SMES Coil Status

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BROOKHAVEN NATIONAL LABORATORY
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Office of Science
U.S. DEPARTMENT OF ENERGY

Overview of Activities

- Status of engineering design and fabrication of parts
- Construction of single pancake coils
- Construction of fixture for testing outer double pancakes
- Test results of outer double pancake coils
- QA for detecting deviations from nominal performance and localization of defect, if any
- Summary

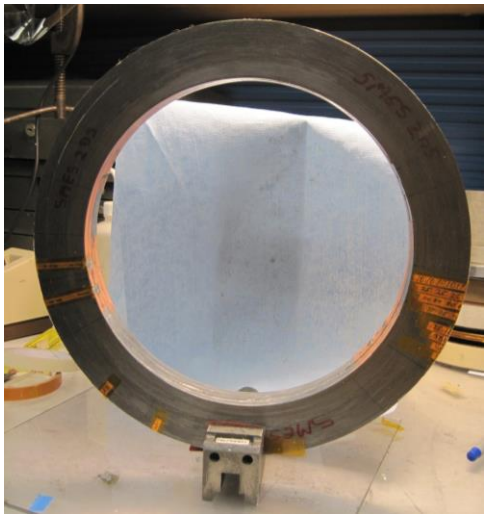
Status of Engineering Design and Fabrication of Parts

- **Detailed engineering design has been carried out to extent that is common between 1.7 MJ and 2.5 MJ SMES**
- **We designed, ordered, fabricated or received parts that are common between 1.7 MJ and 2.5 MJ SMES. In particular support structure tubes have been received and machined**

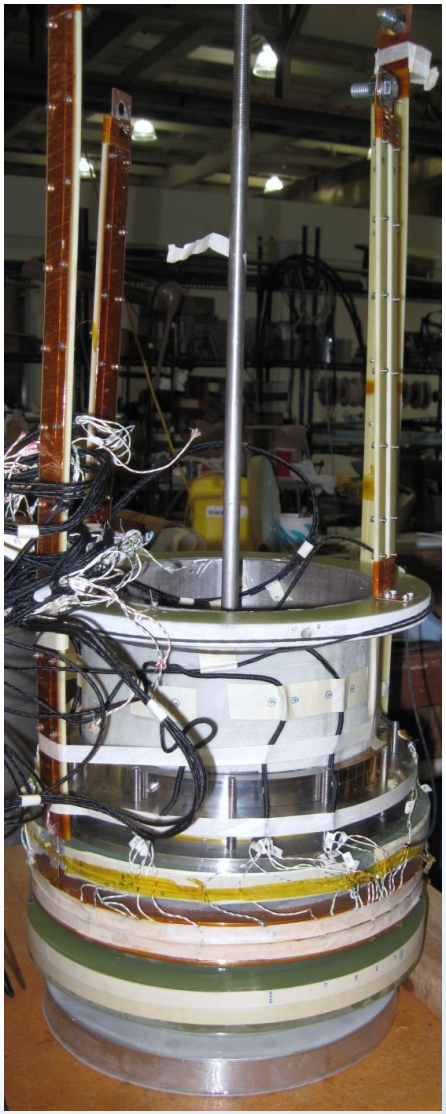
Construction of Pancake Coils

- Construction of all (28) inner pancake coils was reported in last quarter
- Construction of the required number of outer pancake coils (16) for 1.7 MJ has now been completed
- Construction of additional outer pancakes (12) for 2.5 MJ will start only after receiving confirmation of plus-up funding

Construction of Fixture for Testing Outer Double Pancake Coils at 77 K Test



Each outer pancake uses ~200 m of conductor

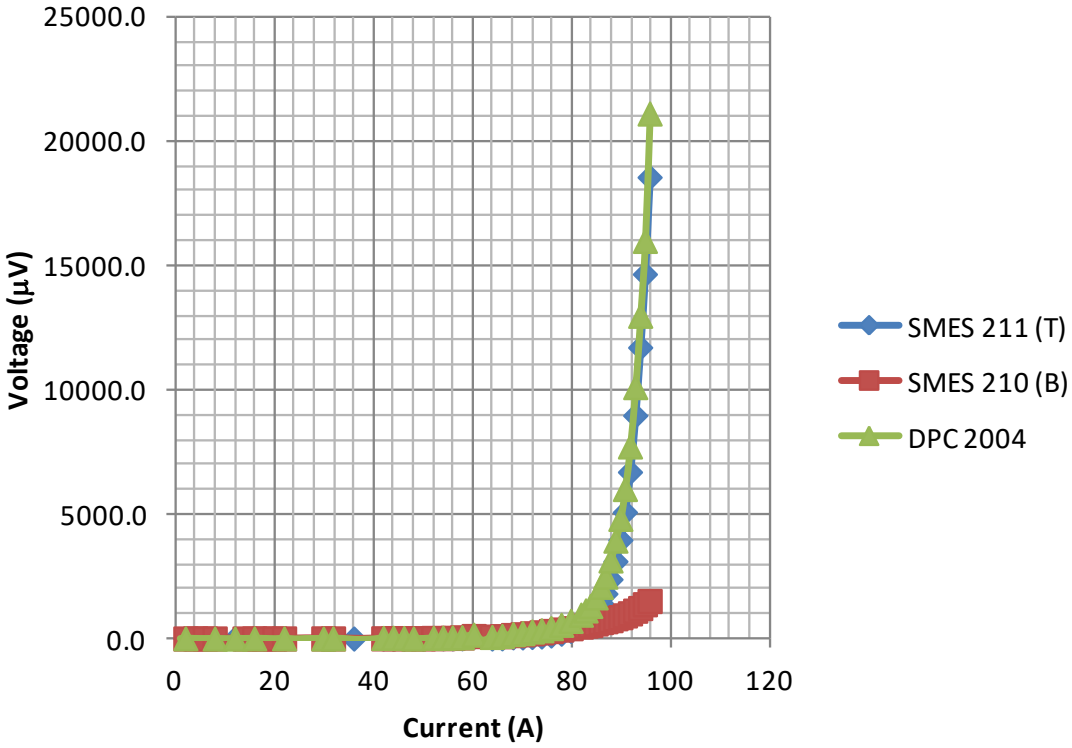


Fixture has four leads to allow testing of the two coils and splice separately

Test Results of Outer Double Pancake Coil DPC2004

(2 pancakes powered in series)

Double Pancake Coil DPC2004 consisting of SMES210 and SMES211 is good



Resistance of the diagonal splice: 4.2 nΩ

I_c for 1μV/cm criteria

SMES210: Beyond the range (>96 A)

SMES211: 95 A, N=23

Double pancake coil: >96 A

I_c for 0.1μV/cm criteria

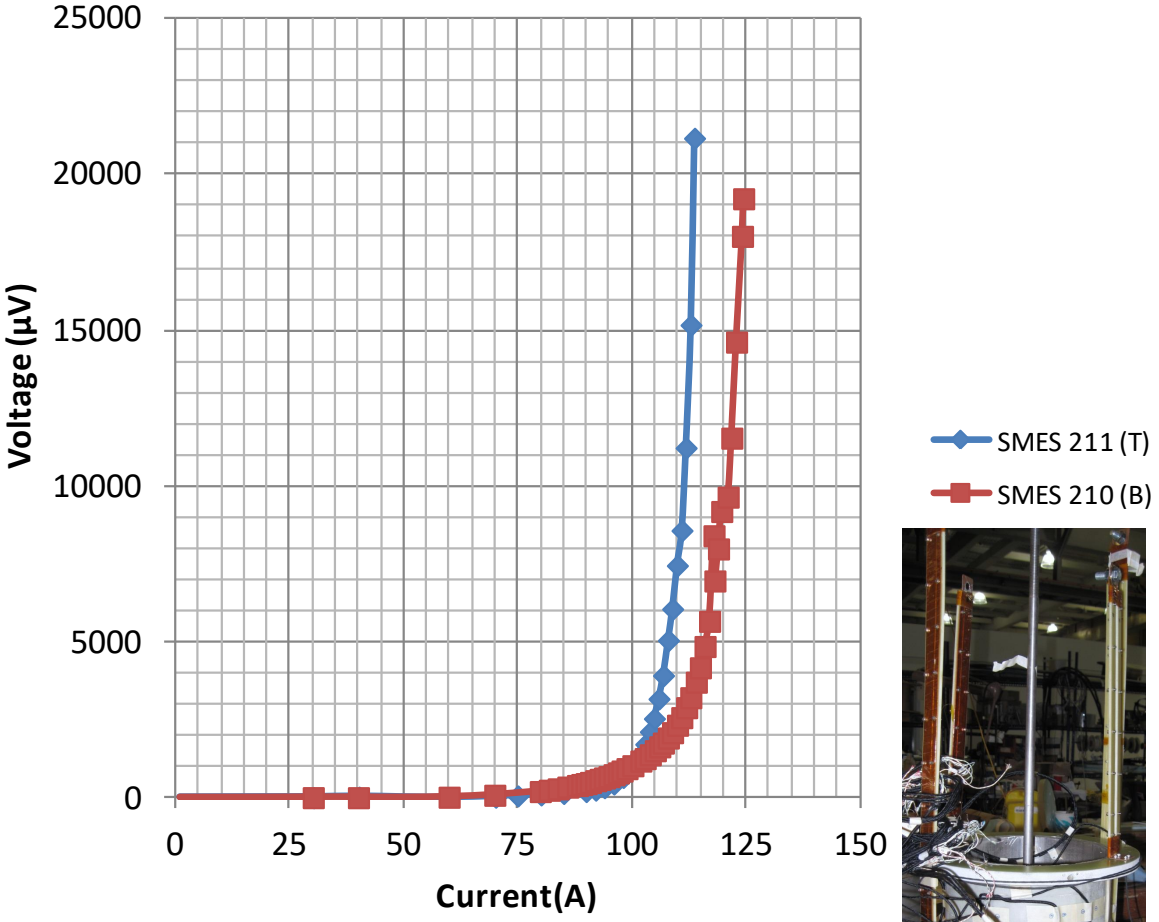
SMES210: Beyond the range (>96 A)

