Recent Results With HTS Pancake Coils

Ramesh Gupta
for
PBL/BNL Team

Background

- Ionization cooling in muon collider needs very high field solenoids (~40 T).
- Use of HTS is essential to generate such high fields in a non-pulsed mode.
- When HTS solution was initially proposed, a few people took it seriously.
- About four years ago PBL/BNL team proposed an experimental program with a series of SBIR to develop/evaluate magnet technology for ~35 T.
- Even though BNL had significant experience with many success stories on HTS over a decade; however, for high fields, there were more questions than confidence.
- I hope that test results presented today would not only make you more upbeat, but would also join me in saying (this time with better confidence) – "why not 40 T?"

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

PBL/BNL Dream for MAP thru SBIRs

SBIRs from Particle Beam Lasers (PBL) with BNL as partner:

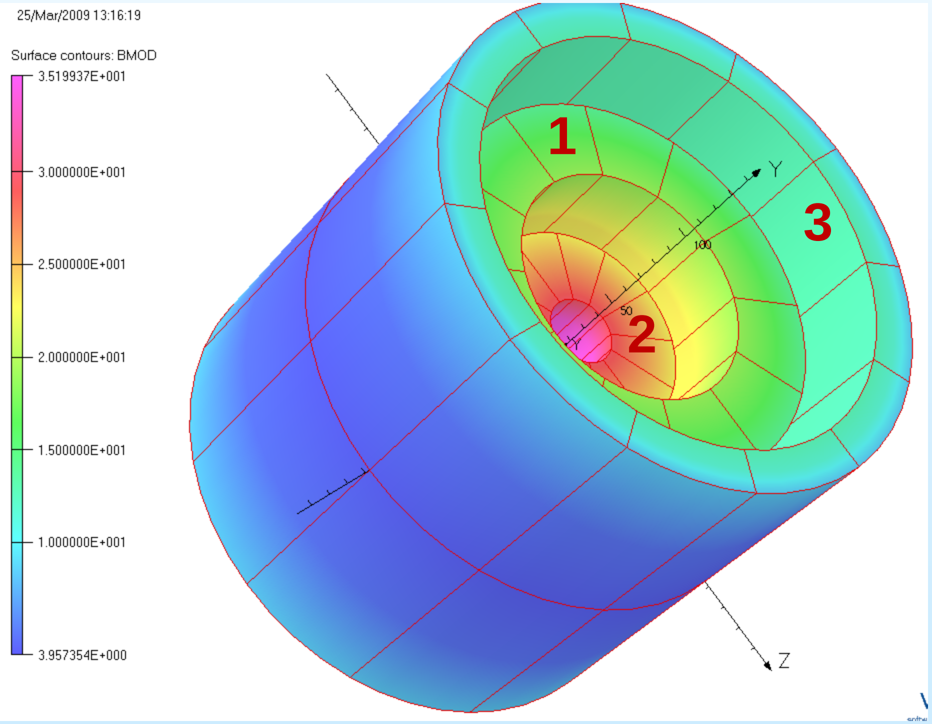
1. **~10 T HTS solenoid (midsert): Phase II funded**
2. **~12 T HTS (insert): Phase II funded**
3. **12-15 T Nb_3Sn (outsert): Phase I funded, Phase II will be applied**

20⁺ T All HTS Solenoid (1 & 2):

addresses challenges with high field HTS solenoids

35⁺ T All Superconducting Solenoid (1, 2 and 3):

addresses challenges with high field superconducting solenoids

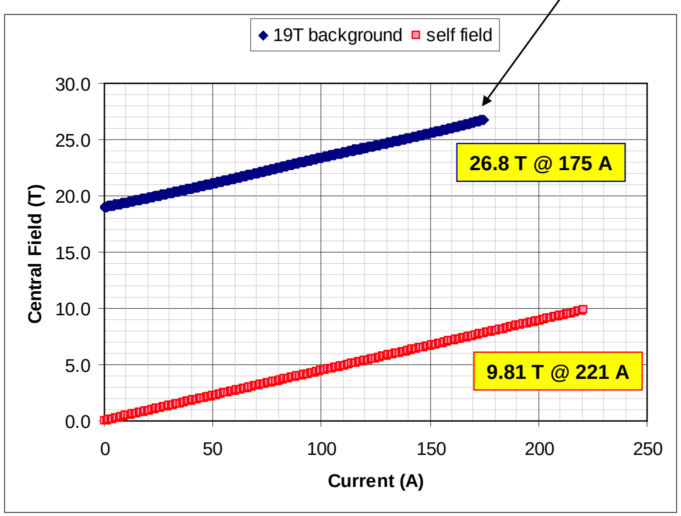


Where are we starting from?

SuperPower/NHFML YBCO Solenoid

High field insert coil achieves world records for highest HTS field, highest magnetic field by a SC magnet

Peak hoop stress ~ 215 MPa, well below tape limit



Ic of Wires in Coil	72 A – 82 A (77K, sf)
4.2 K Coil Ic - self field	221 A
4.2 K Amp Turns @ Ic-self field	612,612
4.2 K Je @ Ic, self field	346.7 A/mm²
4.2K Peak Radial Field @ Ic, self field	3.2 T
4.2 K Central field – self field	9.81 T
4.2 K Coil Ic – 19 T background (axial)	175 A
4.2 K Amp Turns @ Ic – 19 T background (axial)	485,100
4.2 K Je @ Ic, 19 T background (axial)	274.6 A/mm²
4.2 K Peak Radial Field @ Ic, 19 T bkgd (axial)	2.7 T
4.2K Central Field – 19 T background (axial)	26.8 T

MAGNET LAB
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY - LOS ALAMOS NATIONAL LABORATORY - UNIVERSITY OF FLORIDA

SuperPower Inc.

Low Temperature Superconductivity Workshop, 10/29/07 – 19 –

Best stand alone HTS solenoid ~10 T (till a week ago)

We were talking about 20-22 T (that too in a limited budget of SBIRs)

Key Members of PBL/BNL Team

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

D. Cline, A. Garren, J. Kolonko, R. Scanlan, R. Weggel, E. Willen
Particle Beam Lasers

Summary of PBL/BNL Achievements

- Phase II of insert and midsert HTS solenoid has been funded. Phase I of outsert LTS solenoid funded - Phase II to be applied this year.
- All HTS coils needed for both insert (14 coils) and midsert (24 coils) have been built and individually tested at 77 K (selected from 19 + 29 tested coils)
- Half length midsert solenoid (12 coils instead of 24) has been tested at 4 K. This is a successful test of a large aperture (100 mm) solenoid with largest amount (1.2 km) total HTS wire ever
- Full insert has been tested (highest record field for an HTS solenoid)
- Impressive future plans to go for 40 T (Please see a later slide for future plans)

Original Design Parameters (ASC2010)

Target Design field (optimistic)	~22 T
Number of coils (radial segmentation)	2 self supporting
Stored Energy (both coils)	~110 kJ
Inductance (both in series)	4.6 Henry
Nominal Design Current	~220 A
Insulation (Kapton or stainless steel)	~0.025 mm
J_e (engineering current density in coil)	~390 A/mm^2
Conductor	2G ReBCO/YBCO
Width	~4 mm
Thickness	~0.1 mm
Stablizer	~0.04 mm Cu

Outer Solenoid Parameter	
Inner diameter	~100 mm
Outer diameter	~160 mm
Length	~128 mm
Number of turns per pancake	~240 (nominal)
Number of Pancakes	~~28 (14 double)~~ 24 (12)
Total conductor used	2.8 km
Target field generated by itself	~10 T
Inner Solenoid Parameter	
Inner diameter	~25 mm
Outer diameter	~90 mm
Length	~64 mm
Number of turns per pancake	~260 (nominal)
Number of Pancakes	14 (7 double)
Total conductor used	0.7 km
Target field generated by itself	~12 T
External Radial support (overband)	Stainless steel tape

- **The purpose of the program is to find out what limits the actual performance; what R&D is needed to overcome those limitations and how close to target one can reach with the available resources.**

This presentation was originally scheduled for results of one test, but we are going to summarize two tests

1. Test results of half midsert with 12 coils (24 coils required in full)
   - ~100 mm i.d., ~160 mm o.d., each coil uses ~100 meter, 100 micron thick, 4 mm wide 2G tape from SuperPower (with ~45 micron thick copper)

2. Test results of full insert (14 coils)
   - ~25 mm i.d., ~91 mm o.d.,
   - each coil uses ~50 meter of similar 2G tape from SuperPower

Overall test results of both solenoids will be discussed first and a bit more on details and a bit on analysis of the two together will be discussed later

Midsert Solenoid (Half-size: 12 coils)

Construction and Test Results

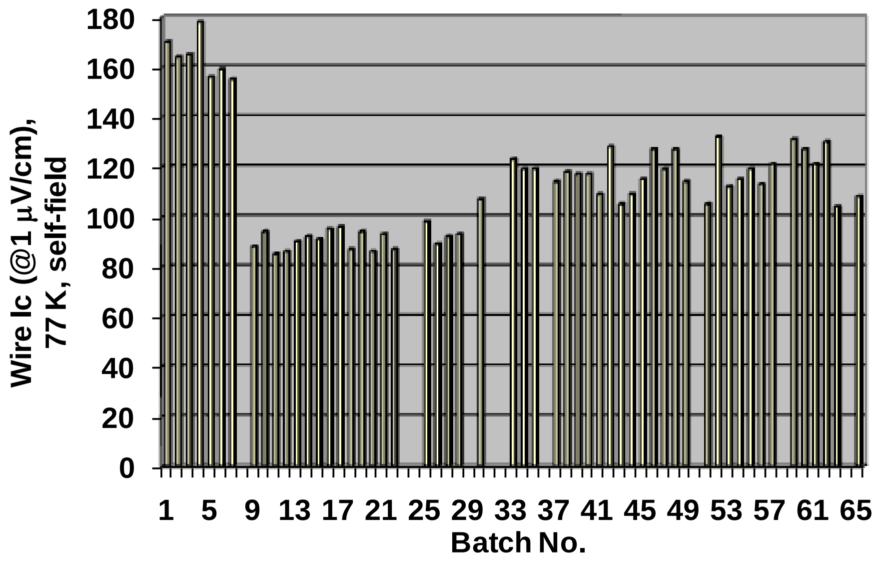
~100 mm i.d., ~161 mm o.d., ~55 mm height (half size)

NOTE: Whole midsert would use 24 identical pancake coils

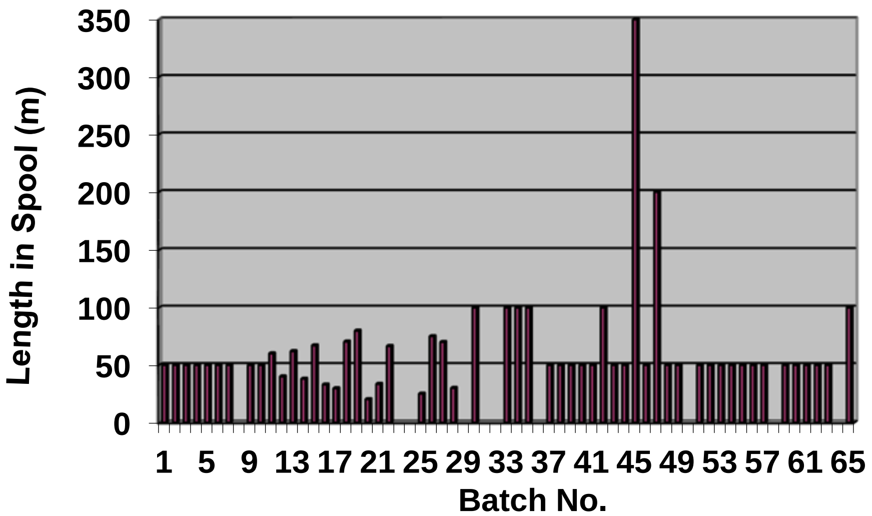
2G Tape from SuperPower

Wire was delivered in several batches.

Somewhat different Ic from batch to batch.



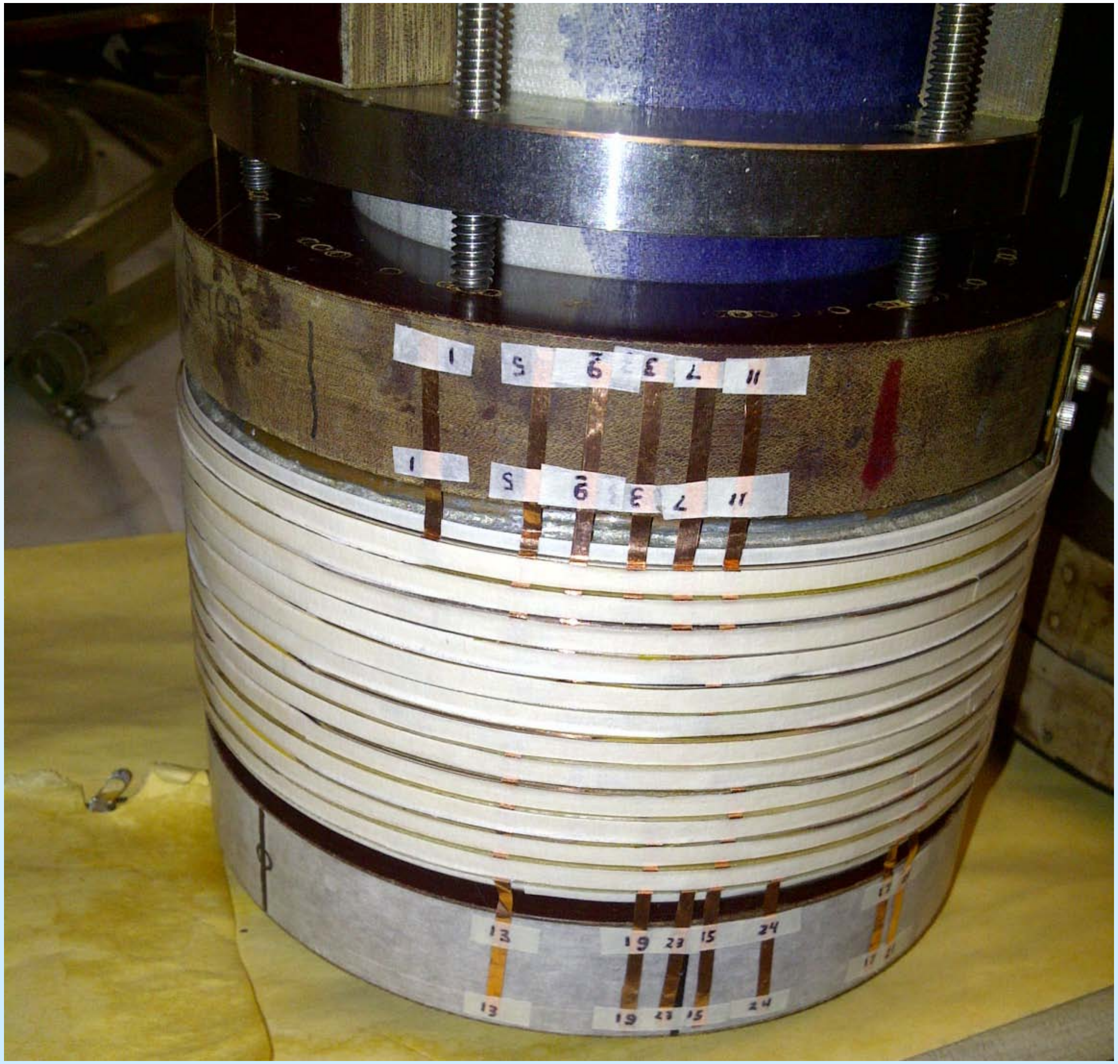
Each coil needs 100 meter tape



To live within means (reduced cost), we allowed vendor to supply wire in short lengths (one splice per coil allowed).

