

Status of High Field Solenoid Development (ReBCO)

Ramesh Gupta
(for BNL/PBL Team)

Muon Accelerator Program 2013 Collaboration Meeting (MAP13)

Overview

- **Goal of the program**
- **Background**
- **Latest test results and other updates**
- **Rapid start of energy extraction with copper discs**
- **Outline of future R&D program under MAP**
- **Schedule and status**

Goal of the Program

A 5-year R&D program for feasibility of high field solenoid (30 T or more) based on ReBCO High Temperature Superconductor (HTS)

The target is to demonstrate 30+ T in one (or more) short magnet(s)

- **Real demonstrations (not just design studies) are necessary since**
 - these are unprecedented fields for superconducting magnets
 - High Temperature Superconductors (HTS), which makes this possible, is a new and challenging conductor and has never been used in such applications
- **Sub-goal #1: One time demonstration**
 - to determine if such fields are possible in superconducting solenoids or not?
- **Sub-goal #2: Protection and Reliability**
 - if possible, is it practical to use them in a real device or not?

5-year is about the right time frame for a variety of reasons

Path to Demonstrate a 30+ T Solenoid

Step-by-step R&D approach consisting of three (or more) coils:

1. >10 T HTS solenoid (midsert): SBIR Phase II with PBL
2. >12 T HTS (insert): SBIR Phase II with PBL
3. >8 T LTS (outsert): Not yet started

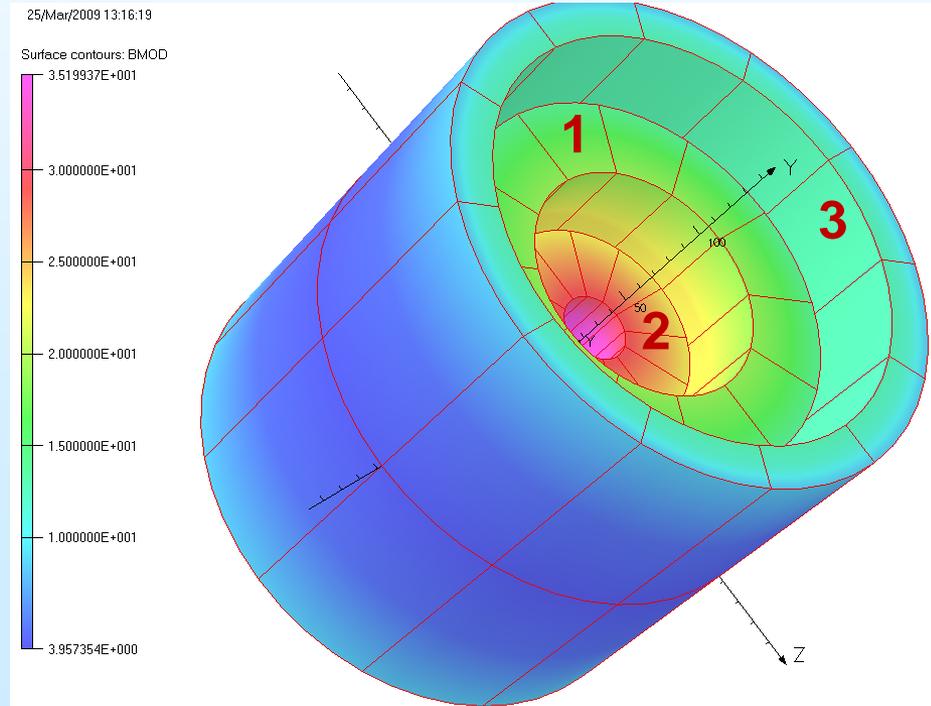
20+ T HTS Solenoid (1 & 2):

addresses initial challenges with high field HTS magnets

30+ T Solenoid (1, 2 and 3):

addresses challenges with high field superconducting solenoids

Synergy and experience (with coils made ~40 km of 4mm tape equivalent) with other HTS R&D programs at BNL creates a unique opportunity.



Background (1)

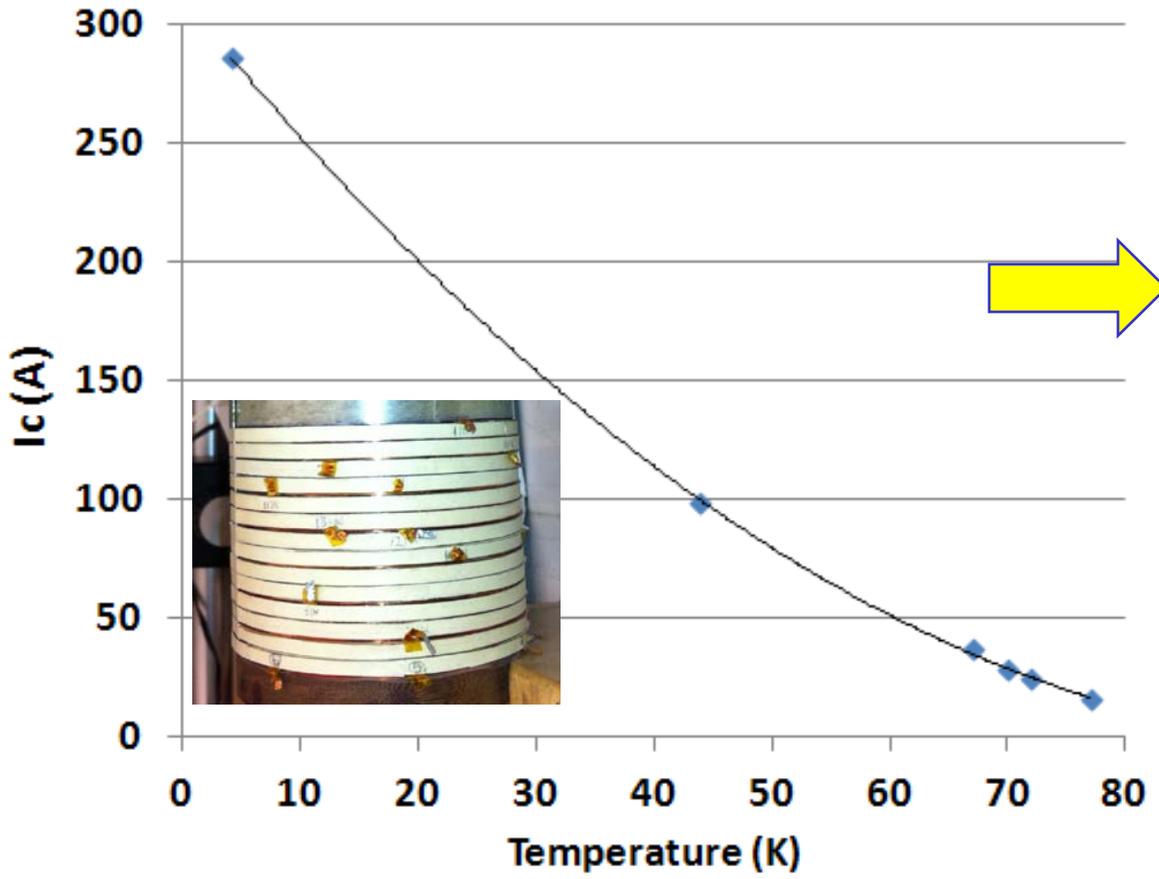
- **PBL (with BNL as a partner) got funded for three Phase 1 and two Phase II SBIRs on high field solenoids for Muon Collider**
 - **First SBIR (Phase I and Phase II) for ~10 T, 100 mm ReBCO midsert**
 - **Second SBIR (Phase I and Phase II) for ~12 T, 25 mm ReBCO insert and for integrating insert and midsert for >20 T all HTS solenoid**
 - **Third SBIR (Phase 1 funded but Phase II was not) for Nb₃Sn outsert**
- **These were presented as bold experimental programs**
 - **Initial results have been impressive (may be too impressive) with record fields generated in HTS coils**
 - **They showed us the potential of the ReBCO high field technology to solve a critical technology challenge for MAP (30 -50 T solenoid)**
- **This should be considered a noteworthy achievement of the SBIR program**

Background (2)

- **Recently we had some surprises**
 - **Murphy strikes (finally) and we get setbacks**
 - **Some pancakes got degraded/damaged during 77 K tests**
 - **This was surprising because**
 - We had tested all of these coils before (some multiple times) and they were OK. We also thought we had established a good test procedures
 - If not for the nature of R&D with new conductor, one would be more prepared to get negative results during high field 4 K tests (not at 77K)
- **With technology potential demonstrated under SBIR programs, the next phase of development now continues with direct funding from MAP**
 - This includes moving forward to understand and overcome above setback (significant portion of this presentation is on that)
 - This also includes more support for engineering, analysis and related R&D

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

Ic vs T



Field on axis:
➤ over 15 T

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

**Real demo of ReBCO (2G)
HTS to create high field**

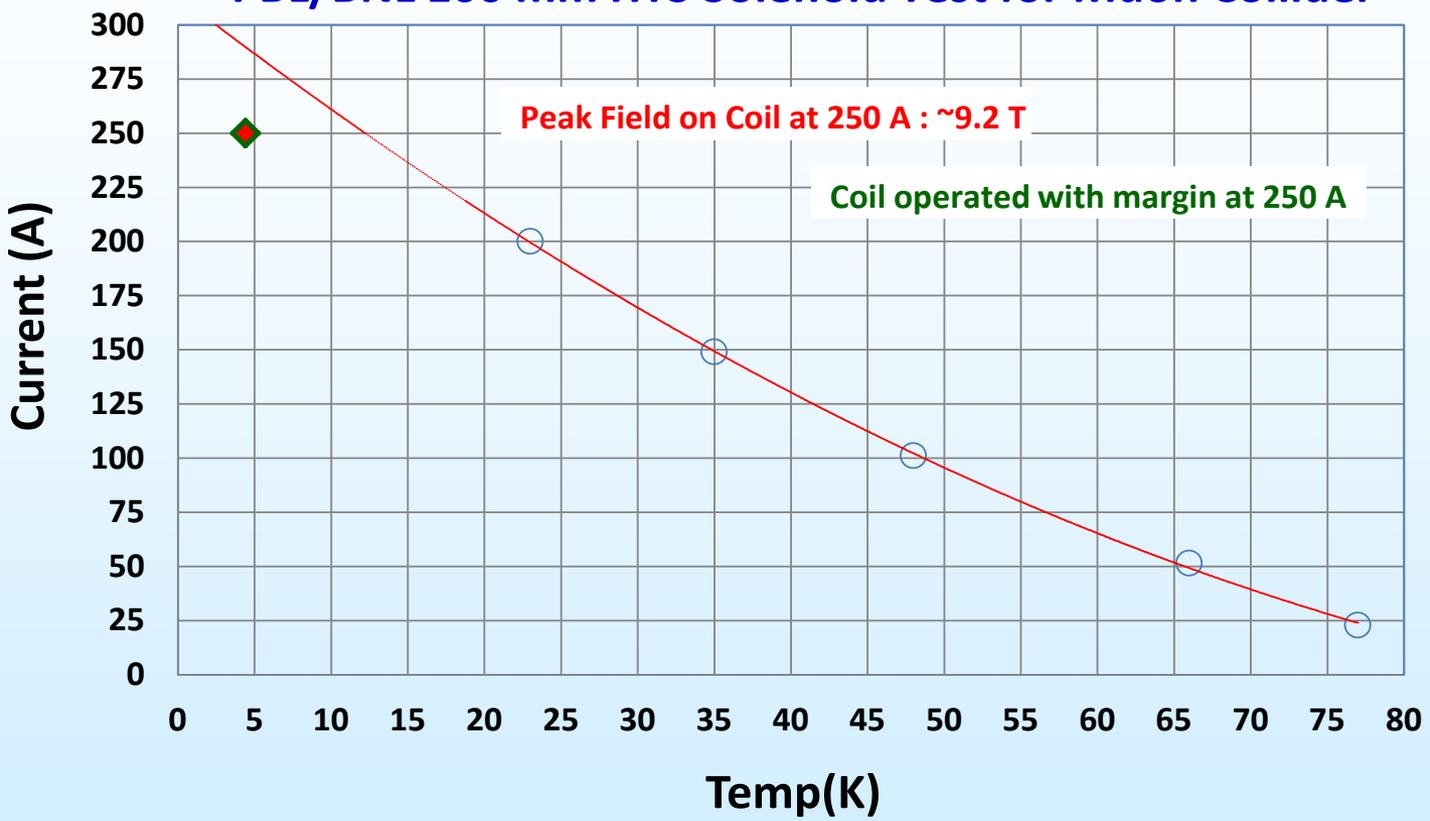
Highest field in an all HTS
solenoid (previous best
SP/NHMFL ~10.4 T)

Overall J_0 in coil:
>500 A/mm² 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



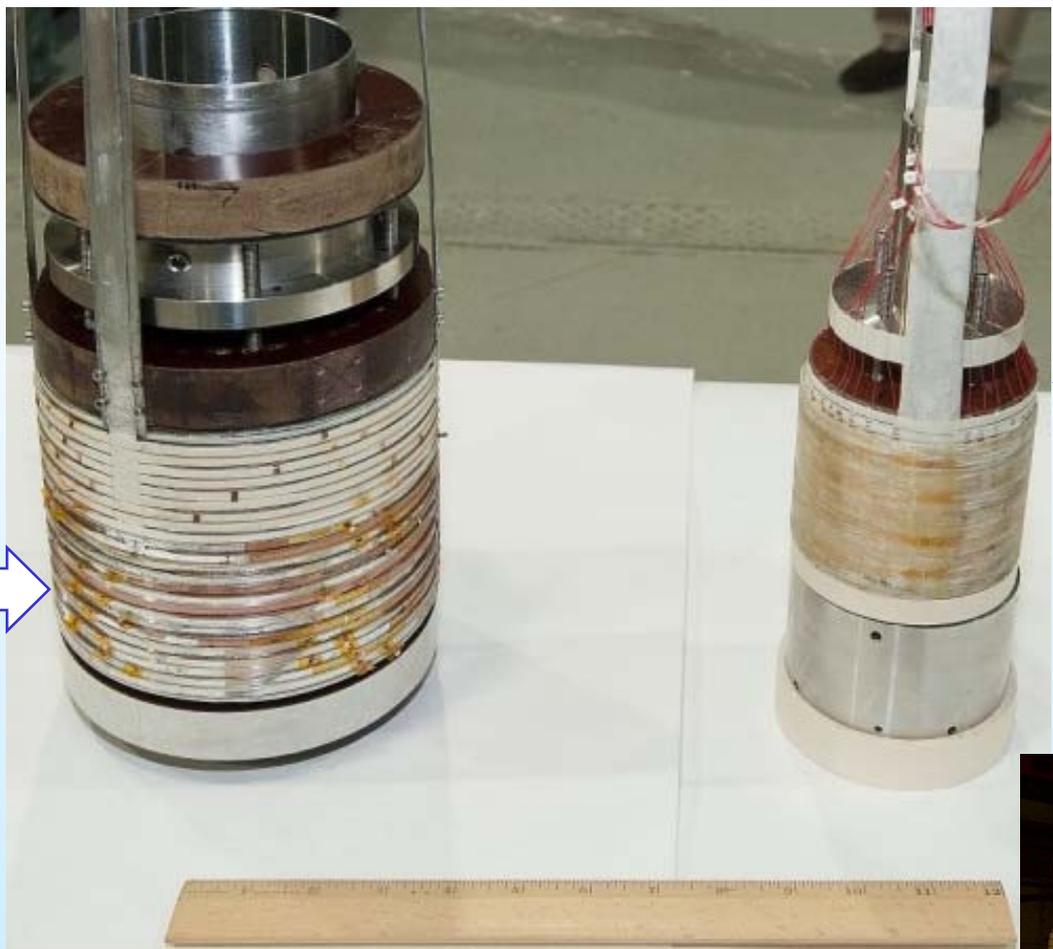
250 A ==>
6.4 T on axis
9.2 T peak
field on coil



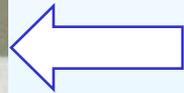
Coil could have reached above 10 T peak (original target), but was not ramped up to protect electronics of that time. Full solenoid with 24 pancakes should create >10 T on axis.

