High Field HTS Solenoid for a Muon Collider

Demonstrations, Challenges and Strategies

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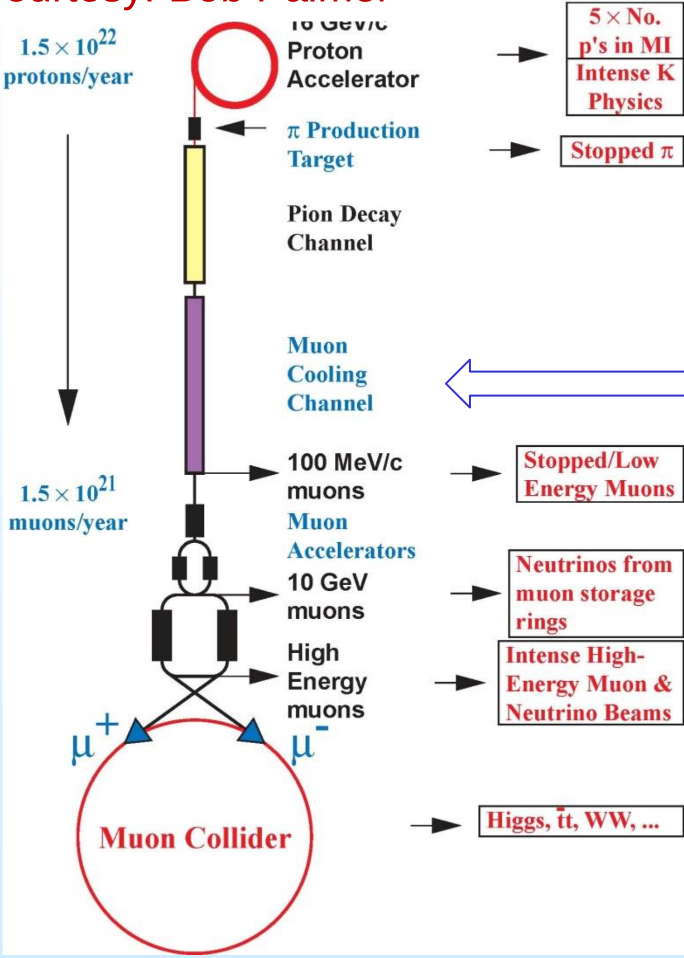
High Field Solenoids for the Proposed Muon Collider

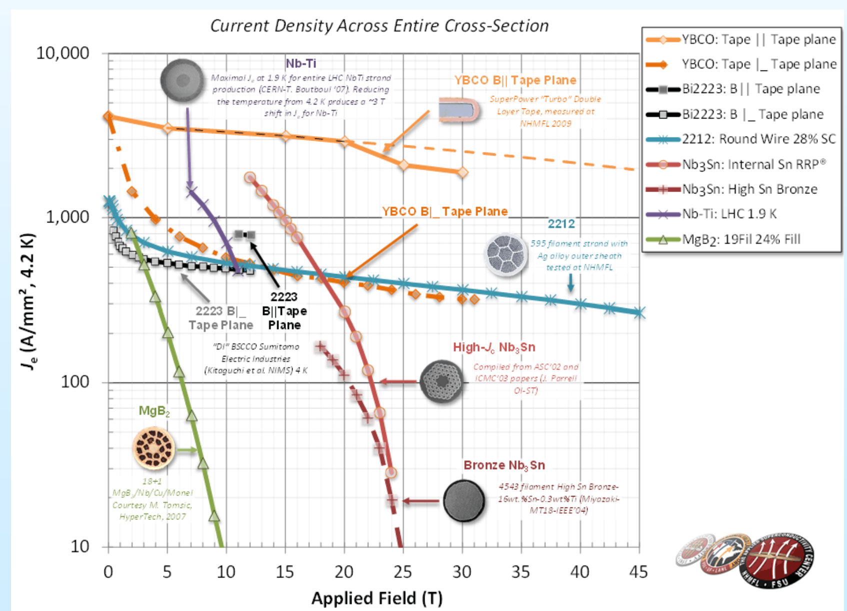
Courtesy: Bob Palmer



One key challenge:

Very High field solenoids (30-50 T)

- Resistive magnets would consume enormous power (**hundreds of MW**)
- **HTS (4K) offers a superconducting solution**



Courtesy: P. Lee, NHMFL

Other Applications of High Fields: NMR, SMES, User Facilities

Overview of the Design

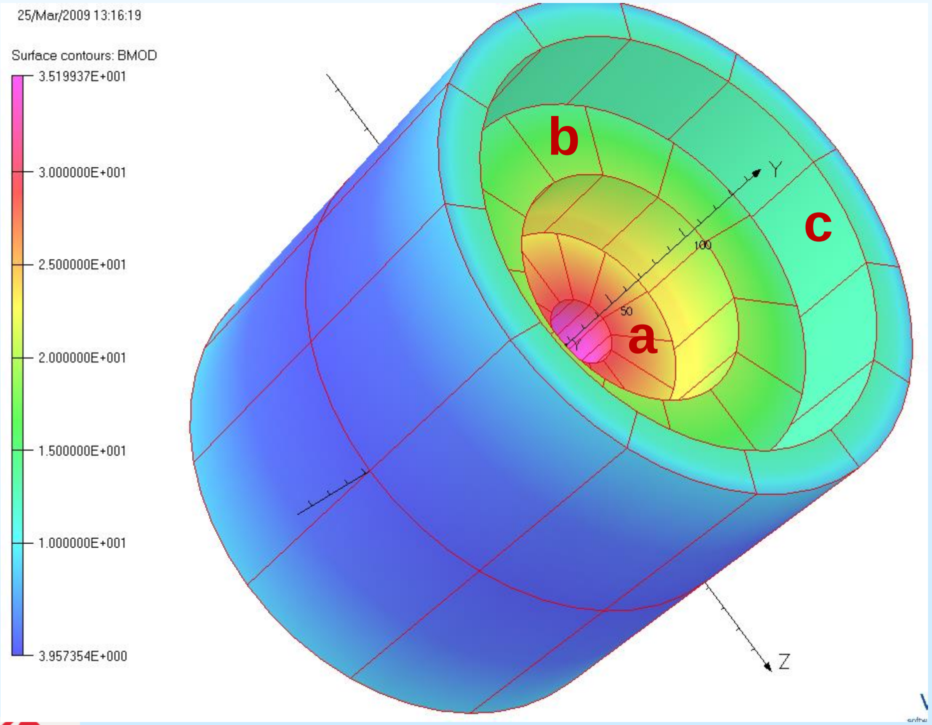
Chosen Path to a 30^{+} T Solenoid

Several significant coils (build and test in their own structure):

