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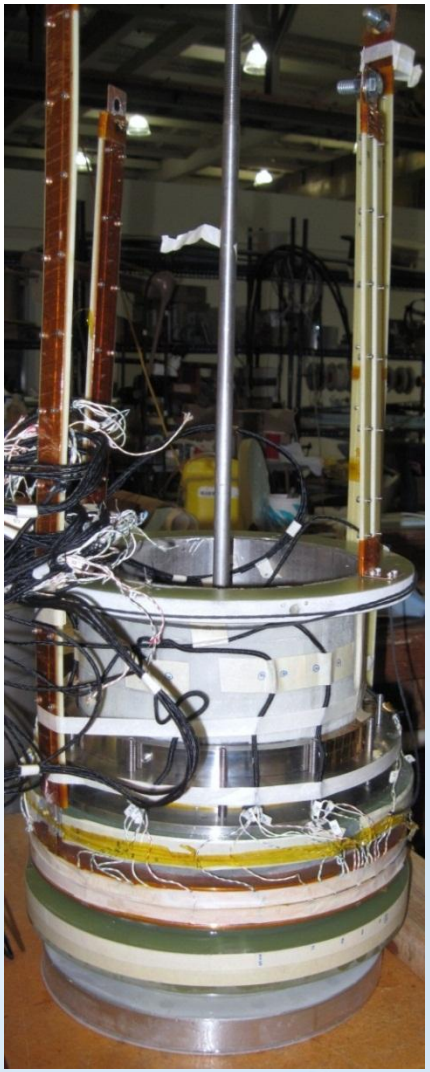
Office of Science
U.S. DEPARTMENT OF ENERGY

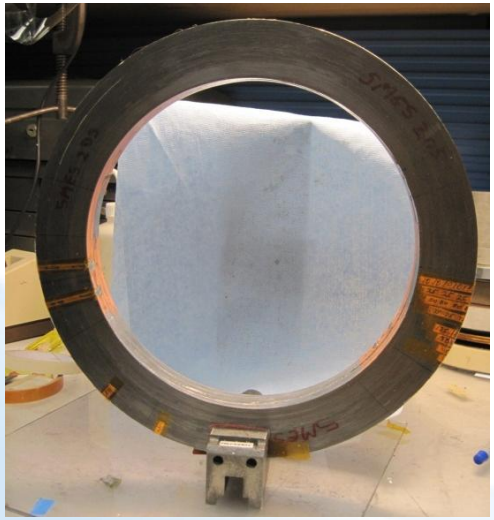
Overview of Activities

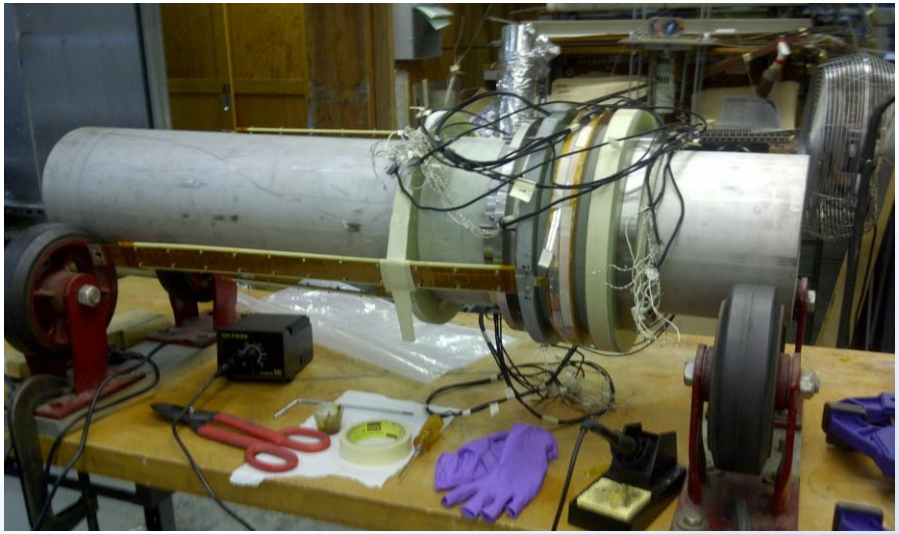
- Construction and test of outer pancake coils
- 1.7 MJ SMES coil design analysis and update
- Status of engineering design and fabrication of parts
- Quench protection system update
- Summary

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)

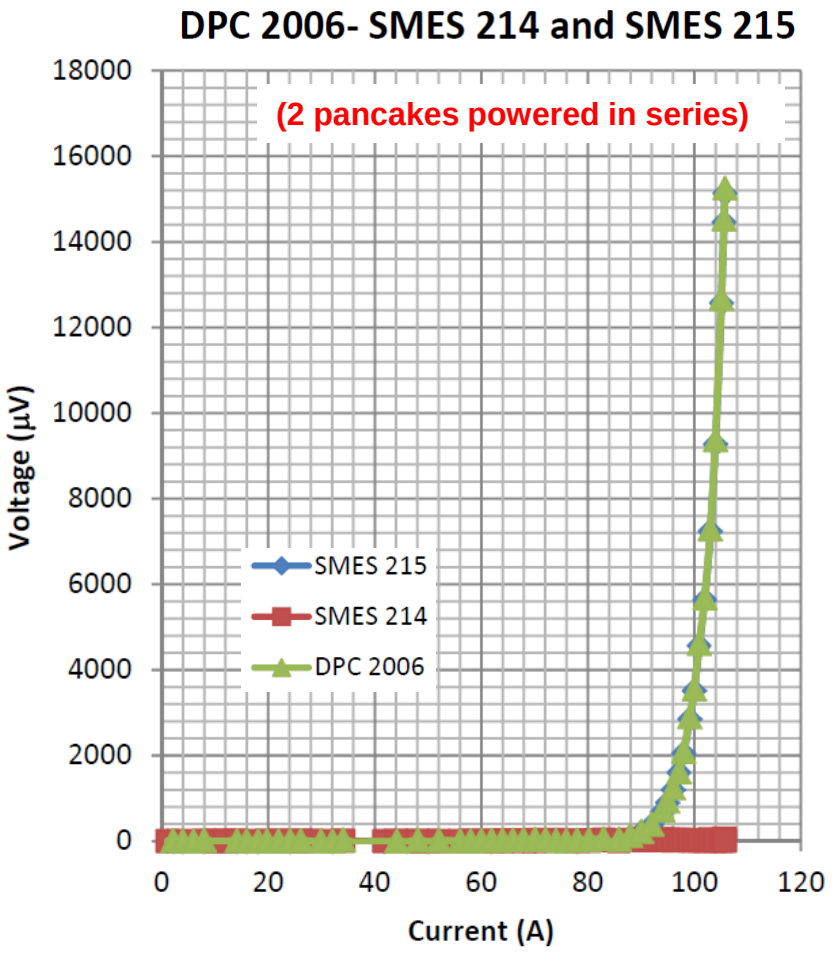


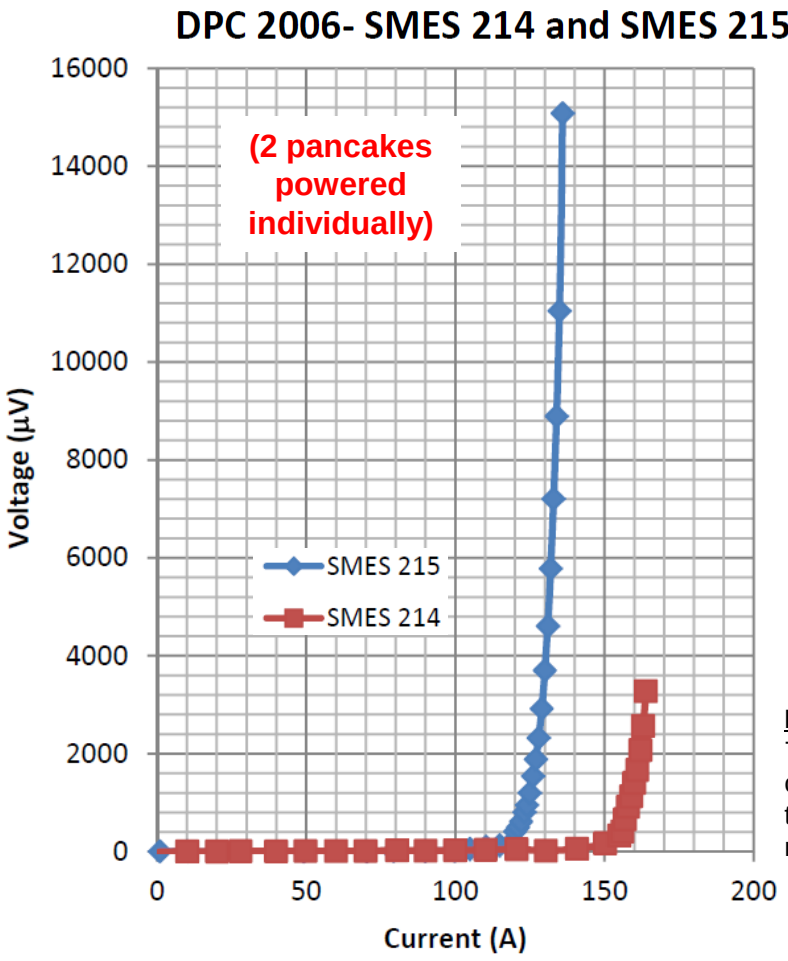




Outer Double Pancake DPC2006

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





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

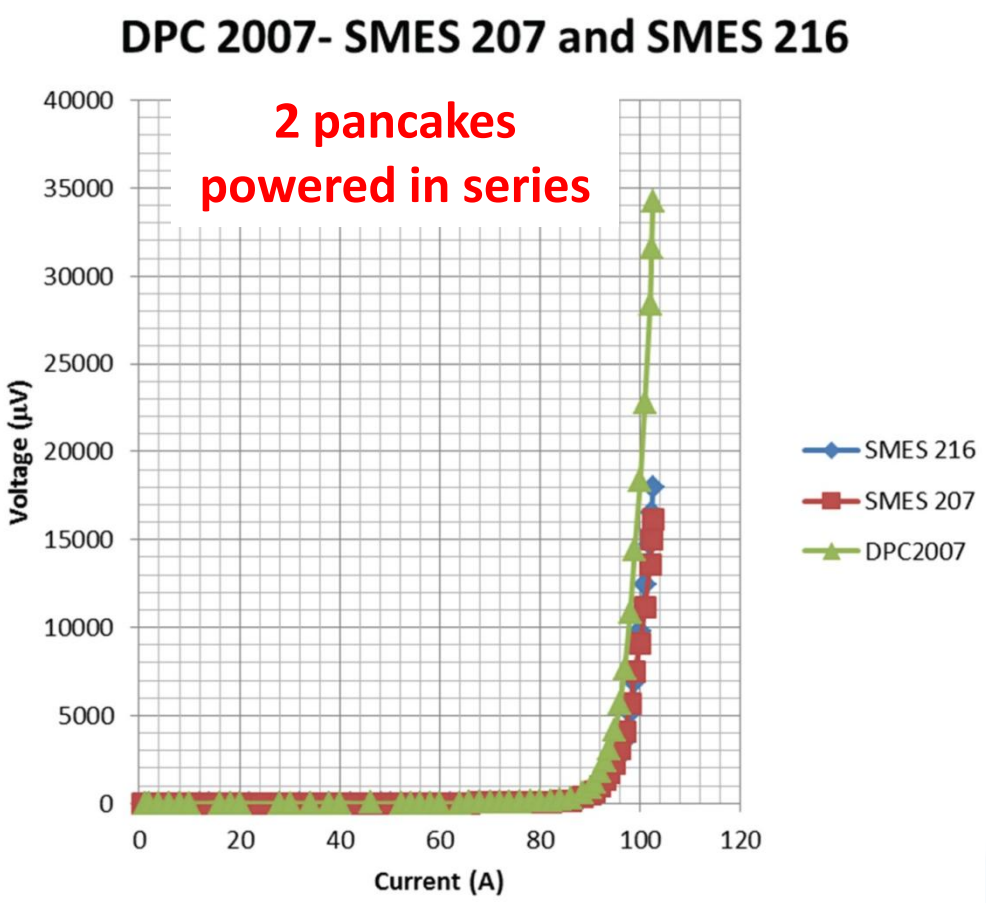
	N	1μV/cm
SMES 215	27	105.5
SMES 214	-	>106
DPC 2006	26	108.5

