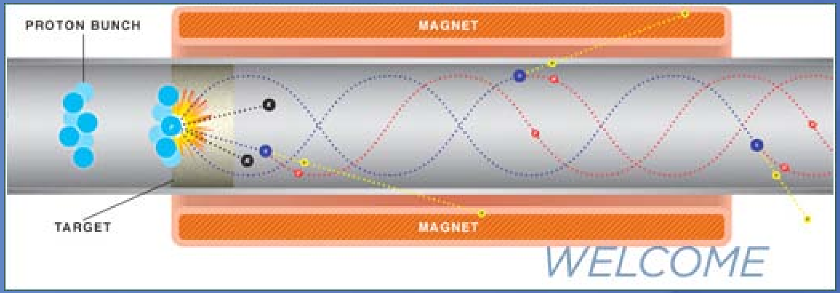
High Field Solenoids

Ramesh Gupta
for
PBL/BNL Team



MAP Winter Collaboration Meeting
Stanford Linear Accelerator Center
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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

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Overview

- Ionization cooling in MAP needs very high field solenoids (35-40 T)
- Use of HTS (a new & challenging conductor) is essential for super-conducting solution (NHMFL 45 T hybrid magnet uses ~30 MW)
- PBL/BNL team proposed an ambitious experimental program with a series (3) of SBIR to develop/evaluate magnet technology for ~35 T
- This presentation summarizes two major achievements already made:

  1. **Largest use (1.2 km) of HTS in a high field magnet**
  2. **Highest field (>15 T) HTS magnet ever built**

- These impressive results are of large importance not only to MAP, but are also breakthrough for high field magnet technology in general

Key Members of PBL/BNL Team

Particle Beam Lasers, Inc. (PBL):

J. Kolonko (President), D. Cline (Principle Motivator),
A. Garren (PI), R.Weggel (PI), R. Scanlan (PI), E. Willen (PI), …

Brookhaven National Laboratory (BNL):

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

A unique team of experienced and daring professionals with mutually beneficial and respectable working relationship – together we are finding a few innovative ways of moving forward with an excellent team spirit !!!

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 (PI: Al Garren)
2. ~12 T HTS (insert): Phase II funded (PI: Bob Weggel)
3. ~12 T Nb_3Sn (outsert): Phase I funded (PI: Ron Scanlan)

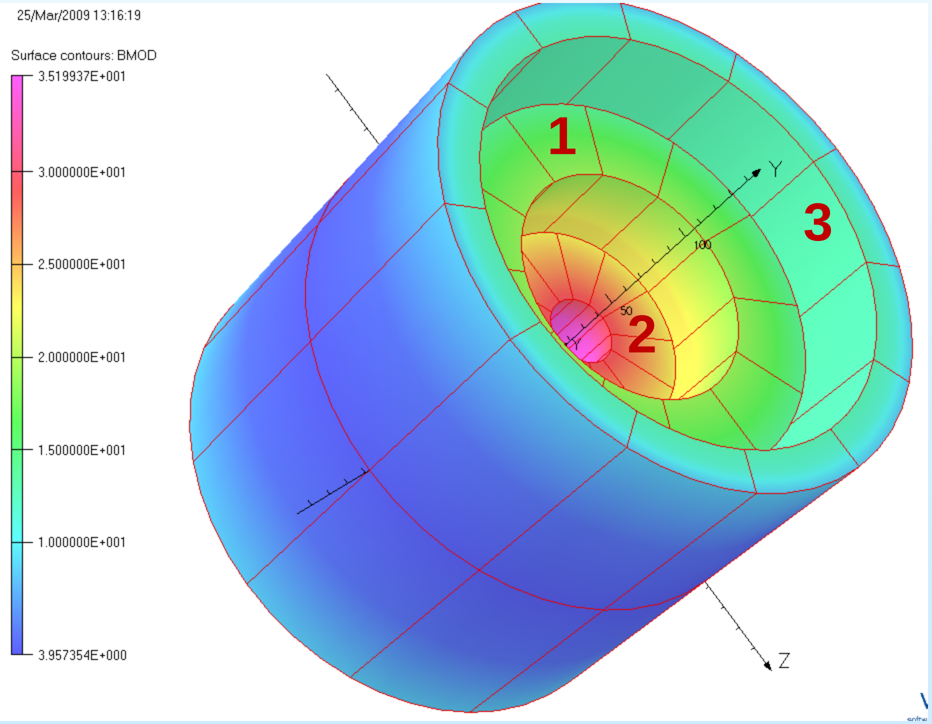
20$^+$ T All HTS Solenoid (1 & 2):

addresses challenges with high field HTS solenoids

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

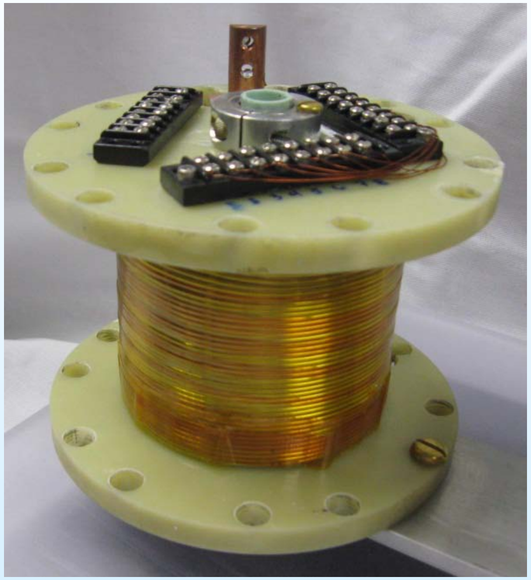
addresses challenges with high field superconducting solenoids

Actual SBIRs cover magnet plus other accelerator issues



Where are we starting from?