a) >12 T HTS solenoid (insert): 25 mm, 14 pancakes, 4 mm tape

b) >10 T HTS (midsert): 100 mm, 24 pancakes, 4 mm tape

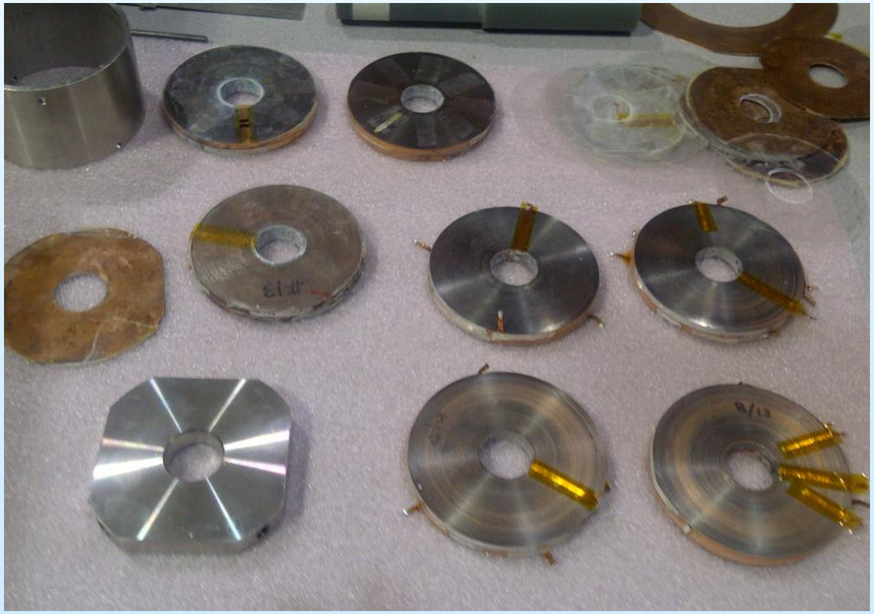
c) >10 T LTS (outsert): NbTi and/or Nb_3Sn, cable (design phase)



- Work initially started with a series of Small Business Innovation Research (SBIR)
- Currently supported by Muon Accelerator Program (MAP)

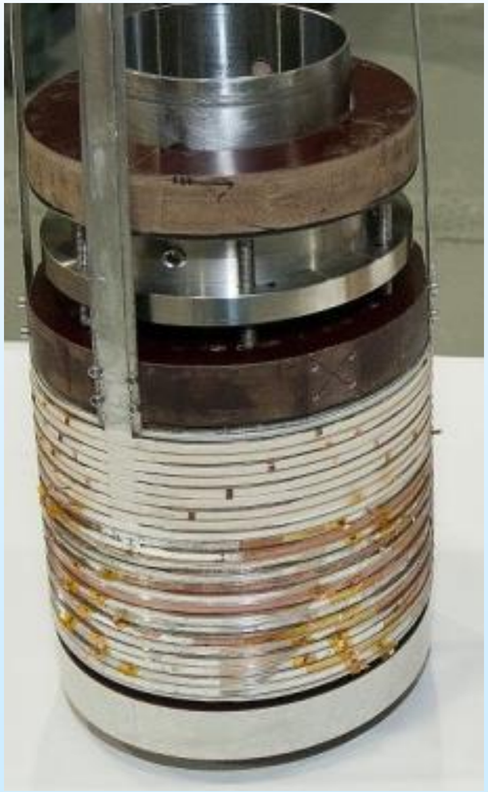
Basic Design and Construction

- Pancakes coils are made with high strength 2G HTS from SuperPower, Inc.
- HTS tape is co-wound with insulating stainless steel tape to reduce hoop stress and to help in quench protection
- Copper discs are used between the double pancakes to reduce thermal gradient during cool-down of large assembly
- No epoxy impregnation (only surface painted)
- A large number of v-taps for extensive 77 K QA testing



