

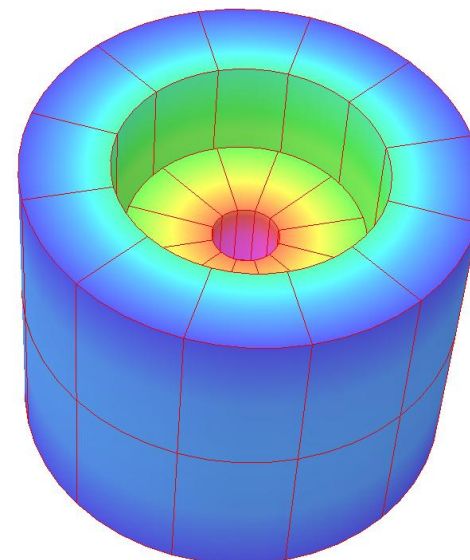
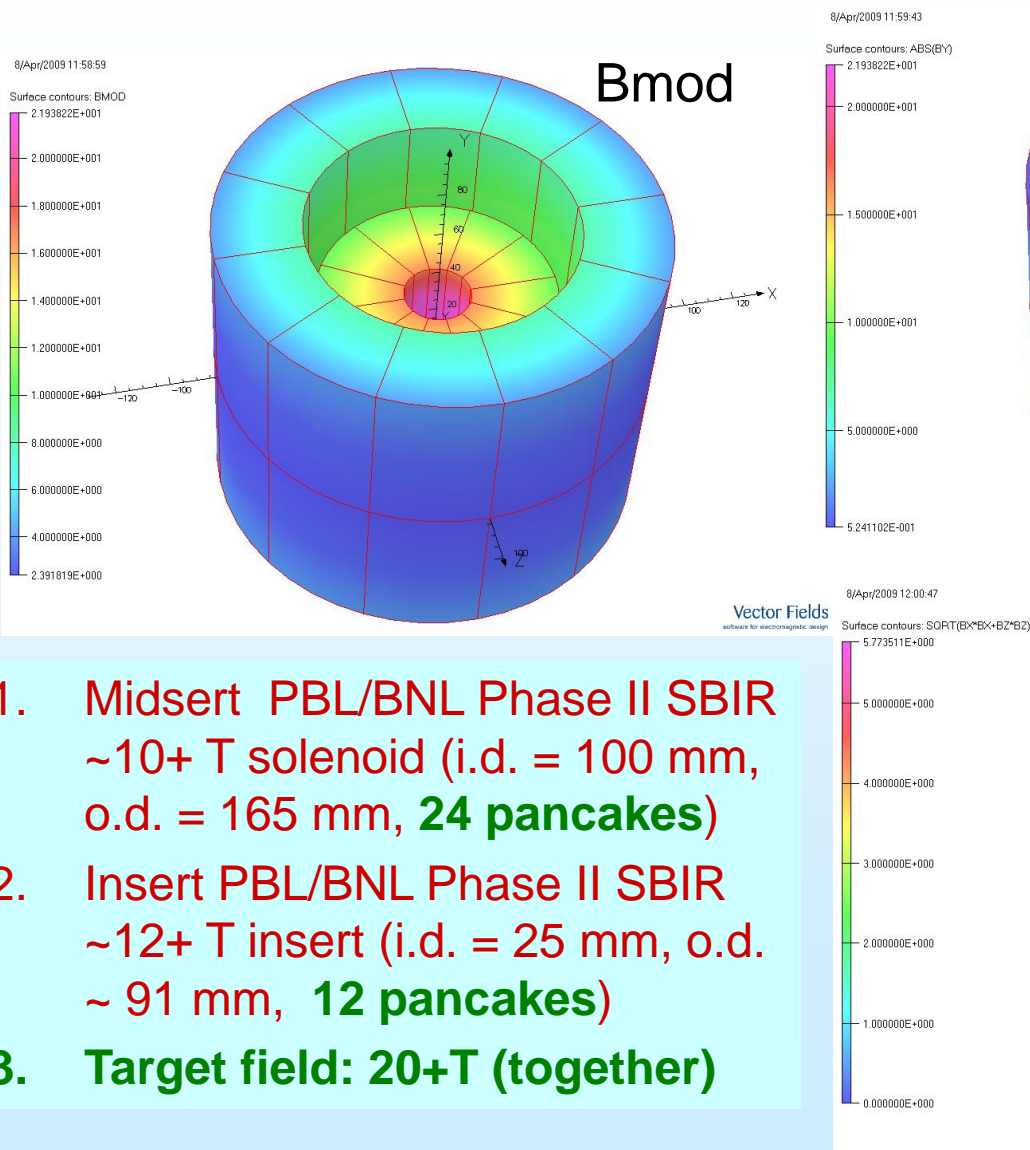
# Status of PBL/BNL HTS Solenoid

Ramesh Gupta  
for  
PBL/BNL Team

# Overview

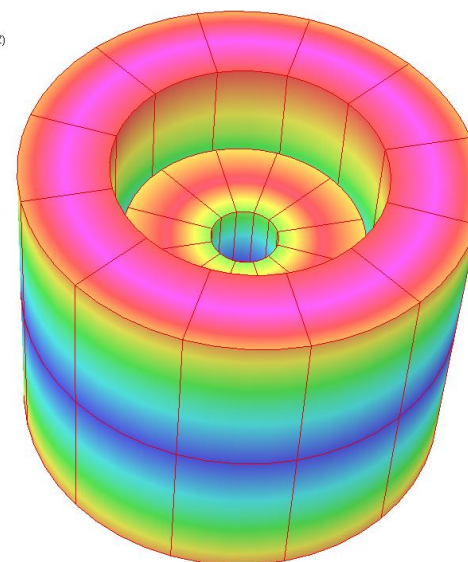
- **Brief overview**
  - **Basic design and previous test results**
- **Progress in coil construction**
- **Progress in quench protection**
  - **New quench hardware**
  - **Coils divided in several sections**
- **Recent test results**
- **Future plans**

# PBL/BNL YBCO Solenoids (two solenoids in two SBIRs)



**Bparallel**

Vector Fields  
software for electromagnetic design



**Bperpendicular**

UNITS	
Length	mm
Magn Flux	T
Density	
Magn Field	A m <sup>-1</sup>
Magn Scalar Pot	A
Magn Vector Pot	Wb m <sup>-1</sup>
Elec Flux Density	C m <sup>-2</sup>
Elec Field	V m <sup>-1</sup>
Conductivity	S m <sup>-1</sup>
Current Density	A mm <sup>-2</sup>
Power	W
Force	N
Energy	J
Mass	kg

