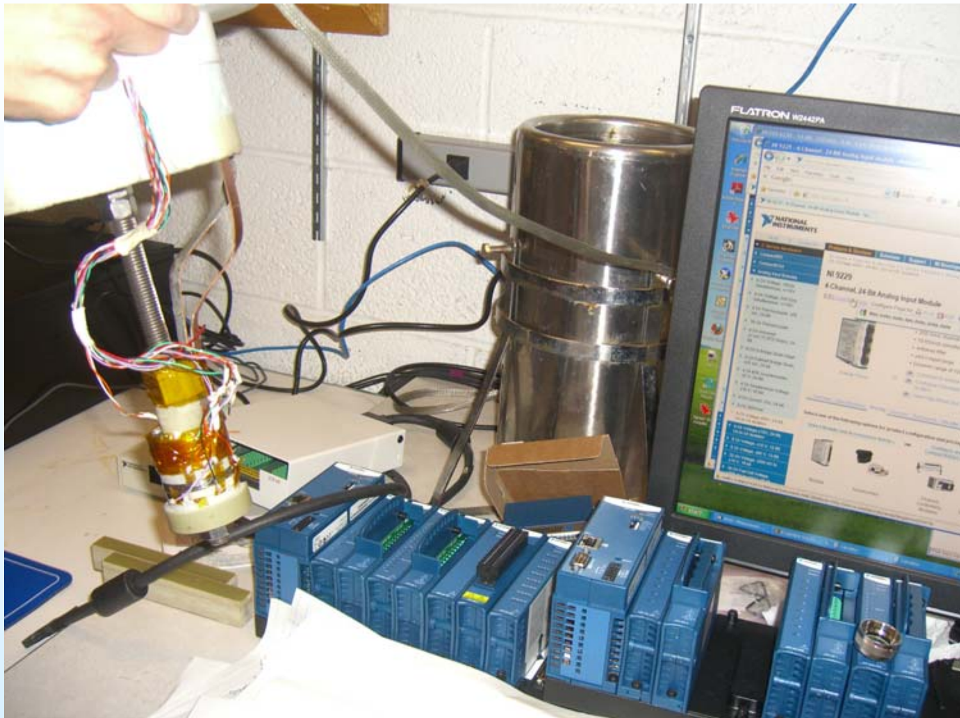
Variety of HTS Coils

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



For example, small double pacakes coils are being used for quench protection studies and bi-filar coils for measuring the influence of axial loading

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



Large coils: ~100 meter wire
(test proven theory)

Small coils: ~10 meter tape
(we can afford to sacrifice them to understand the limit)

Study of Stress on Narrow Face

• 2G HTS from Superpower can tolerate, 700 MPa (may be 1,000 MPa cold) on wide face of the tape

• However, no clear guidance is available for narrow face. Number given were as low as 25 to 50 MPa

• This is a critical for designing a structure for high field magnets.

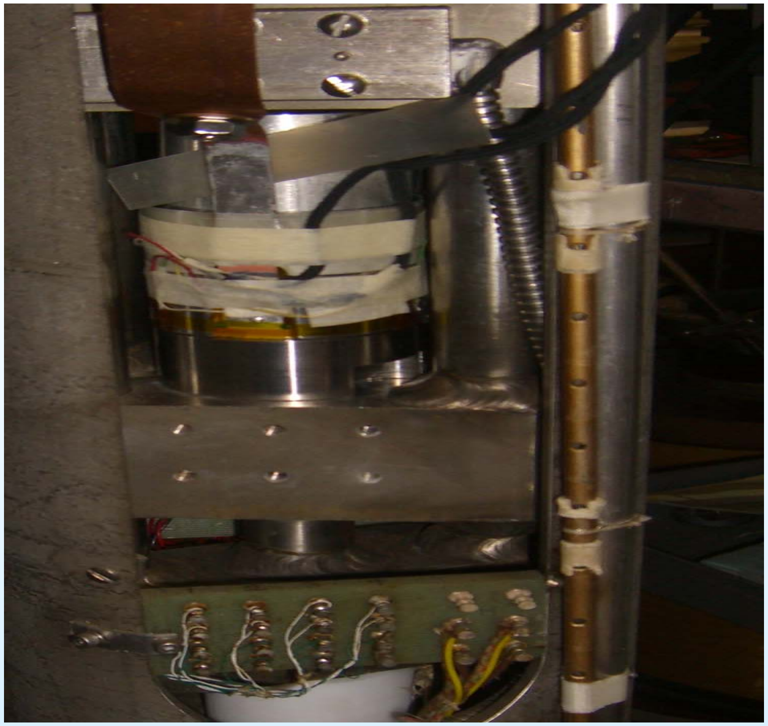
• Results from small coil experimental R&D (note a coil test also simulate a more realistic magnet situation than a small conductor test).

• Stress was applied when coil is cold and superconducting to simulate magnet environment more realistically

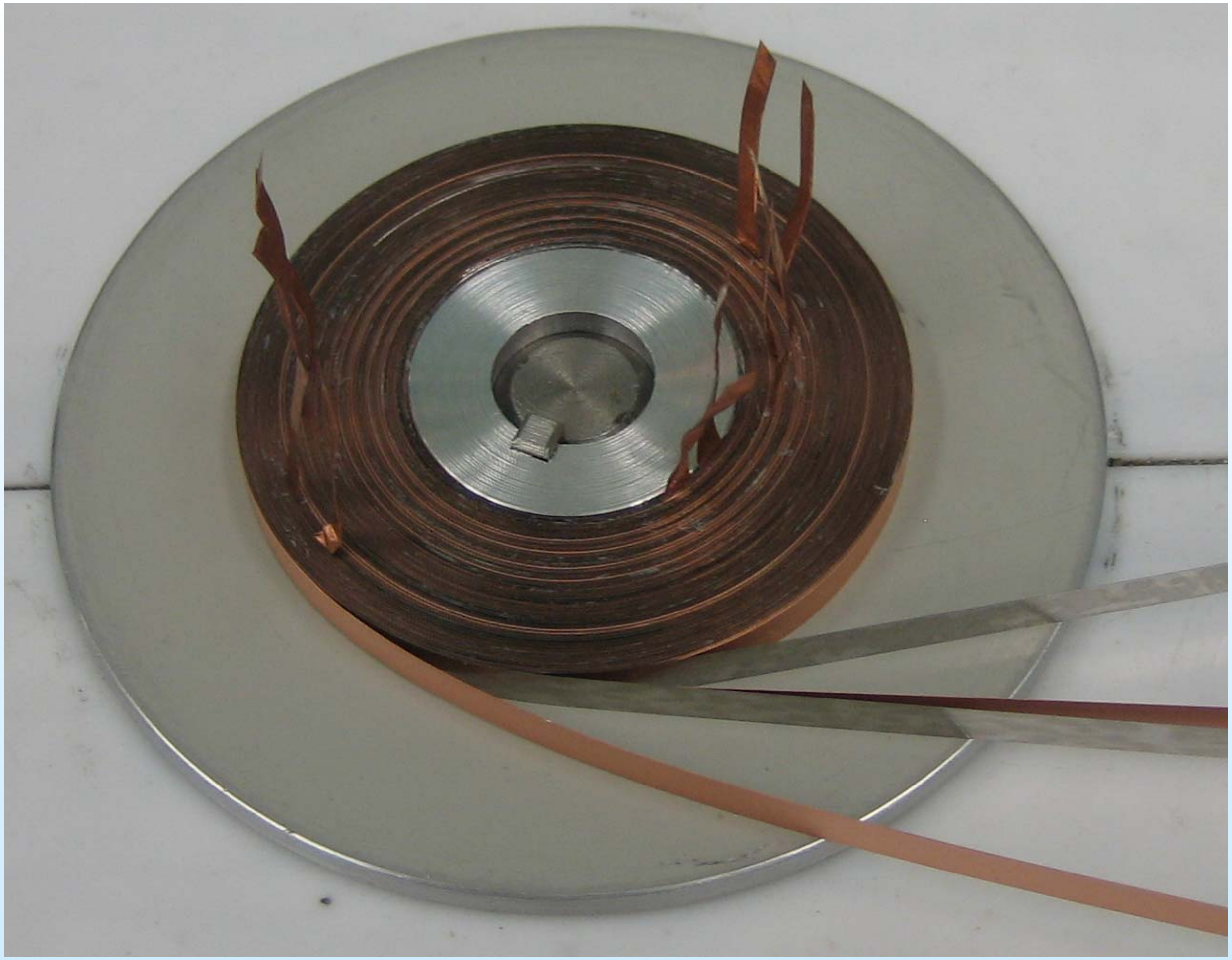
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Measurements to Study the Influence of Stress on the Narrow side of HTS Tape