SMES211: 86.8 A, N=23

Pancake coil SMES210 carries significantly higher critical current than coil SMES211 @77K

Outer Coil SMES210 and SMES211 Used in DPC2004

(each pancake powered separately)



Double Pancake Coil DPC2004 and coils SMES210 and SMES211 used in making them are good

Based on 1μV/cm criteria

SMES 210: 124A, N=18

SMES 211: 113.8 A, N= 23

Based on 0.1μV/cm criteria

SMES 210: 109.2A, N=18

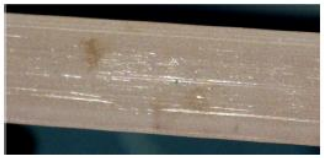
SMES 211: 103.1 A, N= 23

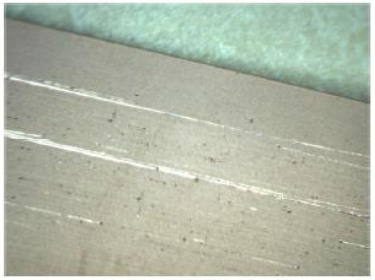
Additional leads in the center of the outer fixture allowed us to determine the performances both coils despite a significant difference in their critical currents (improvement over inner fixture).

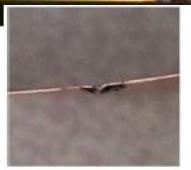
Quality Assurance (QA) Steps in Place

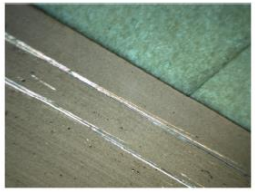
1. **Check surface of the conductor critically during the winding:**
   - Any concern are immediately notified to manufacturer (SuperPower)
   - In particular, we inspect splices, delamination in copper or any scratches, etc. as they may limit the coil performance
   - If the issues is serious, the coil is unwound and conductor is sent back to manufacturer for further inspection
   - Having conductor manufacturer as a collaborator is a major benefit
2. **Perform 77 K test of the double pancake coil assembly:**
   - HTS offers a unique opportunity of carrying out a relatively inexpensive test of the performance of superconducting coil in liquid nitrogen
   - We install several voltage taps to examine the performance of internal splices and of a group of turns (0, 10, 25, 50, 75, …, ~200). Number of these voltage taps will get reduced/eliminated as the technology matures
   - Any deviation from nominal is critically examined. Most of the time we are able use a relatively weaker coil in an area where we have large margin. So far only one coil (out of 33 tested) could not be used

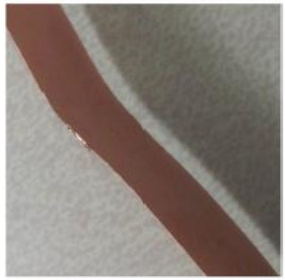
Visual Inspection of Conductor and Splices During Coil Winding (first line of defense in QA)

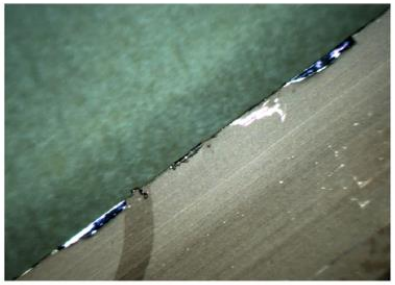



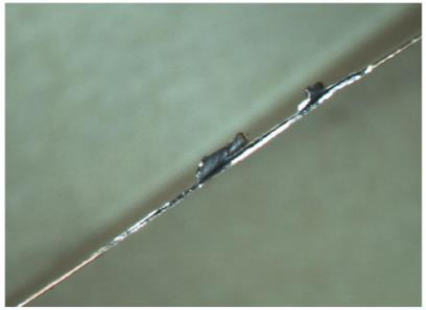









SuperPower is replacing conductor in these and other cases where we were not sure

Because these defects were present for an extended length or at multiple locations, two coils were unwound after significant winding and one was wound after replacing one spool of conductor.

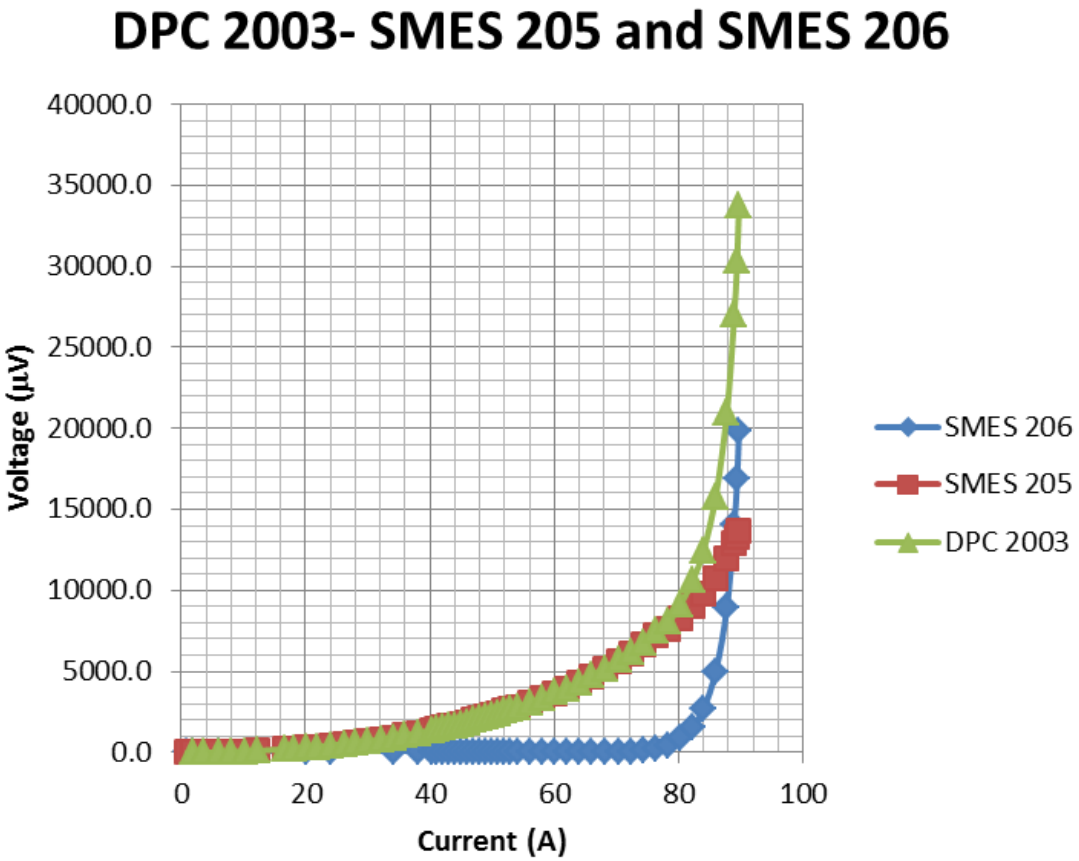
QA and Localization of Defect in Coil

Next four slides show a powerful method in operation:

1. Perform and analyze 77 K measurement of double pancake coil. If there is a defect, isolate the major part in double pancake assembly (splice between two coils or one or both coils).
2. If in splice between two coils, measure the performance of splice joint again with two extra leads incorporated in the new fixture. If in coil, energize the good coil alone to observe detailed performance to certify the coil good.
3. Measure the performance of bad coil. Determine the approximate location of the defect with the help of number of voltage-taps put between the turns.
4. MAP the location of turns to 5-m critical current measurements performed by vendor (SuperPower). Communicate all details to vendor which has a variety of data and extensive measurements to possibly determine the cause. Also go through the internal detailed log (traveler) at BNL to make sure that there was no unusual event or observation.