Fully Constructed (insert + midsert) HTS Solenoid for 20+ T Test

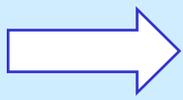
10+ T, 100 mm
HTS solenoid
(midsert) with 24
pancakes (each
pancake made
with 100 m HTS)



15+ T, 25 mm HTS
solenoid (insert)
with 14 pancakes
(each pancake
made with 50 m
HTS)



100 mm HTS solenoids –
half length (12 pancakes) and full length (24 pancakes)



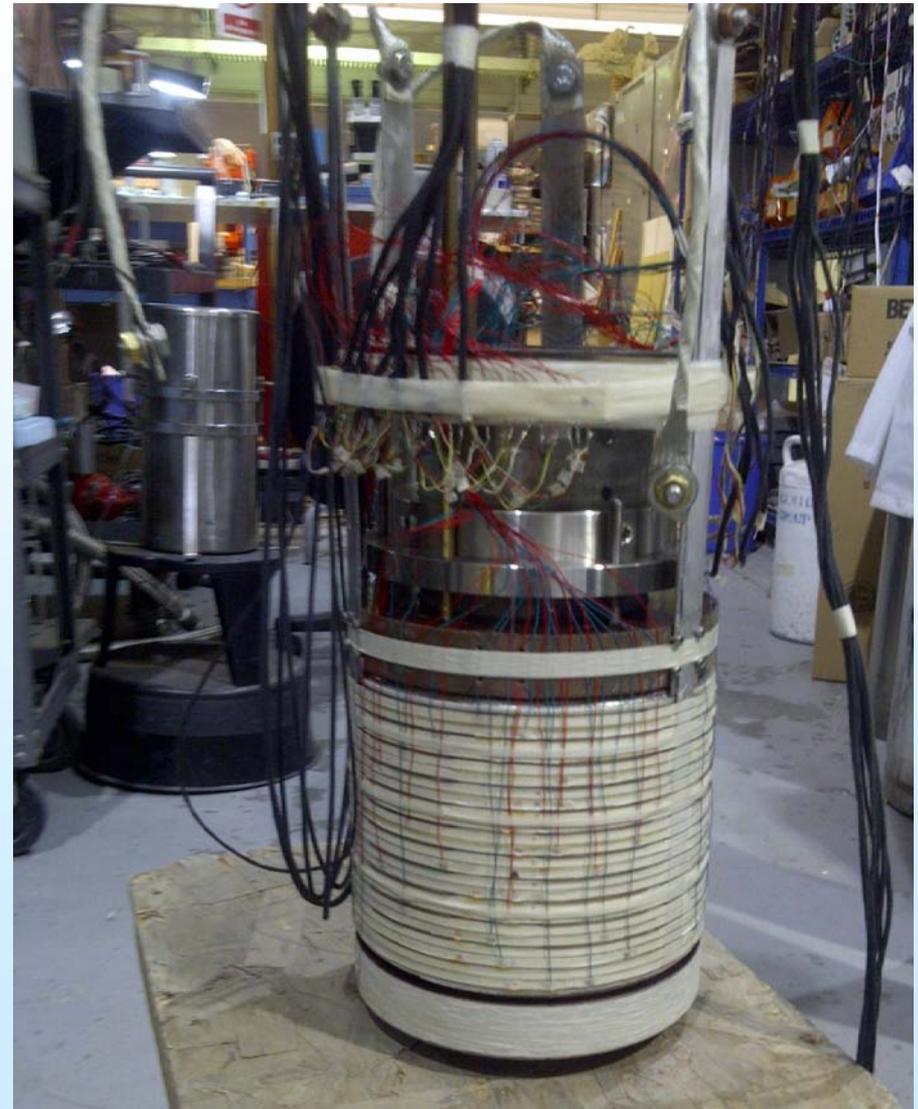
77 K Test Results

PBL/BNL Midsert Solenoid

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

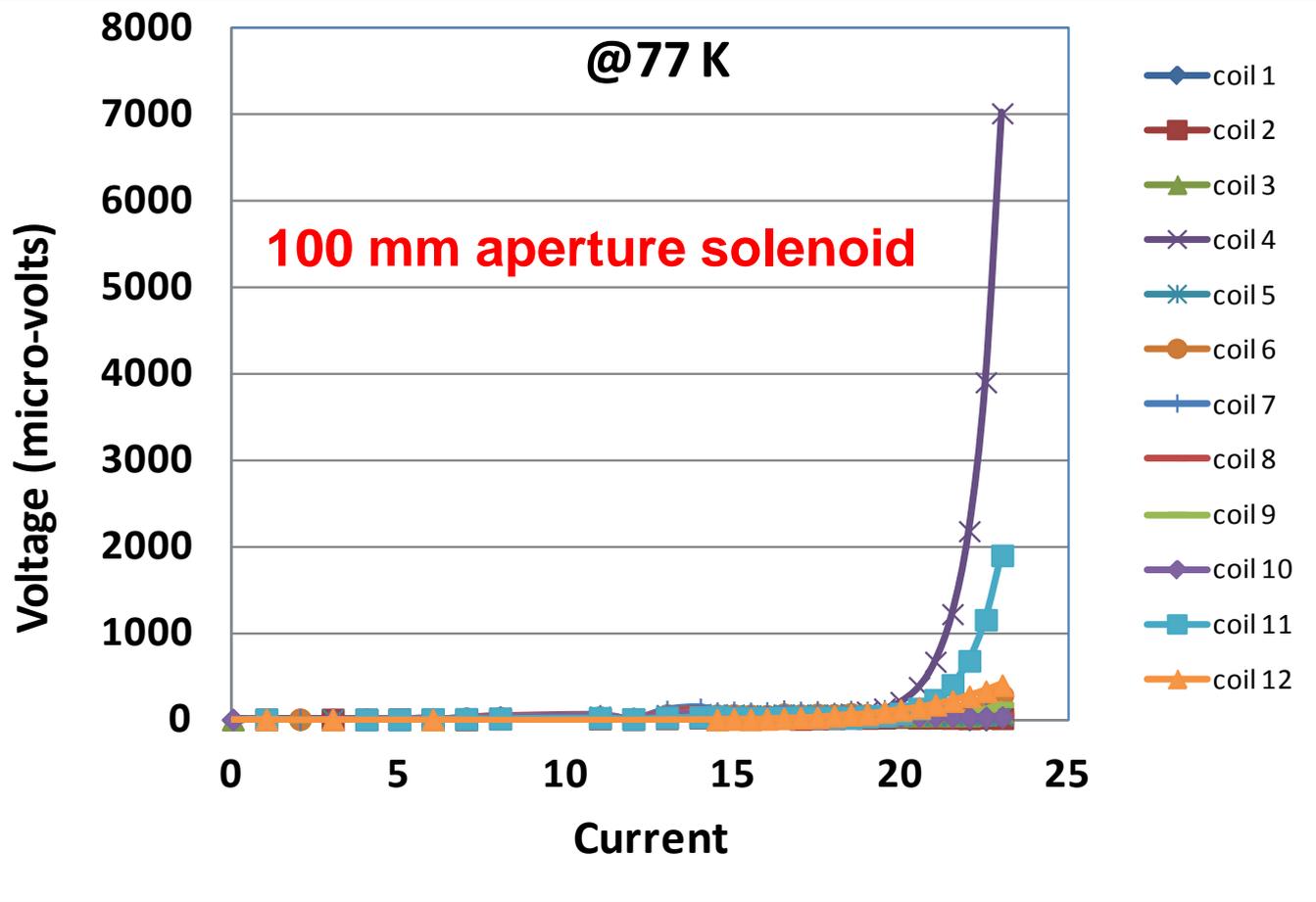


- Picture on left (half solenoid with 12 pancakes, previously tested at 4 K)
 - Picture on right (full solenoid with 24 pancakes, recently tested at 77 K)
- Picture taken in December 2012



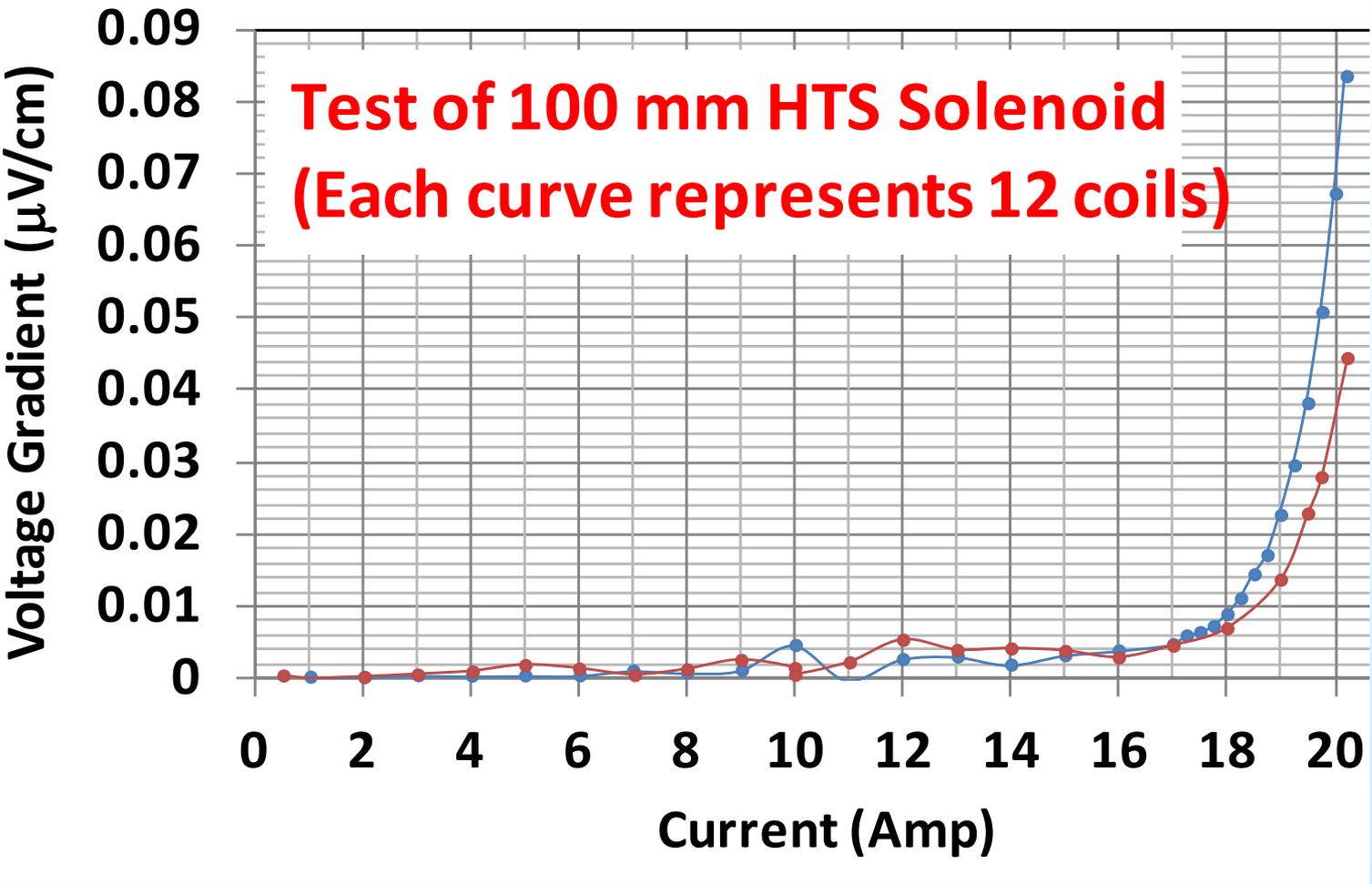
Earlier 77 K Test of Half Midsert (half midsert contains 12 pancakes)

These tests were performed well over a year ago



- Each pancake uses 100 m of HTS tape.
- All pancakes are powered in series
- 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)



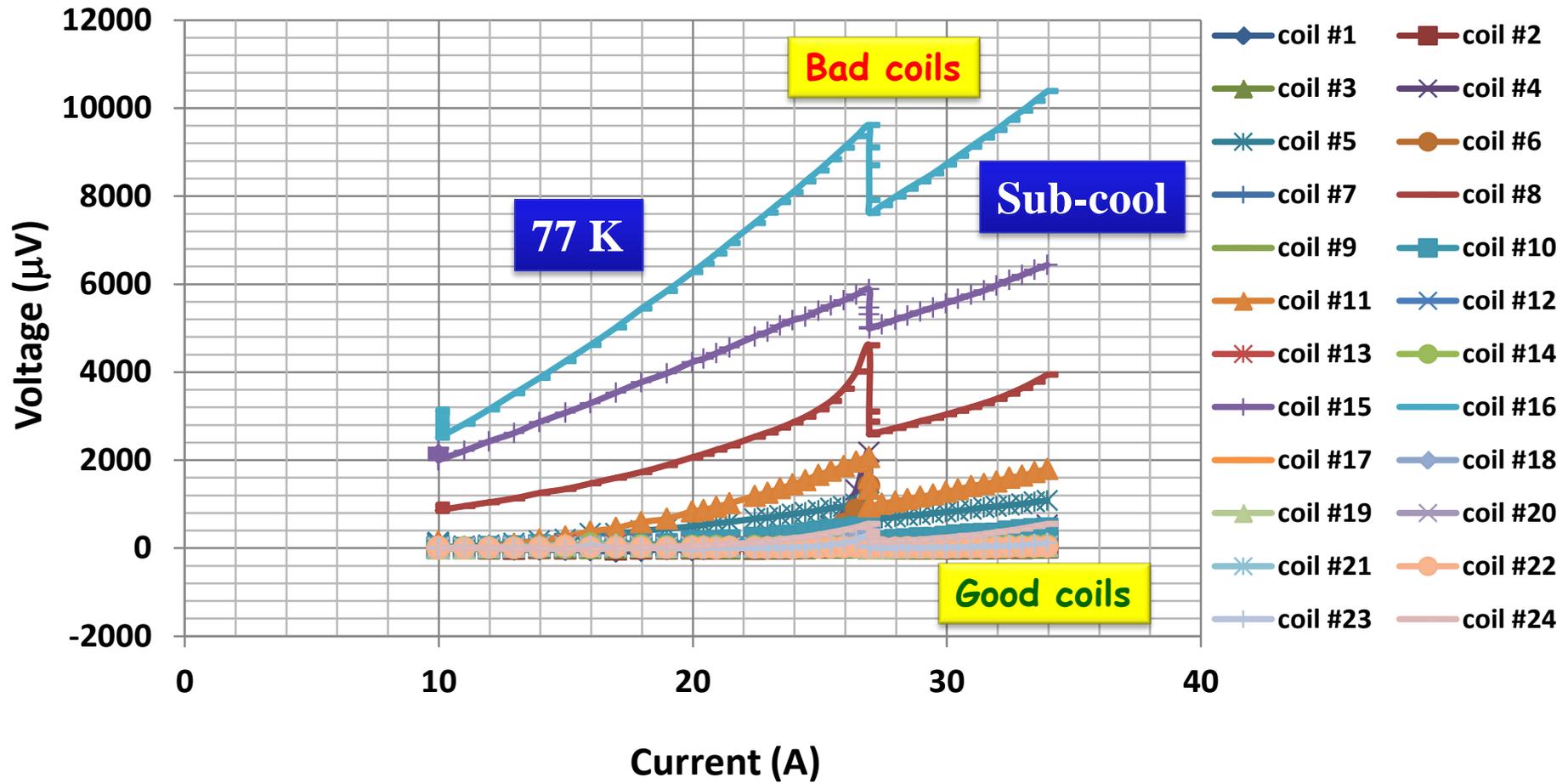
Tests performed in Nov. 2012

- All pancakes are powered in series. Critical current of 24 pancake system: ~20 A for 0.1 µV/cm criterion. It was ~21 A for 12.