**PROBLEM DATA**  
2 conductors

**Field Point Local Coordinates**  
Local = Global

**FIELD EVALUATIONS**  
Line LINE 101 Carte  
(nodal)  
x=0.0, y=-50.0 to 50.0.

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1. Midsert PBL/BNL Phase II SBIR  
~10+ T solenoid (i.d. = 100 mm,  
o.d. = 165 mm, **24 pancakes**)
2. Insert PBL/BNL Phase II SBIR  
~12+ T insert (i.d. = 25 mm, o.d.  
~ 91 mm, **12 pancakes**)
3. Target field: 20+T (together)

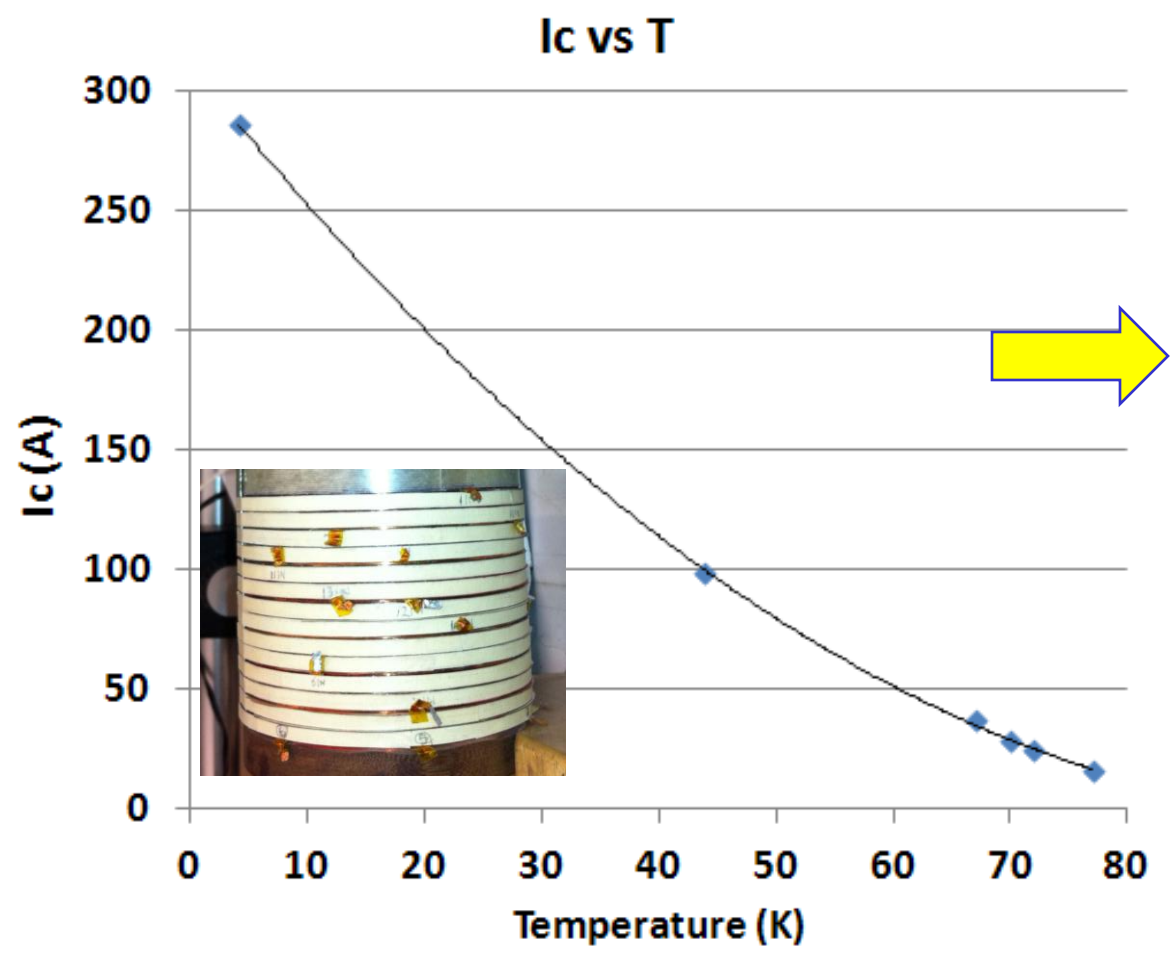
# Design Parameters at ASC2010 (more pancakes than in original design)

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 <sup>2</sup>
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)
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.

# High Field HTS Solenoid Test Results (magnet #1 - insert)



**Field on axis:**  
➤ over 15 T  
**Field on coil:**  
➤ over 16 T  
(original target was 10-12 T)

**Real demo of 2G HTS to  
create high field**

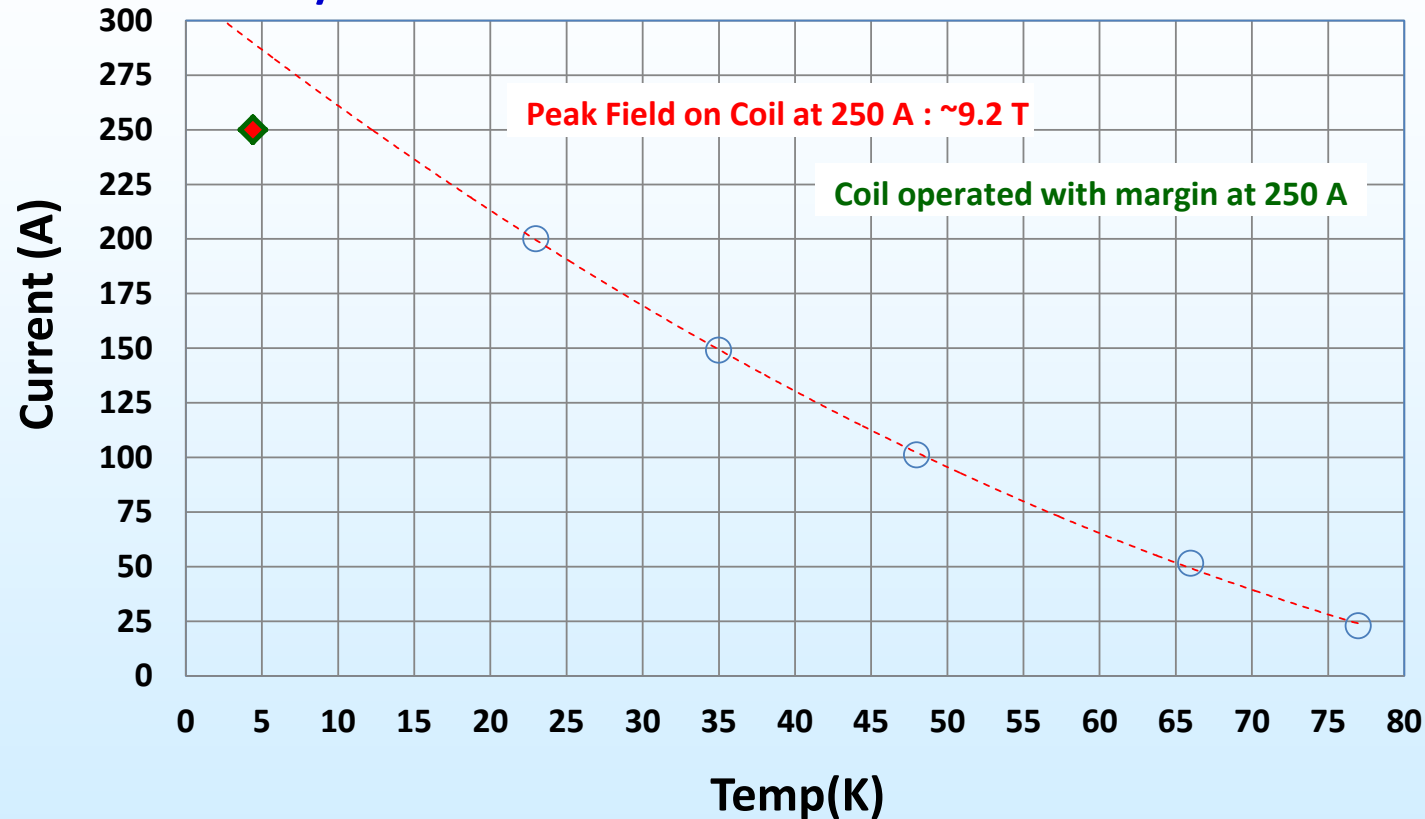
Highest field in an all HTS  
solenoid (previous best  
SP/NHMFL ~10.4 T)