Test Results of Outer Double Pancake 2003

(2 pancakes powered in series)

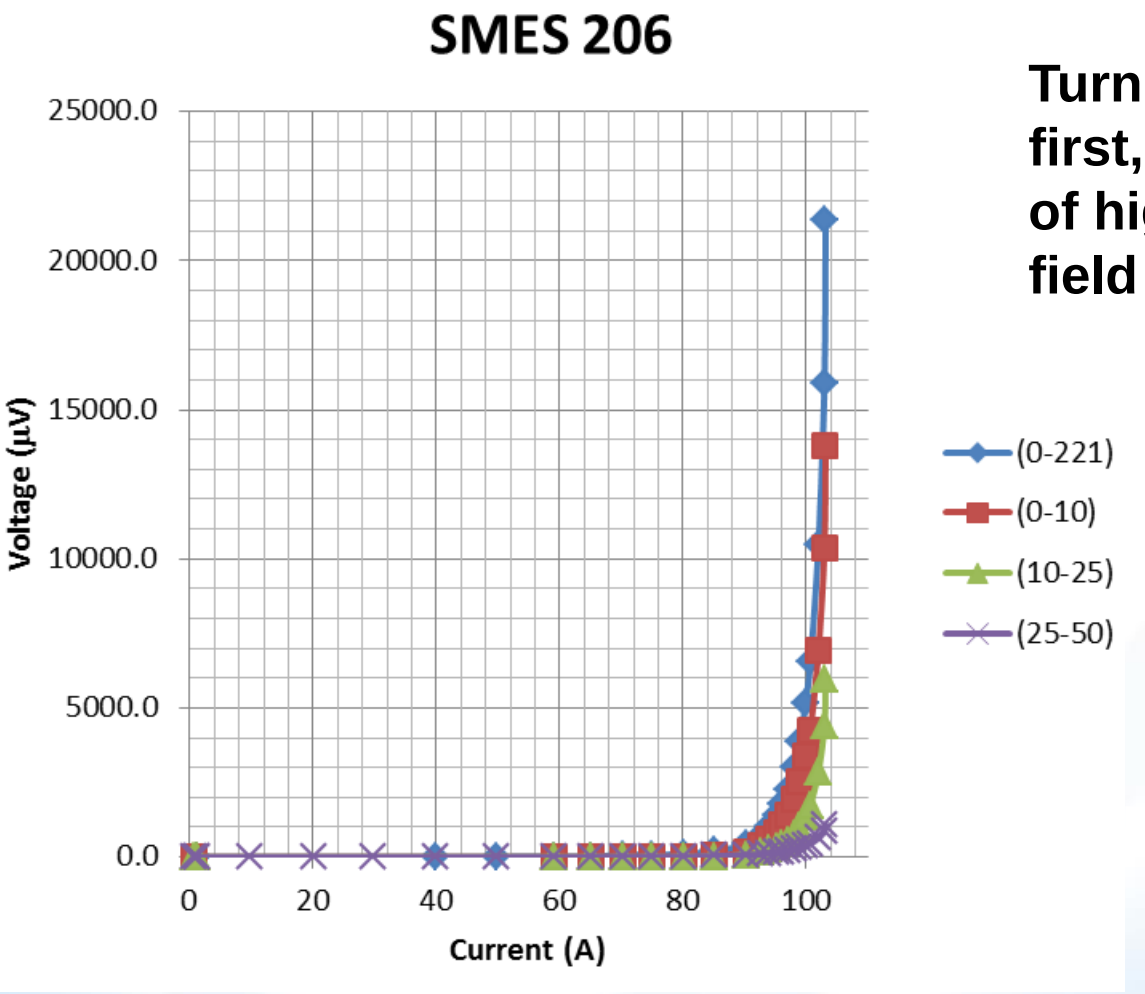


Pancake SMES206 is good but coil SMES205 develops resistive voltage early on.

SMES205 can't be used in the device.

Extra leads in the middle (new in the outer coil setup) allows test of good coil individually when there is an issue with one coil (such as here)

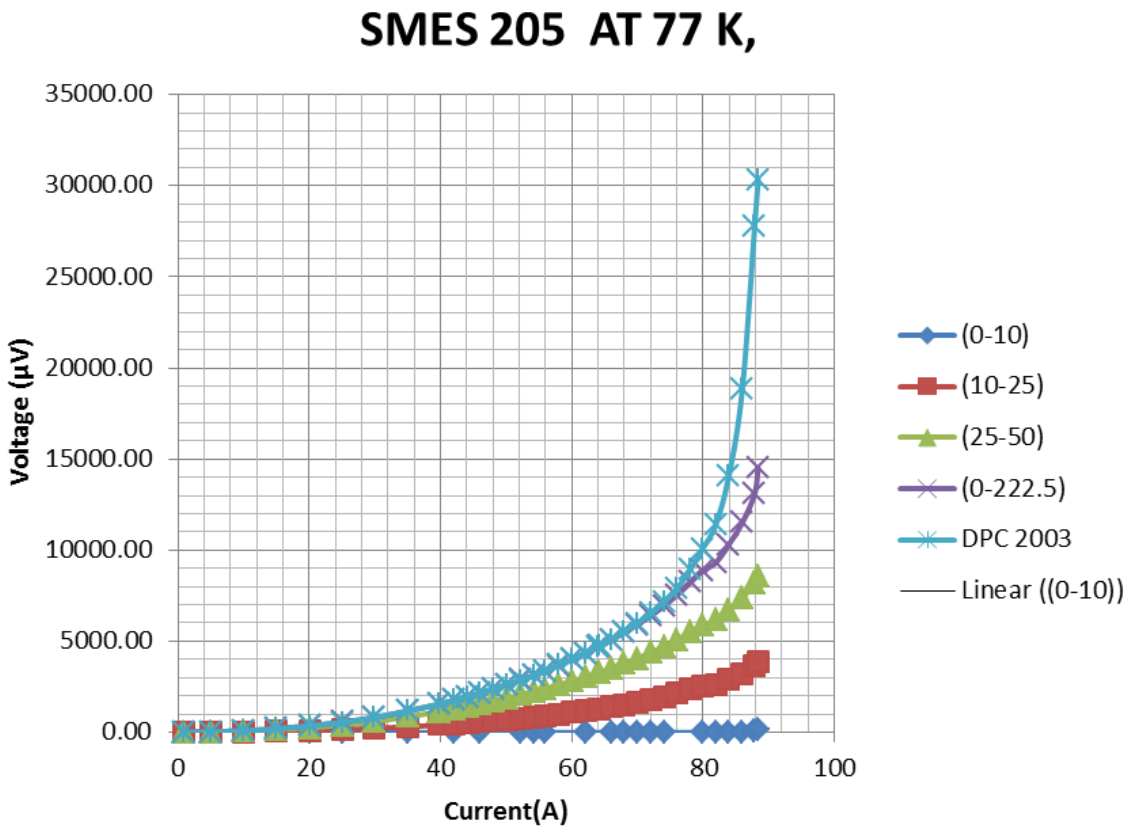
Outer Pancake Coil SMES 206 (good) Powered Alone



Turn #0-10 turns normal first, as expected, because of higher perpendicular field component.

Outer Pancake Coil SMES 205 (bad) Powered Alone

(Measurement of voltage on the coil and on the group of turns)



Early onset of indicates that there is a significant problem in this coil.