SuperPower/NHFML YBCO Solenoid (2009)



4.2 K Coil I_c – Self field	201.9 A
4.2 K Amp Turns @ I_c – self field	746,222
4.2 K Central Field – self field	**10.4 T**
4.2 K Coil I_c – 19.89 T Background (axial)	144 A
4.2 K Amp Turns @ I_c – 19.89 T Background	532,224
4.2 K Central Field – 19.89 T Background (axial)	**27.4 T**

- Best stand alone HTS solenoid 10.4 T (till a month ago)

PBL/BNL Target: 20-22 T (that too with limited budgets of 2 SBIR)

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

Midsert
~~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

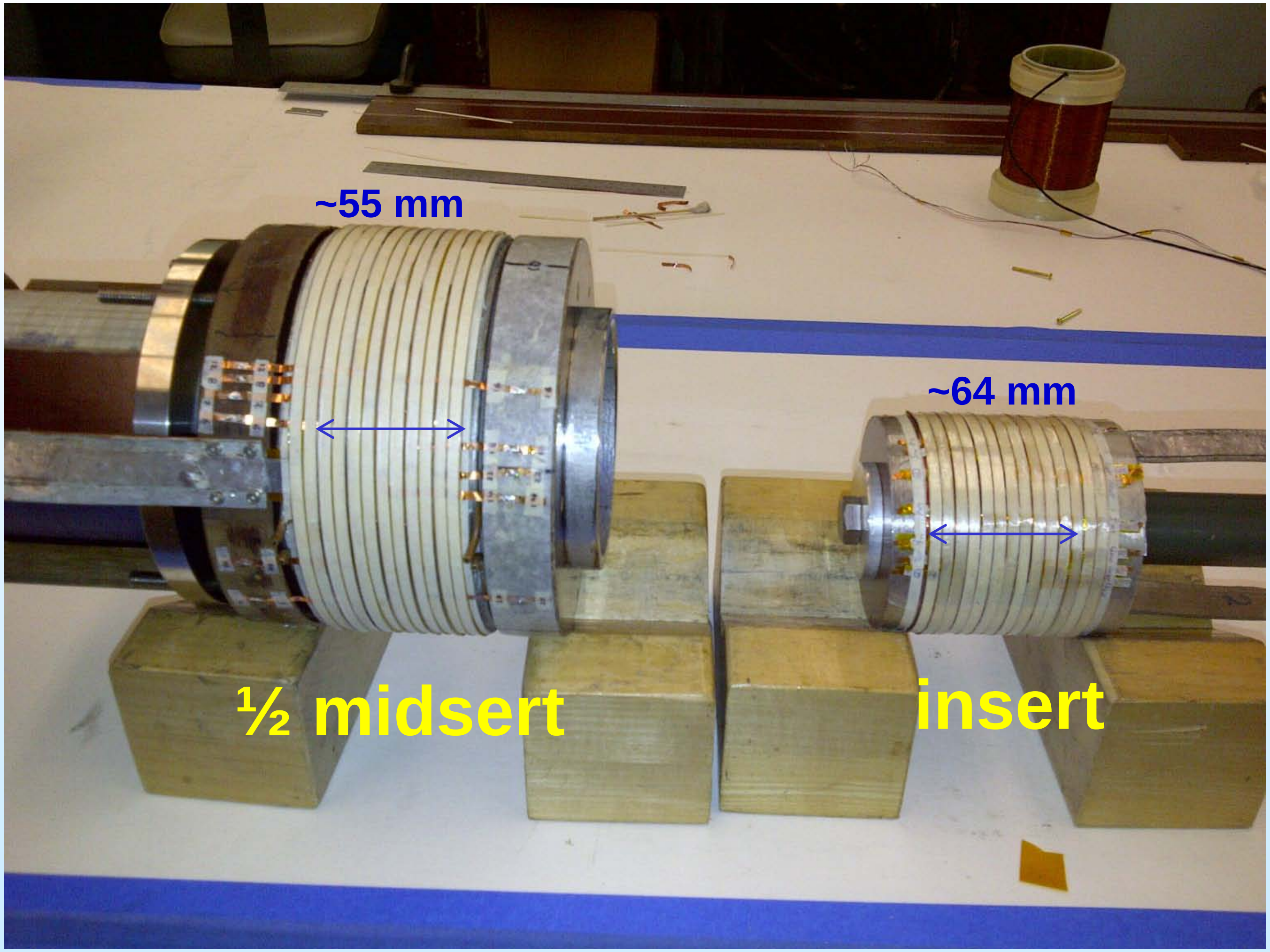
Inner Solenoid Parameter

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

- ❑ **This was thought to be a very ambitious proposal!!!**
- ✓ **We have achieved >60% (6$^+$ T) with only half outer**
- ✓ **We have already exceeded inner by over 25% (15$^+$ T)**

