

Status of SMES Coil Testing and Engineering Design

Ramesh Gupta (BNL PI - SMD)

Piyush Joshi (Electrical Engineer)

Seetha Lakshmi (Post-doc)

Jesse Schmalzle (Mechanical Engineer)

Mike Anerella (Mechanical Engineer)

Peter Wanderer (Division Head)

Superconducting Magnet Division
May 15, 2013

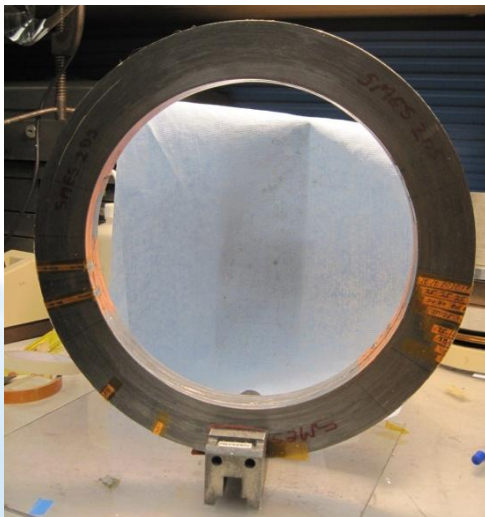
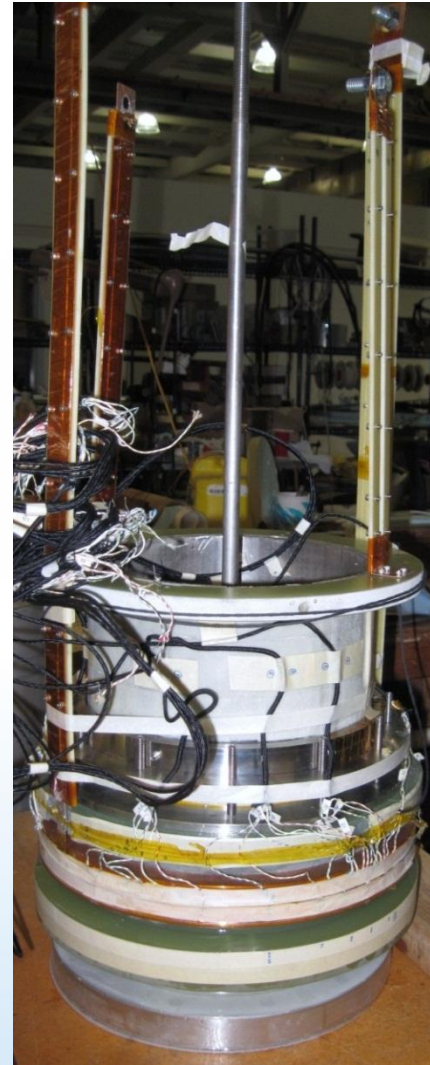


Overview of Activities

- **Construction and test of outer pancake coils**
- **1.7 MJ SMES coil design analysis and update**
- **Status of engineering design and fabrication of parts**
- **Quench protection system update**
- **Summary**

Test of Outer Pancake Coils in Q10

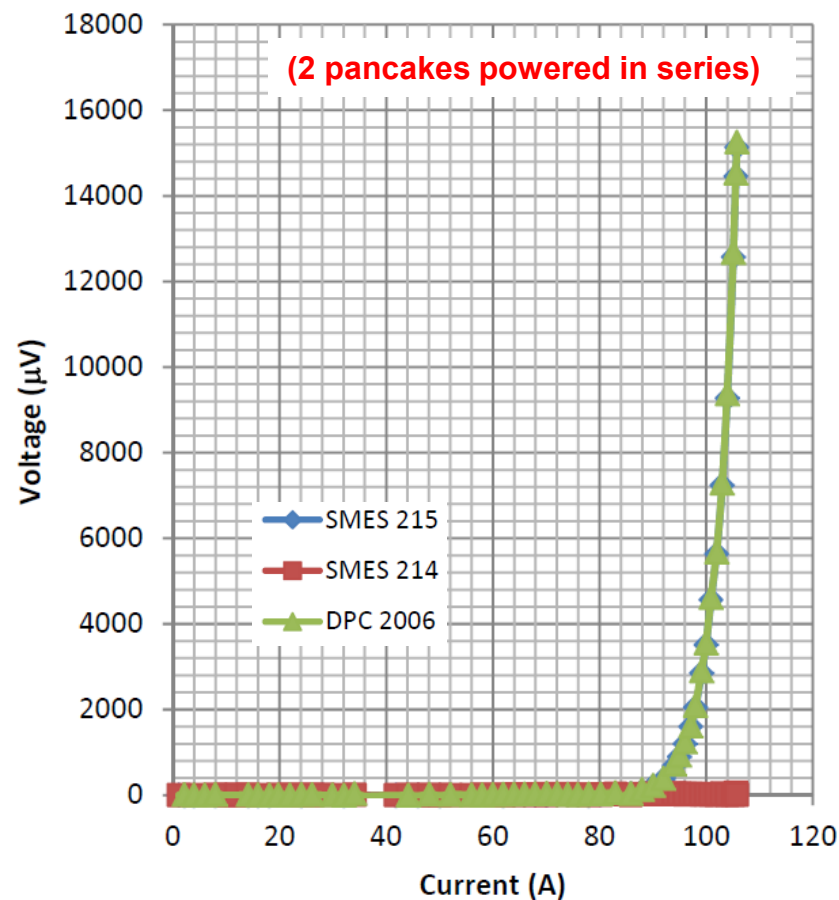
- Six outer double pancake coils assembled from the remaining twelve single pancakes wound in Q9
- Six double pancakes tested
- Four leads allow independent testing of two coils and splice
- Number of voltage taps allow critical QA testing at 77 K
- Six test results fall in three categories. Example of one each presented (others included in the back-up slide section)



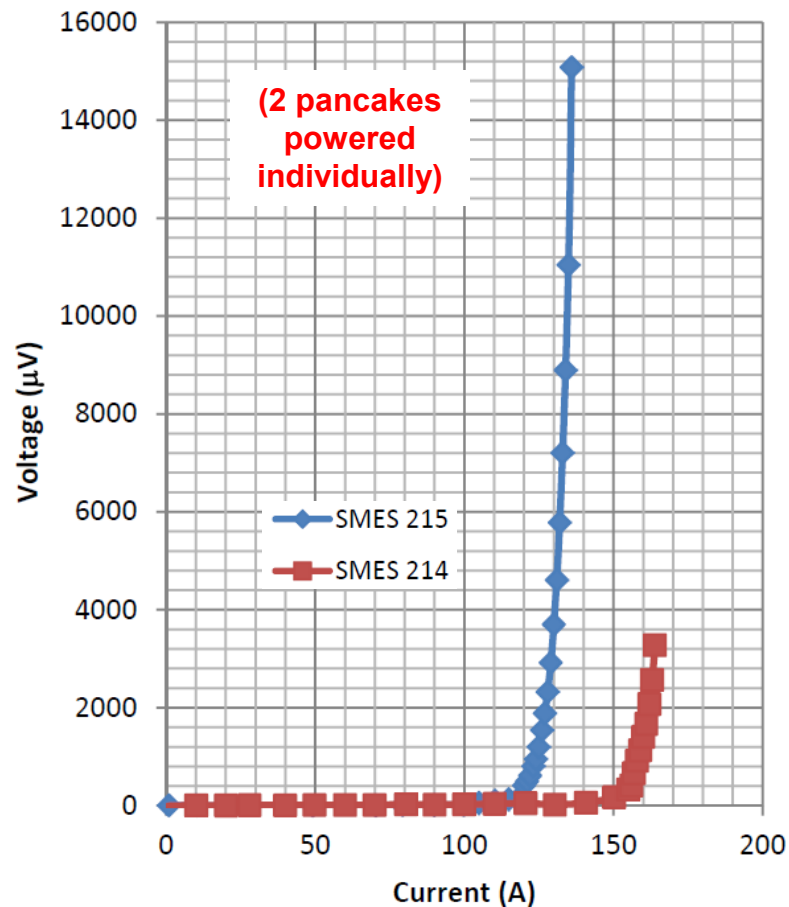
Outer Double Pancake DPC2006

(two single pancakes in double pancake with significantly different critical currents)

DPC 2006- SMES 214 and SMES 215



DPC 2006- SMES 214 and SMES 215



Note:
77K, self-field I_c of conductor used in two pancakes was not so different

- SMES214 has much higher I_c than SMES215
- Coil SMES214 has the highest I_c of all
- See two similar cases in back-up slides

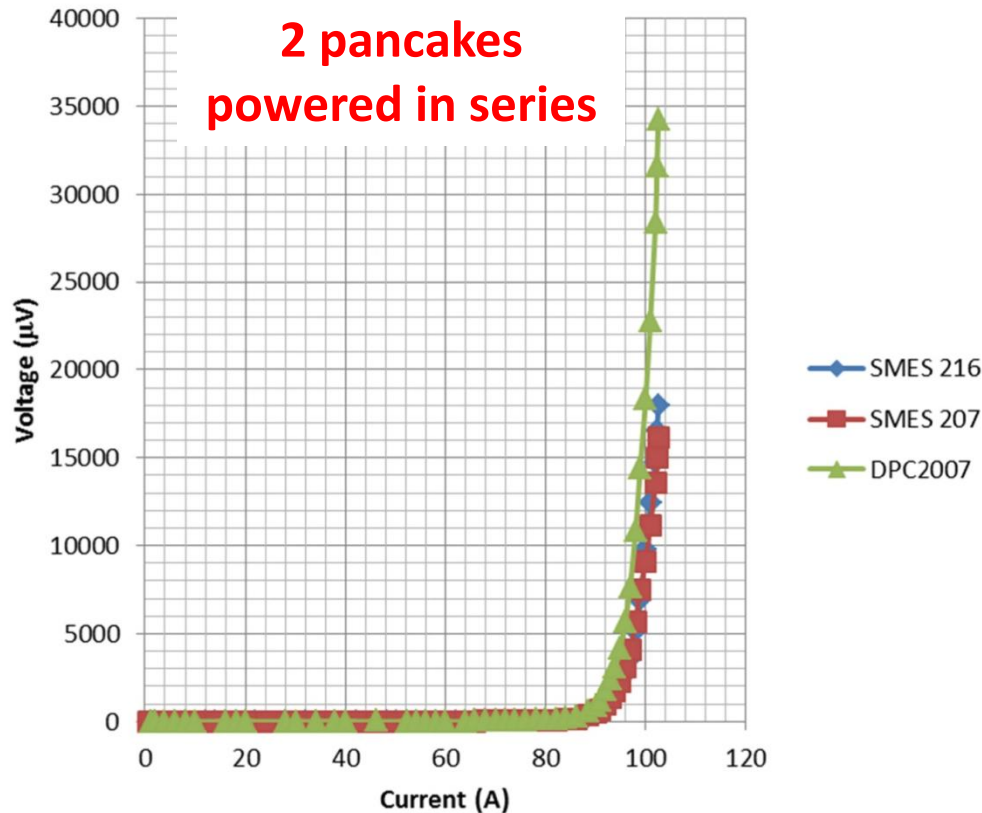
	N	1μV/cm
SMES 215	27	105.5
SMES 214	-	>106
DPC 2006	26	108.5

	N	1μV/cm
SMES 215	29	136.2
SMES 214	33	171.6

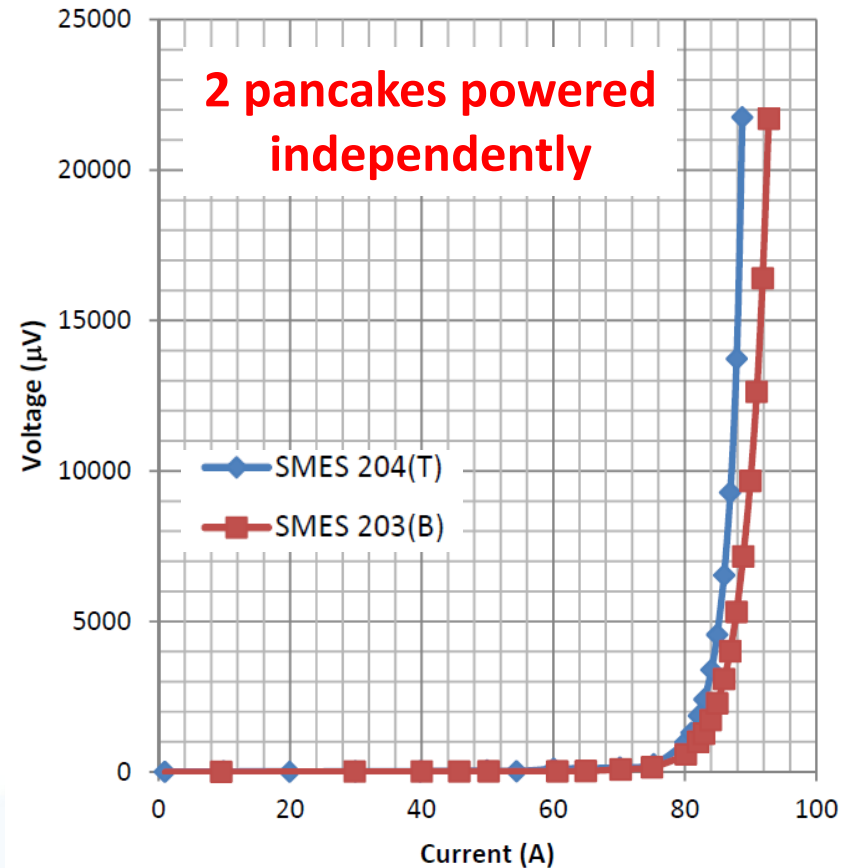
Outer Double Pancakes DPC2007 and DPC2002