**Overall  $J_0$  in coil:**  
**>500 A/mm<sup>2</sup> at 16 T**  
(despite anisotropy)

14 pancake coils with ~25 mm aperture

# Test Results of HTS Solenoid #2 ( $\frac{1}{2}$ Midsert, 12 coils instead of 24)

## PBL/BNL 100 mm HTS Solenoid Test for Muon Collider



250 A ==>  
6.4 T on axis  
9.2 T peak  
field on coil



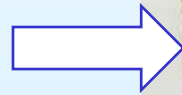
*Coil could have reached above 10 T peak (original target),  
but was not ramped up to protect electronics of that time.  
Full solenoid with 24 pancakes should create >10 T on axis.*

# Progress in Coil Construction

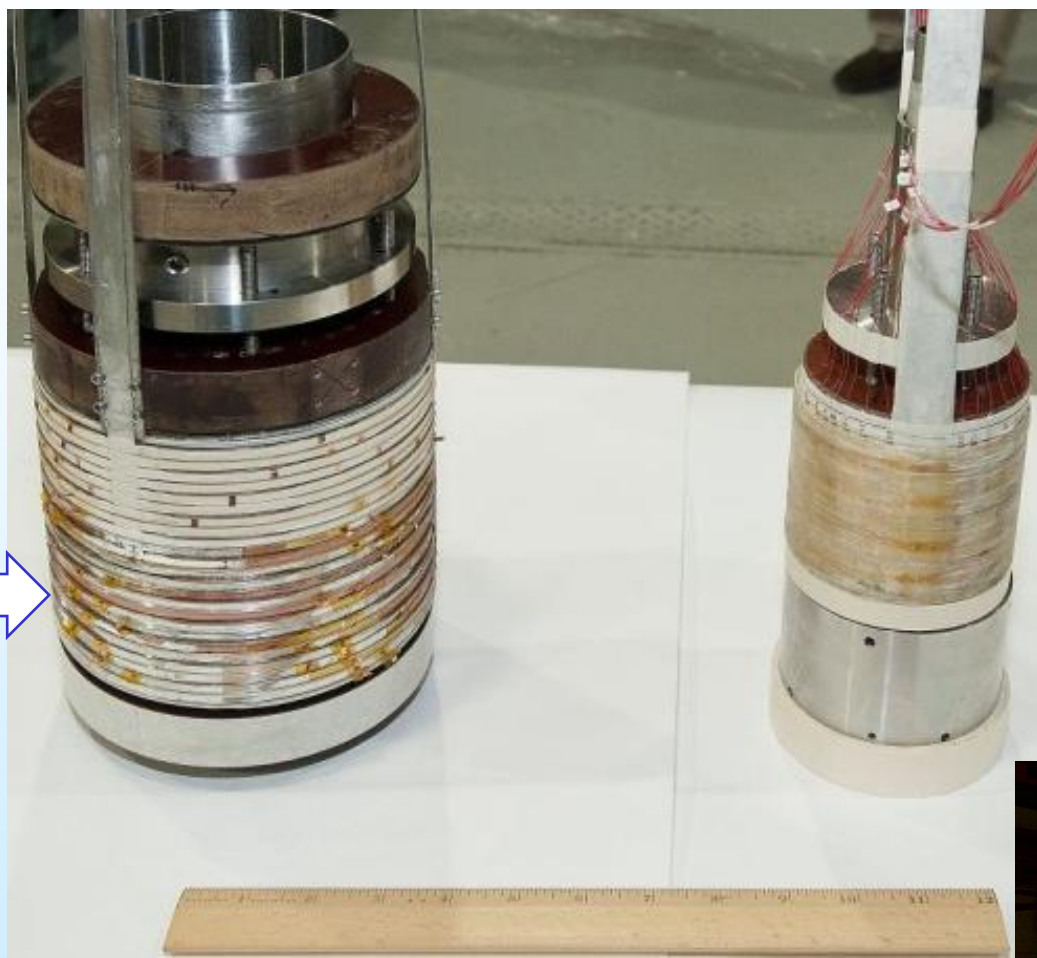


# Fully Constructed HTS Solenoids

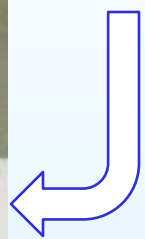
10+ T, 100 mm  
HTS solenoid  
(midsert) with 24  
pancakes for full  
length solenoid



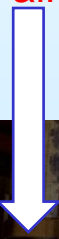
(picture taken a  
few months ago)