Bi-filar Coil for Axial Loading



Load is applied on the narrow face of the coil.

Bi-filar winding is chosen to minimize the influence of magnetic field on performance.

Total length of the winding: 2 X 3 = 6 meter

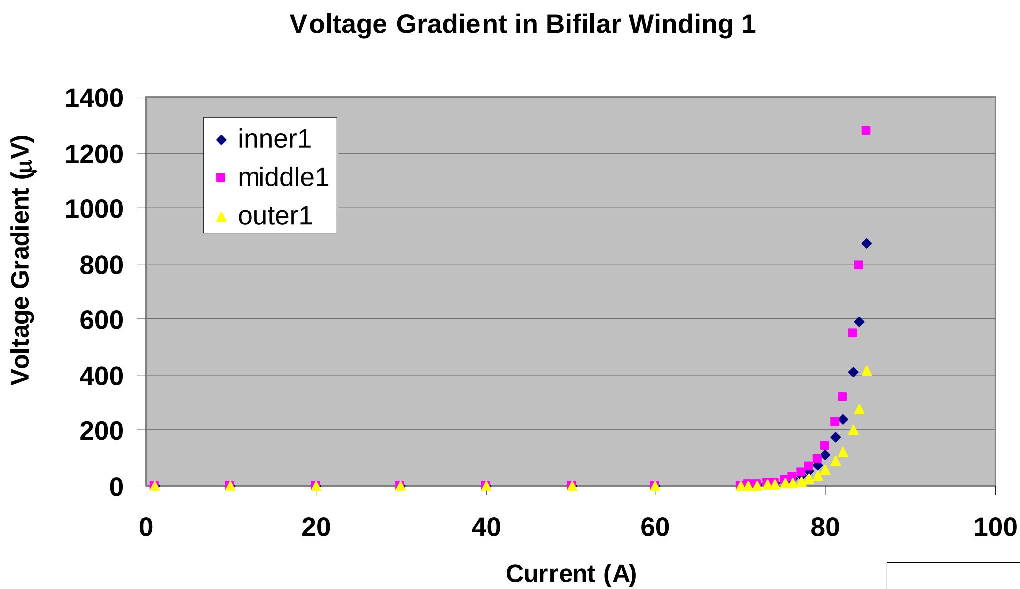
Voltage tap approximately after every meter.

Maximum load 4200 Lbs or 107 MPa (max in current SMES design 106 MPa)

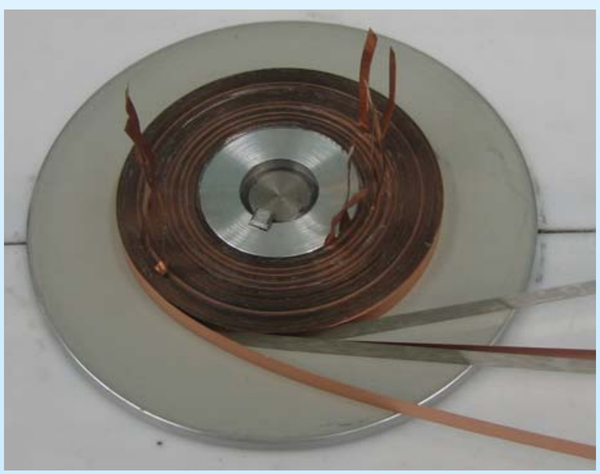
Coil i.d. ~50 mm

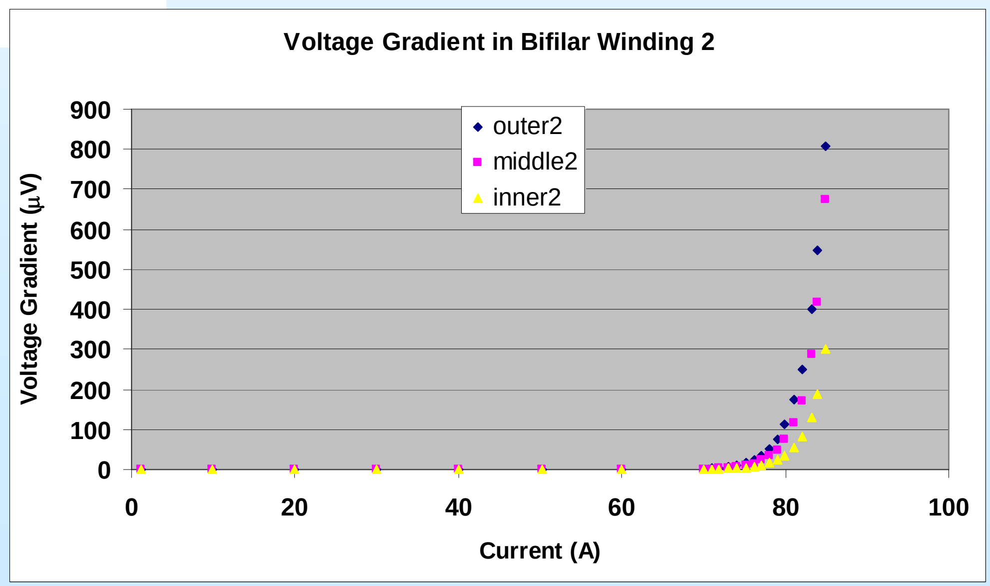
Courtesy: High School Summer Student Eric Evangelou, W. Sampson and Y. Shiroyanagi