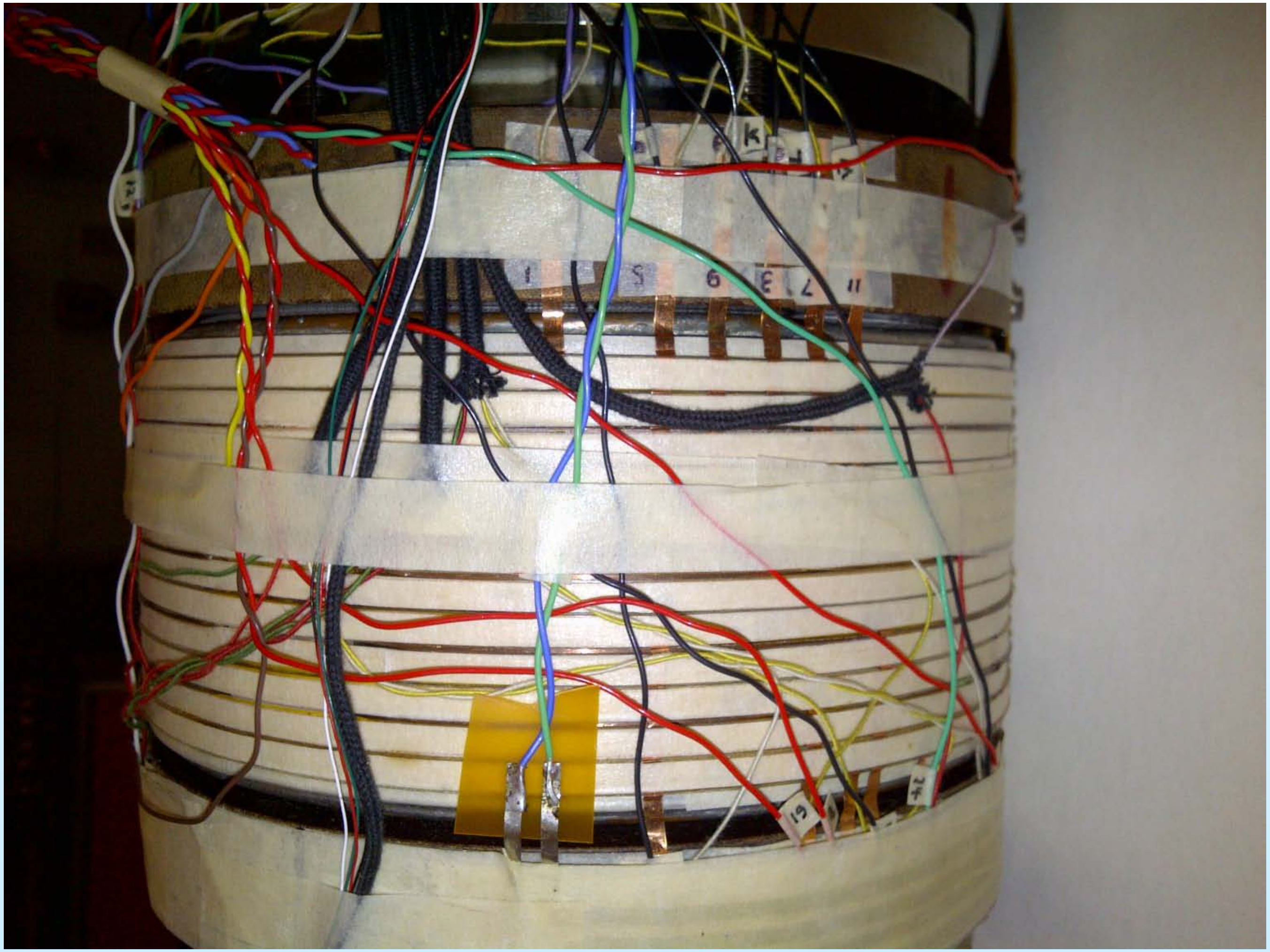
Still as long as 350 meter piece length was delivered (for no extra cost).

Few Pictures



This beautiful solenoid is handcrafted by Bill Sampson

William Sampson Honored With IEEE Award For Applied Superconductivity Research



~100 mm 2G Coils for Midsert

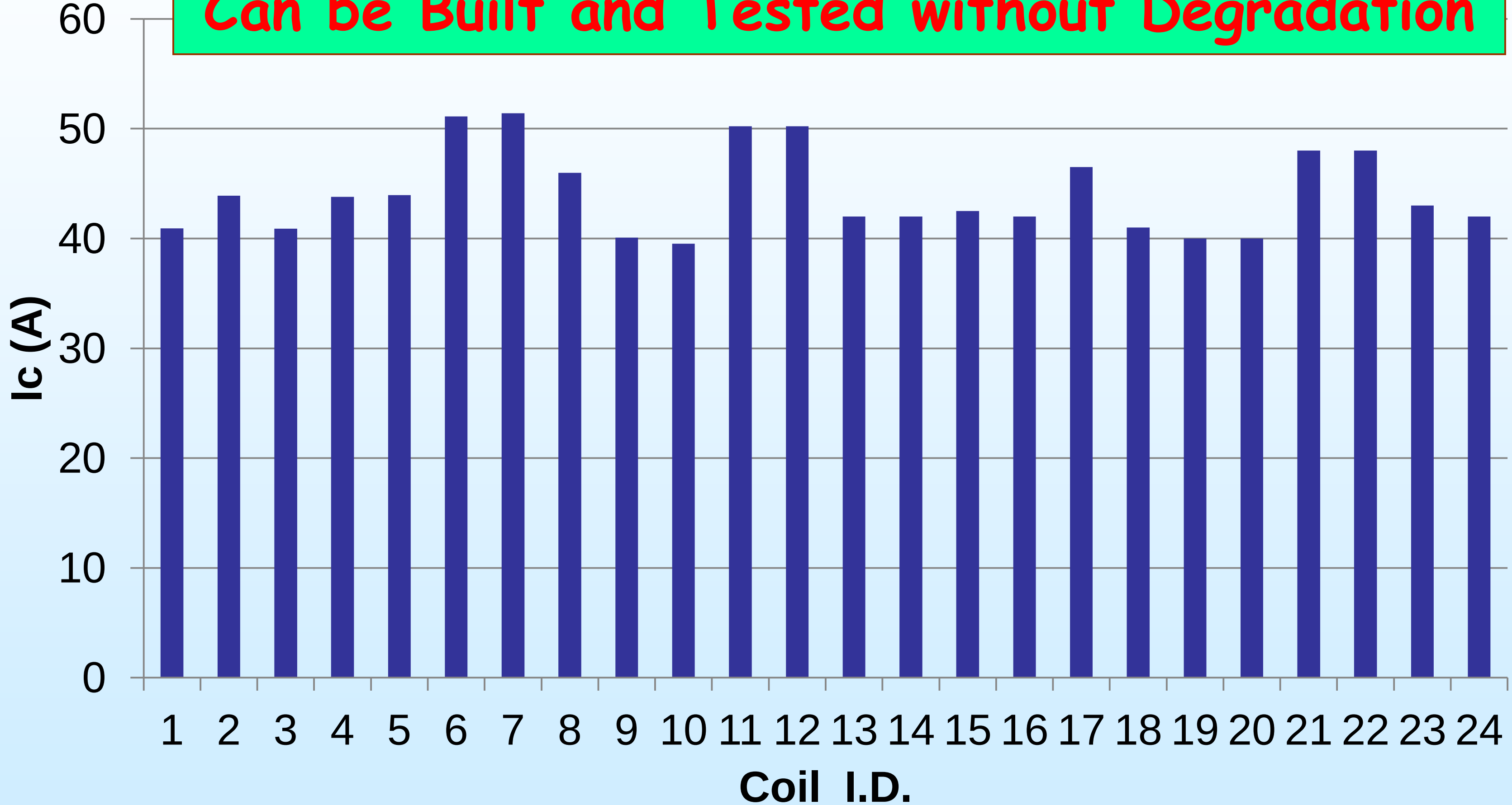
Each coil has ~240 turns and uses 100 meter tape (maximum one splice)

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

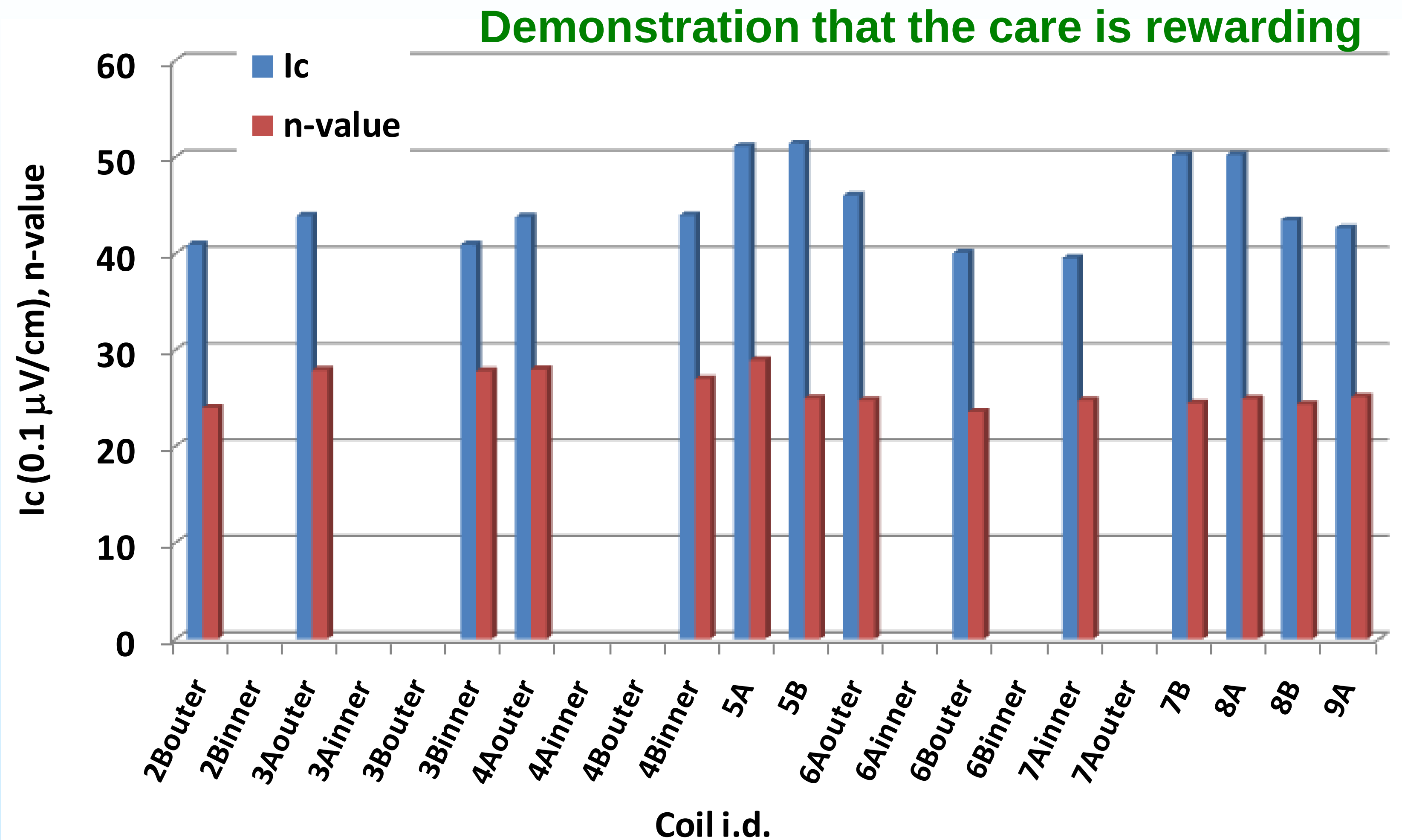
Test Results of 24 Coils at 77K

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

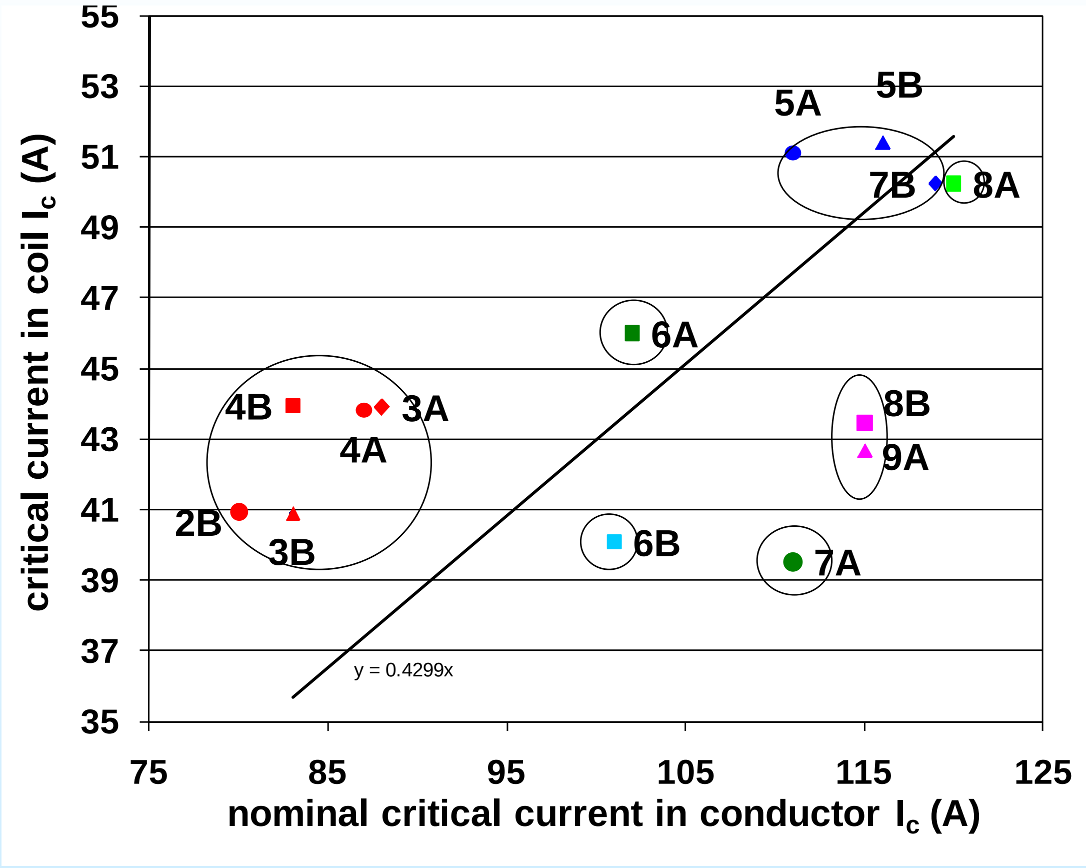
Performance of 2G Coils in LN2



To develop technology, it is important to build and systematically test a large number of coils – real applications will follow.

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

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



Coil Test Setup

What will be the correlation at 4 K?

