Recent Results in High Field Magnet Technology

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The 2014 Kyoto Workshop on HTS Magnet Technology for High Energy Physics – The 2nd Workshop on Accelerator Magnet in HTS

Contents

- **High field HTS SMES solenoid**
  - Summary of design, construction and test results
  - ➢ (achieved new record performance)

A brief discussion on:

- **High field magnets for accelerators**
  - Common coil design for high field magnets
  - ➢ (inherent geometry for higher performance, lower cost)
  - ➢ (good field quality designs demonstrated)

High Field HTS Solenoid for Superconducting Magnetic Energy Storage (SMES)

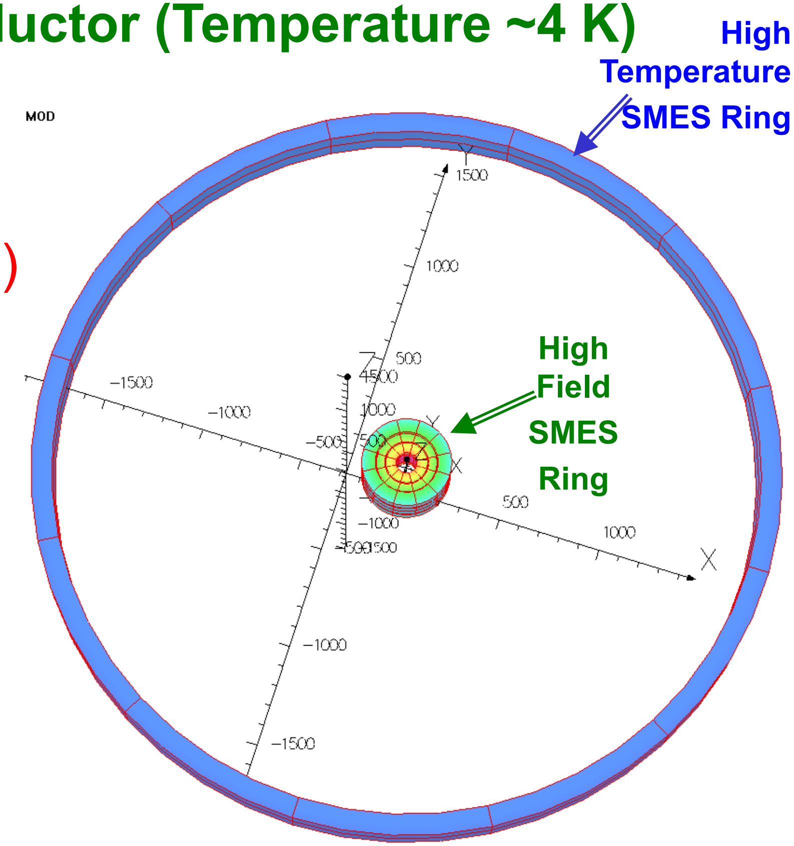
arpa·e CHANGING WHAT'S POSSIBLE — BROOKHAVEN NATIONAL LABORATORY — ABB — SuperPower Inc. — UNIVERSITY of HOUSTON

Conductor: High strength ReBCO from SuperPower (over 6 km, 12 mm wide)

SMES Options with HTS

High Temperature Option (~65 K): Saves on cryogenics (Field ~2.5 T)

High Field (~25 T) Option: Saves on Conductor (Temperature ~4 K)



Previous attempts:

LTS: up to ~5 T

HTS: few Tesla (high temp. to save on cryo)

Our analysis on HTS option:

Conductor cost dominates the cryogenic cost by an order of magnitude

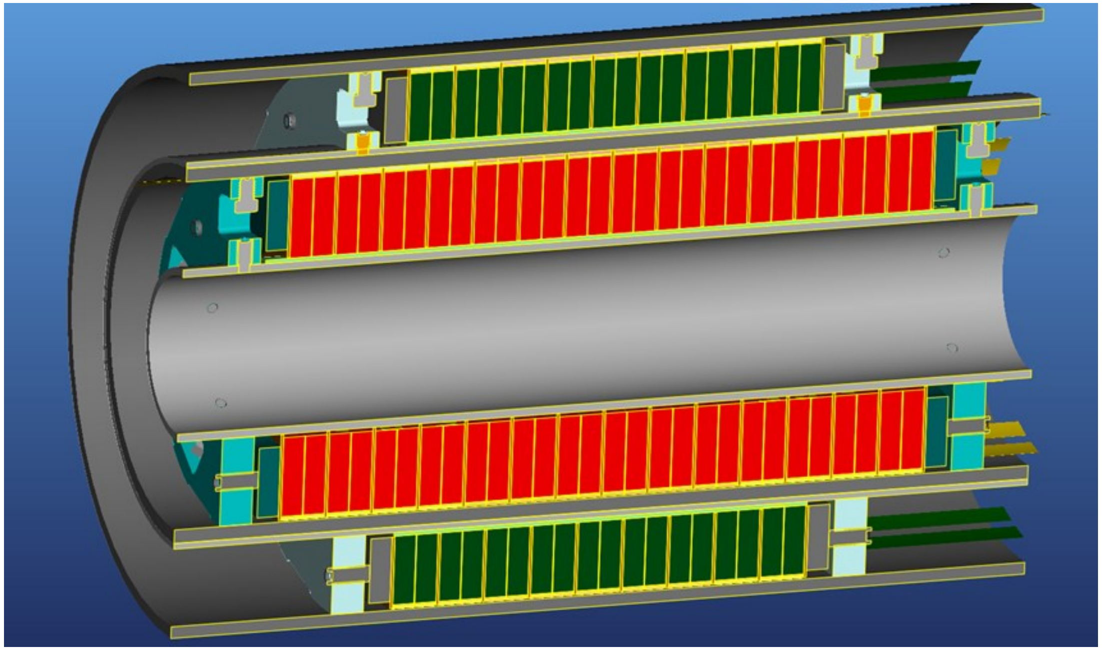
High risk, high reward R&D under arpa-e:

- Very high fields: ~25 T (E α B^2)
  - Only possible with HTS

➢ Also: A medium field and medium temperature option (a new record demonstrated as a part of arpa-e funding)

Very High Field HTS Solenoid

The Basic Demonstration Module



Aggressive parameters

Field: ~25 T

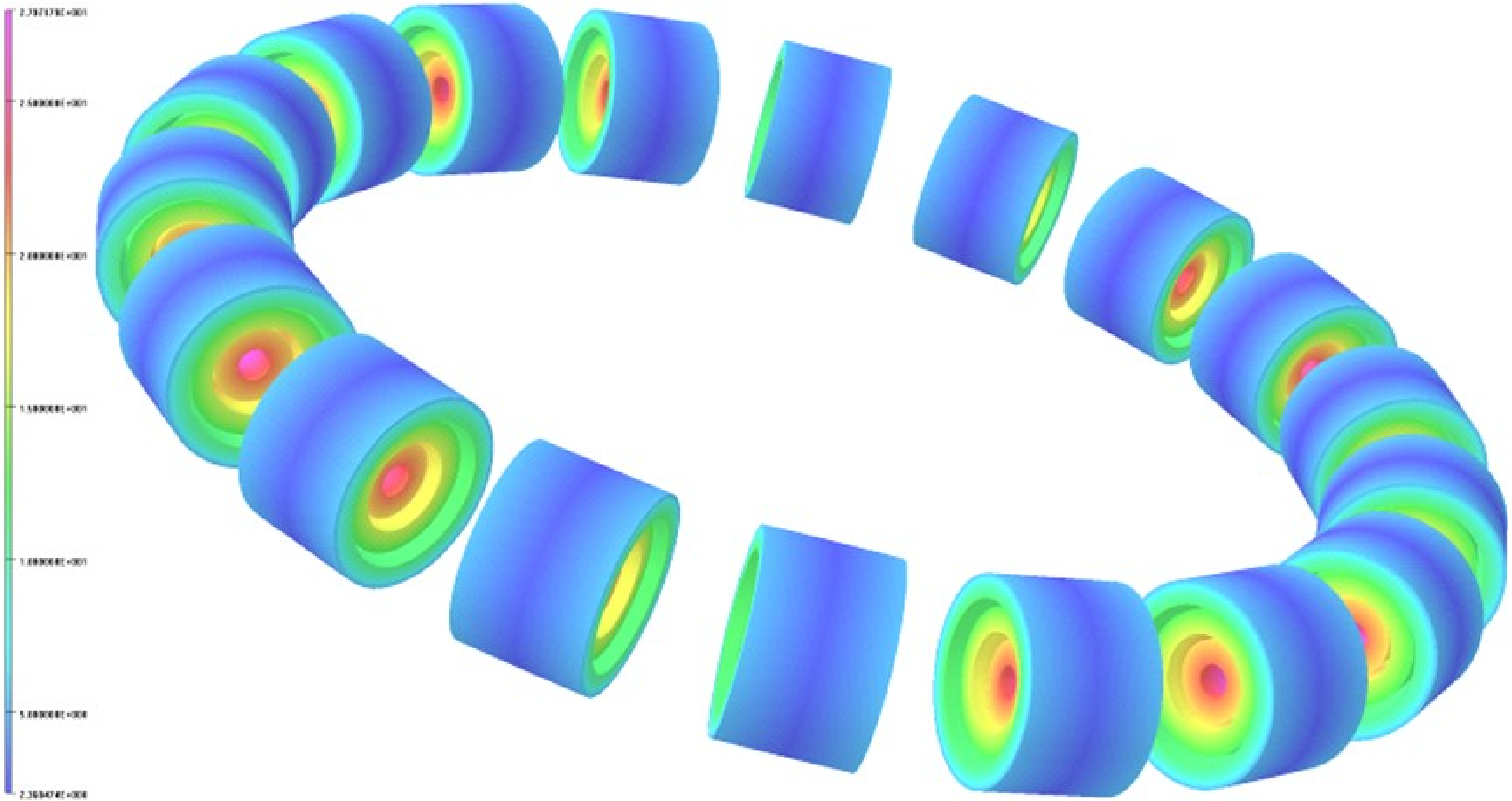
Bore: 100 mm (large)

Hoop Stresses: 400 MPa

Conductor: HTS (new)

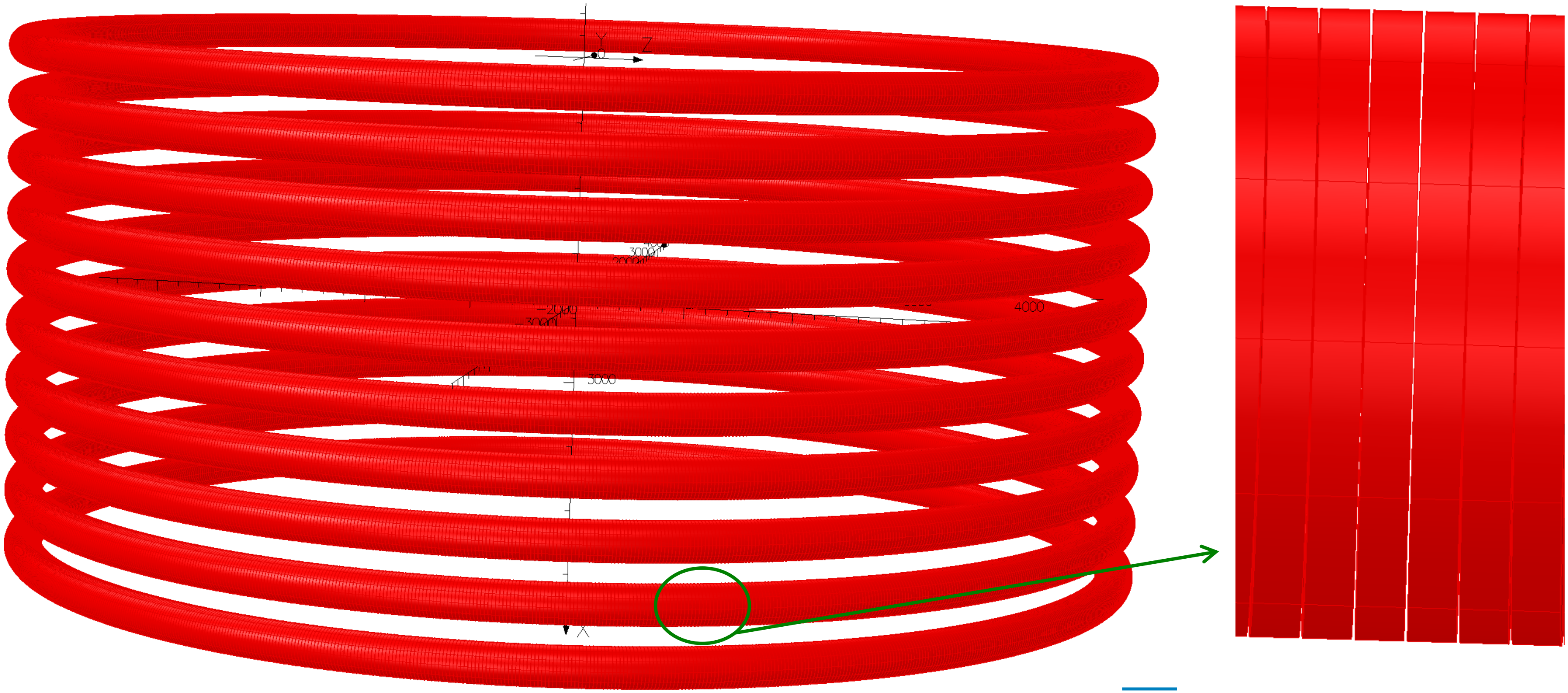
- **Funded by arpa-e as a "high risk, high reward" project**

Concepts of Large Scale SMES



- Torus could consists of a large number of solenoid module
- Field becomes parallel, increasing I_c of ReBCO several times

Concepts for GJ Size SMES for GRID

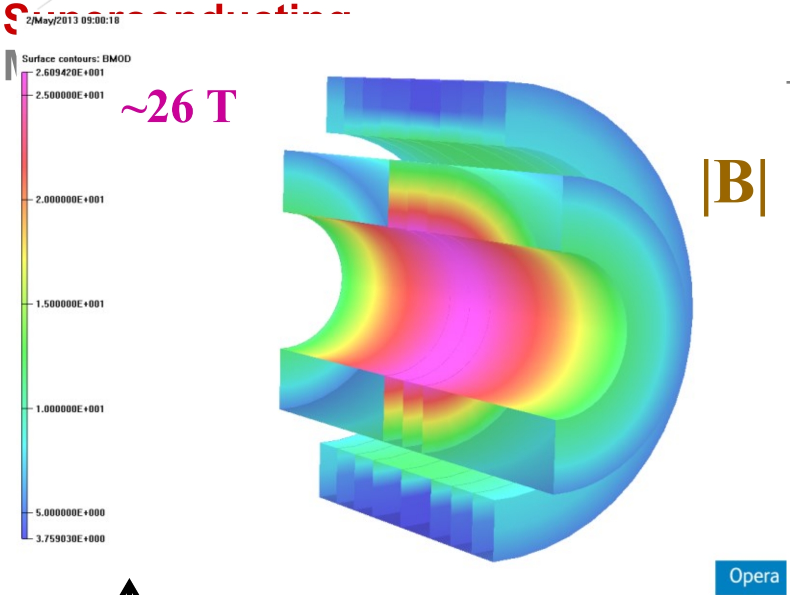


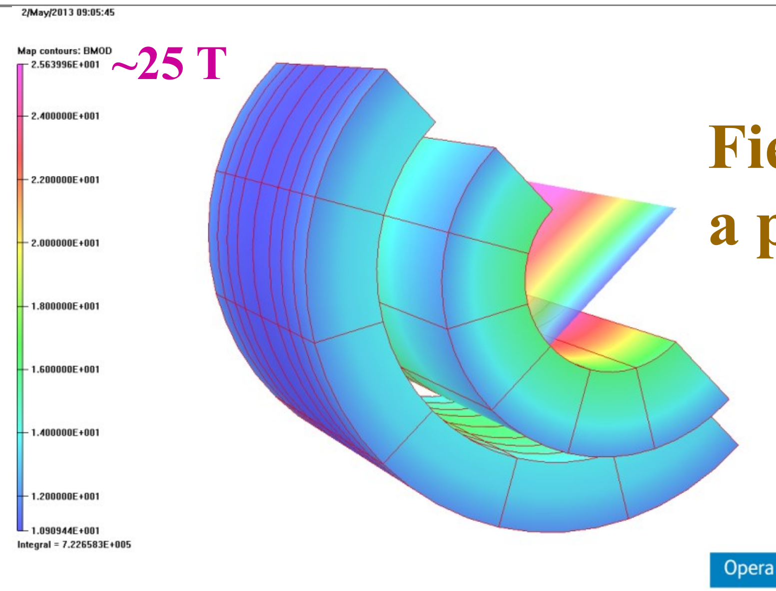
GJ scale compact storage system

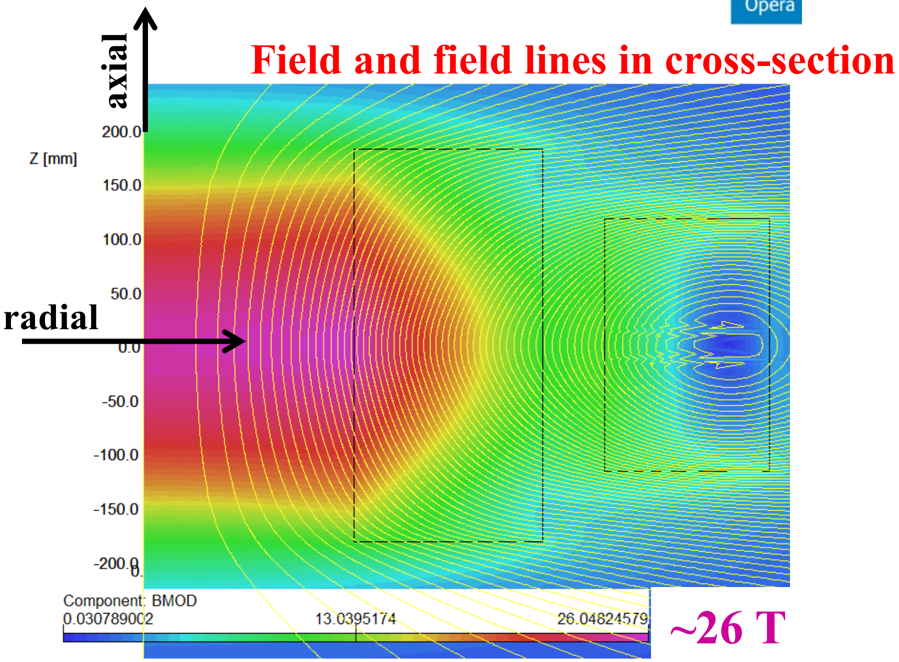
Bo~25 T, $B_{perependicular}$ ~0.4 T (B// efficient for ReBCO)