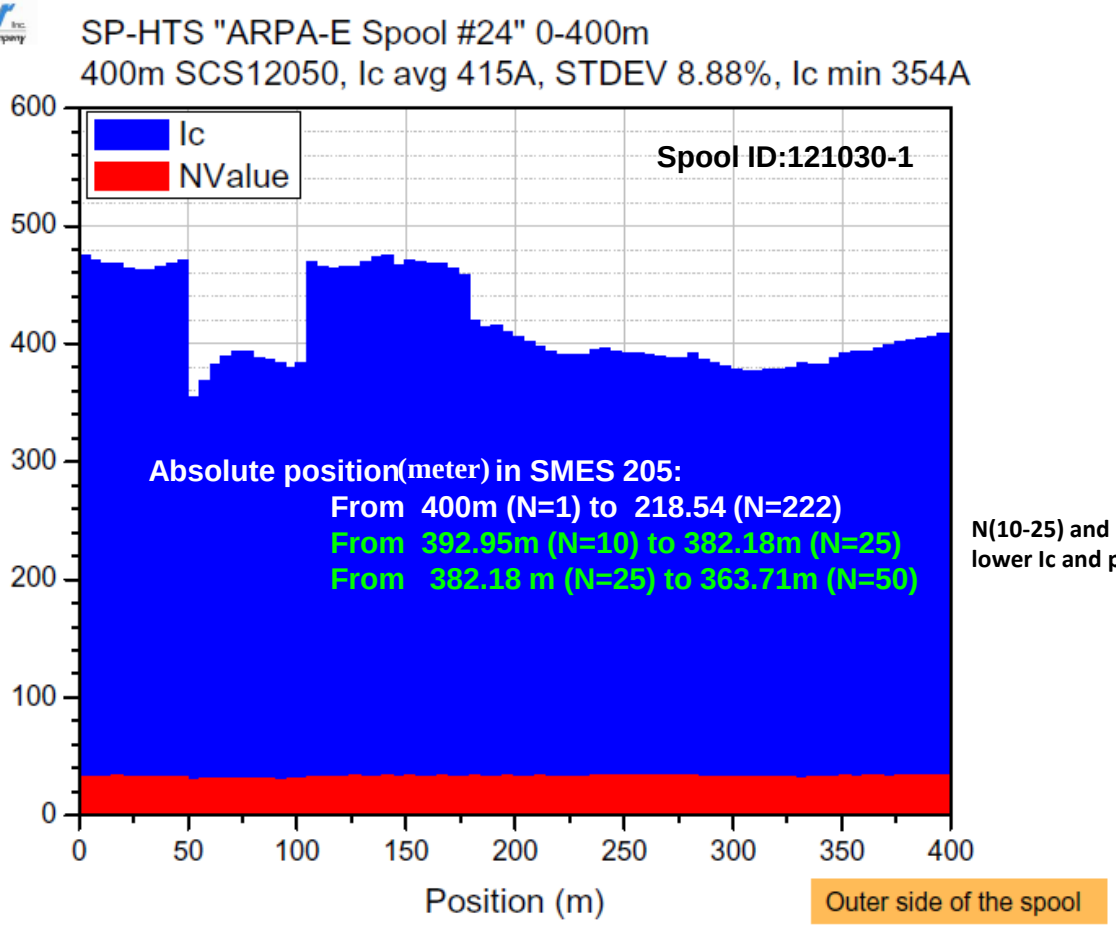
Turn #10-25 and #25-50 see significant voltage before turn #0-10.

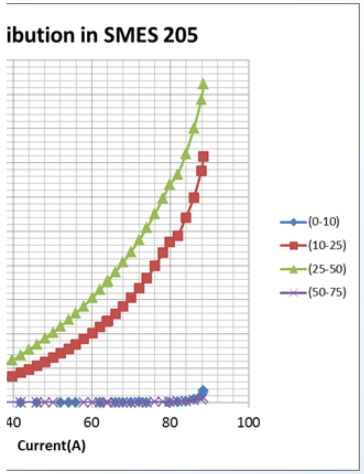
A new outer pancake coil has already been wound which will be used instead of this coil.

SuperPower has offered a replacement conductor.

Detailed Investigation of the Conductor Used in SMES205

Absolute position of conductor in the coil turns of SMES 205





N(10-25) and N(25-50) have lower Ic and poor N value.

#1) started from here

Conductor critical current in self-field is significantly higher than that in the coil where the field is much larger.

Summary

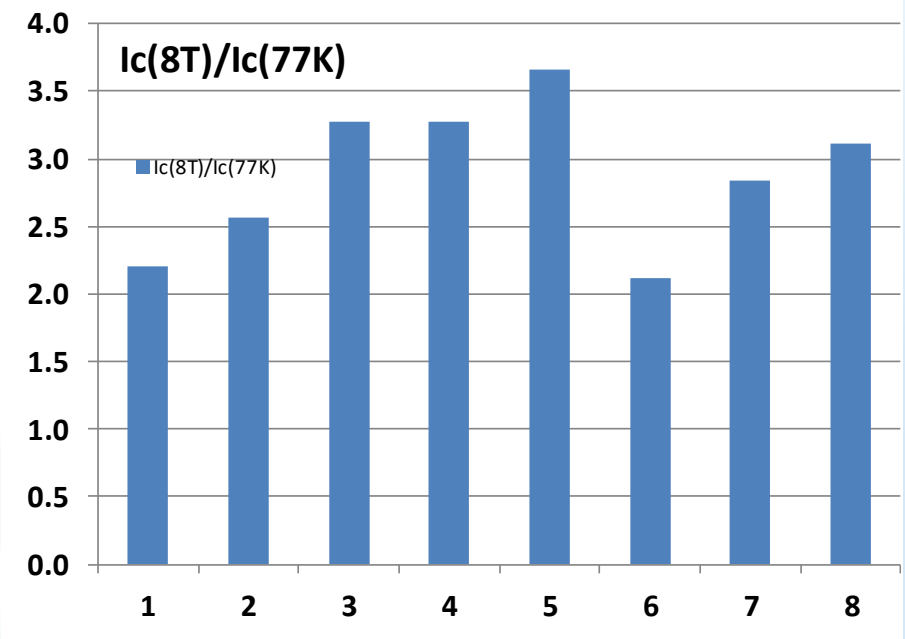
- **Construction of all inner pancakes and all outer pancakes for 1.7 MJ has been completed.**
- **Fabrication of fixture for testing outer double pancake at 77 K has been completed and successfully used. It allows testing of both pancakes even when they have significantly different critical currents.**
- **All inner pancakes and five outer pancakes have been tested at 77 K.**
- **QA in place has been effectively used. We continue to monitor all parts and construction carefully. Successful construction and test of 10 T coil in Q6 gives us a degree of confidence.**

Backup Slides

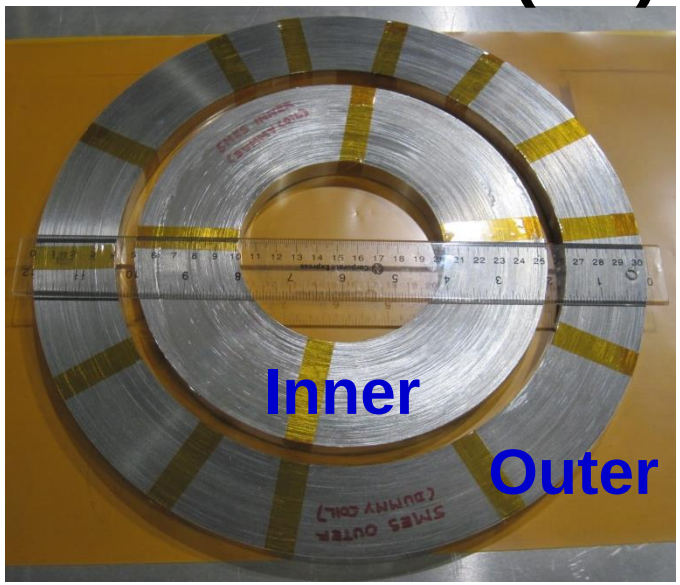
Opportunity to Increase High Field Performance of REBCO

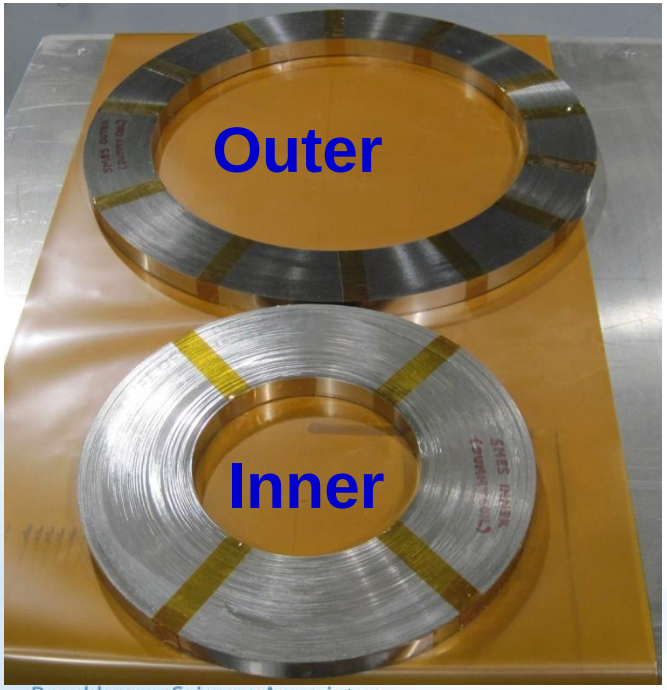
- Critical current of HTS tape is highly anisotropic. Coil performance is limited primarily by its field perpendicular value (or within 20^{o} of this angle)
- BNL measurements of the wire used in coil show that 4K perpendicular field Ic varies as much as ~2X (726A to 1401A)
- Once we understand the sources, we may be able to apply them in production
- See earlier presentations by Selva
- Here is an opportunity for increasing high field Ic by a factor of two or more
- ARPA-E SMES is driving this R&D
- BNL will receive the improved wire from Houston as a part this program

Sample Num	Comments	Tape Width, mm	Ic_Perp(8T)	Ic(77K)	Ic(8T)/Ic(77K)
1	PERP TEST	12	726	330	2.200
2	PERP TEST	12	800	312	2.564
3	PERP TEST	12	1119	341	3.282
4	PERP TEST	12	1324	404	3.277
5	PERP TEST	12	1401	383	3.658
6	PERP TEST	12	773	365	2.118
7	PERP TEST	12	956	337	2.837
8	PERP TEST	12	1369	439	3.118