Surprise/Setback During the 77 K Test of 100 mm Coil made with 24 Pancakes

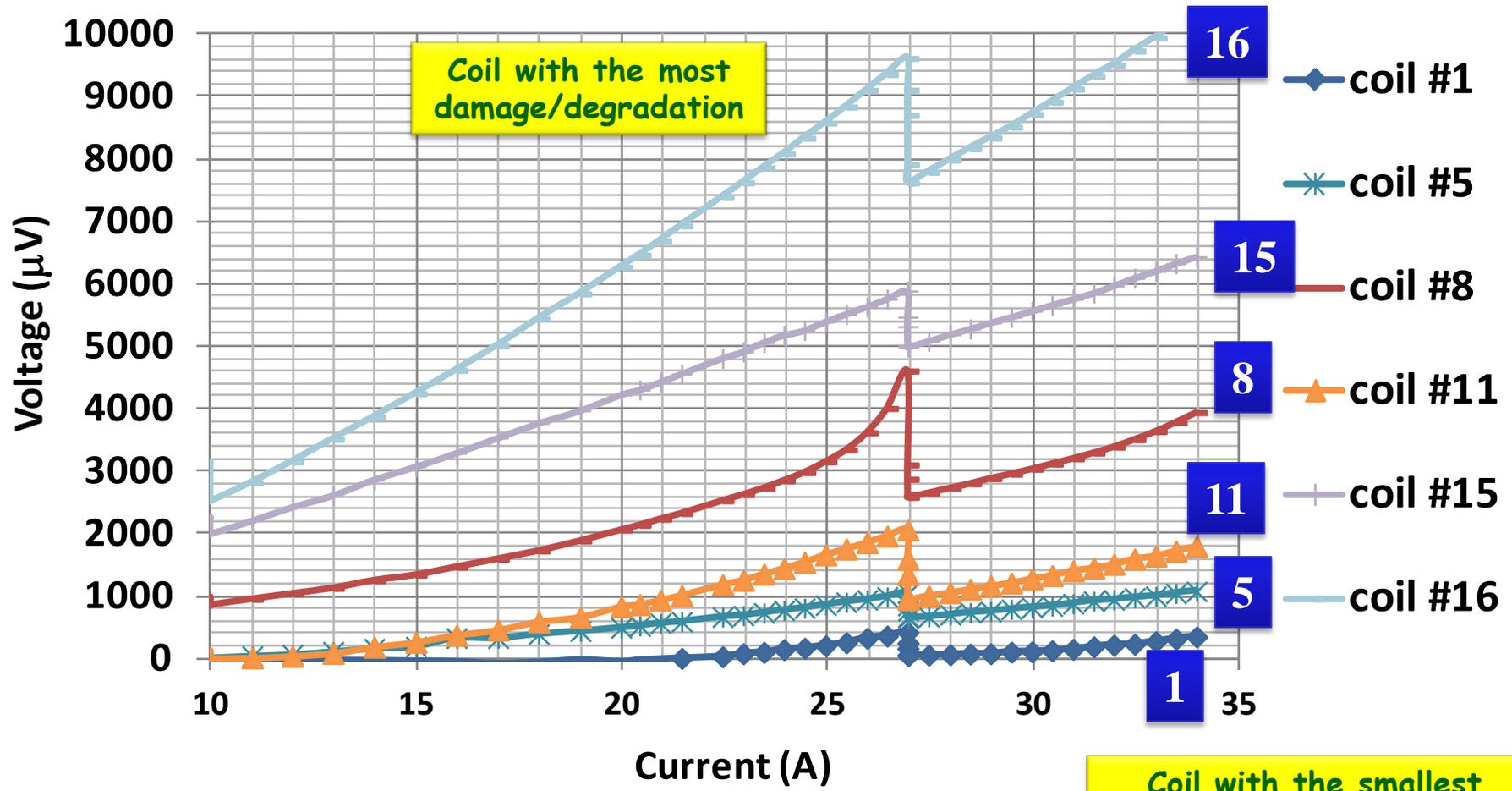
- During the final 77 K QA test before the scheduled high field 4K run, several pancakes started showing early onset of resistive voltages.
- The same assembly has been earlier tested at 77 K and performed well.
- Setback despite the fact that the cool-down was the slowest and the most controlled ever to minimize the thermal strain. Furthermore, copper discs were used between the pancakes to provide uniform cooling
- Only significant work on the coil
 - subject to repeated 77 K tests for debugging quench protection system
 - a few layers of wet fiberglass epoxy support over the individual coil
- No particular order in the location of these (now) underperforming pancakes
- **Several 77 K follow-on tests found no further deterioration in performance**

77 K and sub-cool tests of 100 mm pancakes (powered in series)



Note: Several coils show early on-set of resistive voltages (next slide – location of bad coils)

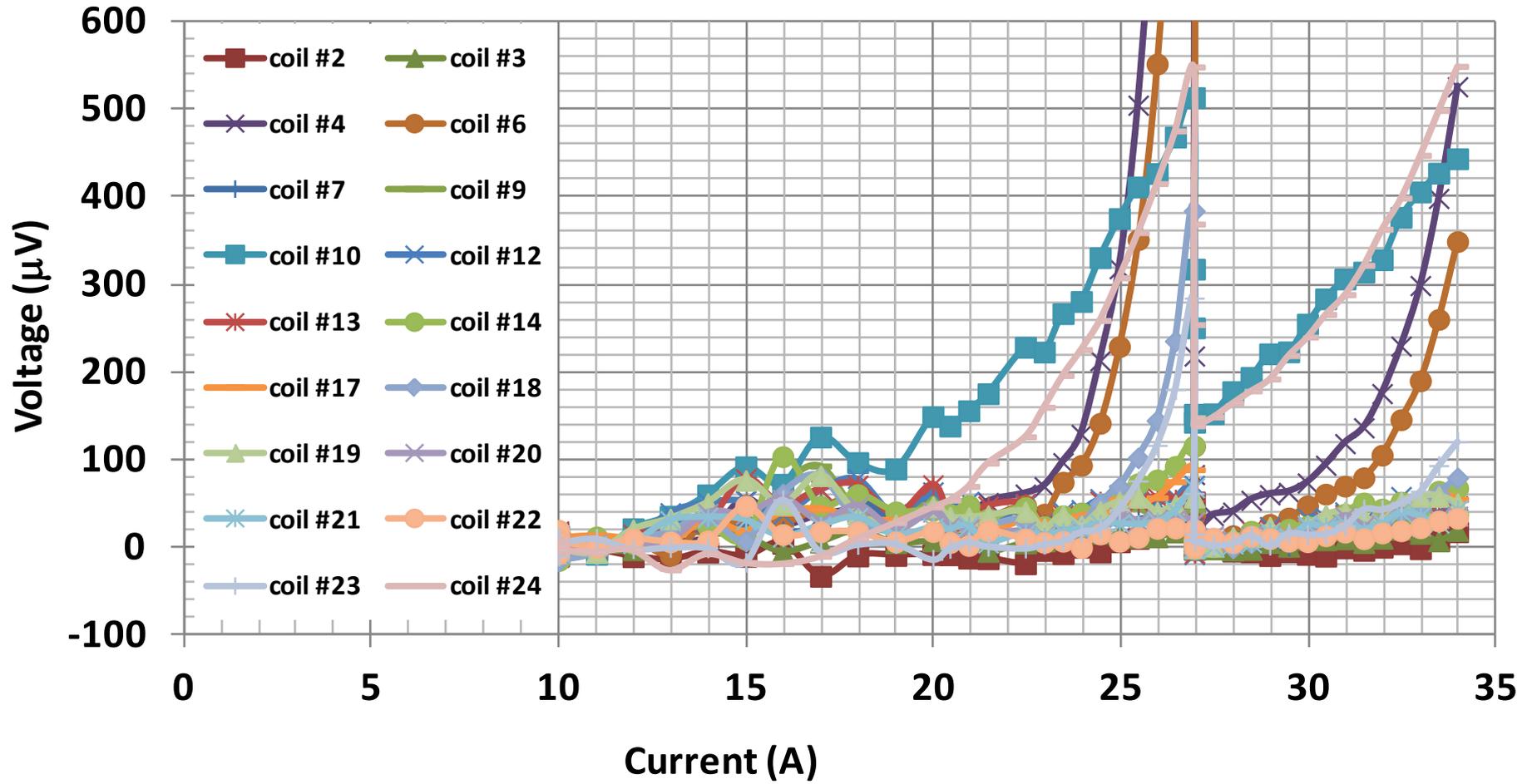
Coils of Concern (6 out of 24) (Varying degree of concern)



Coil with the most damage/degradation

Coil with the smallest noticeable degradation

**Good (or almost good) Coils
(18 of 24)**



Moving Forward

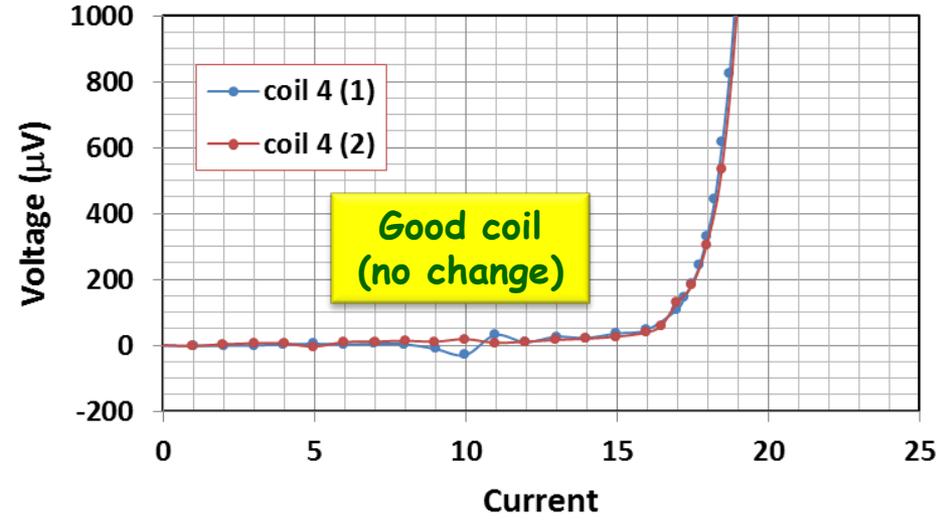
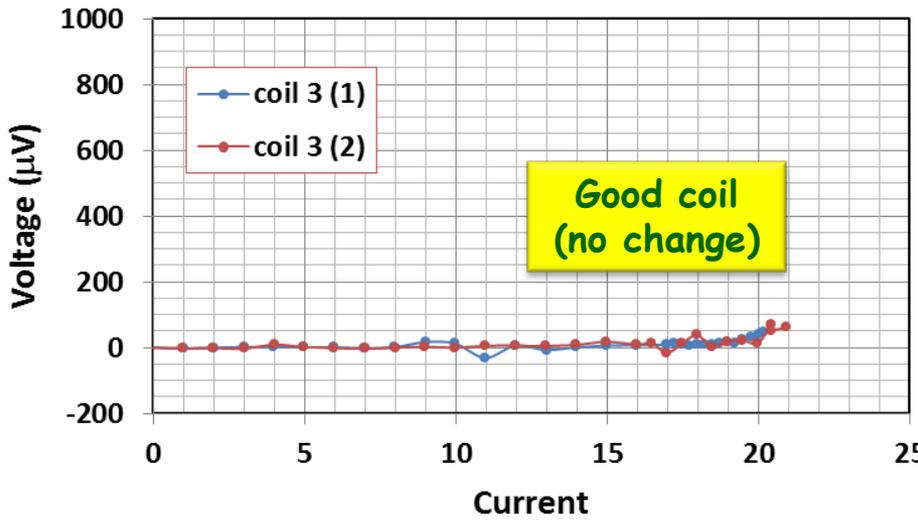
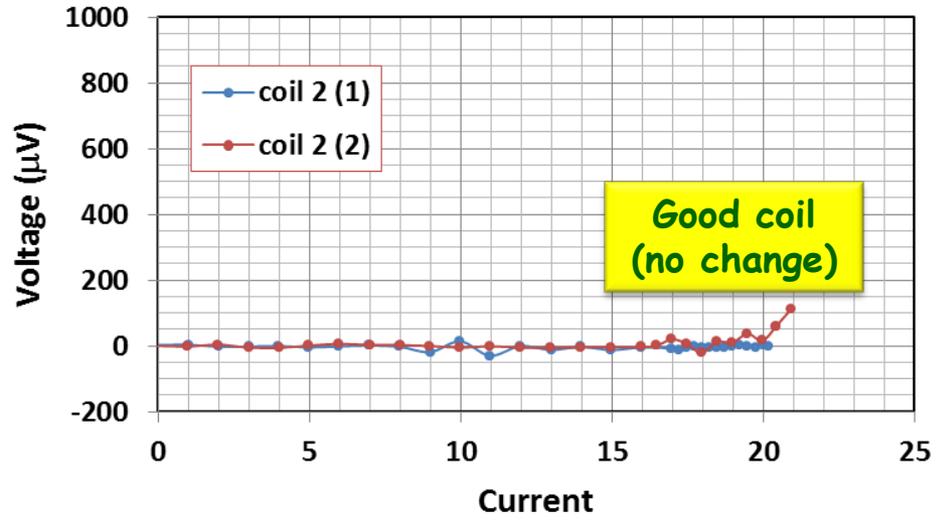
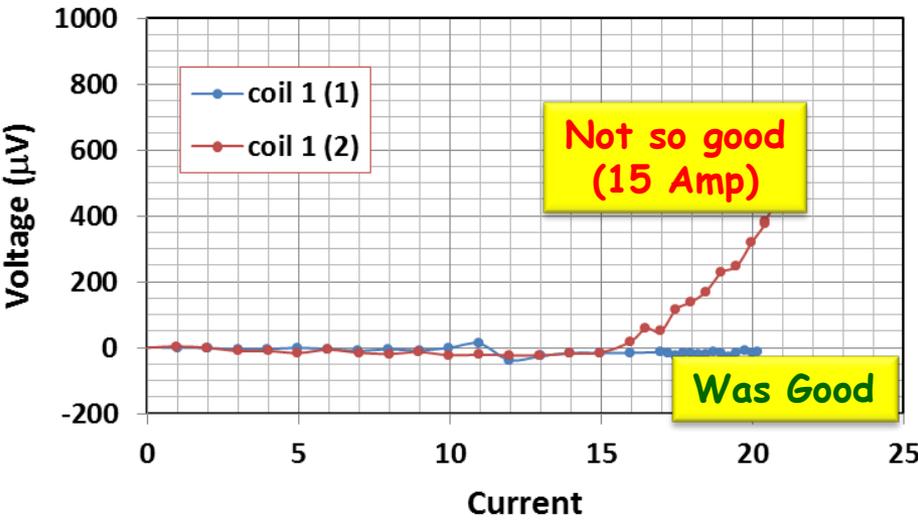
- **Determine the extent of damage and locate the problem area**
 - Several pancakes (at least 6 of 24) clearly show a degraded performance by a varying amount
 - Essentially all internal splices (between two pancakes) show a large increase in joint resistance
- **Can we make a repair and move forward?**
 - There is a significant investment both in terms of time (several years) and conductor (2.4 km). Therefore, there is a strong incentive for repairing
 - **Splices can be repaired. But how about the pancake coils?**
- **Identify the possible cause(s) and way to avoid them in future**

Detailed Study of Individual Coils

- Take solenoid apart to critically examine each of twenty four pancakes
- when they are tested in series bad coils limits a critical examination of coils which are not so bad as one can't push current so high
 - compare performance before and after the incident