Recently Tested HTS Solenoids



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

Major Development and Progress in Advanced Quench Protection for HTS

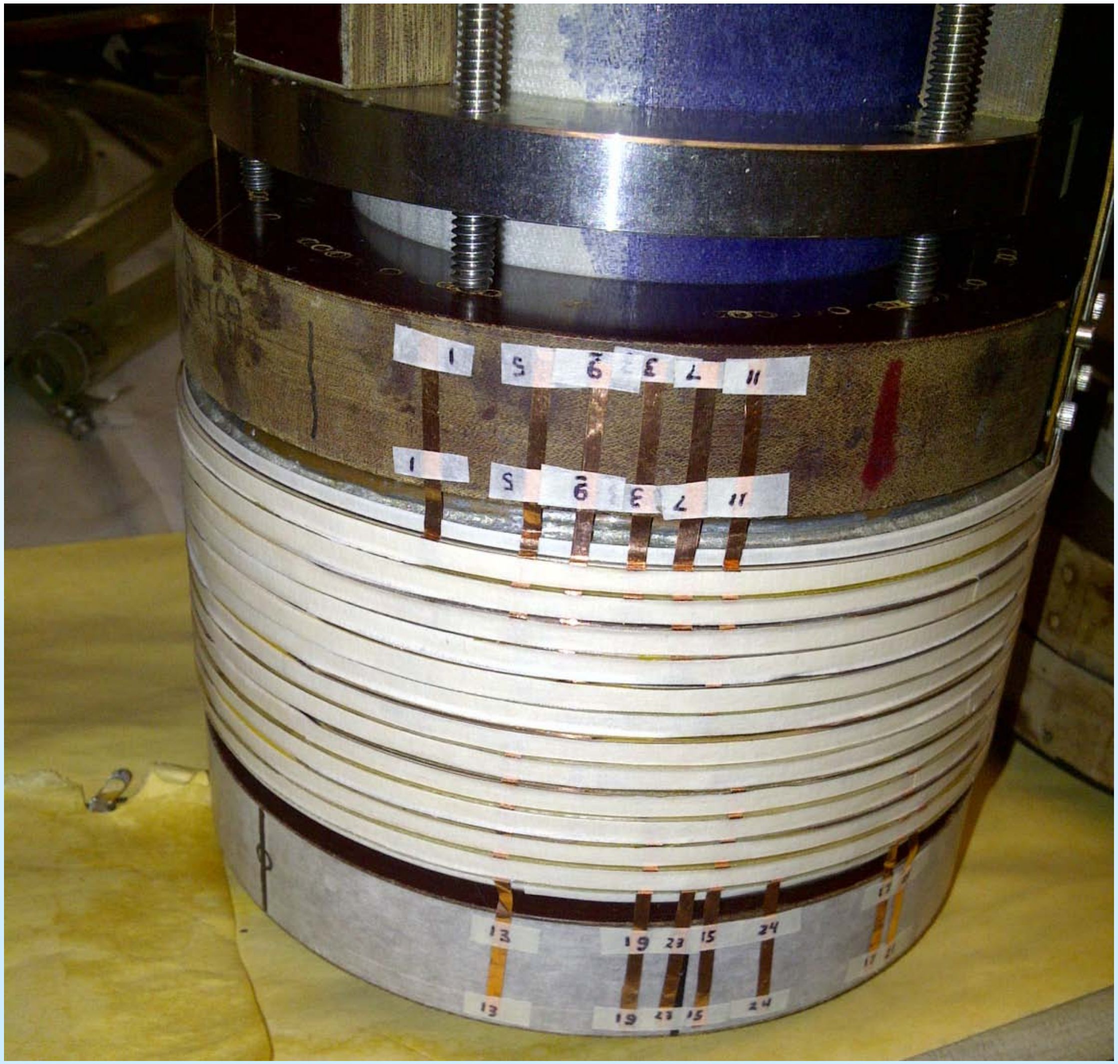
- **Major R&D with new electronics for advanced quench protection system**
- **PBL/BNL SBIR has been critical to the development of HTS technology**

Also significant support from FRIB

Reference:
PAC 2011 paper by Joshi, et al.

Challenge:
Detect small resistive voltage quickly over large noise and inductive signal

Construction and Test of Solenoid #1 (half length midsert)



~100 mm aperture
12 pancakes (instead of 24)