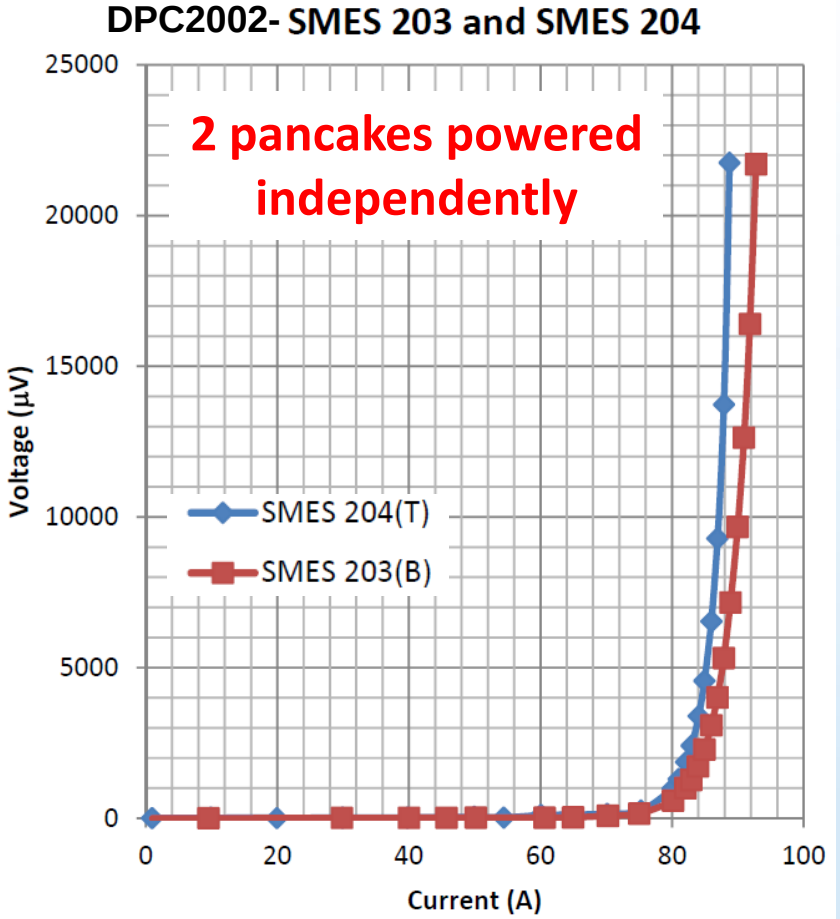
- SMES214 has much higher I_c than SMES215
- Coil SMES214 has the highest I_c of all
- See two similar cases in back-up slides

	N	1μV/cm
SMES 215	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)





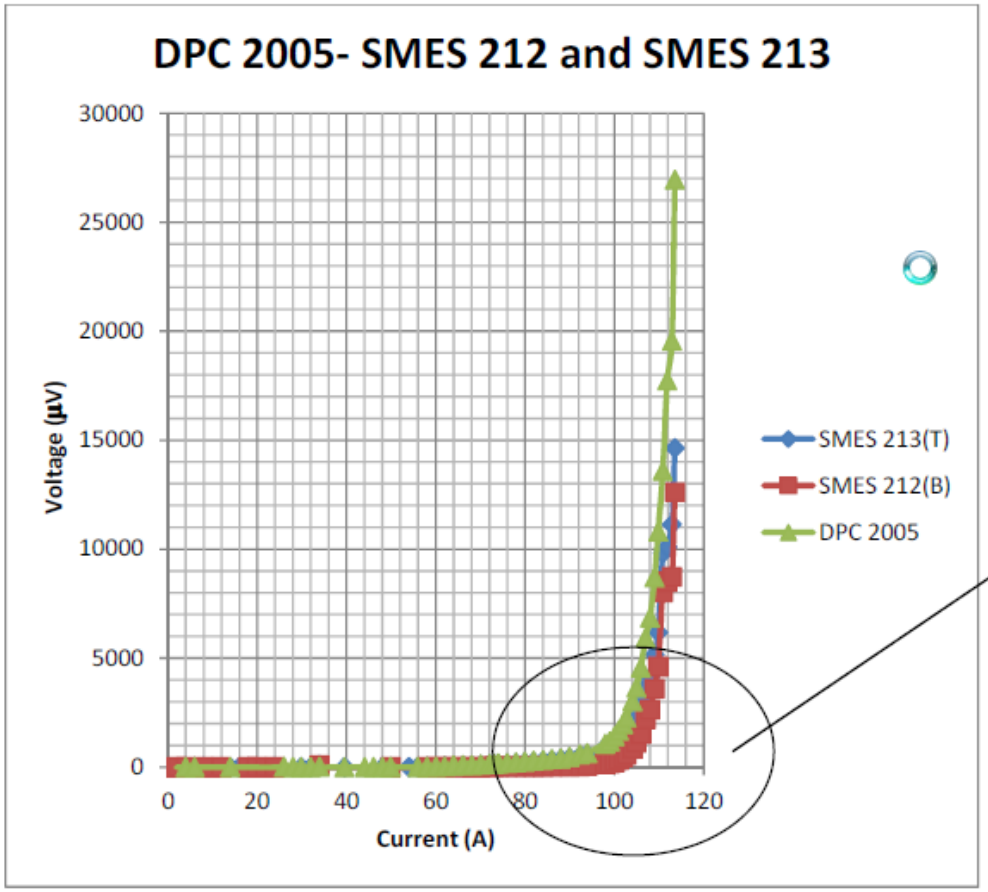
- 216 & 207 in DPC2002 and 204 & 203 in DPC2007 have similar critical current
- See details of the test results in back-up slide section

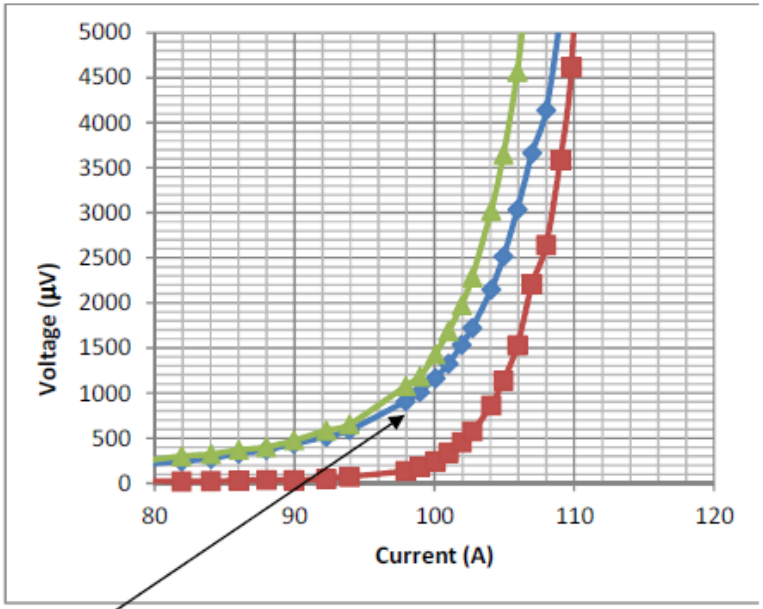
Outer Double Pancake DPC2005

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

- **DPC2005 would appear OK for 1 μV/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





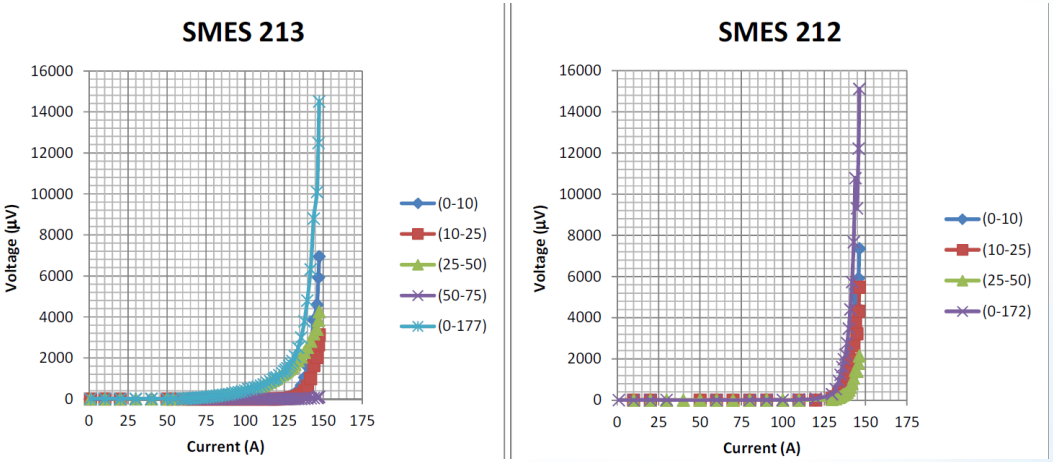
		Ic (A) @	
	N	1μV/cm	0.1μV/cm
SMES 213	20	114.2	101.8
SMES 212	31	113.8	105.7
DPC 2005	23	114.5	103.6

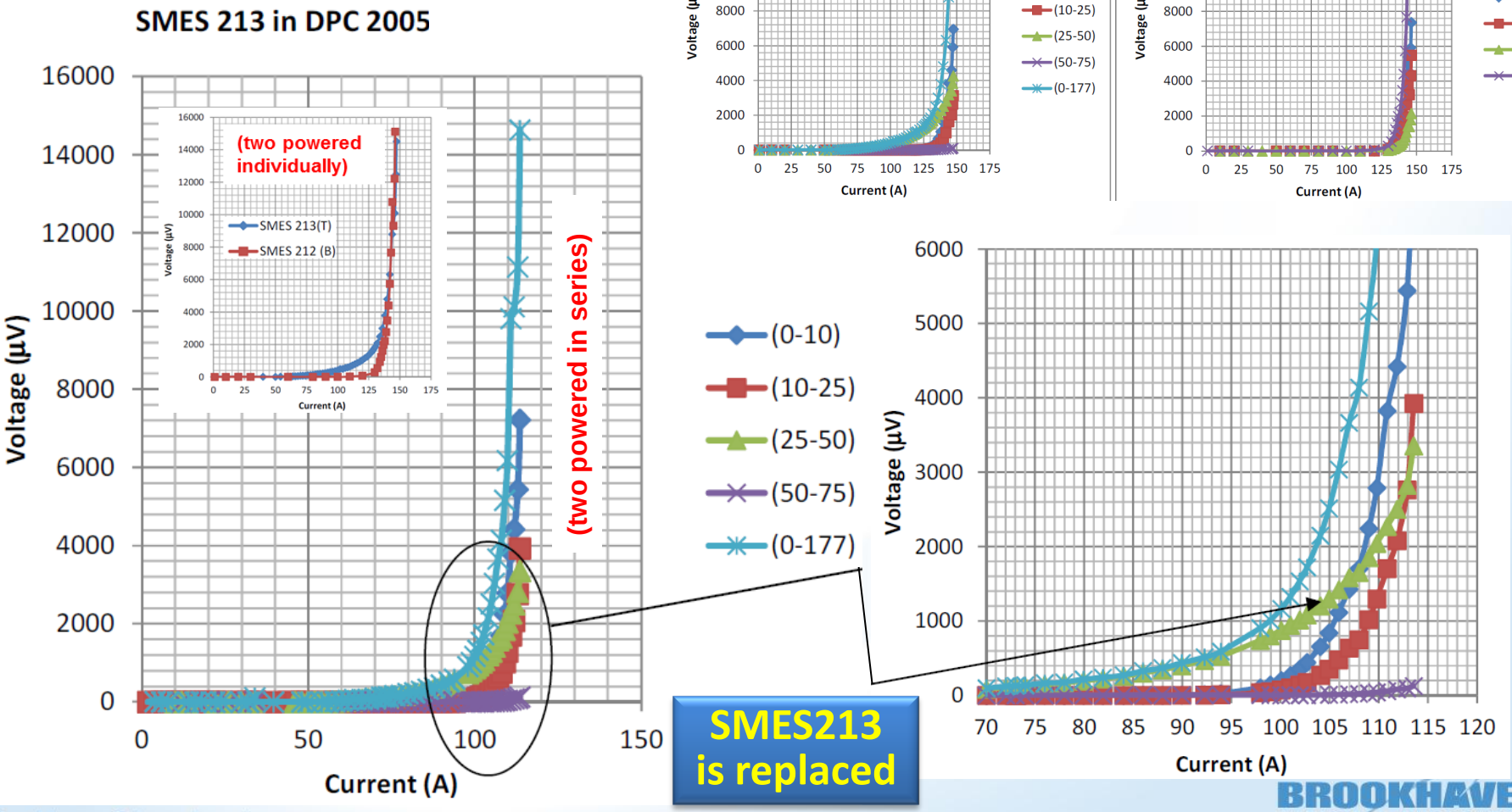
Outer Double Pancake DPC2005

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

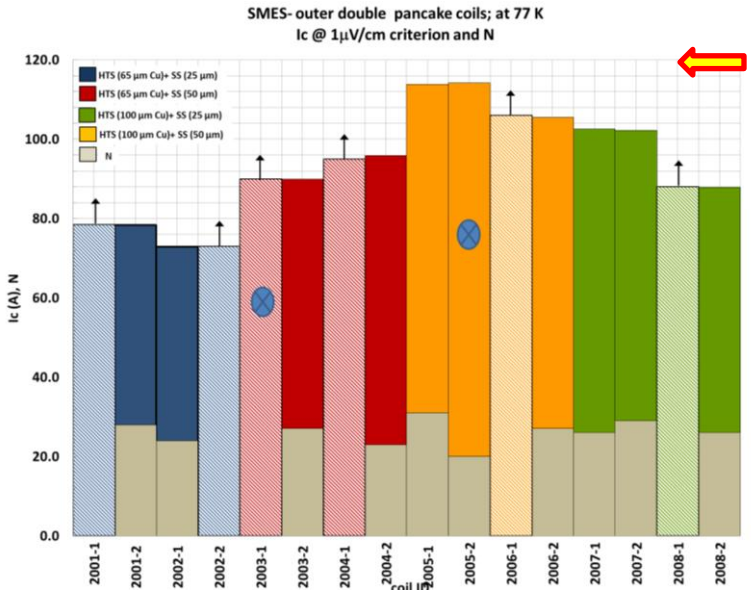
➢ **Note: Power of thorough QA testing and analysis – it identified a weak link that could have potentially limited the performance of the entire 1.7 MJ SMES coil**