pancakes

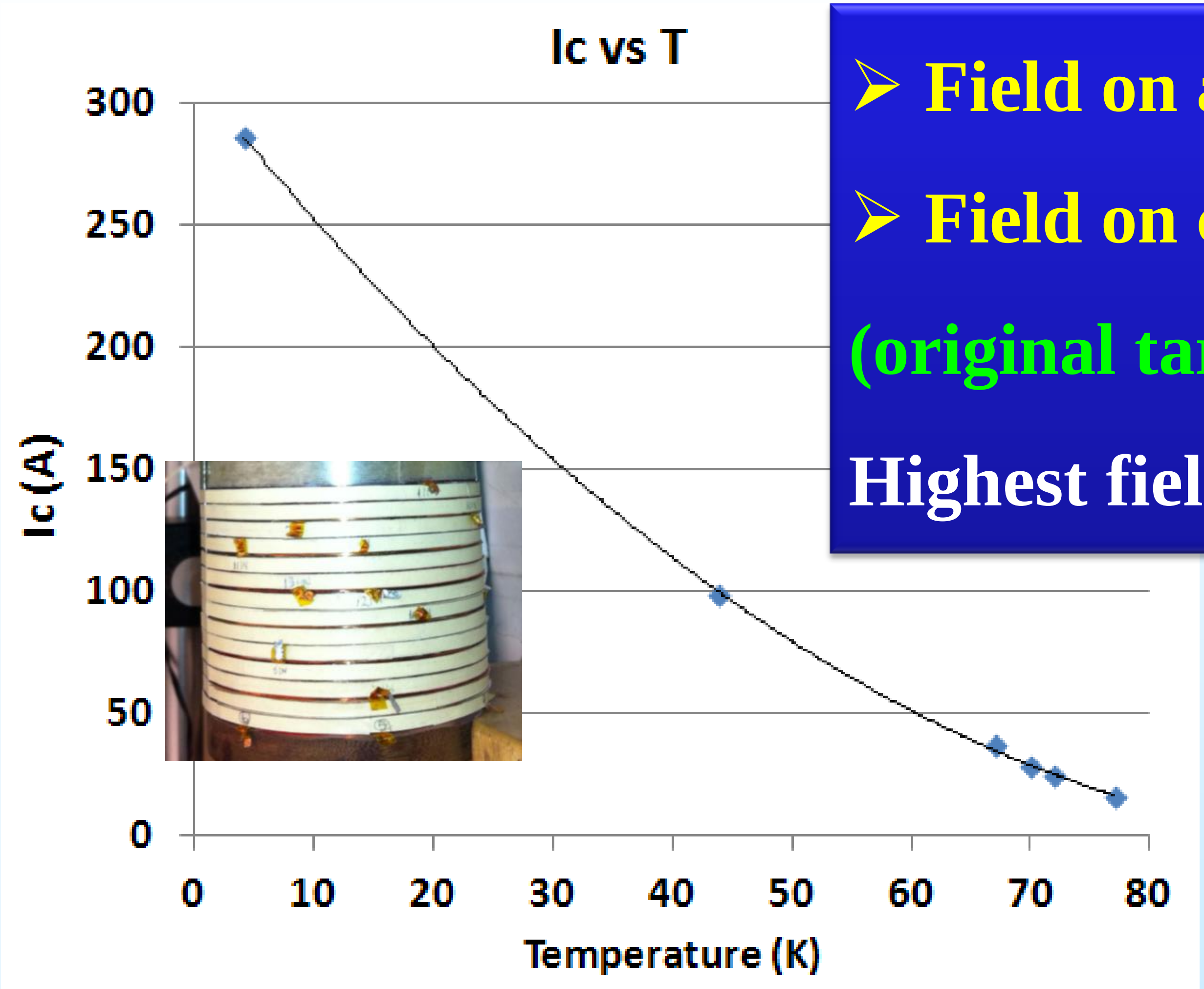
Insert solenoid



Midsert solenoid

Noteworthy Demonstrations

High Field (16T) Demo of HTS Magnet



- **Field on axis: 15.7 T**
- **Field on coil : 16.2 T**

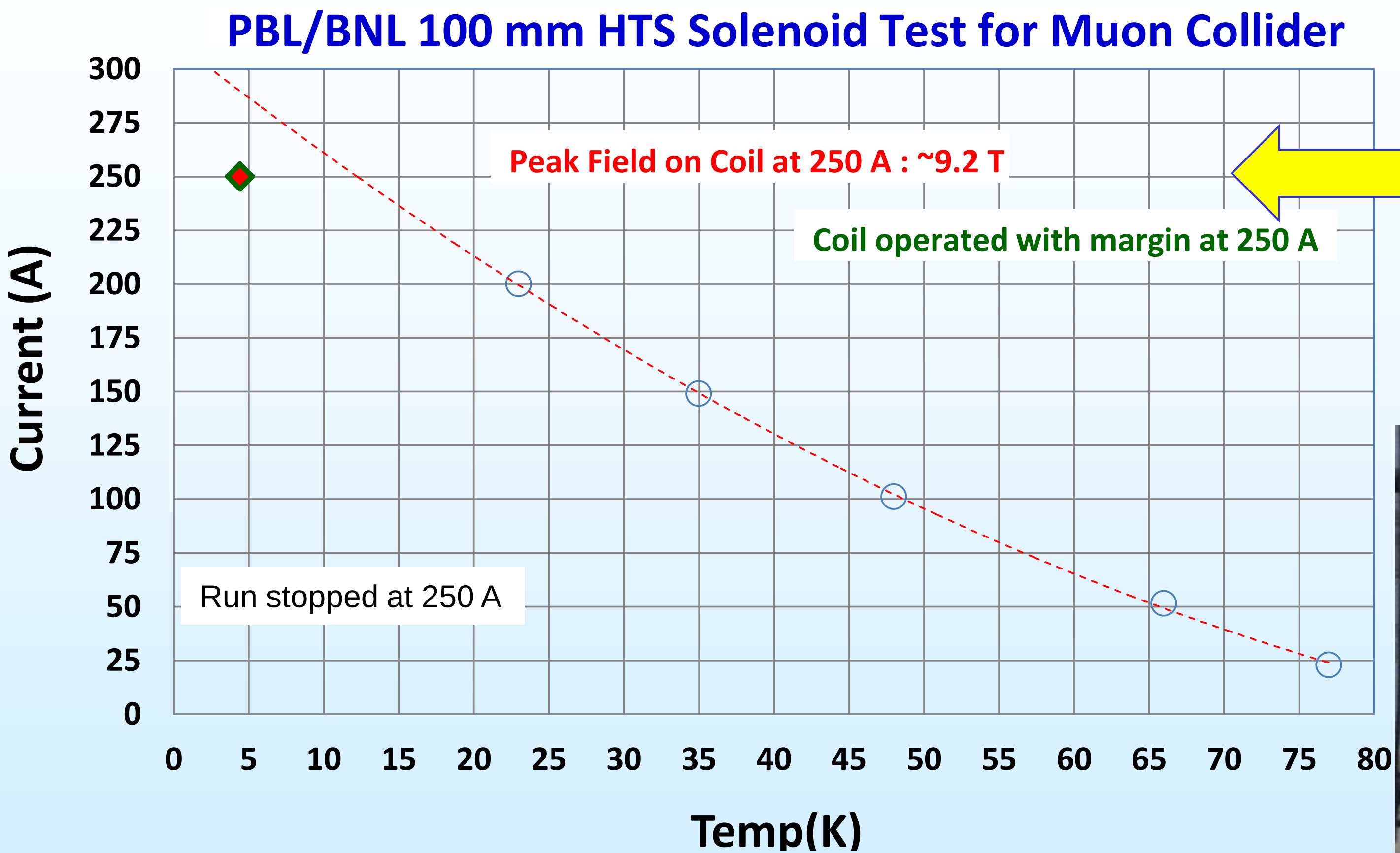
(original target: 10-12T)

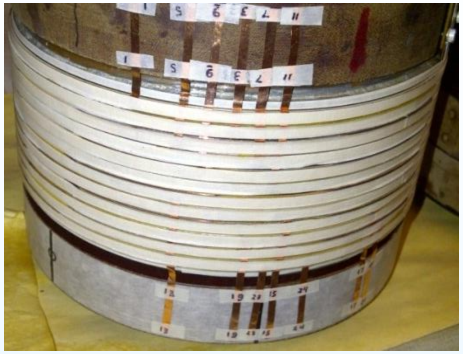
Highest field all HTS solenoid

Overall J_o in coil: >500 A/mm^2 @16 T

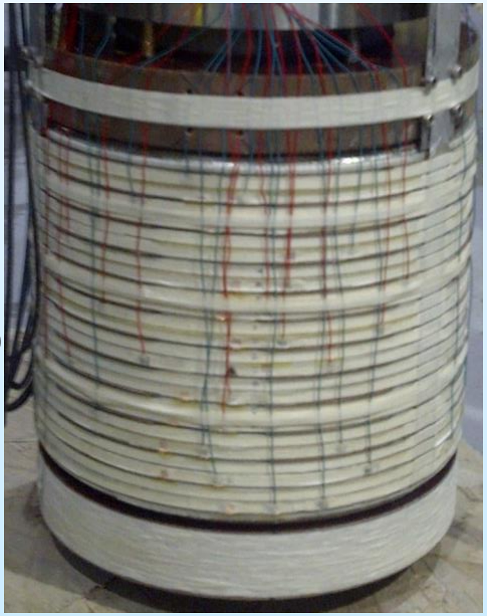
Insert solenoid: 14 pancakes, 25 mm aperture

Large Aperture High Field HTS Magnet





Half midsert (12 pancakes)



Full midsert (24 pancakes)

- **Half midsert operated at 250 A @4 K (6.4 T field on axis, 9.2 T peak field on coil**
- **Design value for full midsert: 220 A for 10 T**

Challenges and Strategies

- **Quench Protection**
- **High Field Conductor**
- **Coils/Magnets**

Quench Protection (avoid runaway situation)

Quench protection of high field HTS magnets is a major challenge!