Key Construction Features

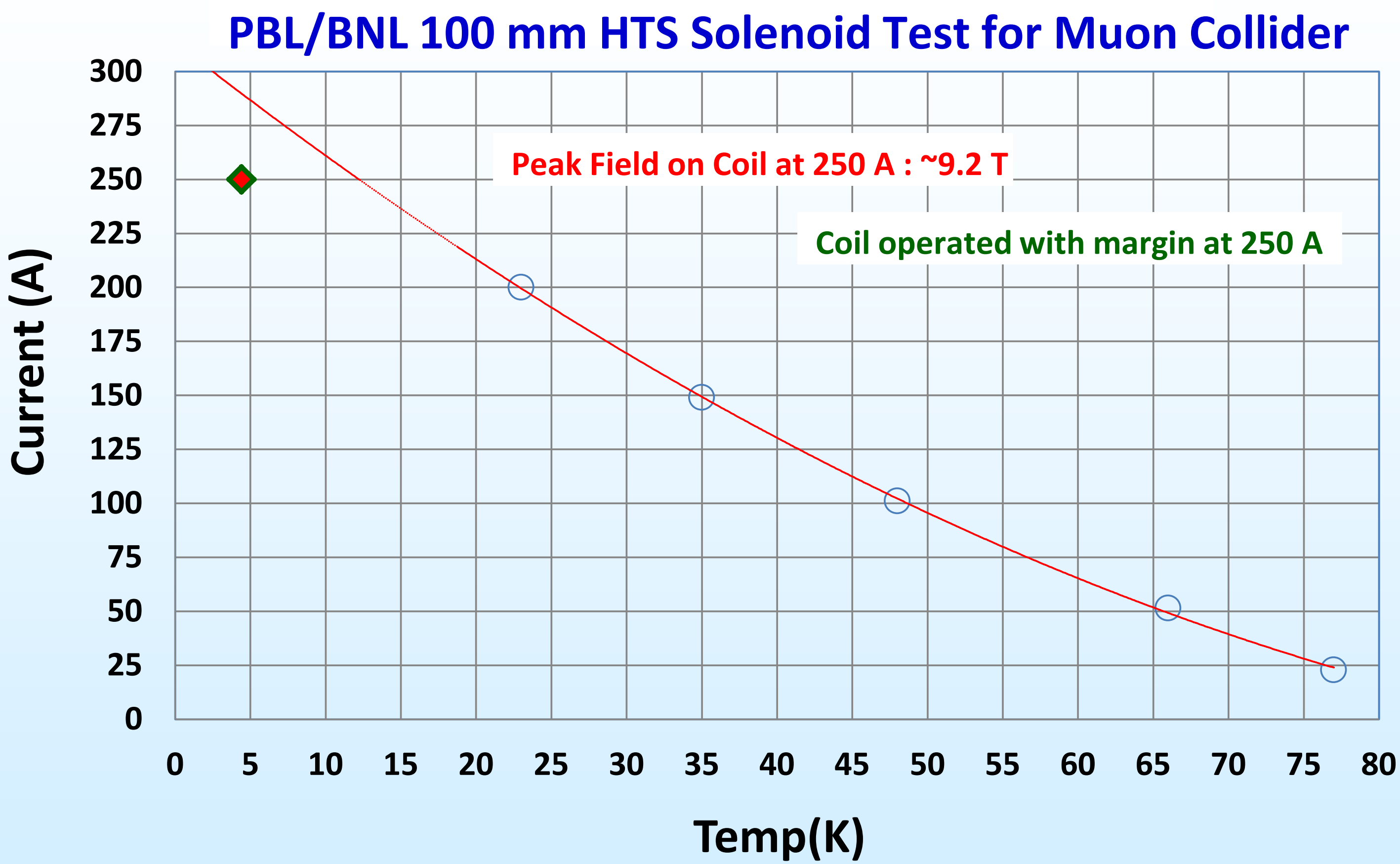
- Stainless steel reinforcement and turn to turn insulation
- G10 or Mylar sheet for coil-to-coil insulation
- Thin copper sheets between coils for thermal and possible energy distribution during quench
- Few layers of stainless steel and fiberglass radial enforcement over the coil
- Each coil individually protected (desirable to ~1 mV but never over few mV)

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Overall Test Results

Measured Critical Current As a function of Temperature



250 A ==> 9.2 T on coil

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

As per Superpower and search of literature, this is the first test of large aperture high field 2G magnet and also one that uses over 1 km (1.2 km) wire

Major Development and Progress on Quench Protection for HTS

Major R&D with new electronics is being performed for quench protection.
PBL/BNL SBIR has been critical to the development of HTS technology.

Another significant support from FRIB.

Quench protection is also a critical issue for our SMES program.

Reference:
PAC 2011 paper by Joshi, et al.

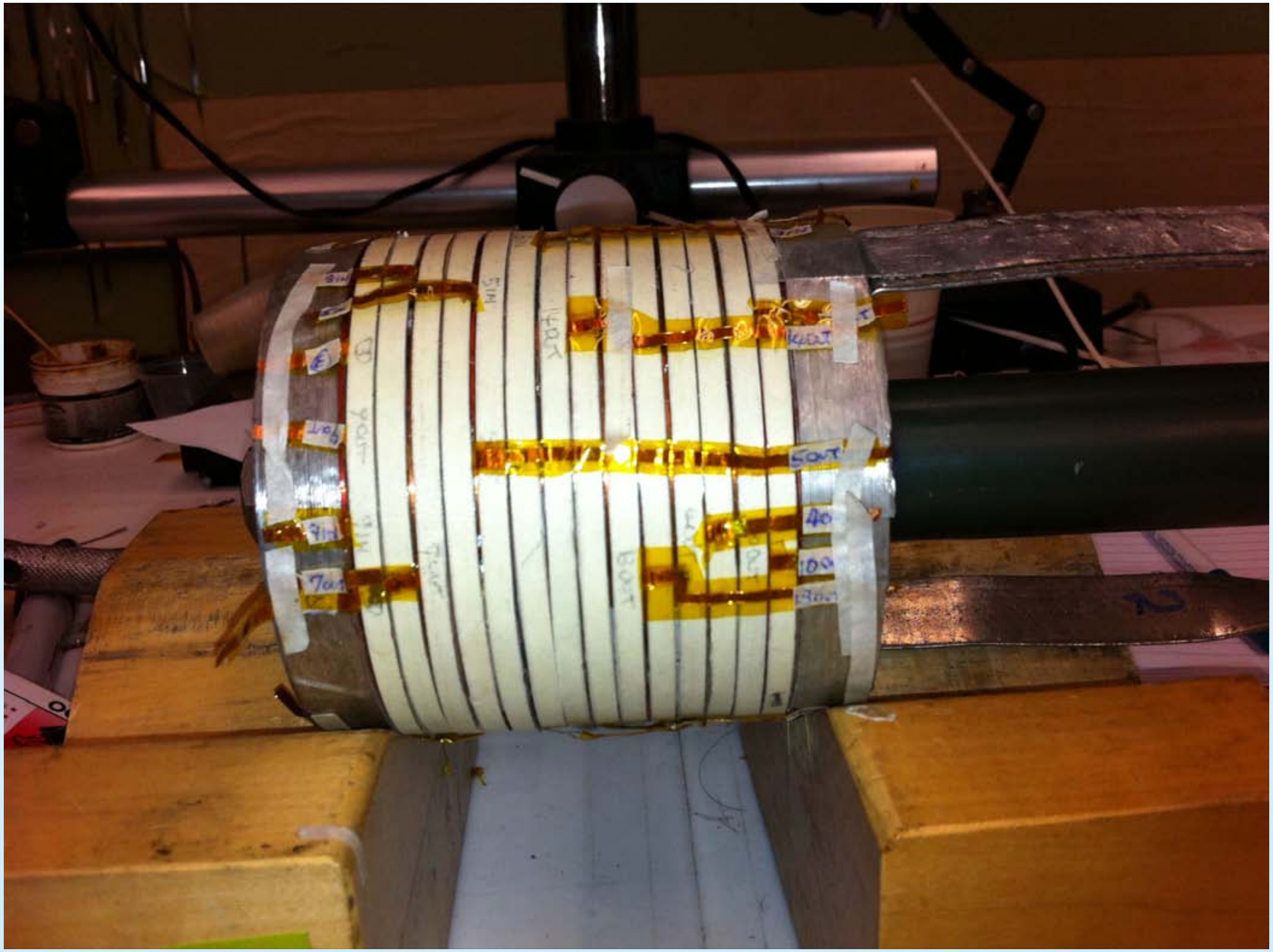
Insert Solenoid (14 coils)

Construction and Test Results

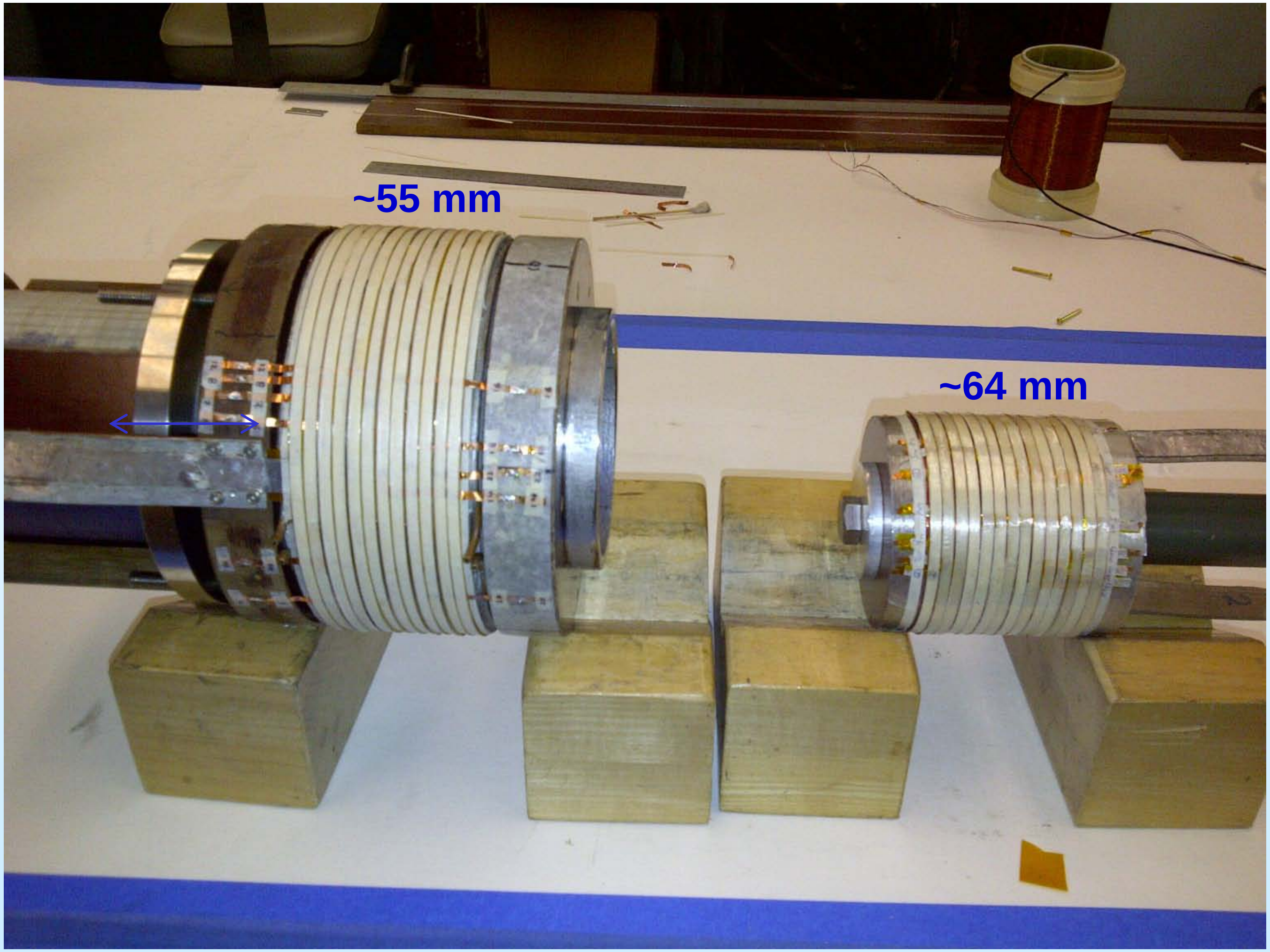
~25 mm i.d., ~91 mm o.d., ~64 mm height

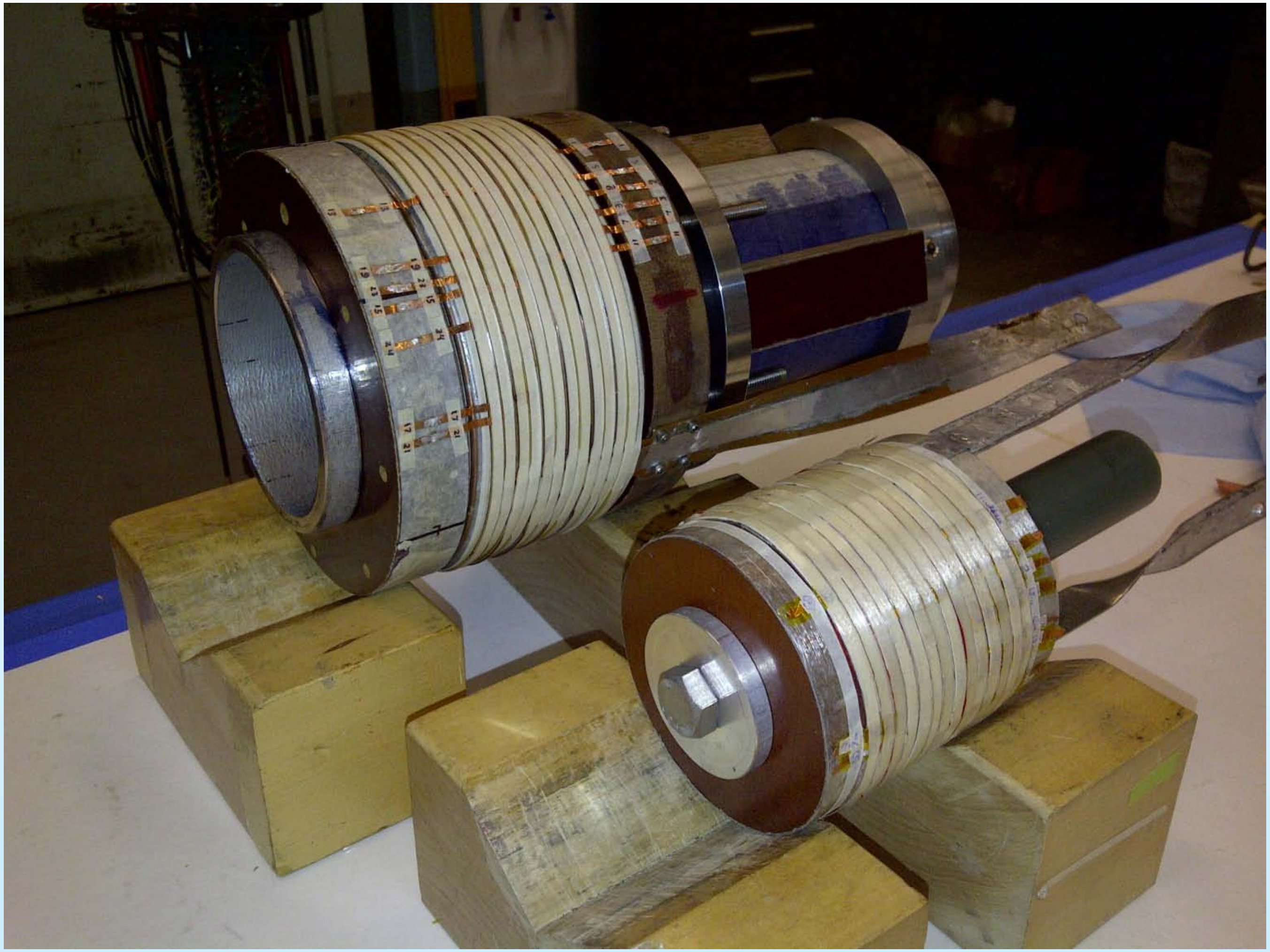
Few Pictures

Most work on the floor was performed primarily by Yuko Shiroyanagi (post-doc)



Two YBCO Solenoids (discussing their engagement plans)