Performance of Bi-filar Coil at 77 K



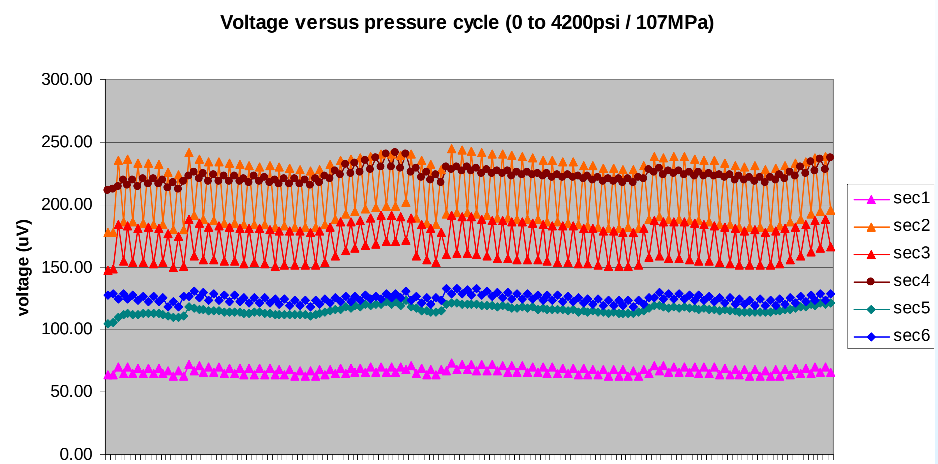
- Voltage is measured as a function of current in six 1 m (100 cm) sections.
- All have similar performance (similar conductor and negligible effect of magnetic field) because of bi-filar.
- To obtain maximum sensitivity, load is applied when the current is fixed near short sample (~82 A) and then change in Ic is derived from the voltage signal.

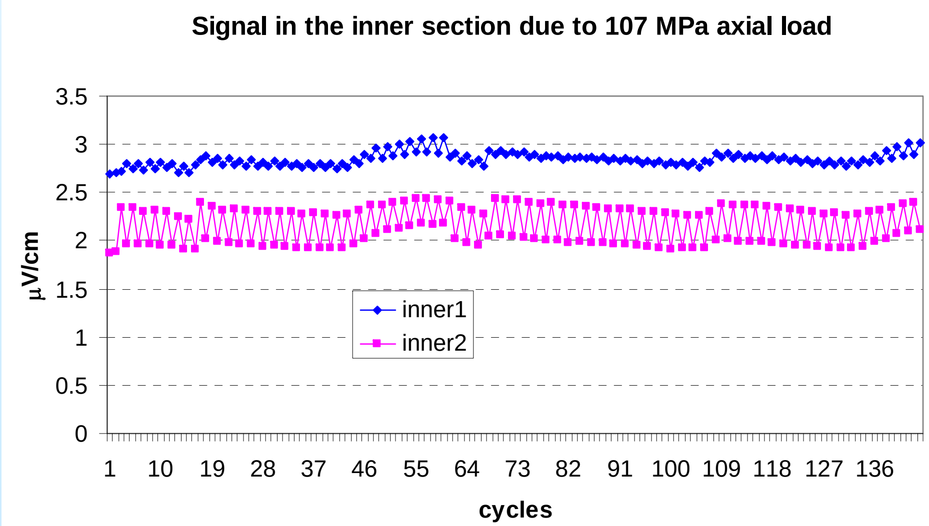


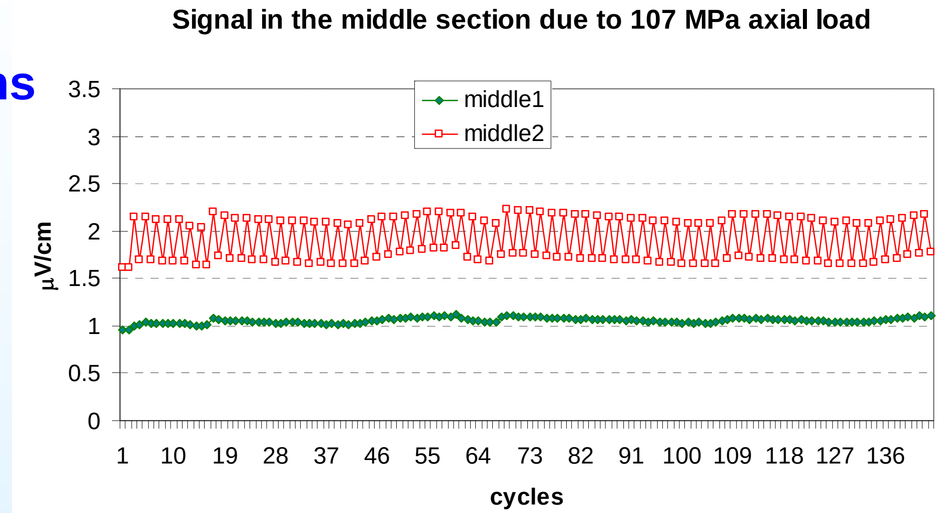


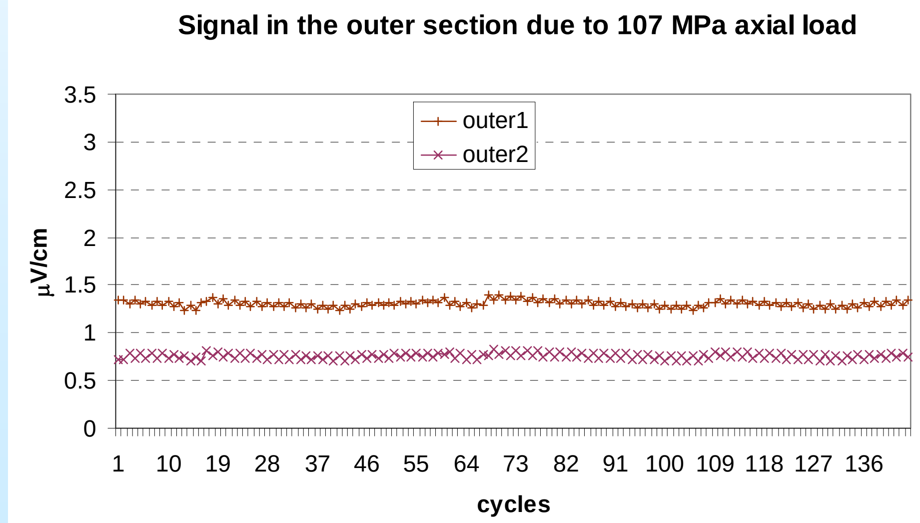
Influence of ~107 MPa Pressure on the Narrow Face of Conductor in 2G HTS Coil