(2 pancakes powered individually)



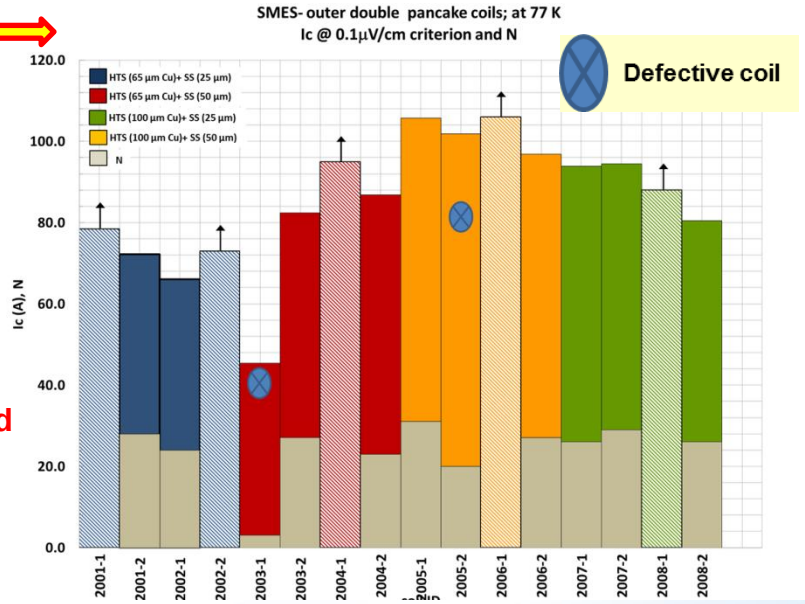


Summary of Outer Coil Performance @77 K



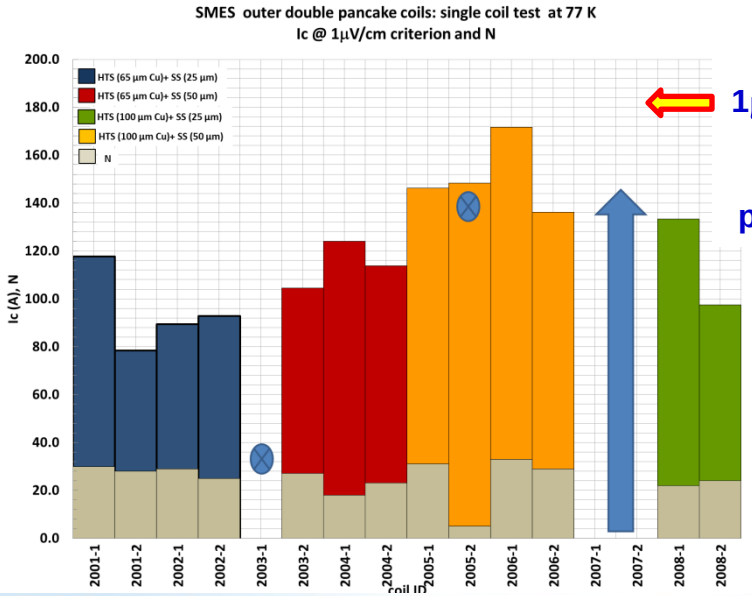
1μV/cm

0.1 μV/cm



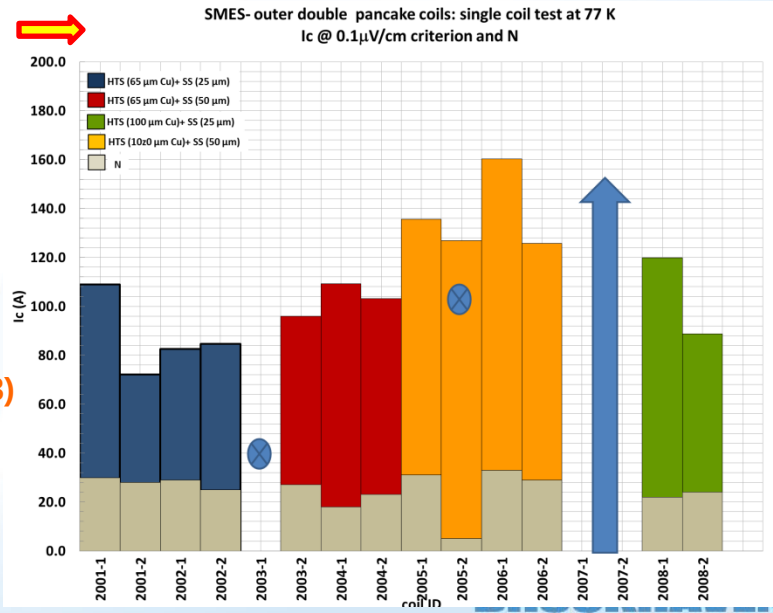
Two pancakes powered in series

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



1μV/cm

0.1 μV/cm



Two pancakes powered individually

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

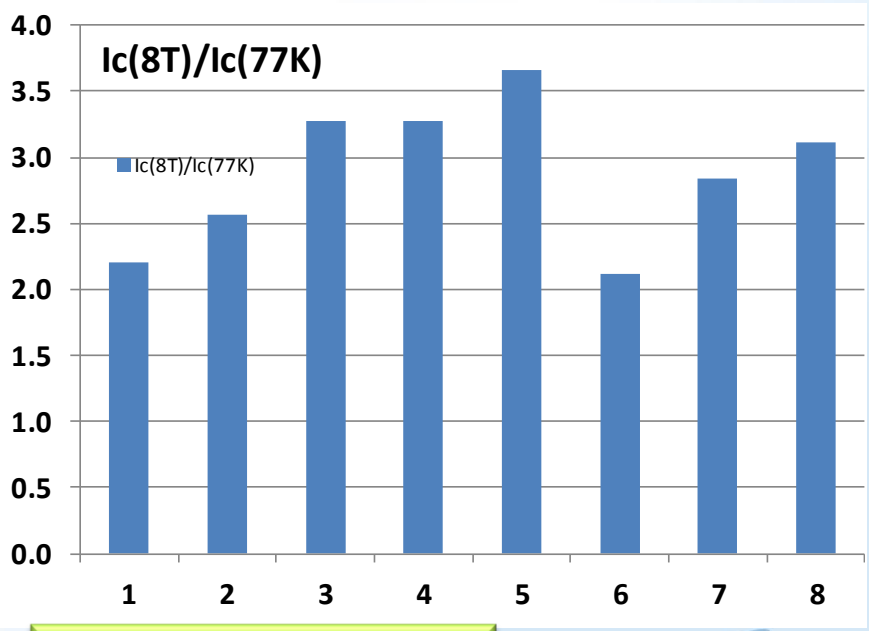
2007-1 and 2007-2 were not tested individually as they had very similar performances

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	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

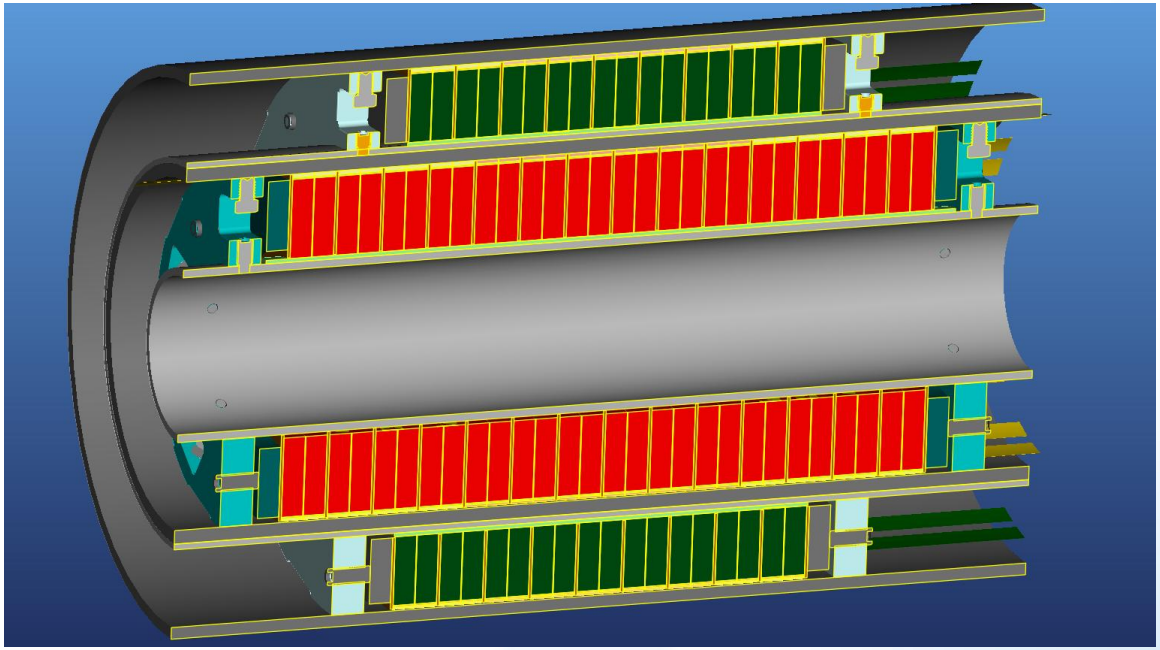


I_c(4K,8T) : 726 A to 1369 A (spec > 700 A)

Lift factor 2.1 to 3.7

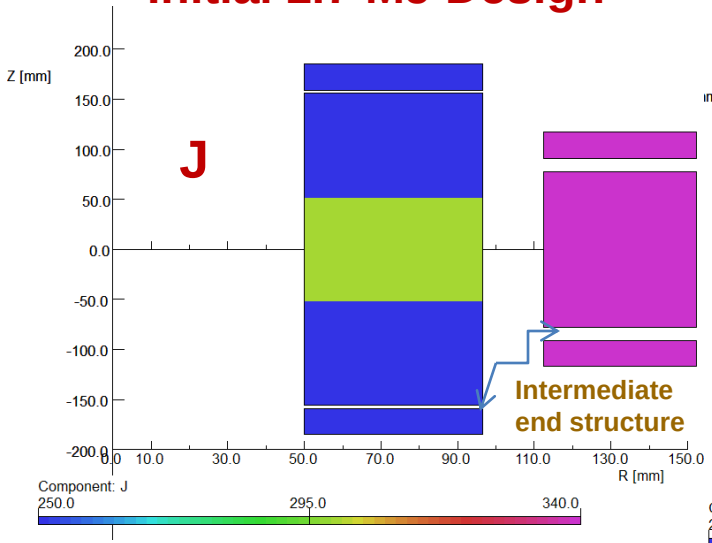
Engineering Design of the 1.7 MJ Coil

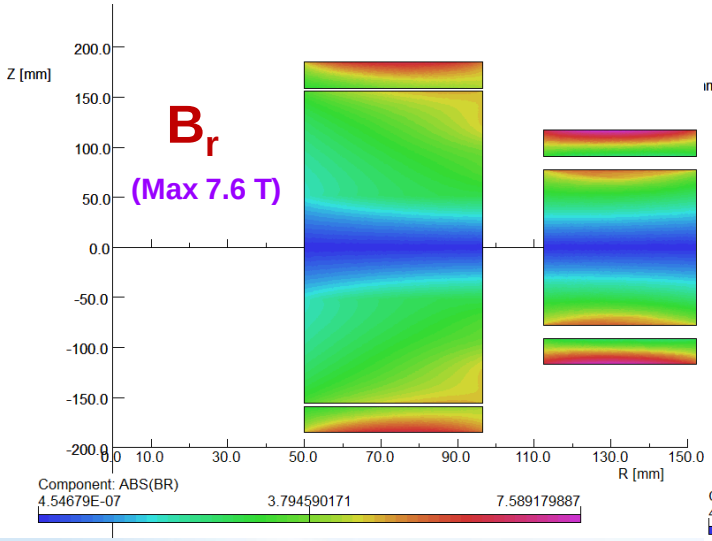
- After getting a final direction on 1.7 MJ choice, a more complete engineering design has been developed (earlier postponed to avoid duplication of 1.7 MJ and 2.5 MJ efforts)