15+ T, 25 mm HTS  
solenoid (insert)  
with 14 pancakes  
already tested



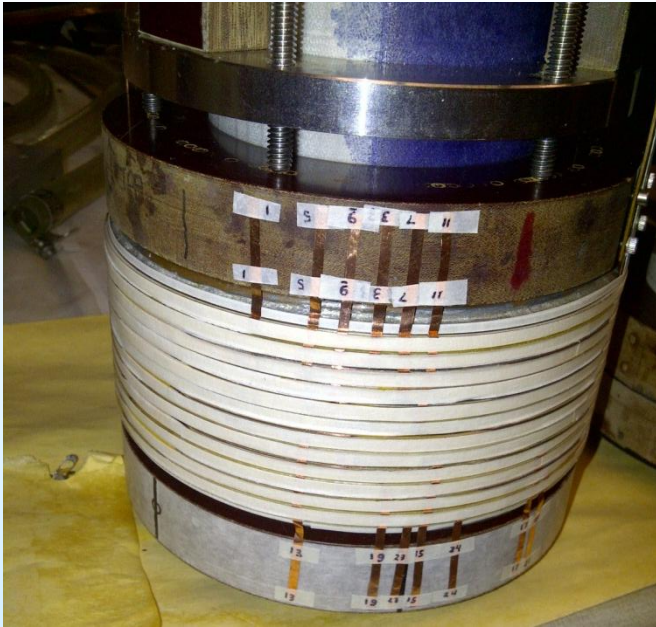
Half length 100 mm  
with 12 pancakes  
already tested and  
reached 6+ T on  
axis (9+ T peak)



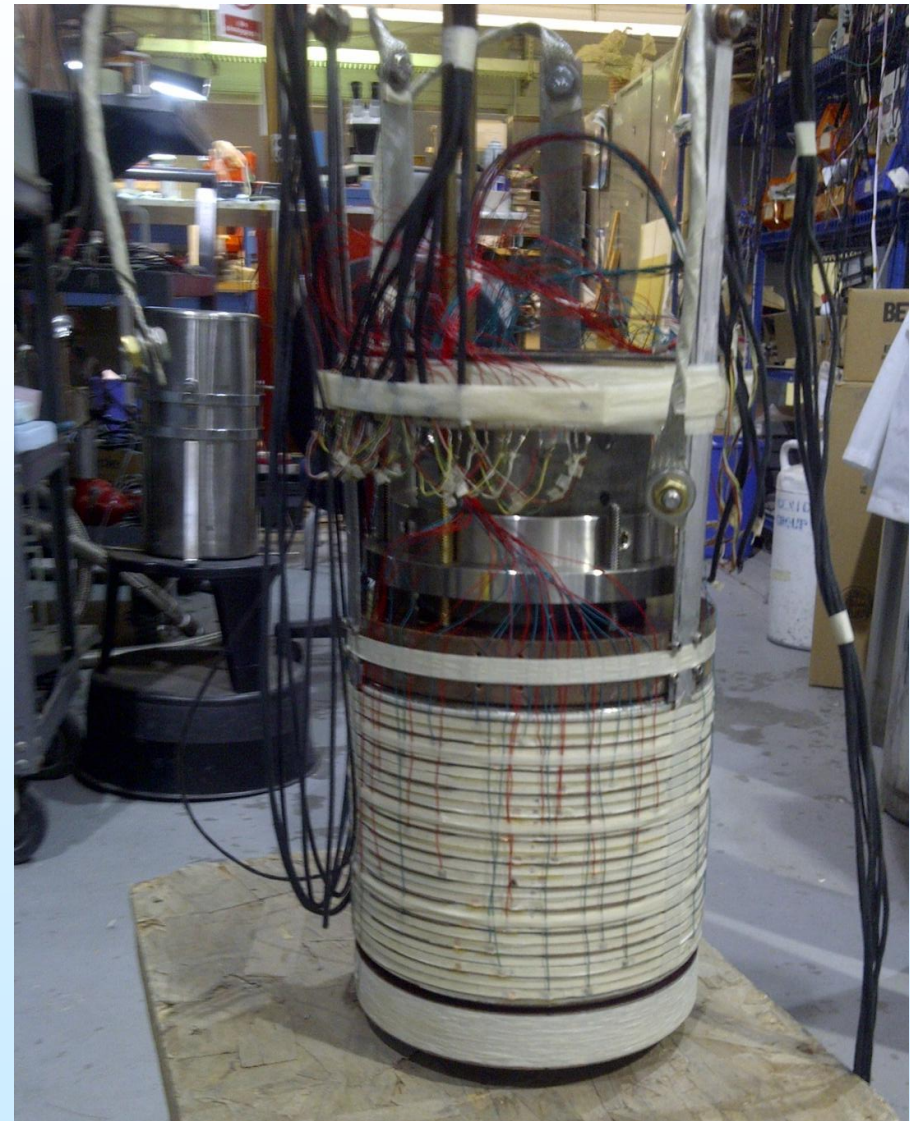


# PBL/BNL Midsert Solenoid

Each 100 mm i.d. pancake uses  
100 meter of conductor.



- Picture on left (half solenoid with 12 pancakes, previously tested at 4 K)
  - Picture on right (full solenoid with 24 pancakes, recently tested at 77 K)
- Picture taken in December 2012