Load ON, Load OFF. Measure change in voltage in ~100 cm (1 m) long six sections









~0.5% reversible change in Ic

Other HTS Programs

Brookhaven National Laboratory

Superconducting Magnet Division

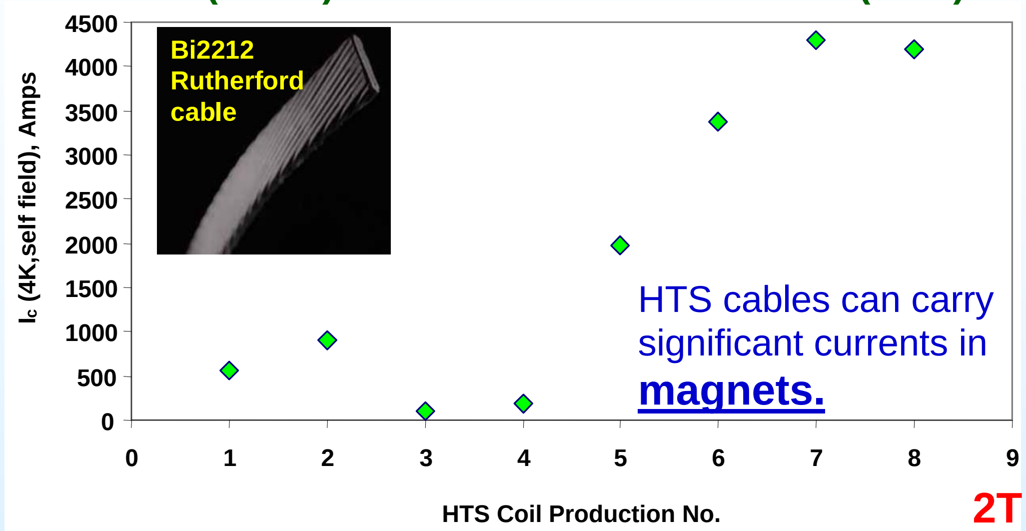
HTS Common Coil Dipole with Bi2212 Rutherford Cable

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

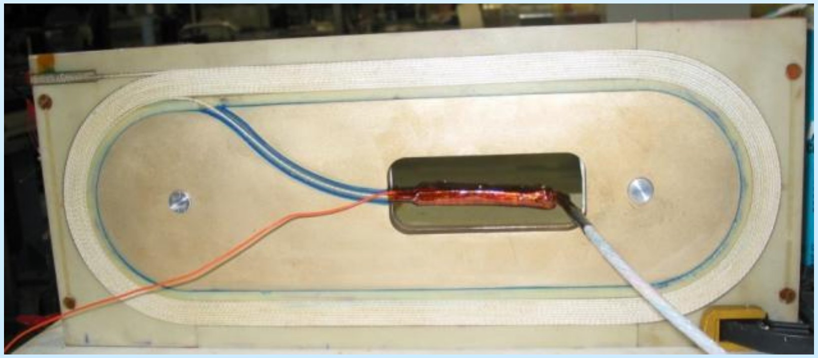
Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag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



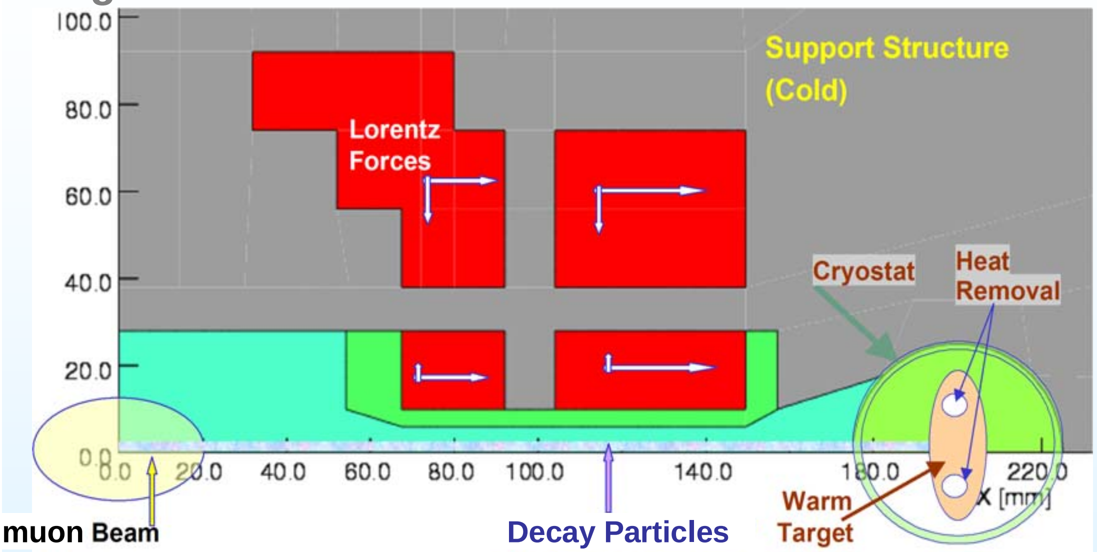
Racetrack HTS coil with Bi2212



BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

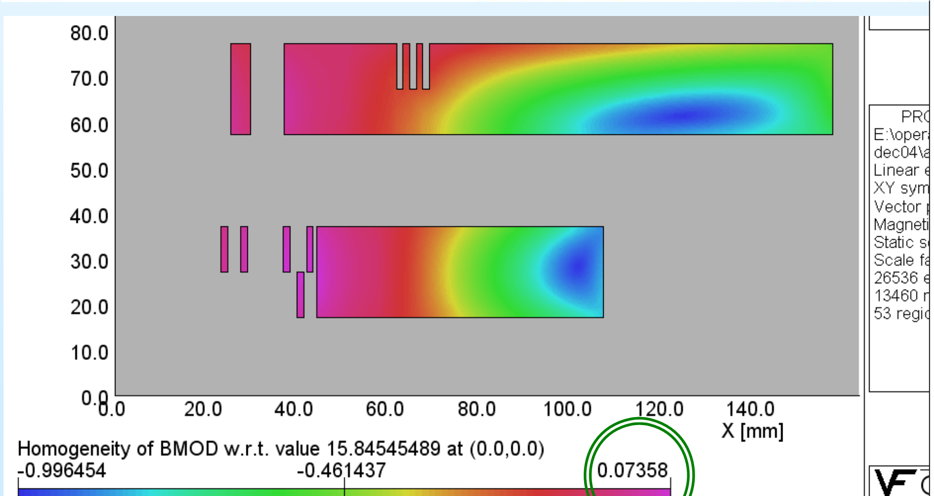
Open Midplane Dipole Phase I SBIR (Another BNL/PBL collaboration)