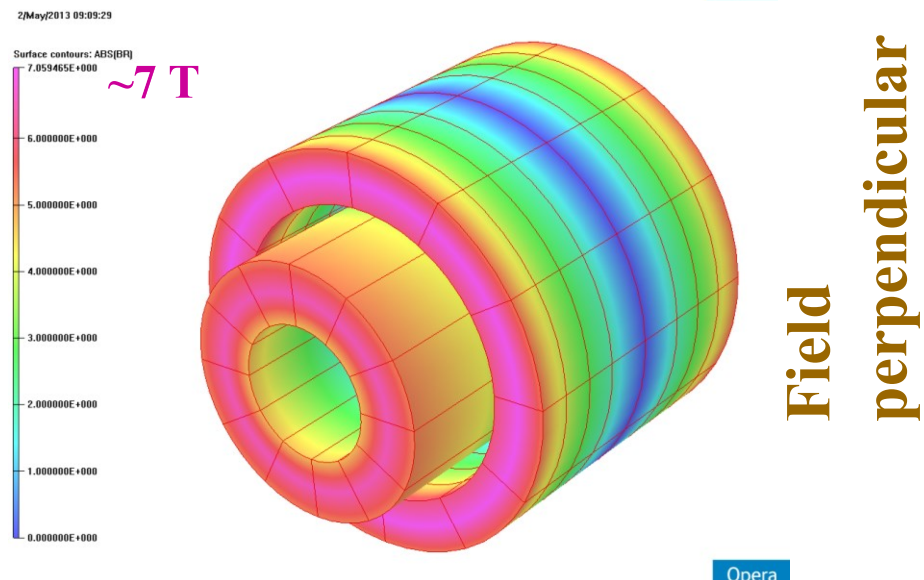
High Field HTS Solenoid Design

Magnetic Design

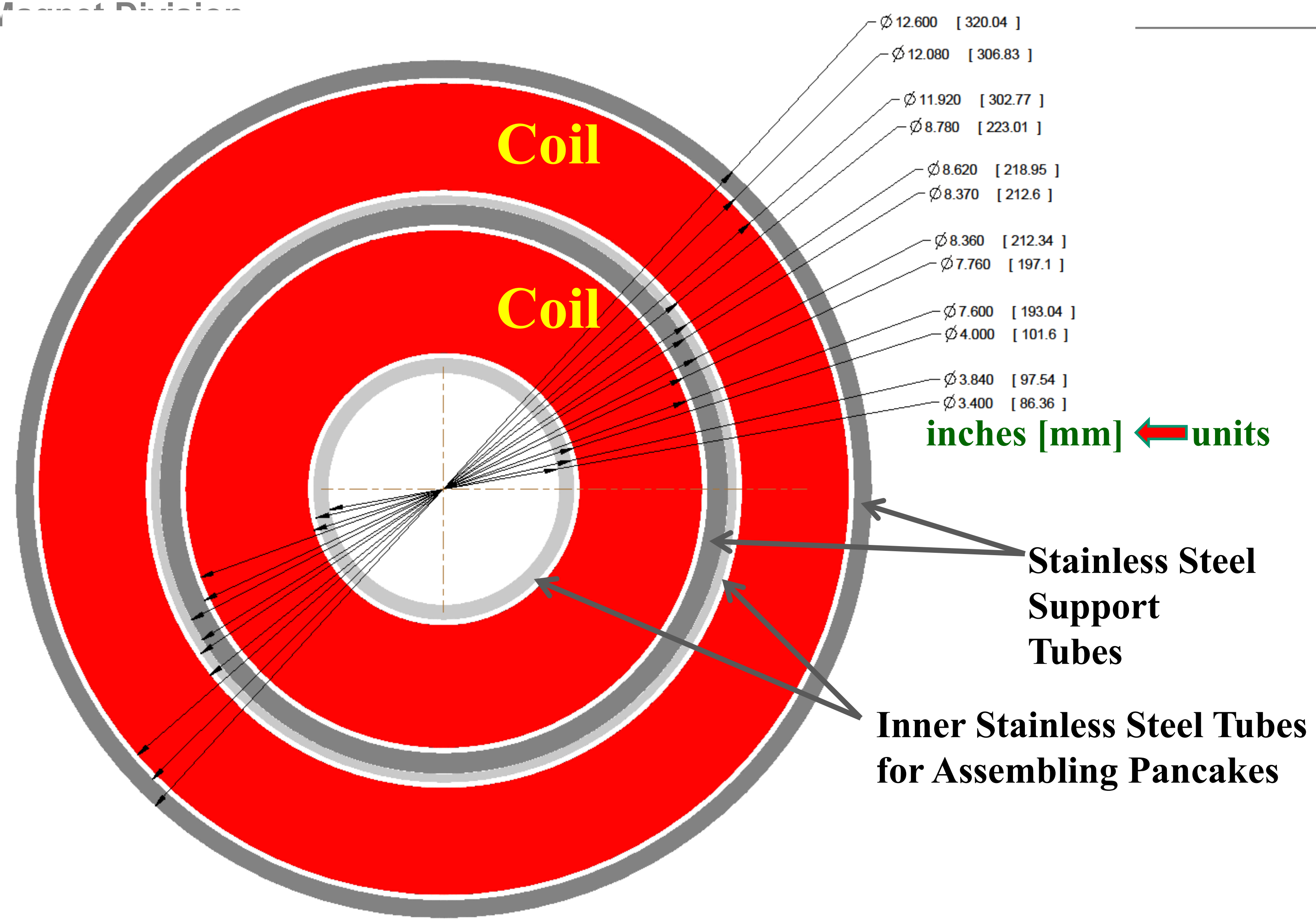








Cross-section of Coil and Support Tube



Nominal Parameters

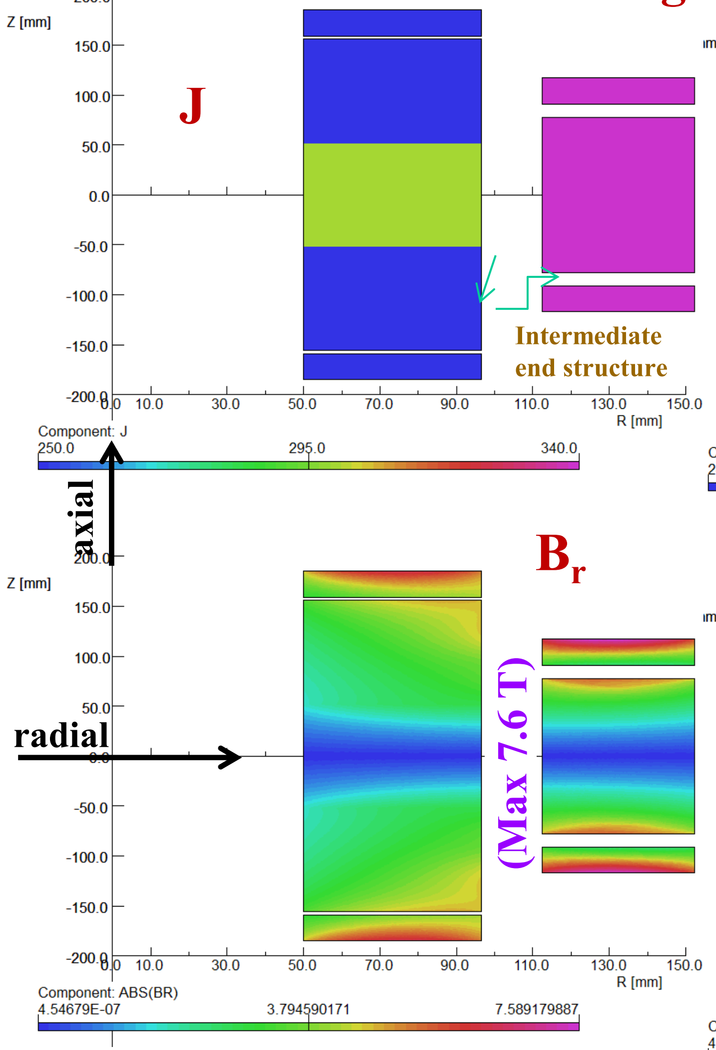
Stored Energy	1.7	MJ
Currrent	700	Amperes
Inductance	7	Henry
Maximum Field	25	Tesla
Operating Temperature	4.2	Kelvin
Overall Ramp Rate	1.2	Amp/sec
Number of Inner Pancakes	28	
Number of Outer Pancakes	18	
Total Number of Pancakes	46	
Inner dia of Inner Pancake	102	mm
Outer dia of Inner Pancake	194	mm
Inner dia of Outer Pancake	223	mm
Outer dia of Outer Pancake	303	mm
Intermediate Support	13	mm
Outer Support	7	mm
Width of Double Pancake	26	mm

Conductor used (ReBCO from SP):

- Well over 6 km (12 mm wide tape)

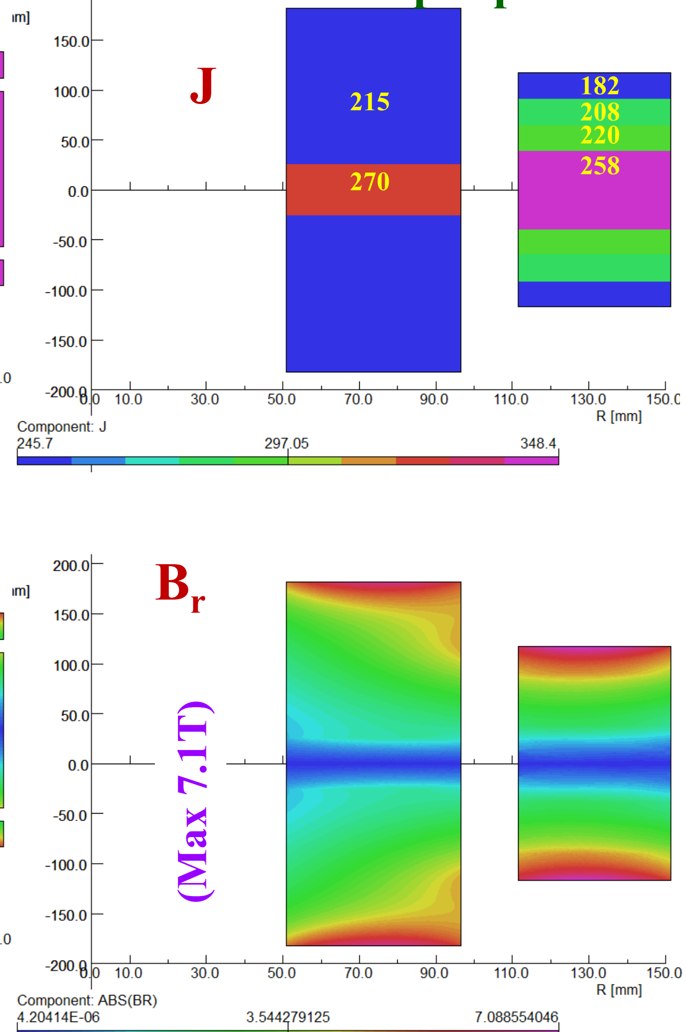
Grading to Optimize Design

Initial 1.7 MJ Design



Optimized 1.7 MJ Design

#of turns per pancake



Adjust within coil

(different pancakes)

- Cu thickness
- SS thickness

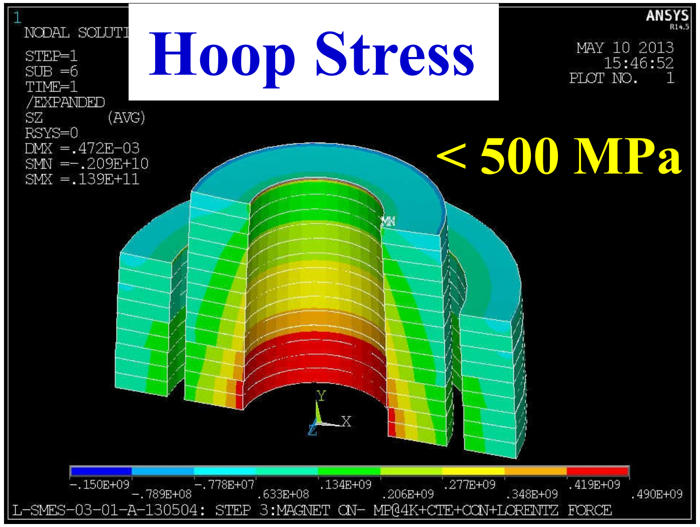
(more cu in ends
more SS in middle)

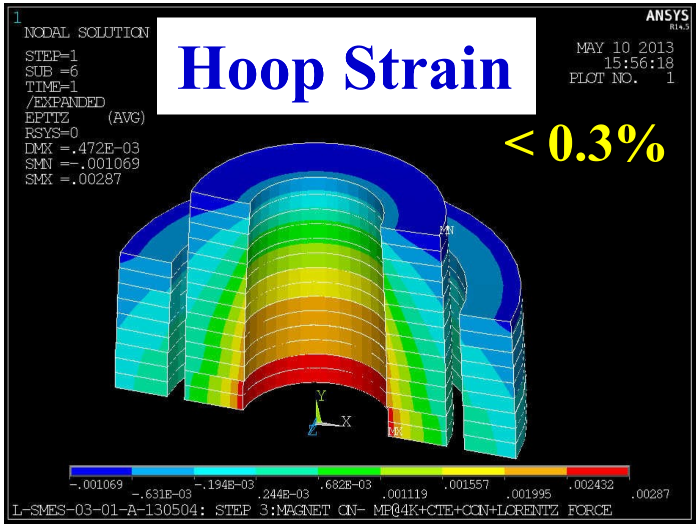
End Result:

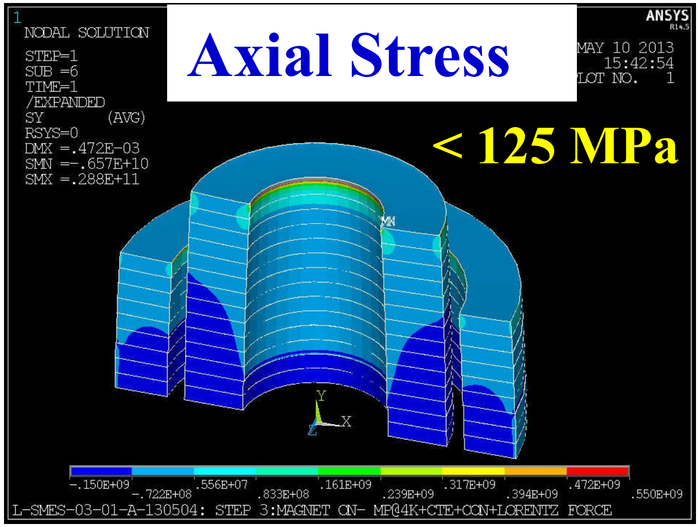
✓ Improved performance

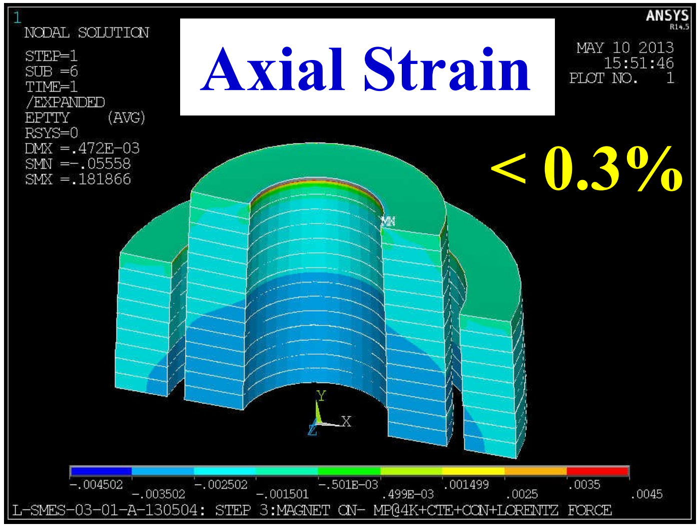
➢ Better mechanical structure and reduced Bperp

Mechanical Analysis (ANSYS)







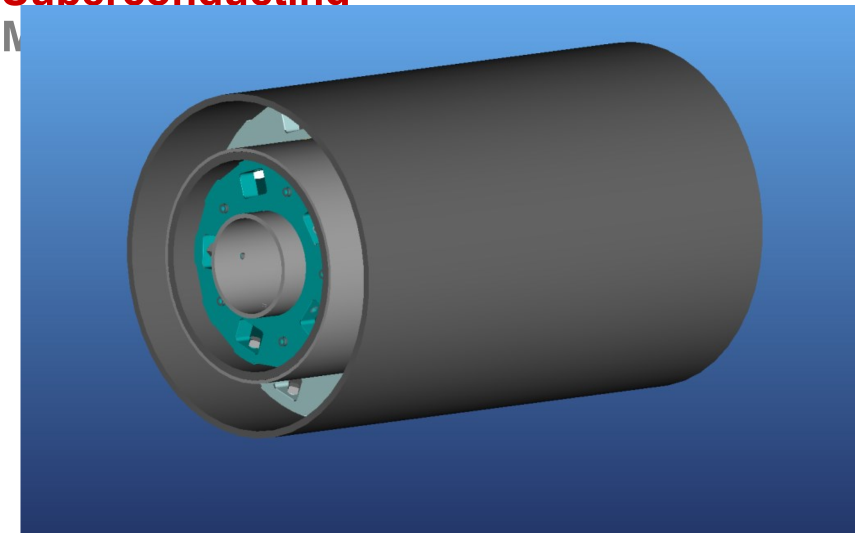


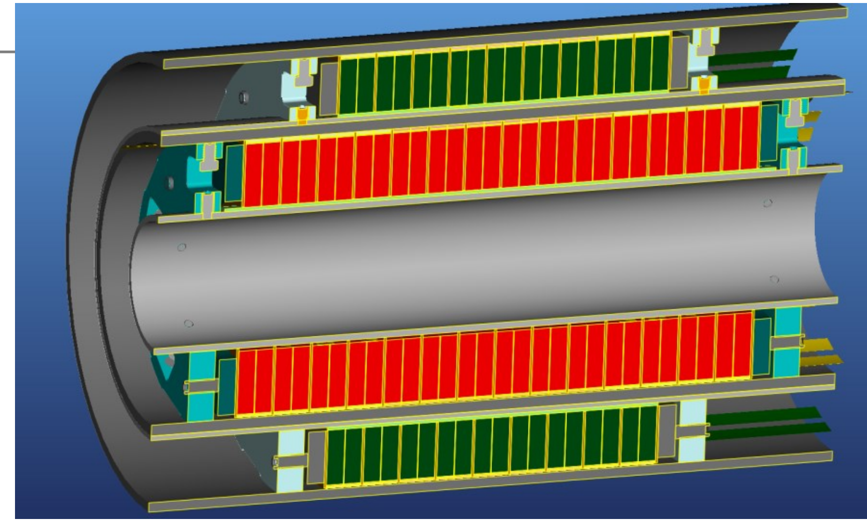
Maximum coil deformation due to Lorentz forces:

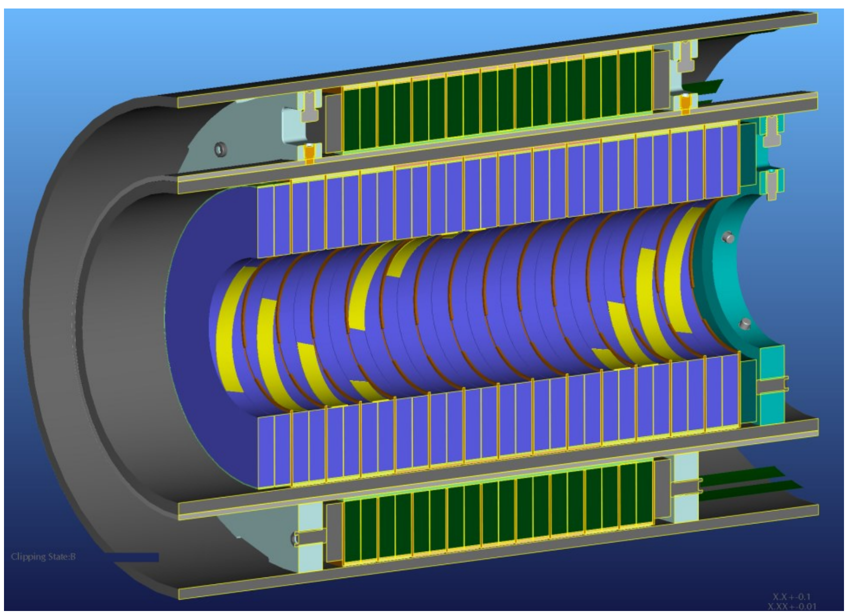
~200 µm

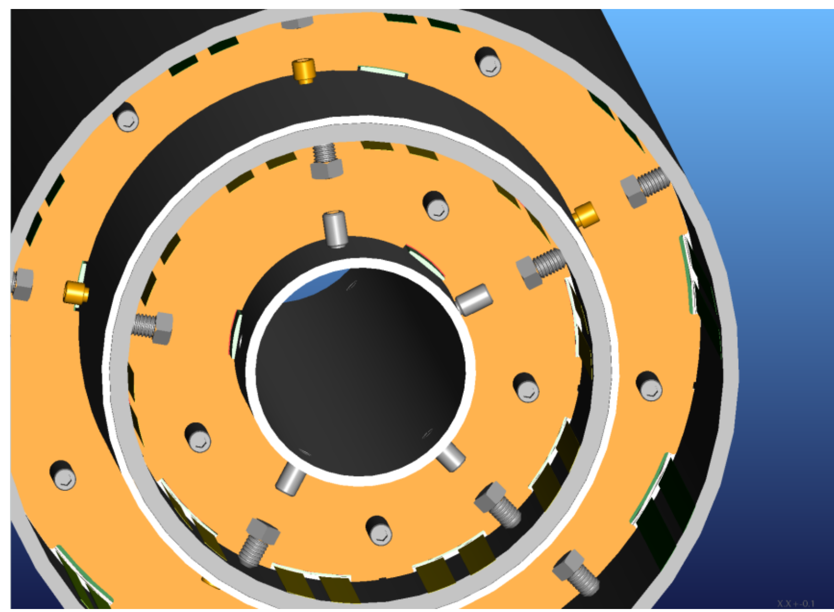
Lakshmi, et al. ASC2014

Engineering Design



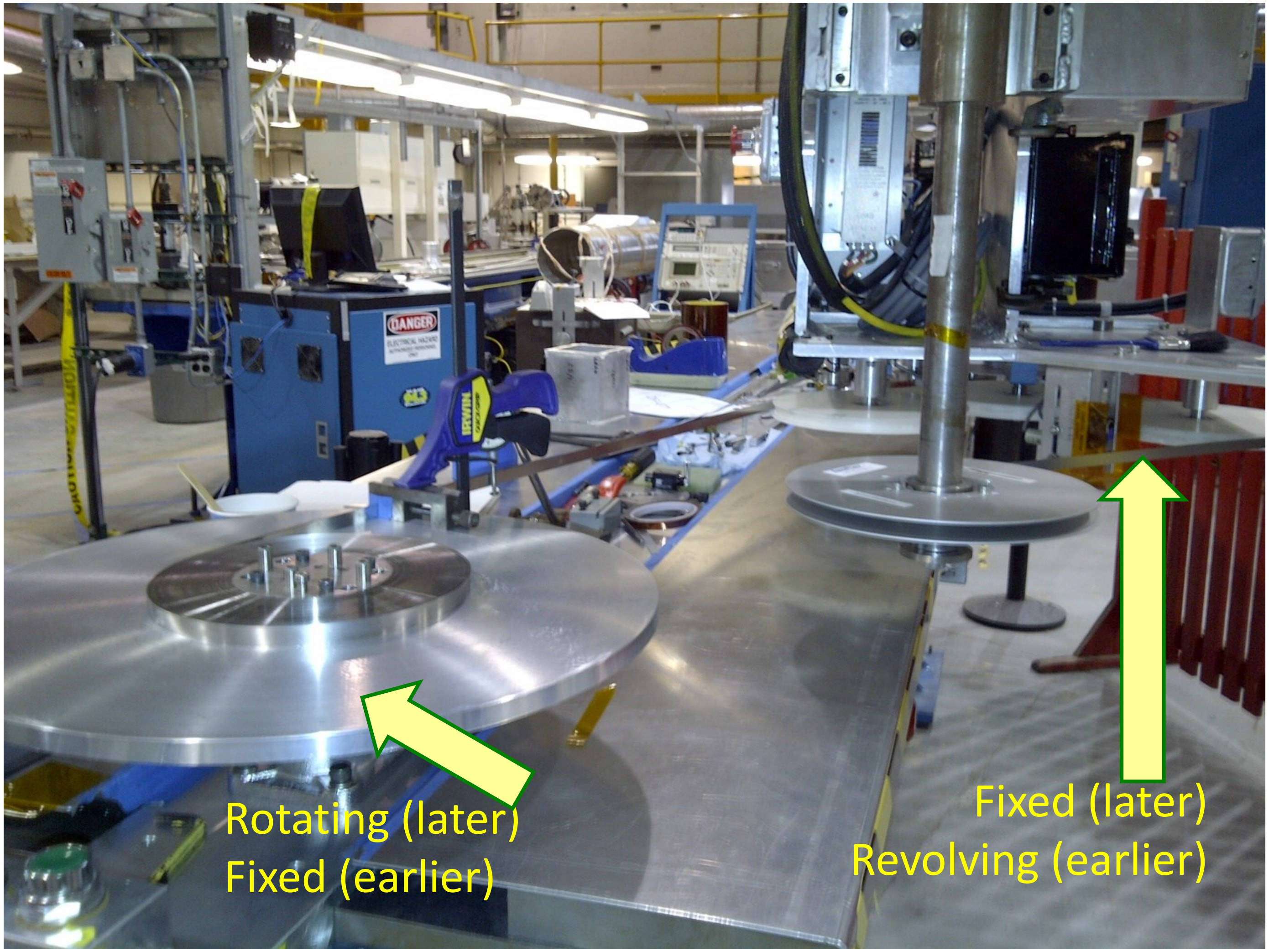






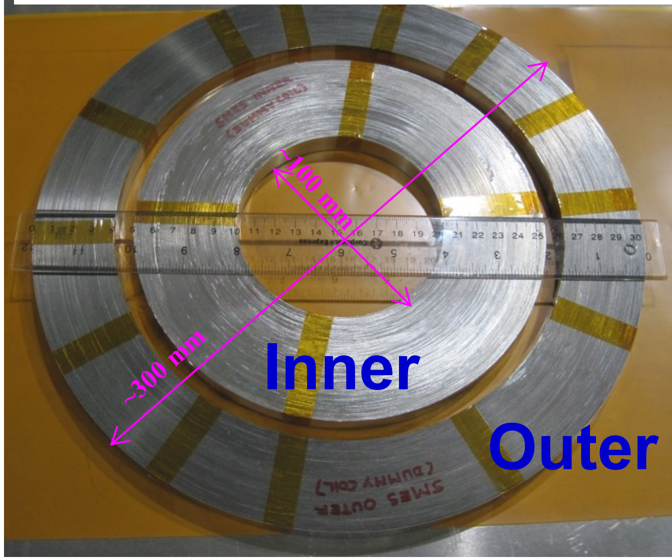
Construction

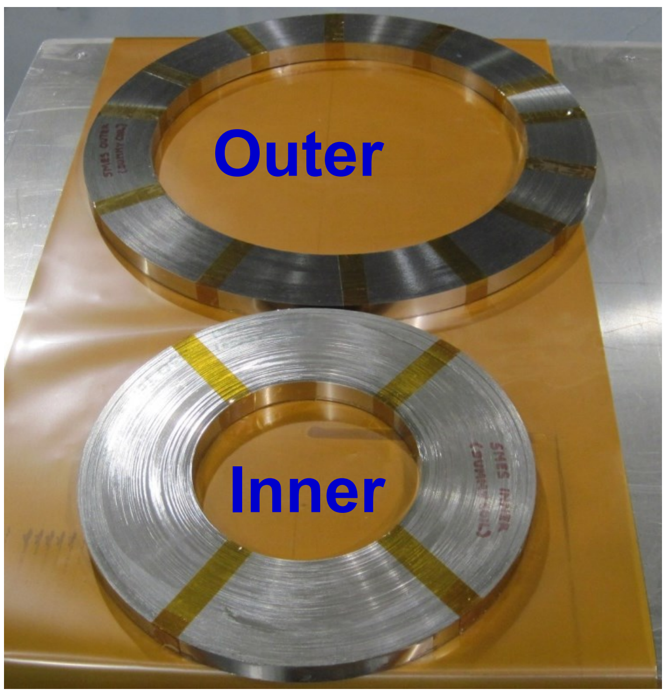
Winding with Computer Controlled Universal Coil Winder



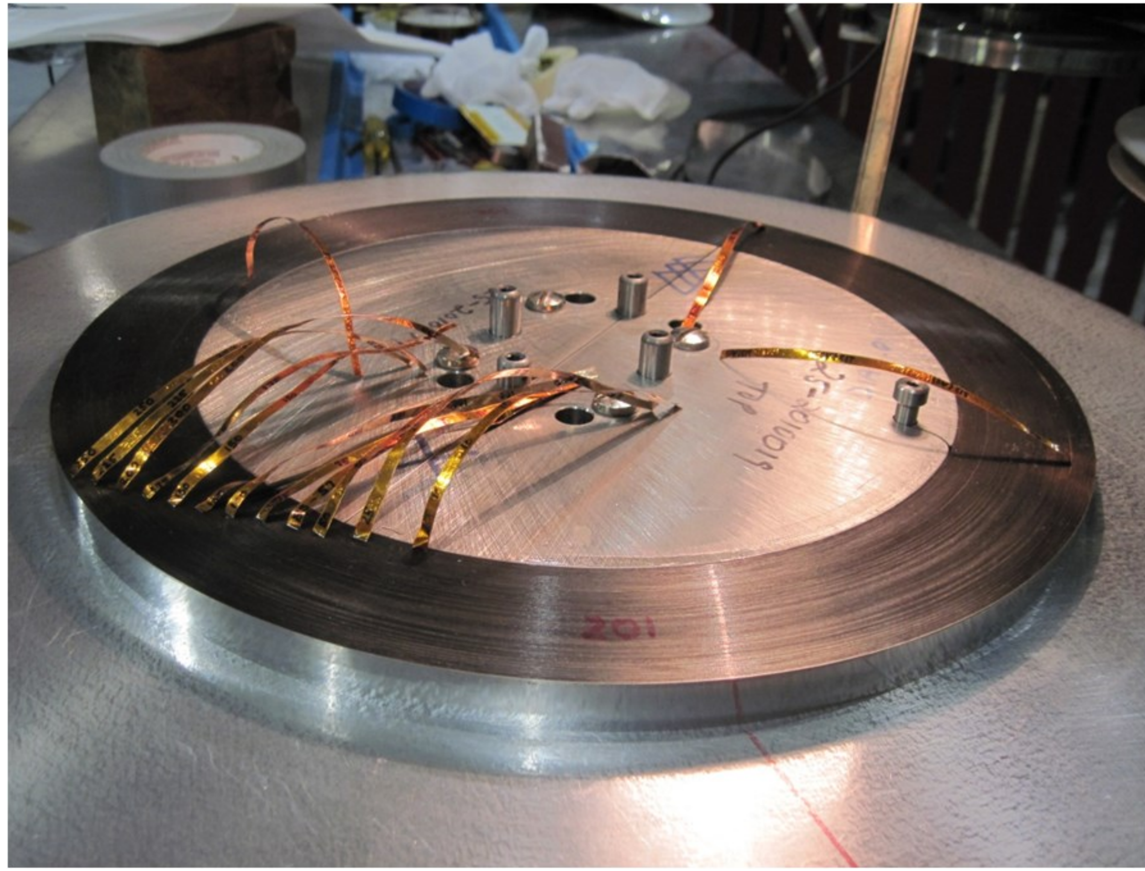
Turn-to-turn insulation: stainless steel tape

Practice coils (SS)



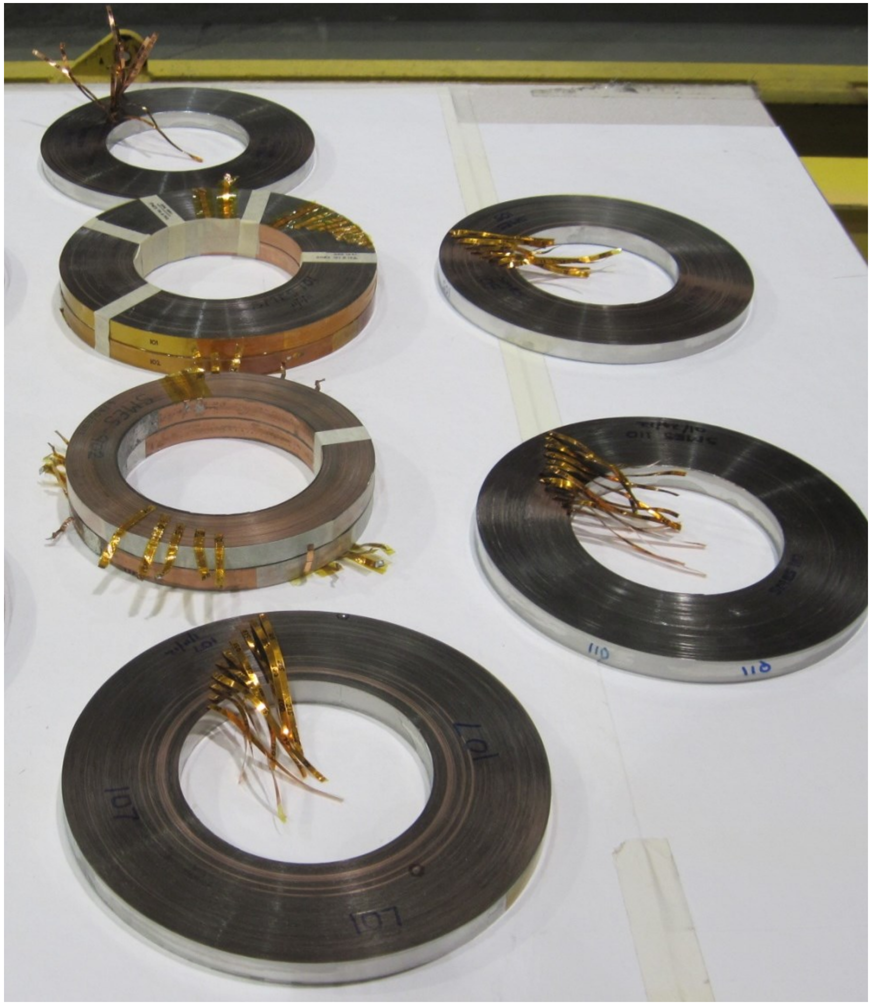


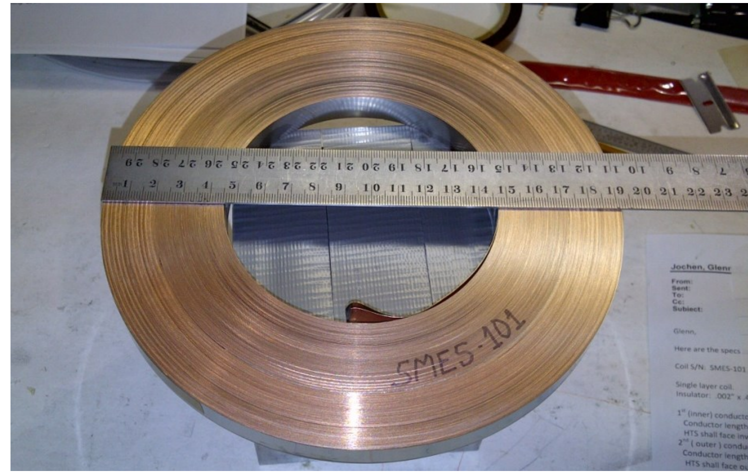
Outer Pancake with v-taps

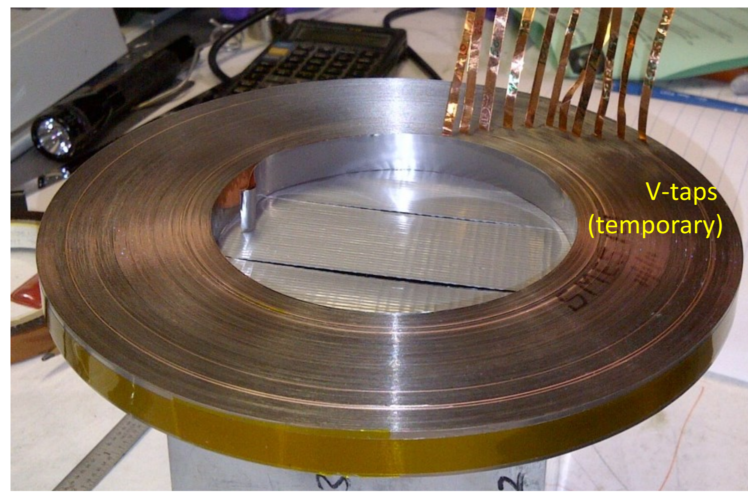


Made with ~210 meter of 12 mm ReBCO tape from SuperPower with SS tape between the turns (No. of turns = 258)