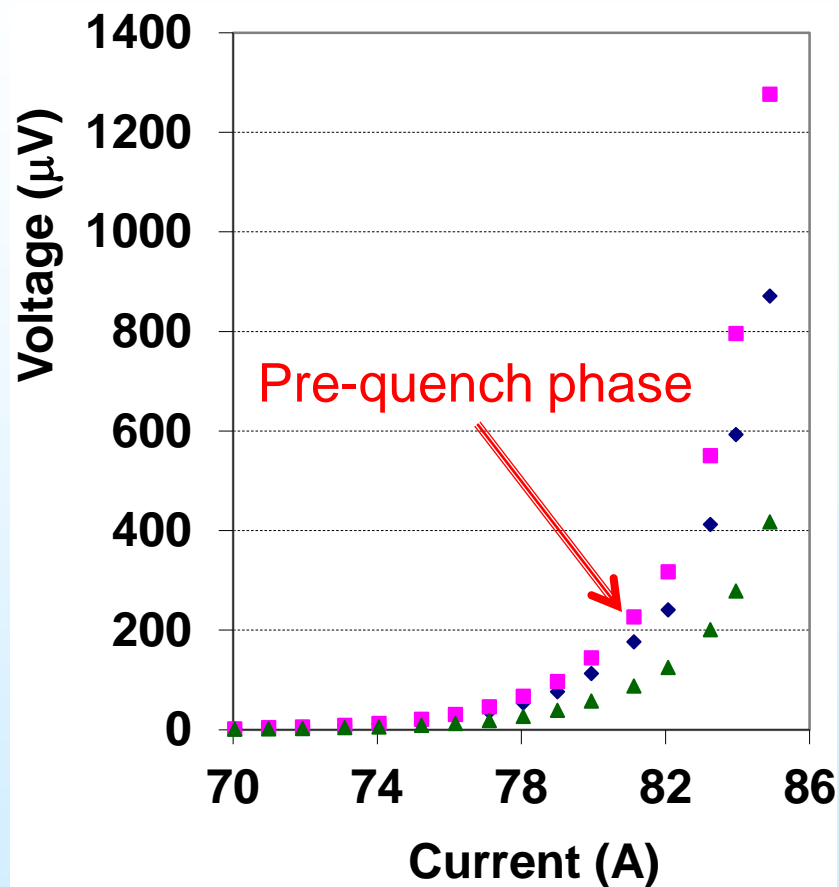


# Progress in Construction

## Quench Protection and Associated Hardware

# BNL Quench Protection Strategy

- Things happen slowly in HTS => quench propagation velocities, increasing coil temperature to quench whole coil, etc., etc.
- Use problems (properties) of HTS “*of things happening slowly*” to our advantage.
- In HTS, there is a long pre-quench phase with very small resistive voltage during which the coils can be safely operated.
- Detect this pre-quench phase early on and initiate quench protection action.
- *This requires detecting small resistive voltage in presence of large noise and inductive voltage – challenge in large systems.*
- *BNL has made significant advances in electronics to detect start of this pre-quench phase well below 1 mV rather than 50-100 mV.*



Use quench protection heaters  
as the final line of defense



# Expansion of Advanced Quench Detection System at BNL

- So far we have tested solenoids with 12 or 14 pancakes (plus splices).
- The next test (insert + full midsert) will have  $14+24=38$  pancakes.
- We are ready to go with these two.

**Cabinet #1 (32 channels, 1kV)**



**Cabinet #2 (32 channels, 1kV)  
(expandable to 64 and 3kV)**



# Advanced Quench Detection System

Construction of the second quench detection module is partly supported by MAP. **Thanks.**

NI FPGA  
based  
Quench  
Detector

NI PXIe  
based  
Data  
Logger



NI PXI  
based  
Data  
Logger

NI FPGA  
based  
Quench  
Detector



# Energy Extraction

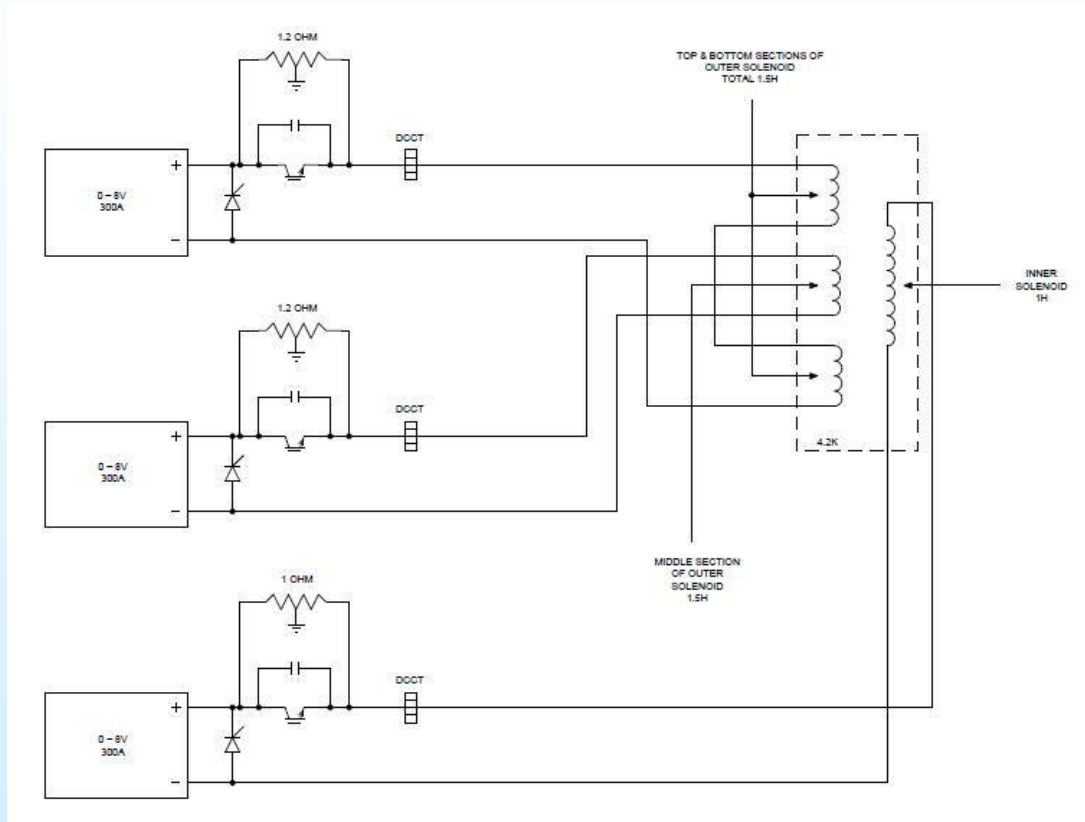
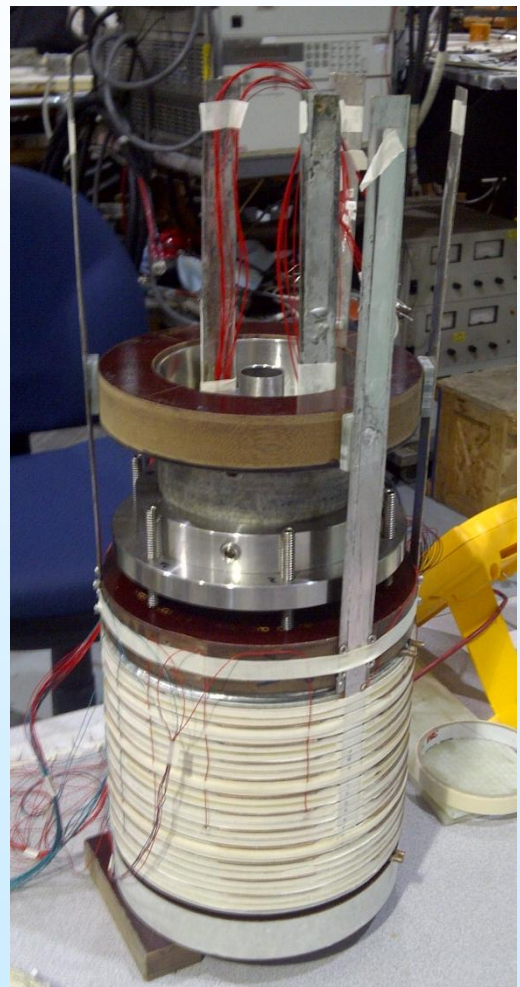
- After detecting quench, we want to extract energy as fast as system allows
- Time constant =  $L/R$  : large inductance requires large resistor for this
- However, large resistor also creates large voltages :  $I \cdot R$
- To avoid a too high voltage, divide coil in sections (reduce inductance)
- Each section will have its own dump resistor and would be powered by a separate power supply