(two single pancakes with similar critical currents in each double pancake)

DPC 2007- SMES 207 and SMES 216



DPC2002- SMES 203 and SMES 204



- 216 & 207 in DPC2002 and 204 & 203 in DPC2007 have similar critical current
- See details of the test results in back-up slide section

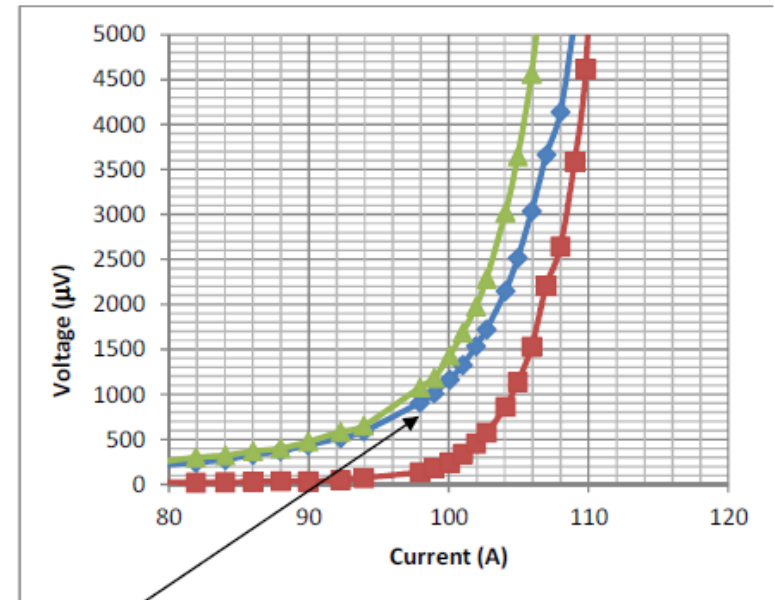
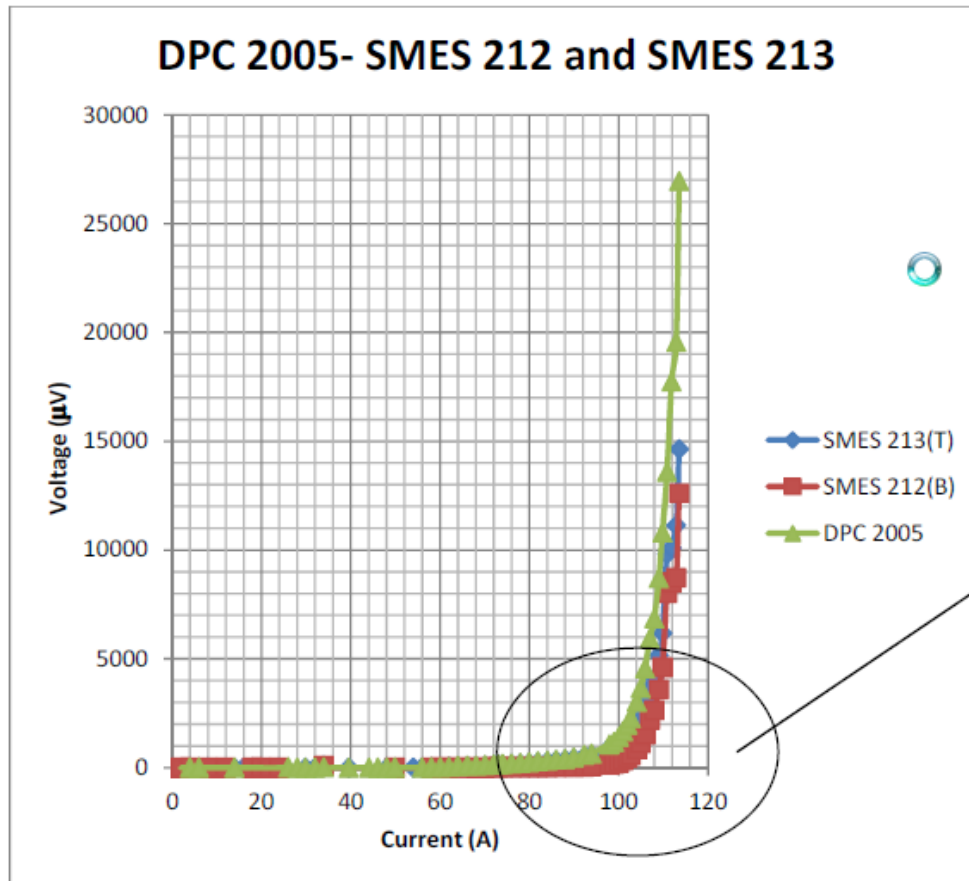
Outer Double Pancake DPC2005

(one single pancake didn't pass 77 K QA test)

- DPC2005 would appear OK for 1 $\mu\text{V}/\text{cm}$ critical current summary of 213 & 212.
- However, a defect is identified when examined carefully

➤ see a broad transition in 213 (212 OK)

Coils connected in series



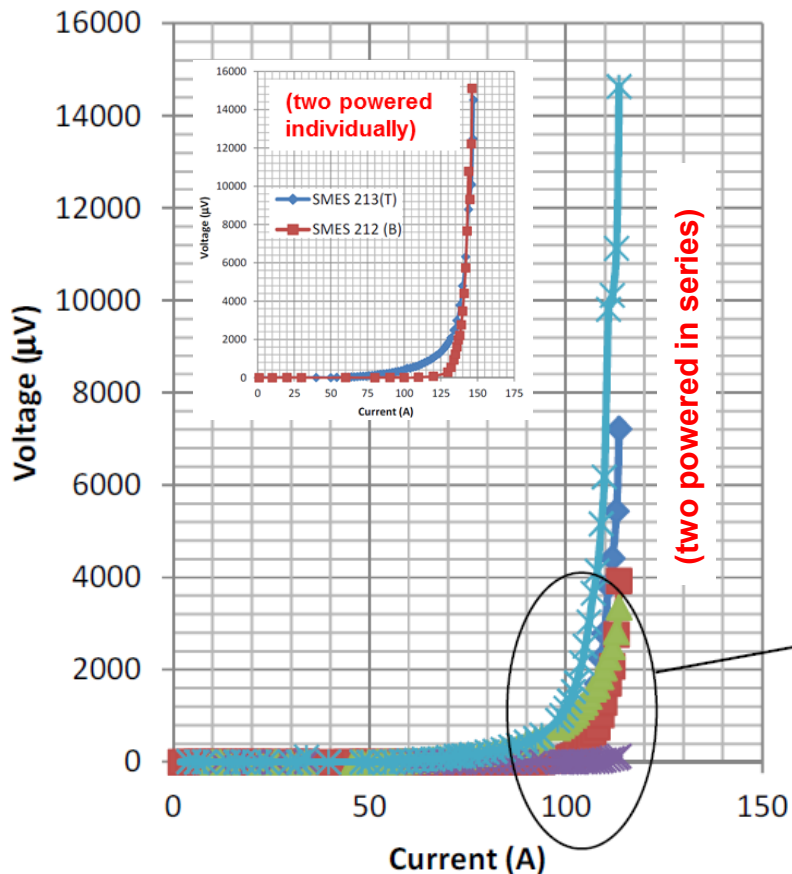
	N	I _c (A) @	
		1 $\mu\text{V}/\text{cm}$	0.1 $\mu\text{V}/\text{cm}$
SMES 213	20	114.2	101.8
SMES 212	31	113.8	105.7
DPC 2005	23	114.5	103.6

Outer Double Pancake DPC2005

- Detailed examination of voltage distribution across the turns show more issues.

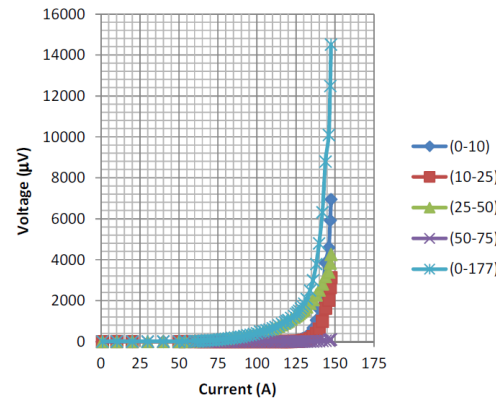
➤ Note: Power of thorough QA testing and analysis - it identified a weak link that could have potentially limited the performance of the entire 1.7 MJ SMES coil

SMES 213 in DPC 2005

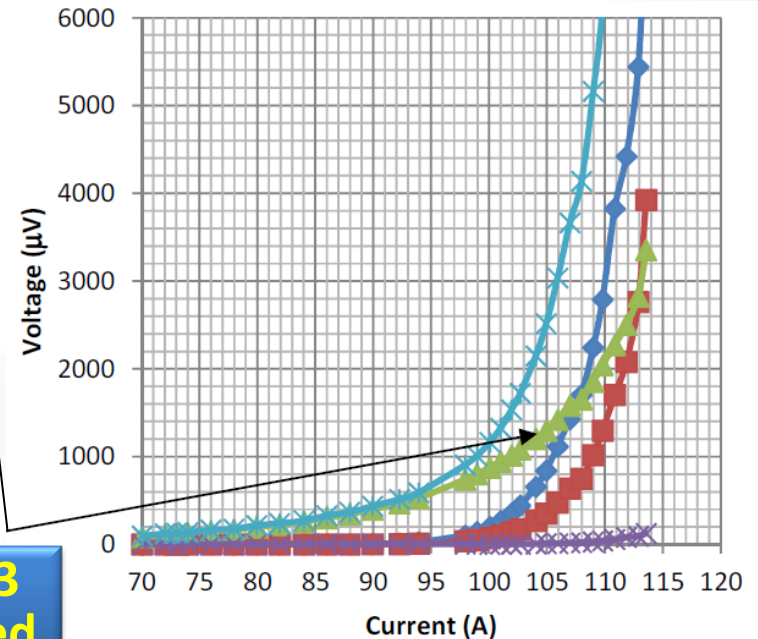
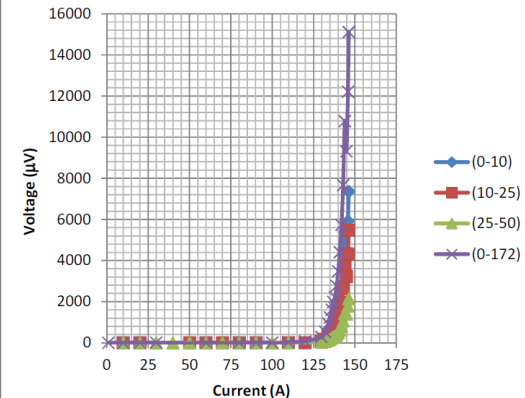


(2 pancakes powered individually)