William Sampson Honored With IEEE Award For Applied Superconductivity Research

This beautiful solenoid was handcrafted by Bill Sampson

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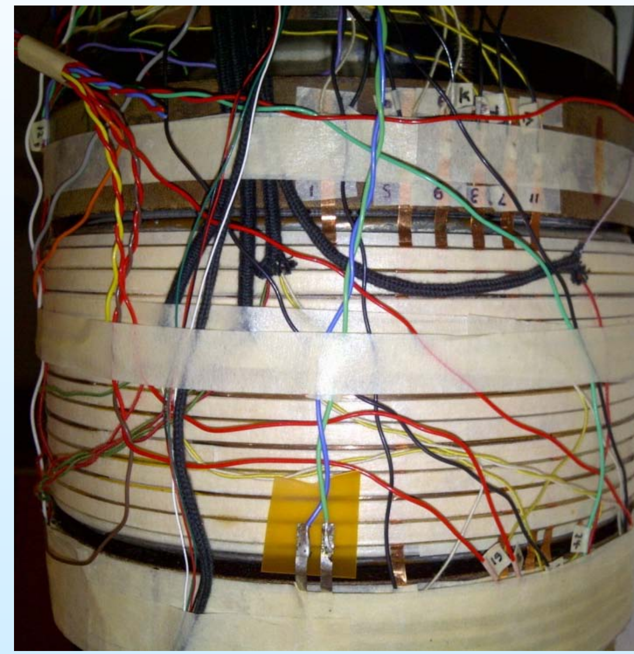
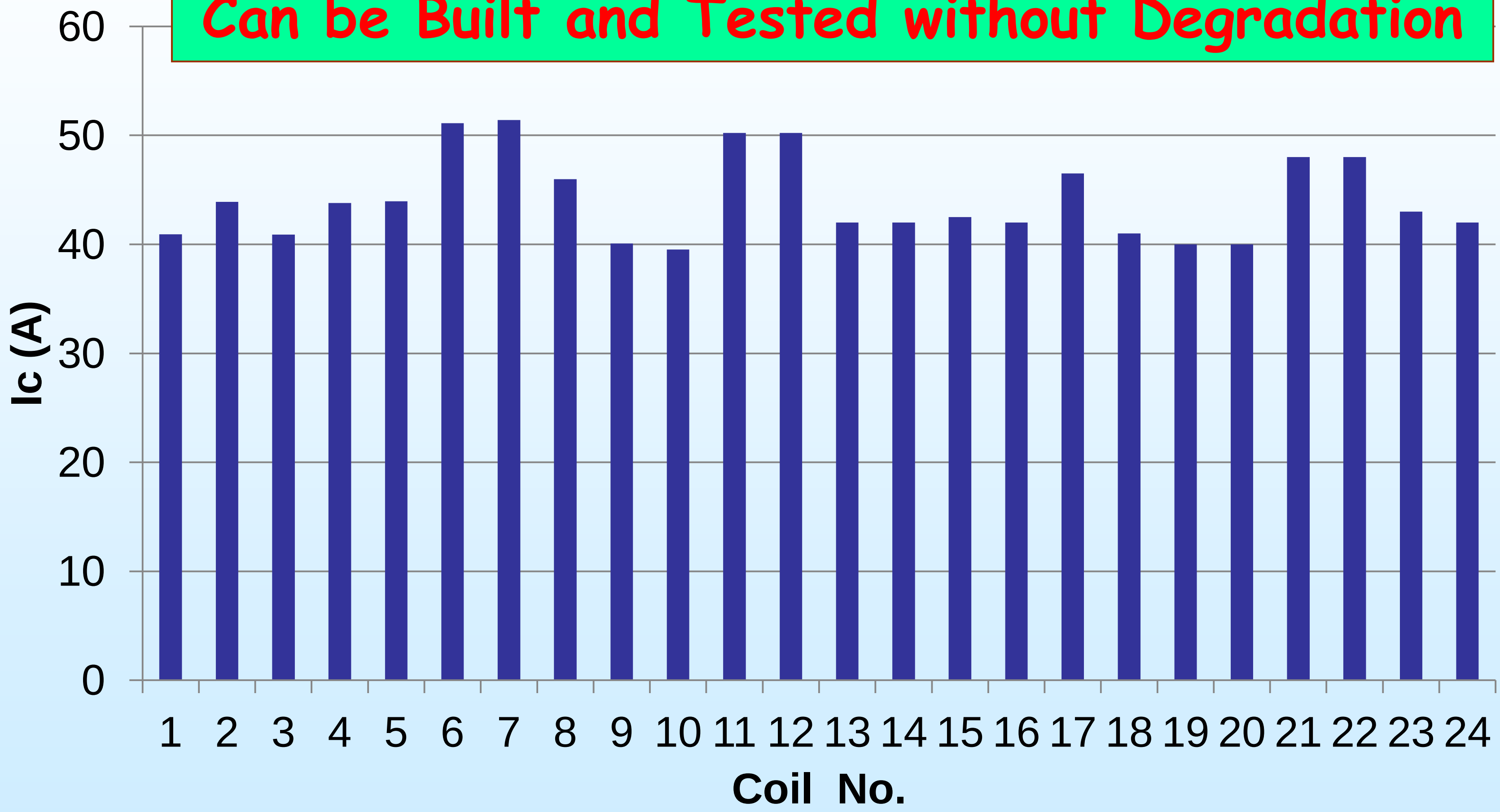
~100 mm 2G Coils for Midsert