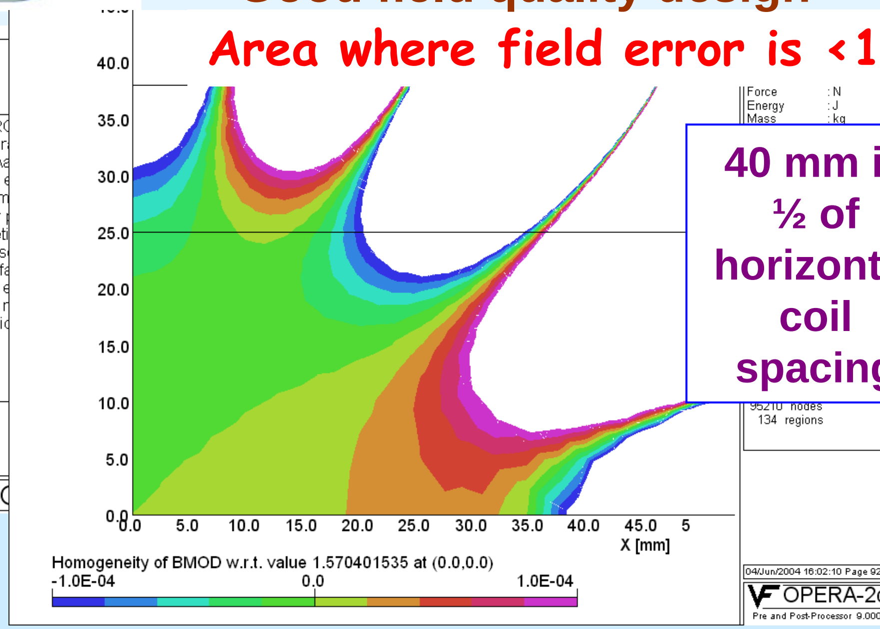
- Use of HTS (a) will allow very high magnetic fields (20 T or above) and (b) can tolerate high heat loads.
- Higher field will allow higher energy and/or higher luminosity.
- Significant progress was made during LARP funding

Good field quality design

Area where field error is $<10^{-4}$



A low peak enhancement: ~7% over Bo



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

A number of HTS magnet R&D programs with different philosophies help each other

- PBL/BNL 20+ T HTS solenoid: Experimental program
- FRIB HTS quad: Conservative design for a real machine
- High energy density 25+ T HTS SMES: High risk, high reward program

HTS is the only conductor that can create very high fields (20+ T)

We have to learn to use that to reach those field levels.

Significant progress has been made in the conductor and magnet technology.

However, many challenges still remain.

A systematic and experimental R&D program is the best way to move forward.

With a variety of programs and a large experience, BNL is playing a major role in moving HTS technology forward. We are open for useful collaborations and help in moving HEP programs forward that may benefit from HTS magnets.

Backup Slides

Near Term HTS R&D at BNL

- Improve electronics for detecting small voltage signal over noise
- Quench detection, protection, etc.
- Increased instrumentation for protection
- Measurement of the impact on conductor of axial loading
- Computer controlled coil winder for adjusting and recording tension during winding
- Systematic R&D with small coils on a number of topics
- A number of topics in SMES

High Field Muon Collider Solenoid
SBIR with PBL (Particle Beam Lasers)

Collaboration:

- A useful collaborative program between PBL & BNL to develop high field superconducting solenoid technology for muon collider.
- PBL brings ideas and funding through SBIR.
- BNL contributes its staff, ideas, facilities and past experience with HTS.

Overall program philosophy and strategy:

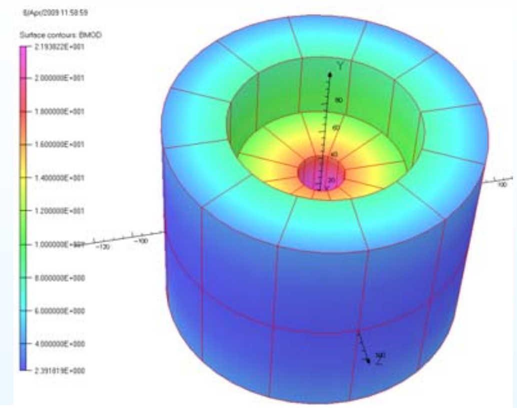
- There is not enough funding in one SBIR to build 35-40 T solenoid.
- However, this could be done with a series of SBIR with each attractive in its own right.
- This approach also provides a natural segmentation which is anyway needed to reduce accumulation of stress/strain on the conductor due to Lorentz forces.
- It also allows lessons learnt from one SBIR (year) to apply to the next.

Unique Features of Phase 1 Nb_3Sn Solenoid Proposal

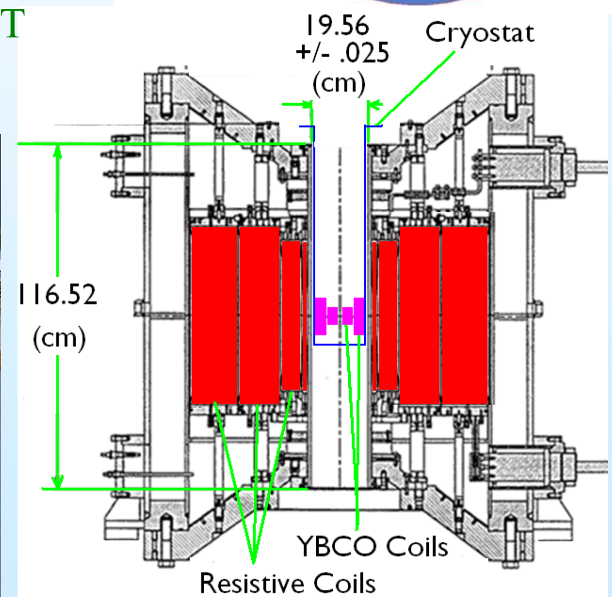
- High field Nb_3Sn solenoid have been primarily built with CICC technology.
- CICC is proven technology. However, it offers a relatively lower J_w as compared to the Rutherford cables, used in accelerator magnets.
- Higher J_w offers many advantages. However, industry is more likely to use this technology after it is proven in solenoids.
- One purpose of this SBIR is to do just that - that will be a significant contribution to high field solenoid technology in itself.
- Another purpose of this SBIR is to build the outsert to build 35-40 T solenoid with other two segments coming from previous two SBIR.

High Field HTS Solenoid for Muon Collider

- Muon collider needs very high field solenoids (30 T – 50 T) and other high field (20+ T) magnets that are only possible with HTS.
- A low cost "build, test and try" PBL/BNL high field solenoid program rather than a more complete fully funded high field R&D Program.
- Component of the program: (1) ~100-165 mm, ~10 T solenoid and (2) 25-95 mm ~12 T insert solenoid (3) Create 20+T field by combing two in one all HTS solenoid (4) test HTS solenoid to field approaching 40 T with NHMFL 19 T resistive solenoid.