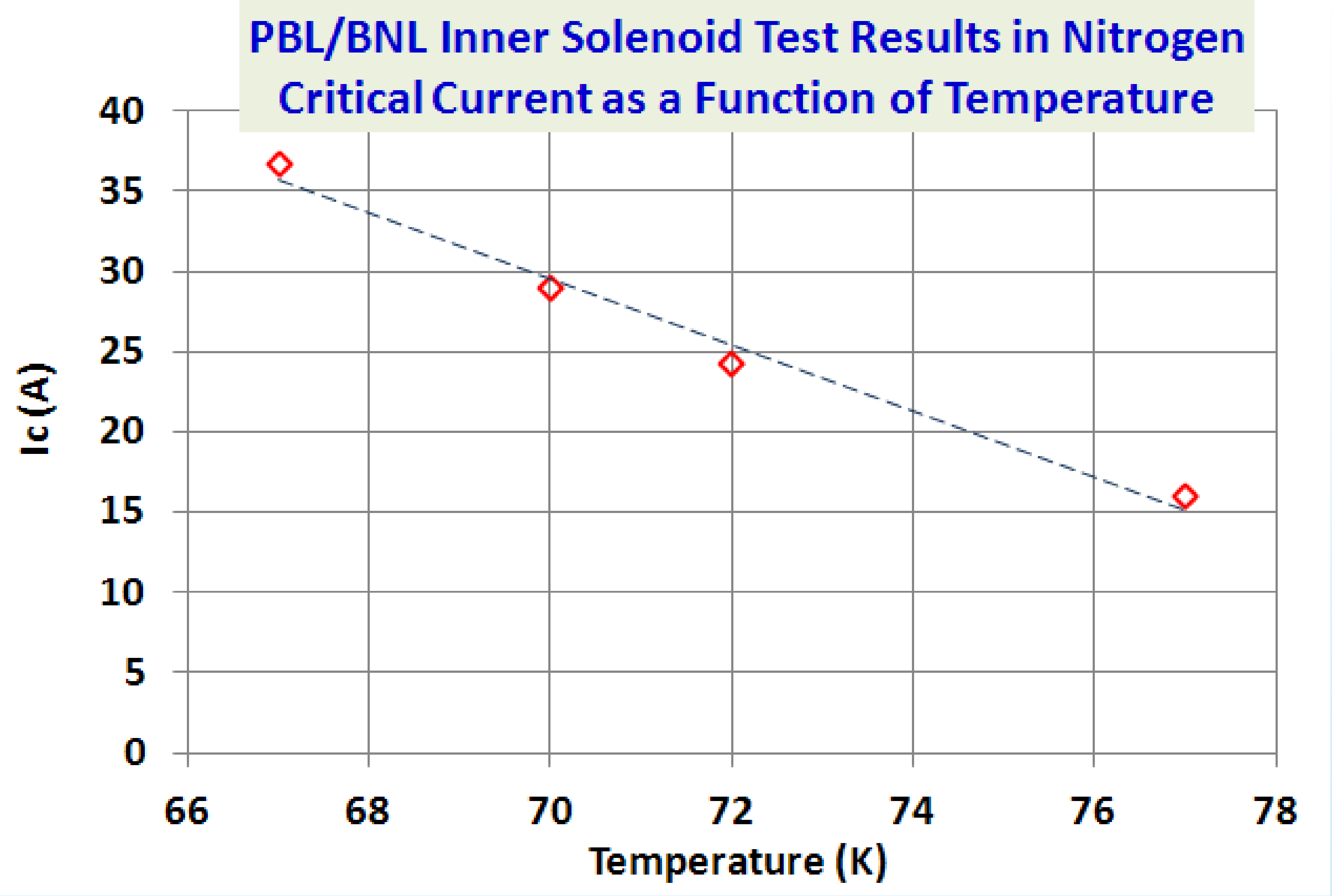




Key Construction Features (similar to that as in midsert)

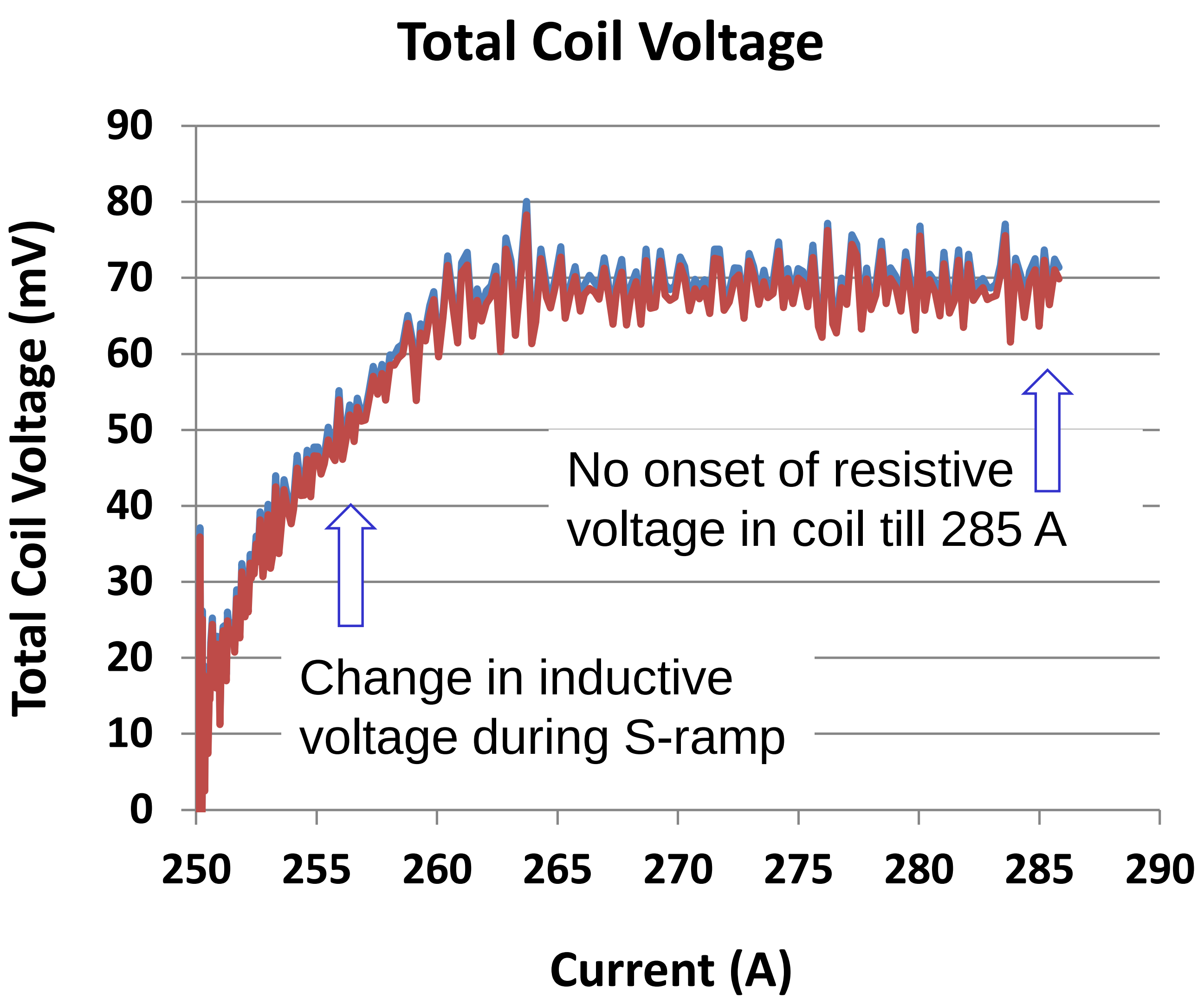
- Stainless steel reinforcement and turn to turn insulation
- G10 or Mylar sheet for coil-to-coil insulation
- Thin copper sheets between coils for thermal and possible energy distribution during quench
- Few layers of stainless steel and fiberglass radial enforcement over the coil
- Each coil individually protected (desirable to ~1 mV but never over few mV)

Summary of Test Results in N_2



(temperature adjusted by pumping)

High Field Test at 4 K



Quench detection is performed on the basis of difference voltage between two pancakes with a threshold at a few mV level.

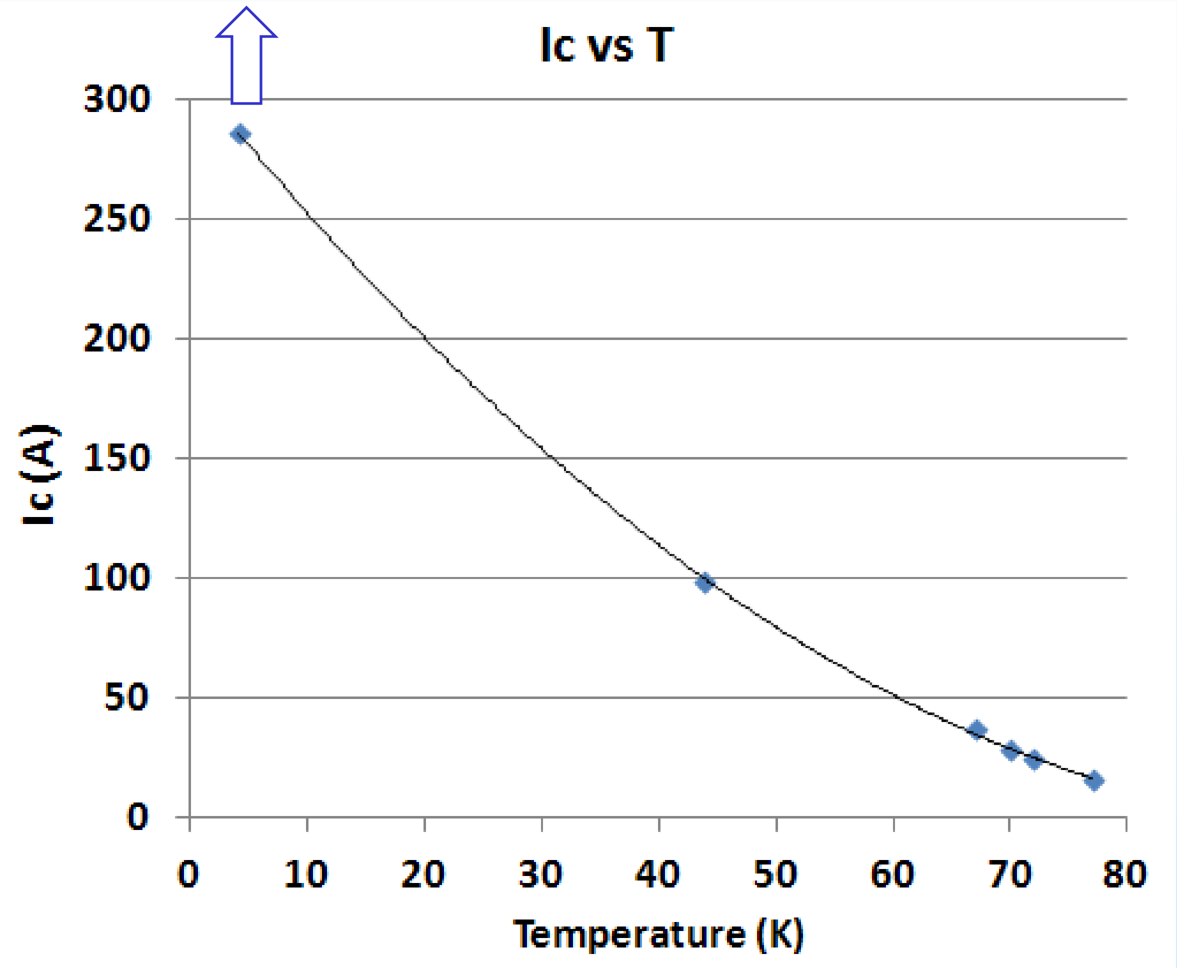
In the middle of the test, we lost a voltage tap at a critical location.

The test was terminated at 285 A.

With 0.045mm X 4.2 mm copper, J_{cu} ~1500 A/mm^2

Summary of All Test Results

Field reached at the center of solenoid at 285 A was over 15 T on axis and over 16 T on coil. This is over 50% better than previous record !!!



The magnet has potential to go to even higher fields, as there was no onset of resistive voltage on the coil yet at 285 A.

When we put the whole package together (insert & full midsert), we will test the magnet to its ultimate limit.

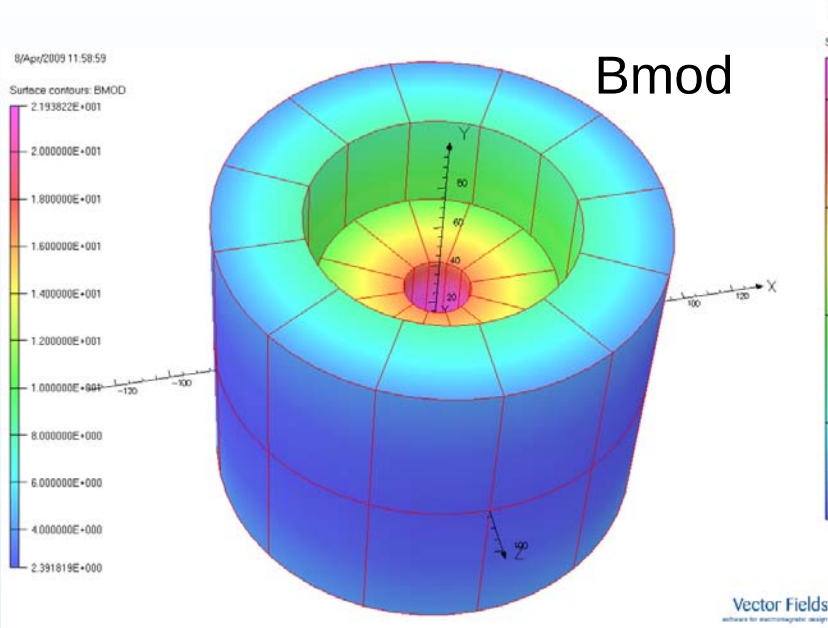
Analysis of Design and Test Results

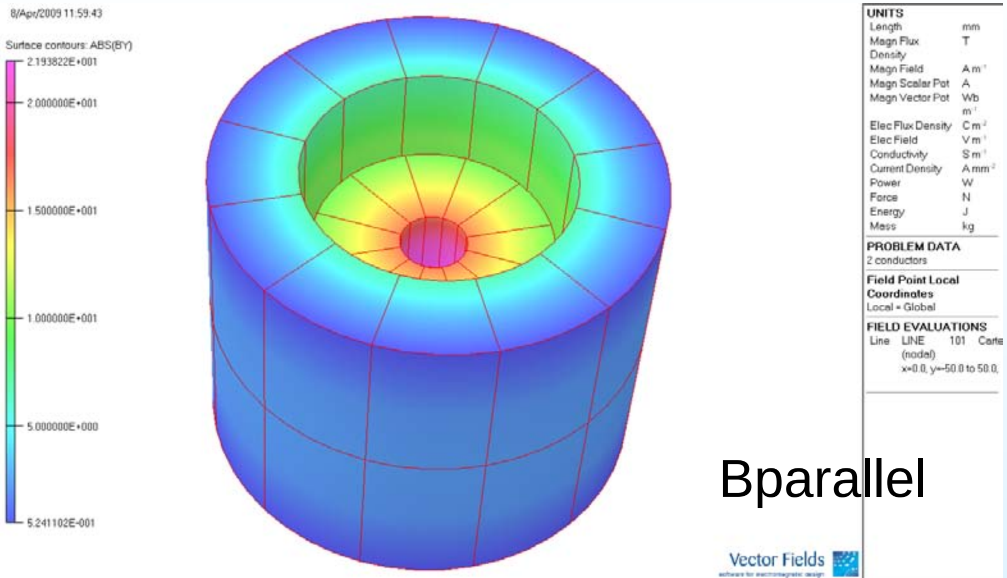
AKA : Take a brake from the celebration of good results and start enjoying the detective work of what weakness is limiting us.