Series of Pancakes



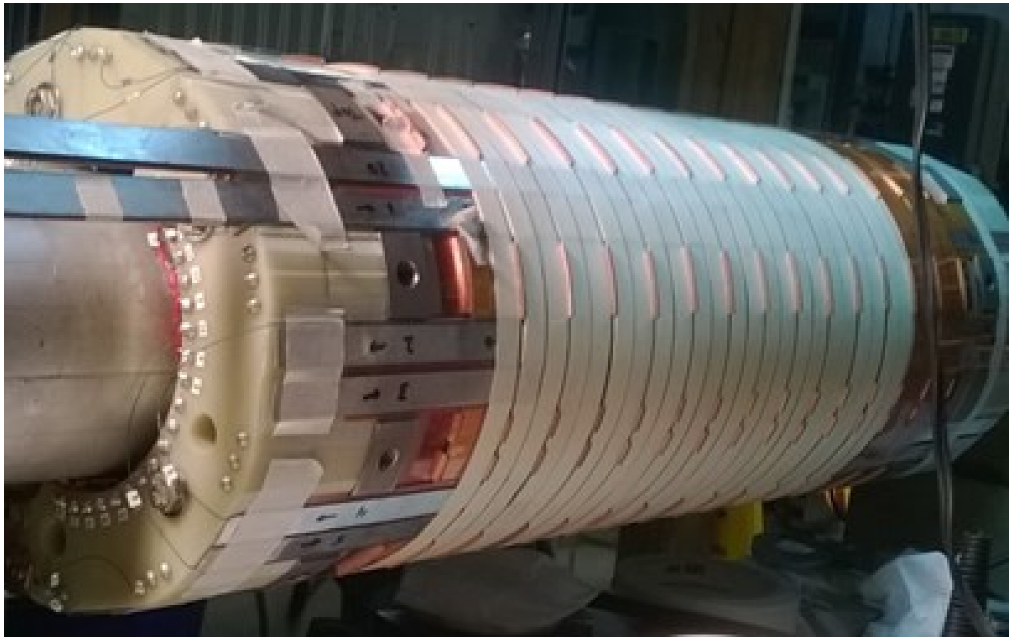




V-taps for intermediate testing

Two Pancakes Connected with Spiral Splice Joint

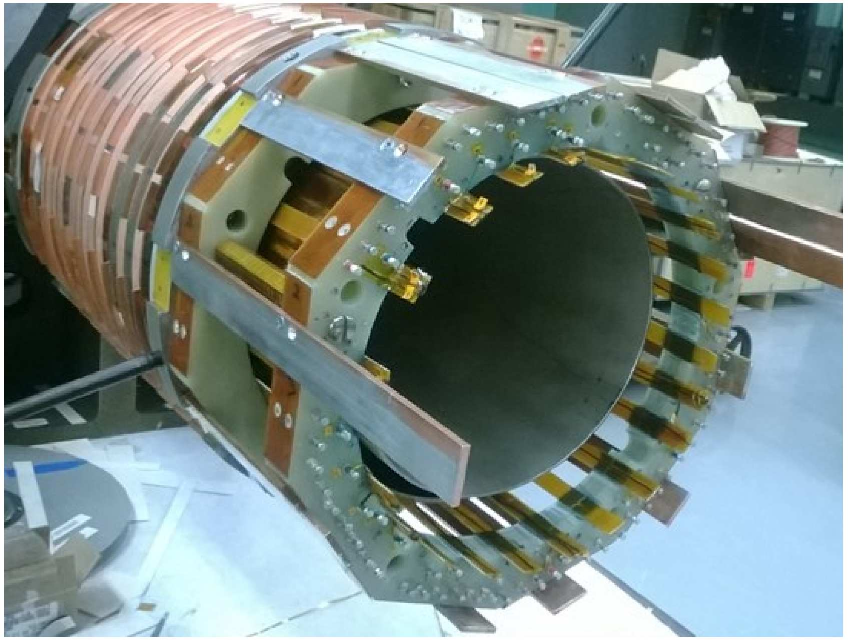
Inner and Outer Coils Assembled



Inner Coil

102 mm id, 194 mm od

28 pancakes

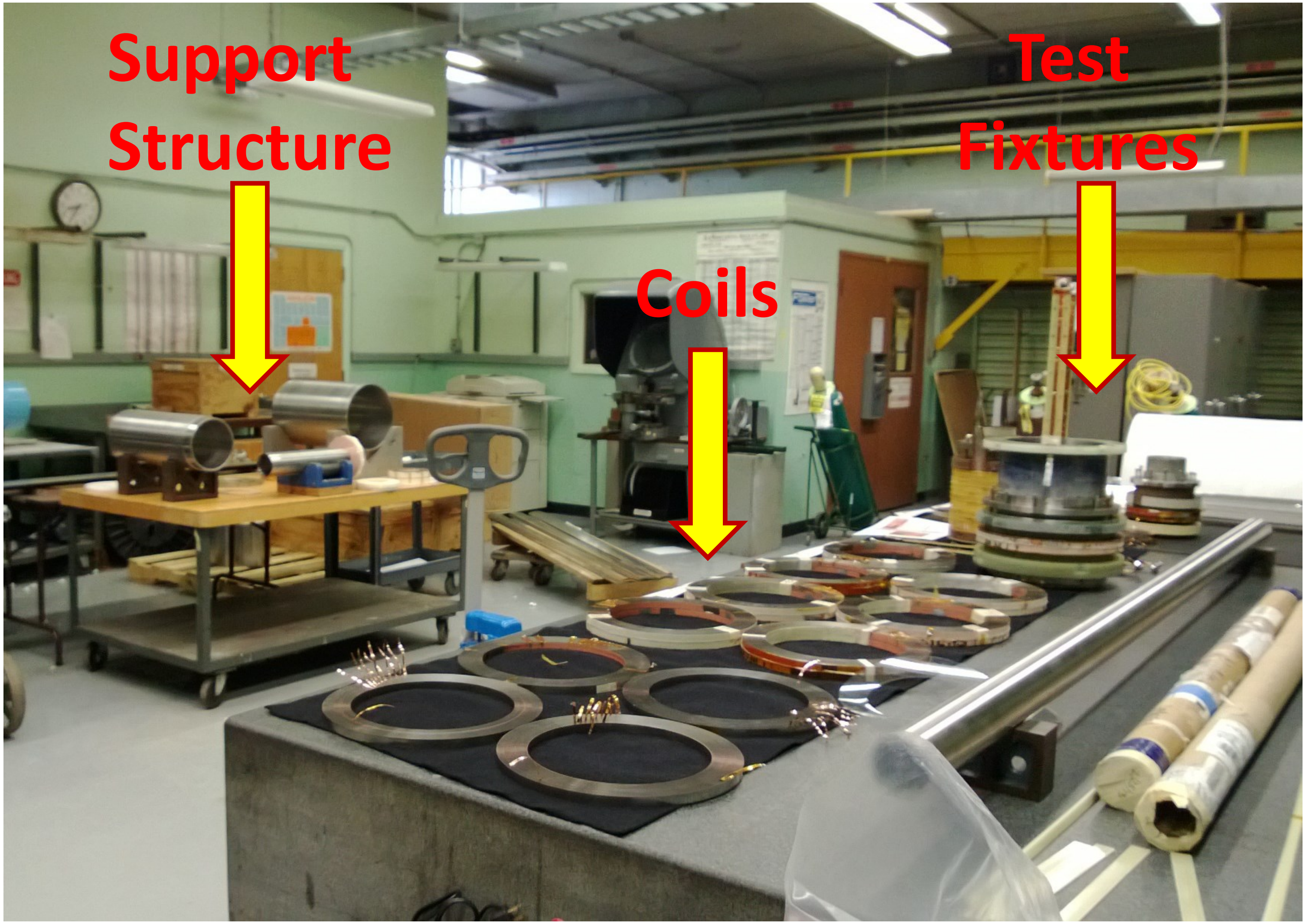


Outer Coil

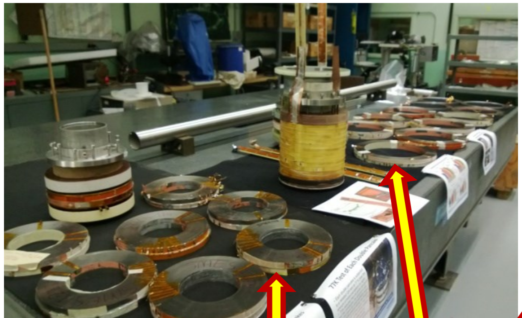
223 mm id, 303 mm od

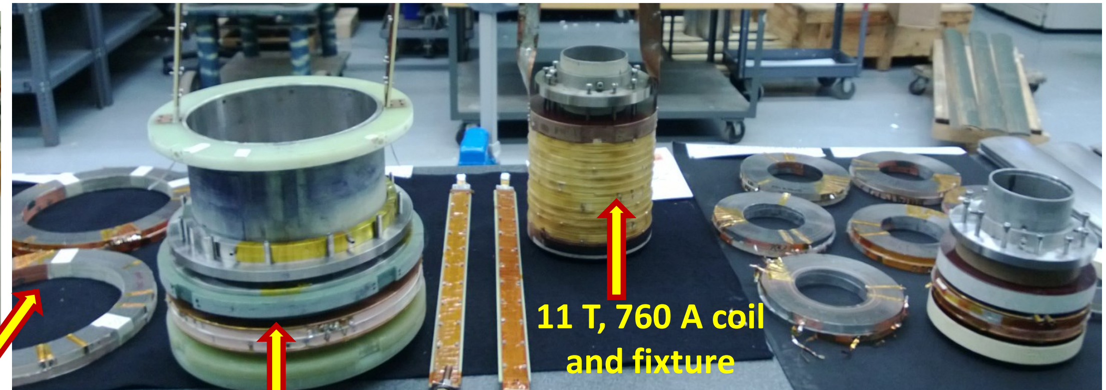
16 pancakes

Coil Parts Prior to Assembly



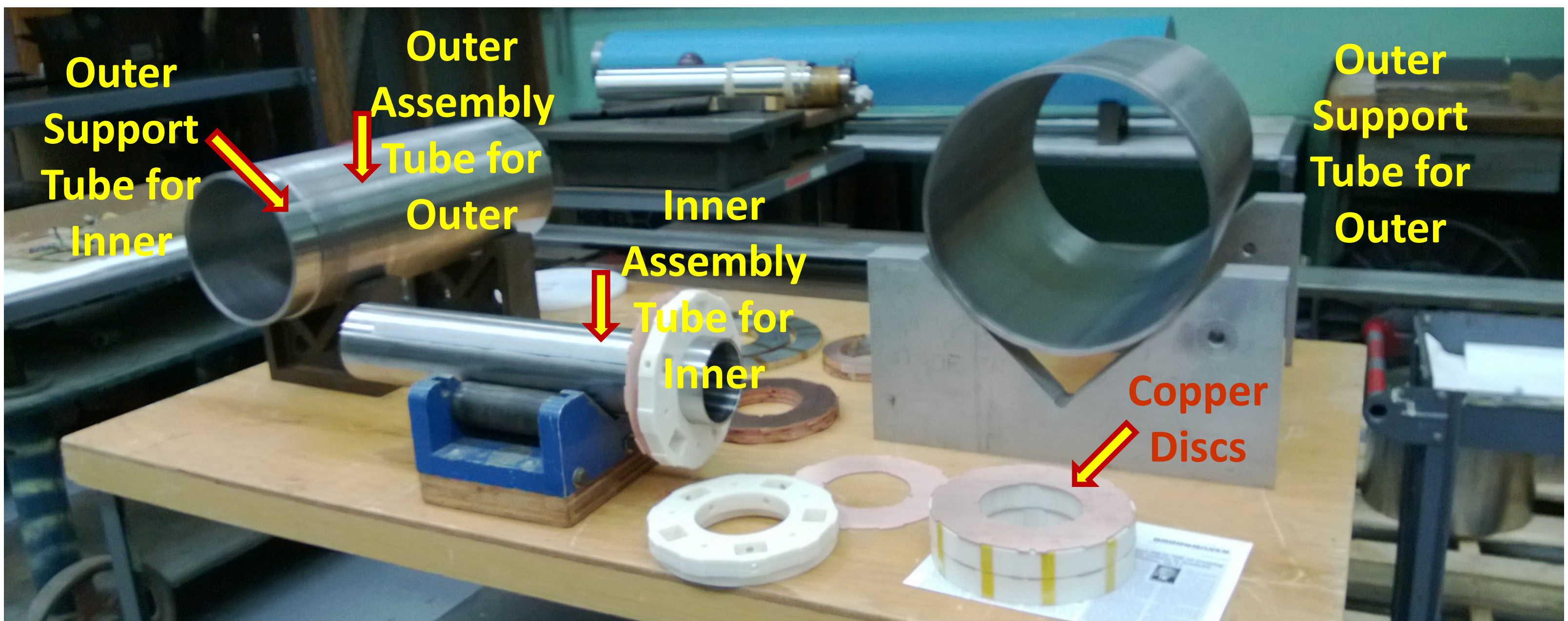
Coils, Test Fixtures and Support Structure



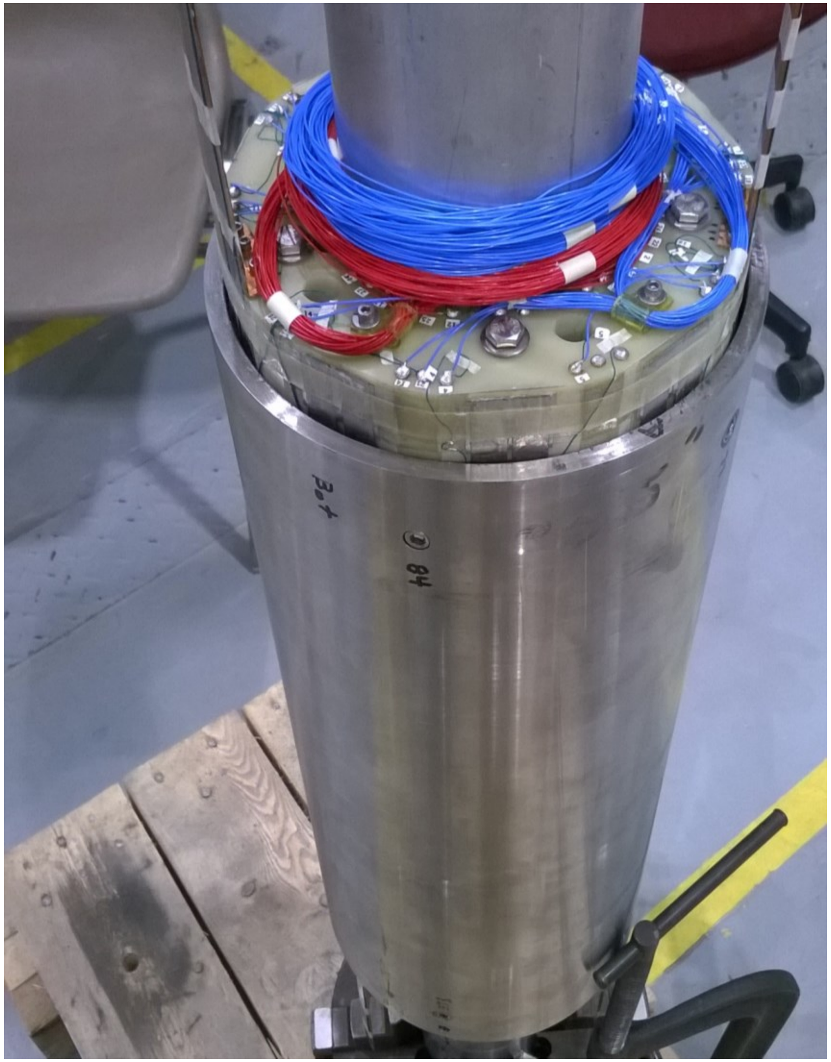


Pancake coils: inner and outer

77 K Test Fixture for outer



Inner and Outer Coils



Inner (in support tube)

Outer (prior to support tube)

Final Assembly

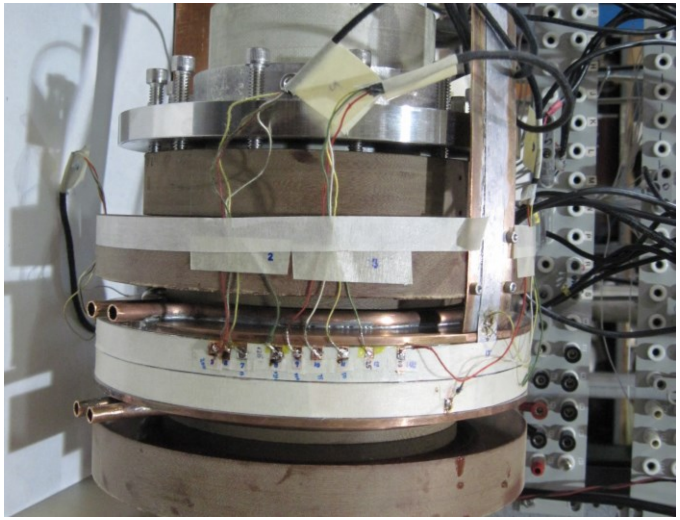
Outer inserted over inner

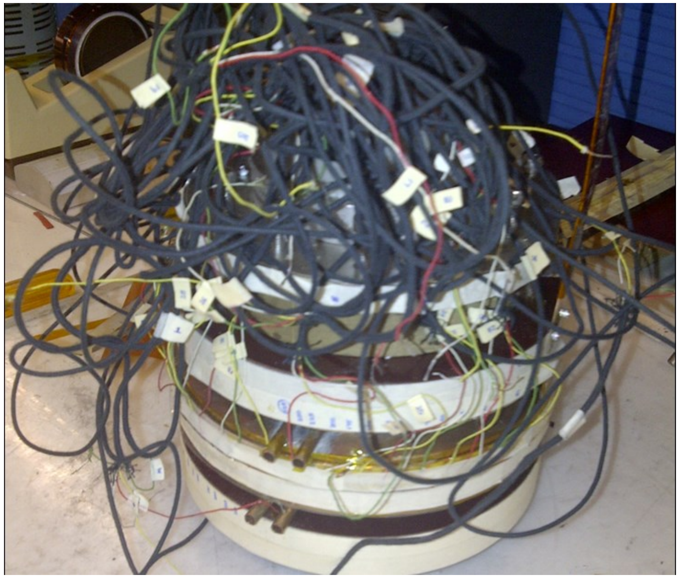
SMES coil in iron laminations

Test Results

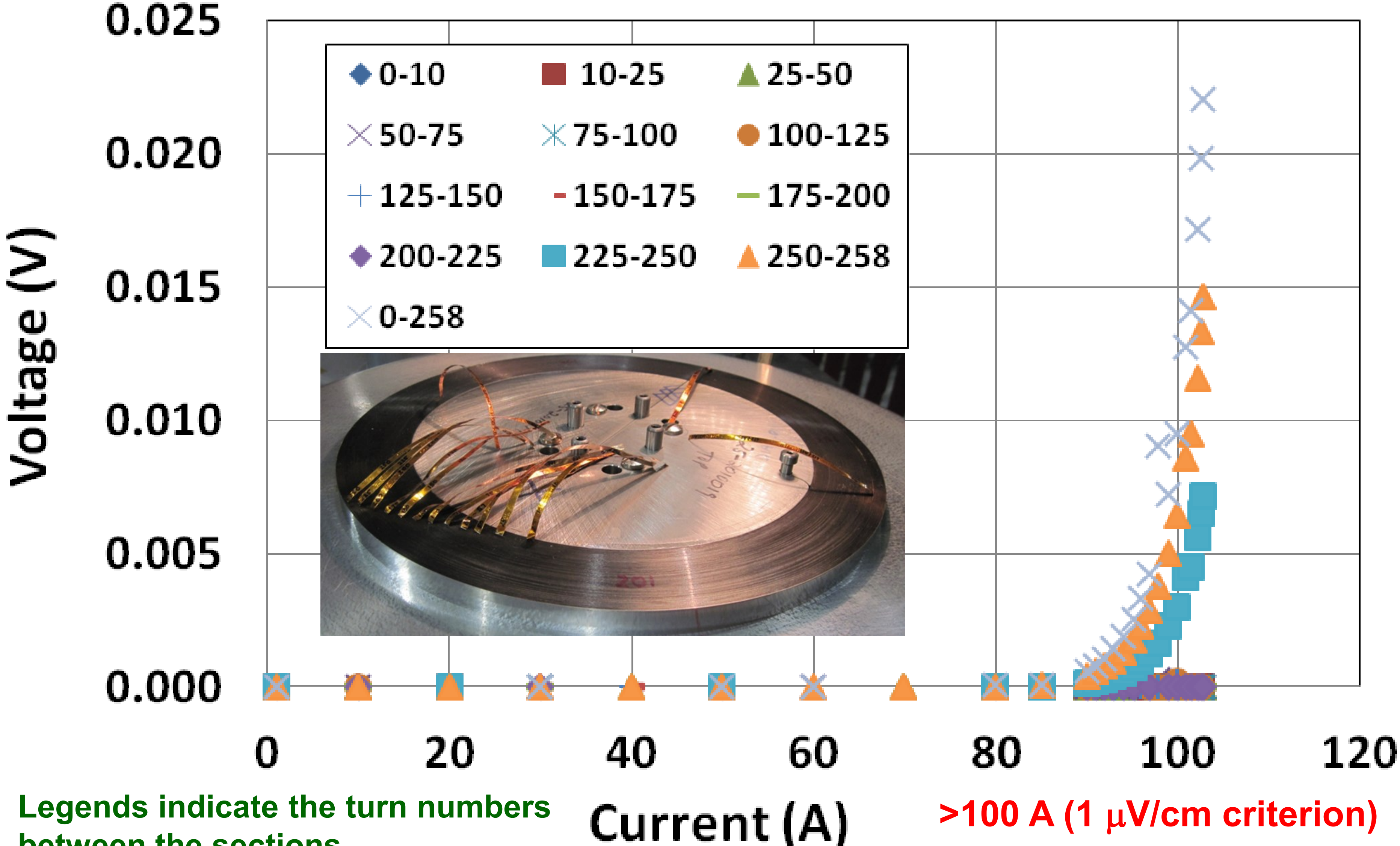
Pre-qualification Tests

- HTS is still a developing conductor
- To ensure that the magnet performance is not limited by a weak link, a series of intermediate QA tests are performed
- Each pancake and each joint is thoroughly tested with a number of voltage taps at 77 K (benefit of HTS)
- Test of a few partial assemblies are also performed at high current/field at 4 K