SMES 213

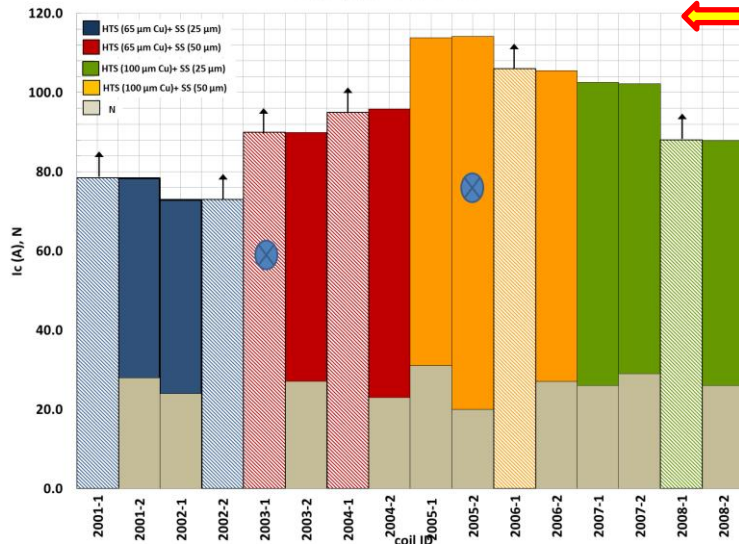


SMES 212



Summary of Outer Coil Performance @77 K

SMES- outer double pancake coils; at 77 K
I_c @ 1μV/cm criterion and N

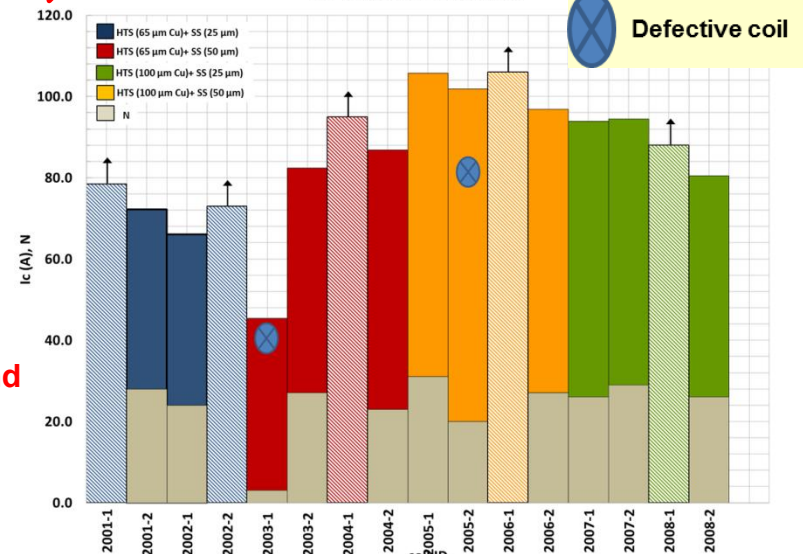


0.1 μV/cm →
← 1μV/cm

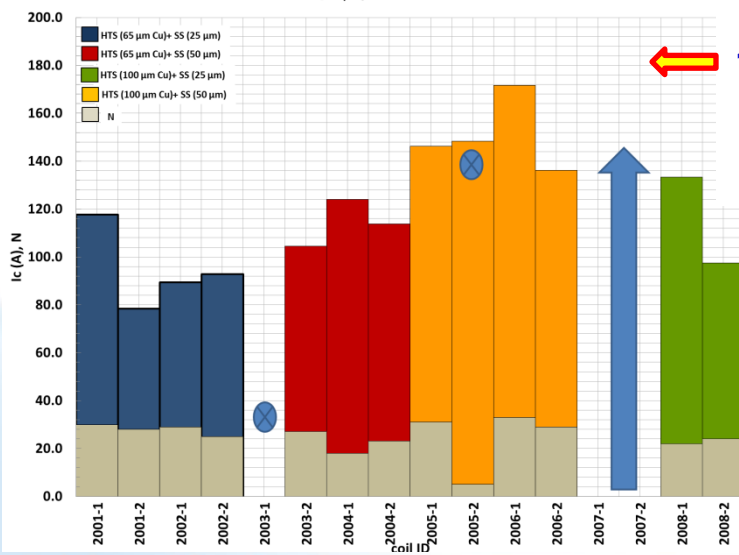
Two pancakes
powered in series

Note: A significant
difference in I_c of
2003-1 (SMES206)
between 1 μV/cm and
0.1 μV/cm criteria

SMES- outer double pancake coils; at 77 K
I_c @ 0.1μV/cm criterion and N



SMES outer double pancake coils: single coil test at 77 K
I_c @ 1μV/cm criterion and N



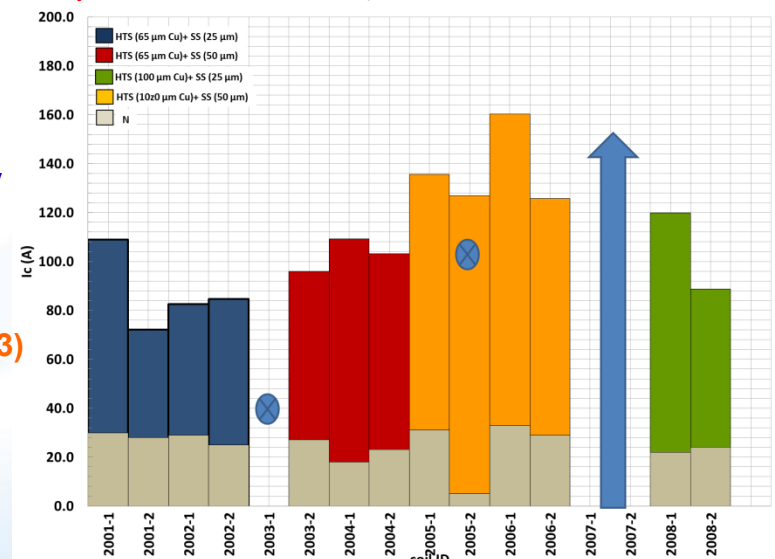
0.1 μV/cm →

Two pancakes
powered individually

Note: Poor n-value
of 2005-2 (SMES213)

2007-1 and 2007-2 were not
tested individually as they had
very similar performances

SMES- outer double pancake coils: single coil test at 77 K
I_c @ 0.1μV/cm criterion and N



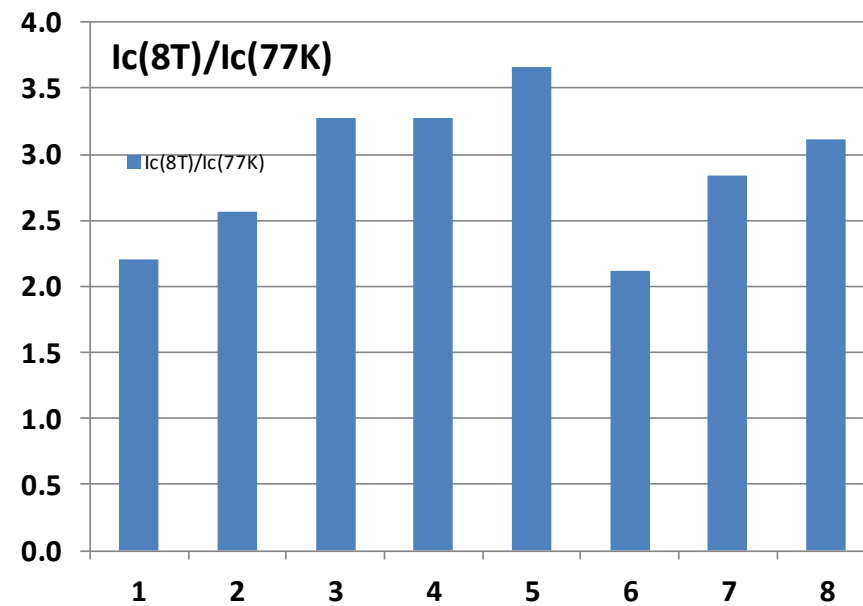
Choosing/Sorting the Locations of Pancakes

- The agreed I_c specification on wire is >700 A at “(4 K, 8 T)”. SuperPower has saved samples from each run. Measured data at “(77 K, self-field)” are available for each run and measured data at “(4K, 8T)” are expected soon from many more.
- BNL did its own measurements of several samples since in-field 4 K values are the one that are relevant for this project. We found a large variation in I_c values.
- The performance of SMES is likely to be limited by the coils in the end region because of a large anisotropy of I_c in HTS. Therefore we want the best coils there.
- In the absence of 4K data, we will sort based on the measured I_c in coils at 77 K.

Short sample measurements at BNL

Sample Num	Comments	Tape Width, mm	$I_{c_Perp}(8T)$	$I_c(77K)$	$I_c(8T)/I_c(77K)$
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

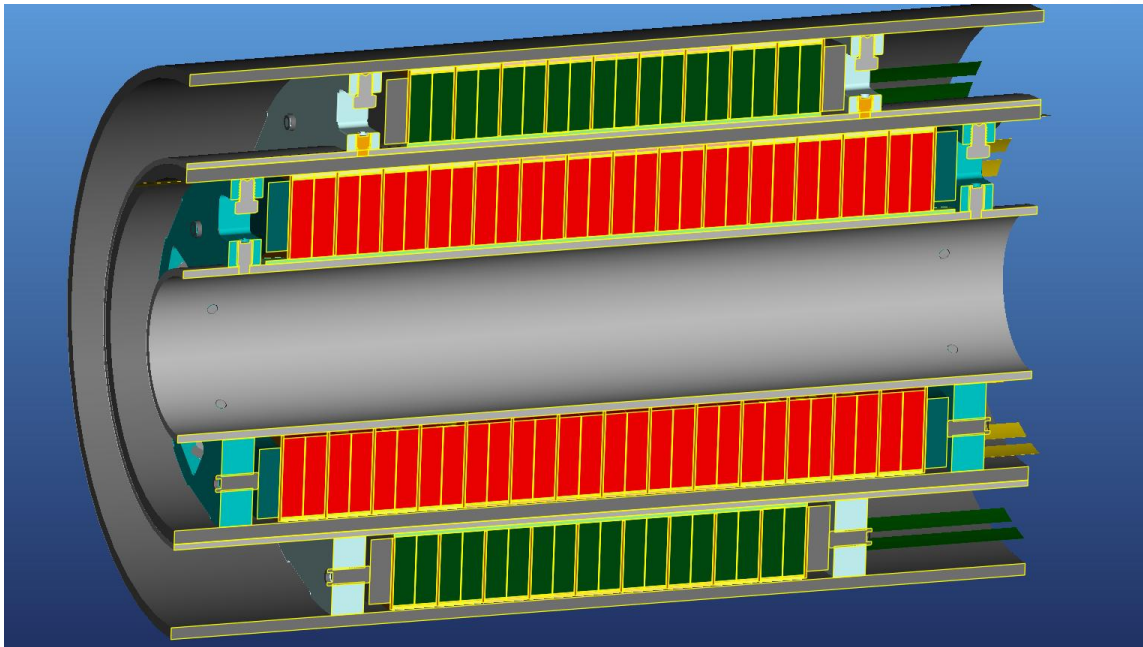
$I_c(4K,8T)$: 726 A to 1369 A (spec > 700 A)



Lift factor 2.1 to 3.7

Engineering Design of the 1.7 MJ Coil

- After getting a final direction on 1.7 MJ choice, a more complete engineering design has been developed (earlier postponed to avoid duplication of 1.7 MJ and 2.5 MJ efforts)



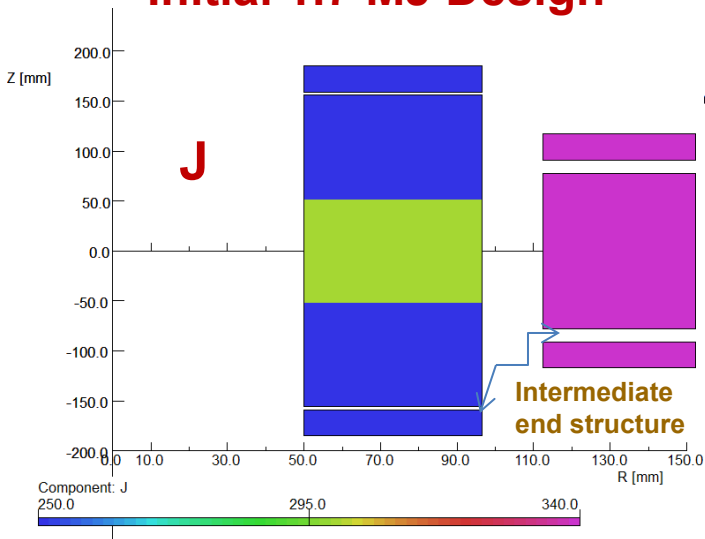
Final Geometry of 1.7 MJ System

- # of turns adjusted to achieve J_e grading to reduce $B_{\perp}$
- Parameters available:
Cu in HTS tape (100 μm & 65 μm) and SS tape (50 μm & 25 μm)
- Complicated “*Intermediate End Structure*” replaced by additional coils; now 46 coils instead of 44 - no cost impact
- Mechanical strength increased in the middle section
- Conductor used: 3988 turns in final design versus 4128 in initial