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



X-section of the NHMFL 19 T resistive magnet with the 12T and 10T YBCO coils inside.

Components of 35-40 T Solenoid

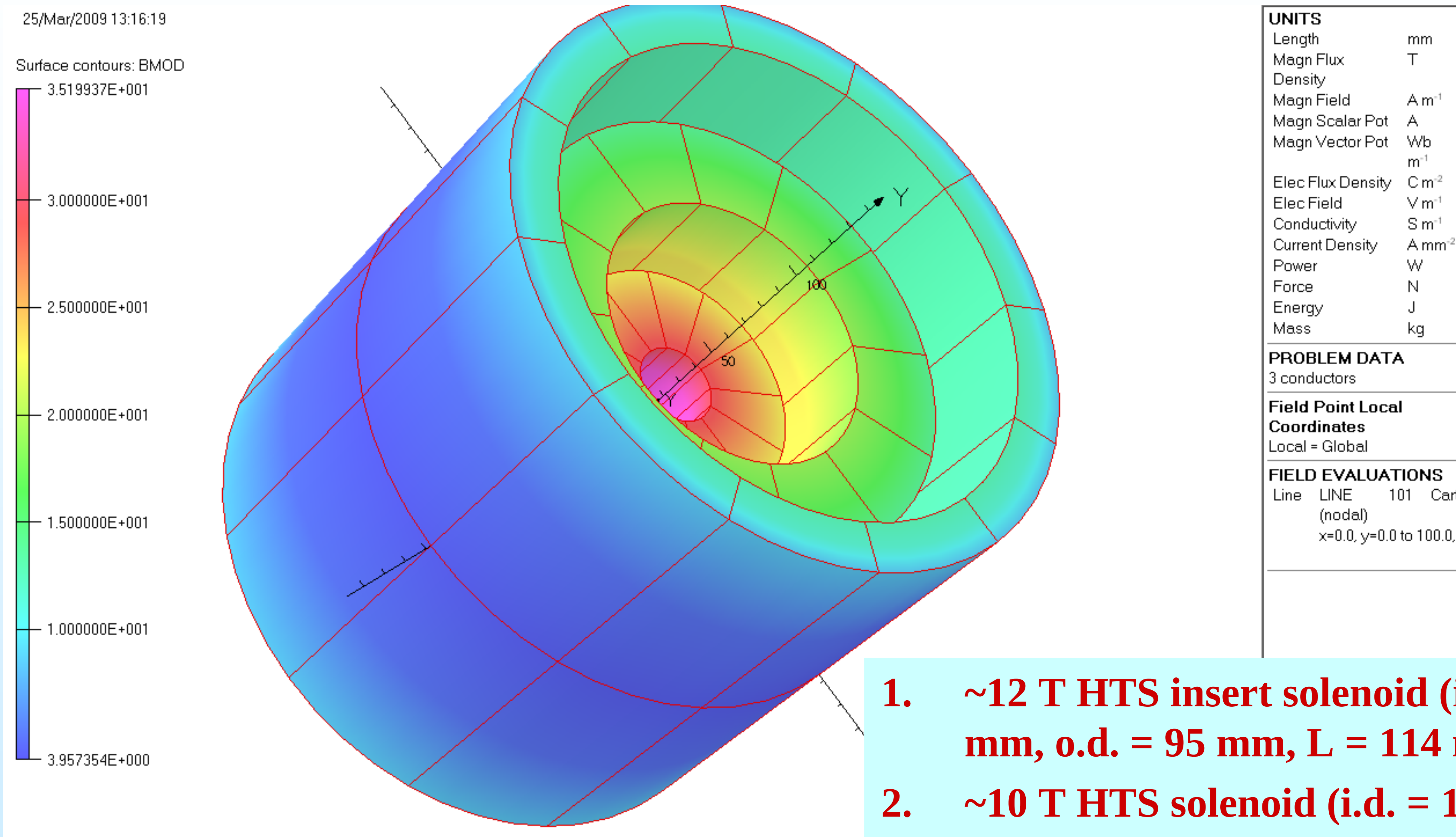
SBIR proposals from PBL:

1. Phase II #1, 08-10 (funded): ~10 T HTS solenoid (i.d.=100 mm, o.d.=165 mm, L ~128 mm)
2. Phase II #2, 09-11 (funded): ~12 T HTS insert (i.d. = 25 mm, o.d. = 95 mm, L ~64 mm)
3. Phase 1, 10-11 (proposed): 12-15 T Nb_3Sn outsert (i.d.=180 mm,o.d.=210^+ mm,L = 200^+mm)

Overall programmatic features:

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

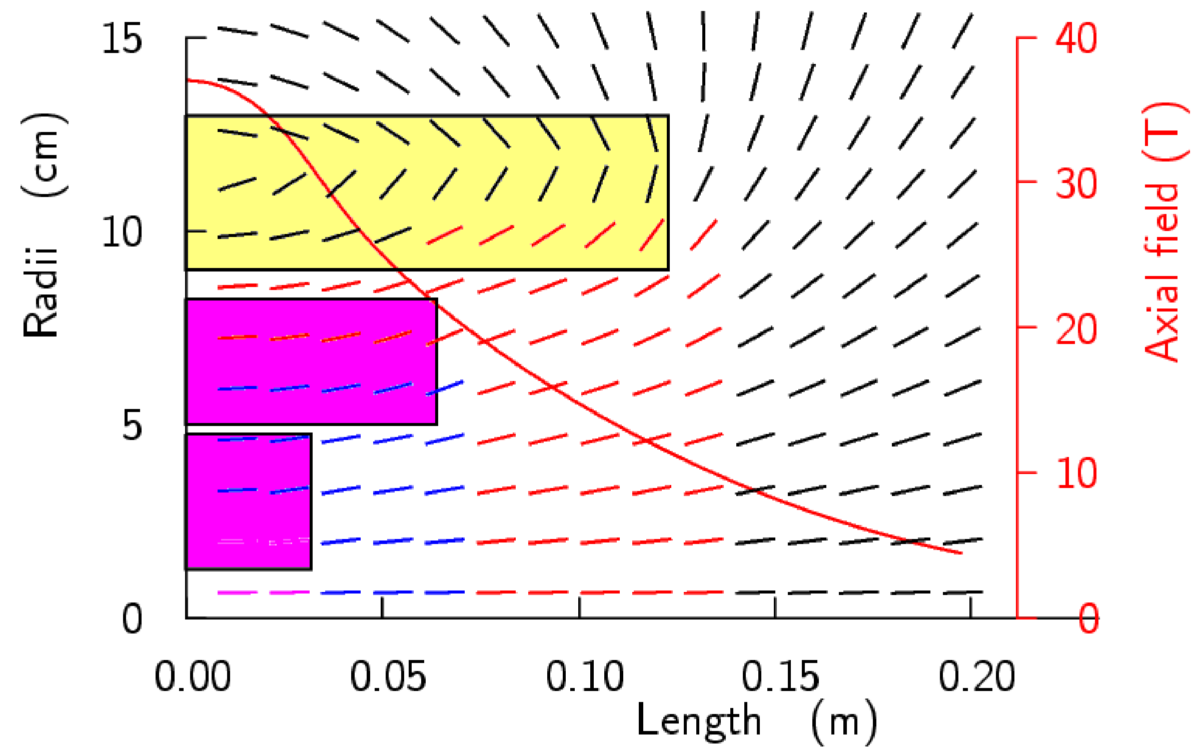
Preliminary Design with 12 T Nb_3Sn outsert