Final Geometry of 1.7 MJ System

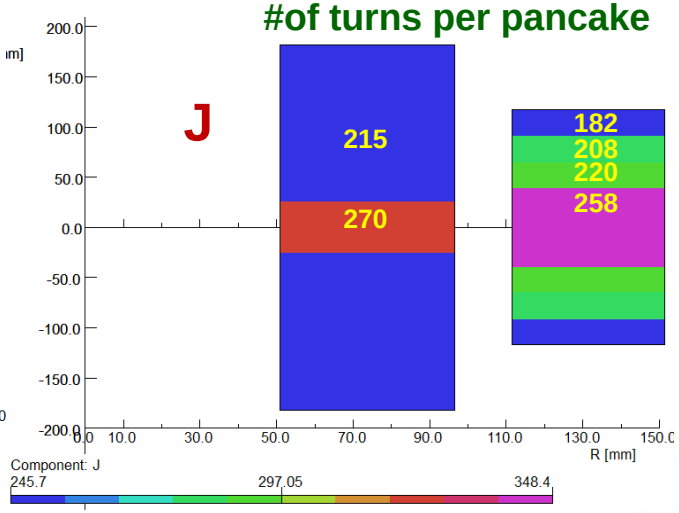
Initial 1.7 MJ Design

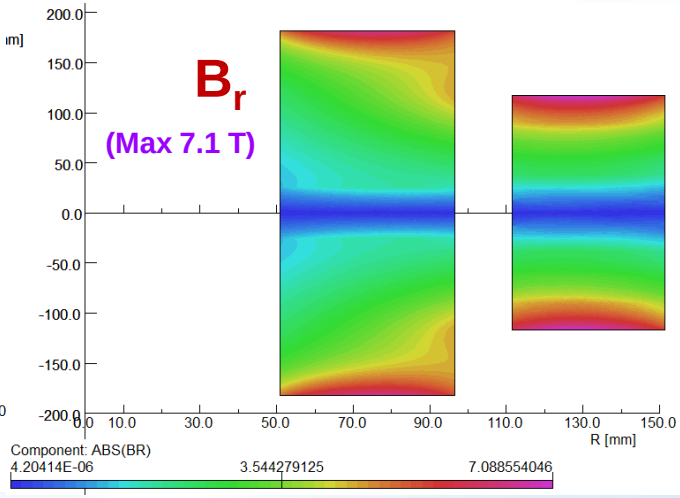




Final 1.7 MJ Design

#of turns per pancake



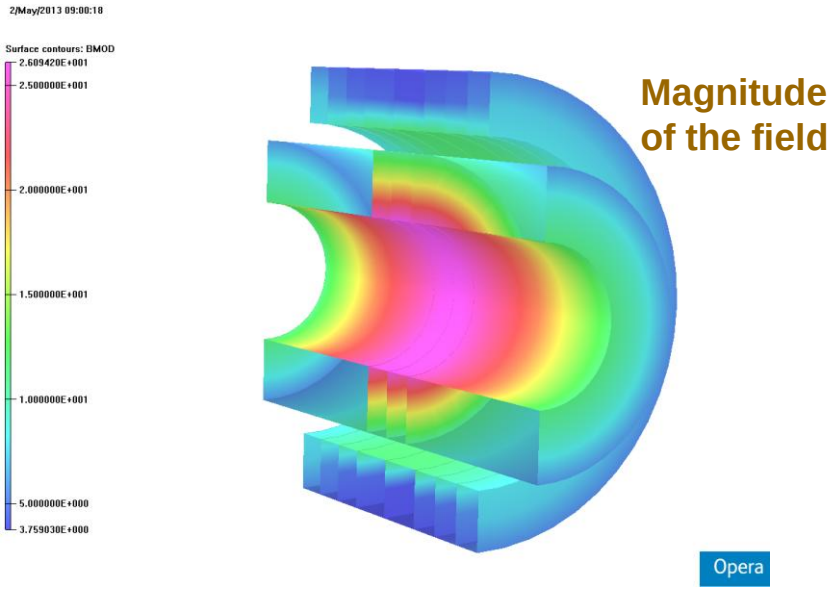


- # of turns adjusted to achieve J_e grading to reduce $B_{perpendicular}$
- Parameters available: Cu in HTS tape (100 μm & 65 μm) and SS tape (50 μm & 25 μm)
- Complicated ***"Intermediate End Structure"*** replaced by additional coils; now 46 coils instead of 44 - no cost impact
- Mechanical strength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

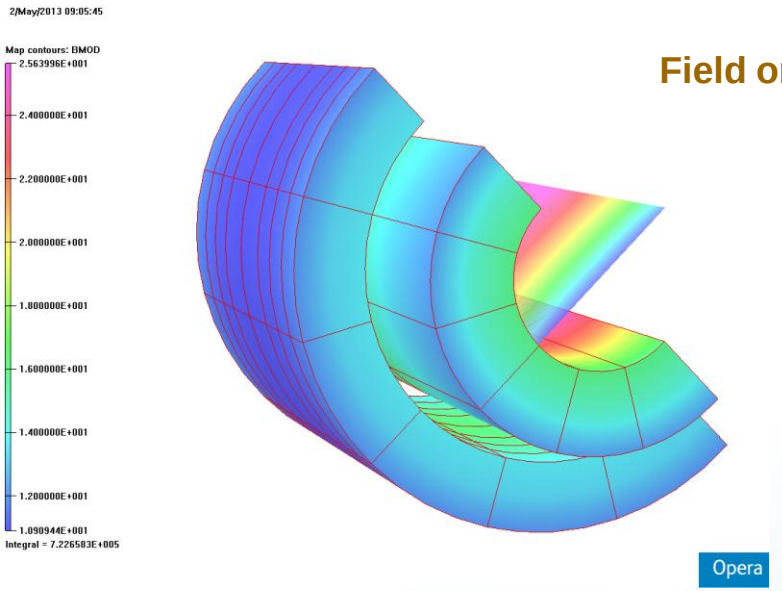
End Result:

- ❑ Improved performance
  - ➢ Better mechanical structure and reduced Bperp

Magnetic Analysis of the Final Geometry (OPERA)

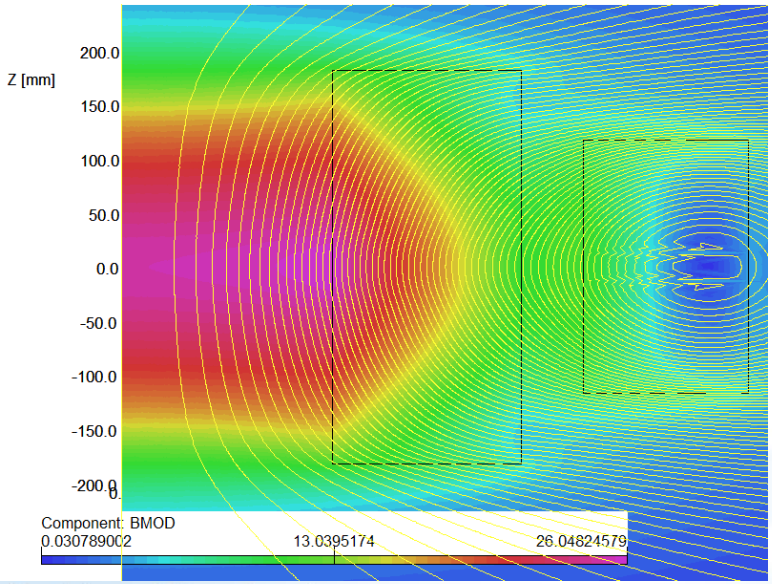


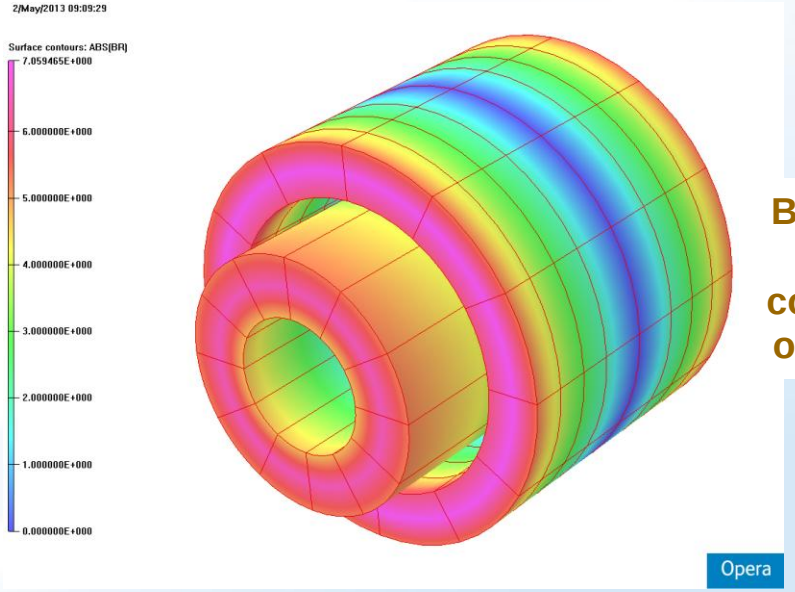
Magnitude of the field



Field on a patch

Field and field lines in cross-section

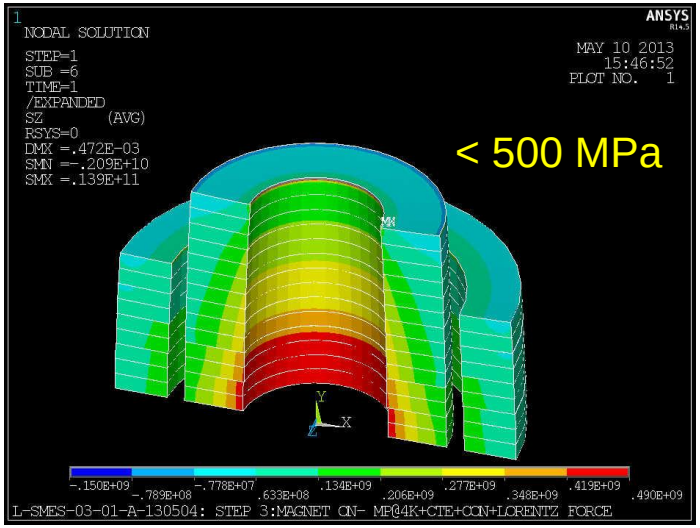




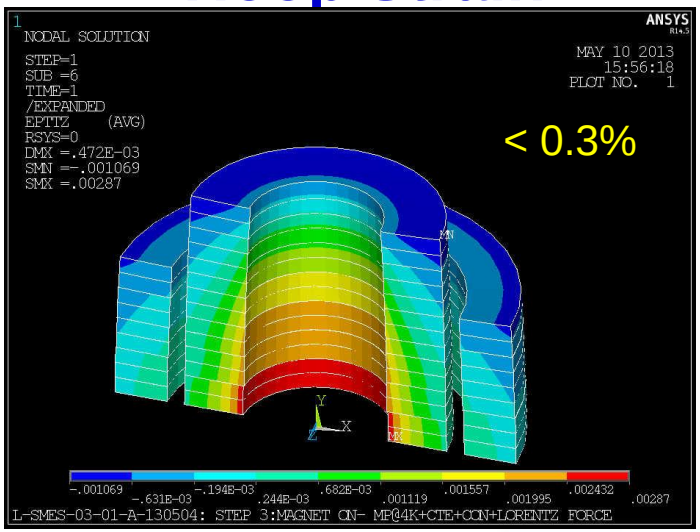
$B_{perpendicular}$ (radial) component of the field

Mechanical Analysis of the Final Geometry (ANSYS)