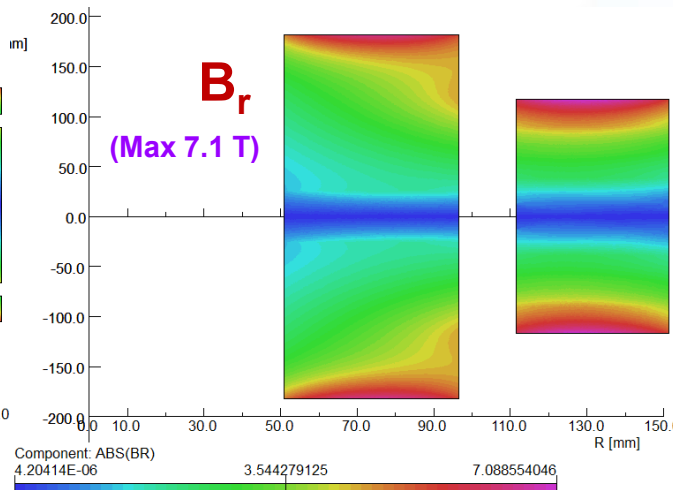
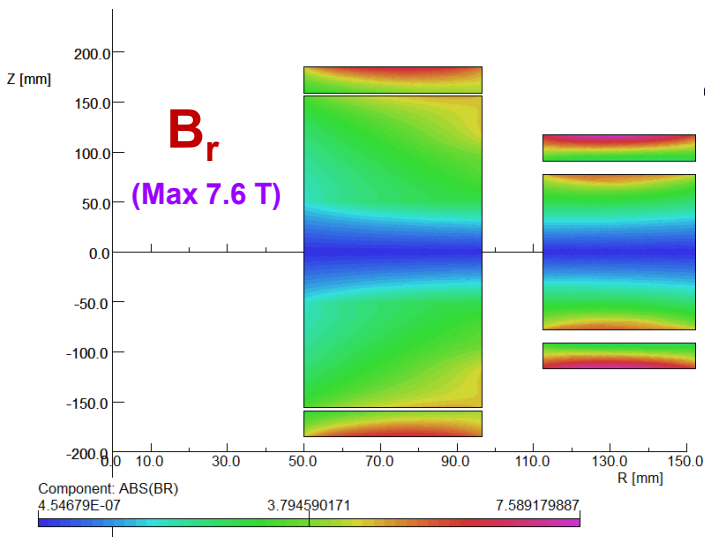
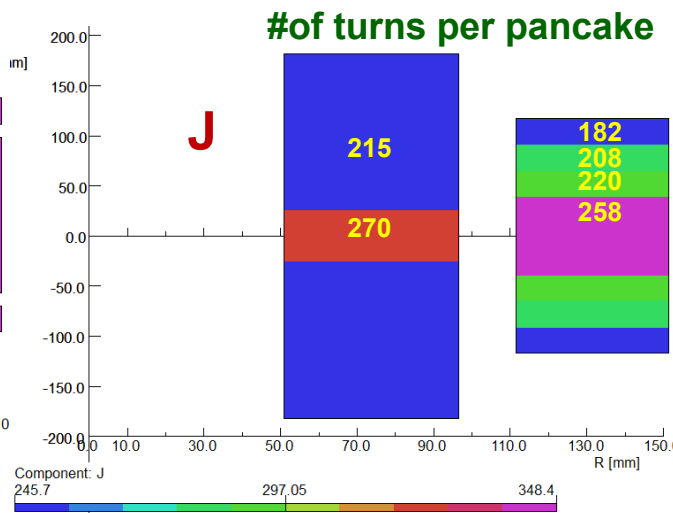
End Result:

- Improved performance
 - Better mechanical structure and reduced Bperp

Initial 1.7 MJ Design



Final 1.7 MJ Design

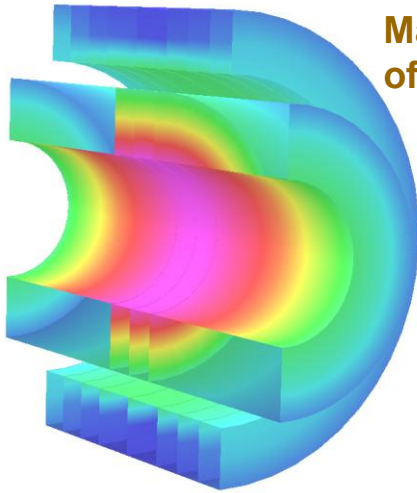


Magnetic Analysis of the Final Geometry (OPERA)

2/May/2013 09:08:18

Surface contours: BMOD

2.569420E+001
2.500000E+001
2.000000E+001
1.500000E+001
1.000000E+001
5.000000E+000
3.759030E+000



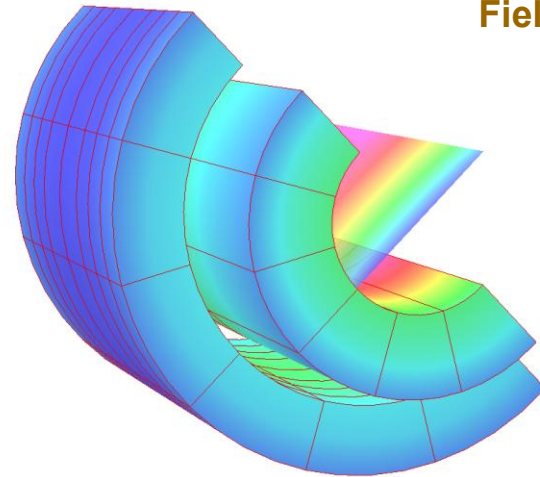
Magnitude
of the field

Opera

2/May/2013 09:05:45

Map contours: BMOD

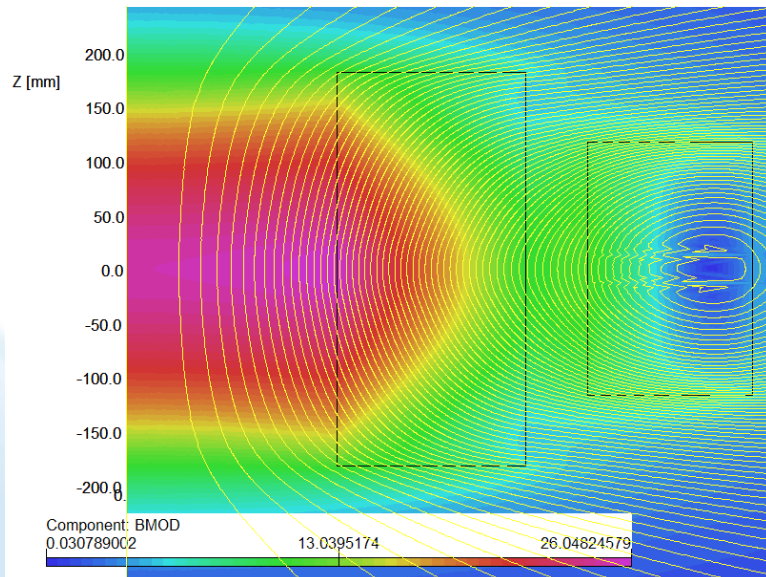
2.563996E+001
2.400000E+001
2.200000E+001
2.000000E+001
1.800000E+001
1.600000E+001
1.400000E+001
1.200000E+001
1.090944E+001
Integral = 7.226583E+005



Field on a patch

Opera

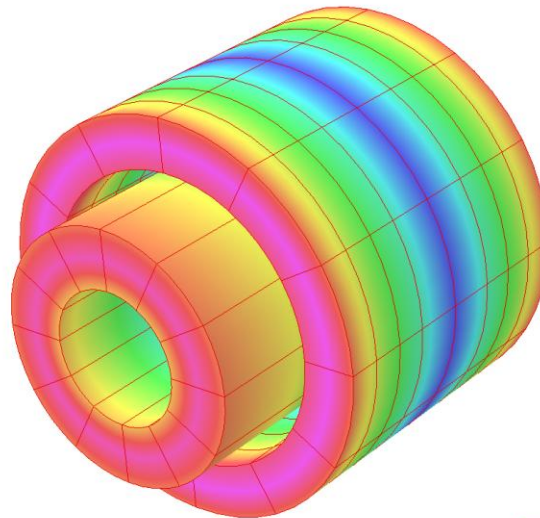
Field and field lines in cross-section



2/May/2013 09:09:29

Surface contours: ABS(BF)

7.059465E+000
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5.000000E+000
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3.000000E+000
2.000000E+000
1.000000E+000
0.000000E+000

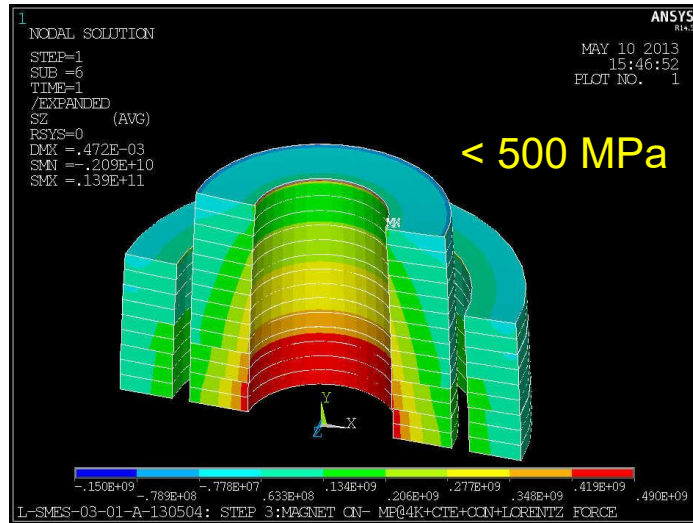


$B_{\text{perpendicular}}$
(radial)
component
of the field

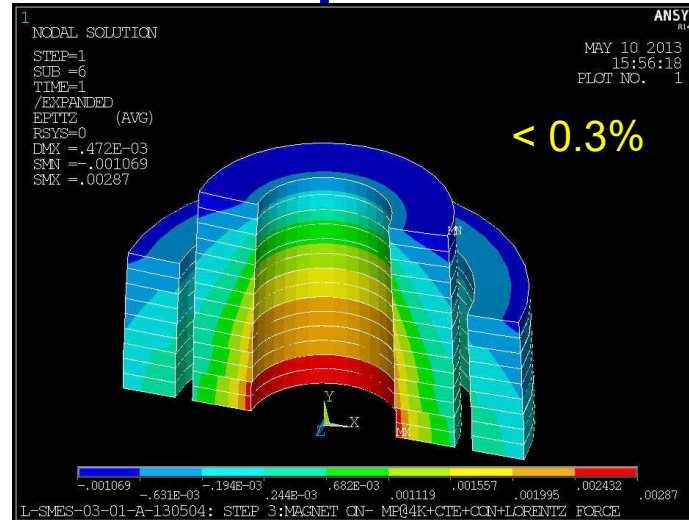
Opera

Mechanical Analysis of the Final Geometry (ANSYS)