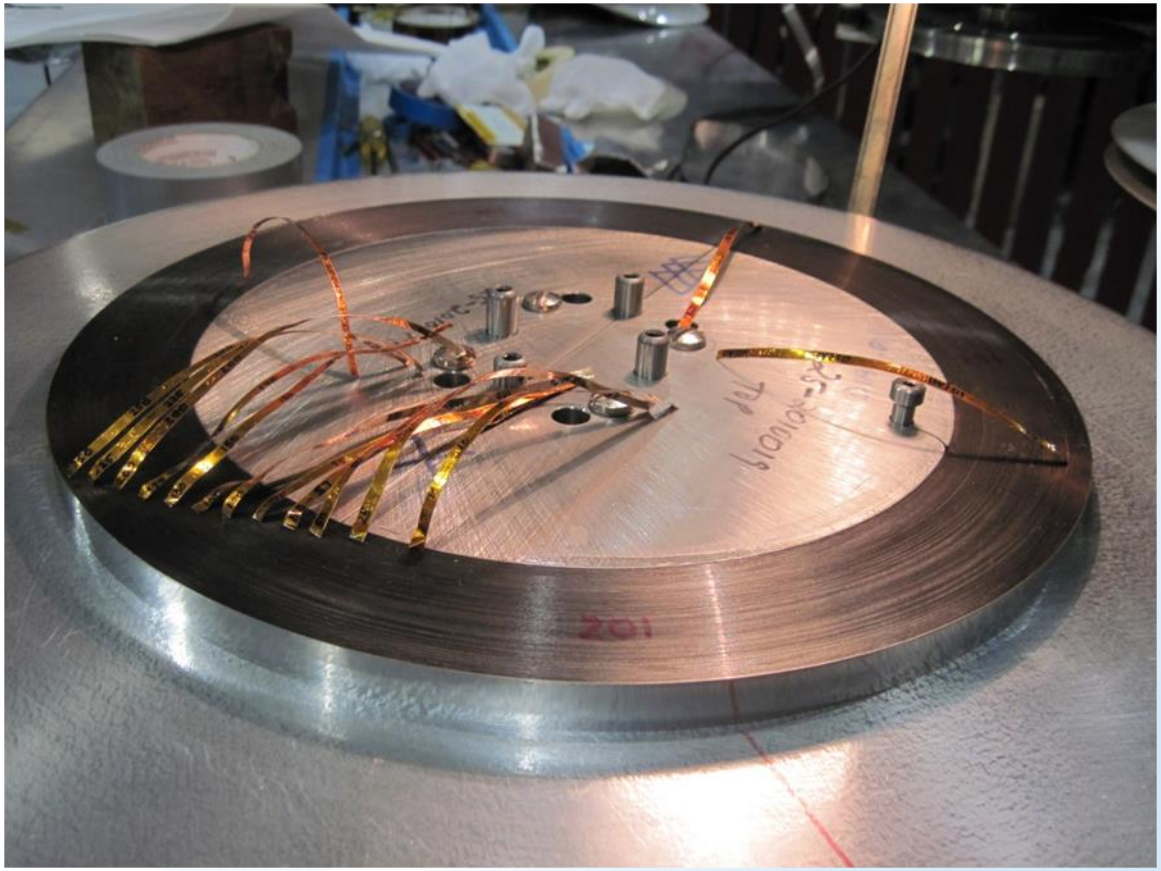


Practice coils (SS)



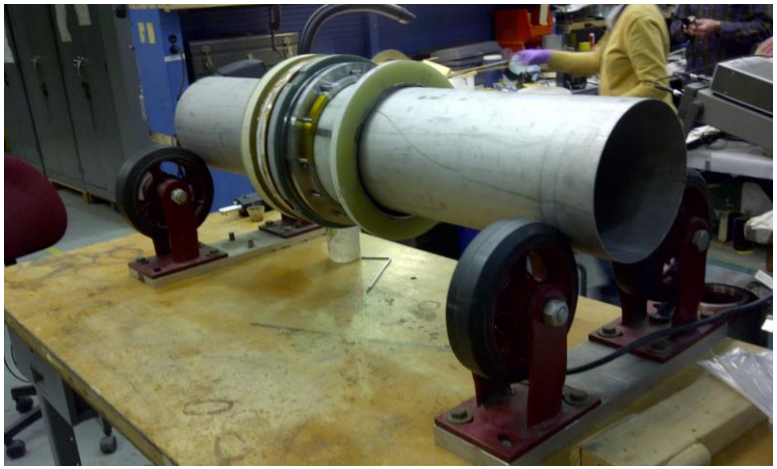


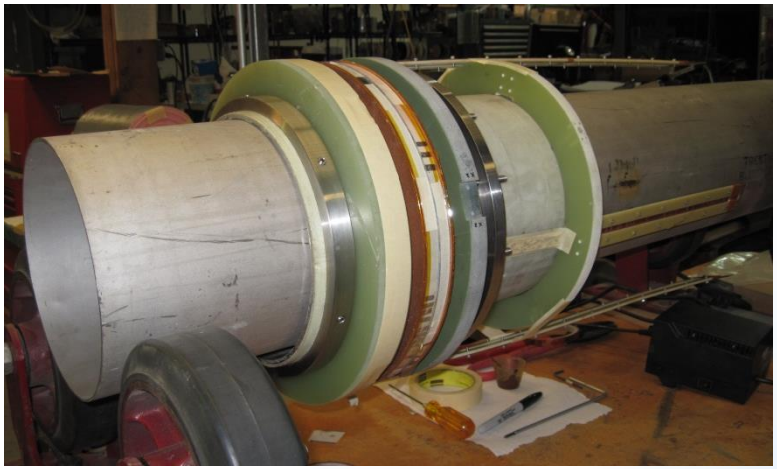
Outer Pancake #1



Made with ~210 meter of 12 mm tape with 65 micron copper.
25 micron of SS tape between turns (No. of turns = 258).