77 K QA Test of a Pancake

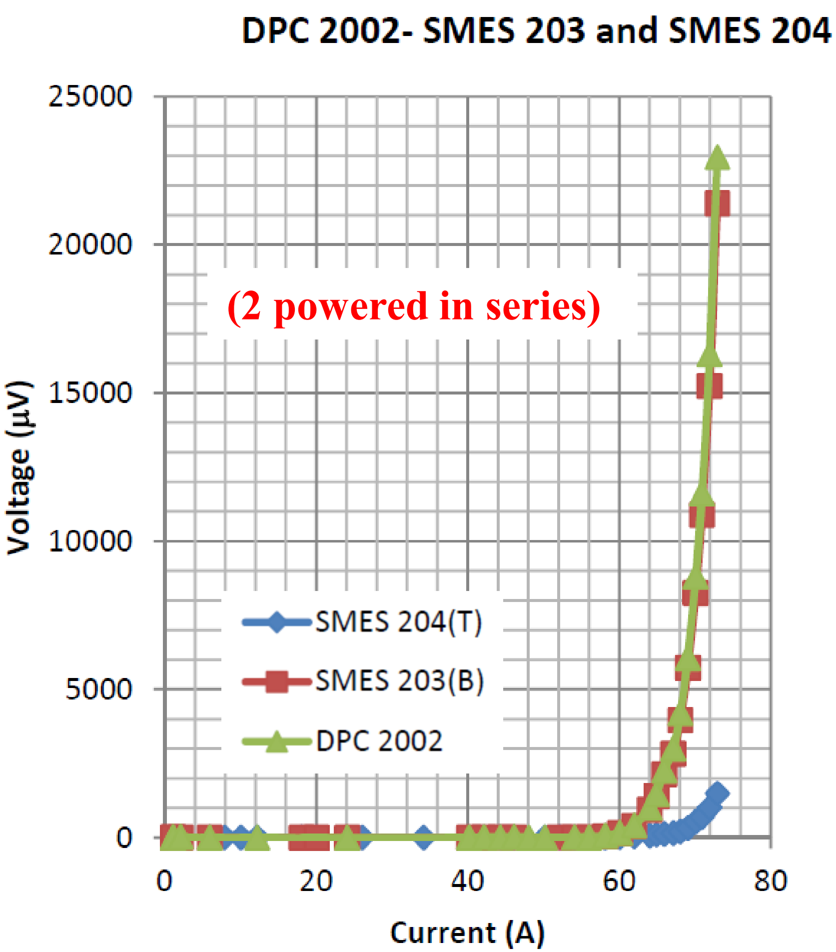


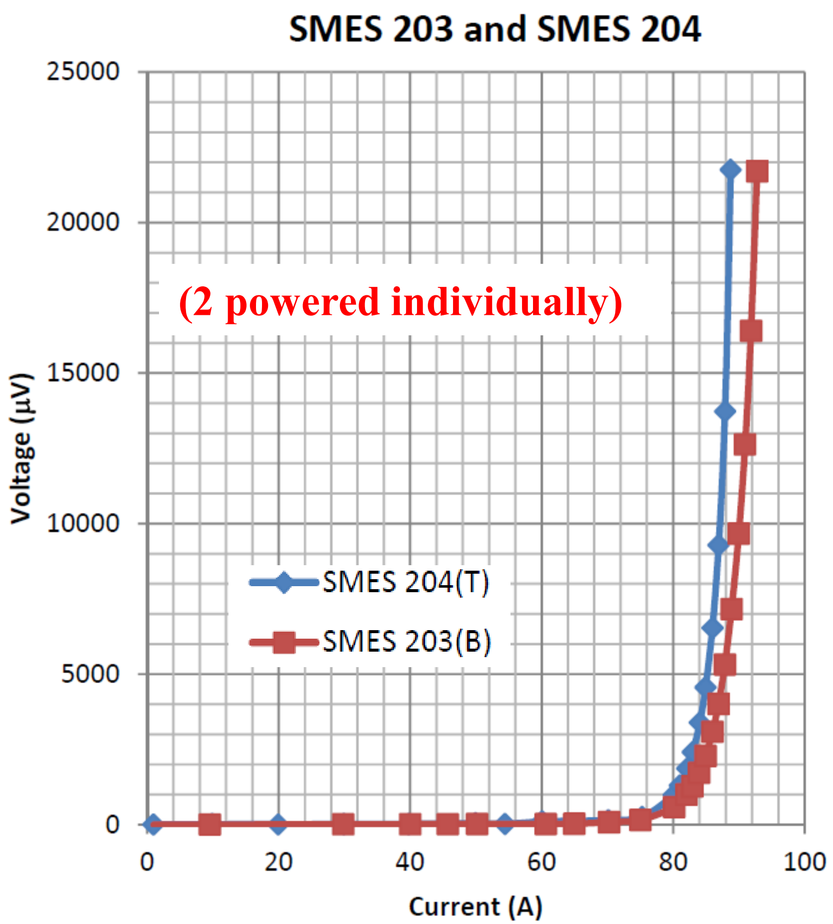
Legends indicate the turn numbers between the sections

>100 A (1 μV/cm criterion)

Double Pancake Coil Test (Type 1)

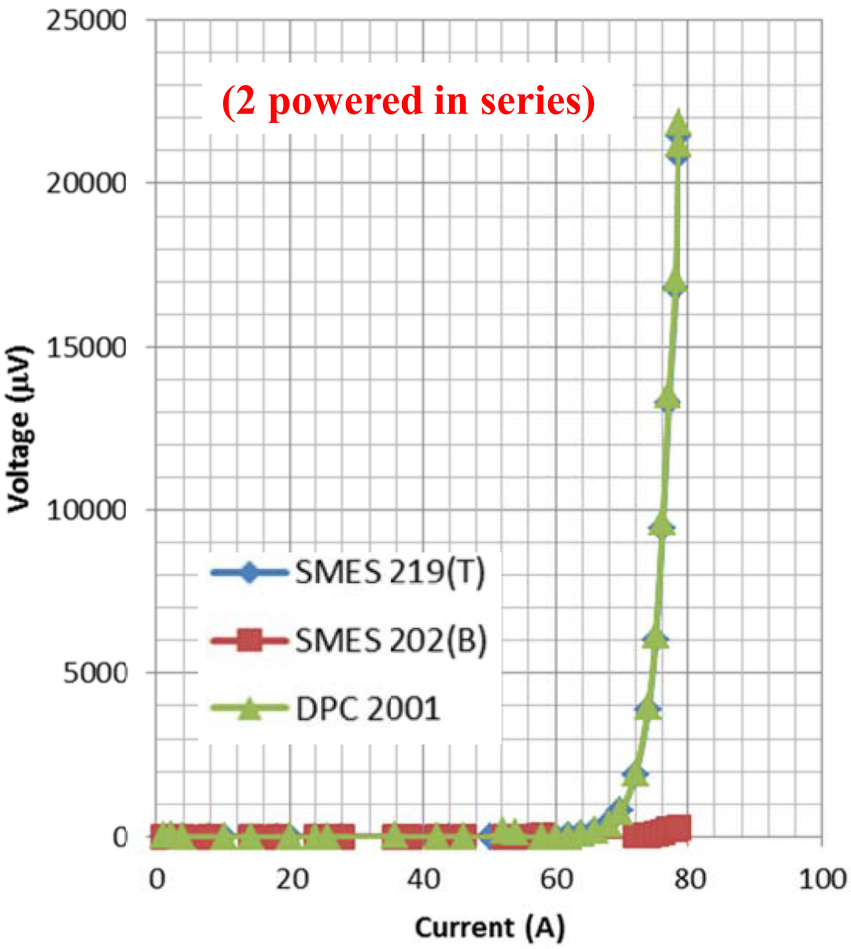
2 pancakes with similar critical currents

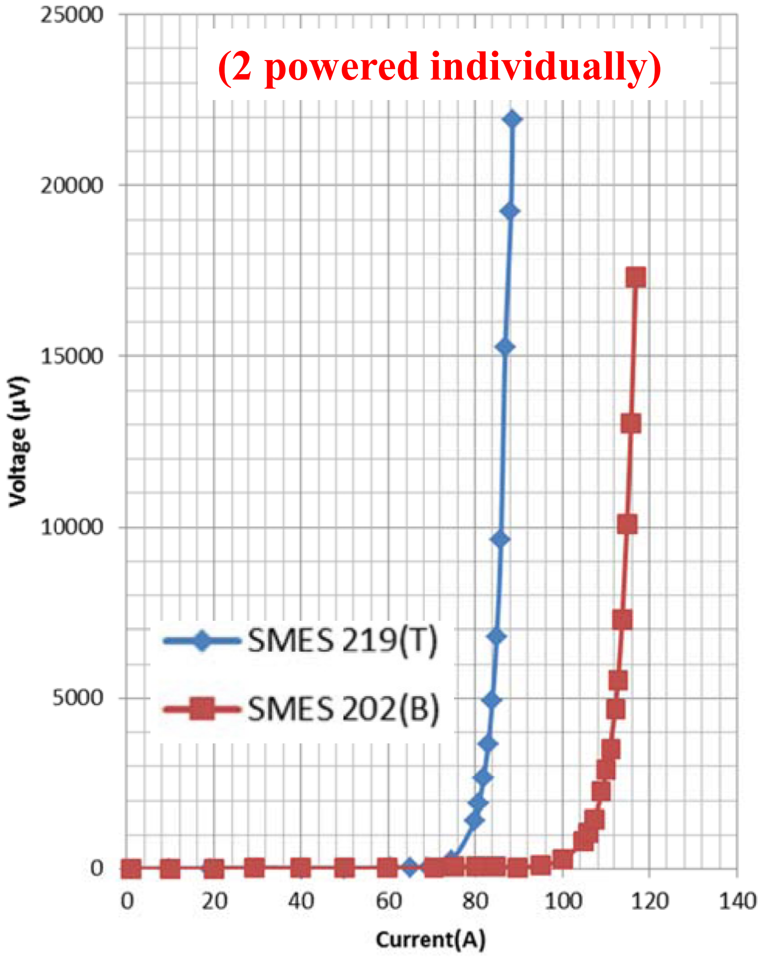




Double Pancake Coil Test (Type 2)

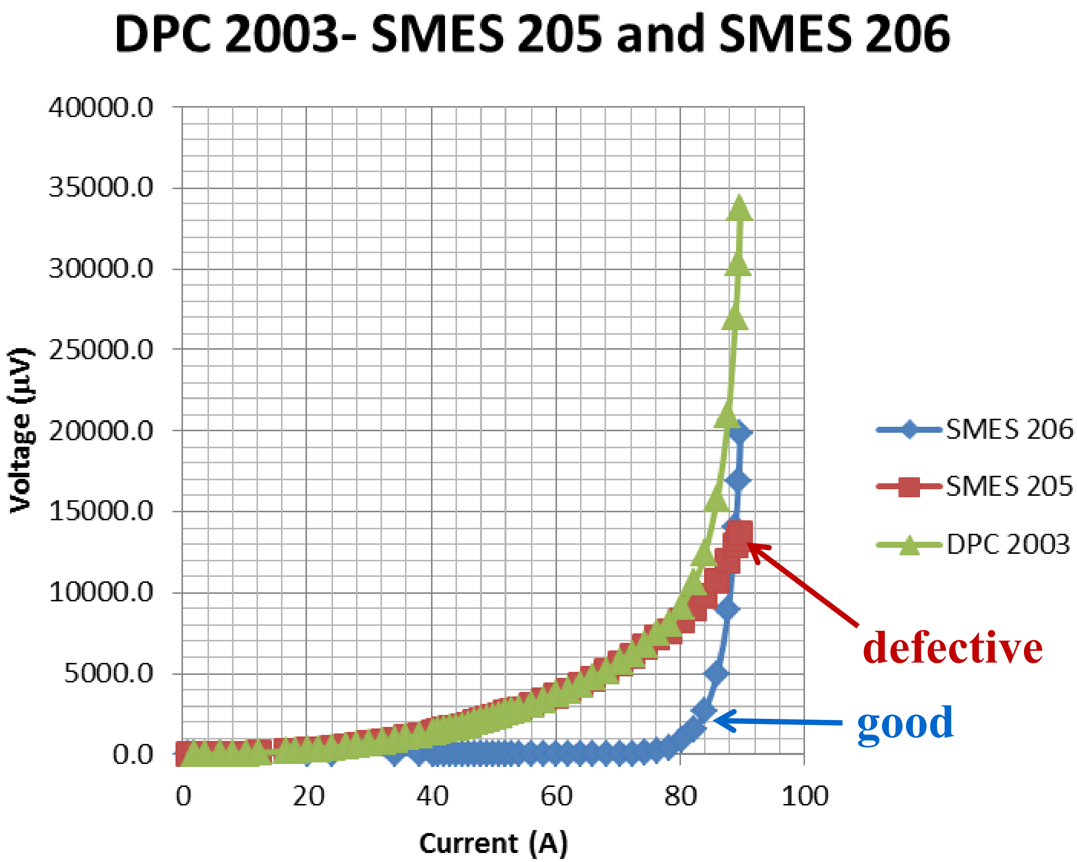
2 pancakes with a significantly different critical current

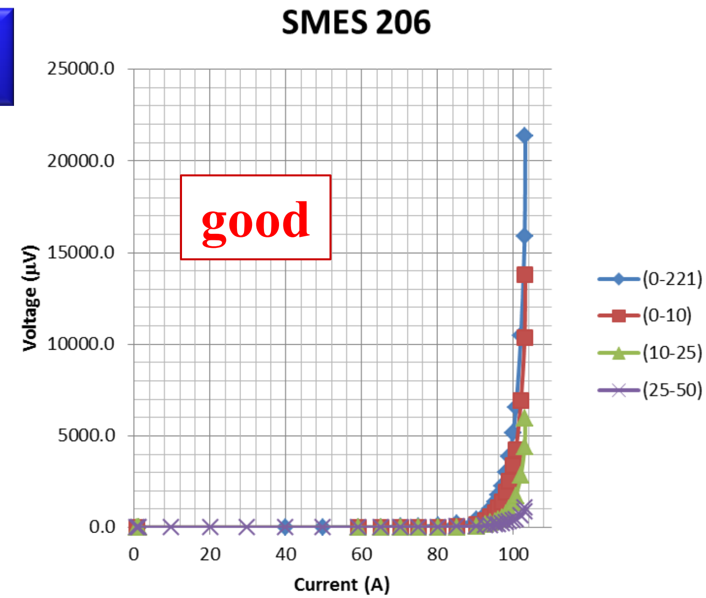


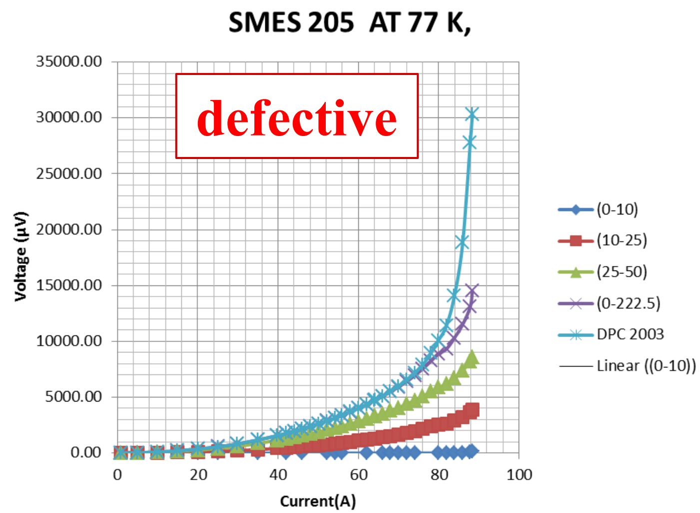


Double Pancake Coil Test (type 3)

one pancake good & one pancake defective



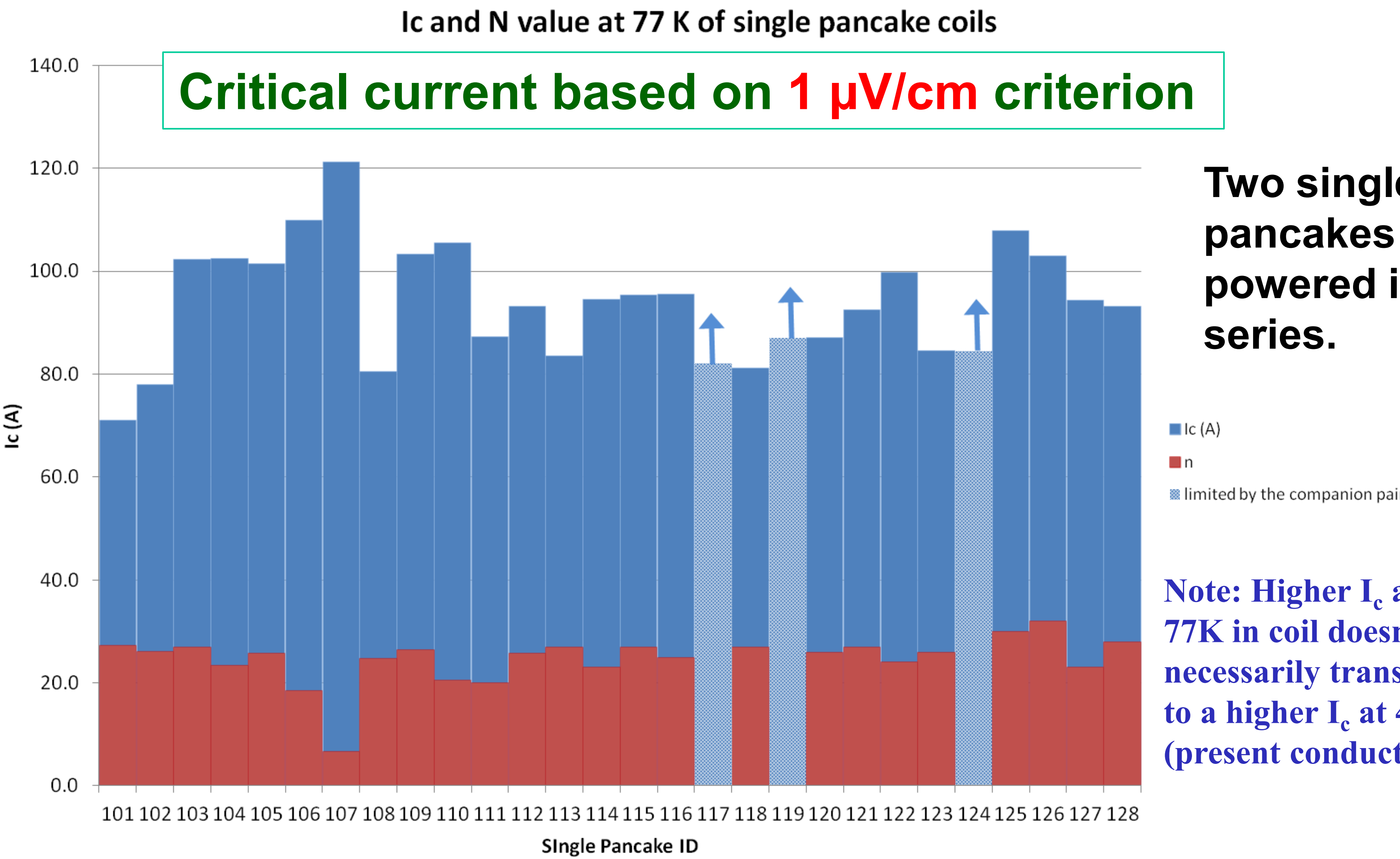




Note: The importance of 77 K QA Test

77 K Test Results of a Series of Pancakes (inner)

Critical current based on 1 μV/cm criterion

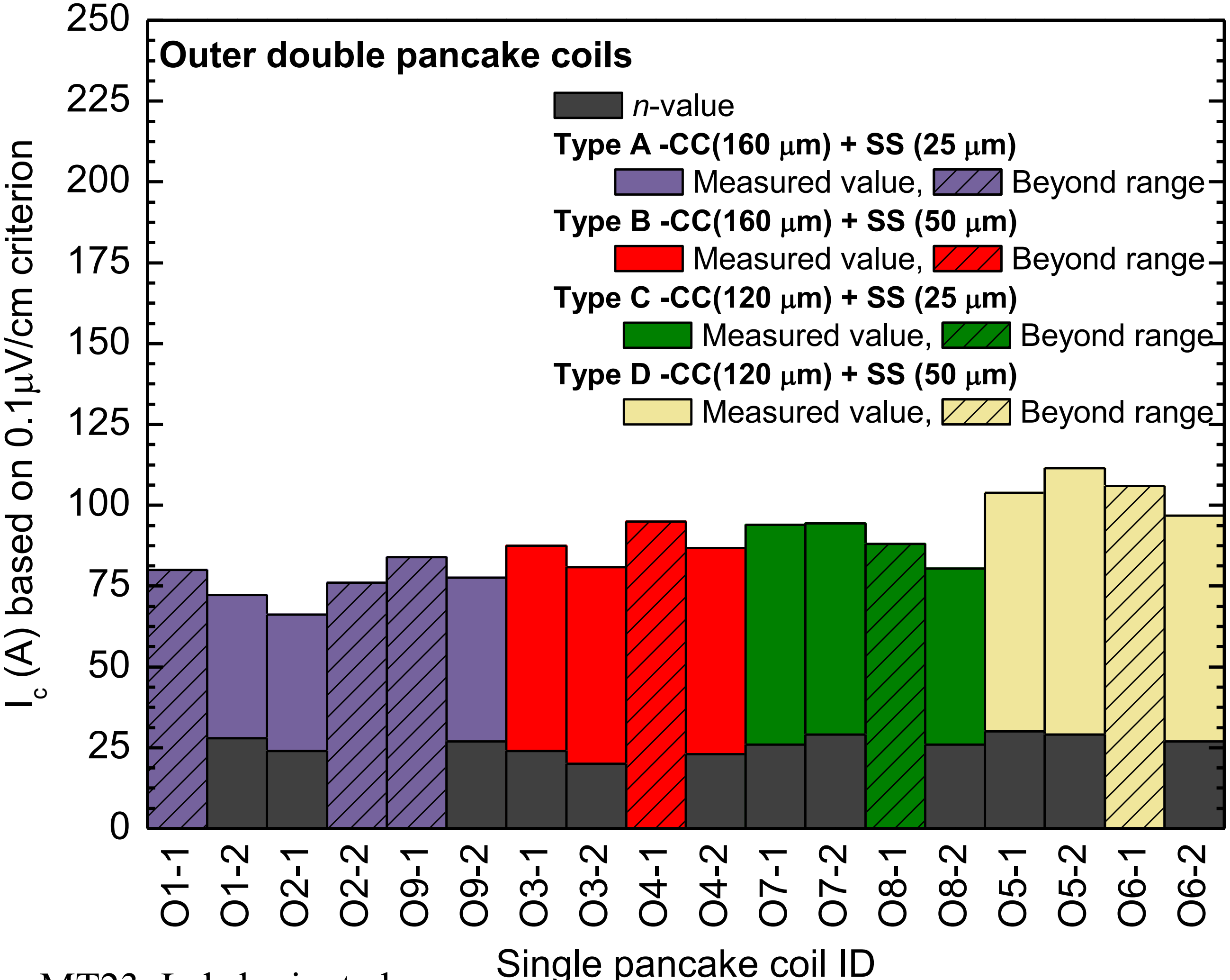


Two single pancakes powered in series.