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



Test Results of 24 Coils at 77K

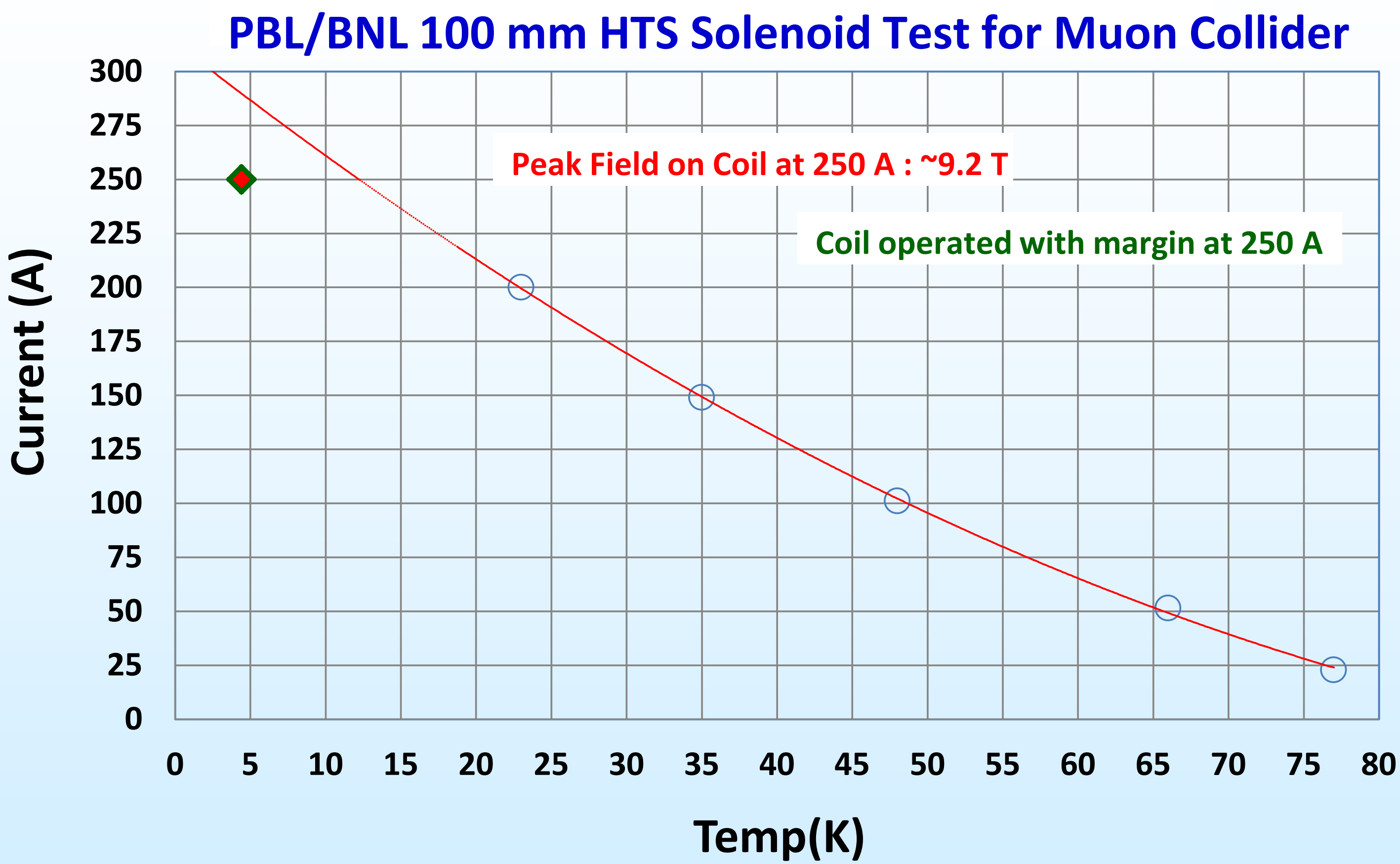
Proof That A Large Number of 2G HTS Coils Can be Built and Tested without Degradation



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

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

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

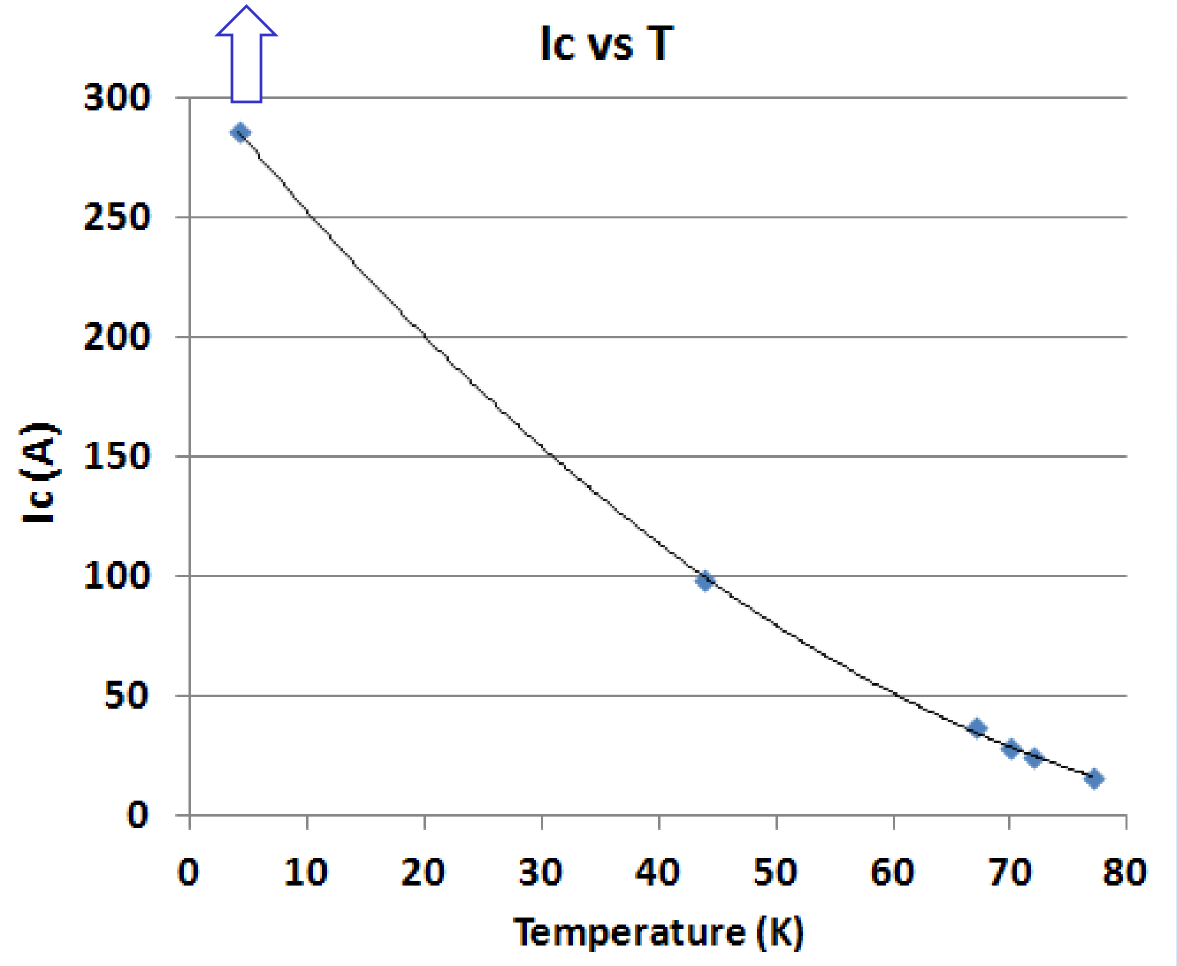
Construction and Test of Solenoid #2 (full length insert)