Intermediate Steps in Preparation for 77 K Test

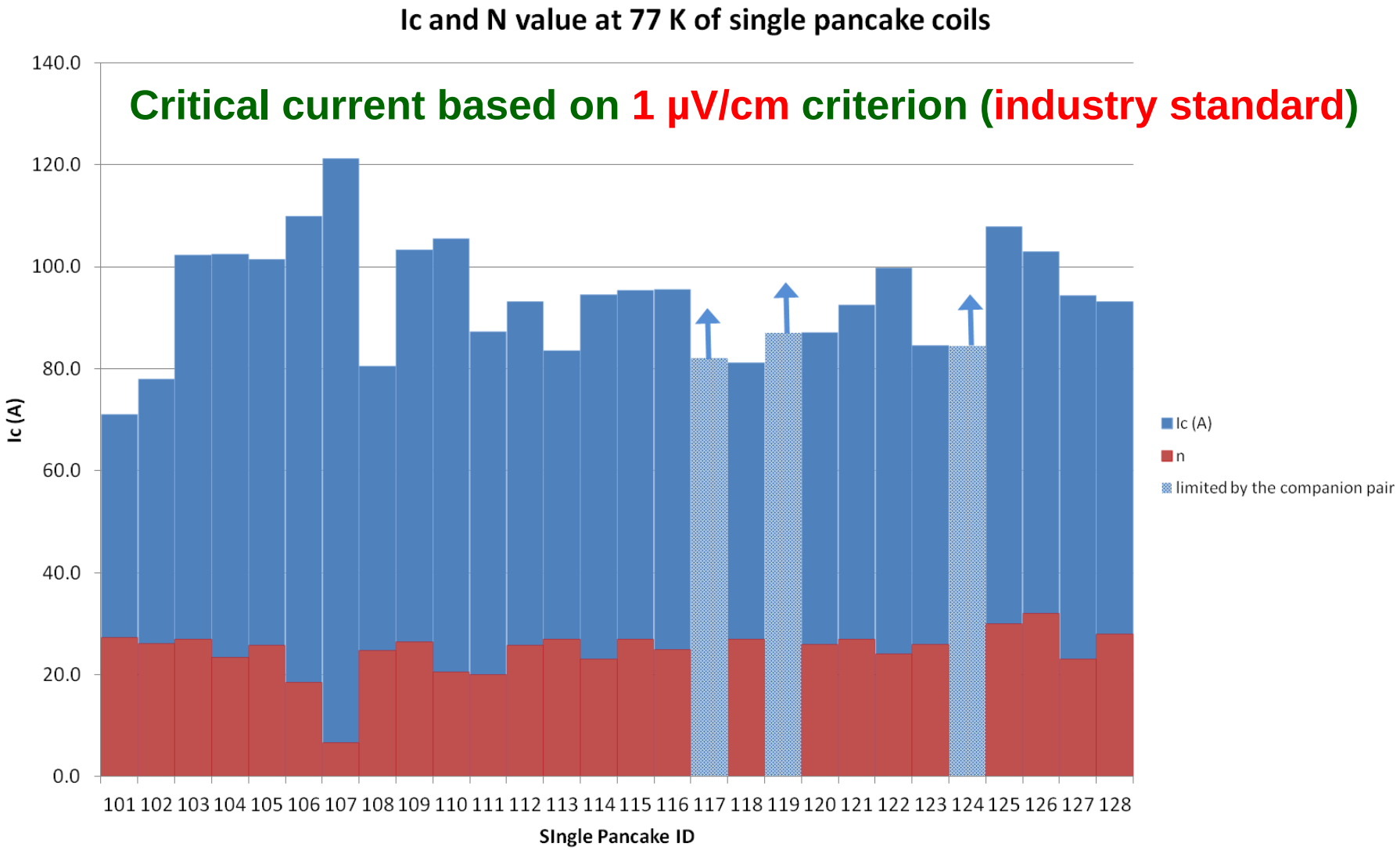




Demanding Requirement on the Conductor

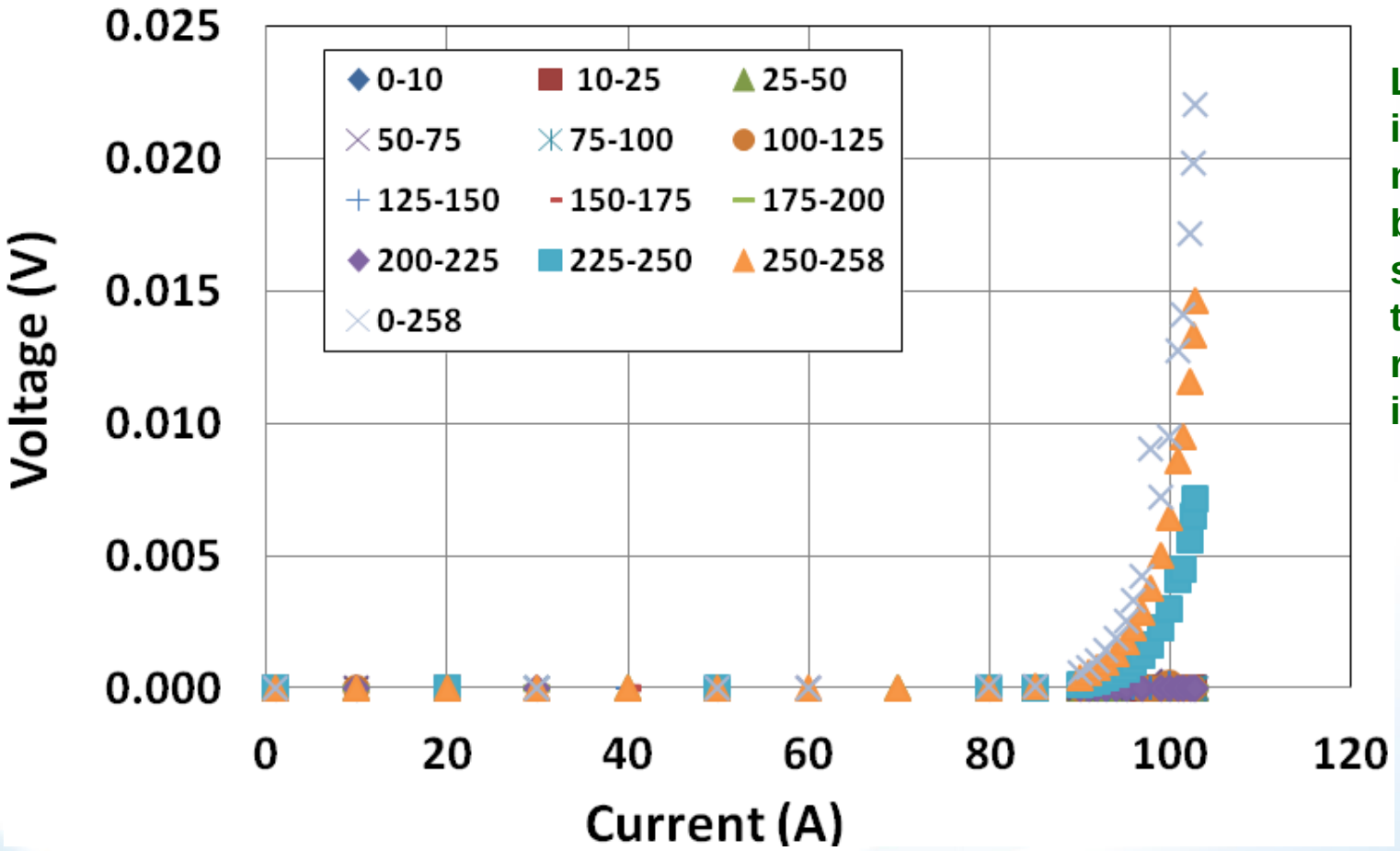
- High strength, high performance conductor is one of the major enabling technology of this project
- This project uses a large quantity of the conductor : 8.4 km of 12 mm width (equivalent to over 25 km of standard 4 mm width)
- The project relies on the unique wire that SuperPower produces in large quantities with requirements never demanded by any project before: very high fields, very high strengths, very high stress/strain tolerances and good bonding with copper stabilizer
- For this reason a conductor that might be OK for other projects, may not be acceptable here. Therefore, the conductor is carefully monitored as it pays out during winding and any deviation is reported
- Variety of examples have been shown. The wire was sent to SuperPower for further inspection. All being replaced voluntarily

Summary of 77 K test of all inner pancakes



Tested in double pancake structure with two single pancakes powered in series.
Arrow indicates lower performing pancake limiting the I_c measurements.

77 K Test Result of the First Outer Pancake

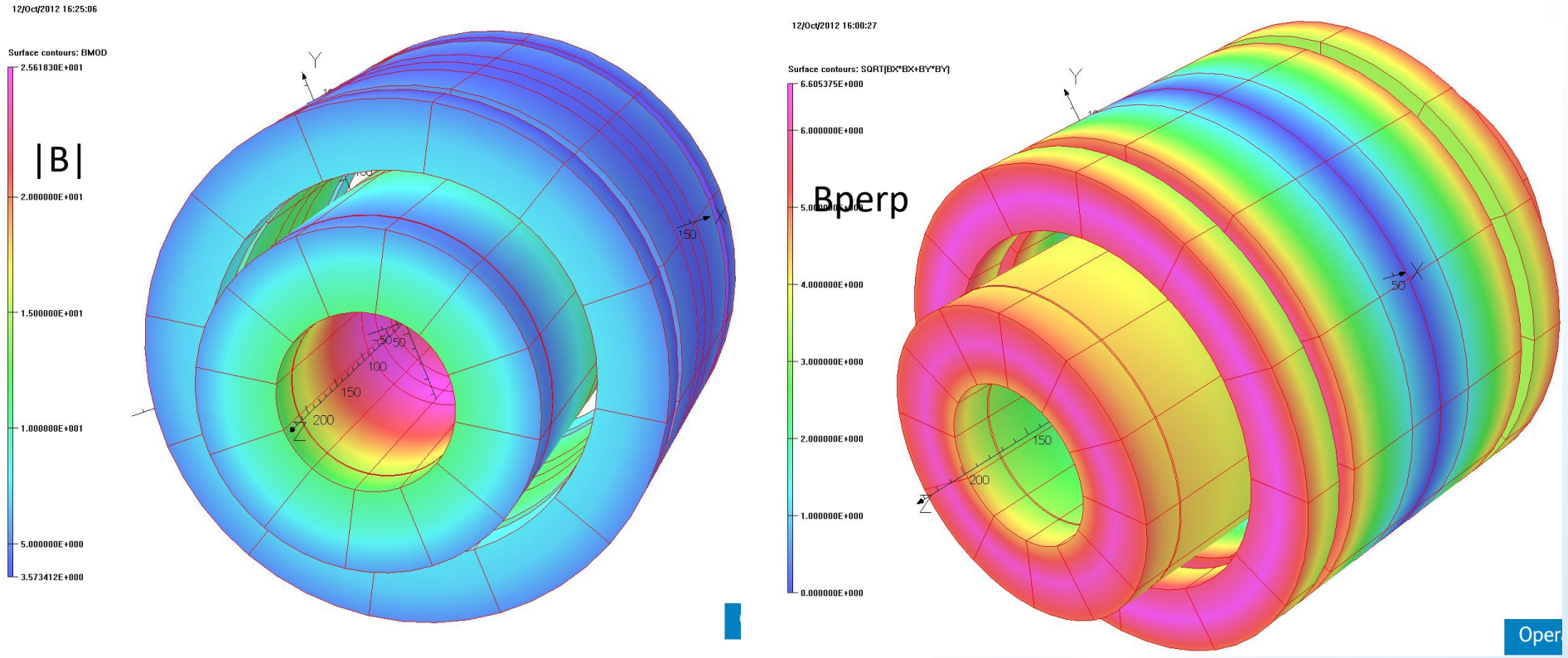


Legends indicate the turn numbers between the sections where the onset of resistive voltage is measured