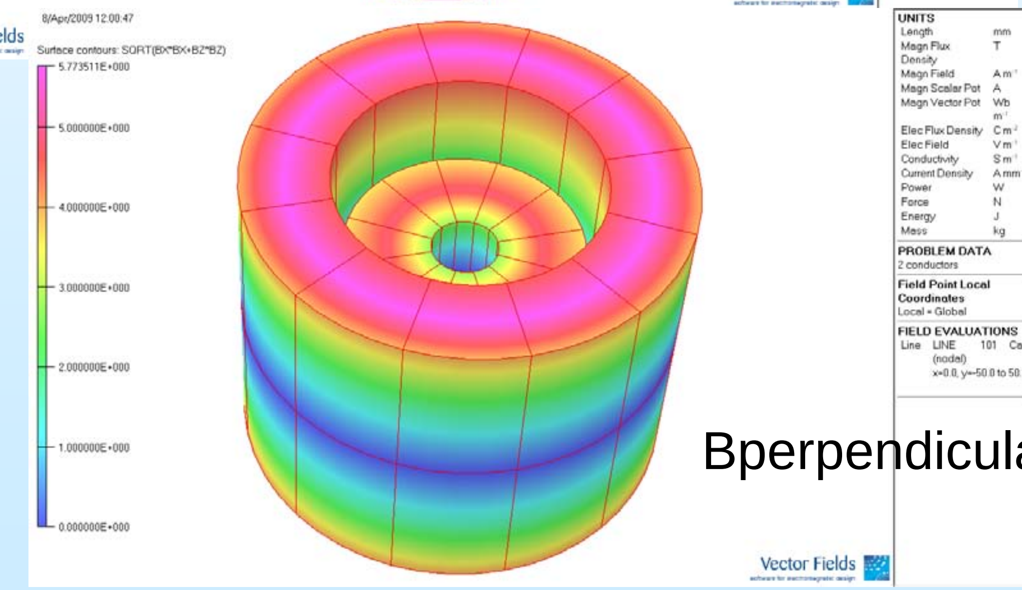
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

PBL/BNL YBCO Solenoids





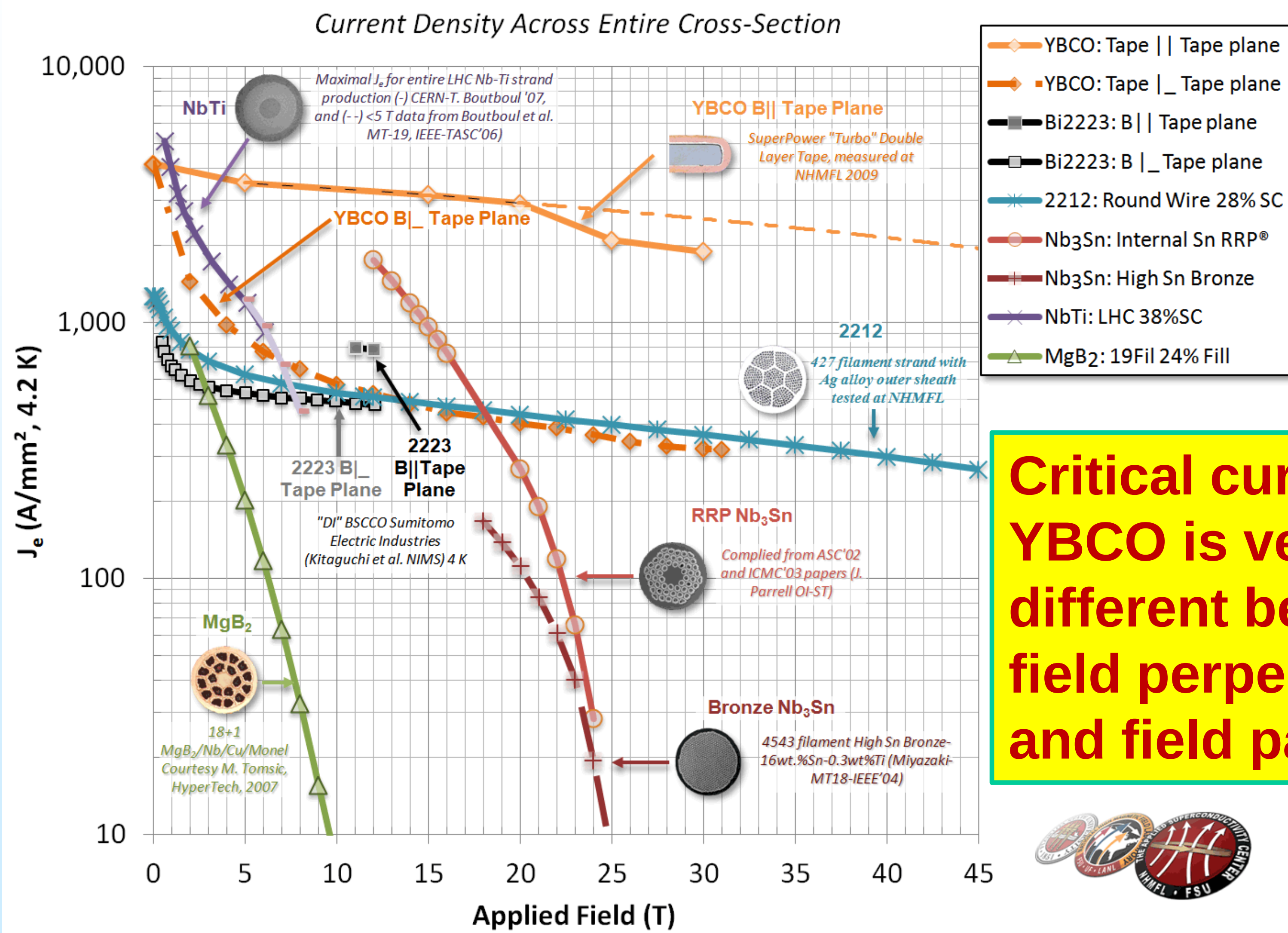


1. First PBL/BNL Phase II SBIR ~10+ T solenoid (i.d. = 100 mm, o.d. = 165 mm, 24 pancakes)
2. Second PBL/BNL Phase II SBIR ~12+ T insert (i.d. = 25 mm, o.d. ~ 91 mm, twelve pancakes)
3. Together 20+T Field

BROOKHAVEN NATIONAL LABORATORY

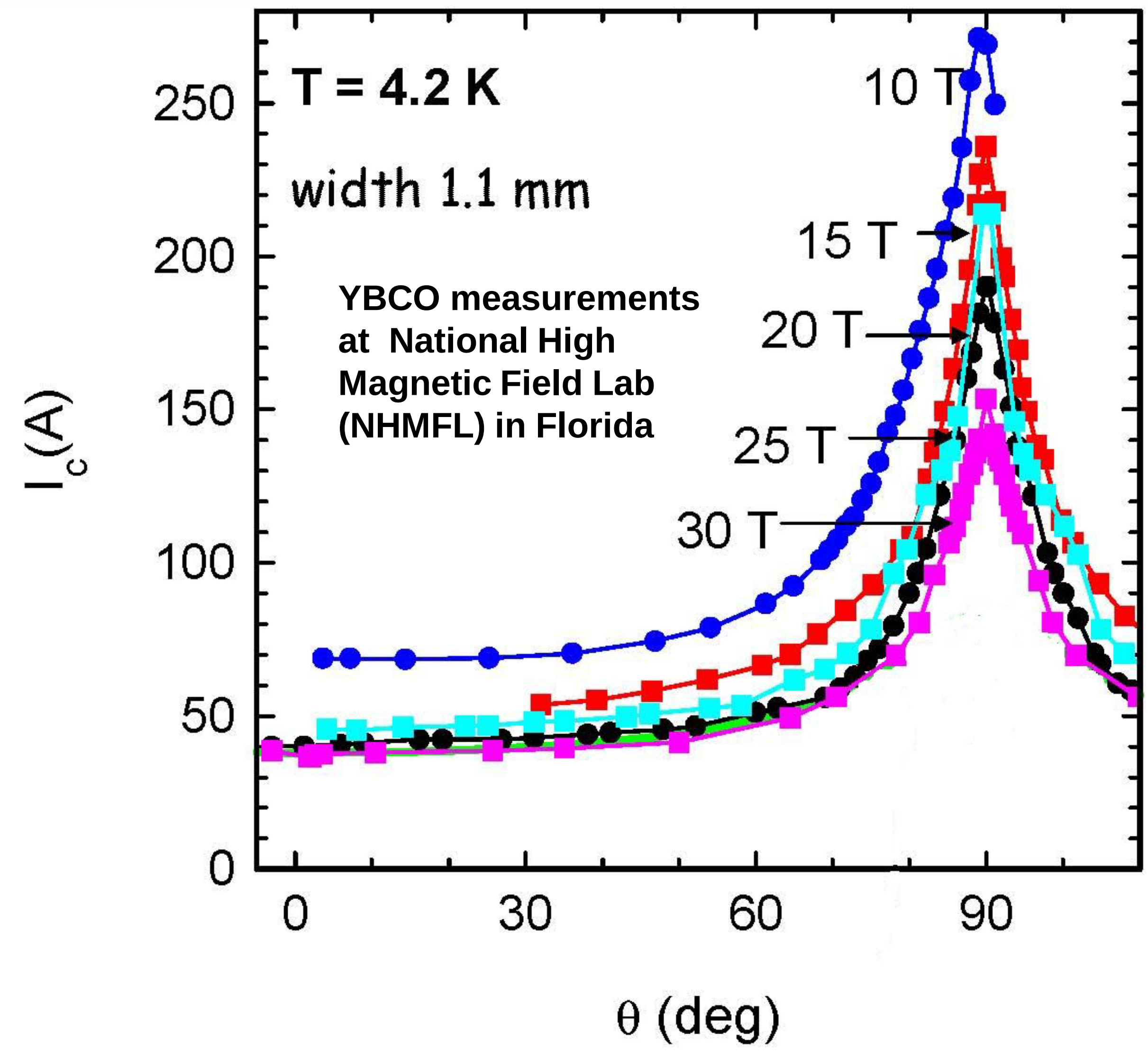
Superconducting
Magnet Division

Performance of Various Superconductors (Famous plot from Peter Lee)



Critical current of YBCO is very different between field perpendicular and field parallel

YBCO Tape: Angular Dependence



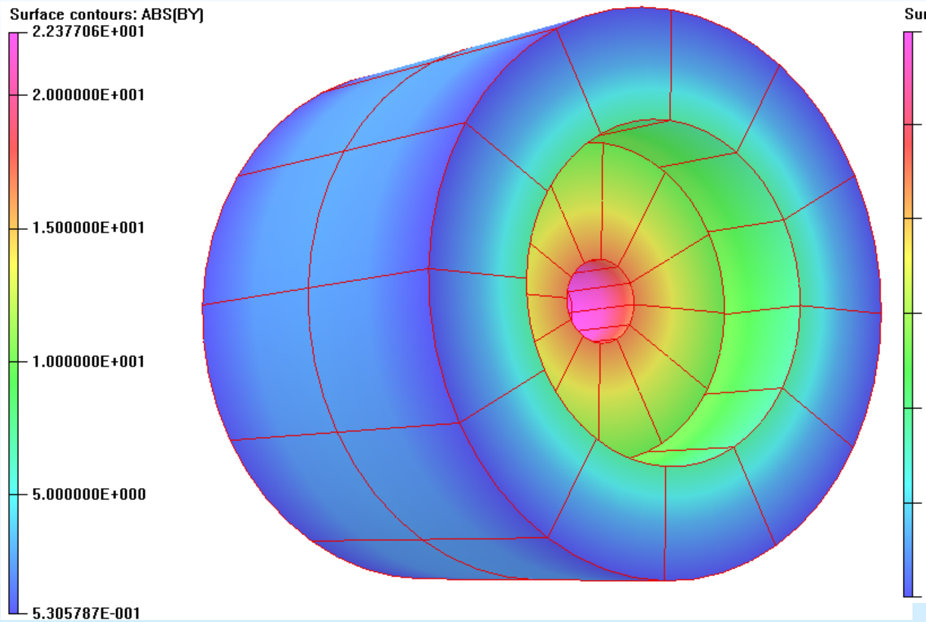
In computing classical short sample limit in magnet, one should use local field and field angle.

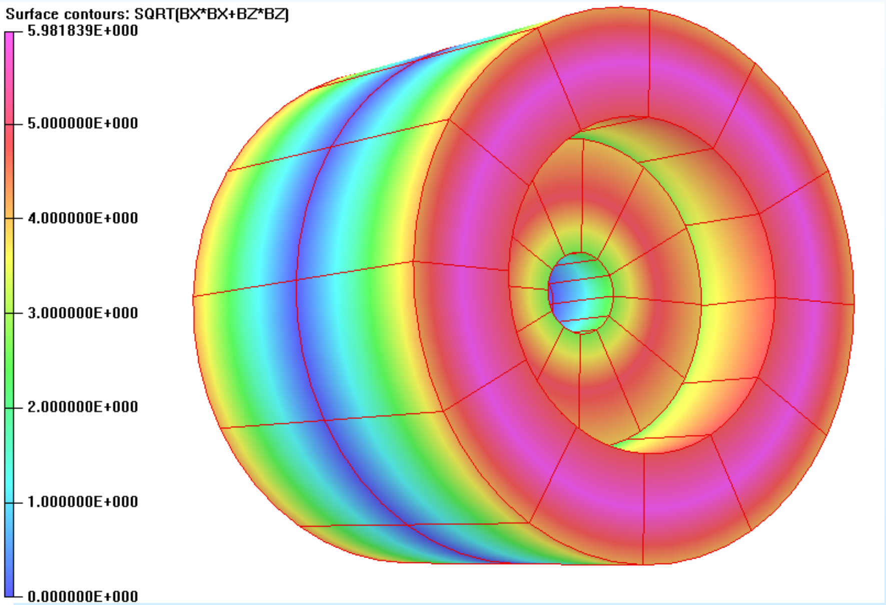
However, a large conductor to conductor variation in scaling makes reliability of such computations challenging.

Field Components

Inner and outer coils together at design field

Field Parallel (~22 T) **Field Perpendicular (~6 T)**





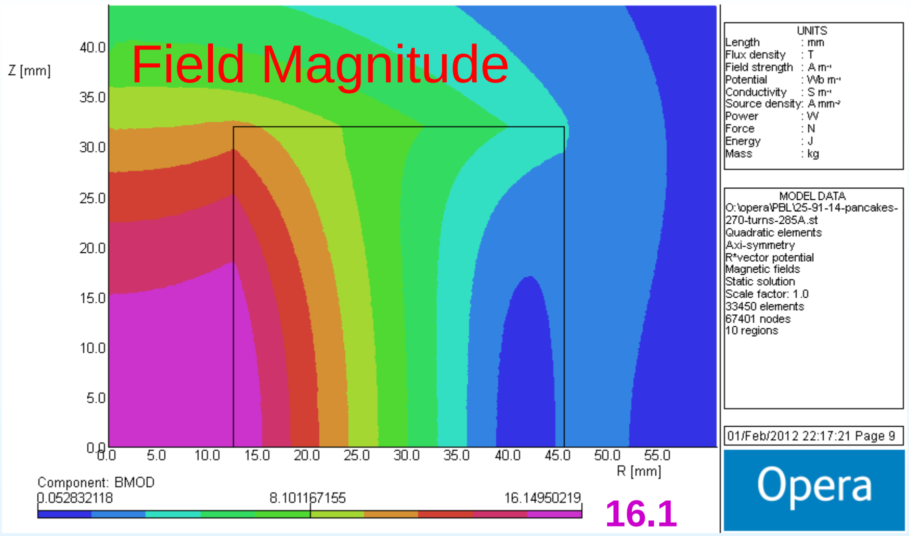
In computing classical short sample limit in magnet, one should use local field and field angle.