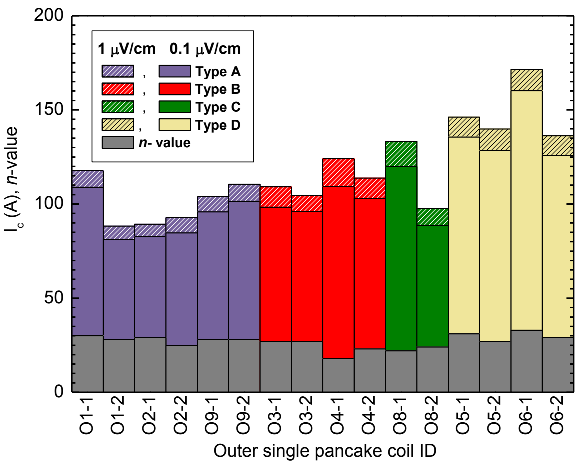
Note: Higher I_c at 77K in coil doesn't necessarily translate to a higher I_c at 4K (present conductor)

77 K Test Results of a Series of Pancakes (outer)

Two pancakes powered in series



Single pancakes tested alone



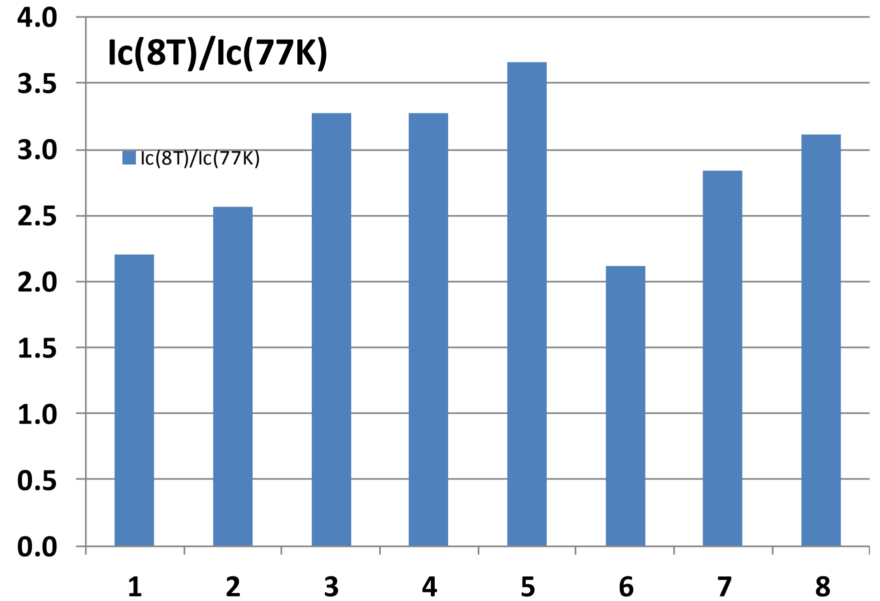
Note: Higher I_c at 77K in coil doesn't necessarily translate to a higher I_c at 4K (present conductor)

MT23, Lakshmi, et al

Significant Variation in Conductor (present conductor technology)

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



Lift factor 2.1 to 3.7

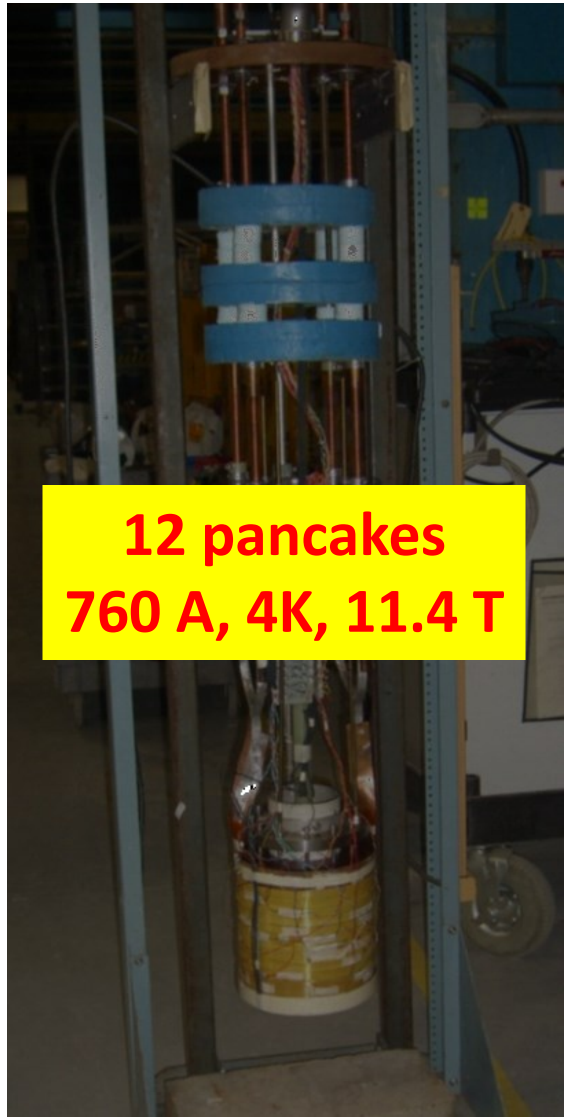
I_c(4K,8T) : 726 A to 1369 A

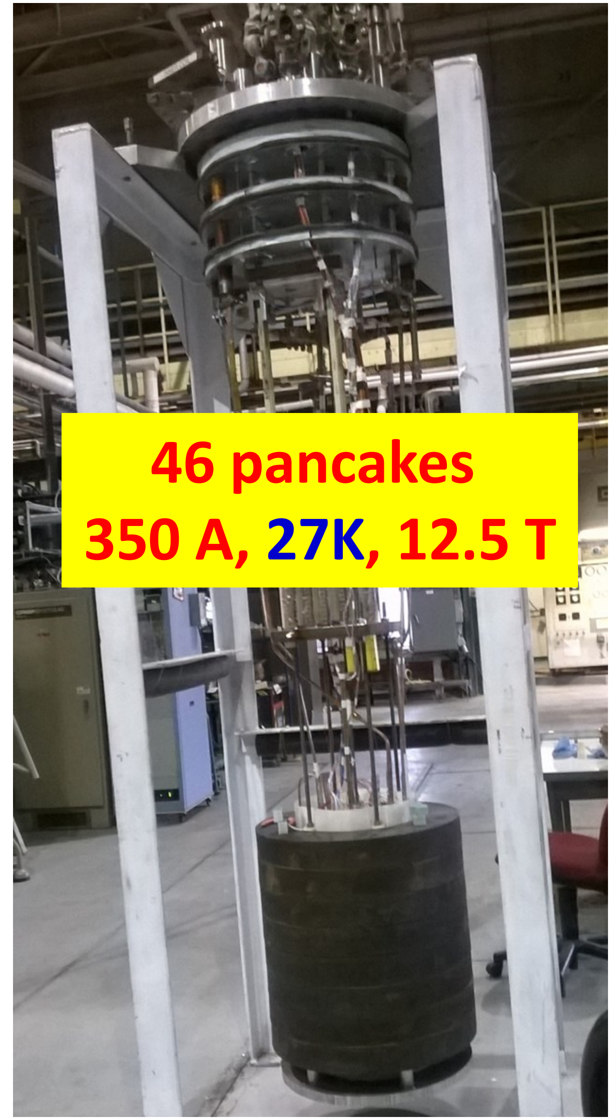
(specifications: 700 A at 8 T)

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

HTS SMES Magnet High Field Test Results
100 mm bore ReBCO SMES Coil





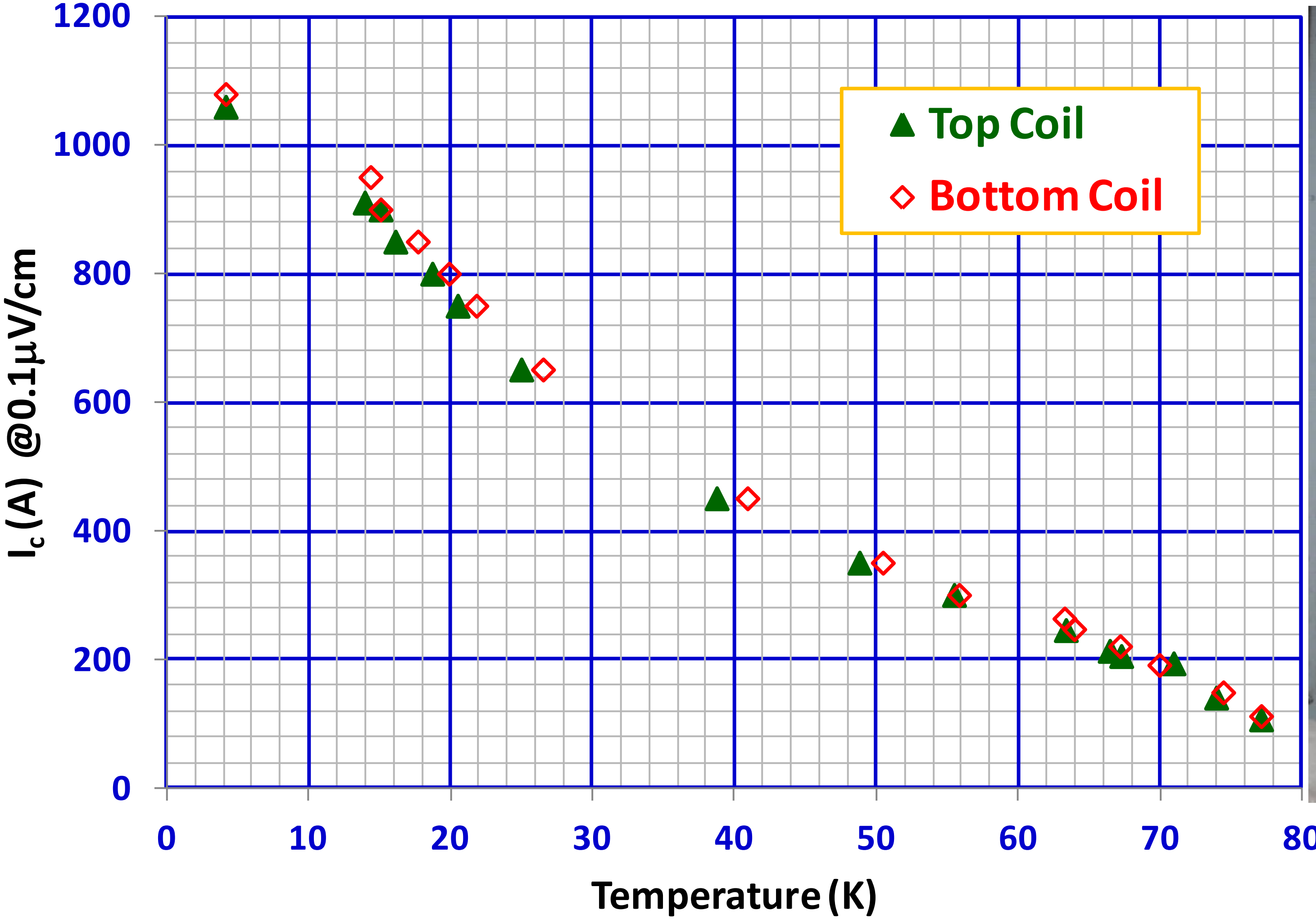
Peak fields higher

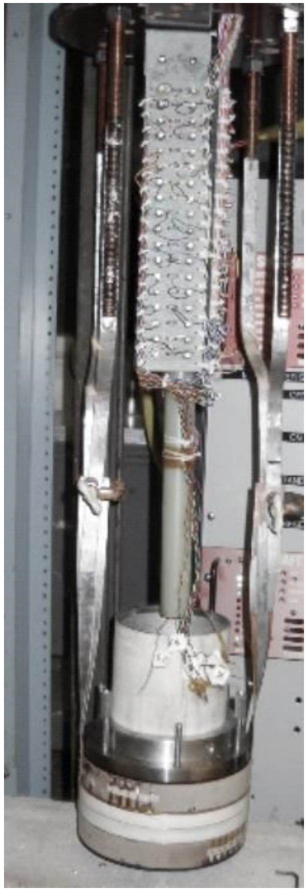
Test Fixture for Double Pancake

High current upgrade for leads (~1kA), fixture, quench protection set-up, etc.

Double Pancake Coil Test

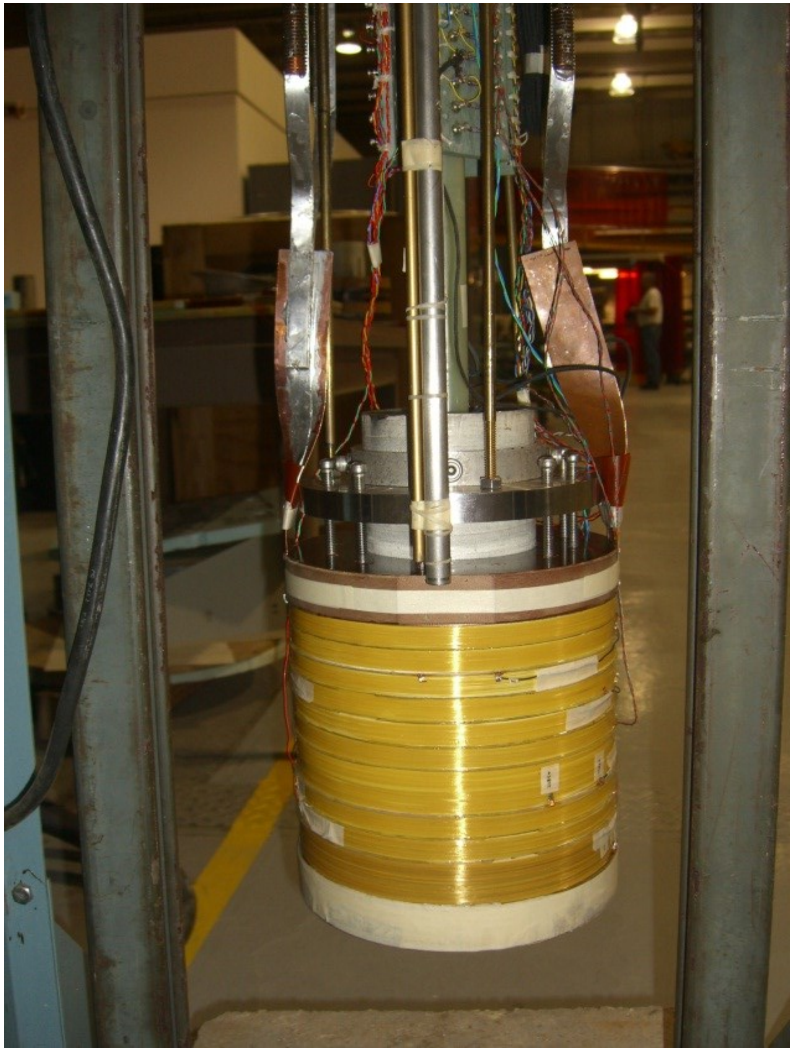
Nominal design current: ~700 A



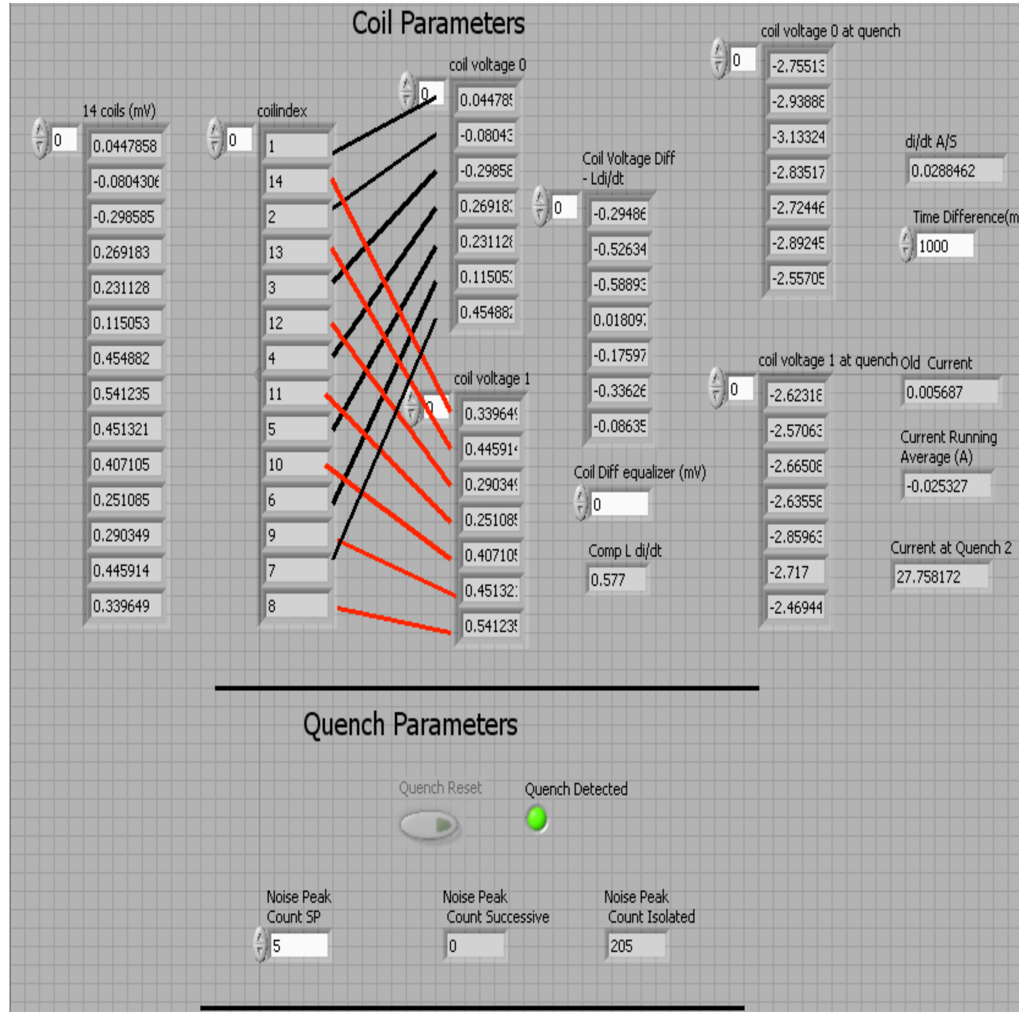


The option of operating over a large range (the benefit of HTS)