- **We take a multi-prong approach to overcome this challenge:**
  - **Advanced quench detection system to detect onset of "pre-quench" phase and start action while it is still safe to operate for some time**
  - **Special electronics to tolerate high isolation voltage (> 1 kV) to allow fast energy extraction once the pre-quench phase is detected**
  - **Inductively coupled copper discs to reduce current instantaneously**
  - **Spread heating across the coil faster because of SS tape insulation**
  - **Also possible: quench heaters as used in LTS magnets (NHMFL)**

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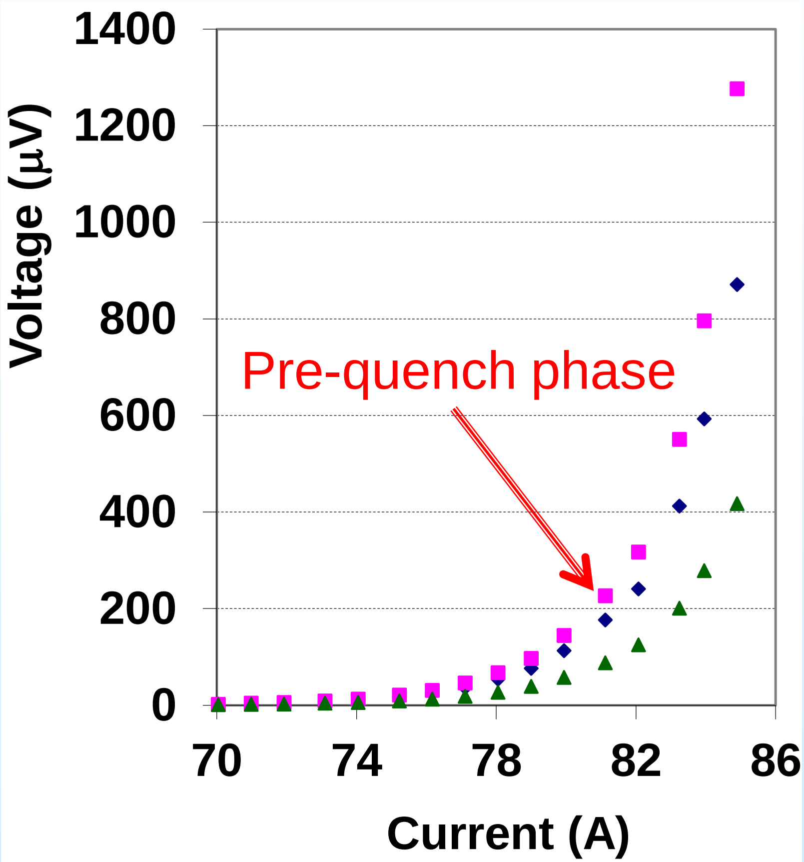
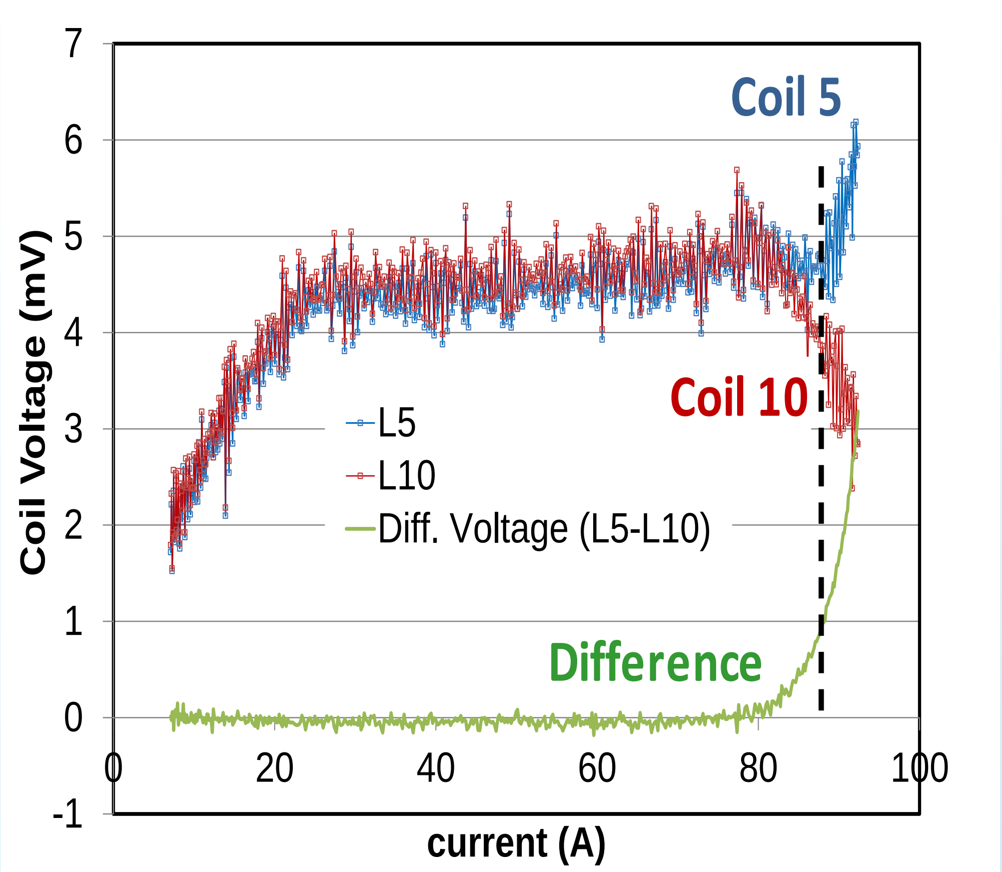
Advanced Quench Detection System

Advanced quench detection system detects onset of small "pre-quench" voltage (<1 μV/cm) in the presence of large noise and inductive voltage



Detection at ~100 μV level (1 μV/cm in 100 m => 10 mV)



Detection while ramp rate is changing

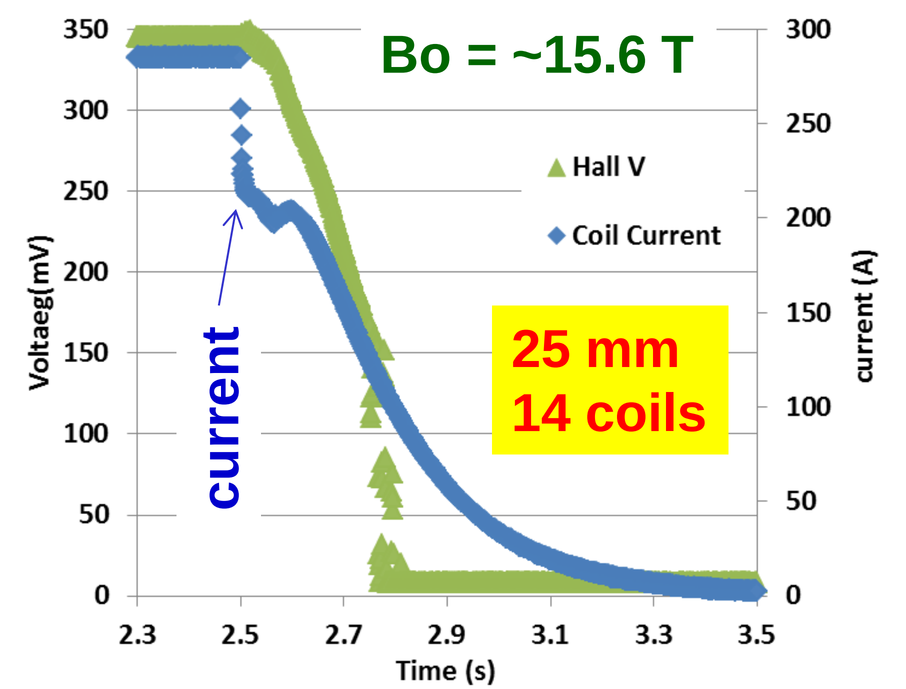
Advanced Quench Detection System with Fast Energy Extraction