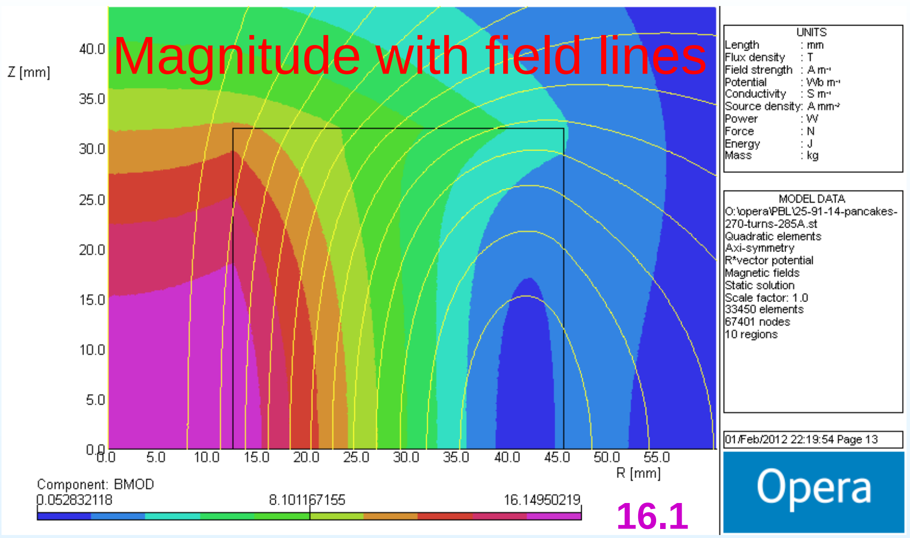
➢ ***Such calculations are being carried out by Bob Palmer.***

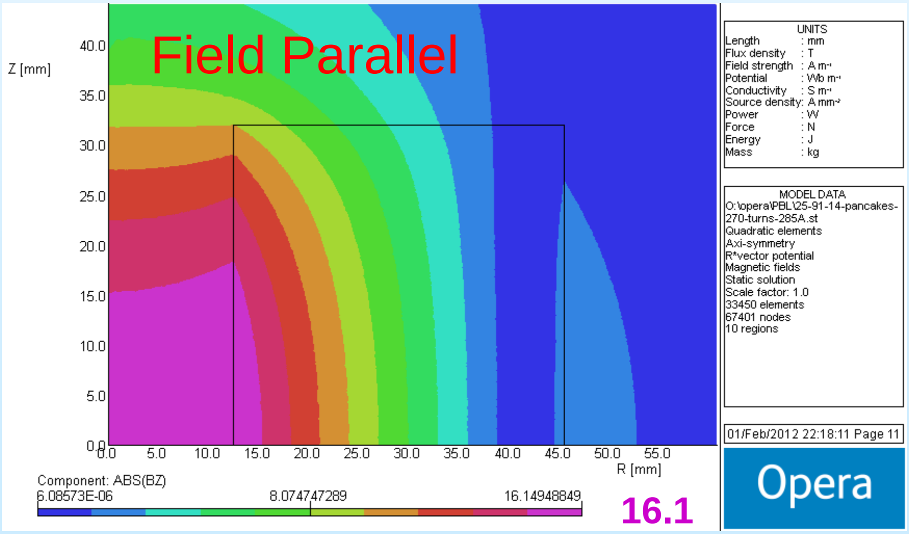
BROOKHAVEN
NATIONAL LABORATORY

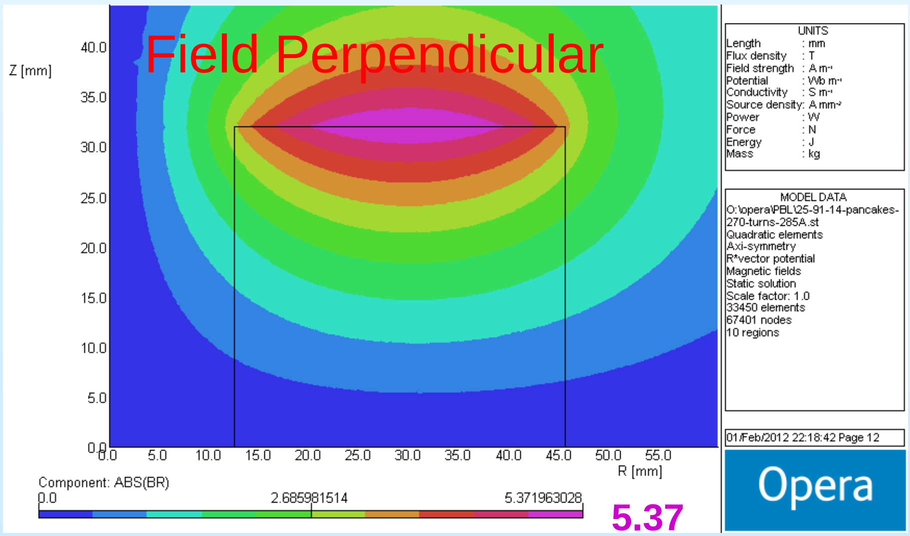
Superconducting
Magnet Division

Insert Solenoid (as tested) (upper-half of axi-symmetric model)





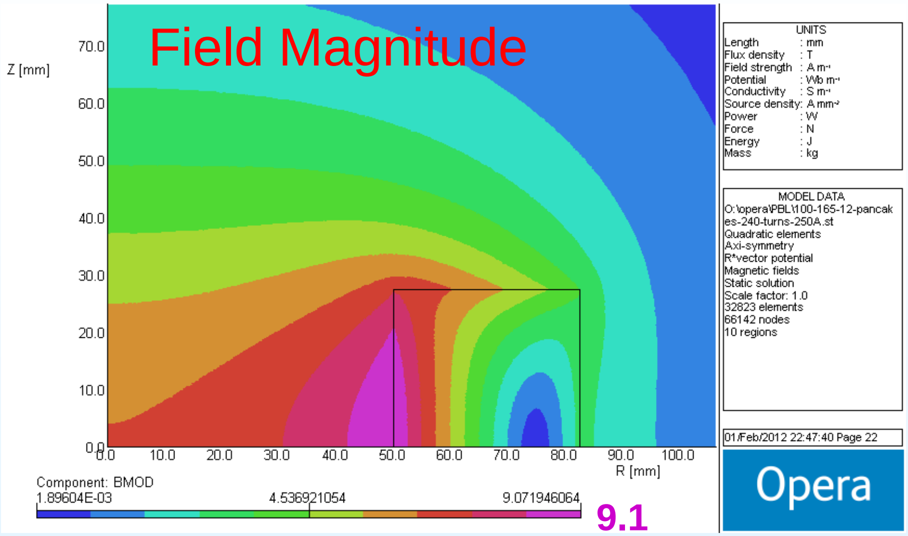


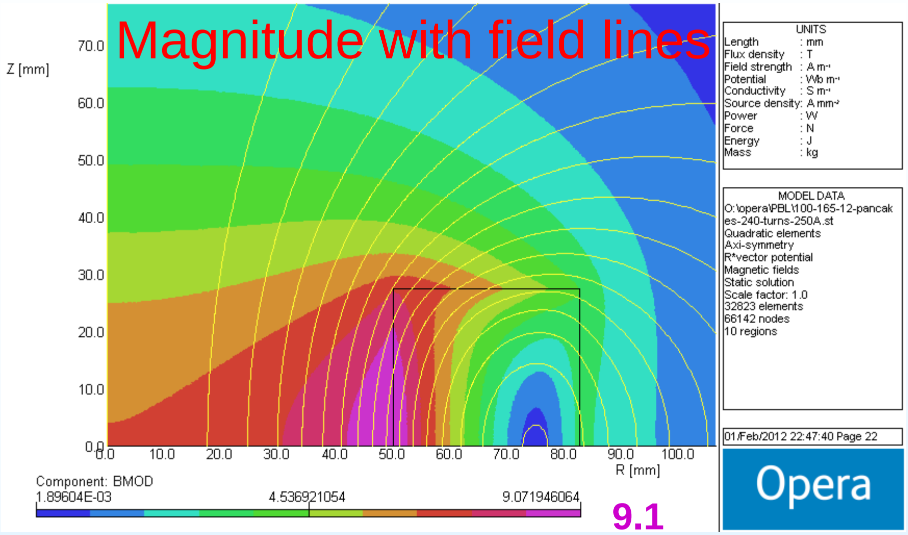


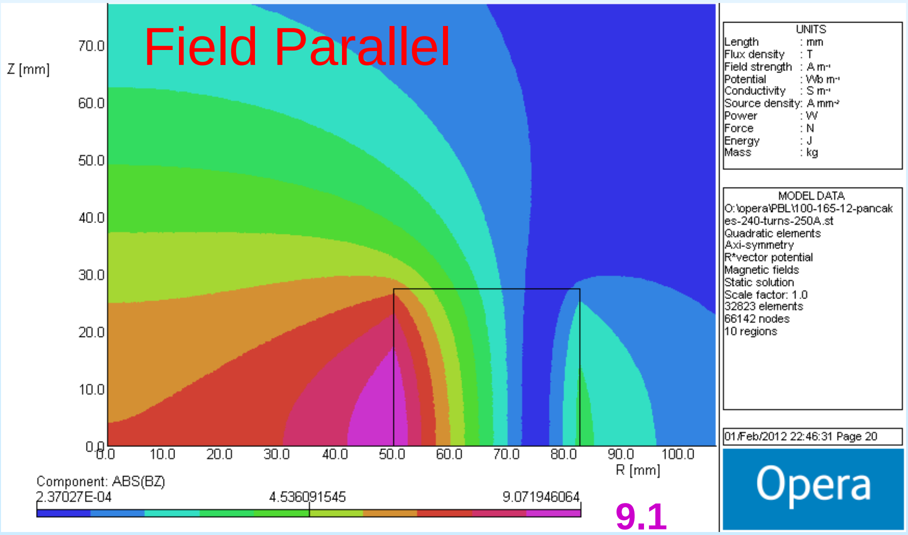
BROOKHAVEN NATIONAL LABORATORY

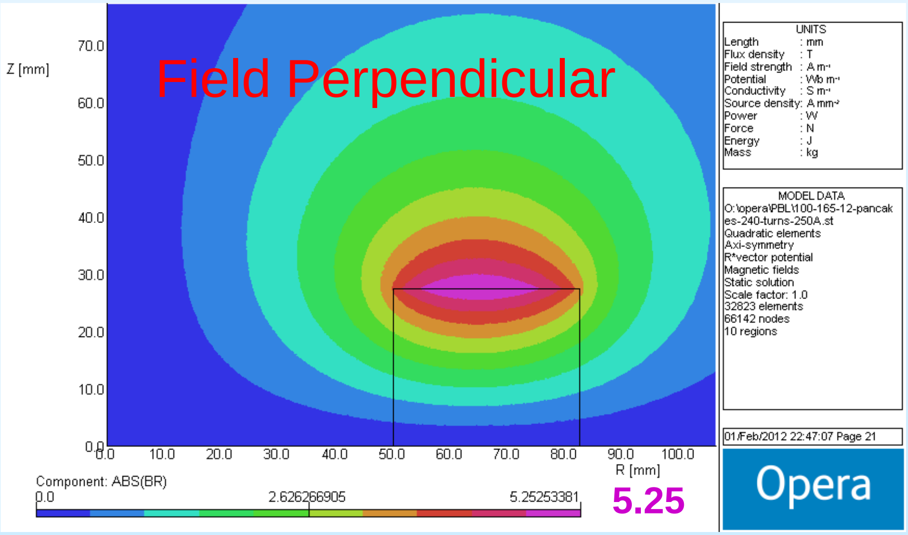
Superconducting Magnet Division

Midsert Solenoid (as tested) (upper-half of axi-symmetric model)



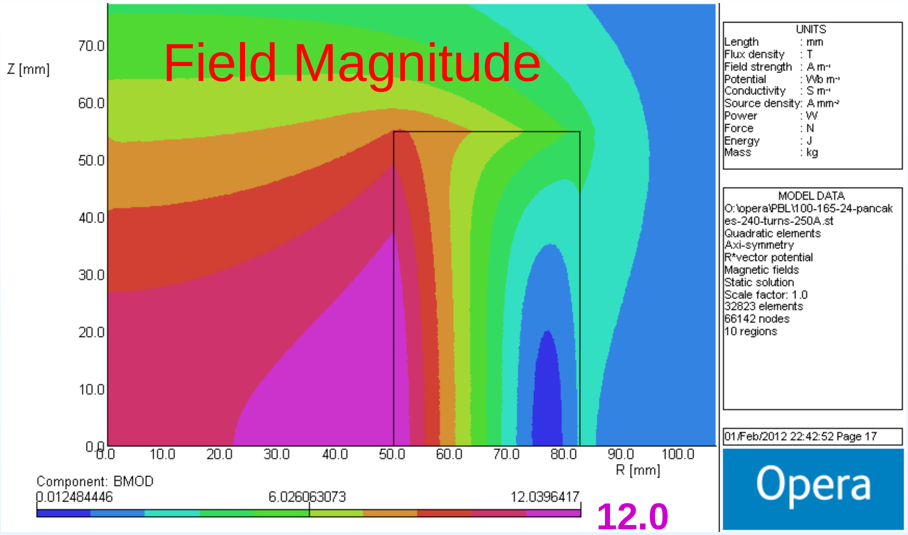


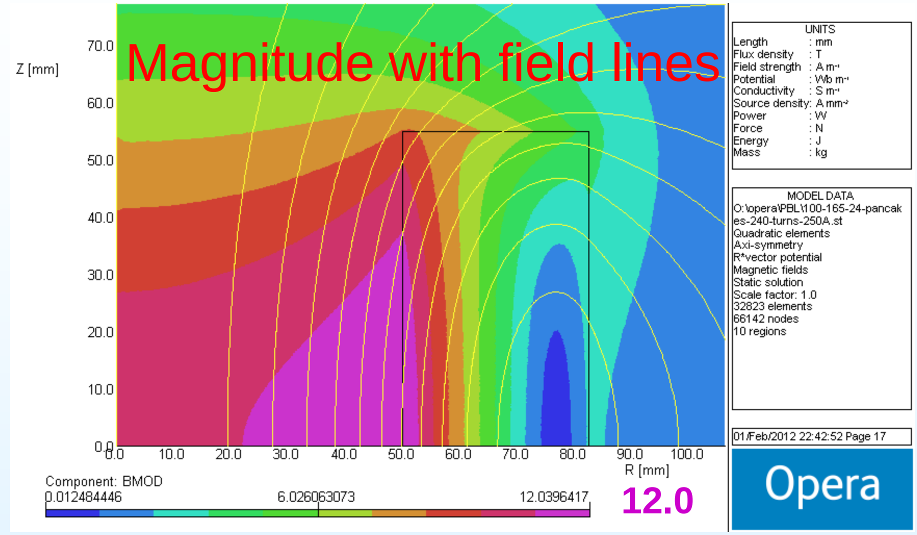


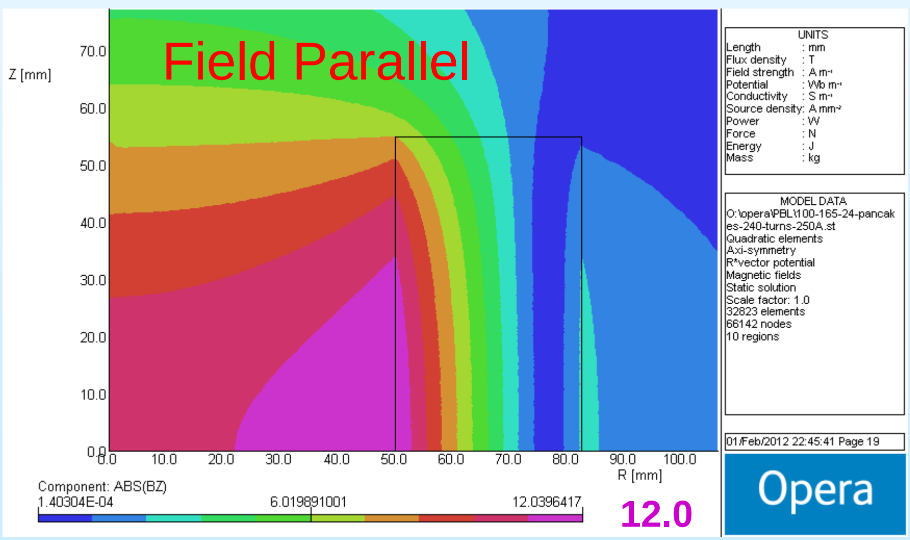


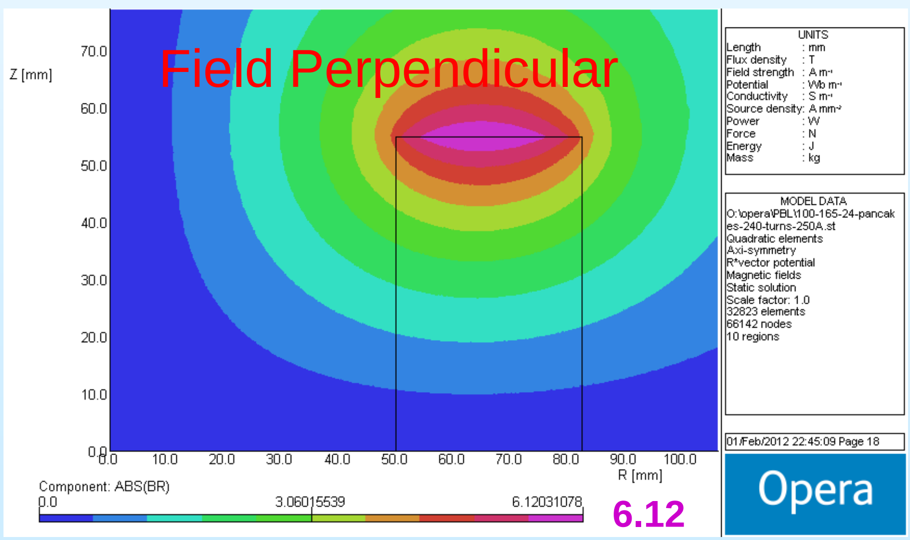
Large difference in field parallel (16.1 to 9.1) but little in field perpendicular (5.37 to 5.25)