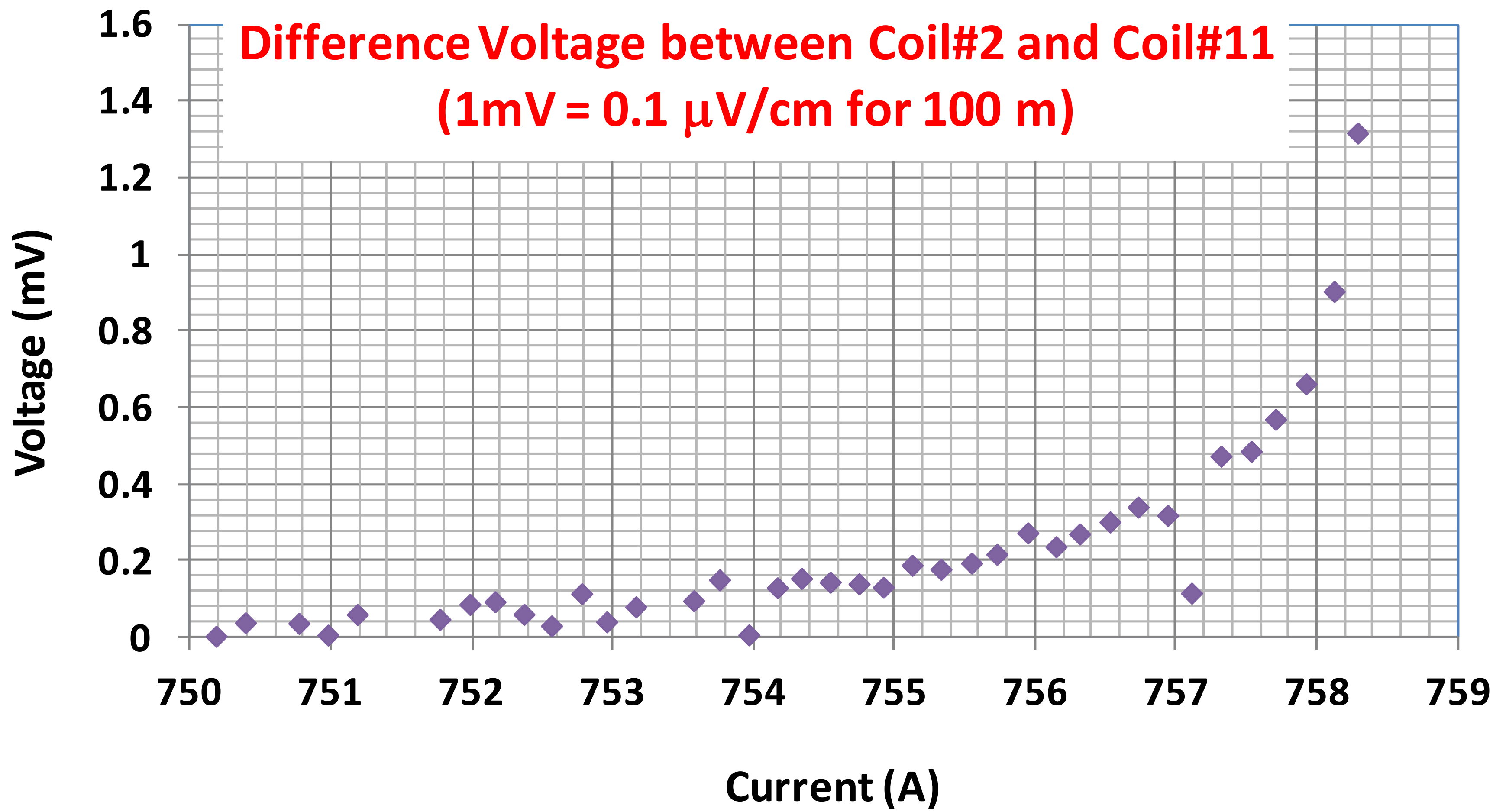
Twelve Pancake Coil Test



Setup for 12 Pancake Coil Test



4 K Test of 100 mm 12 Pancake Coil

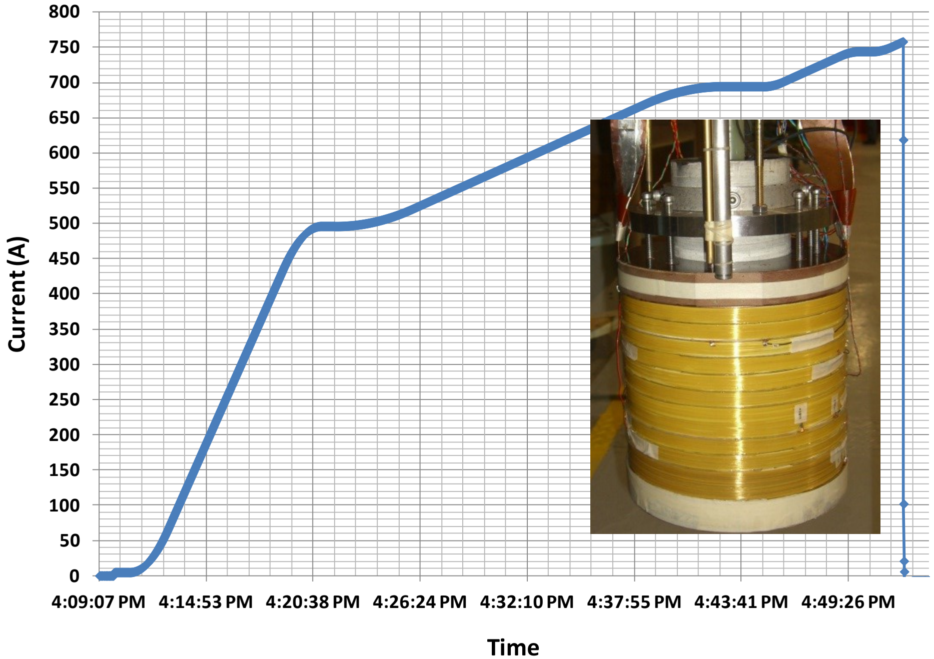


Coil reached <u>11.4 T</u> at ~760 A

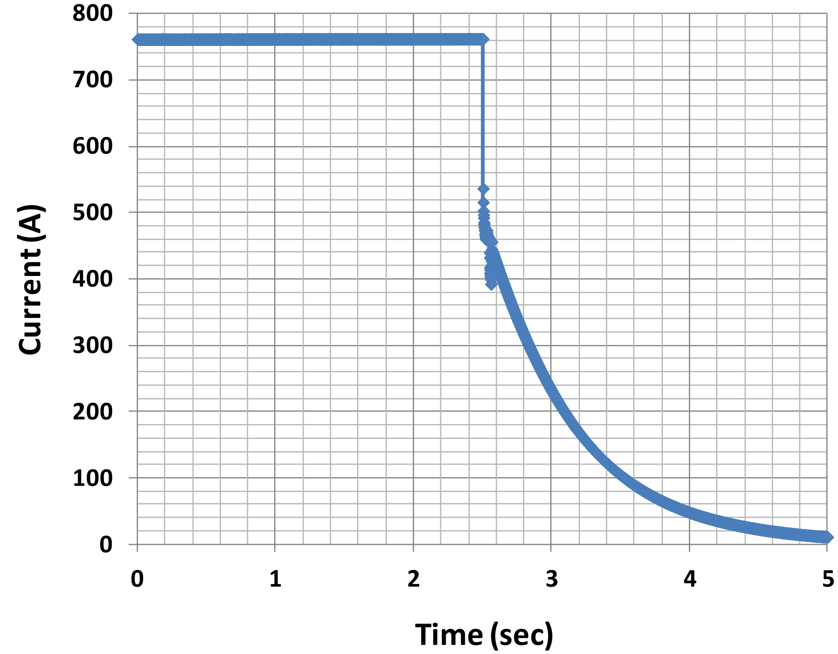
- **exceeded Go/NoGo target of <u>10 T</u>**

12 Pancake Coil Test (and quench)

Charge

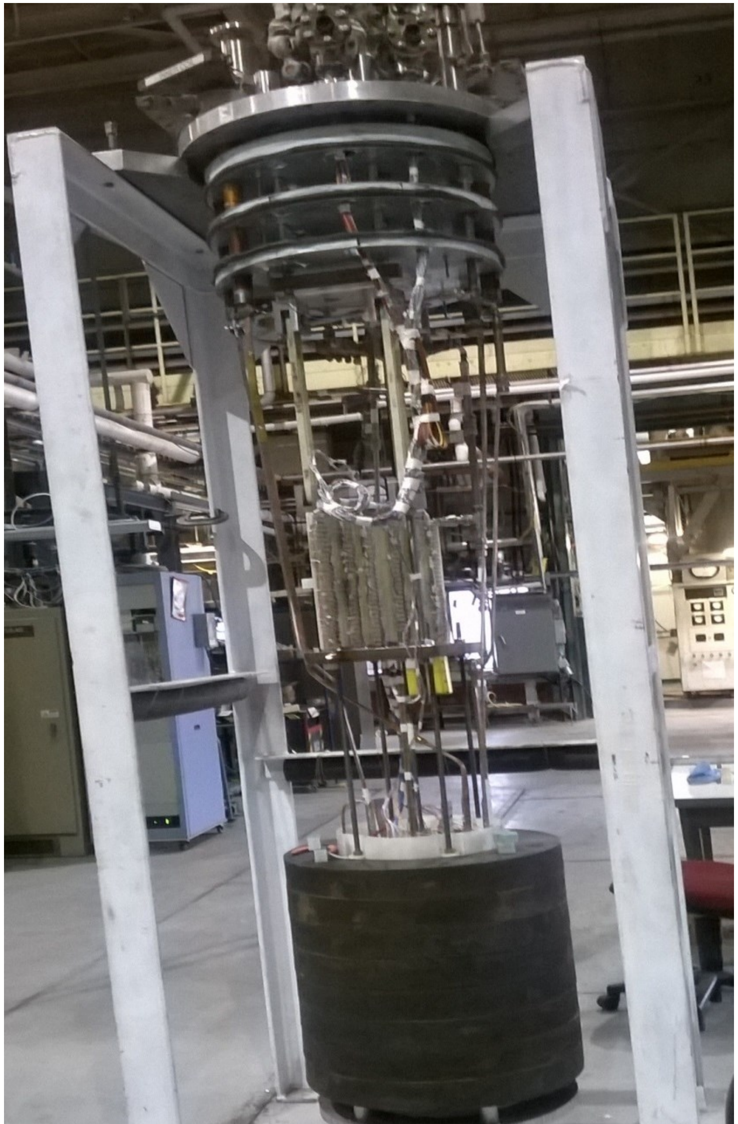


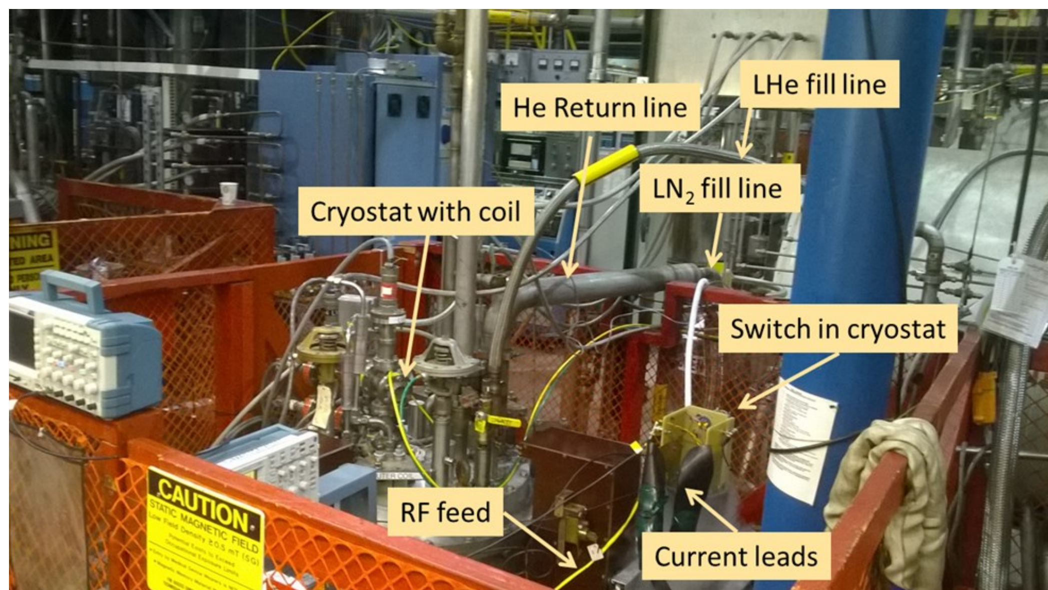
Quench



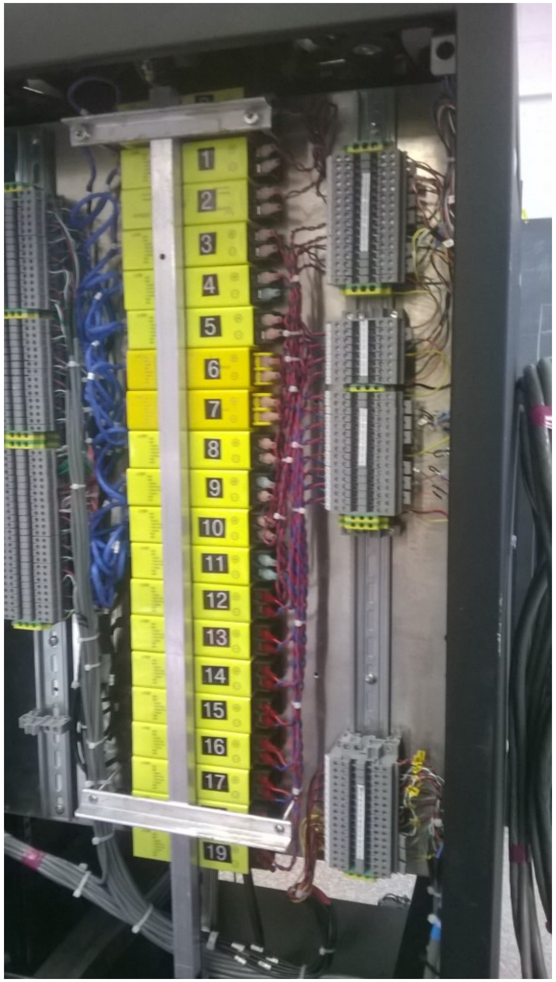
- Energy (~125 kJ) extracted and dumped in the external resistor.
- 77 K re-test (after quench) showed that the coil remained healthy.