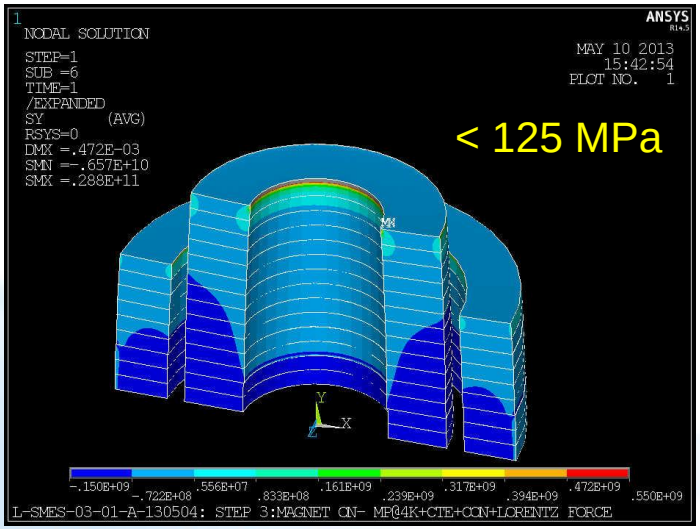
Hoop Stress



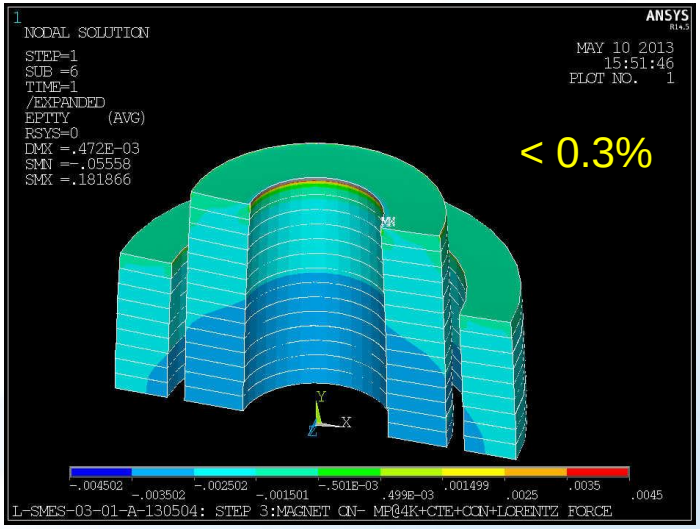
Hoop Strain



Axial Stress

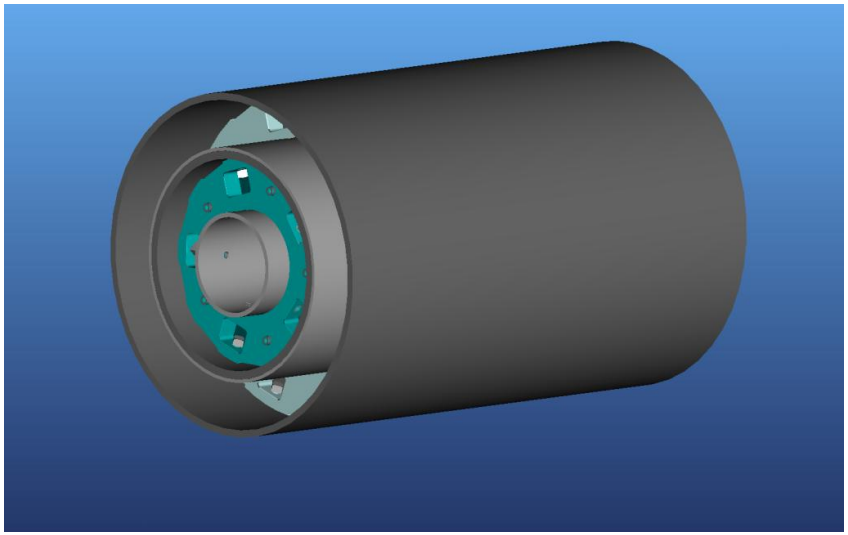


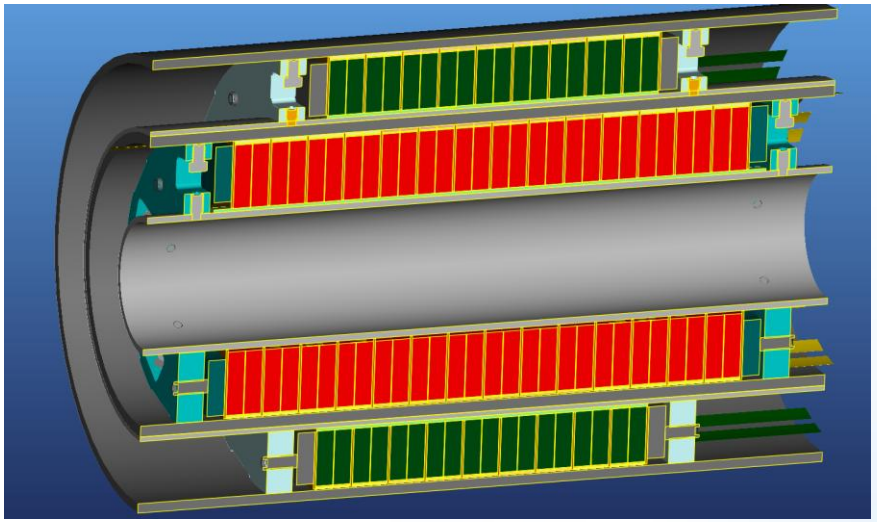
Axial Strain

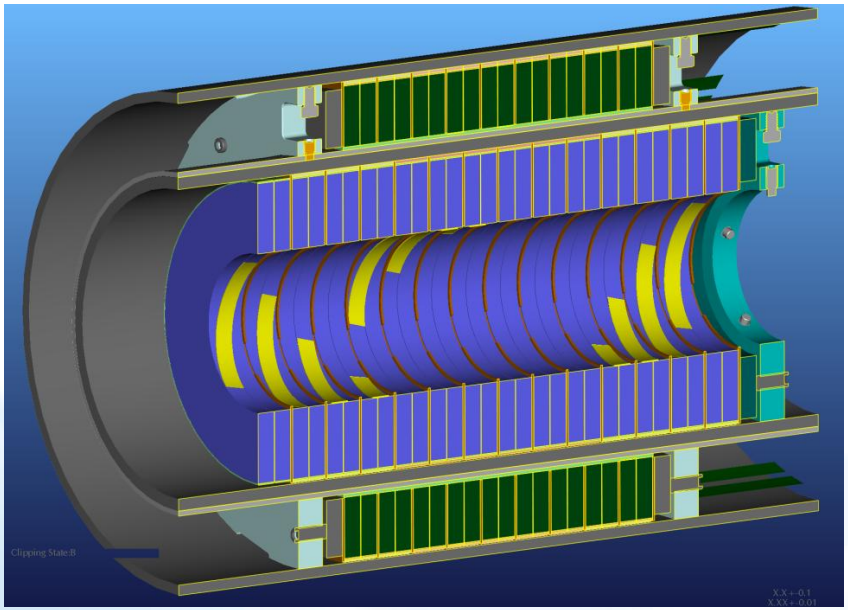


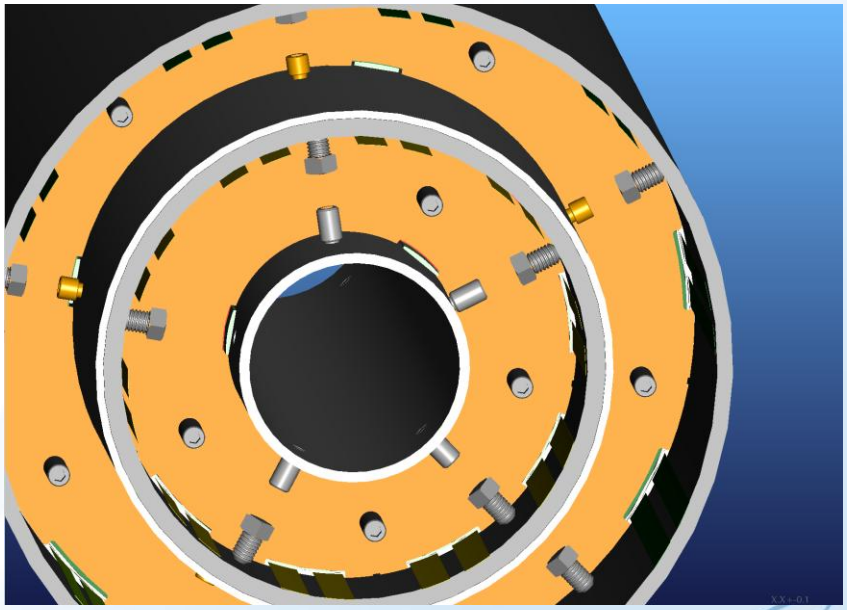
Coil deformation due to Lorentz forces: ~200 μm