Full Midsert (to be tested) (upper-half of axi-symmetric model)









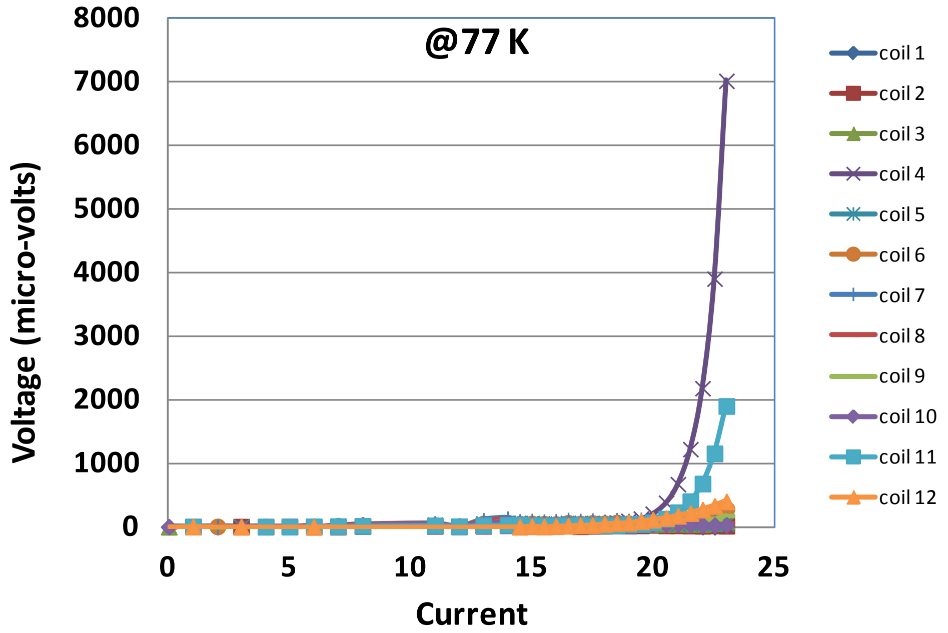
More increase in field parallel (9.1 to 12.0) but less in field perpendicular (5.25 to 6.12)

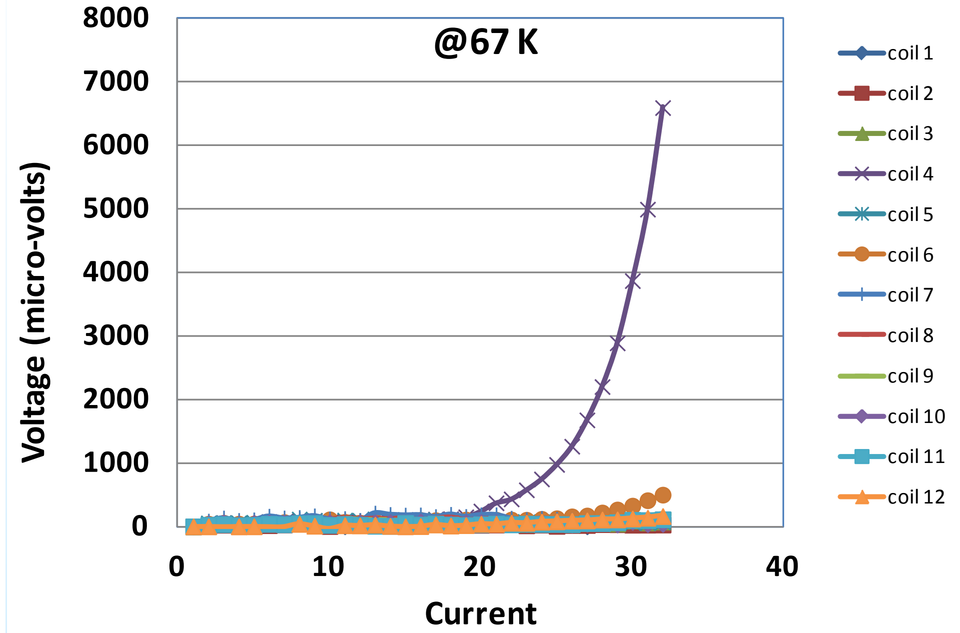
Midsert Solenoid (half - 12 coils)

More details/analysis of test

Coil Voltages in Nitrogen Test (half midsert coil – 12 pancakes)

- Coil voltages in individual coil as a function of current
- Coil numbers are counted from one end to another end

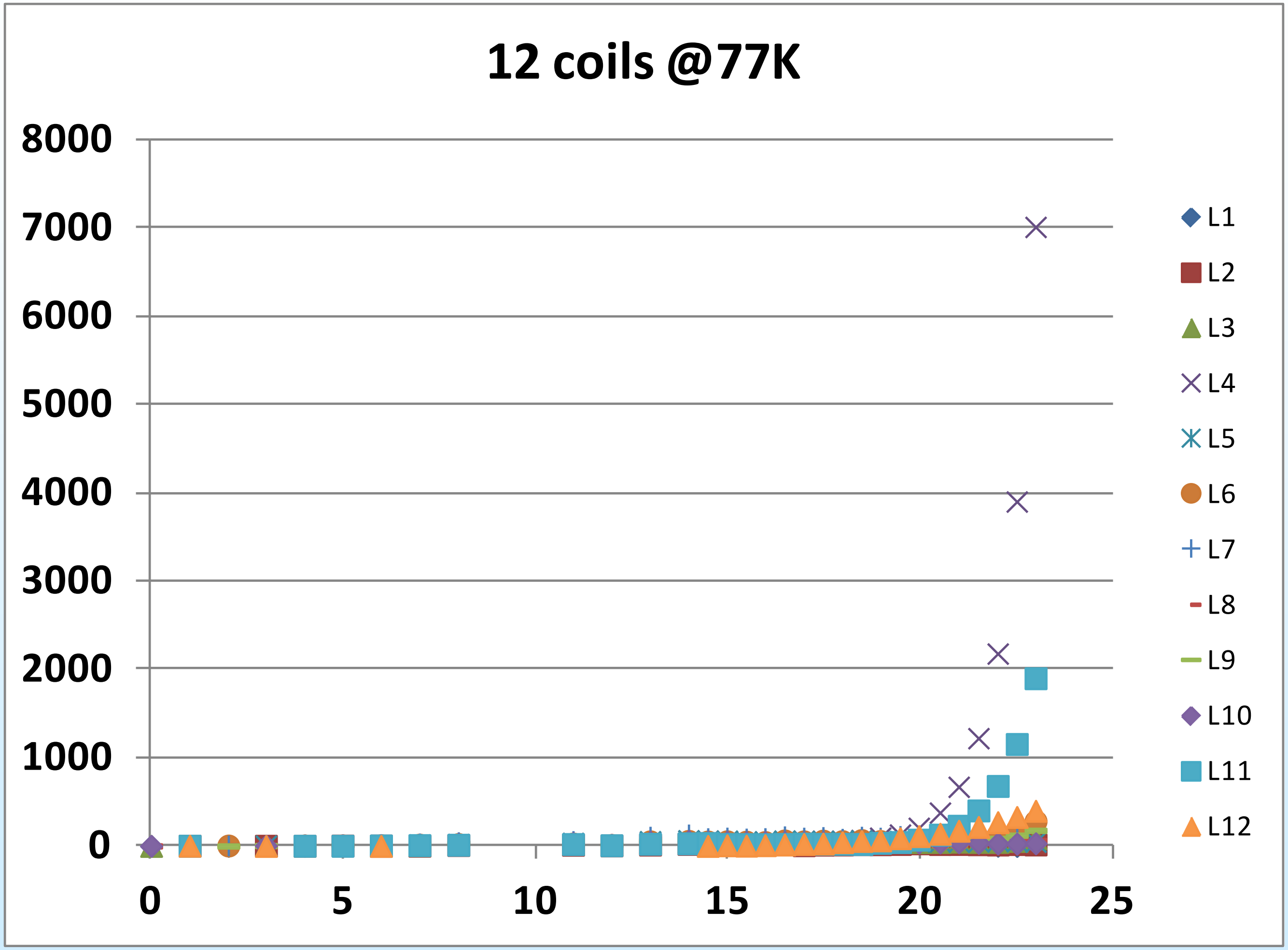




- There is some difference between 77 K results and 67 K results.
- However, the overall performance is not limited by coils in the ends (where field perpendicular is largest). It is limited by 4th coil of the total 12 (i.e. one near the middle).
- However, no single coil stands out as a bad or damaged coil (4th may be weaker coil) .

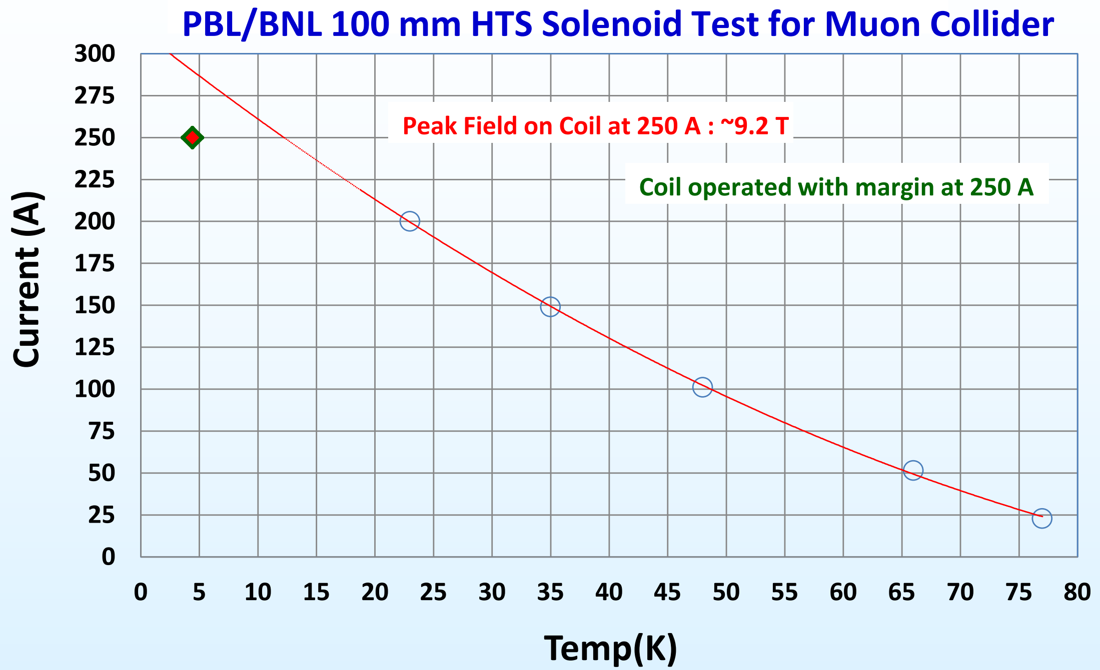
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

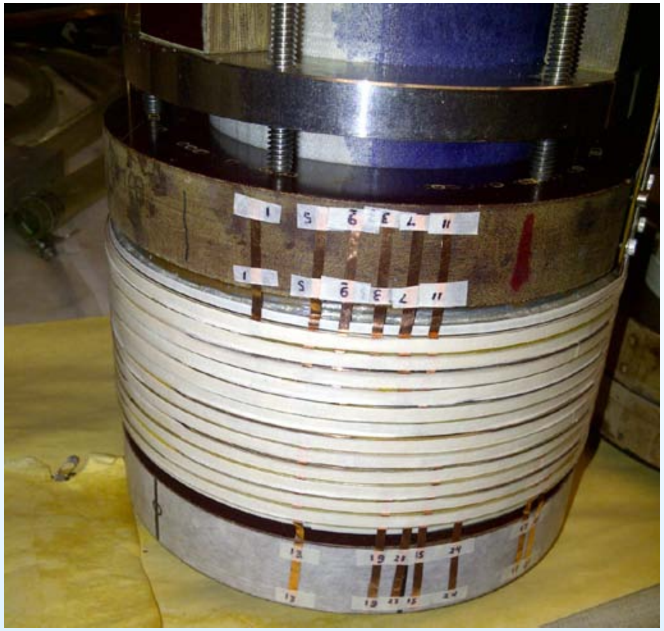
Coil Voltages in Nitrogen Test (half midsert coil – 12 pancakes)



Performance is not limited by coils in the ends but by 4th of 12 (near the middle)
Note: No major difference or stand out.

Cold Test (midsert solenoid)



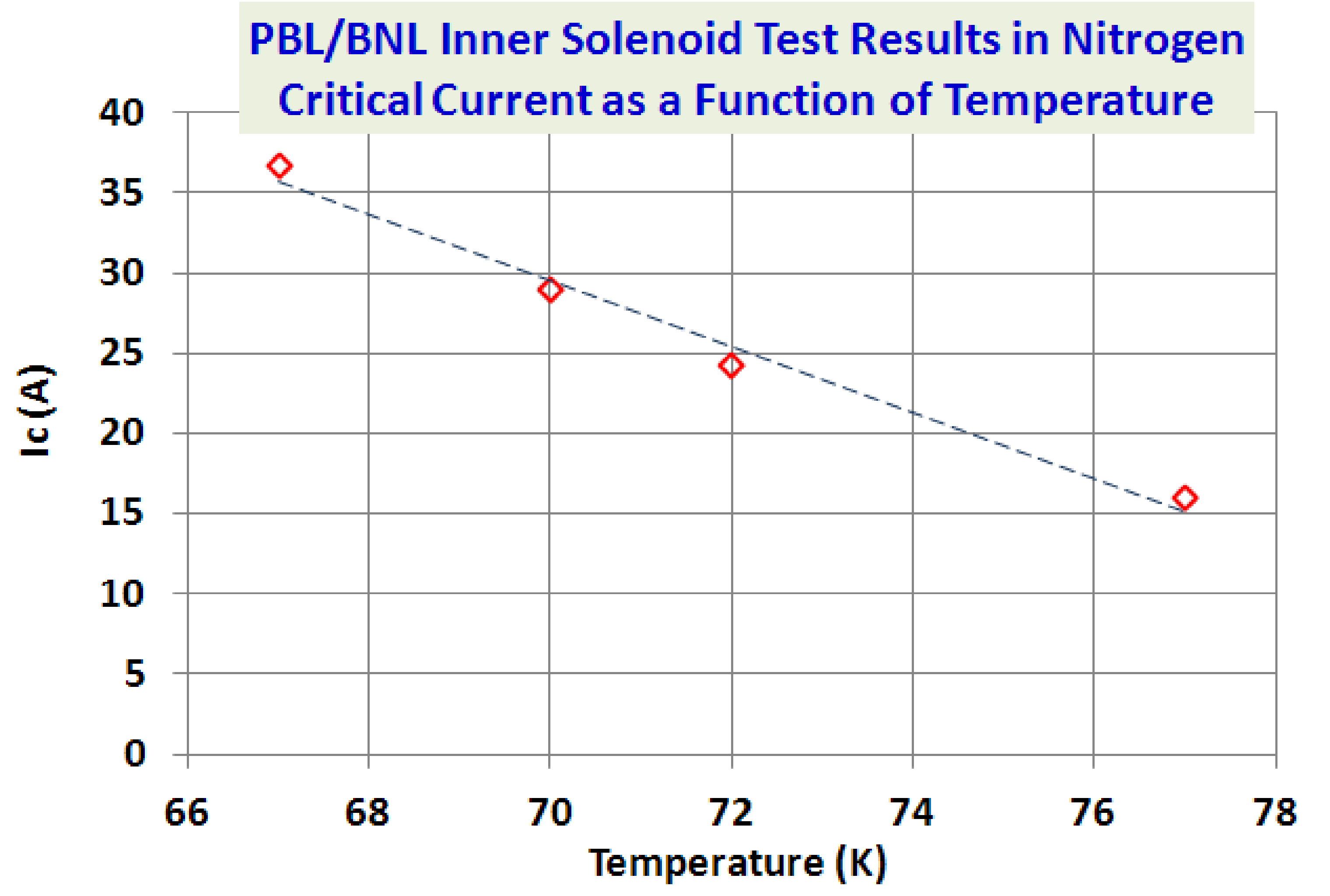


- At all temperatures and at all fields, the performance was always limited by 4th coil (of total 12).
- It was not limited by pancakes at or near the ends.