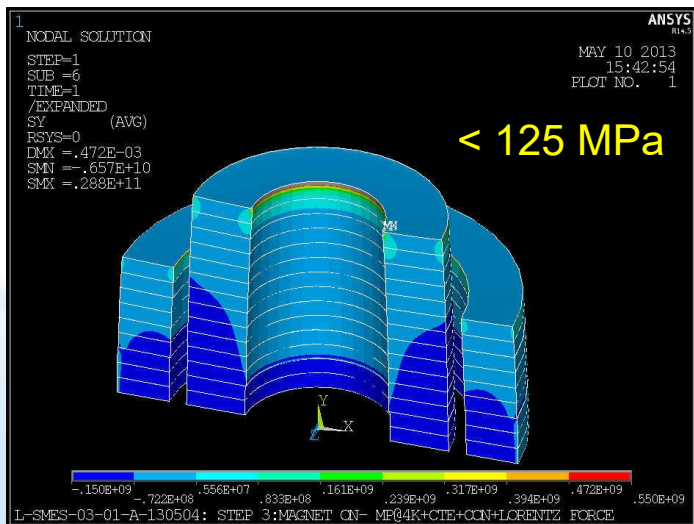
Hoop Stress



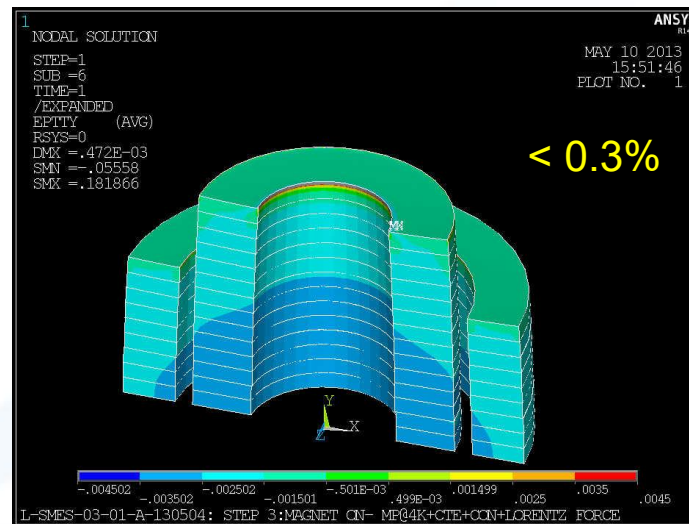
Hoop Strain



Axial Stress

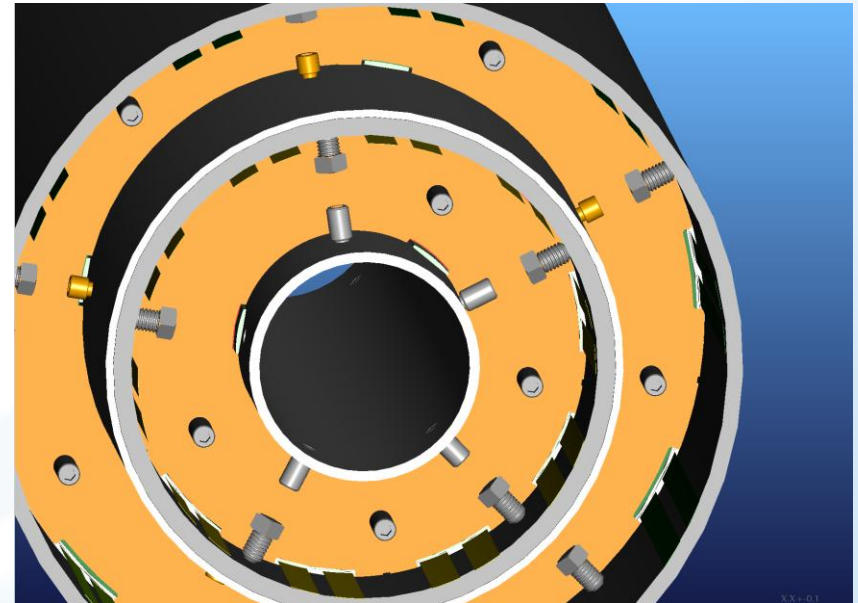
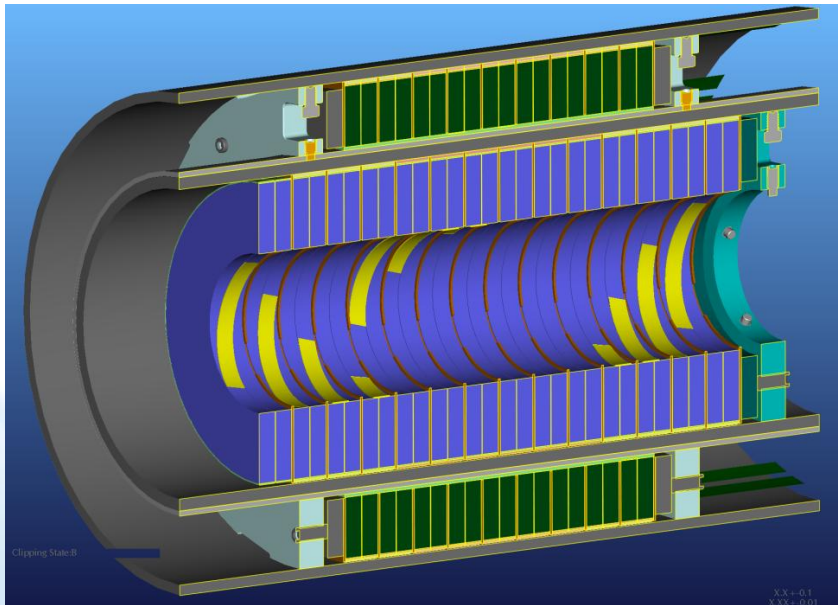
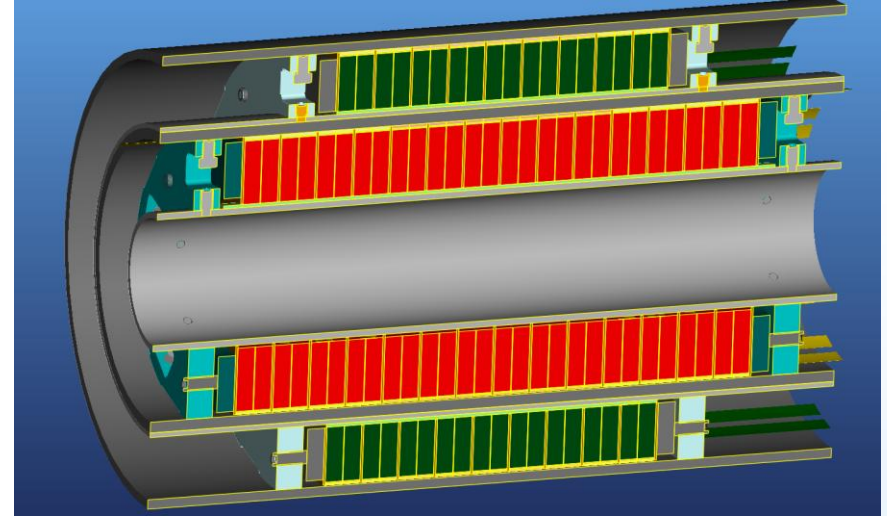
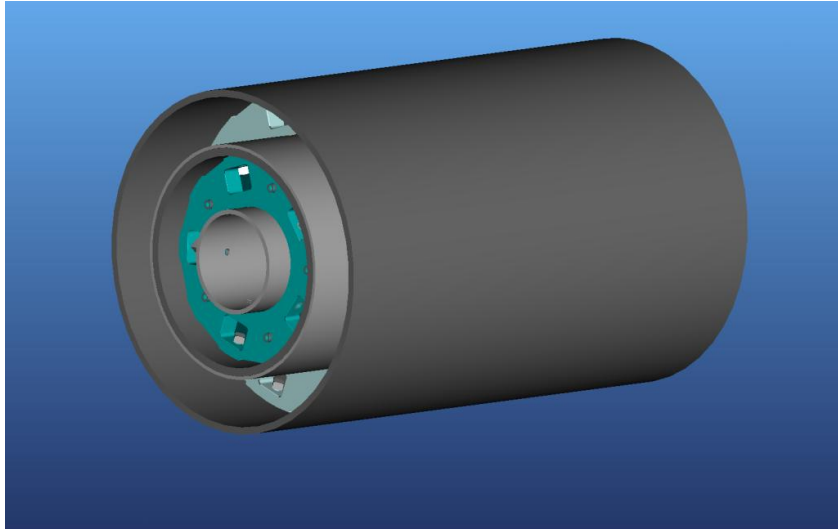


Axial Strain

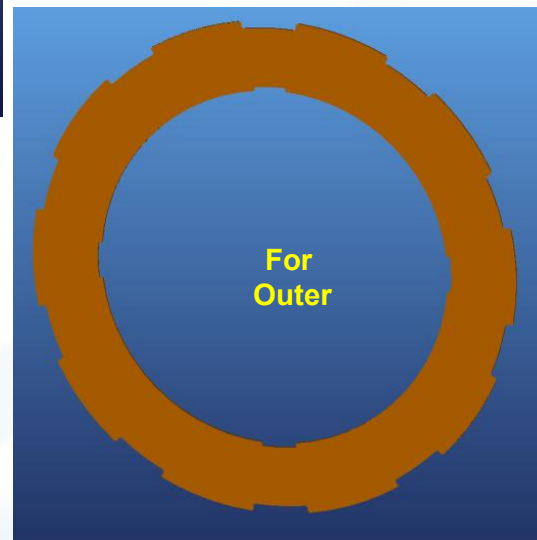
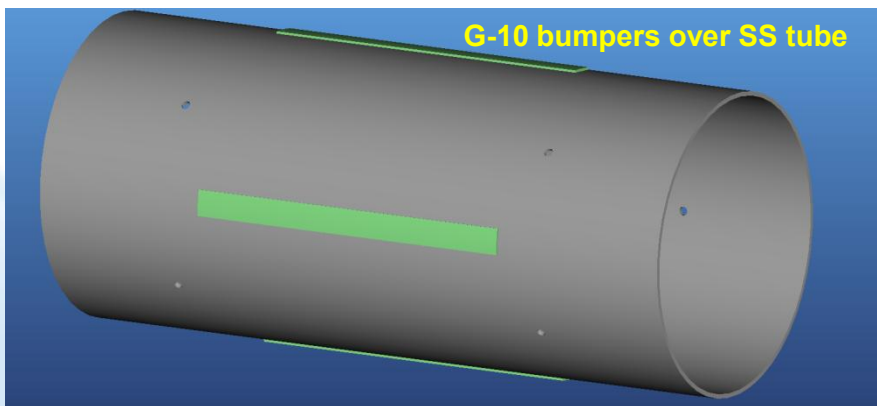
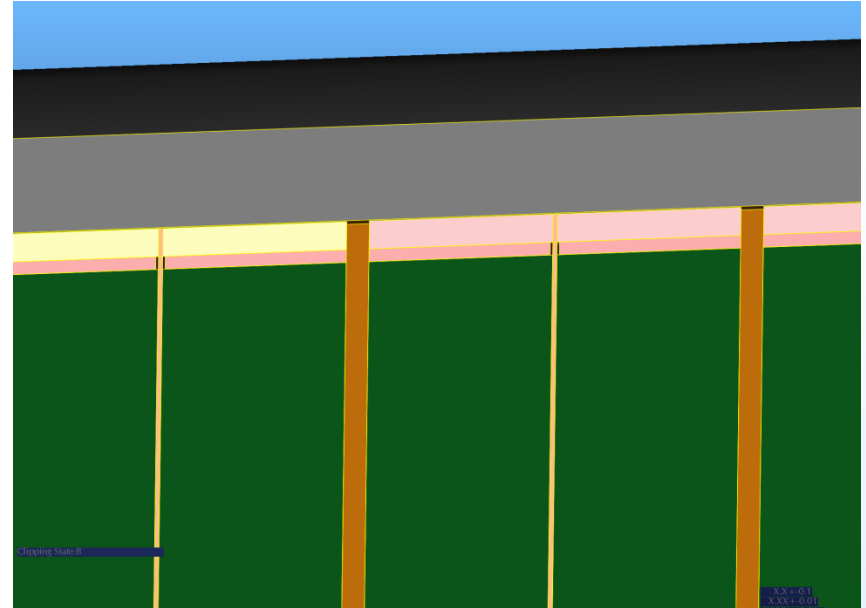
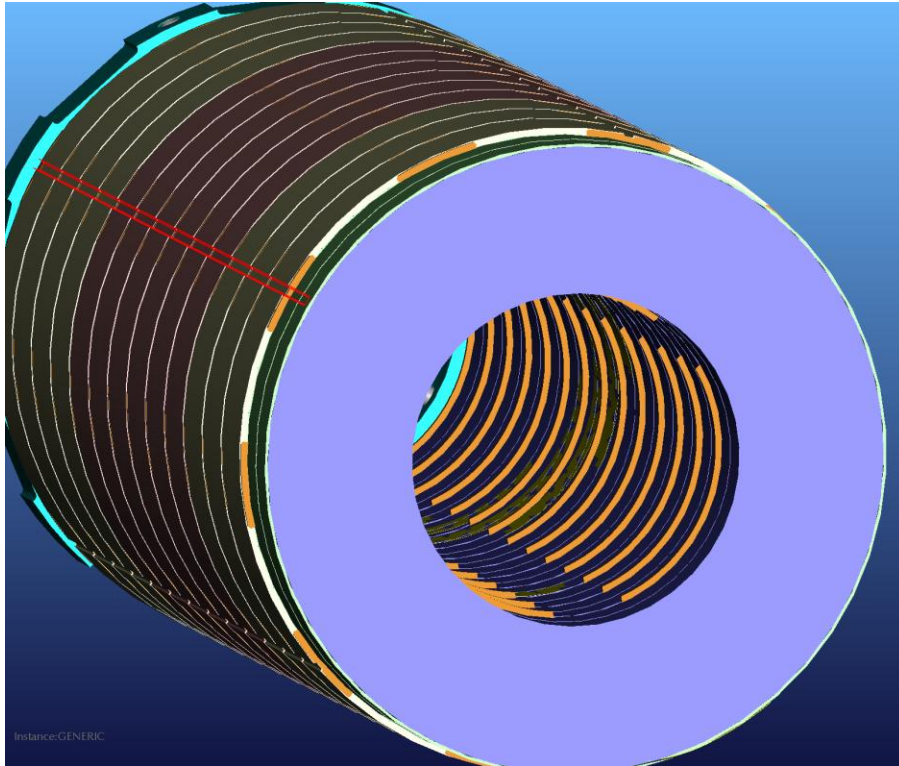