~25 mm, i.d., 14 pancakes

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

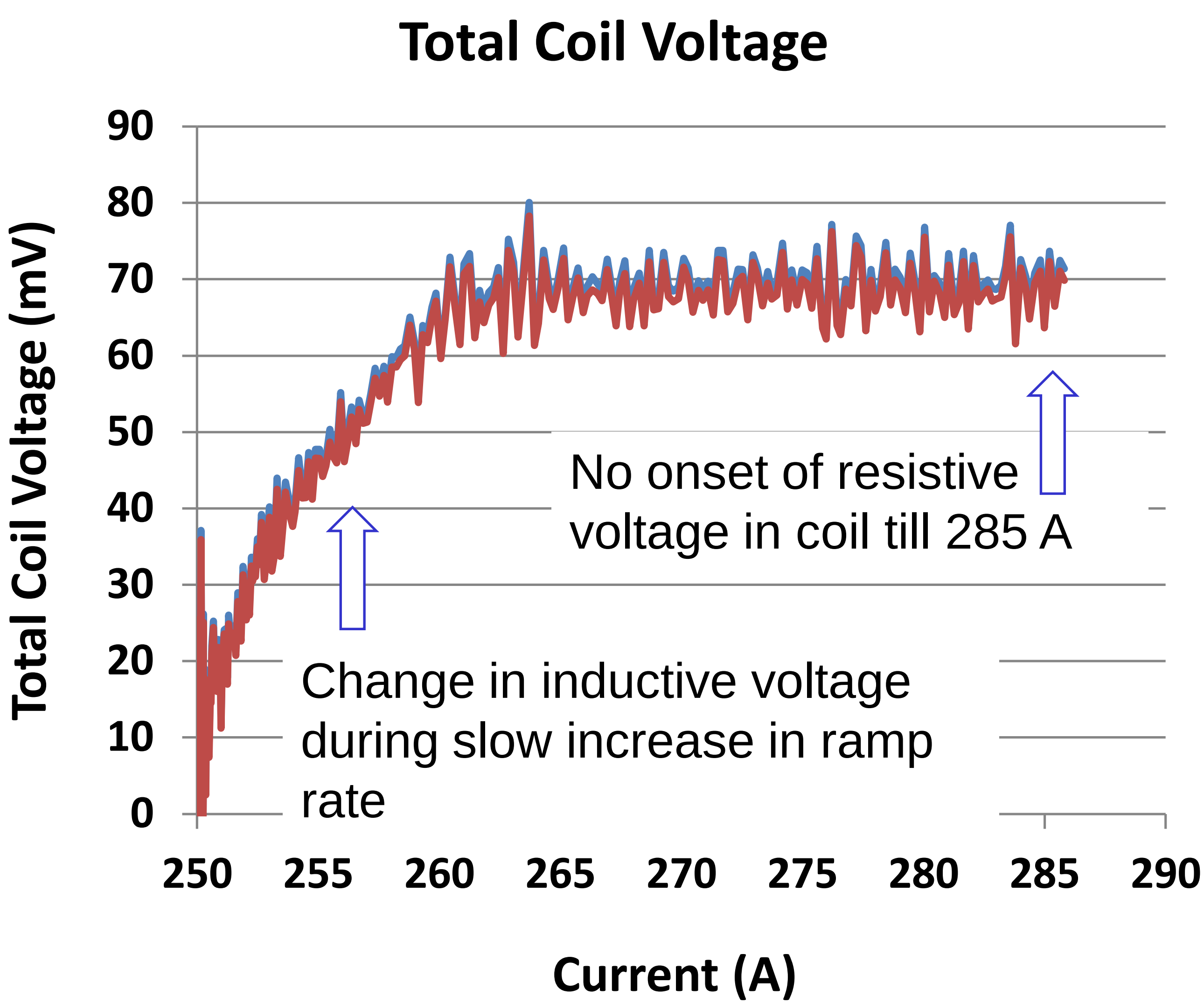
Summary of Test Results #2

Field reached at the center of solenoid at 285 A was over 15 T on axis and over 16 T on coil. This is ~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.