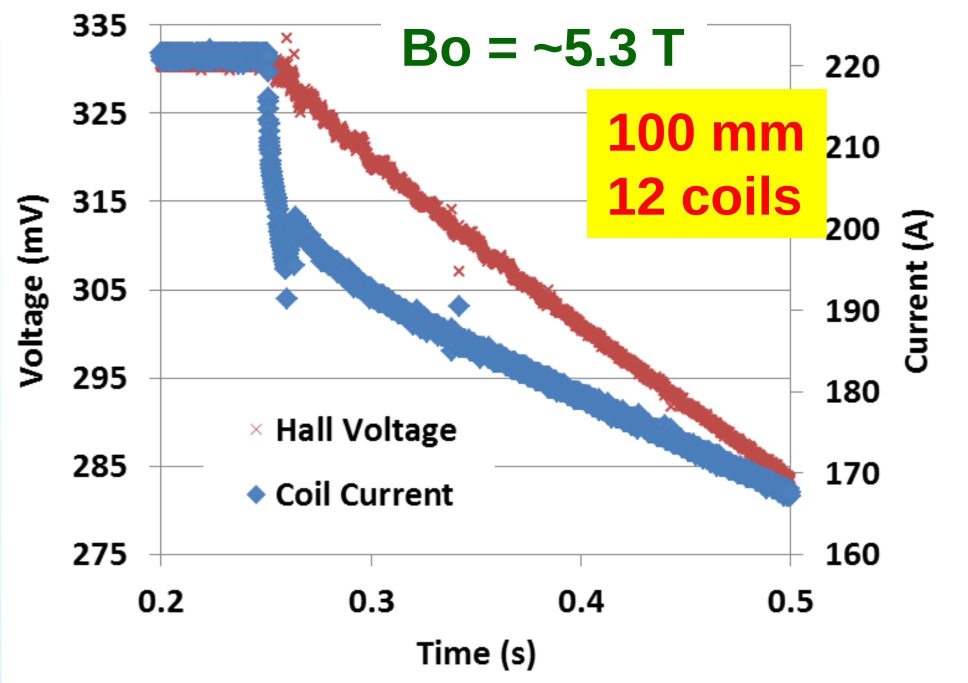
- Fast energy extraction in larger magnets creates high voltages as “L” increases
- Develop electronics that can tolerate high isolation voltage (>1 kV)
- Divide coils in several sections

Cabinet #1 (32 channels, 1kV)

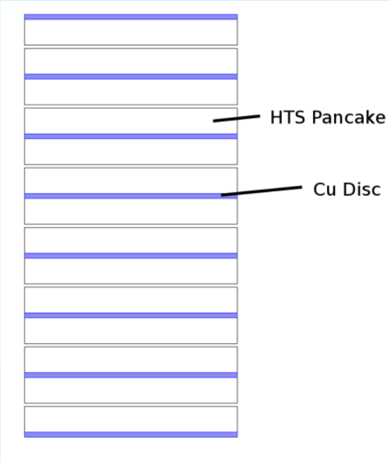
Cabinet #2 (32 channels, 1kV) (expandable to 64 and 3kV)

Instantaneous (<100 μsec) Drop in Current (as soon as the energy extraction started)





Holger Witte (2PoCJ-02)



- Inductively coupled Cu discs
- Partial current transferred from coil to disc (simulation show reasonable agreement)
- Partial energy extracted
- Extra margin at critical time
- Cu discs heat up to 50-70 K

Conductor and Coils

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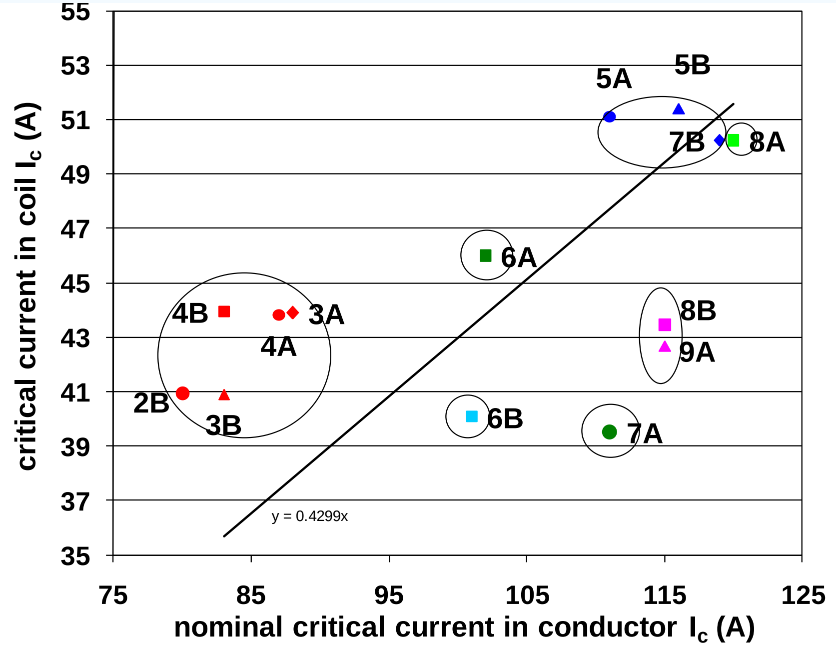
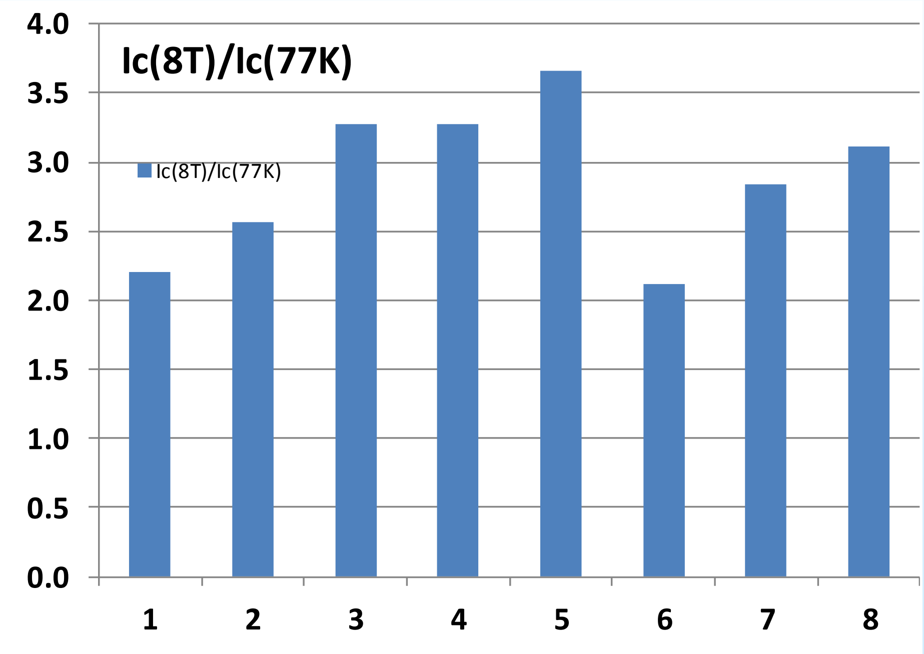
In-field Conductor Performance