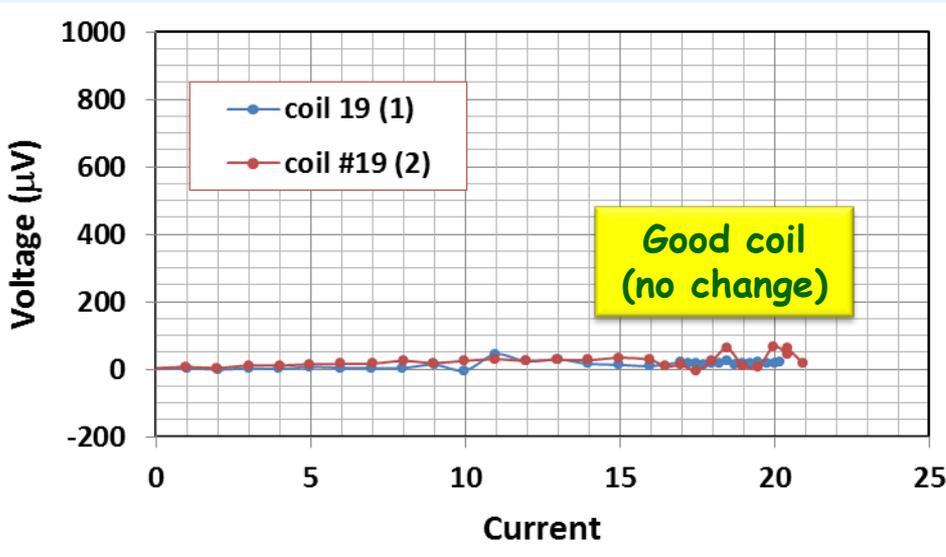
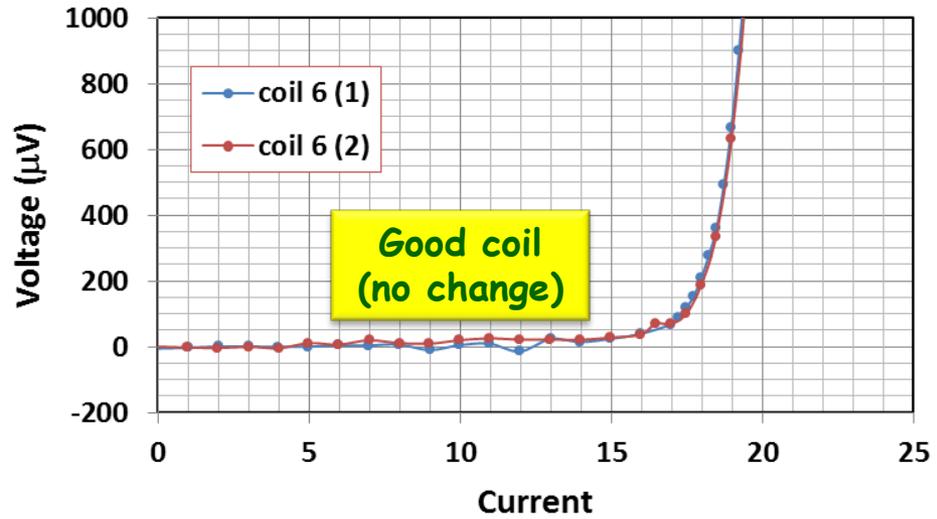
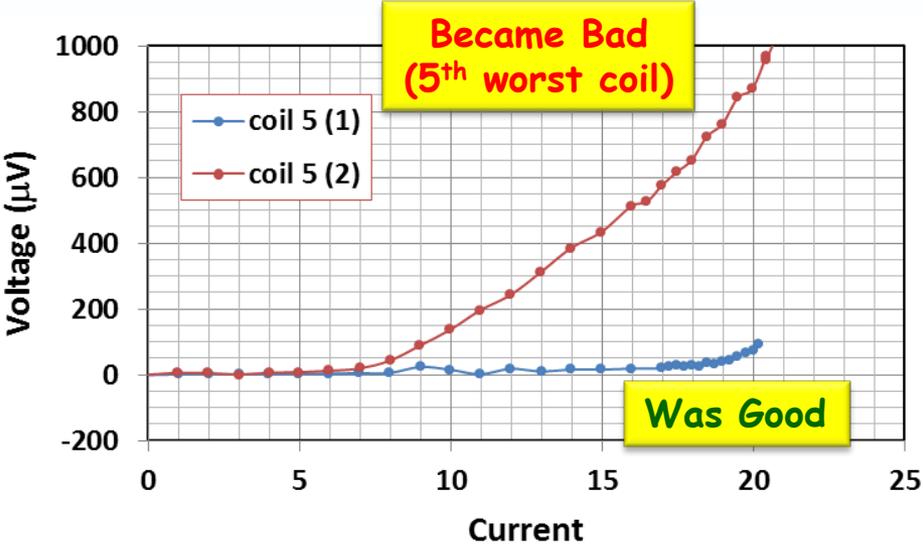
The goal is to determine how many can be used (either as is or after repair)

**Before (1) and After (2) cooldown
(1 mV is 0.1 $\mu\text{V}/\text{cm}$ for 100 meter)**



Coil #2, #3 and #4 seem OK. Coil #1 has changed. Is it useable?

**Before (1) and After (2) cooldown
(1 mV is 0.1 $\mu\text{V}/\text{cm}$ for 100 meter)**

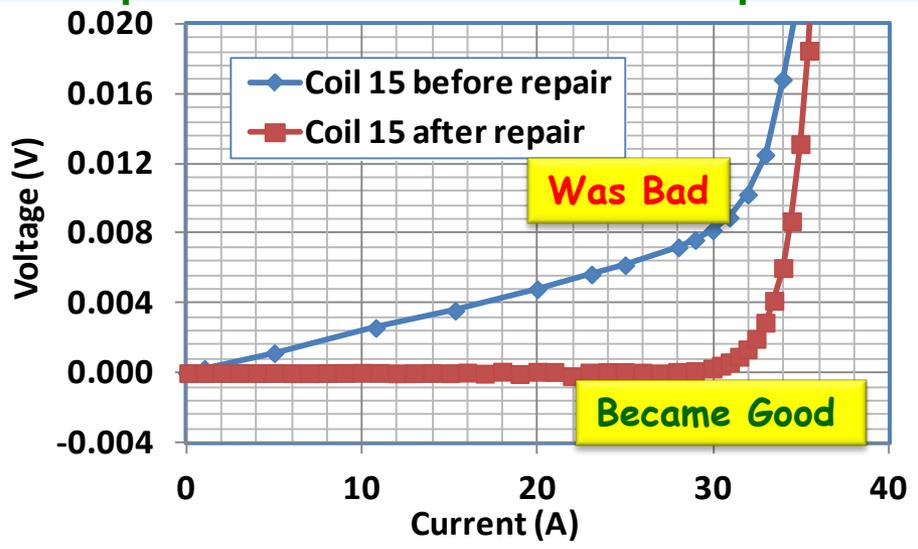


- Coil #5 was good initially but became bad after cooldown.
- Coil #6 and coil #19 are OK.
- Similar analysis on other coils were also performed.
- Only the worst (#15 and #16) will be discussed (next few slides).

Repairing of the Coils

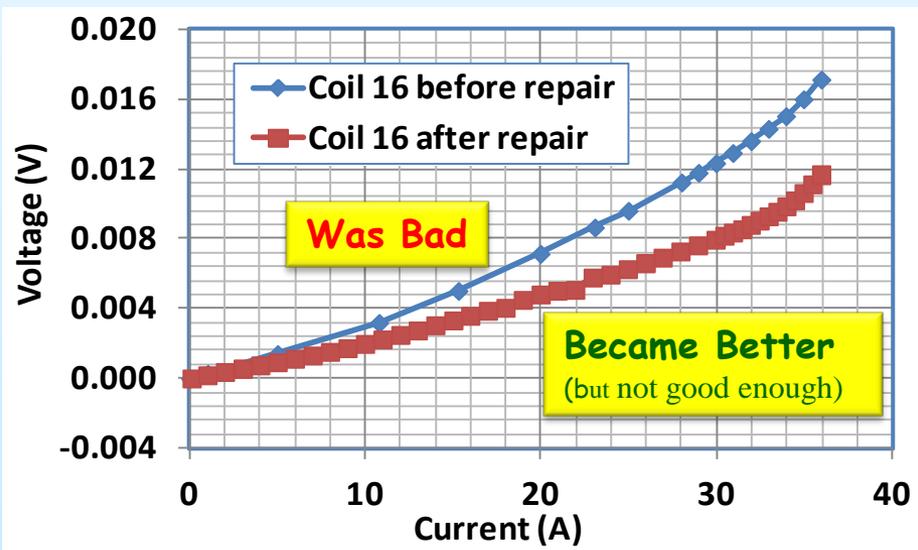
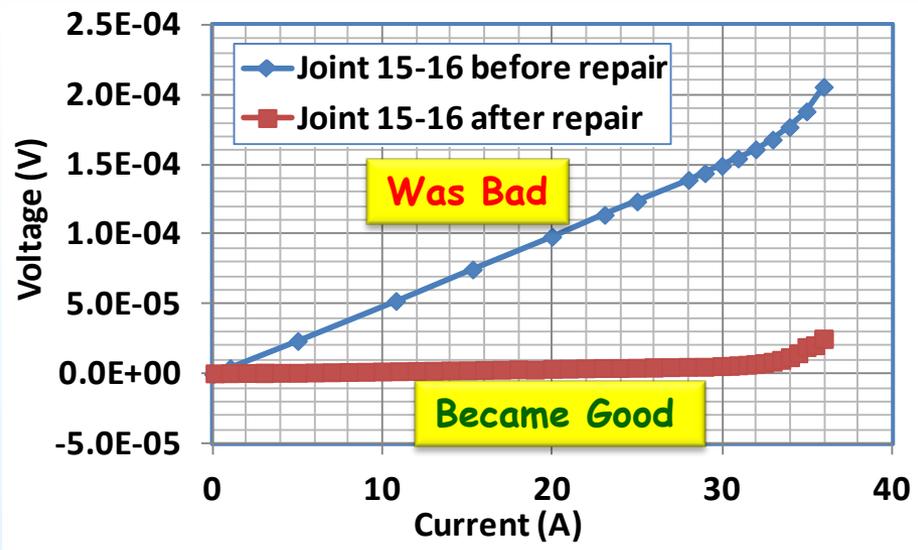
Start with coil #15 (the worst pair).

- Splice joint is replaced with a new type of diagonal joint (used in another program)
- First turn is removed from each pancake
- Coil performance is measured and compared it with that before the repair



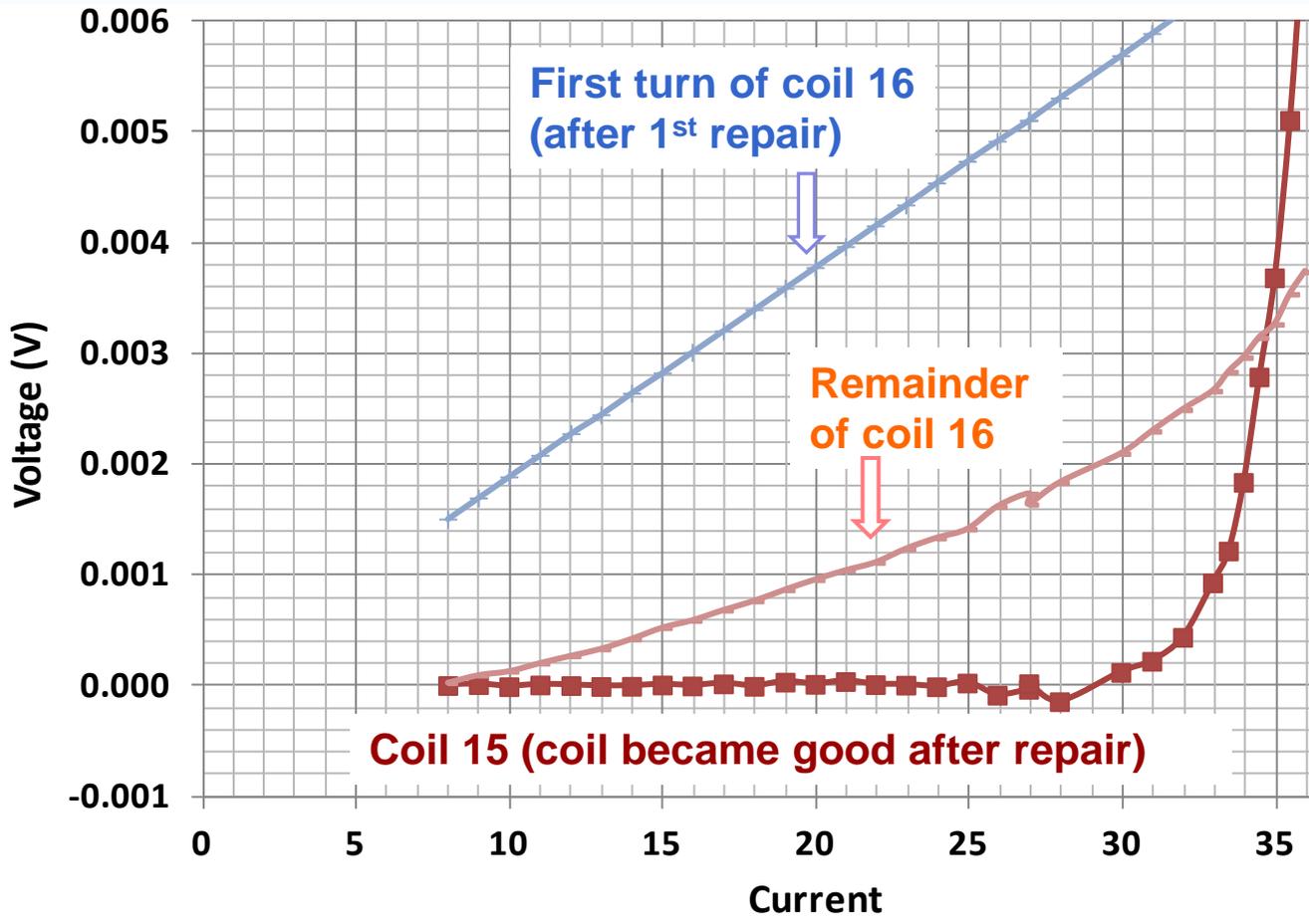
• Outcome: Splice joint and coil #15 got fully repaired. However, coil #16, though got better, but did not get fully repaired.

• Remove one more turn? Now being done.



Inside turn of Partially Repaired Coil #16 (measured separately @77 K)

Since a v-tap can be put on inside turn easily, we decided to do a 77 K measurement to see if there is a defect there before taking this turn out.

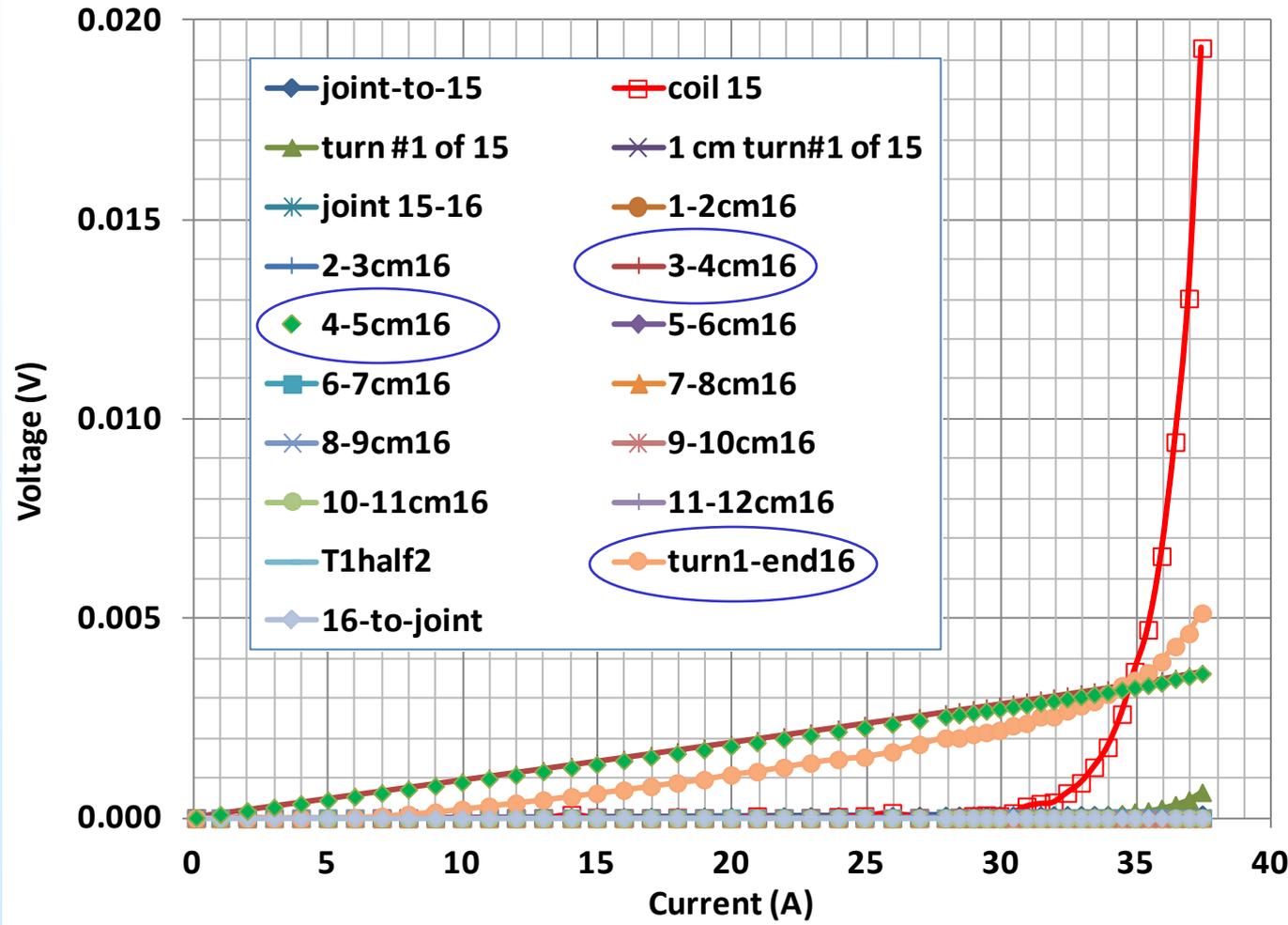


- It appears that removing one turn is not sufficient and we may need to remove more.

- Where exactly is the defect in first turn and how wide/long is the defect?