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 stopped at 285 A.

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

Significance of the Two Test Results

- High field all HTS solenoids can now be successfully built using a significant amount of conductor (~2 km)
- Maximum field on coil >16 T, overall current density (J_o) in coil >500 A/mm^2 – new record for any technology - LTS or HTS
- These results have been accomplished in a rather short period of time and on a rather limited budget. This could perhaps be one of the most significant outcomes of the recent DOE SBIR program
- We still have a lot to demonstrate but the impact is obvious

Future Tasks

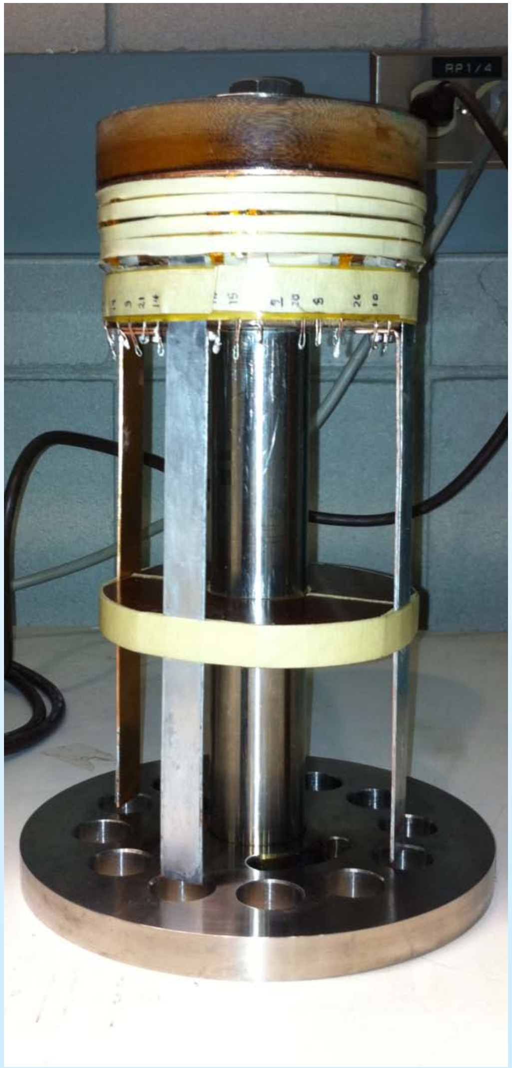
1. Construction and Test of 20^{+} T HTS solenoid
2. Test above in the background field of 20 T resistive magnet at NHMFL to investigate high field magnet technologies at ~40 T
3. Design, construction and test of ~35 T superconducting solenoid

Future Task #1 (funded) Testing of 20+ T All HTS Solenoid

- Further upgrade to advance quench protection system for protecting more coils (28 pancakes in total) and to allow higher voltage during discharge
- Complete construction of full midsert with 24 ~100 mm coils (12 used in last)
- Enhance radial support of the previously tested ~25 mm insert solenoid
- Assemble insert and midsert together in one structure but with separate leads to energize them independently.
- **Re-test 15+ T insert and full midsert with 24 coils and then the two together.**
- **Approximate schedule for the above grand test: 2-3 months from now.**

Above test, if successful, would for the first time demonstrate that very high field magnets (20-25 T) can be made using a large amount (~3 km) of HTS from SuperPower.

HTS PBL/BNL Insert Coil Test in the Background Field of 20 T Resistive Solenoid



23 T

Measured Field in HTS Solenoid (T)

Current in HTS Coils (A)

Mini solenoid (4 coils instead of 14) was taken to NHMFL for initial test of technology for 20^{+} T HTS solenoid

4 T @4K self field, and 23 T in 20 T background field

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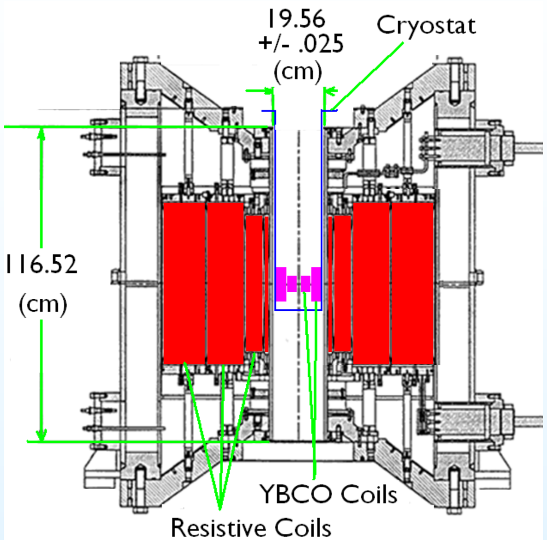
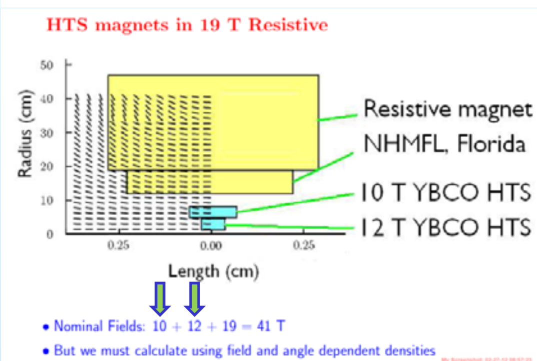
Future Task #2 (not fully funded) 20+ T magnet in ~20 T field for ~40 T Test