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

Layout of Three Solenoids

Courtesy
Bob Palmer

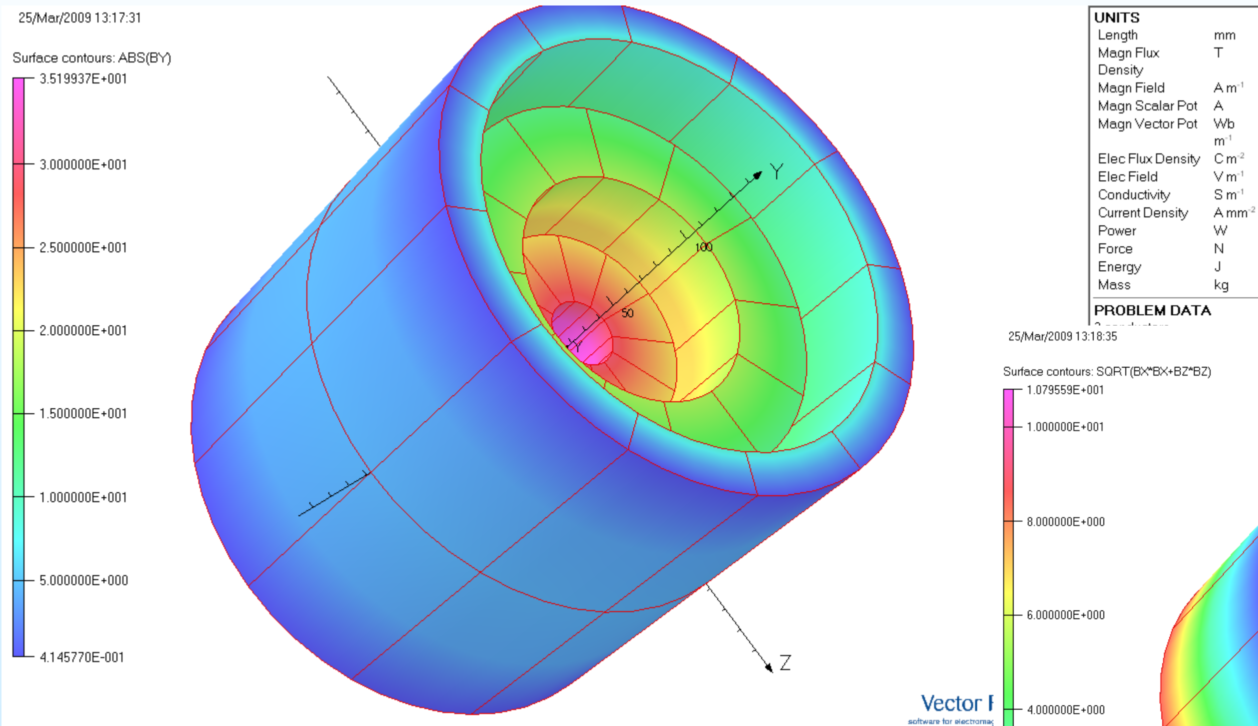


Field directions and axial fields for the combined magnet using the Nb_3Sn coil (yellow) and the two YBCO coils (magenta)

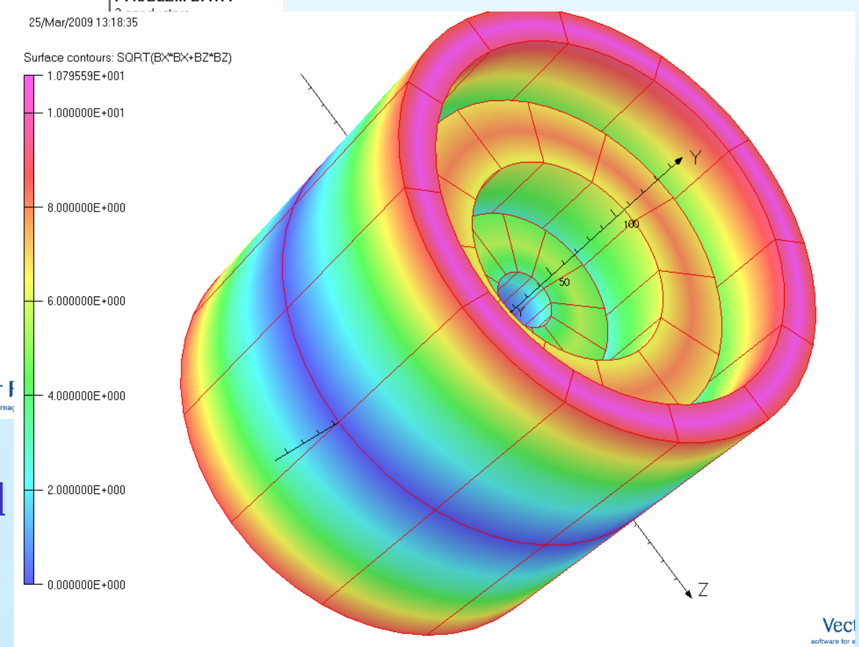
Angular Field Dependence of Ic is in Helpful Direction

Field Parallel (~35.2 T, max)

Inner two are HTS coils and outermost is Nb3Sn



Field Perpendicular (~10.7 T max)