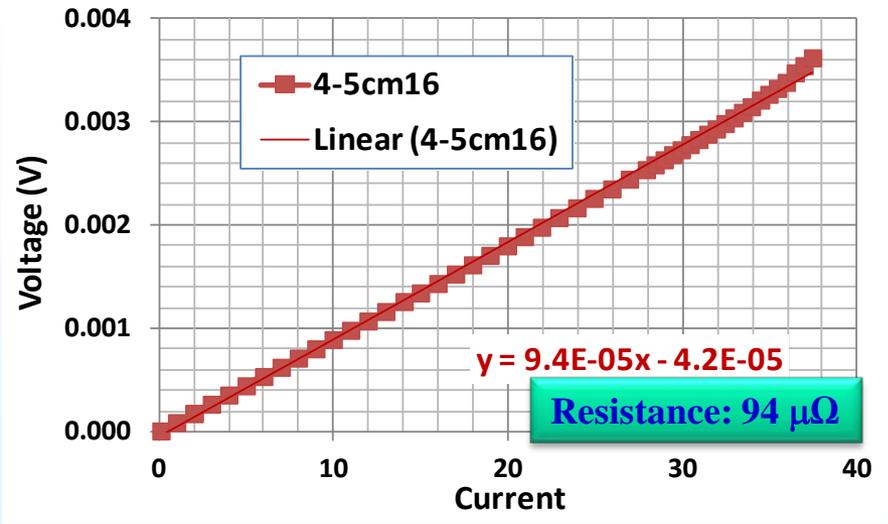
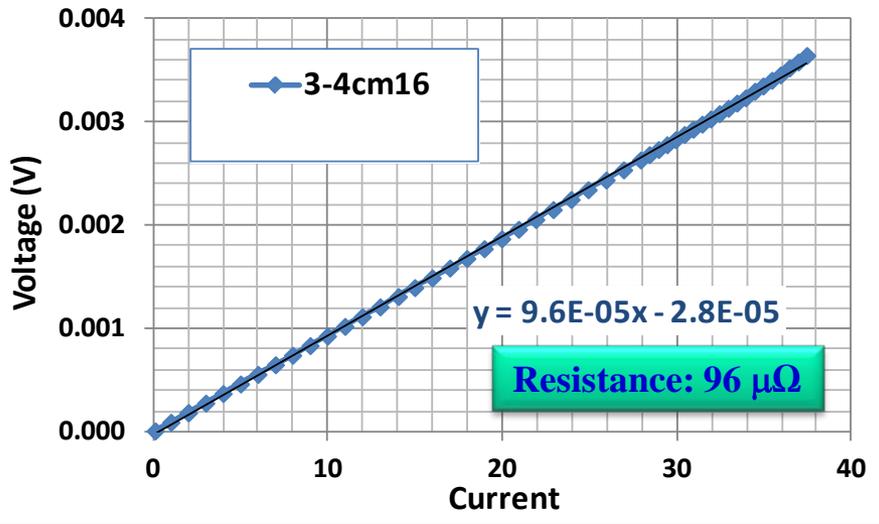
- Do another run with v-taps placed in small (1 cm) interval.

Detailed Analysis of Coil #16 (several v-taps in 1 cm interval)

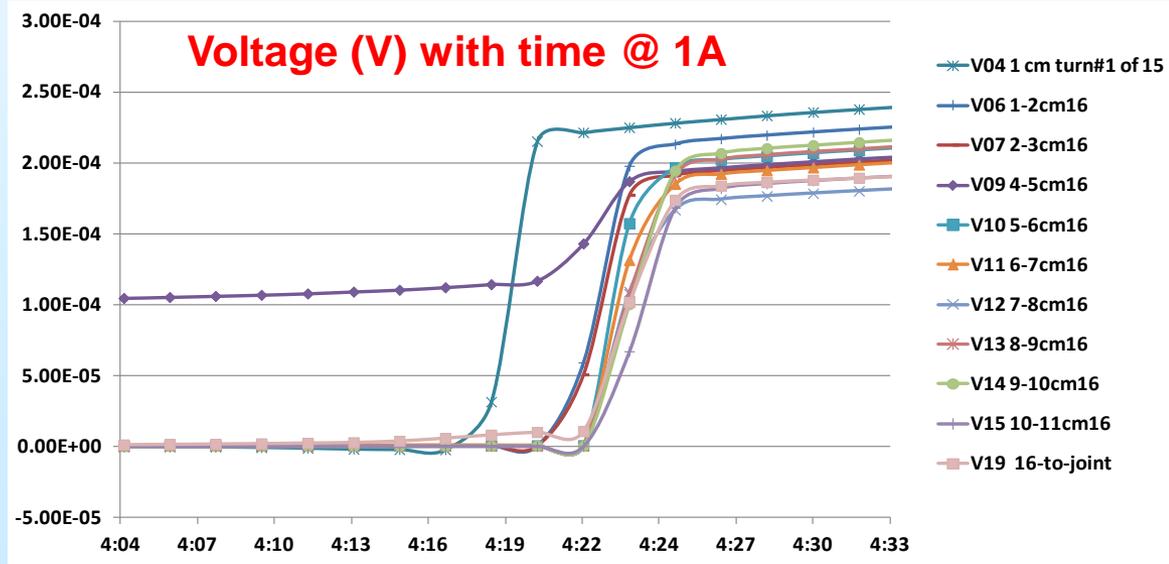


- It seems that the defects in first turn are in the regions 3-4 cm and in 4-5 cm (it could also be one defect spanning in two regions)
- Onset of resistive voltage from ~0 A itself means that there is a total break in current path across the conductor width.

Identification of Defect(s) in Coil 16



- To determine the size of the defect, one needs to know non-sc resistance of the wire (when cold).
- To obtain this, we pass 1 A and let it warm to non-sc state.
- Measured voltage across ~1 cm sections is 0.02 mV (20 μ V/mm).
- Therefore, resistance: 20 $\mu\Omega$ /mm.
- Thus we have two ~4.7 mm long defects or one 9.5 mm long defect.



Status of the Repair

- One more turn of coil #16 has been removed
- Visual inspection of the turn removed shows some delimitation of copper that was electro-plated (likely cause of the problem)
- The double pancake with coil #15 and #16 will be assembled and tested

- One turn of all other 22 pancake coils have also been removed.
- They have been spliced together in 11 double-pancakes with new splice joint

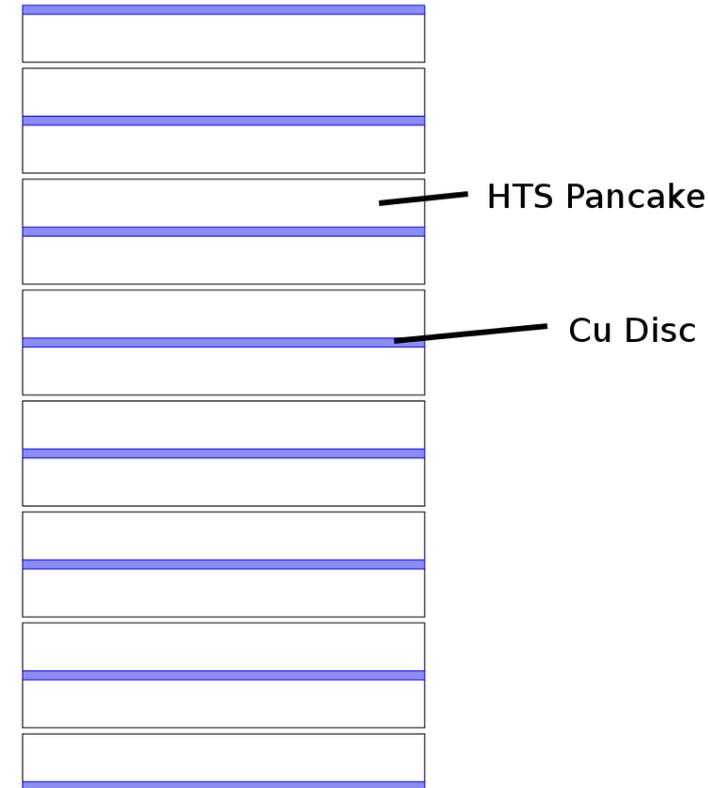
- All of these will be re-tested to pass 77 K QA test
- It is possible some pancakes may require removal of one more turn (coil #15 and #16 were the worst though)
- It is also possible that some coils can't be repaired by removing a couple of turns. In that case, those coils would be removed and the solenoid would have a fewer than 24 coils. We should still be able to achieve the target field.

Updated Design and Test Procedure

- Provide better cooling to reduce thermal gradient
- Use extended copper discs and expose them to better cooling
- Computer modeling and experiments to provide better guidance
- Much slower cooling to reduce thermal gradient
 - Pre-cool with helium gas
- A more controlled test procedure

Copper Discs to Minimize Thermal Strain During Cool Down

- Excessive thermal strain during cooldown may damage HTS coils
- We use copper discs between the double pancakes to provide a more uniform cooling across the coil windings



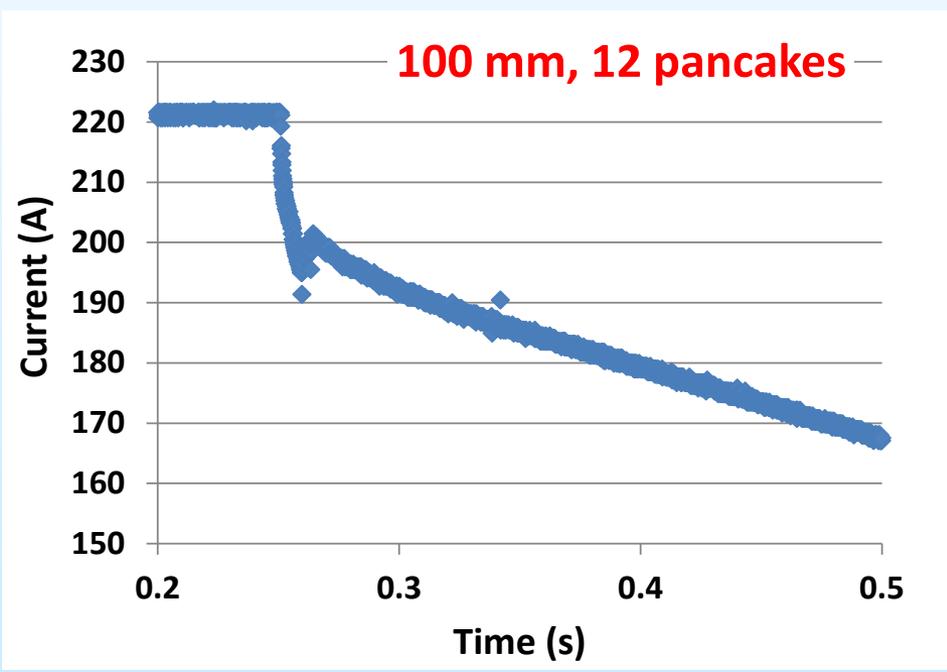
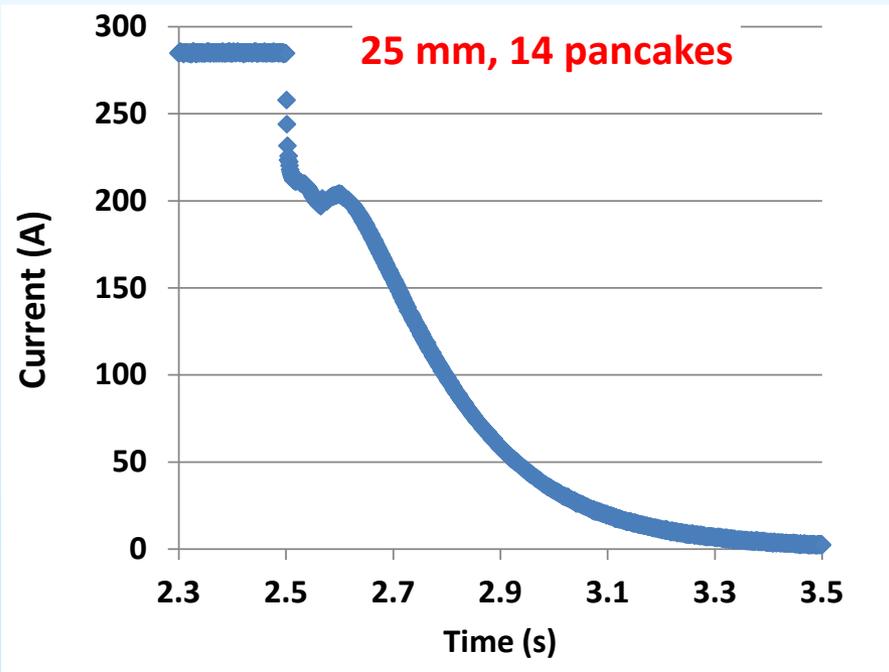
Schematic: Holger Witte

Next few slides: Another significant benefit of using copper discs.
It was not reported earlier due to possible patent and relationship to other programs.

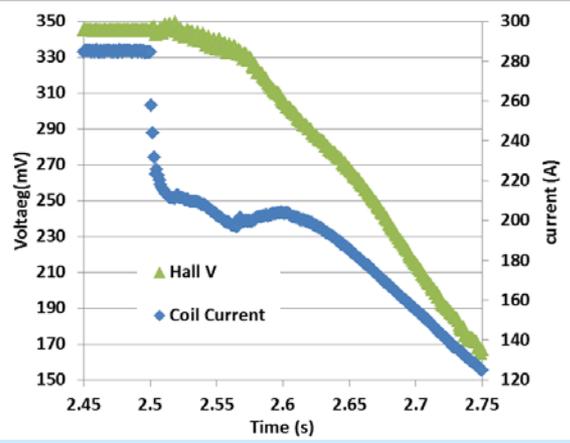
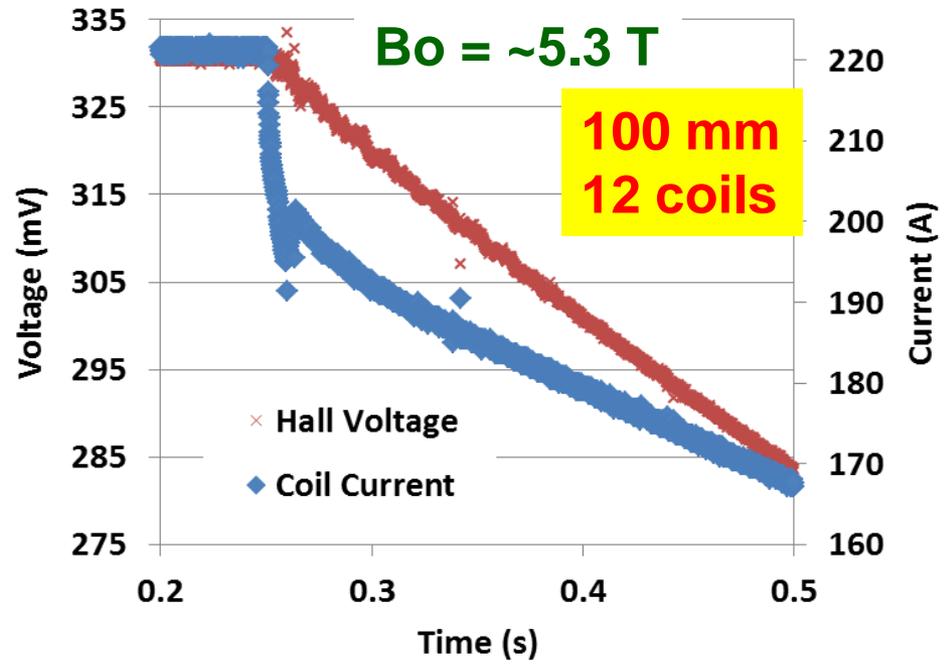
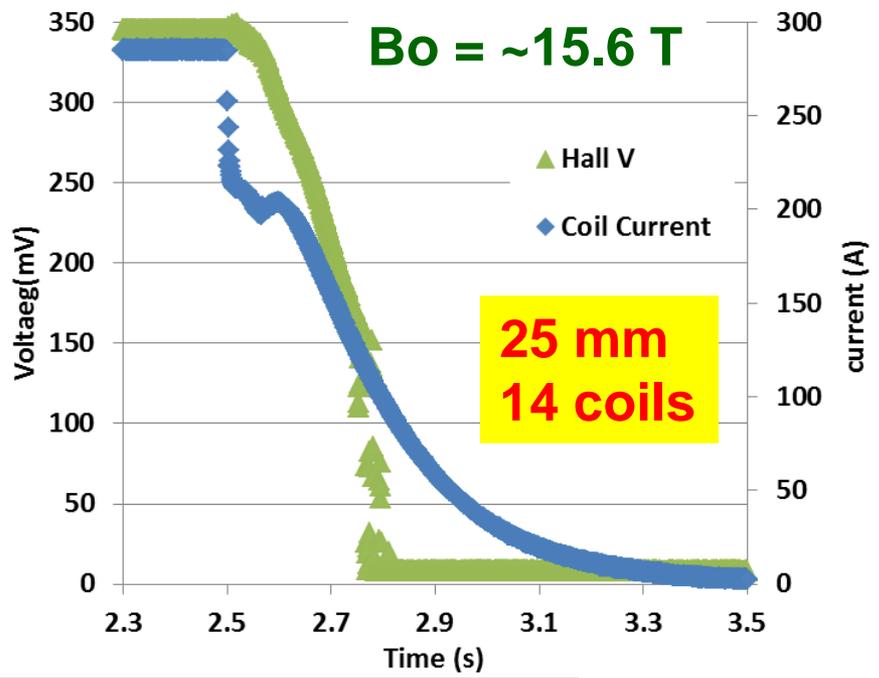
Another Surprise
(one that is being put to good use)

During the quench protection, we observed a sharp initial drop in coil current as soon as the energy extraction started on external dump resistor.