Engineering Design – Magnet Assembly

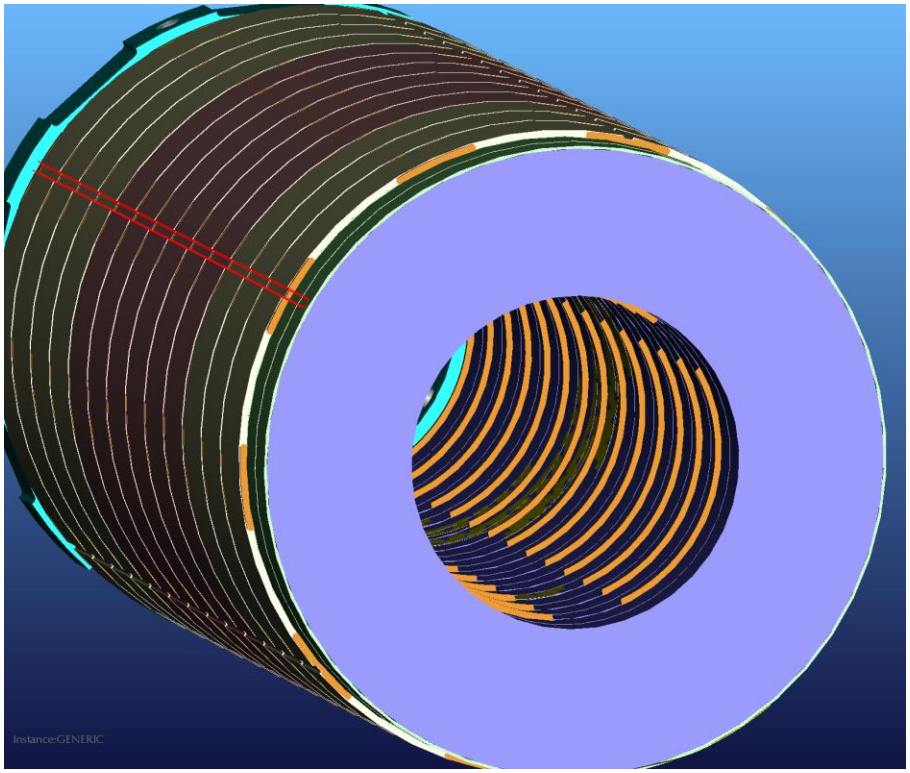


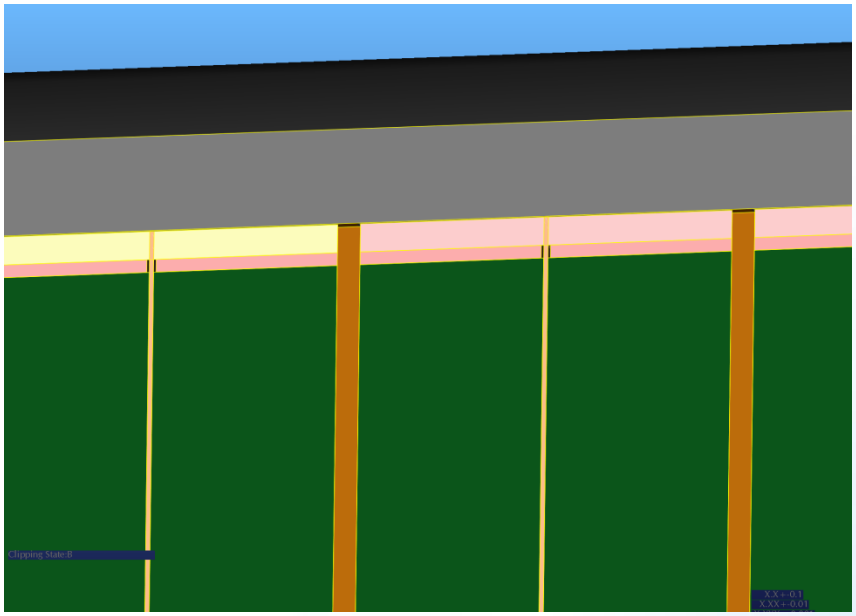


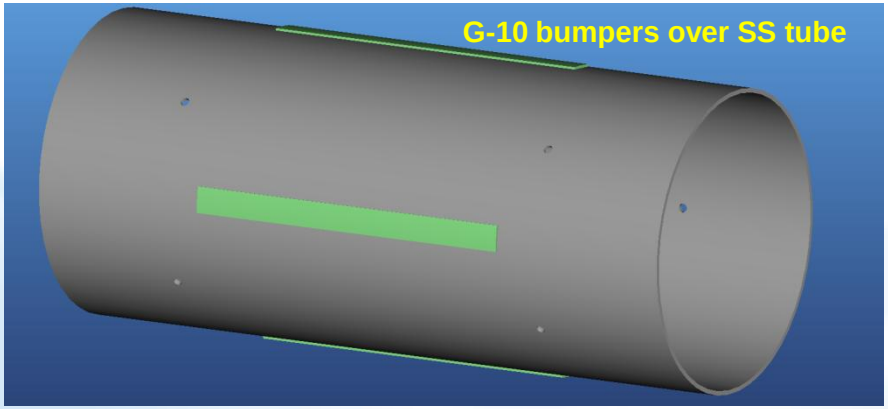


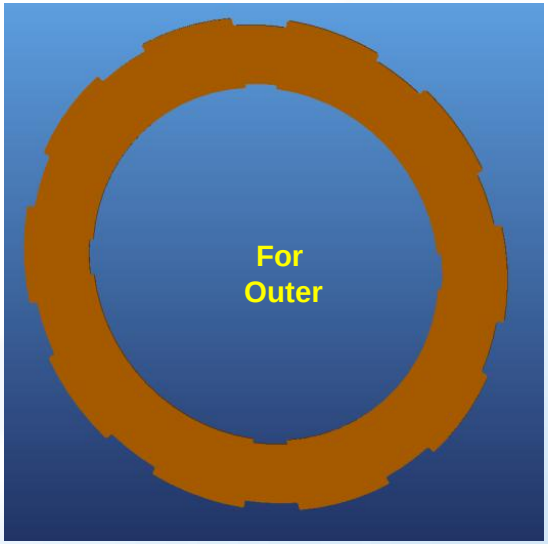


Helium Cooling

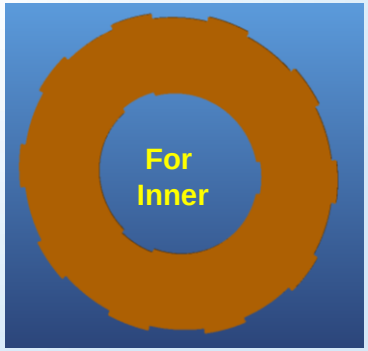




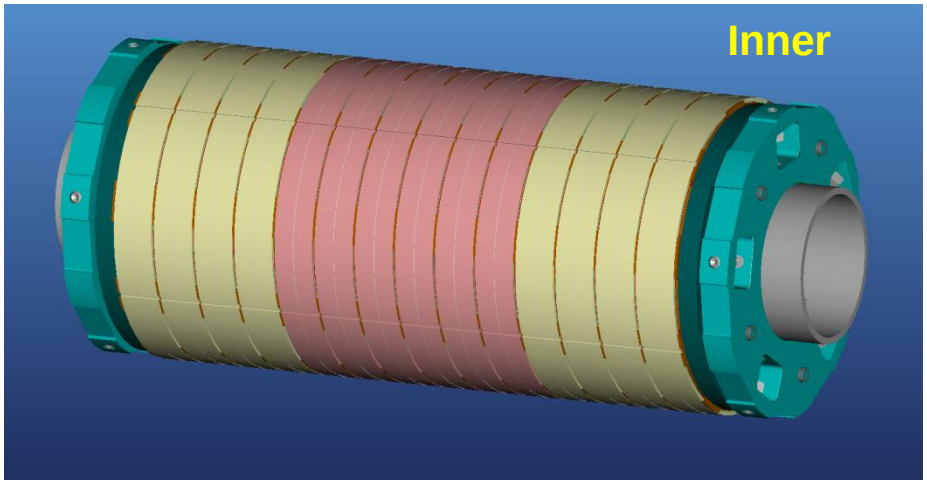




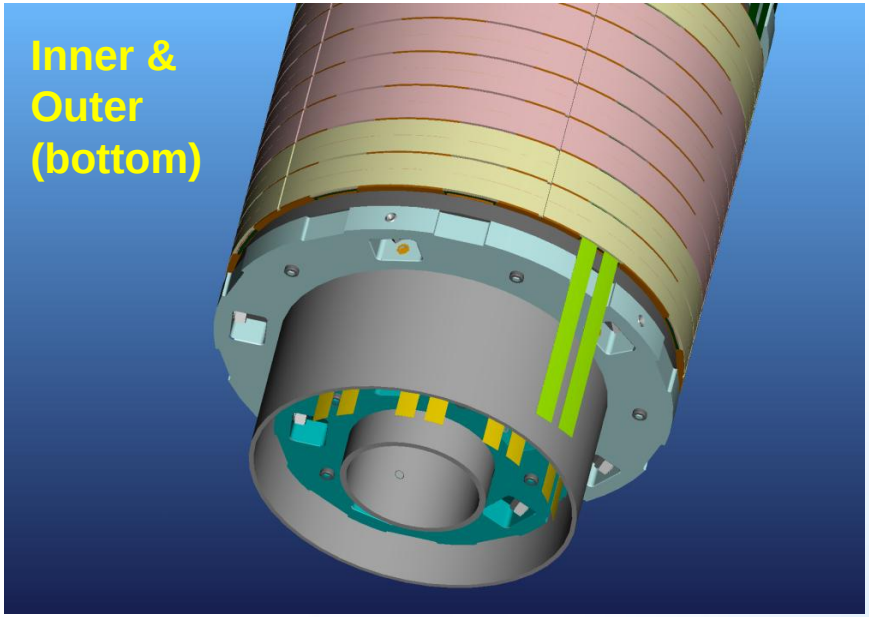
Cu discs

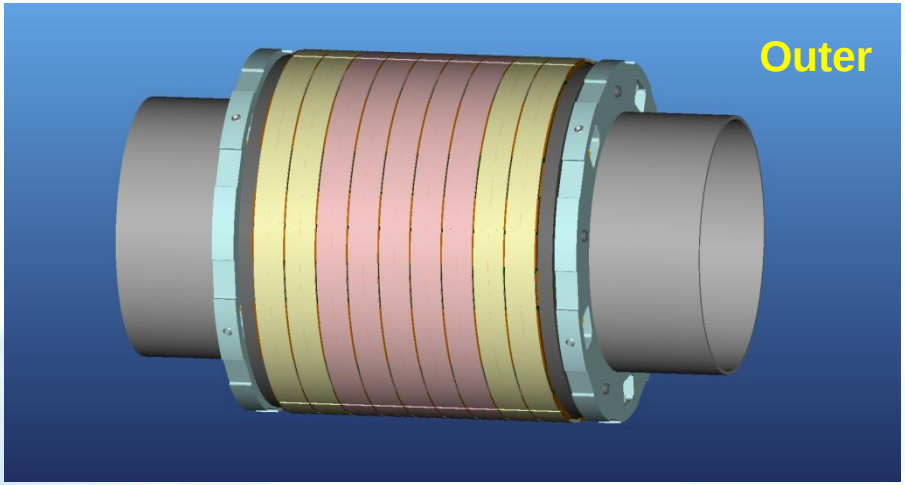


Electrical Connection and Leads

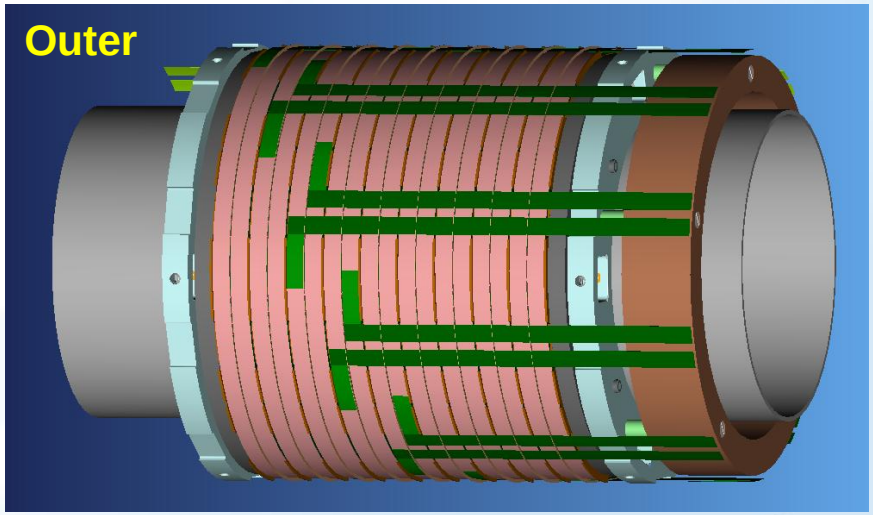


4 – 6 – 4





2 – 5 – 2



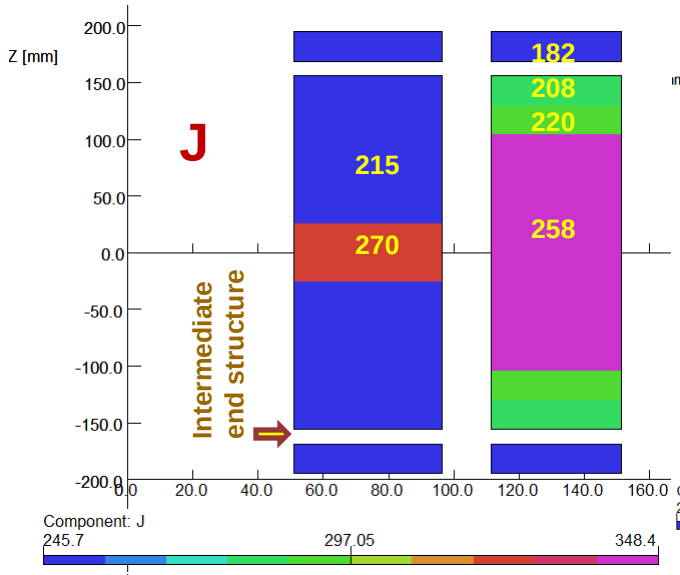
Summary

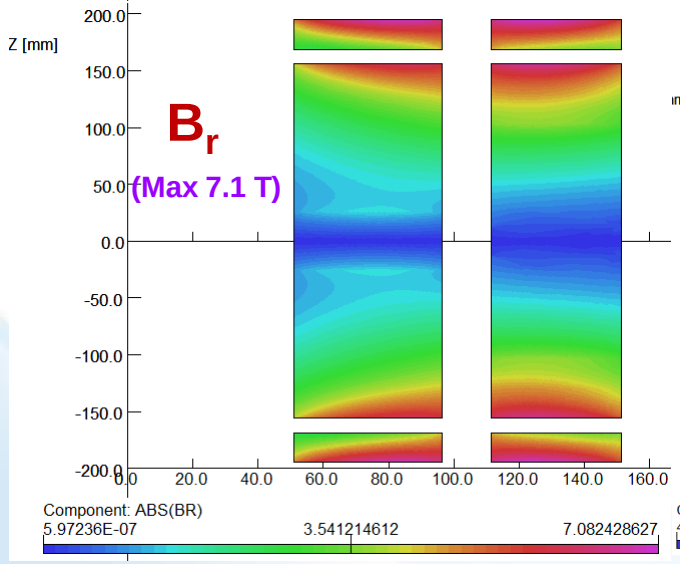
- **Construction of all pancakes coils (28 inner and 18 outer single pancakes) for 1.7 MJ has been completed.**
- **QA tests at 77 K, as instituted for this program, have been found very effective in isolating defective section within the coil. Of 44 pancakes tested so far, only two had issues.**
- **Engineering design has been completed. All parts have been ordered. Many are already delivered and rest expected soon (in about a moth).**
- **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