Insert Solenoid (14 coils)

More details/analysis of test

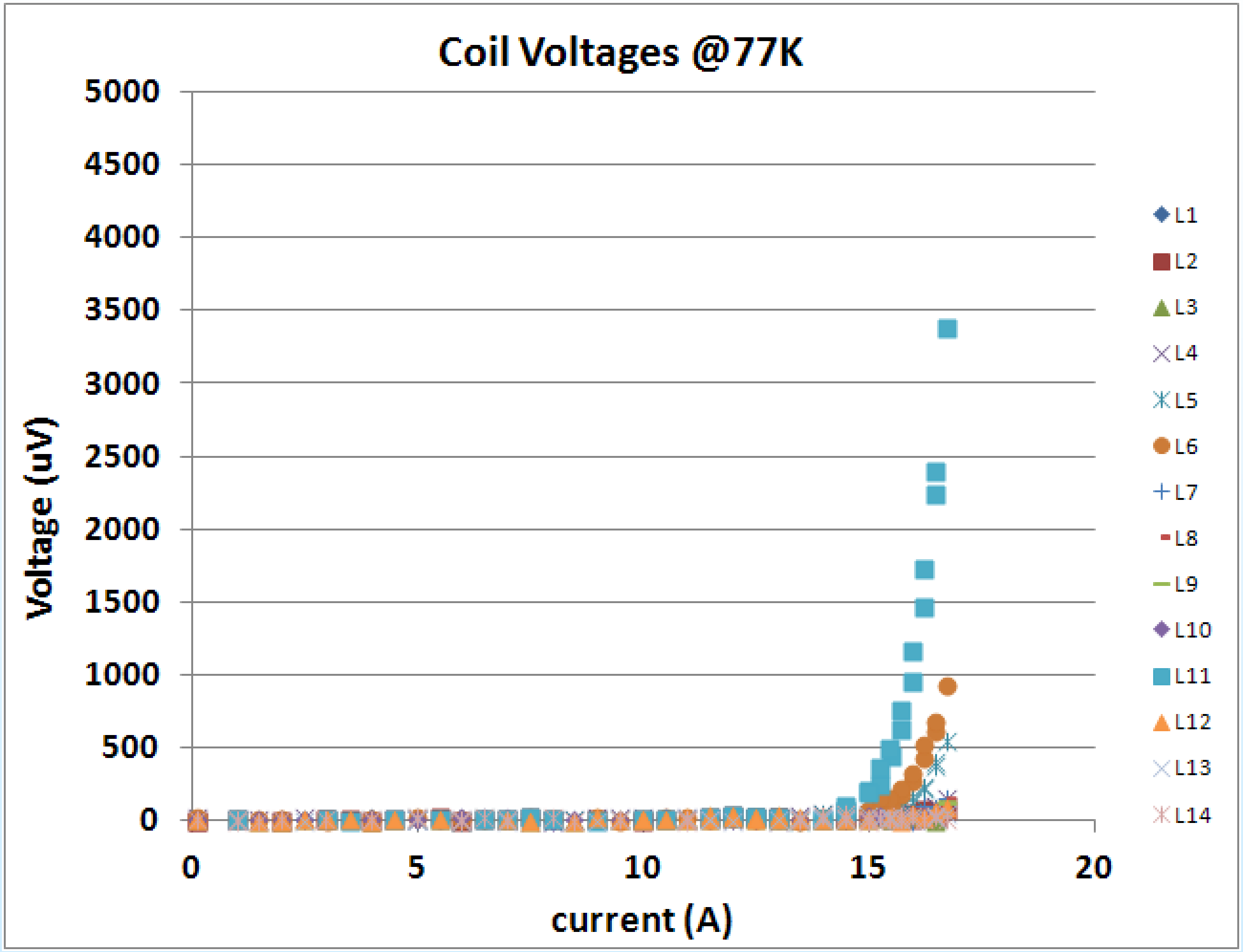
Summary of Test Results in N_2



(temperature adjusted by pumping)

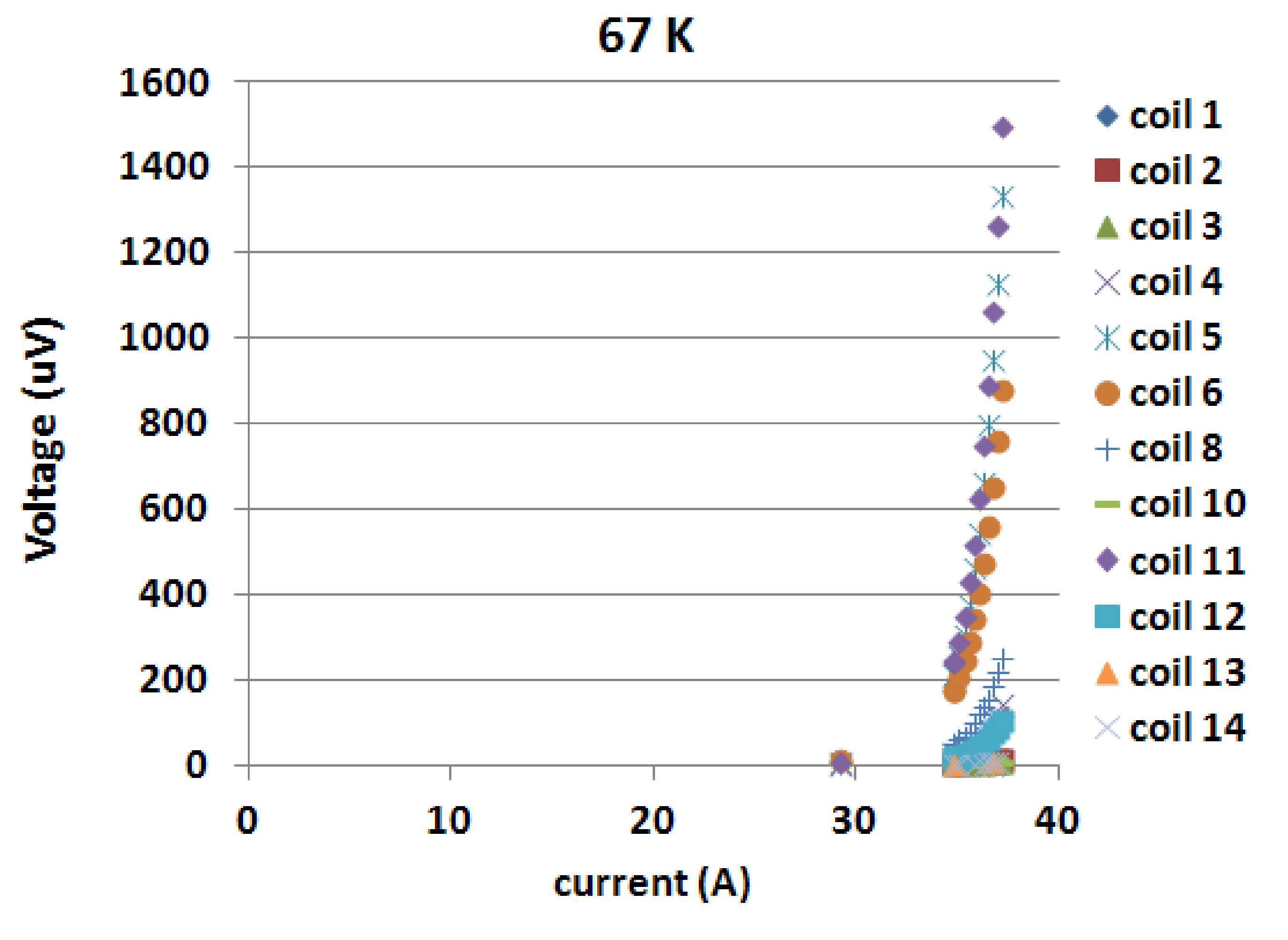
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Detailed Measurements at 77 K



Coil 11th (4th from the end) and 6th and 5th show most signal

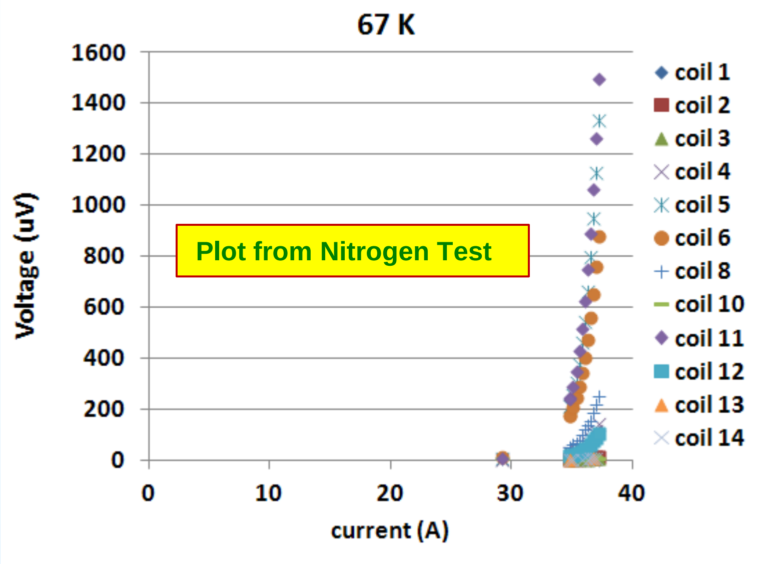
Detailed Measurements at 67 K



Coil 11th (4th from the end), 6th and 5th continue to show most signal (but the voltage signal is more closer or they turn normal together)

Measurements in Helium

In Helium at 44 test, all signal appears to come from the 5th coil



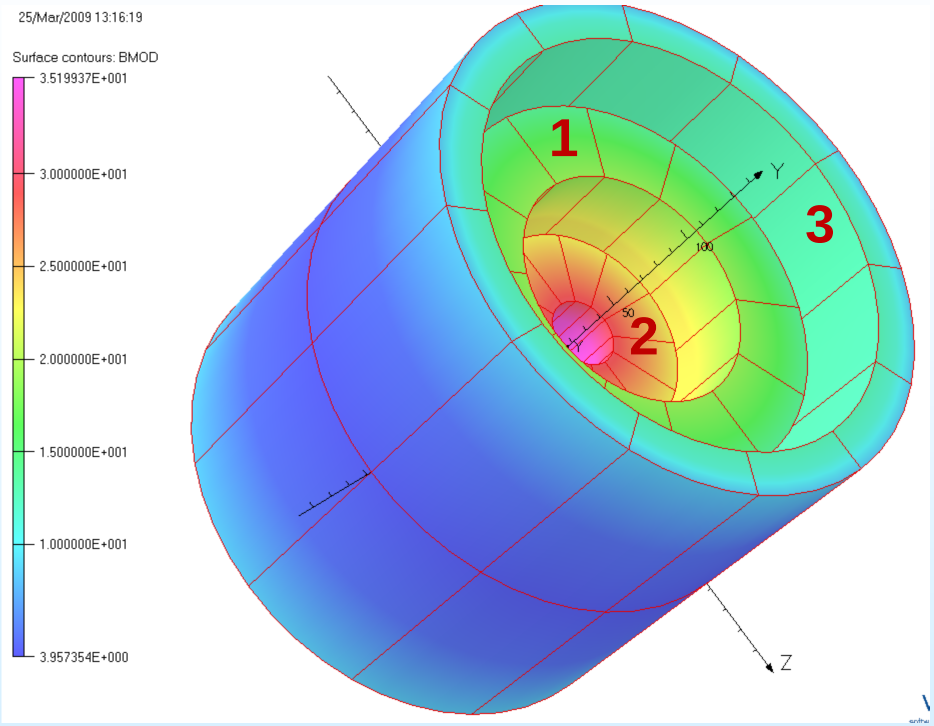
At 4 K, we lost the critical voltage tap at coil 5.
The test was terminated at 285 A (15+T at center, 16+ T on coil).

- **The magnet has potential to go to higher fields as there was no resistive voltage yet on the coil at 285 A.**

Future Plans

- **We plan to combine above two and try testing all HTS technology to ~20 T in two months**
- **We hope to demonstrate a ~100 mm, 10+ T HTS solenoid in several months**
- **We hope to demonstrate 22+ T HTS solenoid by combining two in ~6 month**
- **We hope to test above in the background field of 20 T at NHMFL in about a year**
  - This is included in PBL plan and budget but not in BNL
  - It may need some reinforcement and other preparation at BNL
  - We would also see how our quench protection system fits with the test set-up at NHMFL
- **Build 15 T LTS solenoid (if Phase 2 funded) and integrate above solenoids in a complete 35+ T proof-of-principle superconducting solenoid system for MAP in about 2 years.**

PBL/BNL Phase II and Possibilities of 40 T Superconducting Solenoid System



- At the start of the talk I mentioned a dream of 35+ T solenoid with 20-22 coming from HTS and ~15 T coming from LTS (NbTi+Nb_3Sn)
- The way things are going in HTS, we might hit 25 T.

➢ Why not join us in dreaming for 40 T by adding a bit more from HTS - may be a little bit on two sides of each, a little bit on outside and/or a little bit on inside.

➢ Before any one notices, we may be plotting for additional 5 T from HTS and thus hit 40 T with all starts aligned together (so far they have been).

SUMMARY (1)

- We have built and tested a large number of HTS coils for PBL/BNL SBIR.
- We have demonstrated a ~100 mm, 6+ T HTS solenoid (9+ T on coil) with 1.2 km wire (successful test of largest wire in 4 K high field test coil)
- We have demonstrated 15+ T (16+ T on coil), ~25 mm insert HTS solenoid (highest field ever in HTS solenoid).
- When we started this program, few were optimistic about the outcome. We (PBL/BNL team) took it as a daring low cost experimental program.
- We are slowly solving one problem at a time in a program consisted of several steps, each demonstrating a key part of the technology.
- Results so far have been outstanding and have exceeded most expectations.
- We are showing that 2G HTS wire and coil technology is getting ready for certain high field superconducting magnet applications for which few other solutions seems viable.
- If we achieve our stated goal (35+ T), then this may be referred to as a significantly successful outcome of SBIR/STTR program for a variety of applications.

SUMMARY (2)

- There is also an ongoing PBL/BNL Phase I SBIR for ~15 T Nb_3Sn outsert.

- If Phase II application results into funding, then we hope to demonstrate a ~40 T all superconducting solenoid.

- If successful, we would have solved a major technical issue of MAP and the technology developed will be applicable in a number of other places.

THANK YOU