This was observed both in 25 mm and in 100 mm solenoids.

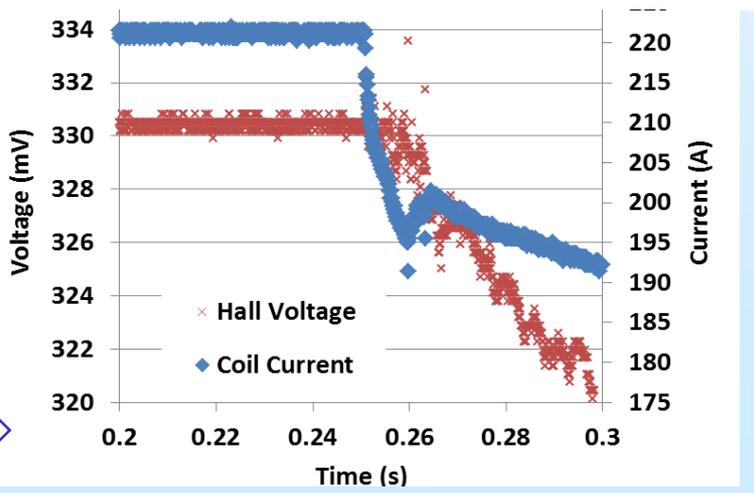


Sharp Drop in Current (but not such sharp drop in field)



Expanded scale
(time)

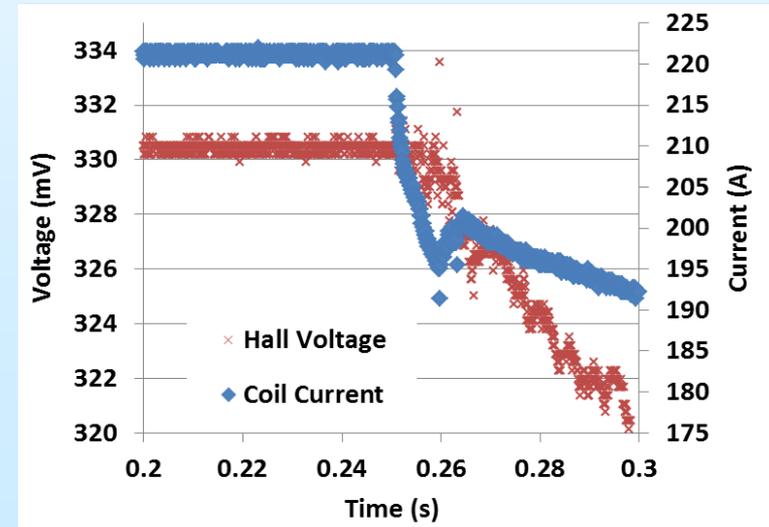
← →



Possible Sources of Sharp Drop in Current

The following sources were initially attributed to the possible sharp drop in current in coil:

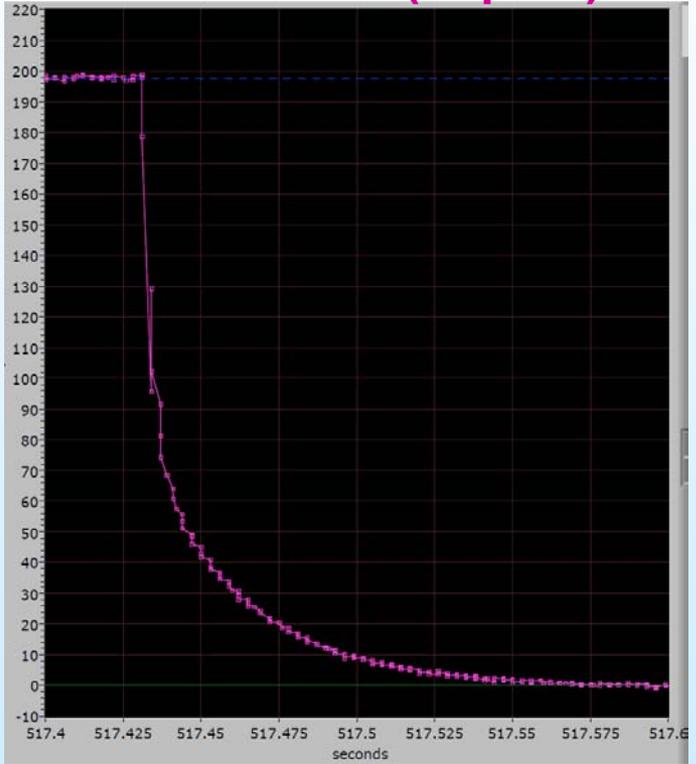
- Instrument malfunction
- Current transfer to the stainless steel tape (co-wound with HTS tape)
- Current transfer to copper discs



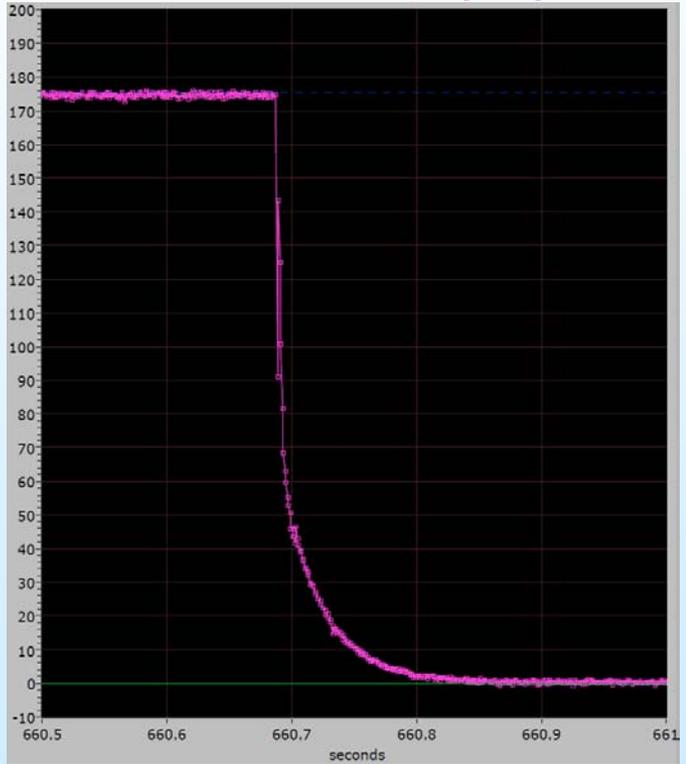
Decay of Current and Field in PBL/BNL Coils for HTS co-wound with SS and Kapton Tape

Discharge of coils made with Kapton and Stainless Steel insulation in 20 T background at NHMFL (total field ~22 T)

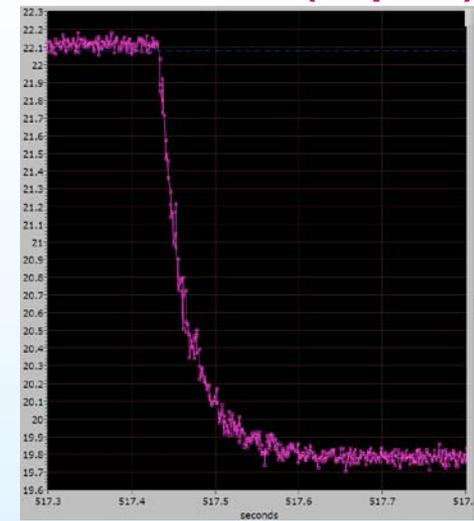
Current vs Time (Kapton)



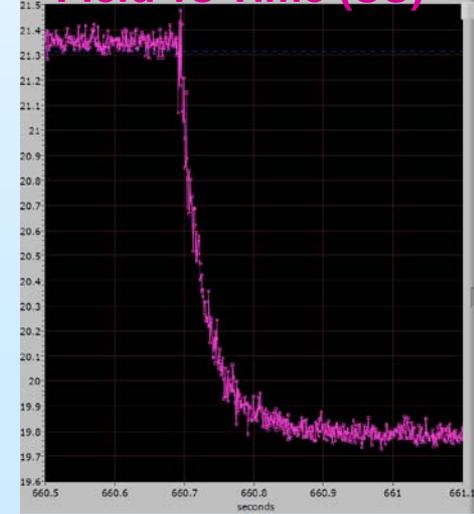
Current vs Time (SS)



Field vs Time (Kapton)



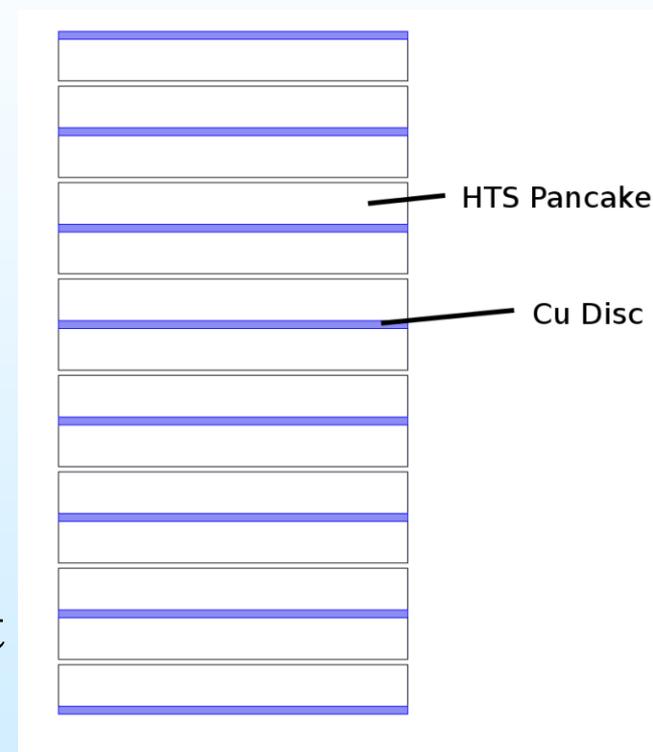
Field vs Time (SS)



Decays after shut-off are similar in both cases (SS and Kapton). Therefore, stainless steel tape can't be responsible for this.

Confirmation with Simulation

- **Initial simulation by Bob Weggel (PBL) showed that inductive transfer of current from HTS coils to copper discs could produce such a behavior.**
- **Since then Holger Witte has done more detailed FEM simulation. That explains the behavior more quantitatively (abstract submitted to MT23).**



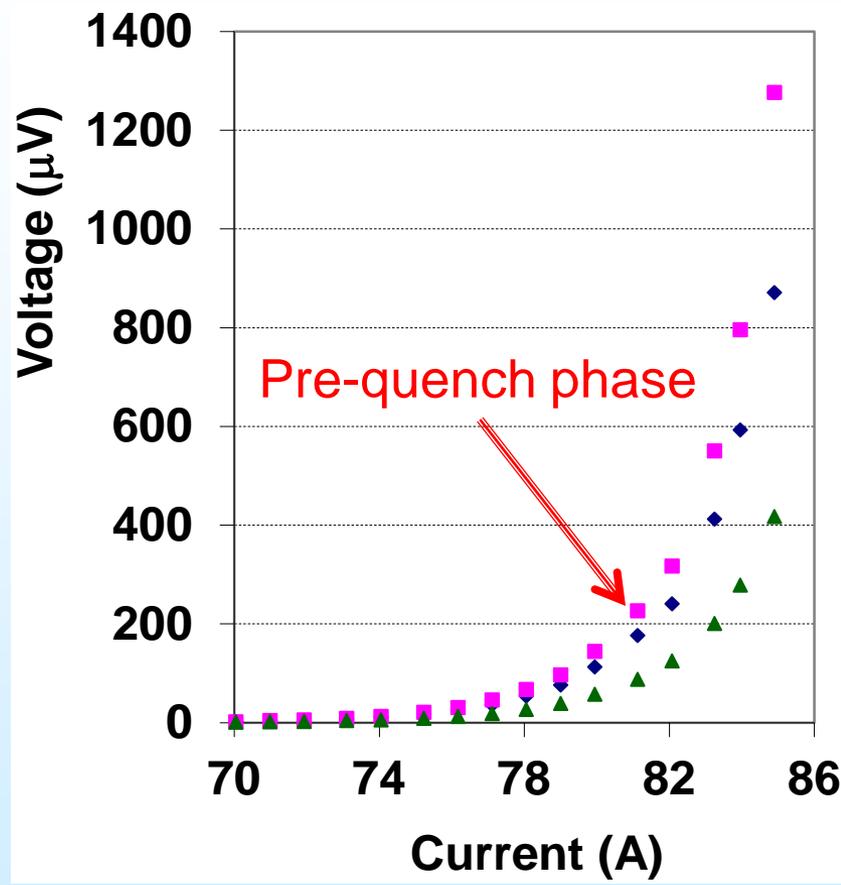
Role of Copper Discs in Quench Protection

- It was quickly realized that such a rapid reduction of current could be used to our advantage in protecting HTS coils
 - energy from the coil is instantaneously extracted
 - One quickly goes below the danger value of current in coil and that may allow coil to operate safely a bit longer
 - Copper discs may help spreading the energy (heating)
- Copper discs now play a major role in quench protection of HTS coils in various programs at BNL

Quench Protection Strategies (continues)

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

- The electronics should be able to withstand high isolation voltage to allow rapid energy extraction ($t=L/R$; $V=I \cdot R$)
- We need many channels to monitor as many pancakes as possible individually (and rest combined in groups)

Cabinet #1 (32 channels, 1kV)

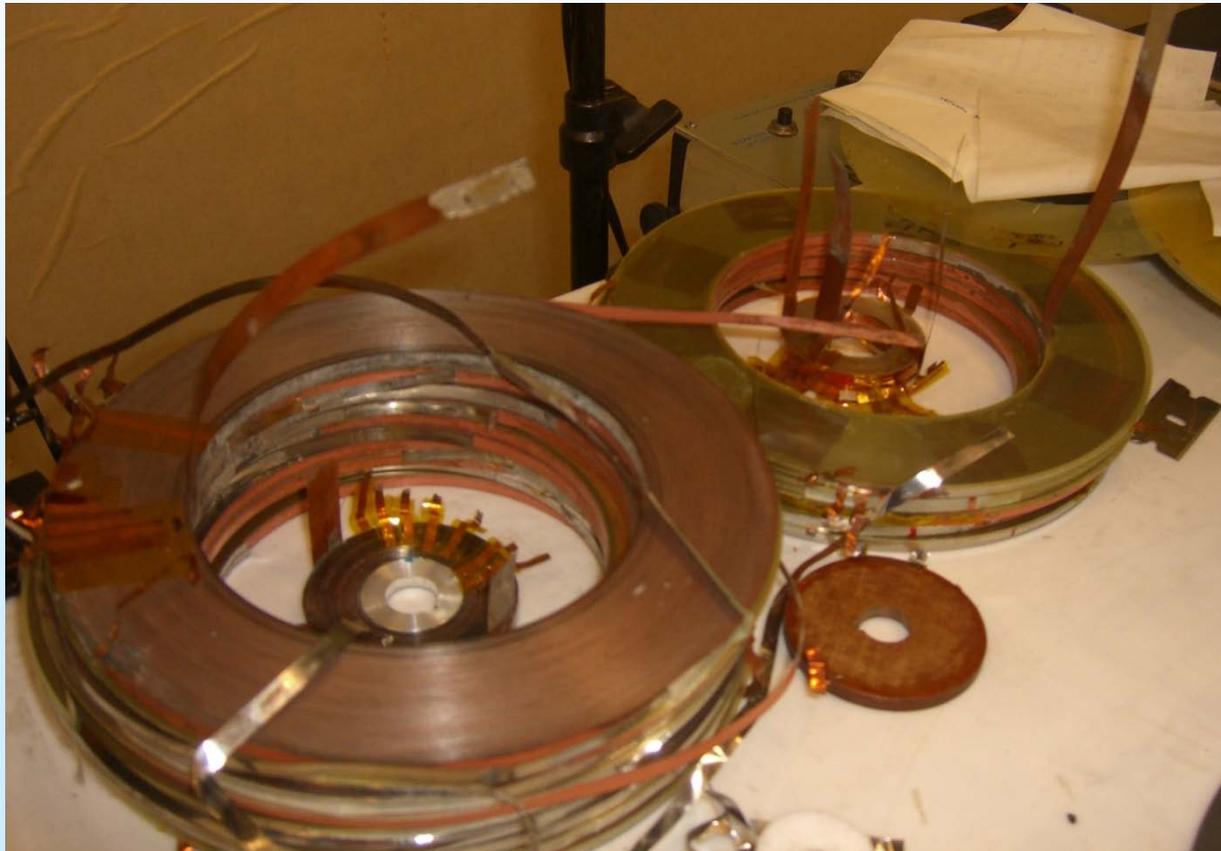


Cabinet #2 (32 channels, 1kV)
(expandable to 64 and 3kV)



Quench Studies in Small HTS Coils

- We want to learn more about quench propagation and quench protection.
- We want to examine what HTS coils can tolerate before getting degraded.
- We want to try different quench protection ideas in small coils.