- HTS vendors typically measure performance at 77 K and self-field
- Magnets need at operating temperature and operating field
- We observe large variations in in-field scaling of coil and conductor

Correlation - conductor and coil (77 K)



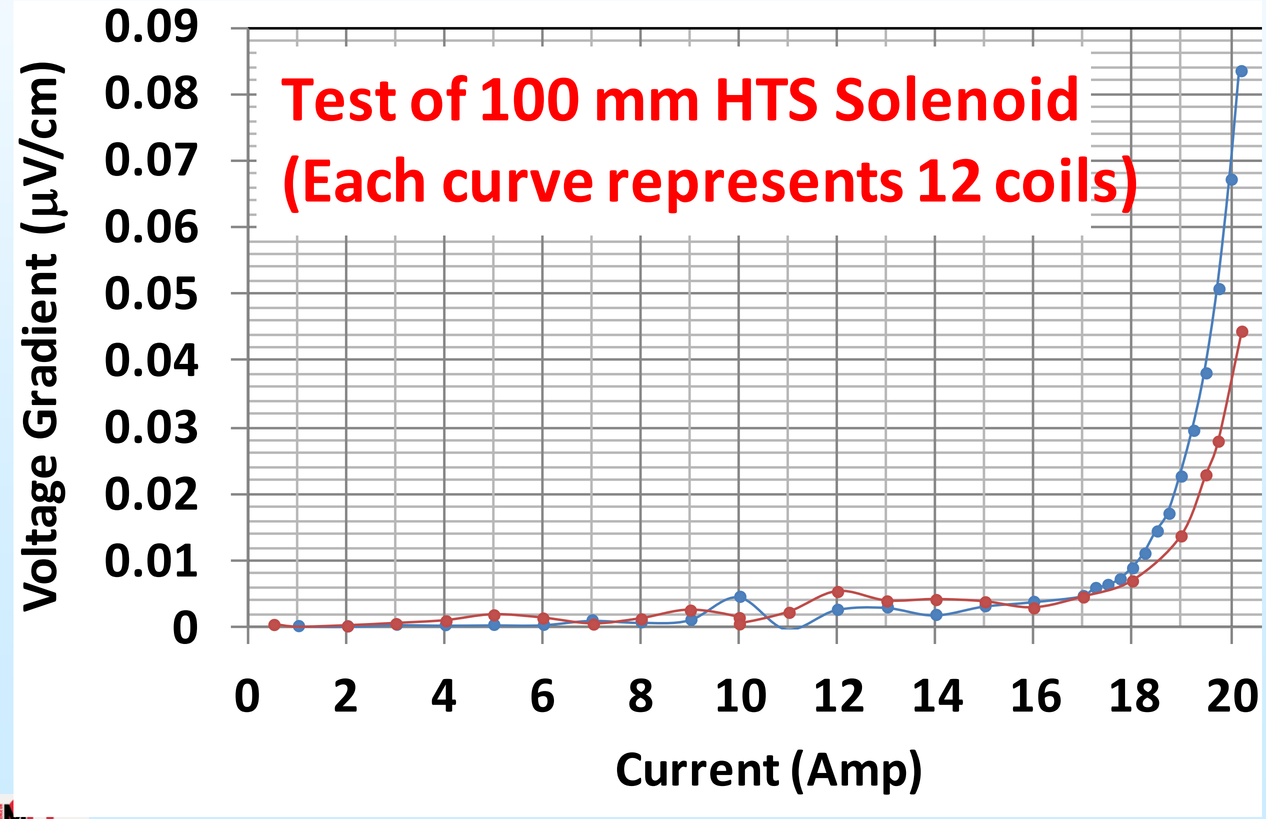
Measured Bperpendicular scaling(4K) at BNL

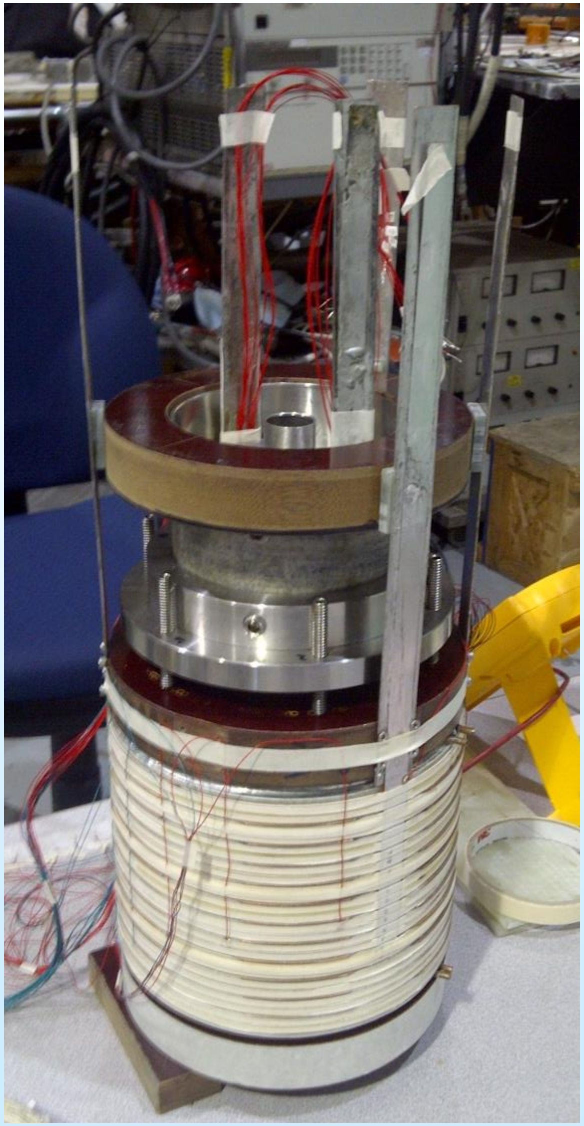


- A potential to improve in-field performance & to make it more uniform
- A production conductor requires spec at operating conditions (4K,8T?)
  - We may also need to specify/tighten various mechanical spec