Multiple power supplies also permits a dynamic grading, which in principle should allow higher field tests



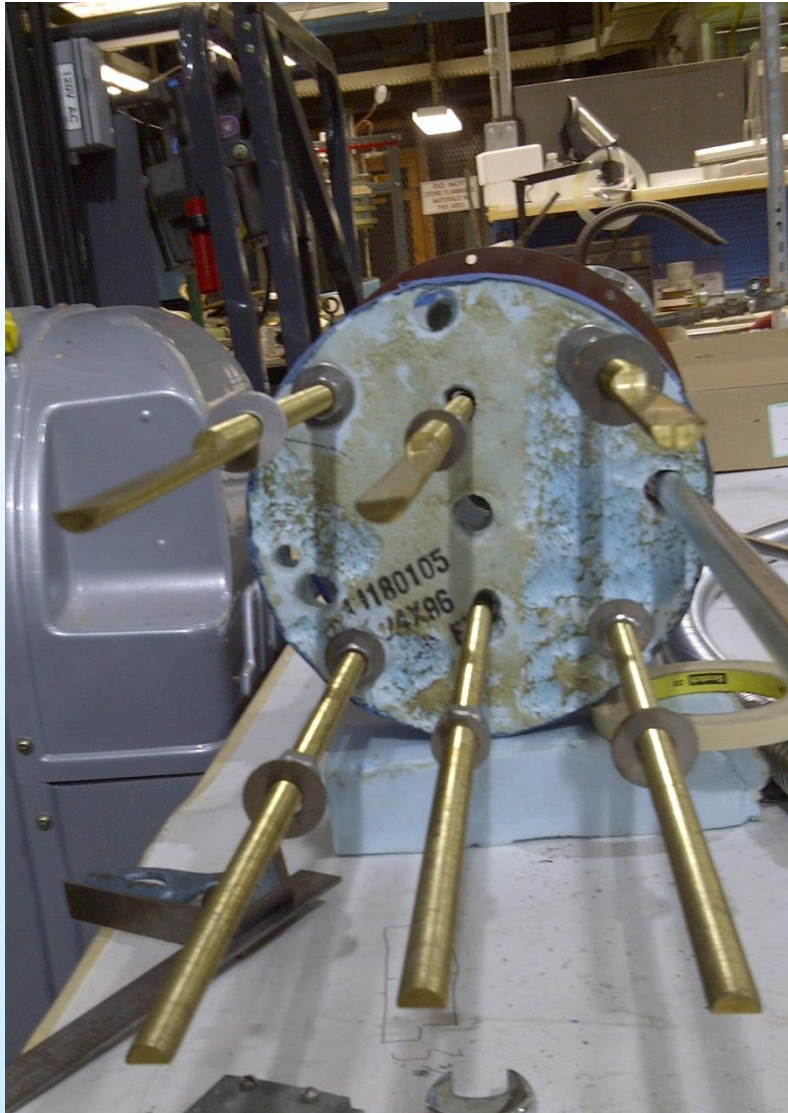
# Solenoid with Multiple (3) Sections (38 pancake coils)

#1 : insert (14 pancakes), #2 and #3 : two half midserts (12 pancakes each)



- Solenoid is sectionalized to extract energy fast on external dump resistors while keeping voltage low
- Bonus: Can also be used to provide electrical grading

# Preparation of Top Hat with Six Leads (to divide solenoid in three sections)



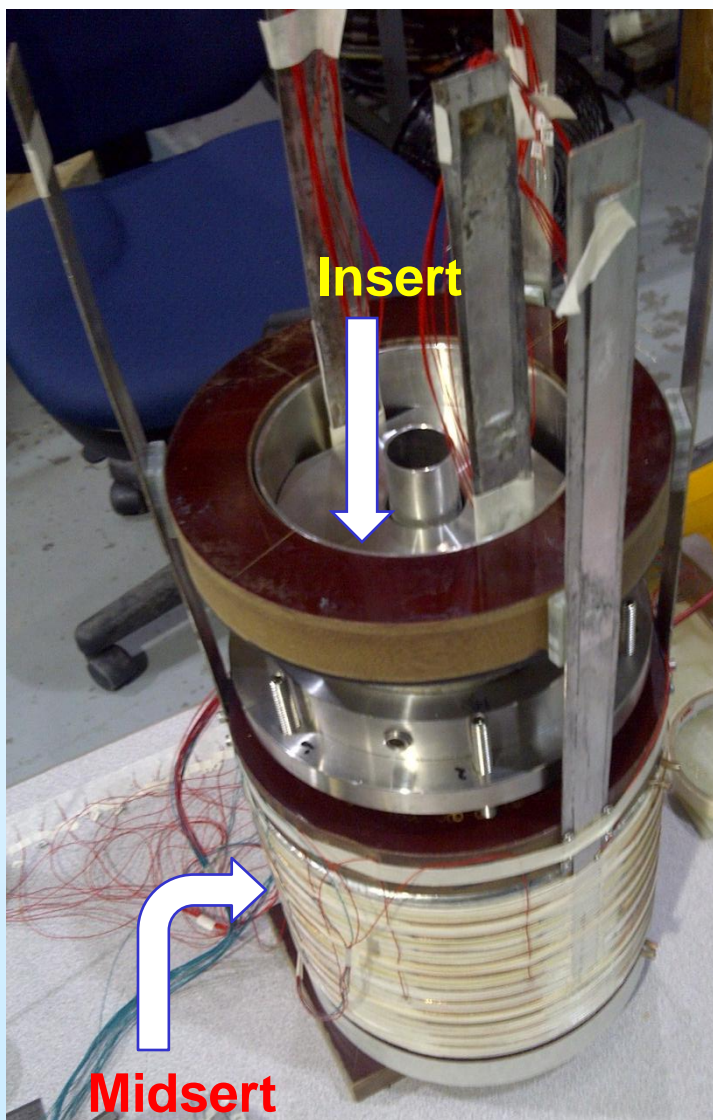
# Recent Test Results

- 77 K tests of midsert plus insert are performed prior to 4 K high field test
- These 77 K tests also debug and optimize new quench detection system
  - Mixed outcome