Carryout various quench related studies in small single pancake, double pancake and bi-filar coils.

In these studies coils can be operated beyond the safe value (and possibly get destroyed) to find out what the limit is?

Conductor Performance Measurements

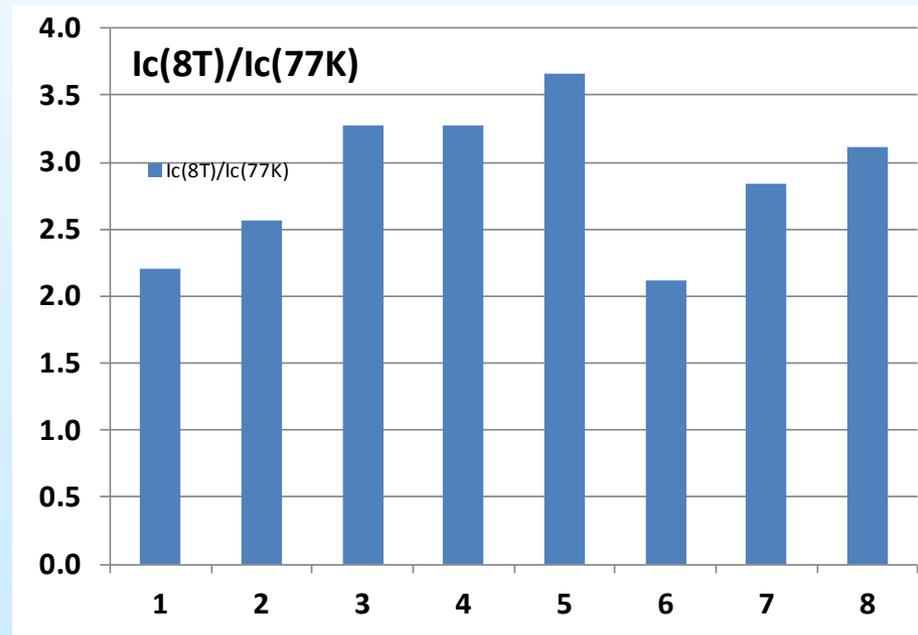
- HTS vendor typically measure performance at 77 K, self-field
- We find a large variation in scaling between 77 K and 4K, in field
- We need to monitor it and know this scaling for the conductor used in making magnet

For measuring performance in field parallel



- There are also some issues with the mechanical property of the conductor.
- This (and other similar studies) is part of R&D that needs to be carried out.

Measured field perpendicular scaling (Ghosh)



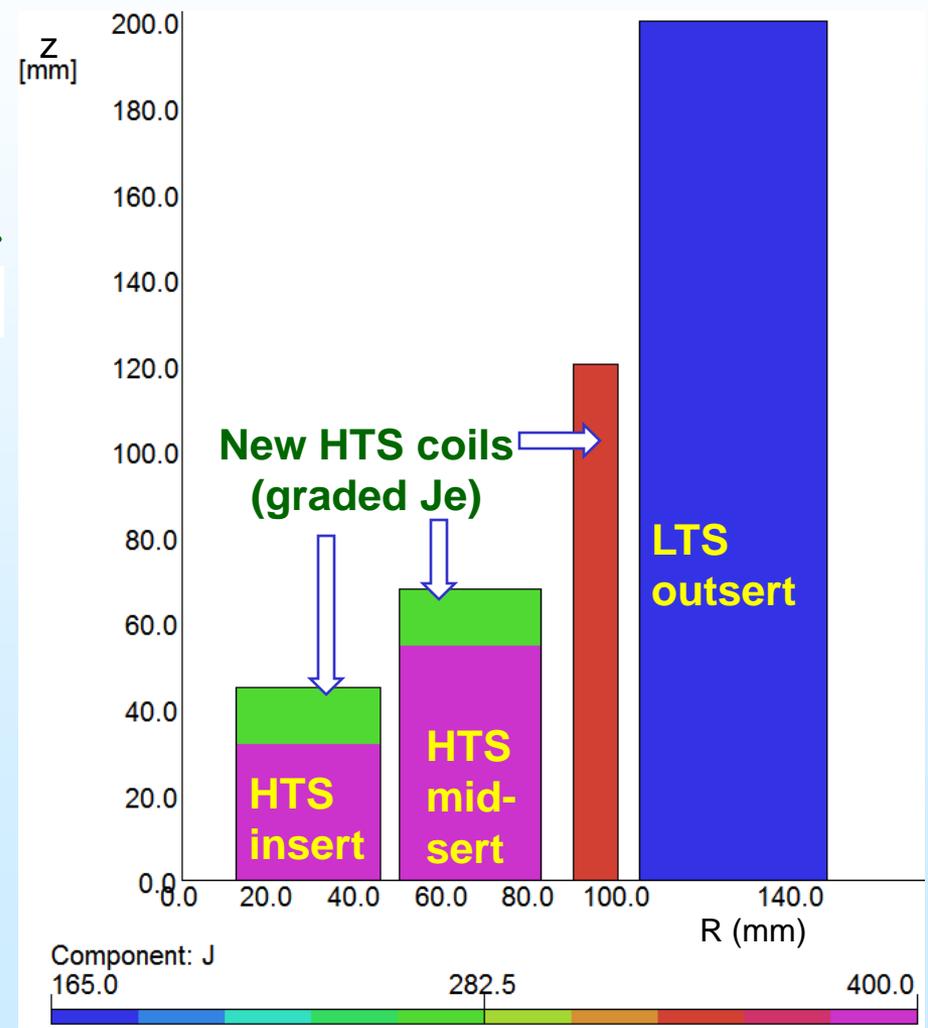
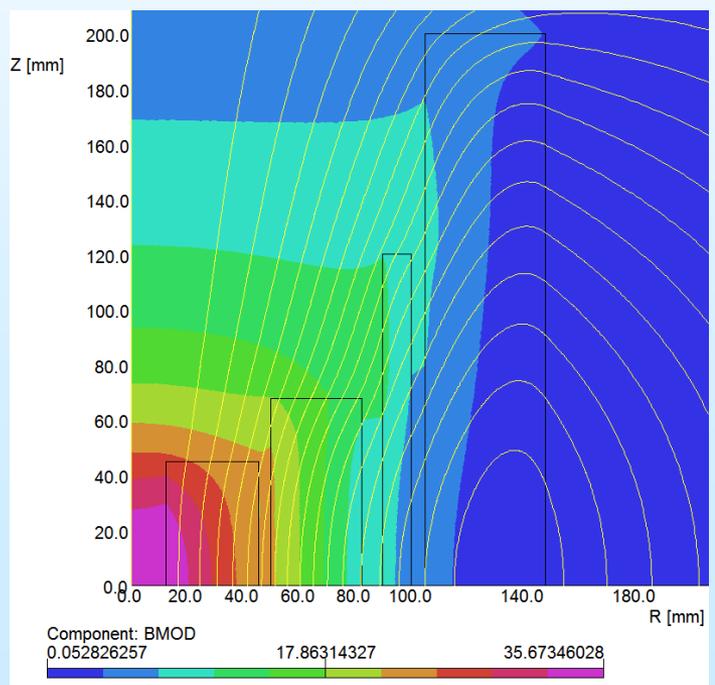
Proposed 35 T Design

Strategy: Leverage existing coils and parts as much as possible to reduce costs.

It is a highly leveraged program.

It is built upon the major progress and coils made with PBL/BNL SBIRs.

Construction of LTS outsert is also leveraged.



NbTi Solenoid based on Several Existing Components and Proven Design

Parameters	Value
Wire, bare	1.78 mm X 1.14 mm
Wire, insulated	1.91 mm X 1.27 mm
Wire I _c specification (4.2 K, 7 T)	>700 A
Turn-to-turn spacing (axial)	1.98 mm
Turn-to-turn spacing (radial)	1.42 mm
Number of layers (main coil)	22 (11 double layers)
Additional trim layers in ends	4 (2 double layer)
Length of additional trim layers	173 mm on each end
Coil inner diameter	200 mm
Coil outer diameter	274 mm
Coil length	2360 mm
Yoke length	2450 mm
Maximum design field	6 T
Current for 6 T	~440 A
Peak Field on the conductor @ 6 T	~6.5 T
Computed Short Sample @4.2 K	~7.0 T
Stored energy @ 6 T	~1.4 MJ
Inductance	~14 Henry
Yoke inner diameter	330 mm
Yoke outer diameter	454 mm
Operating field (on the axis)	1 T to 6 T
Relative field errors on axis	<6 X 10 ⁻³

- Two of these solenoids were recently tested to 6.6 T (test stopped 10% above design field)
- Design, technology and may be some leftover material available



Status of ReBCO High Field Solenoid Development Tasks (FY2013)

- Prepare the advanced quench detection system for testing 100 mm PBL/BNL solenoid (Q1/Q2)
- Complete the construction of 100mm PBL/BNL solenoid consisting of 24 pancakes (Q1/Q2)
- Perform the test of quench protection system with 100 mm PBL/BNL solenoid at 77 K (Q2)
- Disassemble the 100 mm aperture (midsert) PBL/BNL solenoid to examine individual pancakes (Q3)
- Identify the source of degradation in PBL/BNL solenoid during the 77K system tests in Q2 (Q3)
- Devise a formal procedure for testing a group of pancake coils at ~77K (Q3)
- Failure Analysis Report on Coil Autopsy Studies (Q3)
- Repair and assemble 100 mm PBL/BNL solenoid for high field test at 4K (Q4)
- Integrate the advanced quench protection system for testing above solenoid at 4K (Q4)
- Perform high field test of the repaired 100 mm PBL/BNL solenoid at 4K (Q4)

On schedule upto Q3. Q4 may get slightly delayed because of conflict in scheduling with other programs

Status of ReBCO High Field Solenoid Development Tasks (FY2014)

- Complete the test of individual pancakes of 25 mm PBL/BNL insert solenoid (Q1)
- Assemble 25 mm (insert) PBL/BNL insert solenoid for high field test at 4K (Q2)
- Integrate insert and midsert HTS solenoids for producing >20 T (Q3)
- Integrate insert and midsert solenoids with the advanced quench protection system (Q3)
- Readiness Review prior to test (Q3)
- Perform conceptual engineering design of >30 T solenoid consisting of HTS and LTS (Q3)
- **Initiate mechanical and thermal analysis in support of the above programs (Q3)**
- **Perform high field (>20 T) test of the combined solenoid at 4K (Q4)**
- **Write a report (to be followed by a conference paper) on the test results (Q4)**
 - Wind HTS coils for quench studies which can also be tested to their limit (FY2015 Q1)

FY15 Task
Move to FY14

Some tasks takes advantage of synergy with other ongoing ReBCO programs at BNL (some exhausted). Surprises or reduction in budget may delay tasks listed in red (scope contingency).
Request to move quench studies to FY14 (may be under GARD).

Status of ReBCO High Field Solenoid Development Tasks (FY2015)

- ~~Wind HTS coils for quench studies which can also be tested to their limit (Q1)~~
- Perform preliminary engineering design of >30T solenoid consisting of HTS and LTS (Q1/Q2)
- Review of >30 T Solenoid Design (Q2)
- Perform quench studies and test to limit studies (at 4 K) in specially wound coils (Q2)
- Wind additional HTS coils needed to achieve >30 T in a hybrid (HTS + LTS) solenoid (Q2)
- Complete mechanical and thermal analysis of >30 T design with ANSYS or similar programs (Q2/Q3)
- Perform 77 K tests of new (additional) HTS coils wound at 77 K (Q3)
- Production Readiness Review (Q3)
- Start construction of the NbTi outsert solenoid (Q4)

Completing tasks listed in FY13 and FY14 will allow 30+ T design to be carried out on a stronger technical footing.

Summary

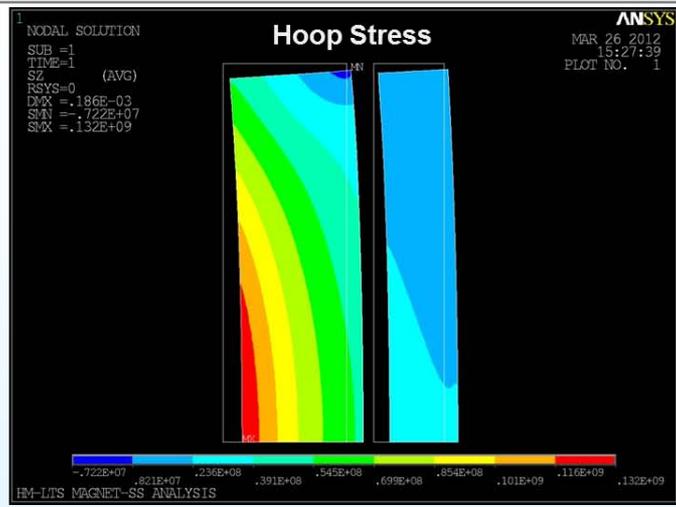
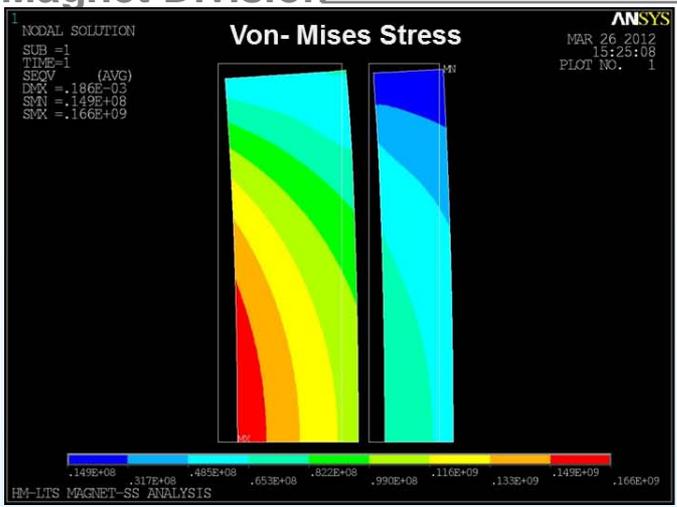
- **We are optimistic about the viability of HTS (partly by the record fields already created)**
 - High strength ReBCO is particularly suitable here
- **We had some setback recently**
 - Cause primarily understood and a way forward found
 - It has been demonstrated that coils can be repaired
 - Direct support from MAP is crucial to deal with such setbacks which are hard to avoid during R&D Phase
- **Copper discs play a unique role in quench protection in addition to minimizing the thermal strain on HTS coils**
- **Even though initial results are encouraging, a series of issues point to the need of a several year R&D program to determine if this technology is really feasible or not**

Back-up Slides

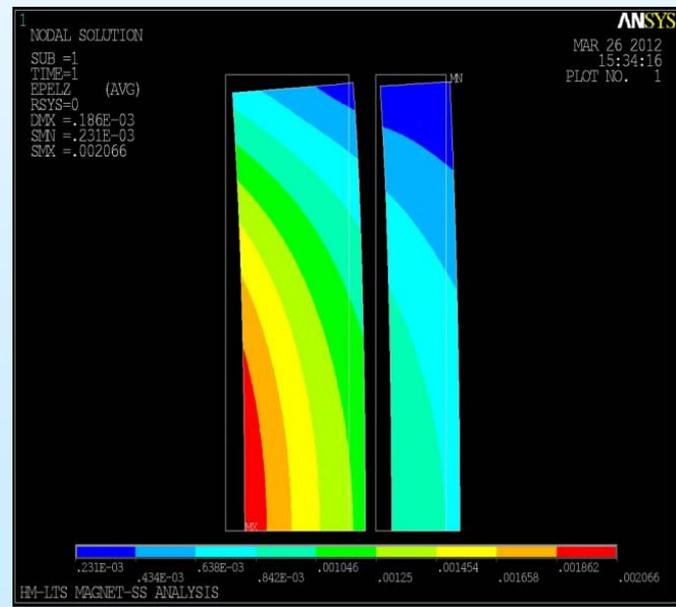
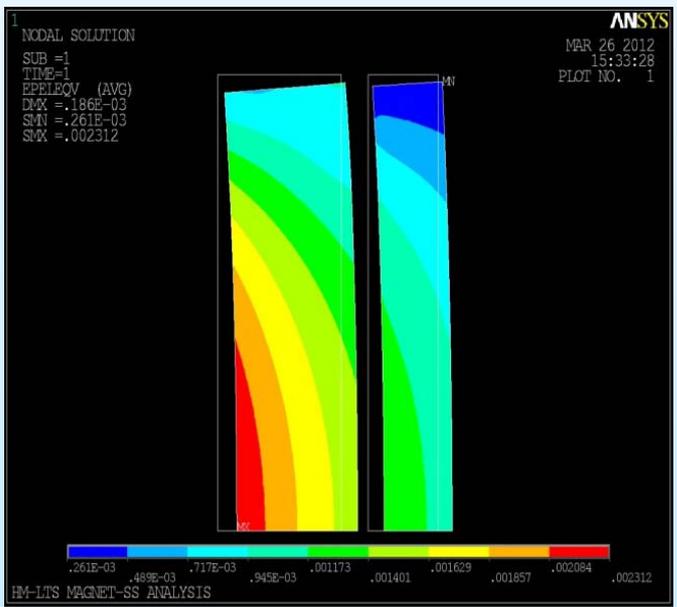
Magnet Engineering

- Because of limited funds, very little magnet engineering was carried out during SBIR programs.
- In SBIR program, we chose an approach where funds were used in most effective way to open and show the possibility.
- In MAP program, we have to demonstrate the technology.
- Therefore, as we move to the next phase, we have to significantly increase both magnet engineering and magnet analysis.