Preparation of Combined HTS Midsert and HTS Insert for High Field (>22 T) Test

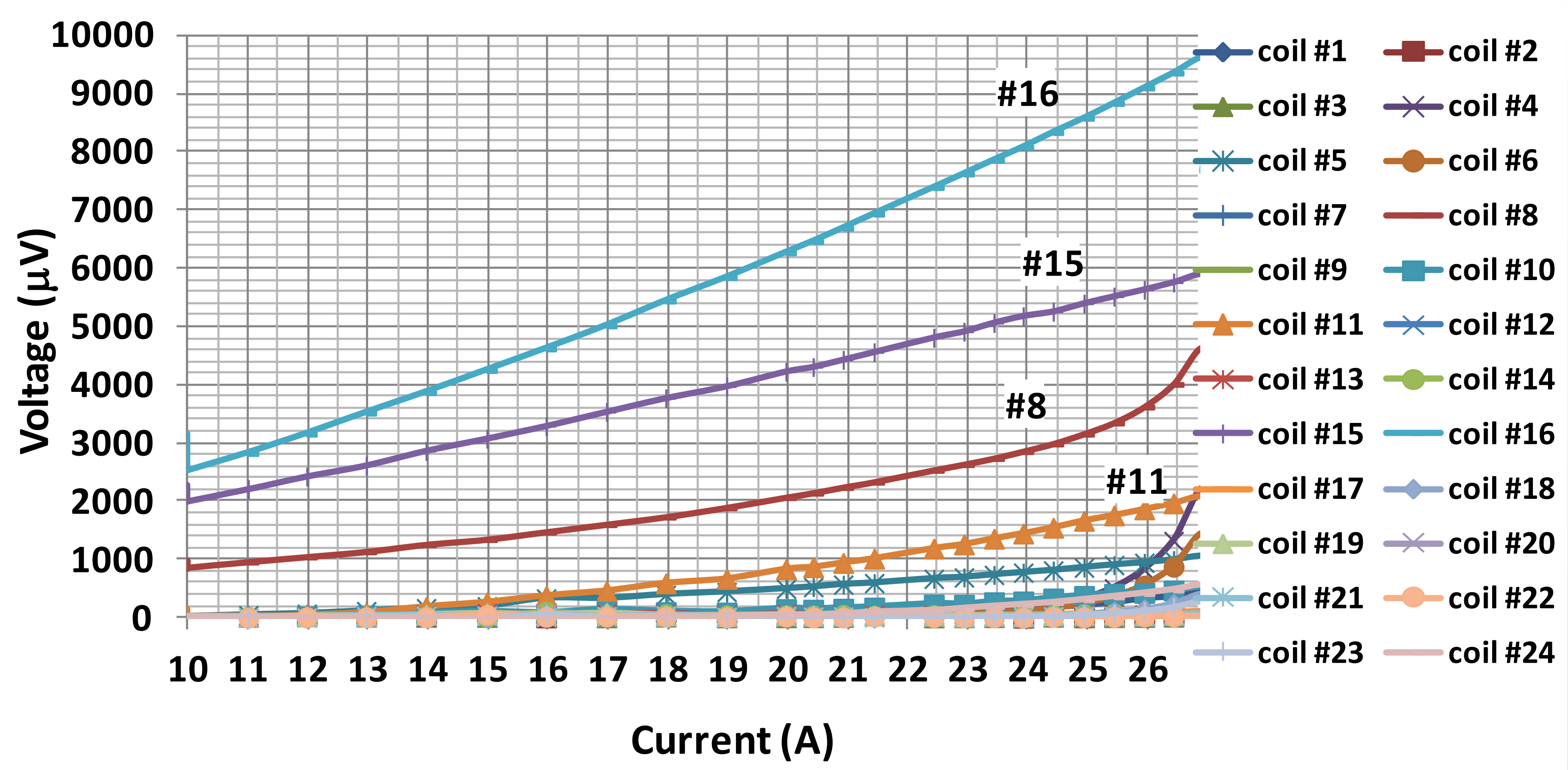
- **HTS Insert (14 pancakes, ran at 16 T peak field) and Midsert (24 pancakes, 12 ran at 9 T peak)**
- **Expected on axis field at 4 K: > 22 T (design)**
- **All worked well during 77 K Pre-test**





HTS coils prone to damage during cool-down

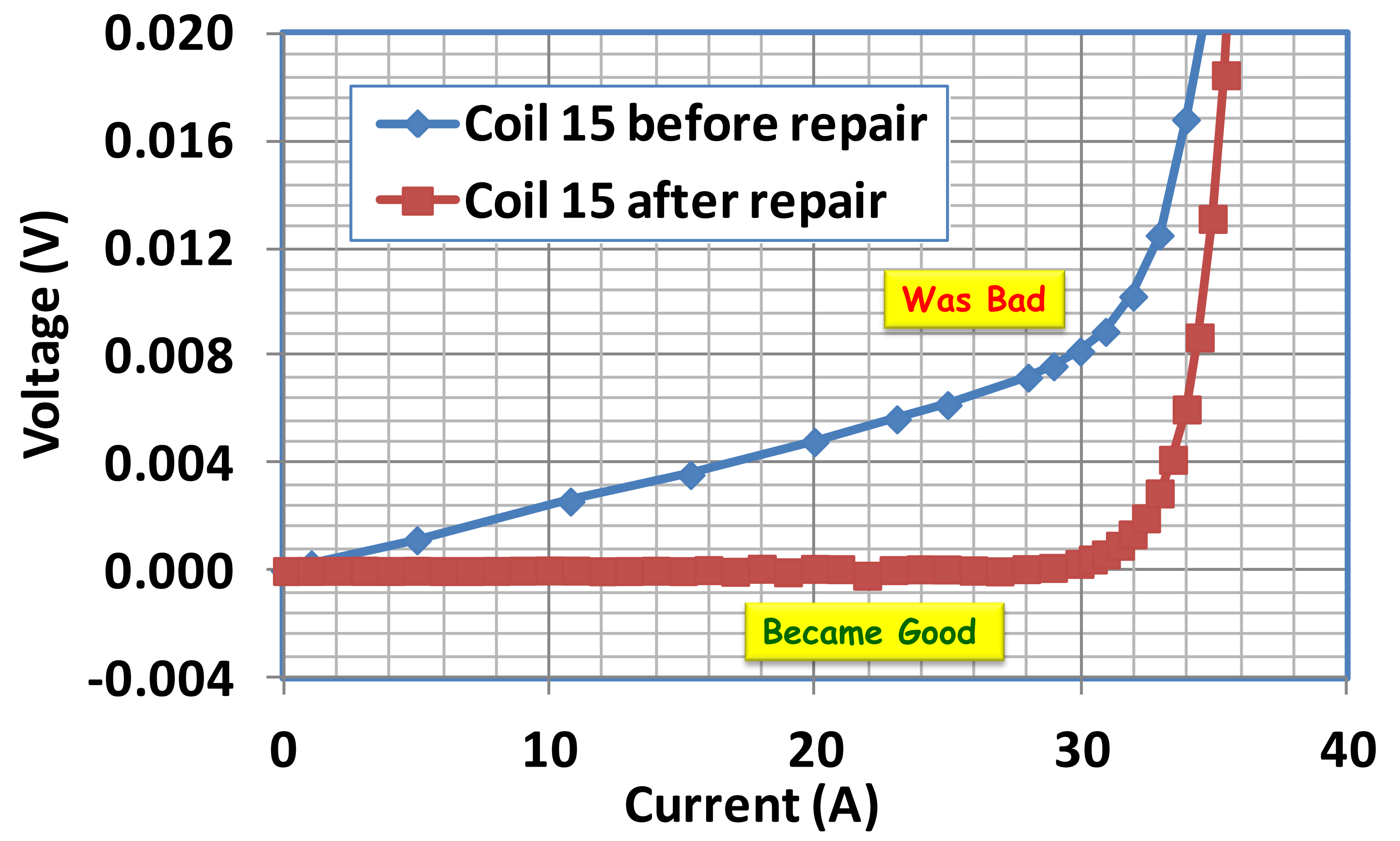
- Several pancakes got degraded during one @77 K test with LN_2