Coil deformation
due to Lorentz
forces: $\sim 200 \mu\text{m}$

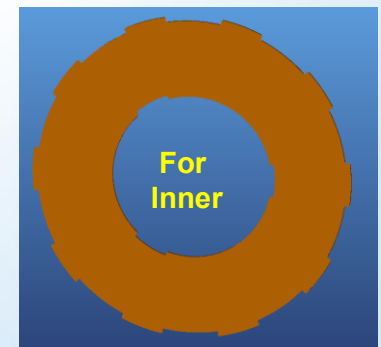
Engineering Design – Magnet Assembly



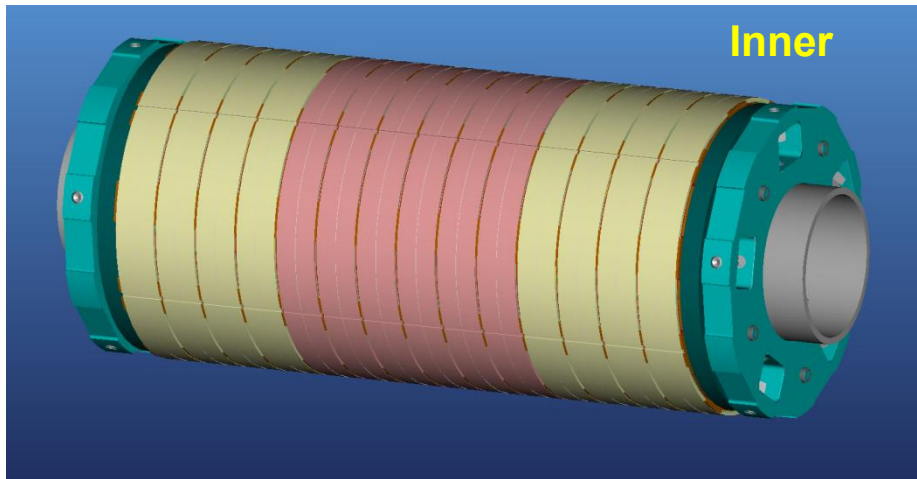
Helium Cooling



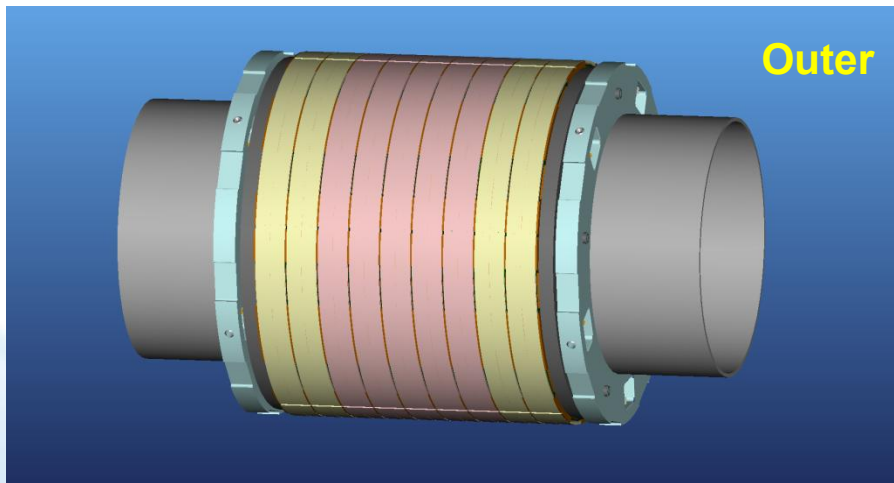
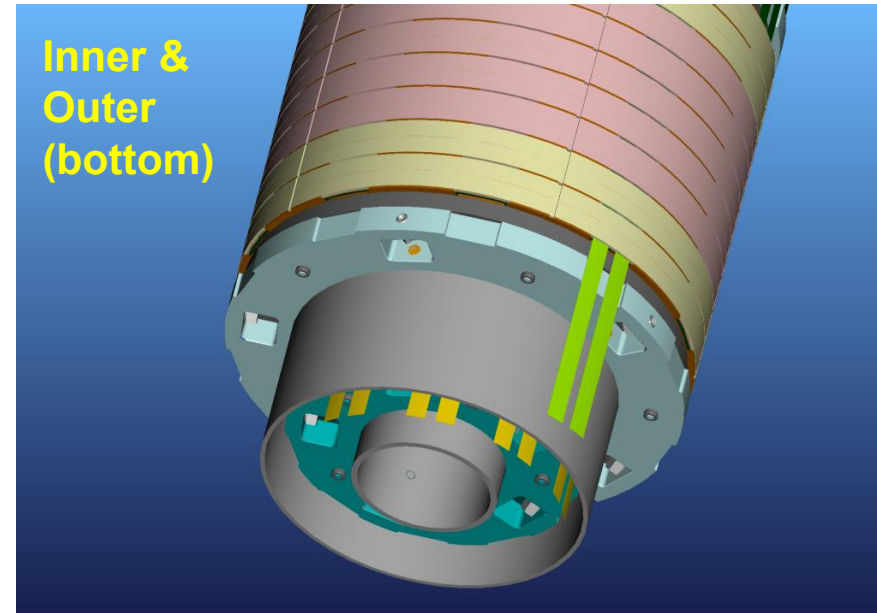
Cu discs



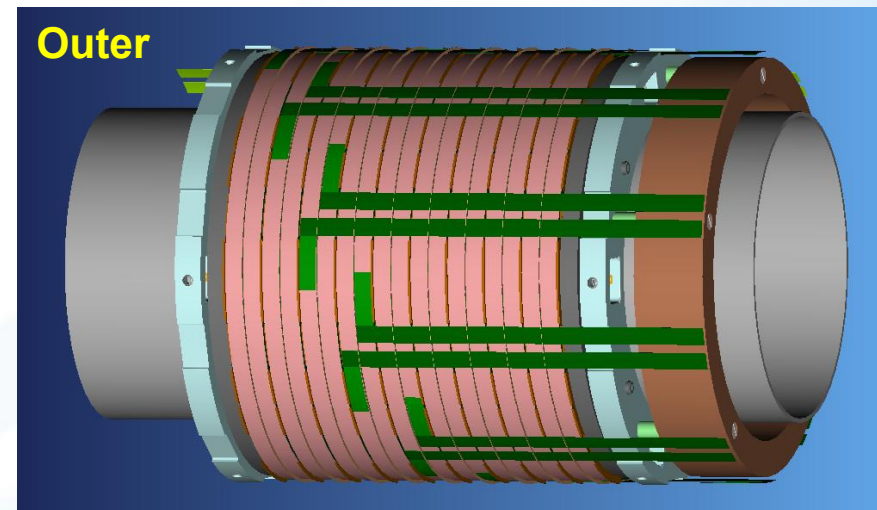
Electrical Connection and Leads



4 - 6 - 4



2 - 5 - 2



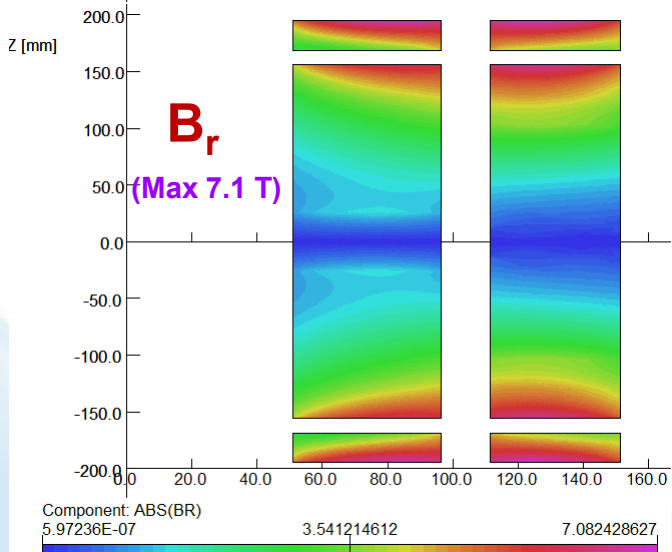
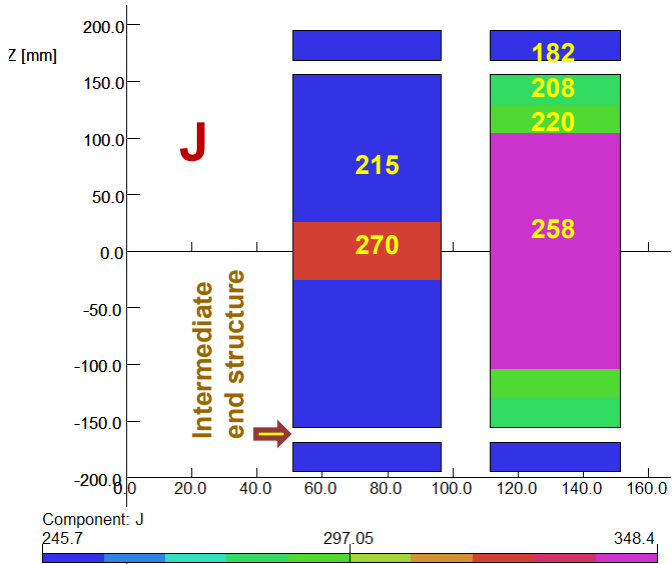
Summary

- Construction of all pancakes coils (28 inner and 18 outer single pancakes) for 1.7 MJ has been completed.
- QA tests at 77 K, as instituted for this program, have been found very effective in isolating defective section within the coil. Of 44 pancakes tested so far, only two had issues.
- Engineering design has been completed. All parts have been ordered. Many are already delivered and rest expected soon (in about a month).
- Initial quench protection system built and tested. Now being upgraded for higher isolation voltage. All components have been identified, tested and purchase order placed.

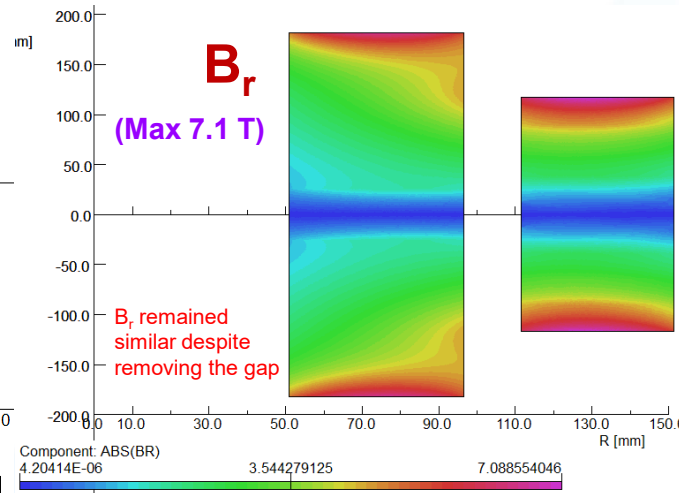
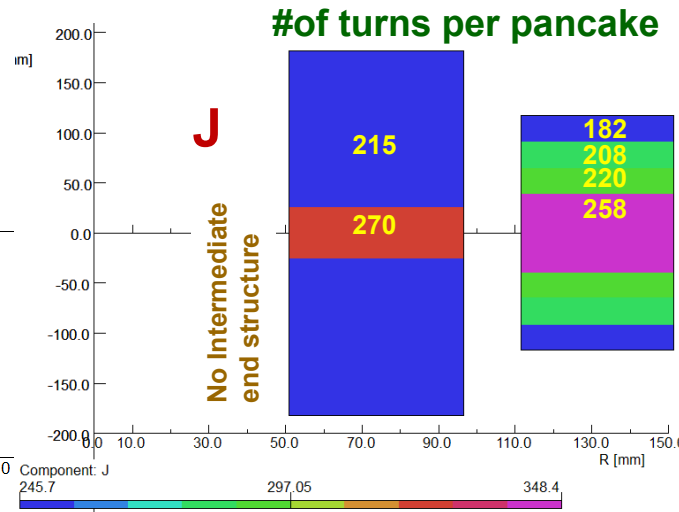
Backup Slides

Comparison of 2.5 and 1.7 MJ Systems

2.5 MJ Design



Final 1.7 MJ Design



- Construction continued with a guidance that both options (2.5 MJ & 1.7 MJ) should remain open.