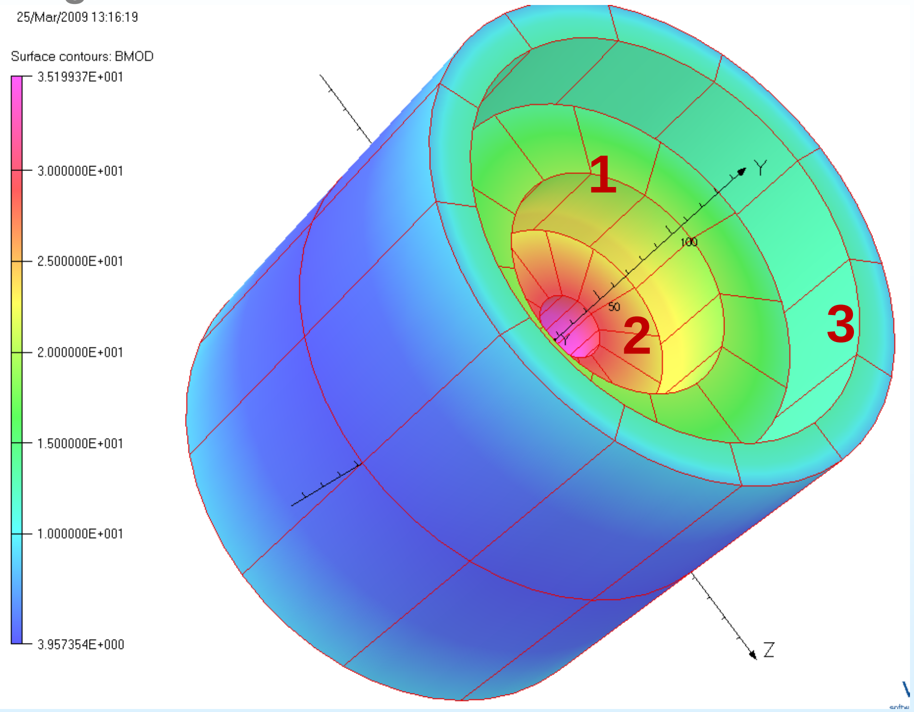
Above figures from Bob Palmer

We could be doing better than his speculation for high fields. How often does that happen?

- Purpose: Test high field magnet technology to ~40 T with 20+ T coming from PBL/BNL solenoid and rest ~20 T coming from resistive solenoid at NHMFL.
- BNL will need to install outer support structure to deal with large hoop stresses in the background field.
- To allow space for this structure, a number of turns may have to peeled-off and whole solenoid has to be re-assembled to fit within the space of NHMFL solenoid.
- BNL would also have to update structure and quench protection to take care of off-centric forces and various fault scenarios that could induce large voltages and forces on the 20+T HTS solenoid.
- PBL expenses at NHMFL are included in the SBIR, but above & other preparation work at BNL are not.

✓ Budgetary help from MAP will make this test possible

Future Task #3 (if Phase II gets funded)
35^{+} T Superconducting Solenoid for MAP



- The ultimate target of the series of PBL/BNL SBIR is a 35^{+} T solenoid.
- We anticipated that 20-22 will come from HTS (expensive) and the rest from LTS (NbTi+Nb_3Sn – cheaper).
- PBL (PI: Scanlan) to submit Phase II for the development of LTS solenoid - the last module of the dream package.

- Current high field LTS solenoids are low current, high inductance devices.
- PBL/BNL proposes to bring accelerator magnet technology to solenoids to develop a high current/low inductance solution (better for quench protection).
- When integrated with previous HTS solenoids, it aims to demonstrate a base technology for a 35^{+} T sc solenoid – a major way forward for MAP.

SUMMARY

- **We have made significant progress in developing magnet technology for MAP:**
  - **We have demonstrated a large aperture high field coil (~100 mm, 9+ T on coil) made with a large amount (1.2 km) of 2G HTS wire.**
  - **We have demonstrated 15+ T (16+ T on coil), ~25 mm insert HTS solenoid (highest field ever in HTS solenoid).**
- **Our goal has been to show that HTS technology can be used in making very high field superconducting magnets for which few other solutions seem viable.**
- **If we achieve our stated goal (35^{+} T), then this may be referred to as a major success story of SBIR program with a variety of applications in other fields.**
- **A significant work still remains to be done. For example, completing remaining tasks, scaling and demonstrating technology in operational circumstances, etc.**
- **Our approach has been that once the viability of HTS for producing high field magnets is established, more funding should flow to take this to the next level.**