Pancake reaches over 100 A (1 μV/cm criterion)

- **Coil and winding techniques are acceptable**
  - ✓ **OK to proceed**

1.7 MJ SMES Coil Design



No. of Pancakes: 28 inner and 16 outer (28 outer will give 2.5 MJ)

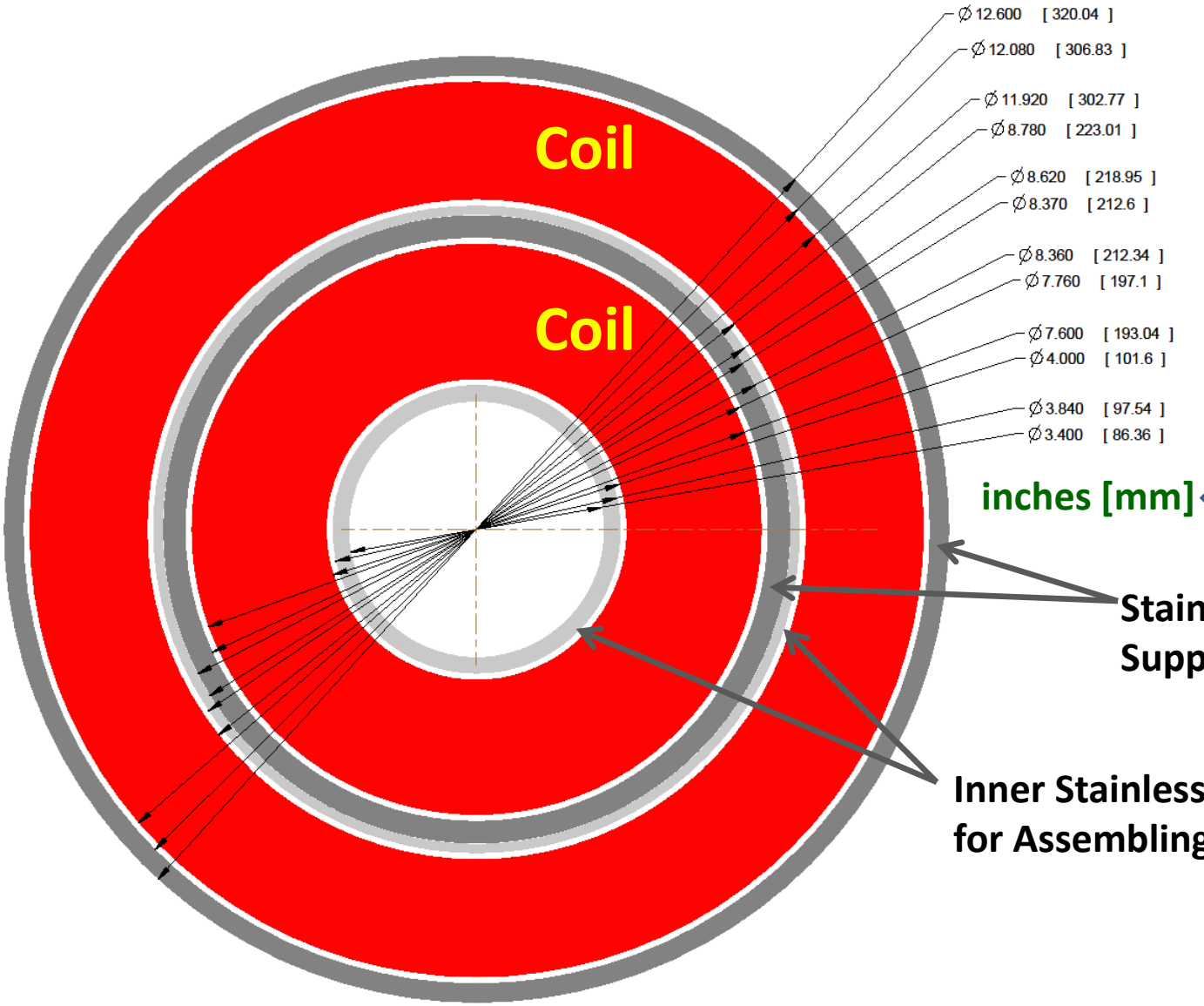
Strategy: Optimize for 1.7 MJ but do not prevent 2.5 MJ upgrade

Note: Use high strength conductor in the middle section

Nominal Parameters of 1.7 MJ SMES Coil

Stored Energy	1.7	MJ
Currrent	720	Amperes
Inductance	7	Henry
Maximum Field	25	Tesla
Operating Temperature	4.2	Kelvin
Overall Ramp Rate	1.2	Amp/sec
Number of Inner Pancakes	28	
Number of Outer Pancakes	16	
Total Number of Pancakes	44	
Inner dia of Inner Pancake	101	mm
Outer dia of Inner Pancake	193	mm
Inner dia of Outer Pancake	223	mm
Outer dia of Outer Pancake	303	mm
Intermediate Support	15	mm
Outer Support	7	mm
Width of Double Pancake	26	mm

Cross-section of Coil and Support Tube Structure



Note: The cross-section remains the same for 1.7 MJ or 2.5 MJ (or something in between). Only the number of double pancakes to be assembled changes.

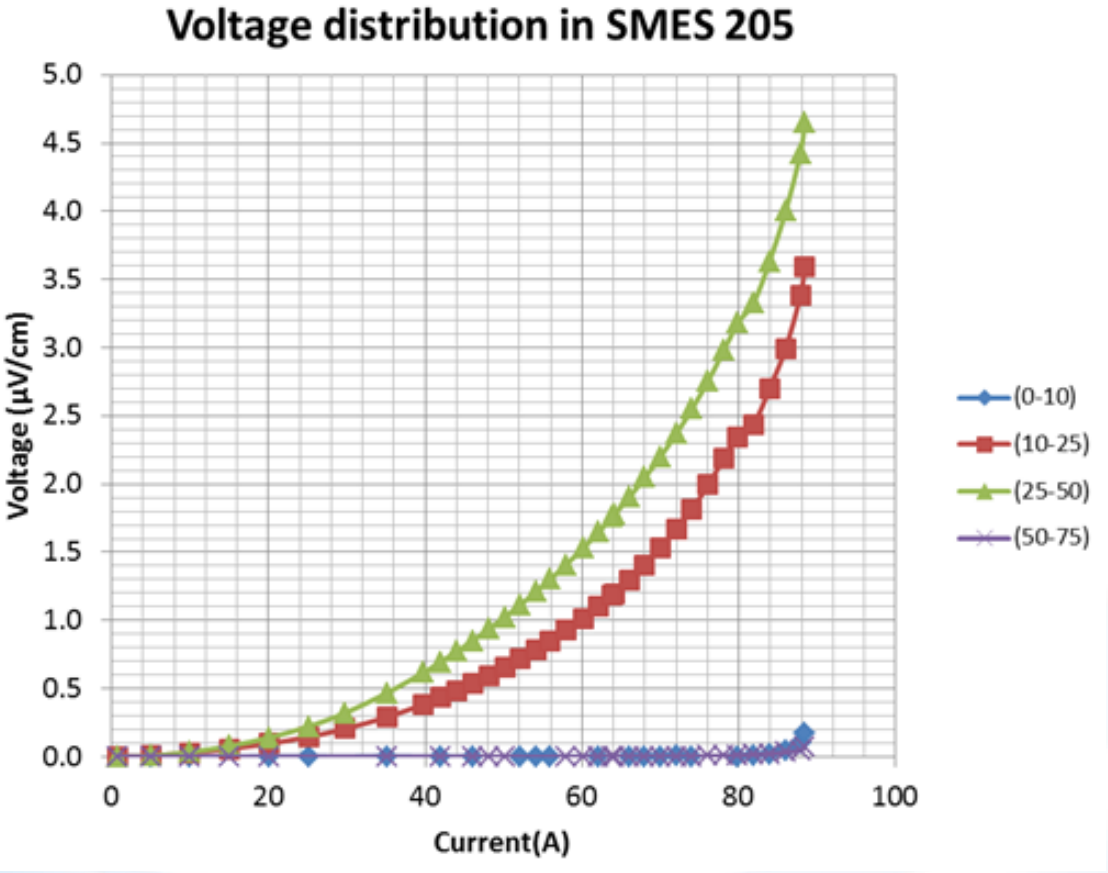
inches [mm] ⇦ units

Stainless Steel Support Tubes

Inner Stainless Steel Tubes for Assembling Pancakes

Coil SMES 205 Powered Alone

(Voltage gradient on the coil and on group of turns)



Pancake SMES205 is suspected because the turn #10-25 and turn #25-50 see an early onset of resistive voltage.