Mechanical Analysis



Von Mises and hoop stress in distribution from ANSYS in an LTS solenoid design



**Courtesy:
S. Lakshmi**

Von Mises and hoop strain in distribution in an LTS solenoid design from ANSYS

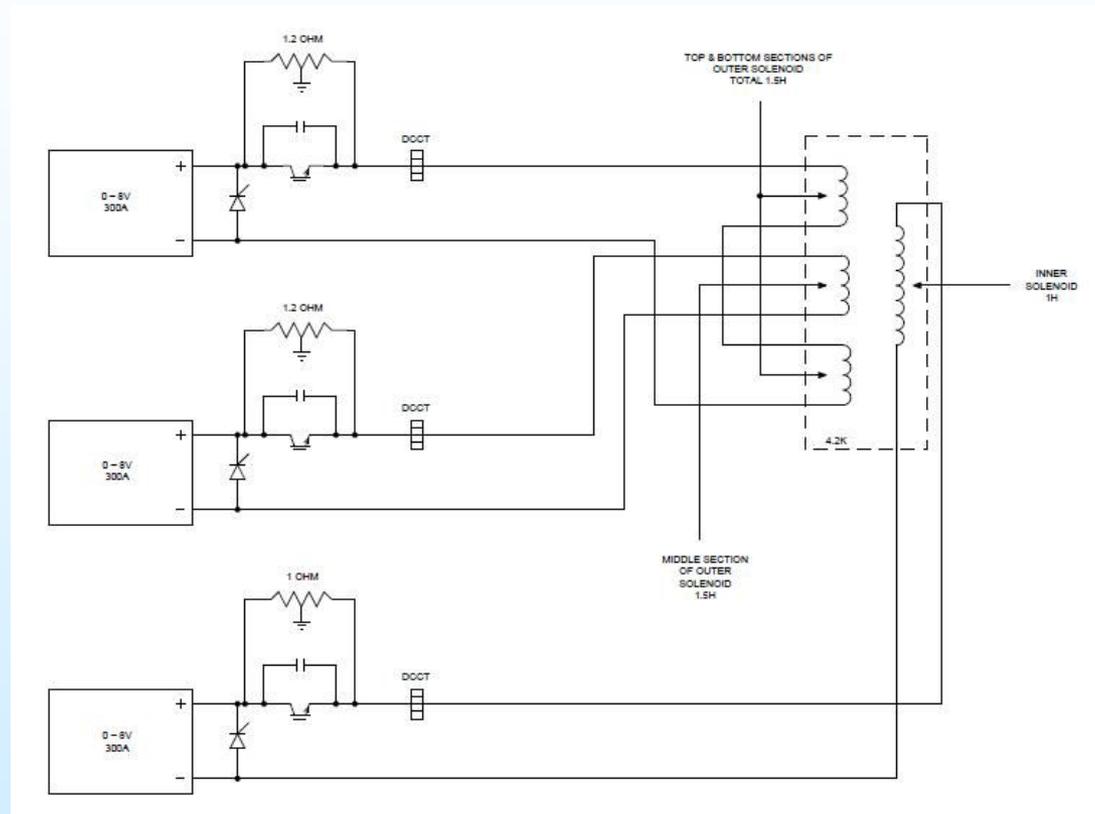
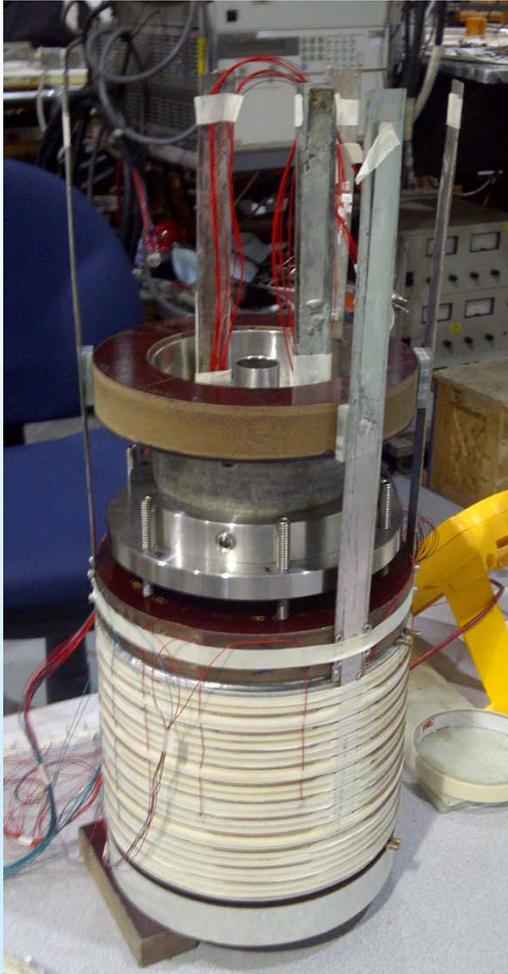
Energy Extraction

- 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)

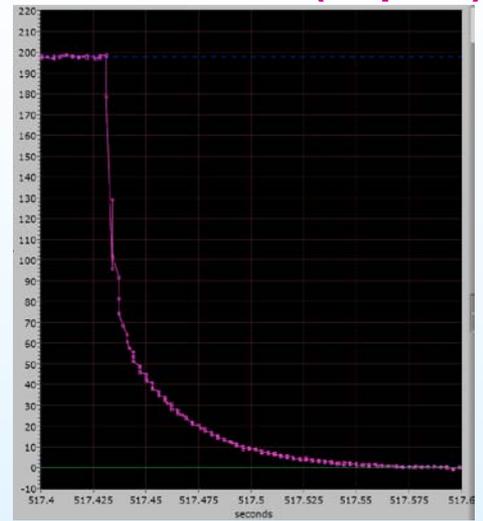


- Solenoid is sectionalized to extract energy fast on external dump resistors while keeping voltage low
- Bonus: Can also be used to provide electrical grading

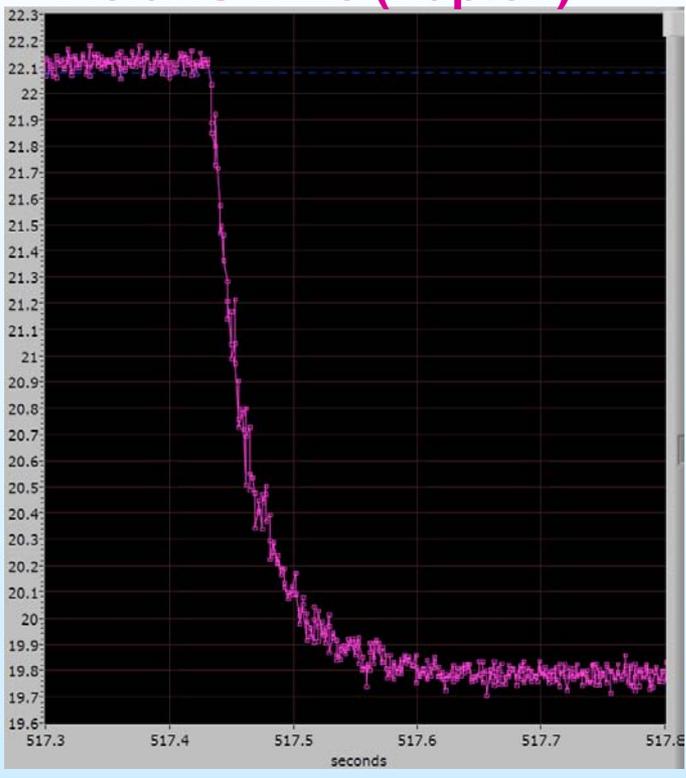
Test of PBL/BNL coils at NHMFL with HTS tape co-wound with SS and Kapton Tape (2)

Discharge of coils made with Kapton and Stainless Steel Insulation in 20 T background (total field ~22 T)

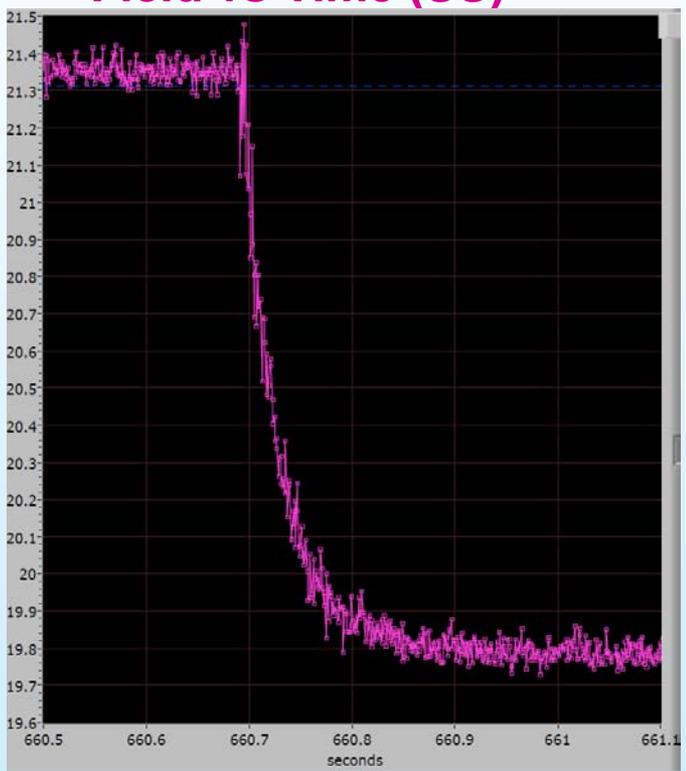
Current vs Time (Kapton)



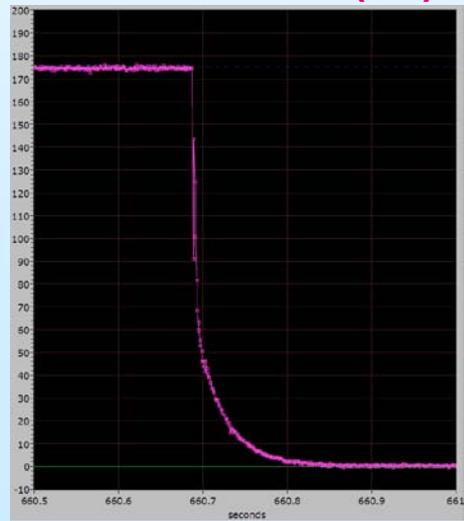
Field vs Time (Kapton)



Field vs Time (SS)

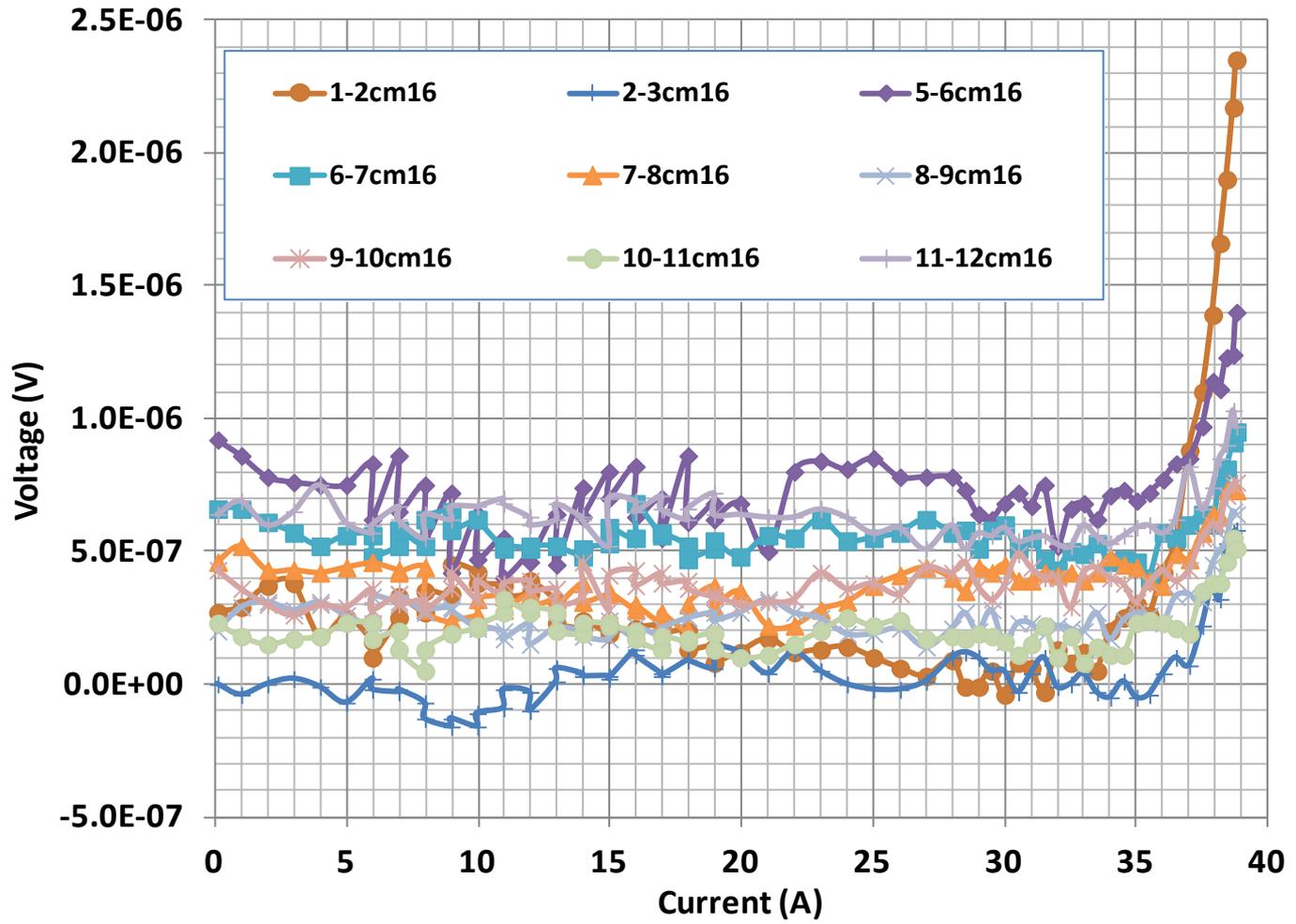


Current vs Time (SS)



Decays after shut-off are similar in Kapton and SS coils. Therefore, stainless steel tape can't be responsible for this.

Variation of Critical Current in Small (1 cm long) Sections



Measure I_c by taking advantage of the fact that we have many voltage-taps in small (~1cm) sections.

I_c seems to be reasonably uniform. In almost all cases, onset of resistive voltage starts at ~36A

Note: Very small scale (voltages in micro-volts)