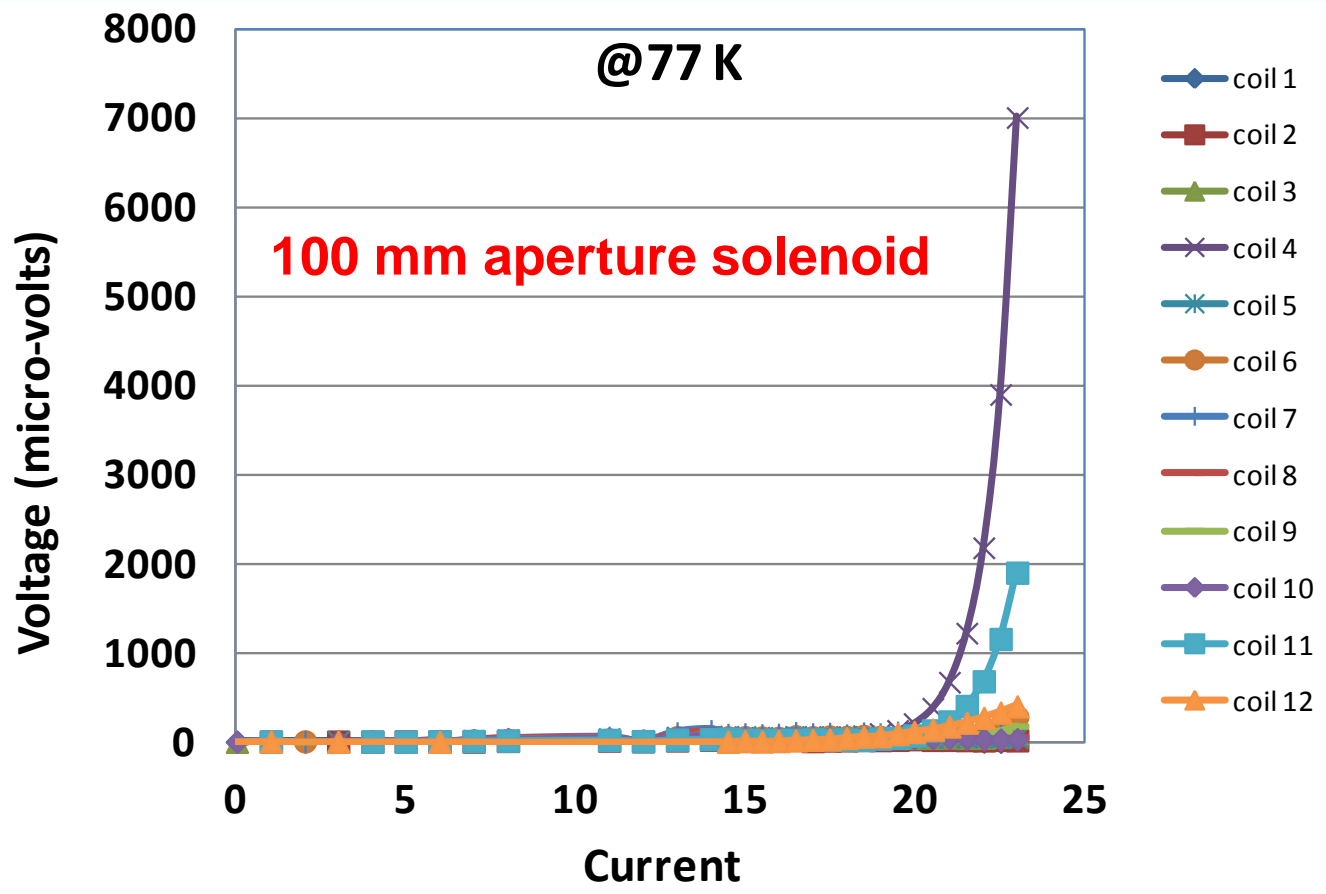
# Combined Solenoid Tests at 77 K (HTS Insert inside HTS Midsert)

- Two solenoids have been tested together @77K in various configurations - insert, midsert, sections, and various combinations
- Expanded quench detection system (hardware +software) is being fully developed and tested with large number of channels and coils



# 77 K Test of Half HTS Midsert (half midsert contains 12 pancakes)

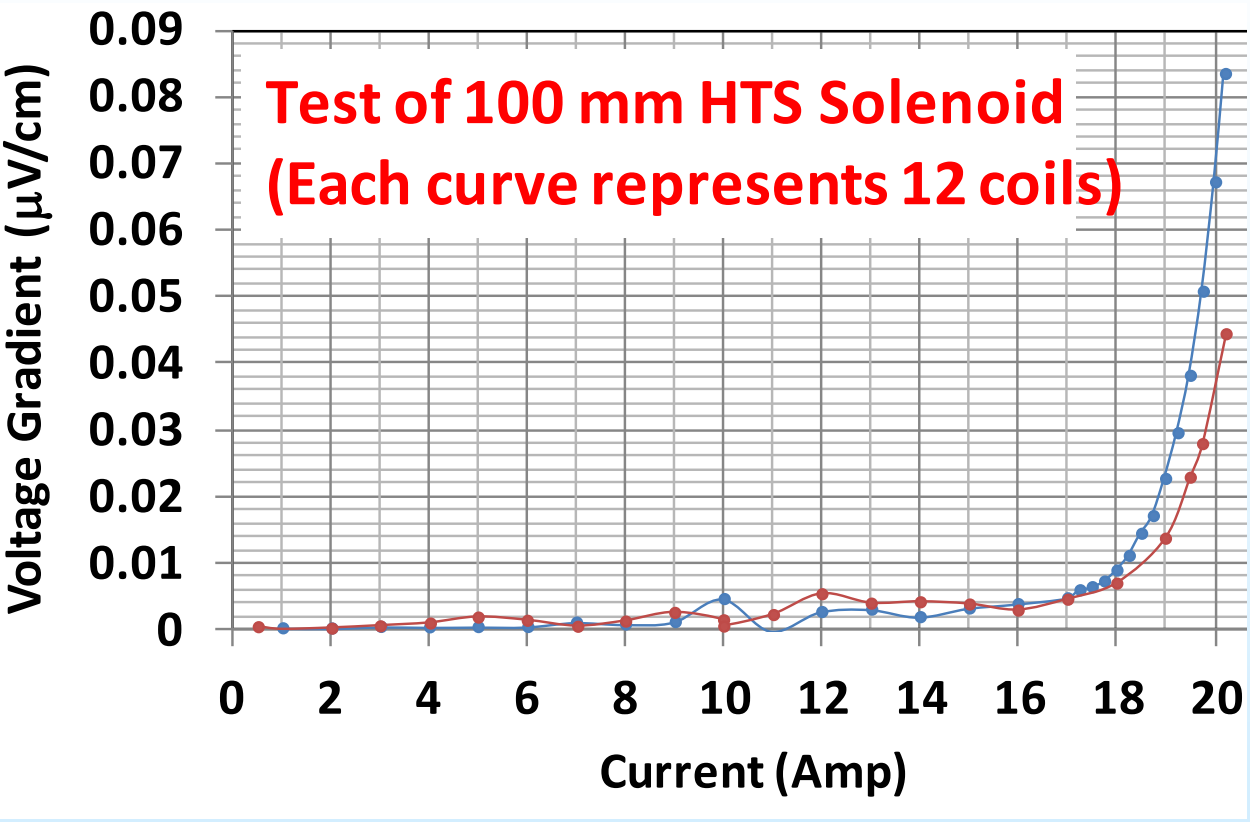
These tests were performed about a year ago



- Each pancake has 100 m of HTS tape.
- All pancakes are powered in series – voltage is measured across each pancake and across each joint.
- Critical current of 12 pancake system: ~21 A for 0.1  $\mu\text{V}/\text{cm}$  criterion.