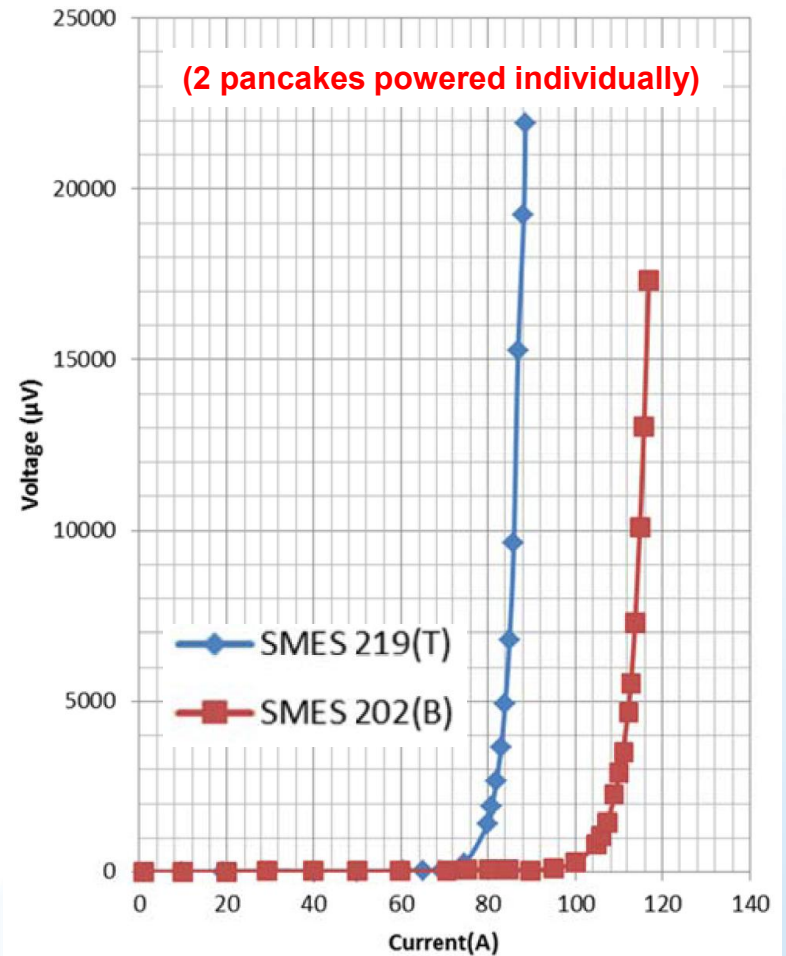
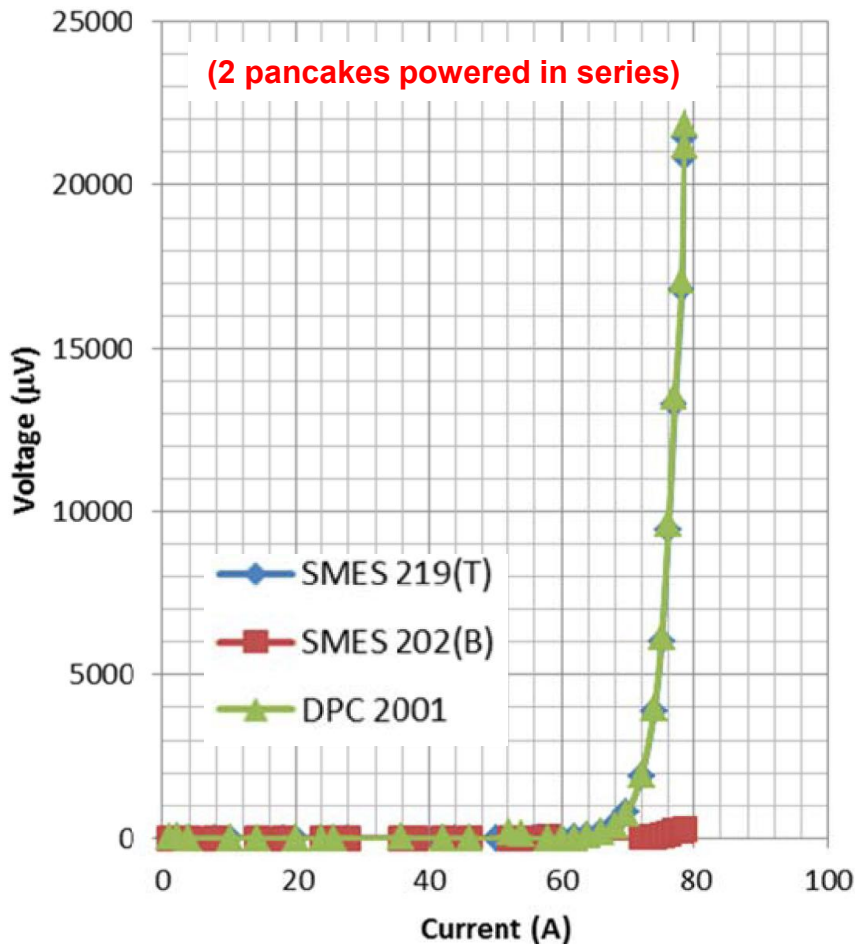
- 2.5 MJ (left, 56 coils) and 1.7 MJ (right, 48 coils)

- # of turns adjusted to achieve J_e grading to reduce $B_{\perp}$

- Parameters available: Cu in HTS tape (100 μm & 65 μm) and SS tape (50 μm & 25 μm)

- Complicated “Intermediate End Structure” replaced by coils in the final 1.7 MJ design

Outer Double Pancake DPC2001



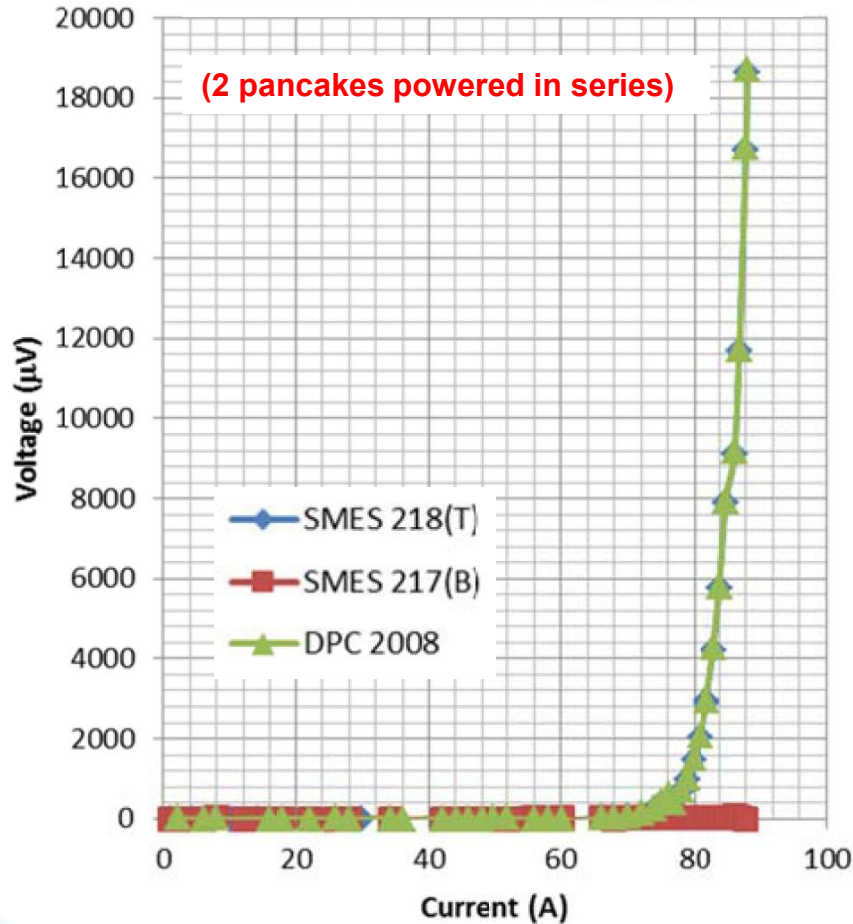
	N	1μV/cm	0.1μV/cm
SMES 219(T)	28	78.3	72.2
SMES 202(B)	29	>78.5 A	
DPC 2001	28	>78.5 A	74.0

SMES202 carries much higher critical current than SMES219 @77K

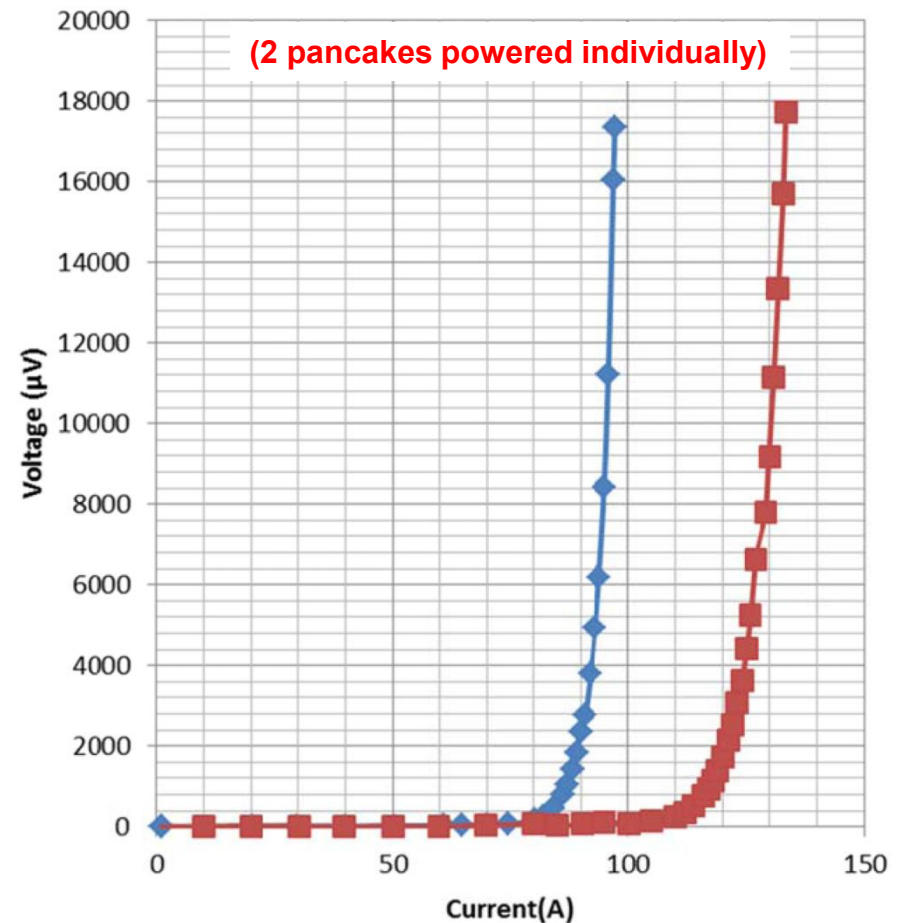
	N	I _c	
		1μV/cm	0.1μV/cm
SMES 219	28	88.3	81.2
SMES 202	30	117.7	108.9

Outer Double Pancake DPC2008

DPC 2008- SMES 217 and SMES 218



DPC 2008- SMES 217 and SMES 218



	N	1μV/cm	0.1μV/cm
SMES 218(T)	26	87.9	80.4
SMES 217(B)		>88 A	
DPC 2008	25	>88A	82.4

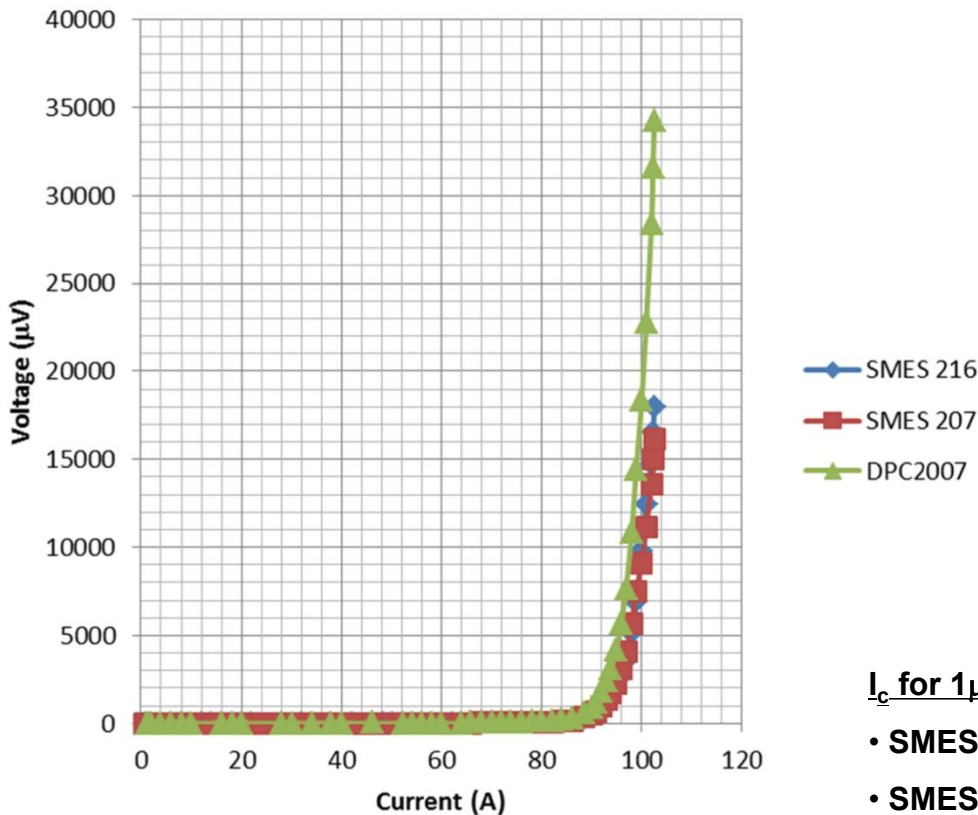
SMES217 carries much higher critical current than SMES218 @77K

	N	1μV/cm
SMES 218	24	97.5
SMES 217	22	133.3

Outer Double Pancake DPC2007

(2 pancakes powered in series)