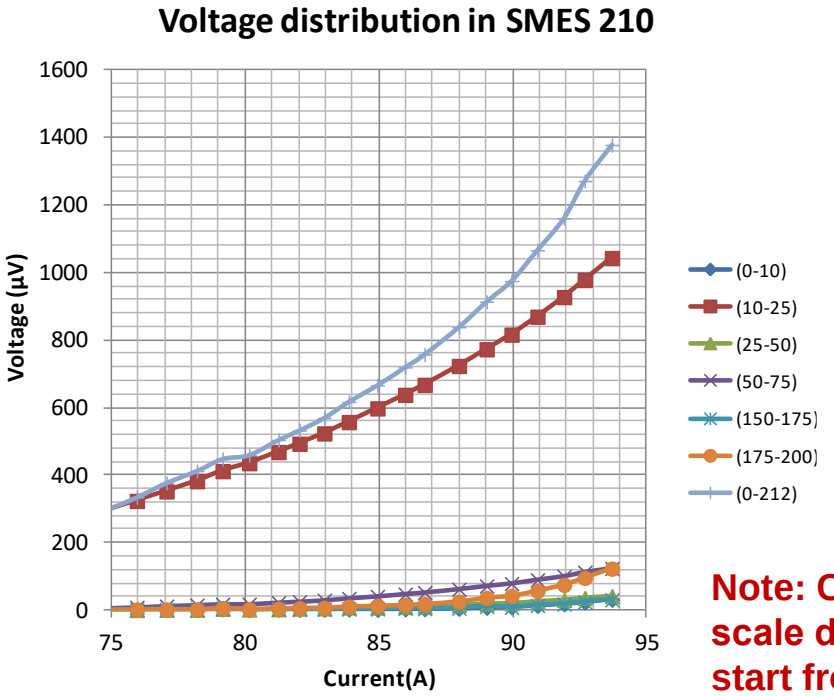
This could be either due to a mishap during winding or a weak portion of the conductor was not caught by visual inspection.

Critical current is usually defined at 1 μV/cm but that definition is relevant here.

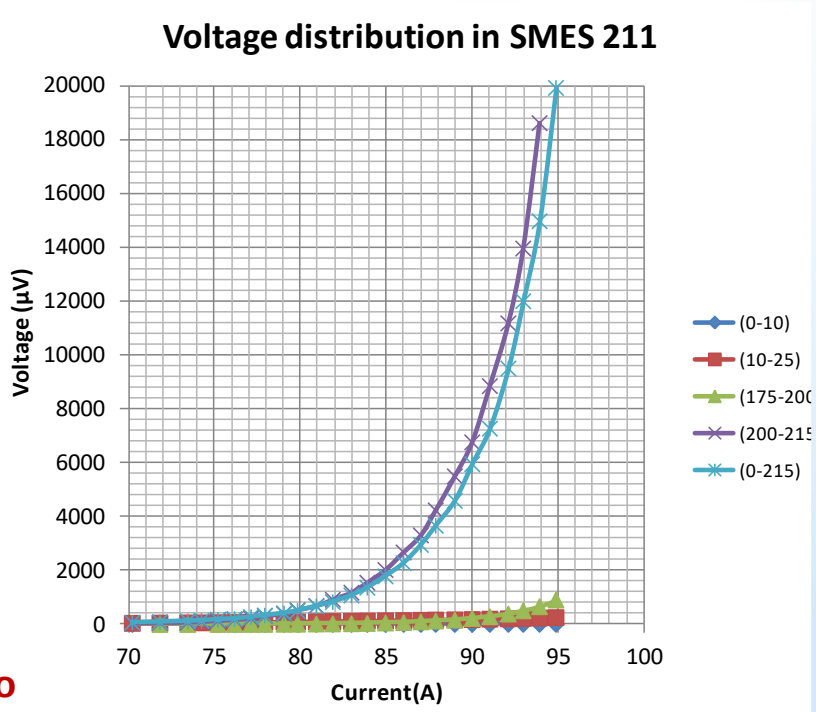
Test Results of Double Pancake 2004

(2 pancakes powered in series)

Note: In both coils the onset of voltage doesn't start in turn#1-10. However, there is no defect in the coil. This has been seen before and is likely due to variation in in-field performance due to variation in doping.



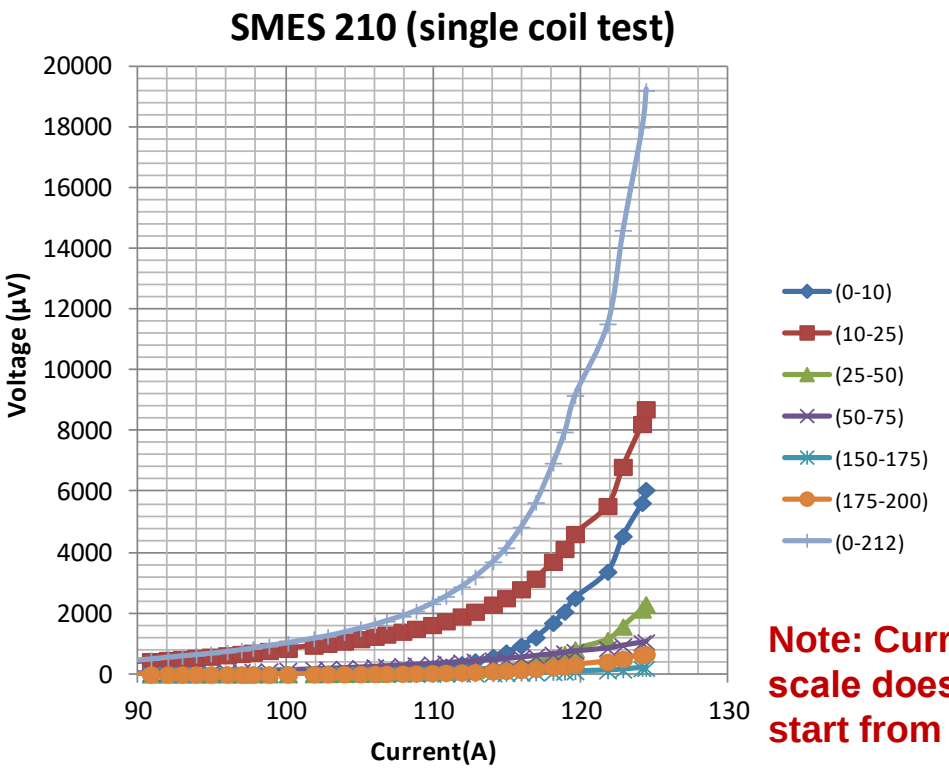
Note: Current scale doesn't start from zero

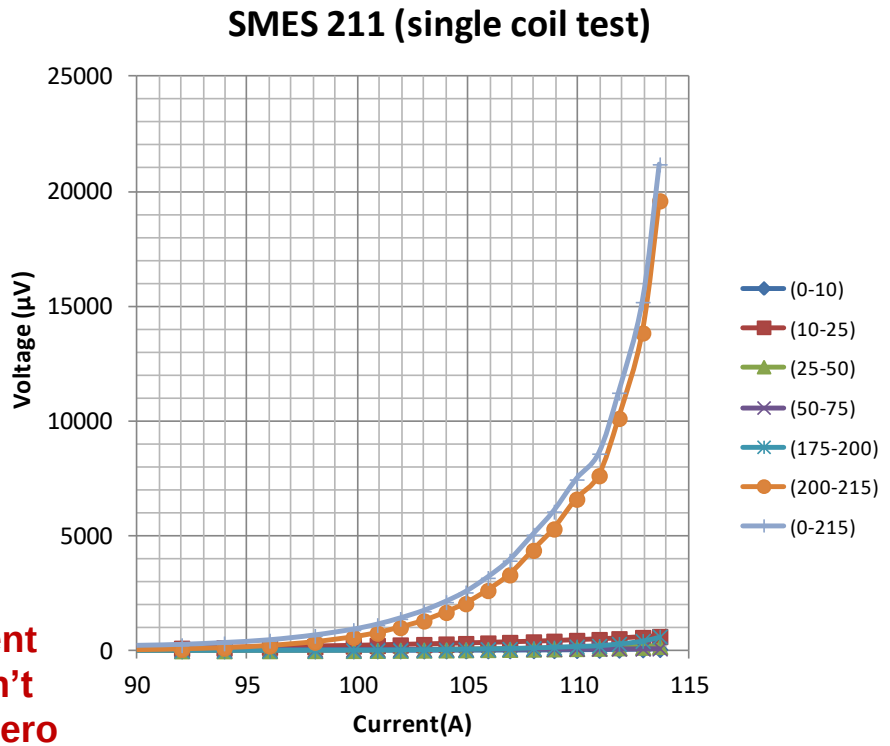


Extra leads in the middle (new in the outer coil setup) allows detailed test of individual coil separately when there is a significant difference in performance (such as here).

Coil SMES210 and SMES211 Powered Alone

(Measured voltage on the coil and on group of turns)





Note: Current scale doesn't start from zero

Note: In both coils the onset of voltage doesn't start in turn#1-10. However, there is no defect in the coil. This has been seen before and is likely due to variation in in-field performance due to variation in doping.