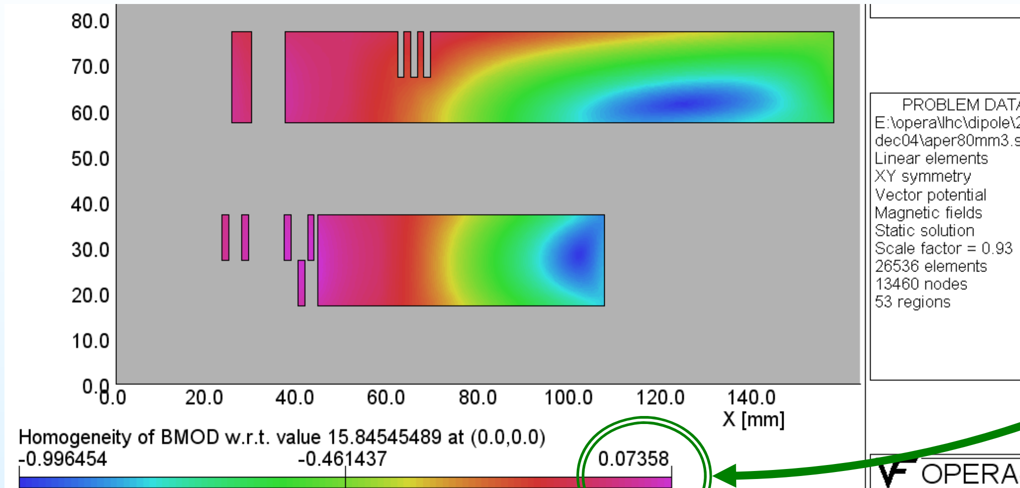


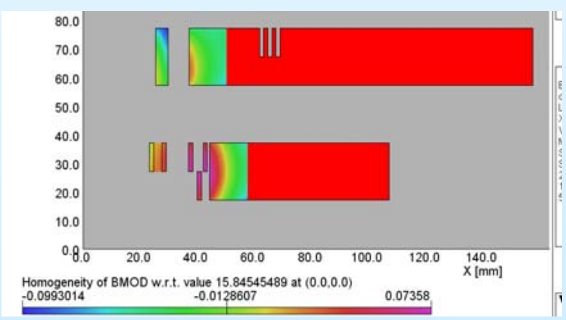
2G HTS carry significantly more current in field parallel direction than in field perpendicular

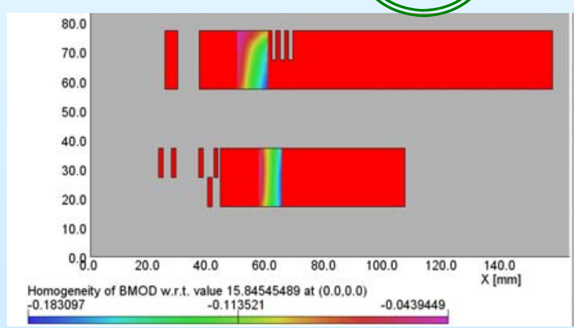
Challenge #2: Peak Field

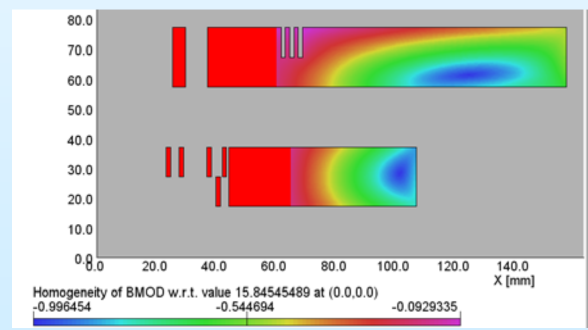
Several designs have been optimized with a small peak enhancement: ~7% over B_o

Relative field enhancement in coil over the central field









Quench Field: ~16 T with J_c = 3000 A/mm^2, Cu/Non-cu = 0.85

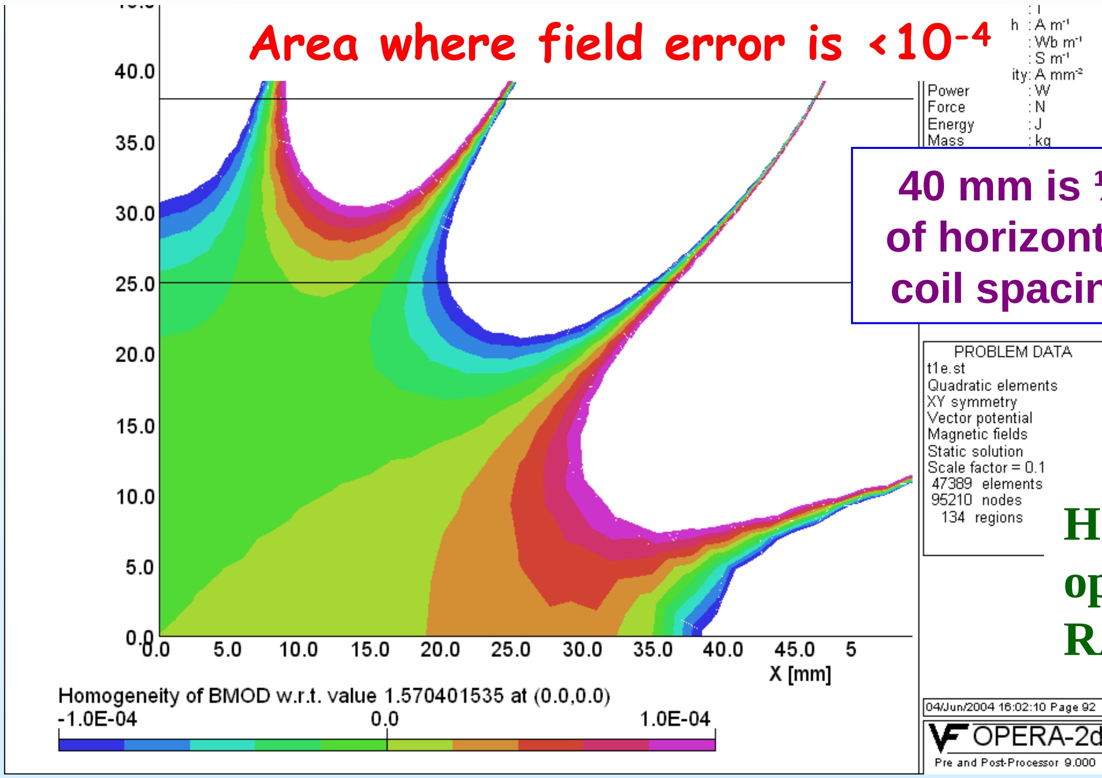
Quench Field: ~15.8 T with J_c = 3000 A/mm^2, Cu/Non-cu = 1.0

Field Harmonics and Relative Field Errors in an Optimized Design

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Proof: Good field quality design can be obtained in such a challenging design:



40 mm is ½ of horizontal coil spacing

Harmonics optimized by RACE2dOPT

(Beam @ x=+/- 36 mm at far end)

(Max. radial beam size: 23 mm)

Geometric Field Harmonics:

	Ref(mm)	Ref(mm)
n	36	23
1	10000	10000
2	0.00	0.00
3	0.62	0.25
4	0.00	0.00
5	0.47	0.08
6	0.00	0.00
7	0.31	0.02
8	0.00	0.00
9	-2.11	-0.06
10	0.00	0.00
11	0.39	0.00
12	0.00	0.00
13	0.06	0.00
14	0.00	0.00
15	-0.05	0.00
16	0.00	0.00
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00

Field errors should be minimized for actual beam trajectory & beam size.
It was sort of done when the design concept was being optimized by hand.
Optimization programs are being modified to include various scenarios.
Waiting for feed back from Beam Physicists on how best to optimize.
However, the design as such looks good and should be adequate.