DPC 2007- SMES 207 and SMES 216



Both coils carry about the same current

I_c for 1μV/cm criteria

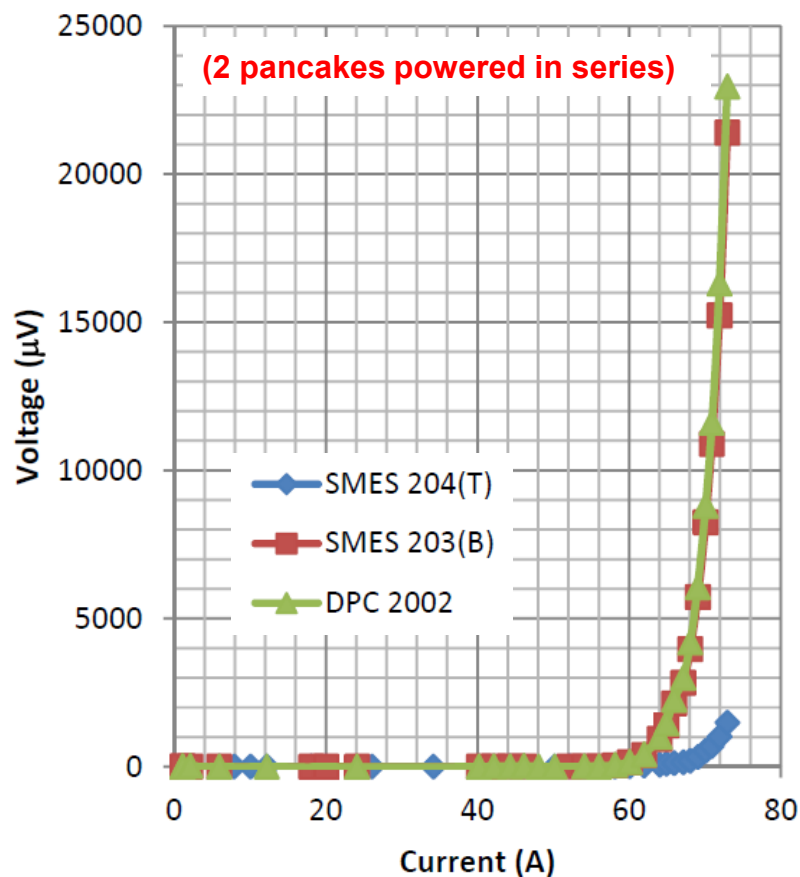
- **SMES216:** 102.2 A, N=29
- **SMES207:** 102.5 A, N=26
- **DPC2007:** 102.3 A, N=28

I_c for 0.1μV/cm criteria

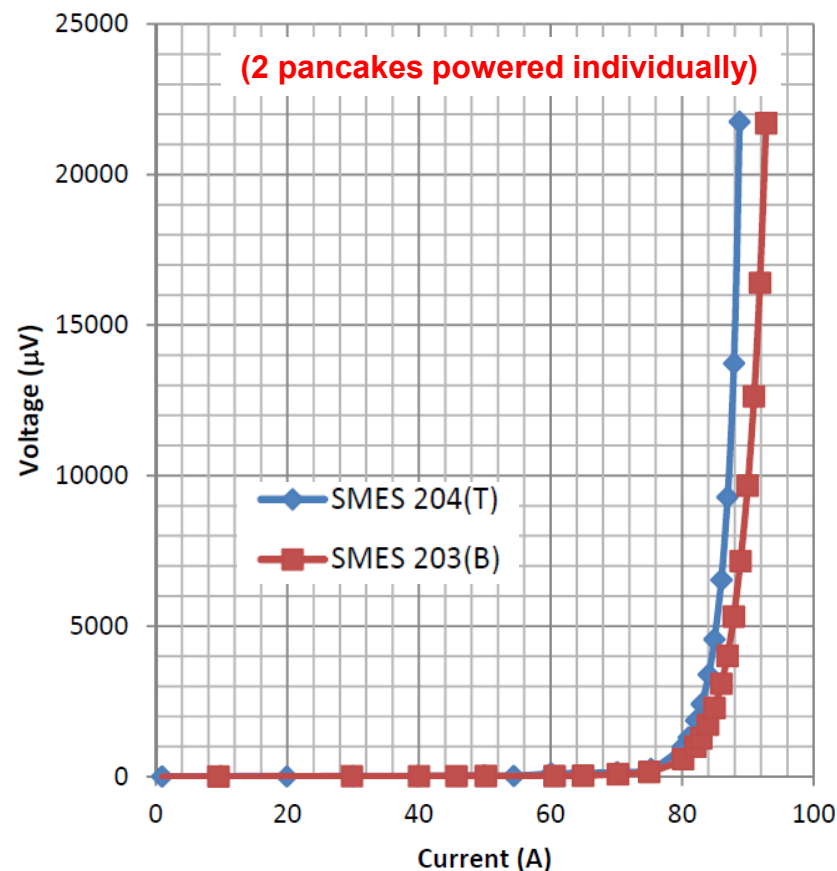
- **SMES216:** 94.4 A, N=29
- **SMES207:** 93.9 A, N=26
- **DPC2007:** 94.2 A, N=28

Outer Double Pancake DPC2002

DPC 2002- SMES 203 and SMES 204



SMES 203 and SMES 204



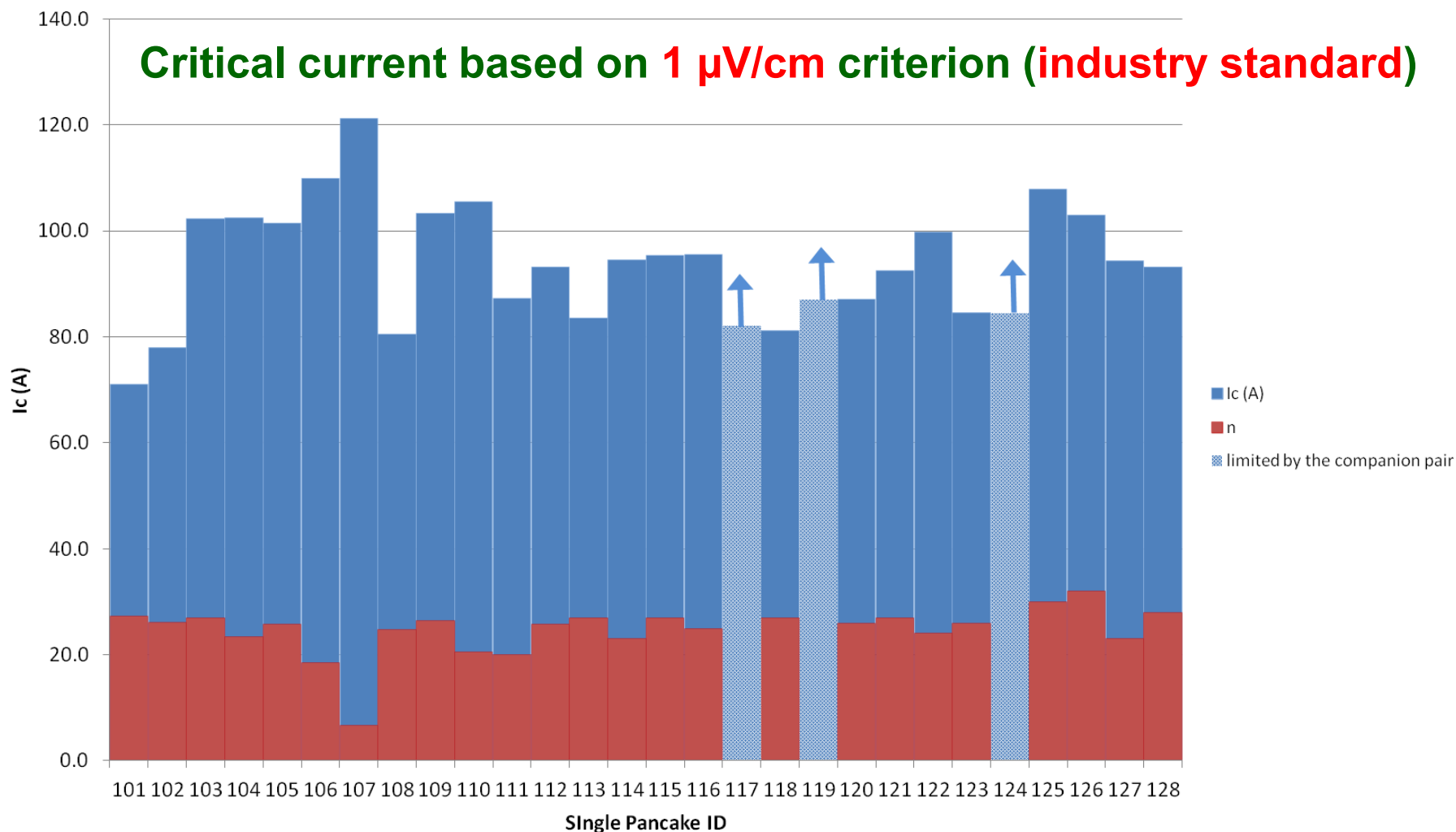
	N	1μV/cm	0.1μV/cm
SMES 204(T)	28	>73 A	>73 A
SMES 203(B)	24	72.9	66.1
DPC 2002	24	>73 A	67.9

SMES204 carries higher critical current than SMES203 @77K

	N	I _c (A) @	
		1μV/cm	0.1μV/cm
SMES 203	29	89.3	82.6
SMES 204	25	92.8	84.6

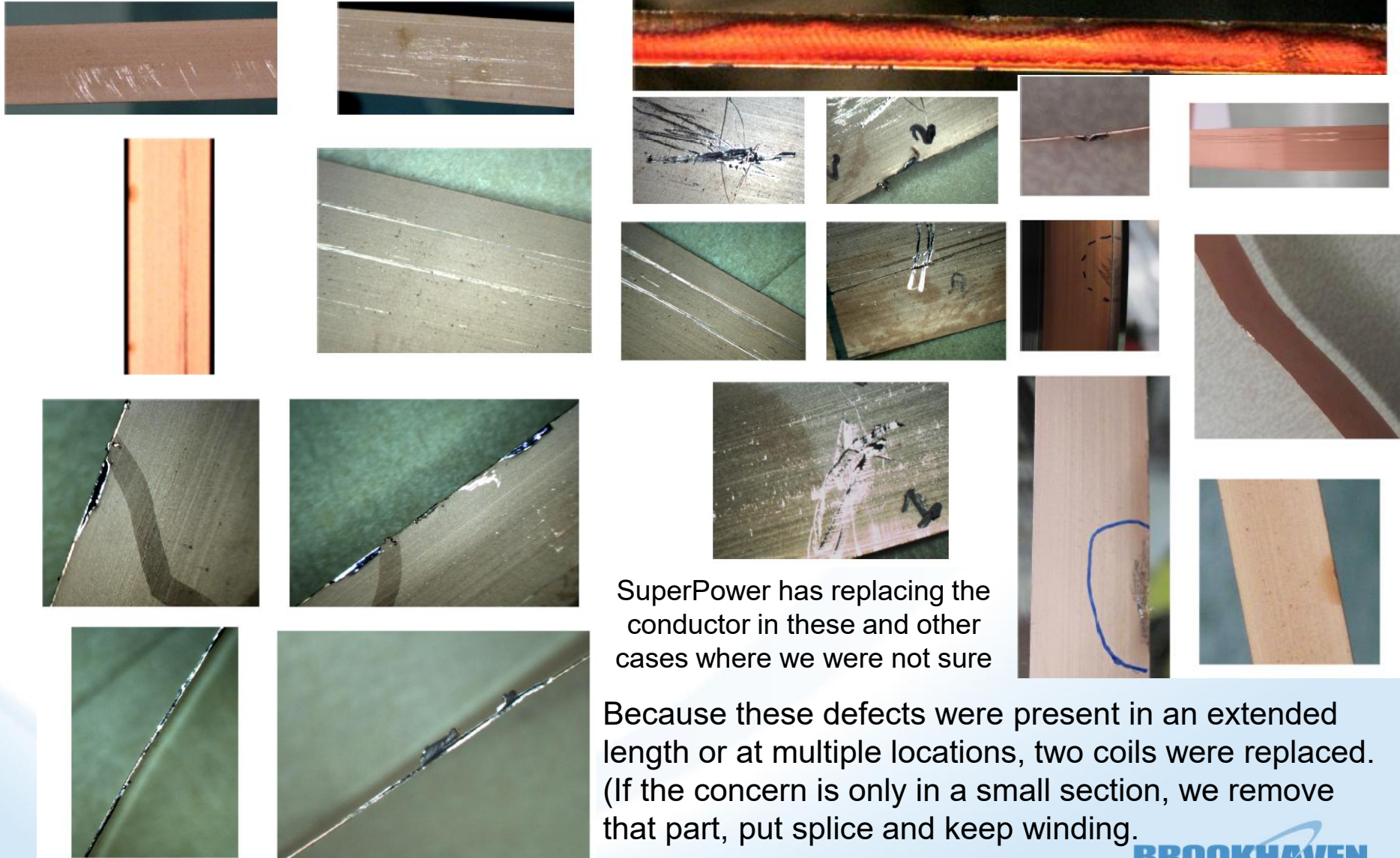
Summary of 77 K test of all inner pancakes

I_c and n value at 77 K of single pancake coils



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

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



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

Because these defects were present in an extended length or at multiple locations, two coils were replaced. (If the concern is only in a small section, we remove that part, put splice and keep winding.