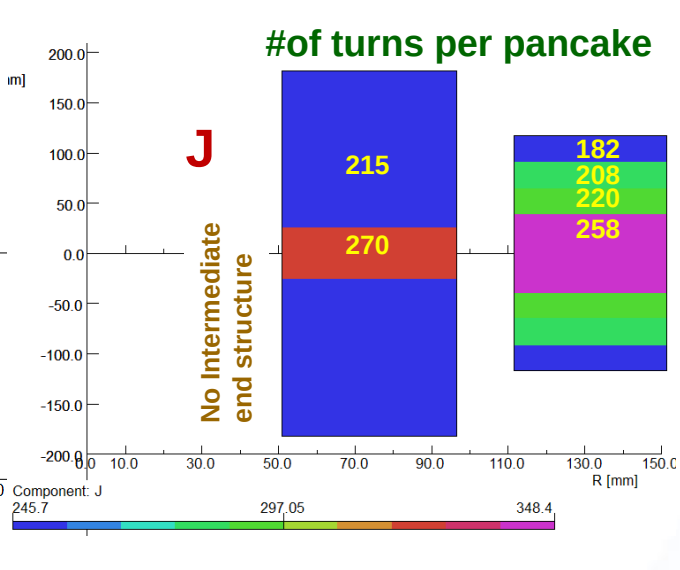
2.5 MJ Design

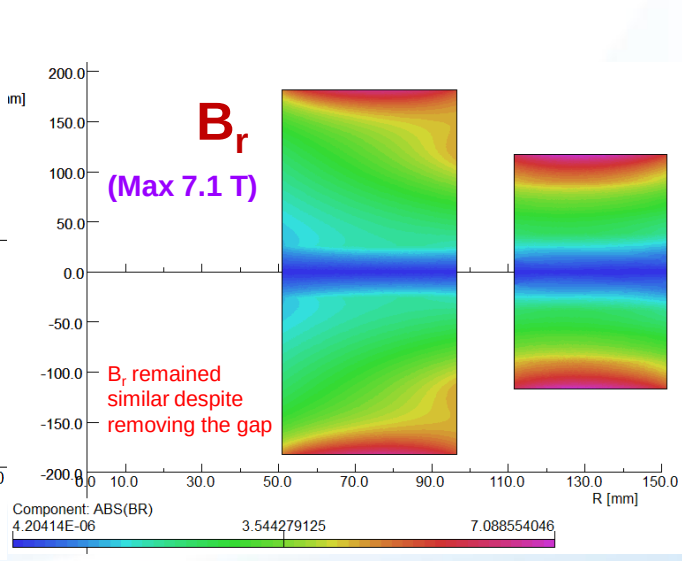




Final 1.7 MJ Design

#of turns per pancake

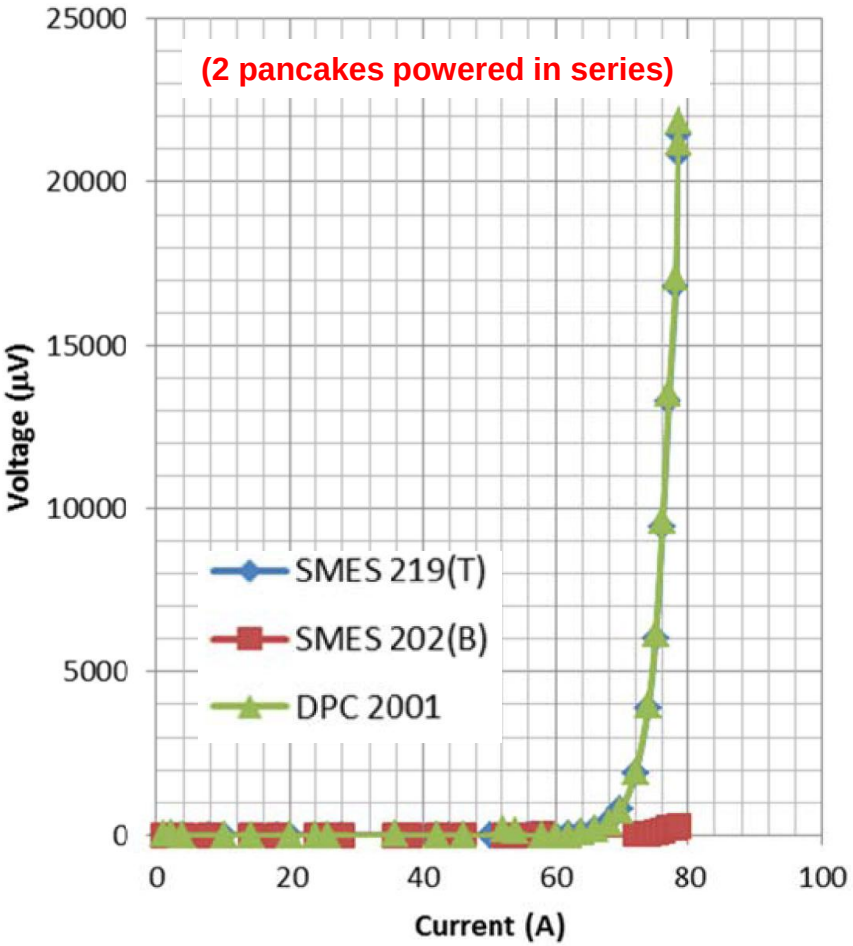


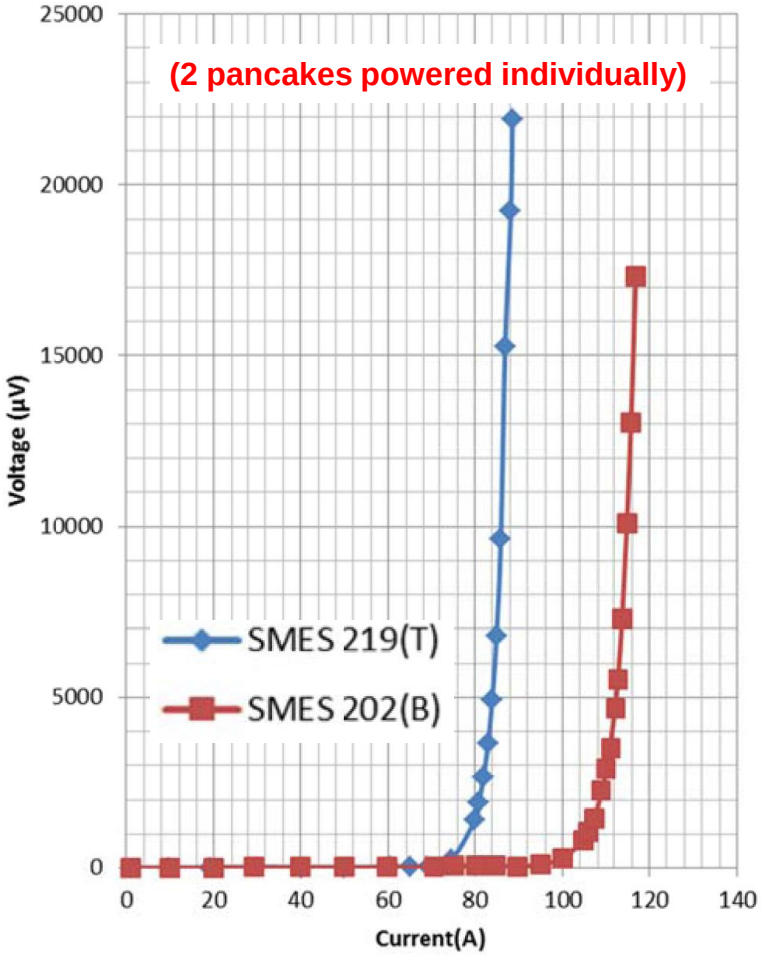


- Construction continued with a guidance that both options (2.5 MJ & 1.7 MJ) should remain open.
- 2.5 MJ (left, 56 coils) and 1.7 MJ (right, 48 coils)

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



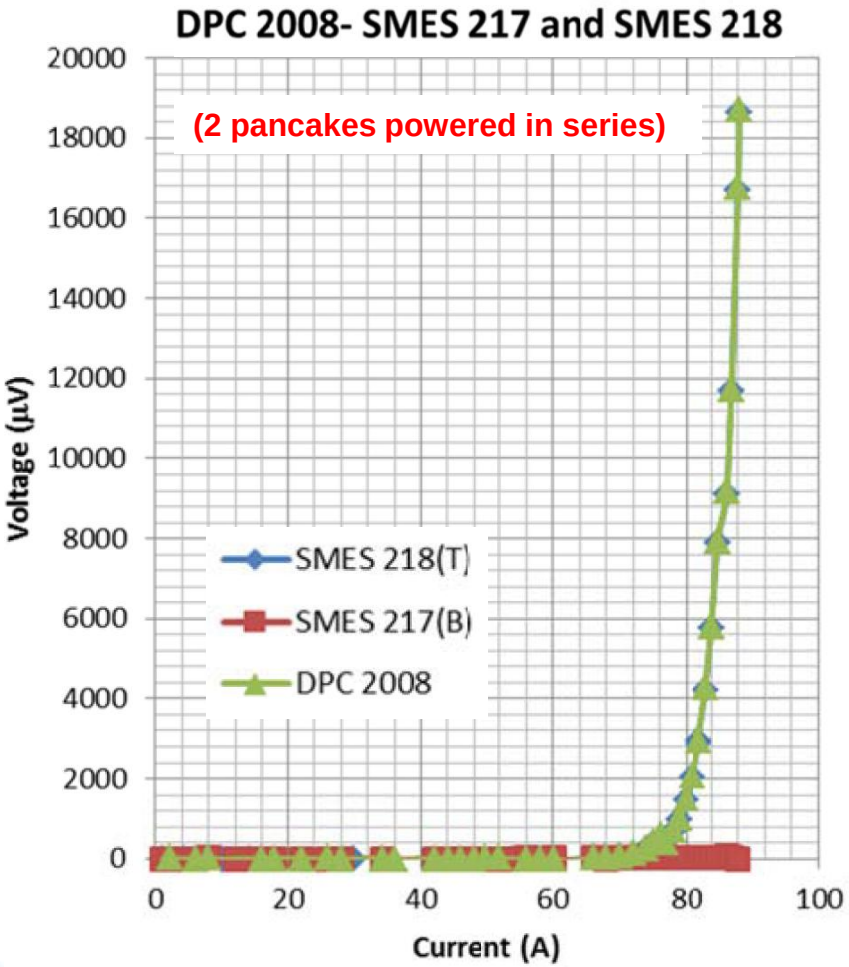


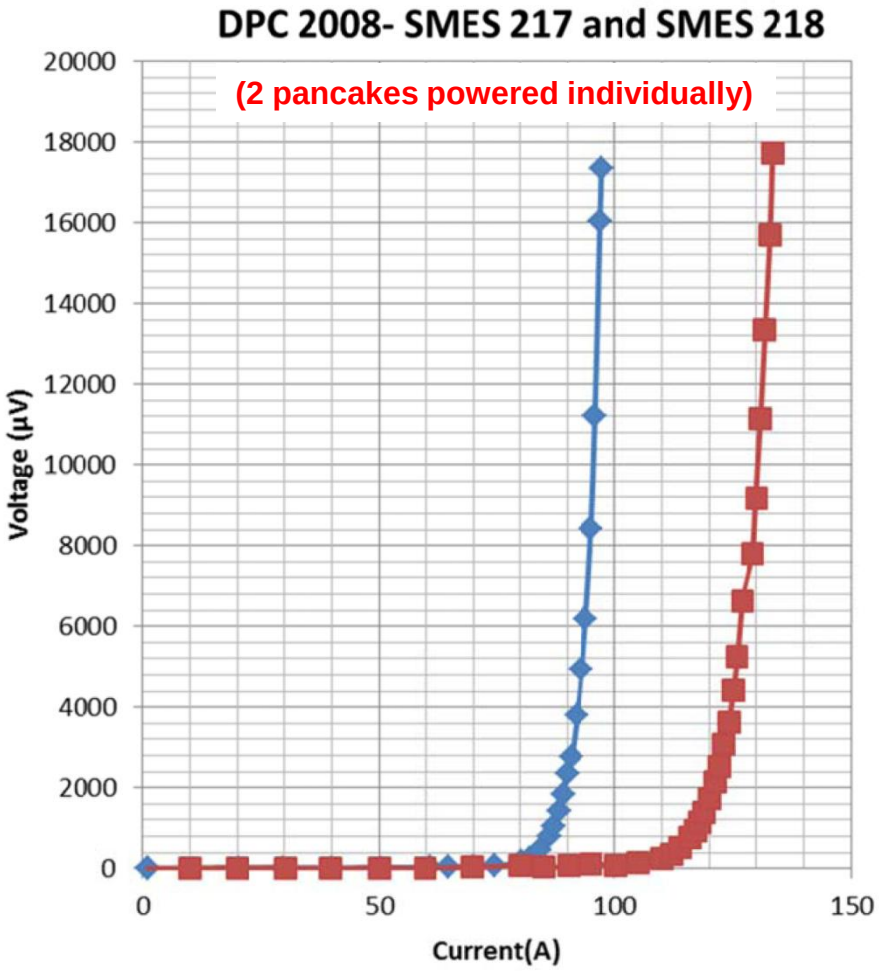
	N	1μV/cm	0.1μV/cm
SMES 219(T)	28	78.3	72.2
SMES 202(B)	29	>78.5 A	
DPC 2001	28	>78.5 A	74.0

SMES202 carries much higher critical current than SMES219 @77K

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

Outer Double Pancake DPC2008





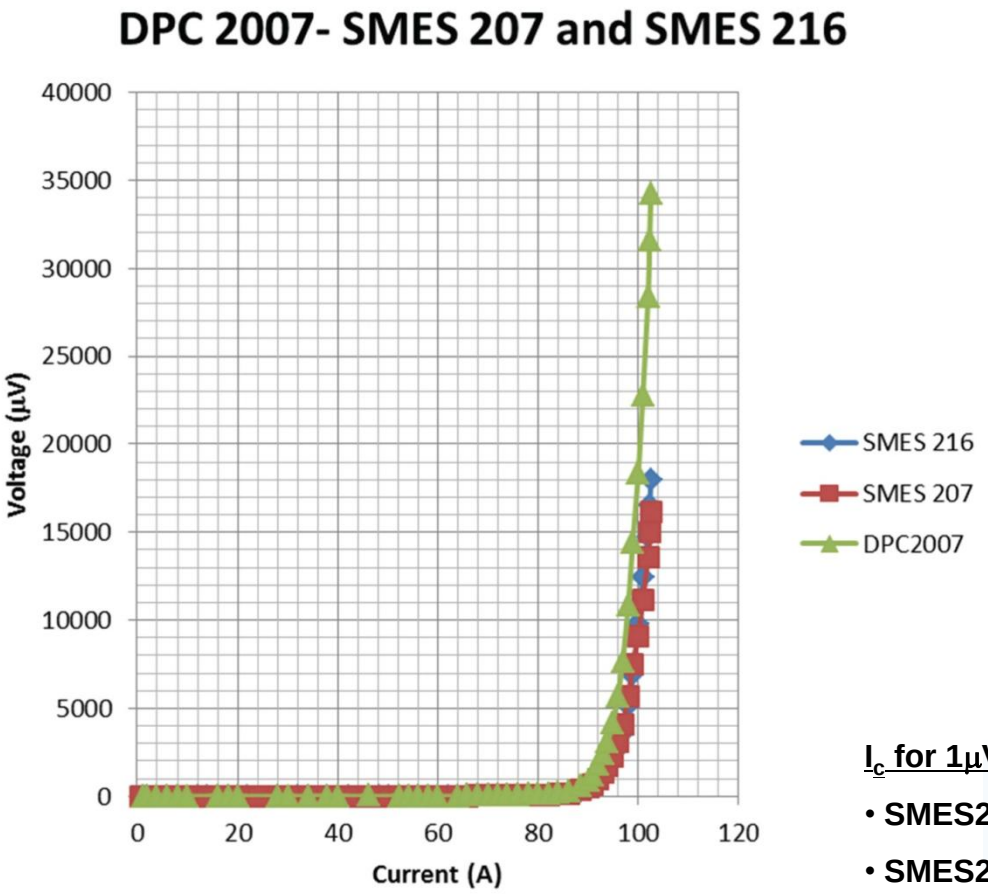
	N	1μV/cm	0.1μV/cm
SMES 218(T)	26	87.9	80.4
SMES 217(B)		>88 A	
DPC 2008	25	>88A	82.4