- All coils have been tested successfully several time before this event
- No further degradation seen after repeated test after this event
- Likely cause: excessive thermo-mechanical strain during system testing

Repairing the Pancakes

Several pancakes (half) could be repaired by simply removing inner-most turn and making a new splice between two single pancakes



Strategies for Way Forward

- **Extended copper discs, etc. to provide better cooling**
- **Slower cooling to reduce thermal gradient within coil**
- **A more robust conductor**

- Interesting, currently more issues are being seen and reported during the 77 K testing rather than the 4 K high field testing where the conductor is supposed to be exposed to large Lorentz forces.
- Developing a better defined test procedure may help in interim.

Summary

- **Record high fields (~16 T) demonstrated in an all HTS coil**
- **Multiple strategy help in quench protection – particularly the use of copper discs and advanced electronics**
- **HTS coils are sensitive to thermo-mechanical strain.
A more robust conductor and magnet design will help**
- **High strength ReBCO has demonstrated the potential for creating high field magnets suitable for many applications. The target field of >22 T in an all HTS and >30 T in all superconducting magnet seems within reach**
- **As with any ambitious R&D program, one has to be prepared for some surprises and some systematic R&D**

Extra Slides

Original Design Parameters (as presented at 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~~ Midsert 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)**

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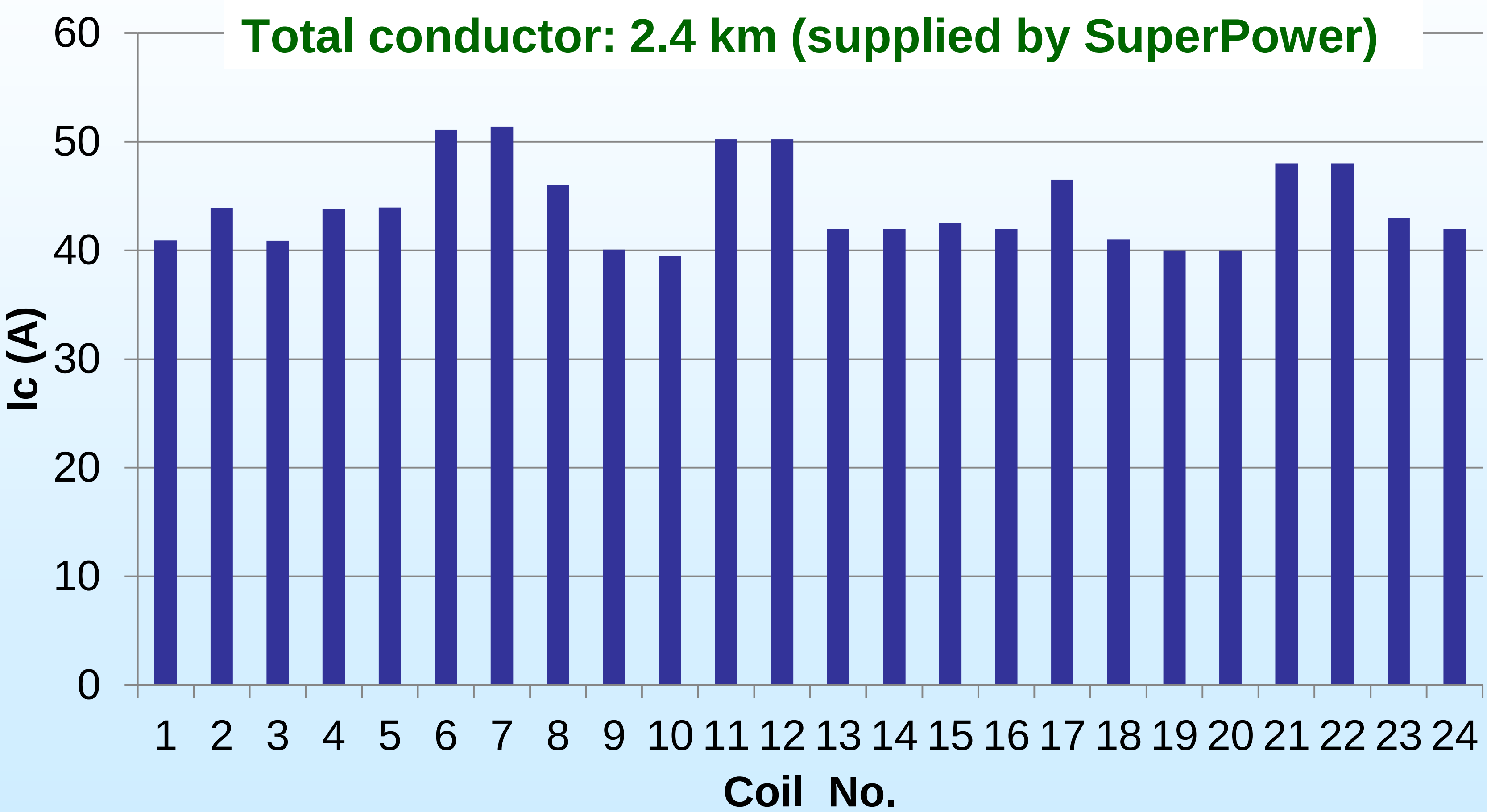
77 K QA Test of 100 mm Pancakes

A Large Number of 2G HTS Pass Extensive Initial Testing in LN_2



Field @40 A: Bparallel ~0.5 T and Bperpendicular ~0.3 T