# 77 K Test of Full HTS Midsert (full midsert contains 24 pancakes)

These tests were performed recently (about a month ago)



- Each pancake is made with 100 meter of HTS.
- All pancakes are powered in series – voltage is measured across each coil and also across 12 coils.
- Critical current of 24 pancake system:  $\sim 20$  A for  $0.1 \mu\text{V}/\text{cm}$  criterion. It was  $\sim 21$  A for 12.

**Everything looks good for the full-size midsert solenoid  
(this is expected to reach over 10 T at 4 K, if everything is OK)**



## 77 K Test of HTS Insert Solenoid (insert contains 14 pancakes)



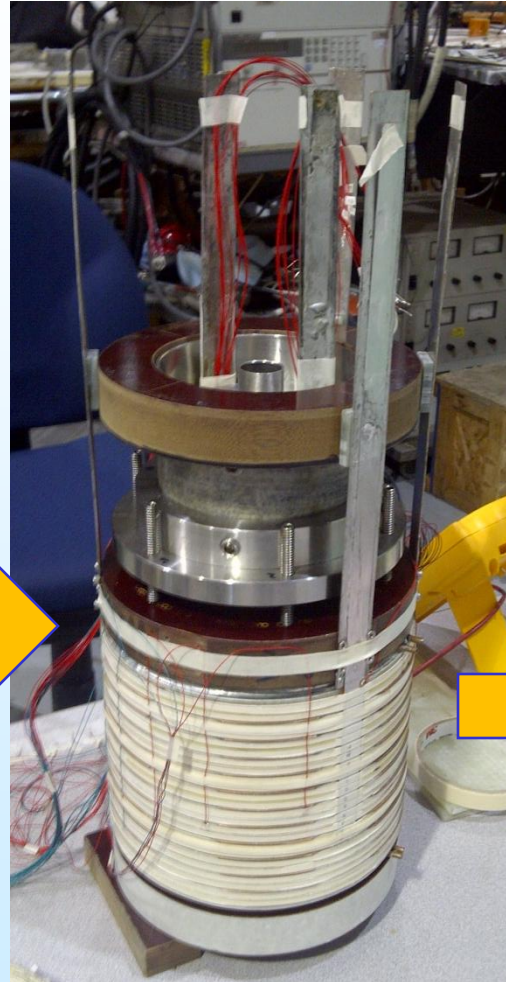
- Whereas the midsert solenoid worked well, we came across a major surprise in insert solenoid
- 77 K test results showed that it became resistive right from the beginning, when the voltages on the pancakes of insert solenoid were first measured.
- This indicates a major problem. The question is how widespread this problem is? One joint, one pancake or multiple failures?
- The insert solenoid was inside the midsert solenoid during this test.
- It may be noted that though this was the first power-up cycle of the insert solenoid, this was not the first cool-down. It was cooled many times during a number of tests of midsert solenoid and of quench system.
- Insert solenoid had to be taken apart for further investigations (recall – this has reached over 15 T).



# HTS Insert Solenoid



HTS insert solenoid



HTS insert (not visible)  
inside the midsert



HTS insert taken apart with  
a few parts displayed



# Investigation on Insert Solenoid



- We have taken the HTS insert apart and we are carrying out 77 K QA test of each individual double pancake – one at a time.
- There are seven double pancakes and so far we have determined the status of five.
- In each test, we measure the splice joint, the overall voltage in each single pancake.
- In addition, in some cases we installed a few intermediate voltage taps to determine the region of defect within the pancake.
- Two double pancakes (four single pancakes) look bad and three double pancakes (six single pancakes) look good. Splices, look OK.
- Out of fourteen pancakes, bottom four are found bad, then next two and top four are found good.
- We hope that other four, which are in between, are good. We will verify that.
- In the case, we had intermediate voltage taps, the bad section has been found in the outer section.

# History of Construction and Tests of HTS Insert Solenoid

- After reaching 15+ T, the insert solenoid was taken apart to repair lost voltage taps and to make the overall assembly more robust.
- The re-assembled solenoid was tested at 77 K and was found OK.
- Kevlar strings were put on the o.d. of the insert solenoid to deal with the additional Lorentz force expected when this solenoid is put in the background field of midsert solenoid to reach a target field of 20-22 T.
- The insert solenoid was tested again at 77 K and was found OK
- The pancake coil of midsert solenoid are assembled on SS tube. We want to use this SS tube as an intermediate support structure between the two coils.
- Fiberglass epoxy was put on the insert solenoid and outer surface machined to provide a close fitting between midsert and insert.
- Insert and midsert were assembled together and various 77 K tests, as described in previous slides, were performed.
- After the failure the two solenoids were taken apart and the insert was tested by itself. It showed the same problem again.
- The insert solenoid took too long to cool and to become superconducting.

# Possible Source of Problem

- Whereas the investigation continues, the most likely explanation we have is that excessive thermal strain caused the problem.
- Fiberglass-epoxy on the outer surface prevented good and uniform cooling.

# Future Plans

- Instead of carrying out a high field combined test of midsert and insert solenoid, we will carry out the 4 K test of full midsert solenoid.
- We will use similar construction techniques as we used in previous half midsert and other high field solenoids that successfully reached high fields.
- The re-construction of insert solenoid is currently put on hold.
- We will perform the test of remaining pancakes at 77 K to determine how many are good (hopefully ten).
- A possible future program may be to re-build insert solenoid with fewer coils and with lesson learned. This should naturally lead to test of this with midsert.
- SuperPower has also offered (but not confirmed) to supply extra conductor to replace damaged coils.
- If things work well (which we are optimistic), we should still reach  $>20$  T, funding permitting.
- Expect test of midsert solenoid (hopefully reaching above 10 T) before MT-23.