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)



Both coils carry about the same current

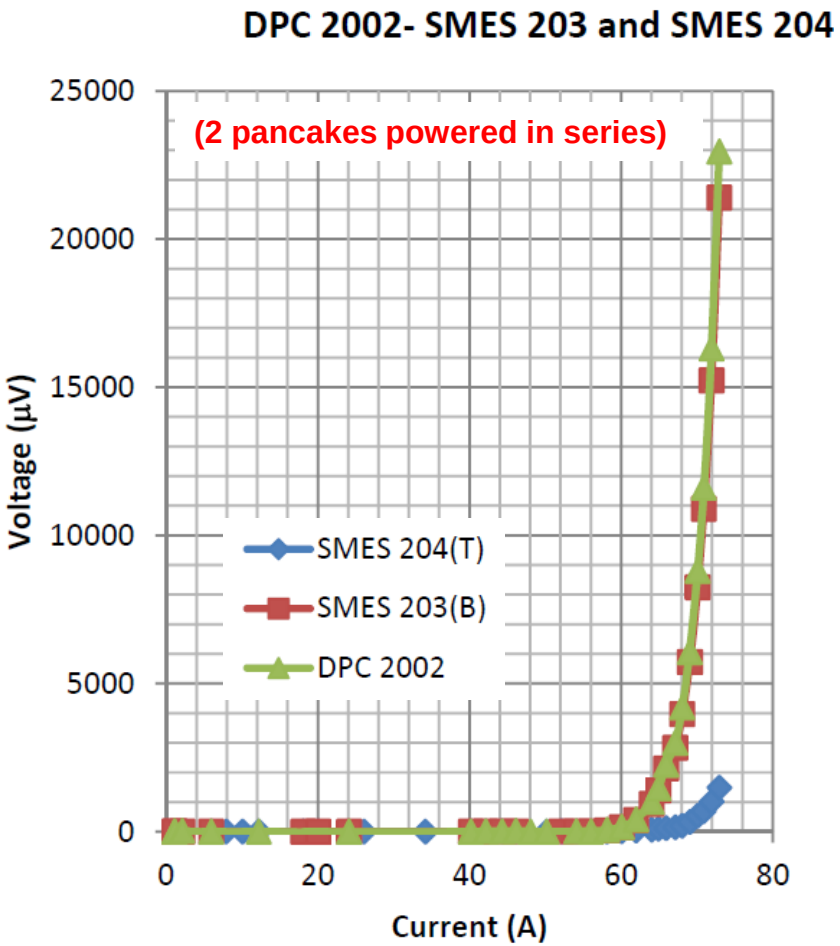
I_c for 1μV/cm criteria

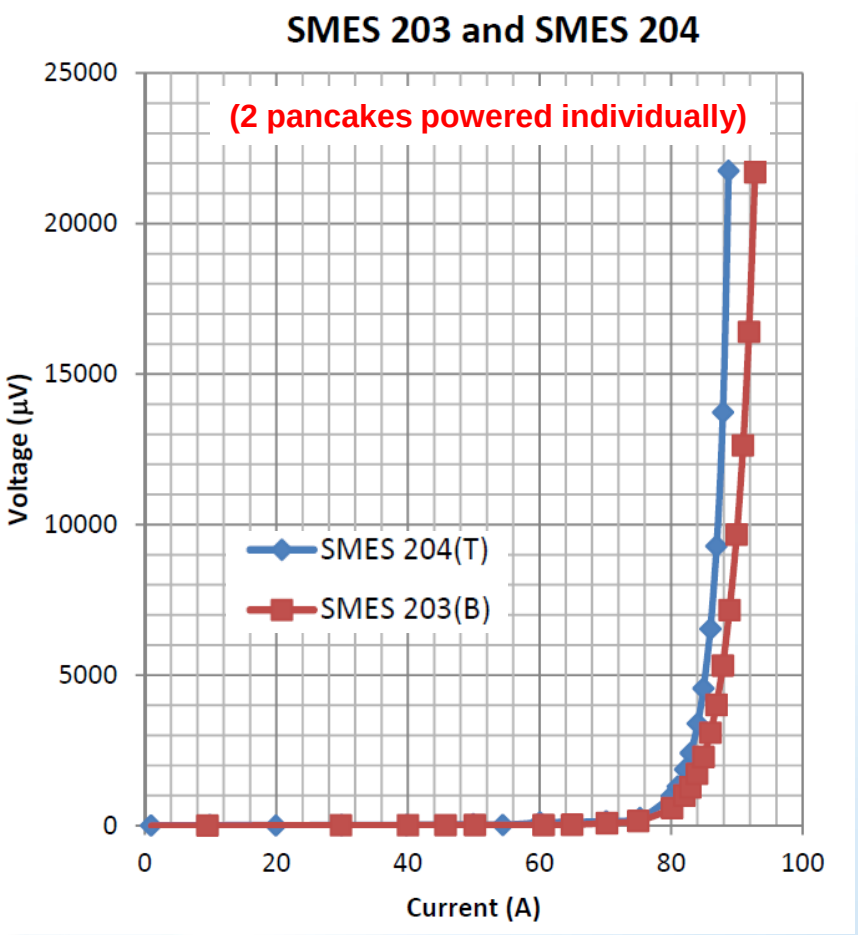
- **SMES216:** 102.2 A, N=29
- **SMES207:** 102.5 A, N=26
- **DPC2007:** 102.3 A, N=28

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



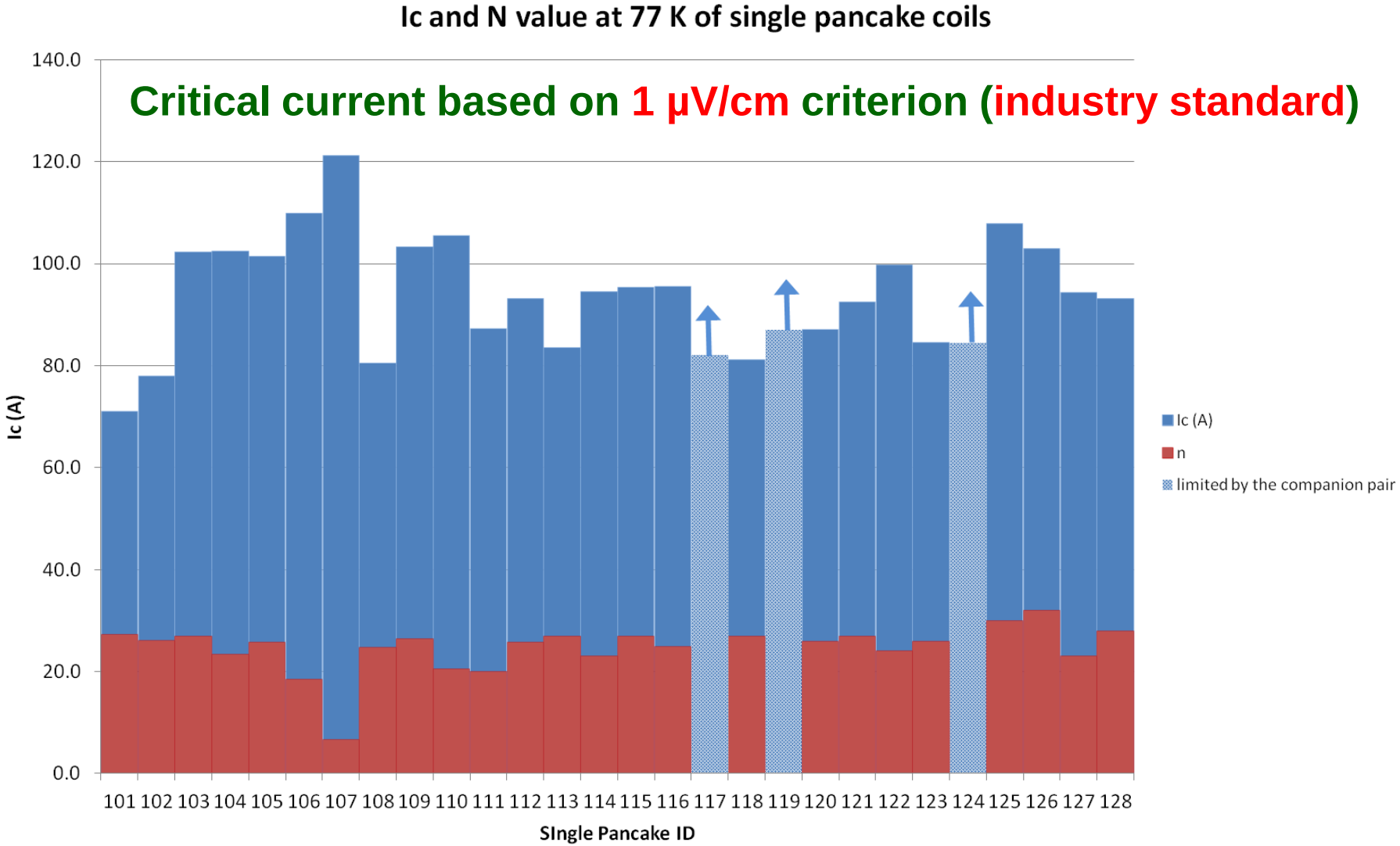


	N	1μV/cm	0.1μV/cm
SMES 204(T)	28	>73 A	>73 A
SMES 203(B)	24	72.9	66.1
DPC 2002	24	>73 A	67.9

SMES204 carries higher critical current than SMES203 @77K

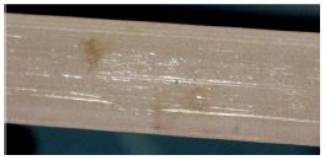
		Ic (A) @	
	N	1μV/cm	0.1μV/cm
SMES 203	29	89.3	82.6
SMES 204	25	92.8	84.6

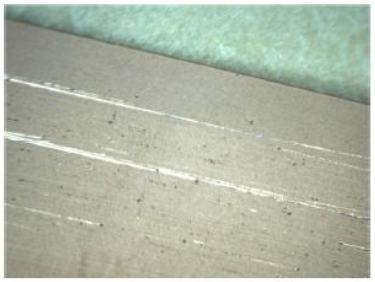
Summary of 77 K test of all inner pancakes

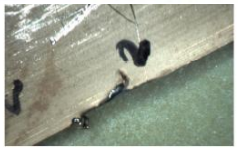
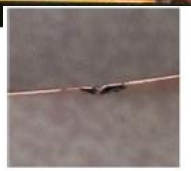


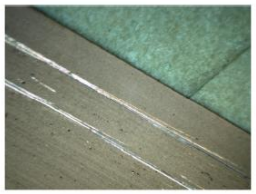
Tested in double pancake structure with two single pancakes powered in series.
Arrow indicates lower performing pancake limiting the I_c measurements.

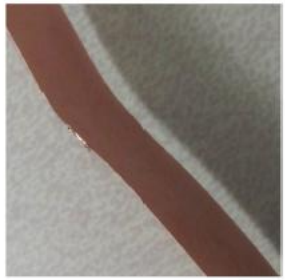
Visual Inspection of Conductor and Splices During Coil Winding (first line of defense in QA)

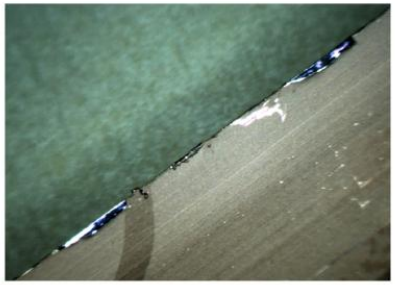



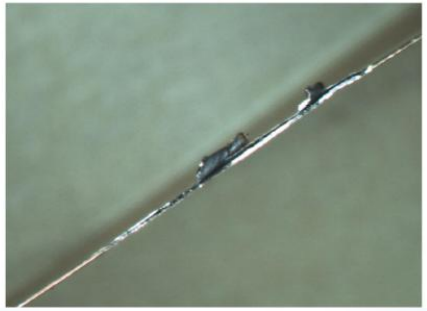









SuperPower has replacing the conductor in these and other cases where we were not sure

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.