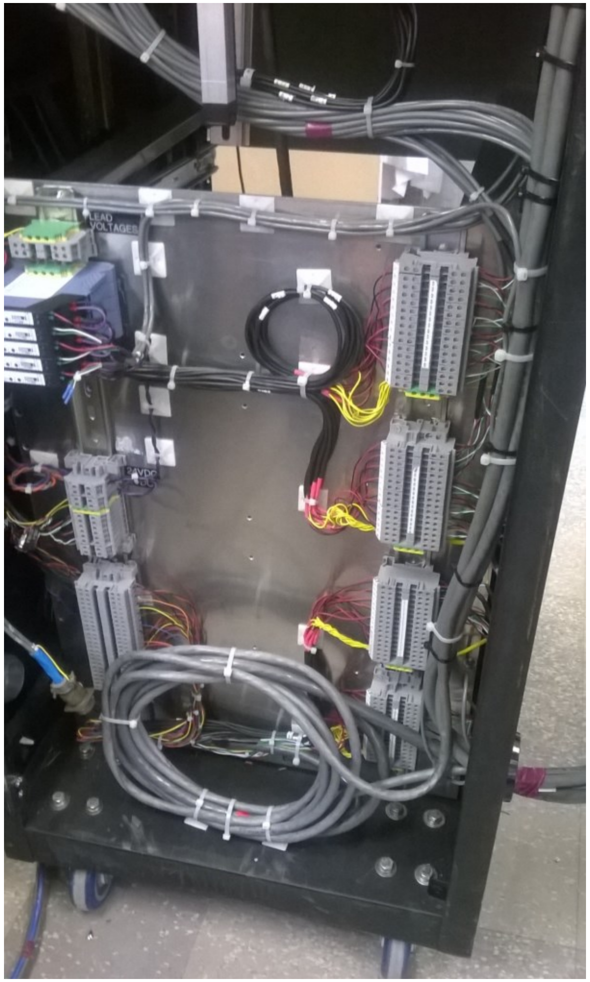
Preparation for the Final Test

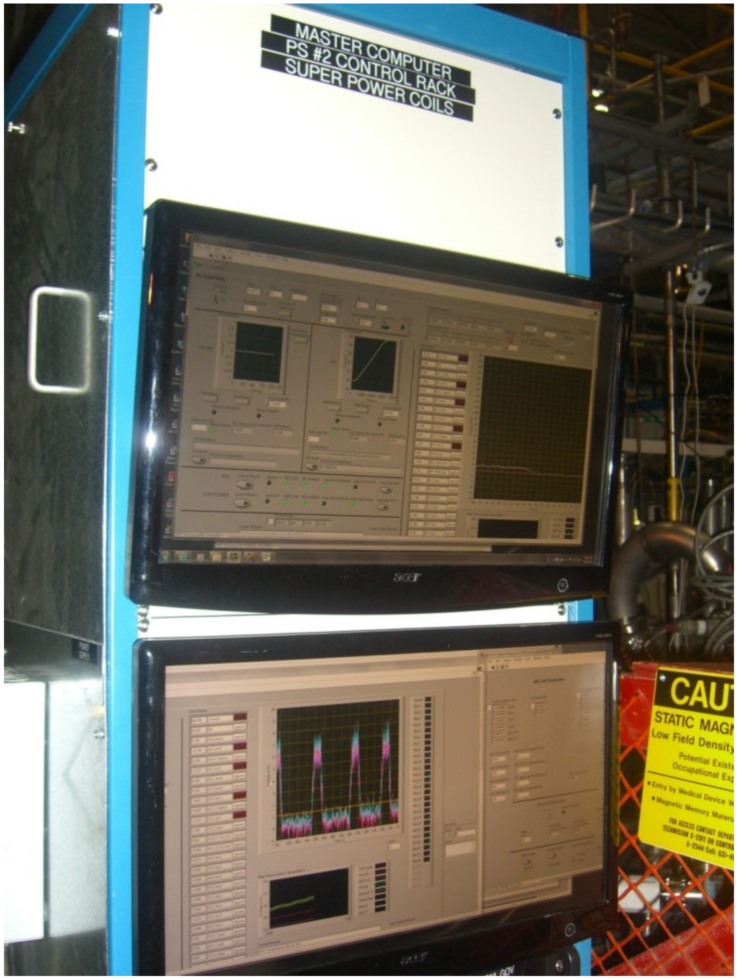




Back Panel and Control System

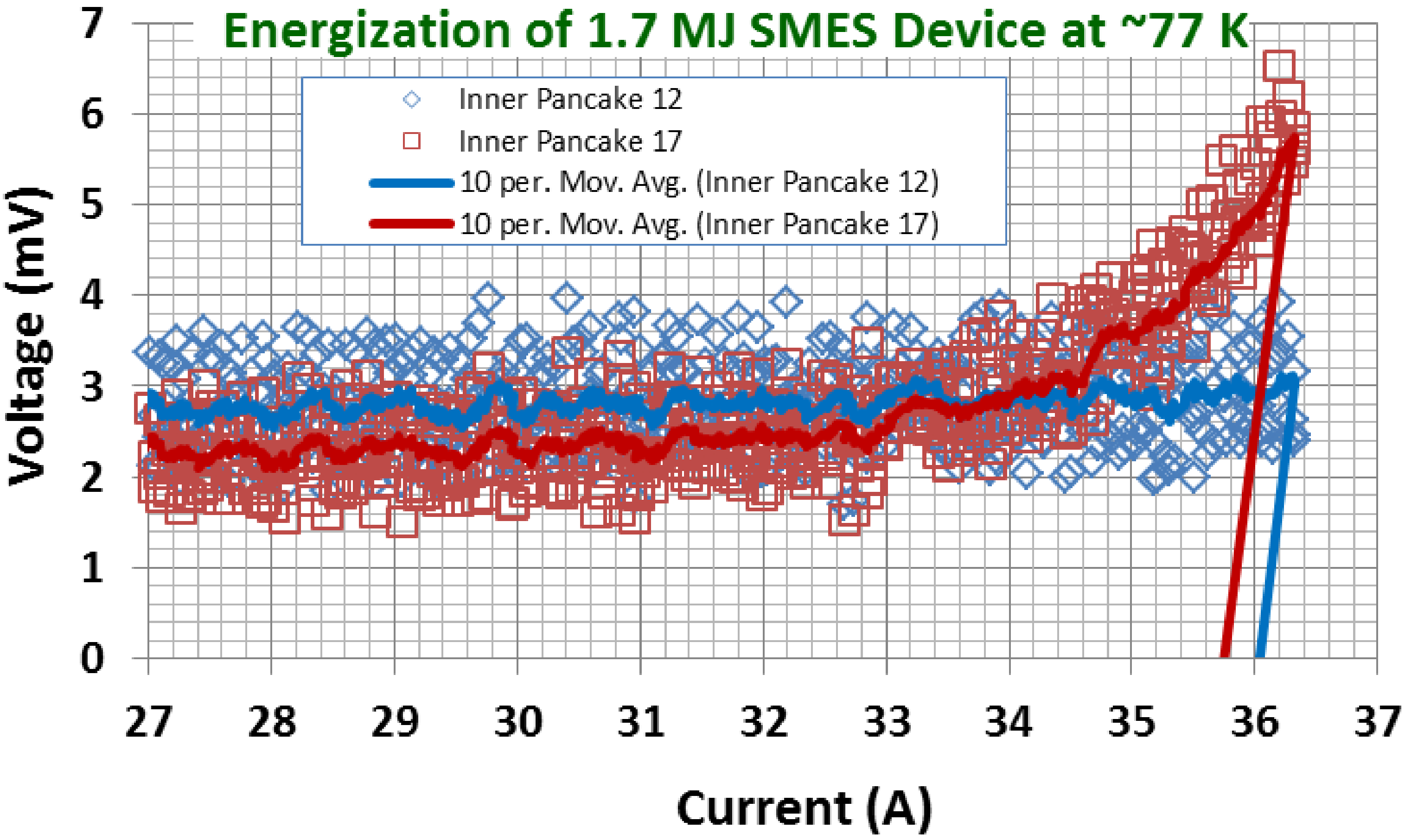






Low noise (~1 mV detection) and high isolation voltage (> 1 kV)

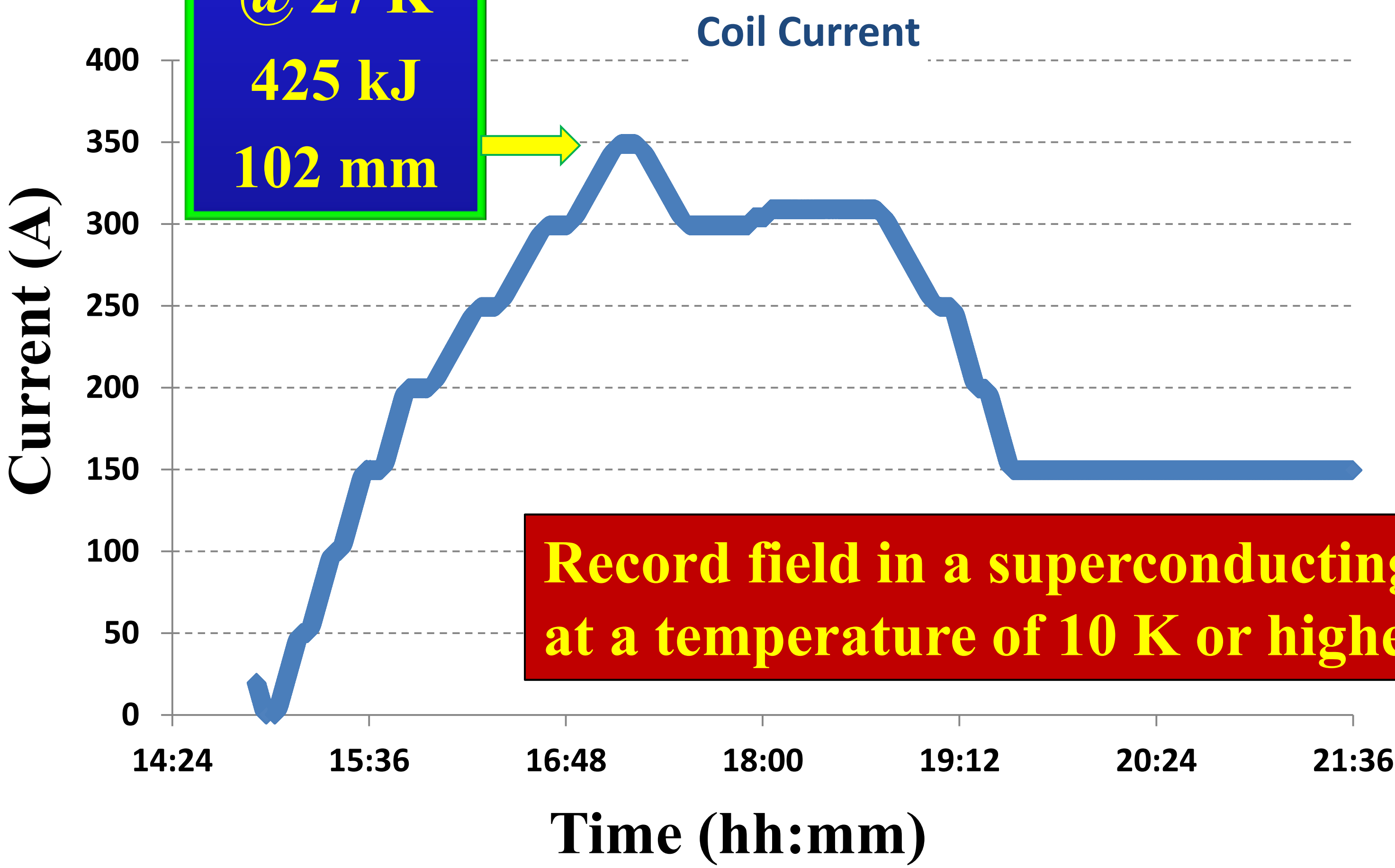
Test of Quench Protection System at 77 K



Power supply was shut off and energy extracted when the quench threshold reached. No degradation in coil performance observed

SMES Coil Run on 5/21/2014

350 Amp
12.5 Tesla
@ 27 K
425 kJ
102 mm



27 K can be obtained by liquid neon

Record field in a superconducting magnet at a temperature of 10 K or higher.

Present Status

- The design goal was 1.7 MJ at ~700 A with 25 T at 4 K.
- We tested the unit at several temperatures between 20-80 K, including the 350 Amp (12.5 T) test at 27 K.
- During one such test, the system tripped due to a data entry error at ~165 A – well below the current the magnet was tested earlier
- This trip resulted in damage to a few current leads in the inner coil. It appears that there was arcing, perhaps during shut-off.
- SuperPower has taken the charge of repairing and further testing

Take away from the High Field HTS SMES R&D

- Even though we didn't reach the design goal of an aggressive program of 25 T, in large aperture (~100 mm) superconducting magnet with large hoop stresses (~400 MPa) in the first attempt itself, we did learn several things in the process beside creating new records.
- This is the first time that such a large amount of HTS (over 6 km of 12 mm wide tape) has been used in a 4K, high field application.
- The experience and technologies developed should be useful to other future programs, such as very high field magnets for FCC.
- Demonstration of 12.5 T at 27 K is higher than what any one even proposed for SMES. The last most ambitious proposal (not funded) was for 11 T at 20 K by Chubu Electric with Furukawa.

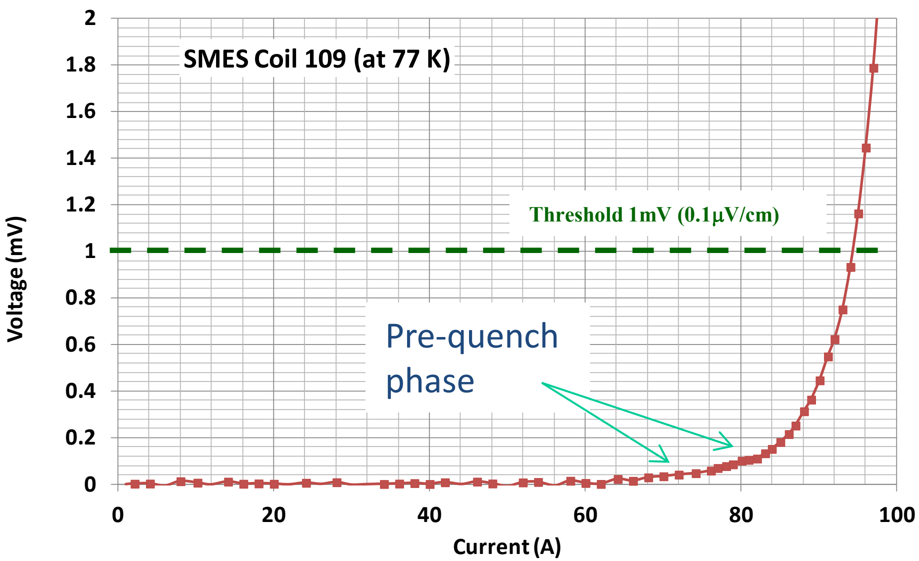
Quench Protection

Quench Protection Strategy Used at BNL

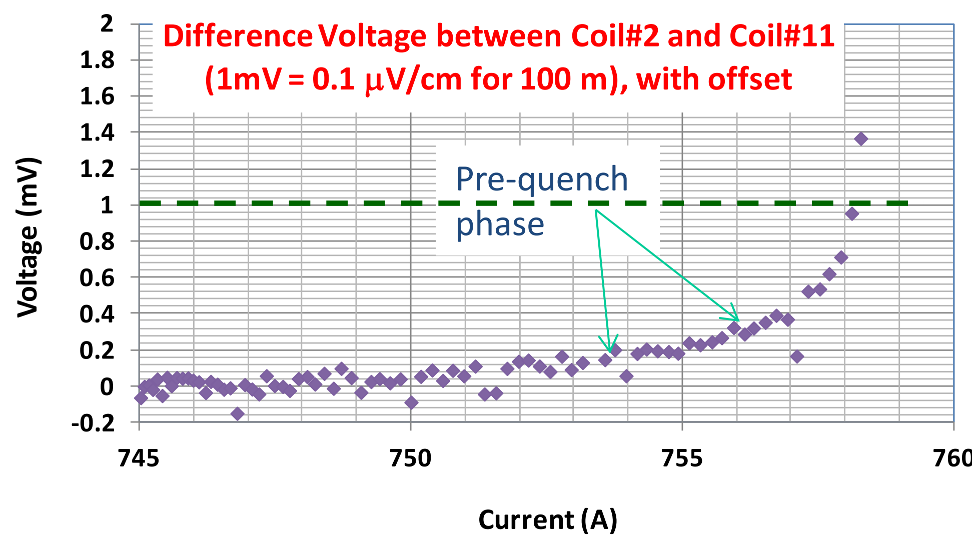
Strategy used at BNL in various HTS programs:

- ➢ Detect early and react fast
  - ✓ An advance quench protection system

- Developed an advanced low-noise electronics and noise cancellations schemes to detect pre-quench voltage (phase) where HTS coils are operating safely
- Uses electronics to handle high isolation voltage (>1kV)
- ○ Use inductively coupled copper discs to quickly extract energy initially



Twelve coil test at 4K (~12 T, ~120 K)



Advanced Quench Detection System with Fast Energy Extraction

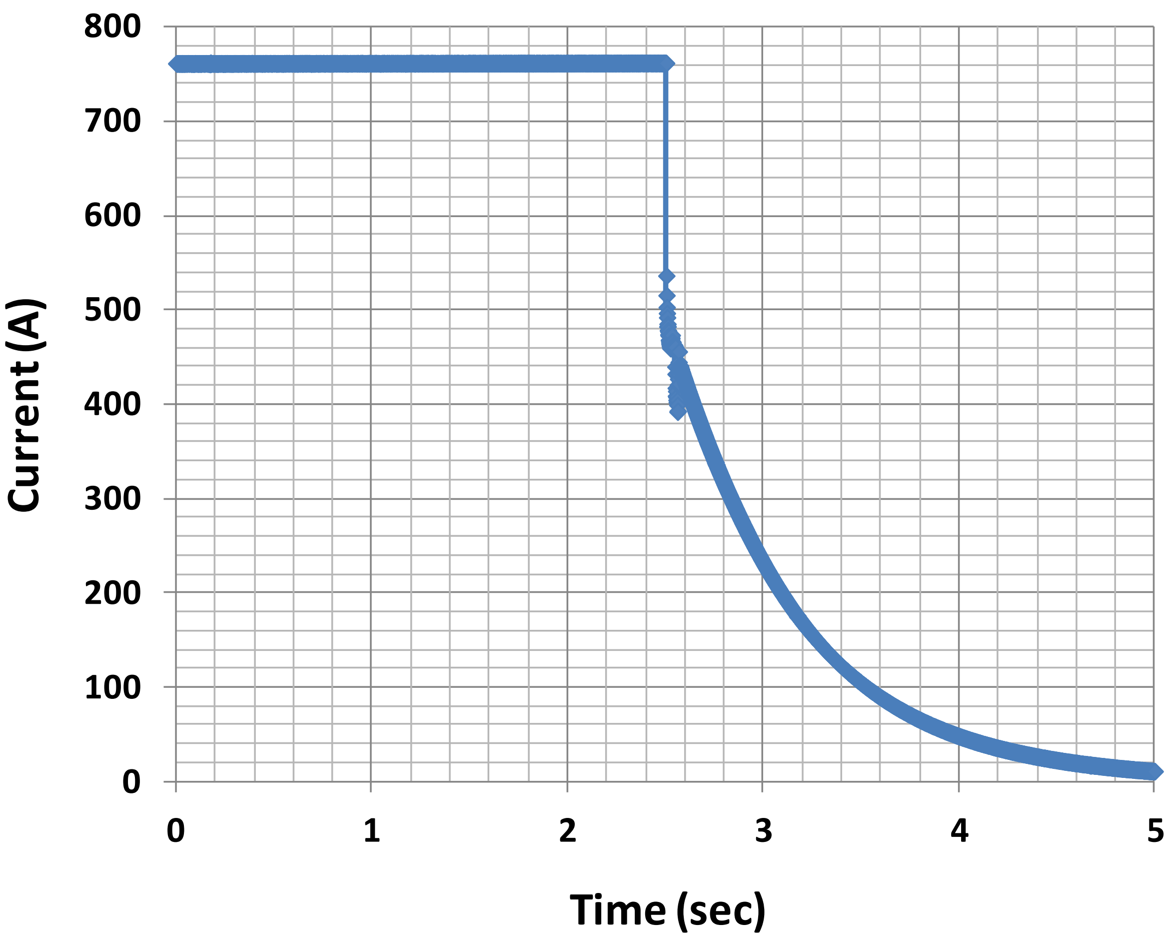
- Fast energy extraction in larger magnets creates high voltages as "L" increases
- Develop electronics that can tolerate high isolation voltage (>1 kV)
- Divide coils in several sections

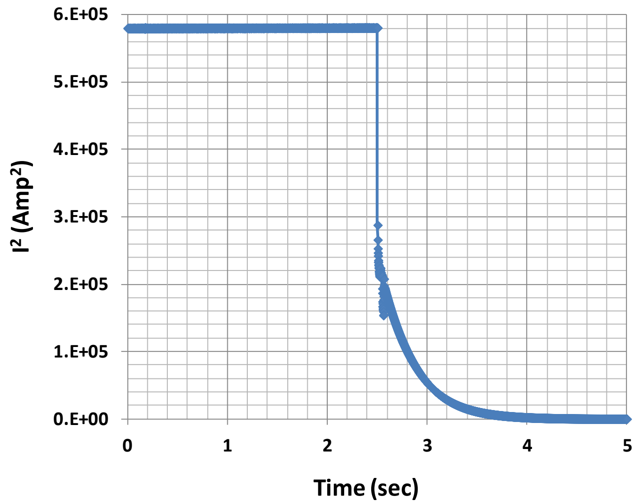
Cabinet #1 (32 channels, 1kV)

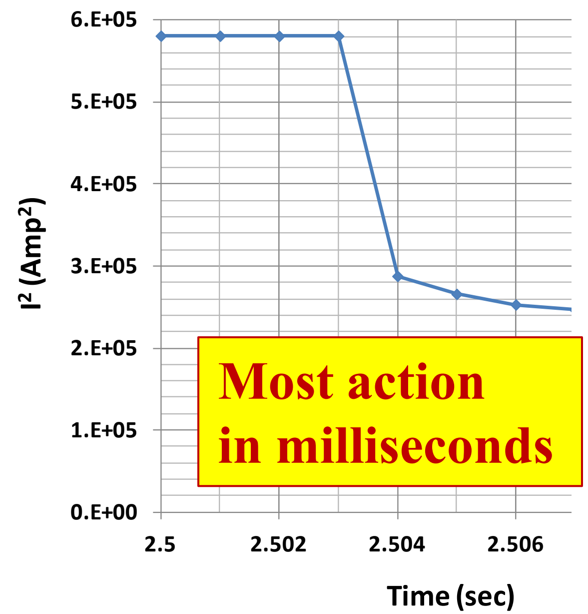
Cabinet #2 (32 channels, 1kV)

Copper Disc for Initial Energy Extraction

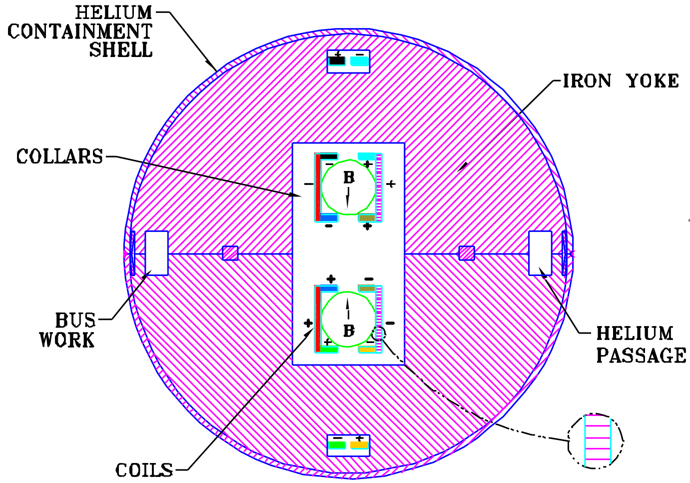
Cu discs between double pancakes are inductively coupled





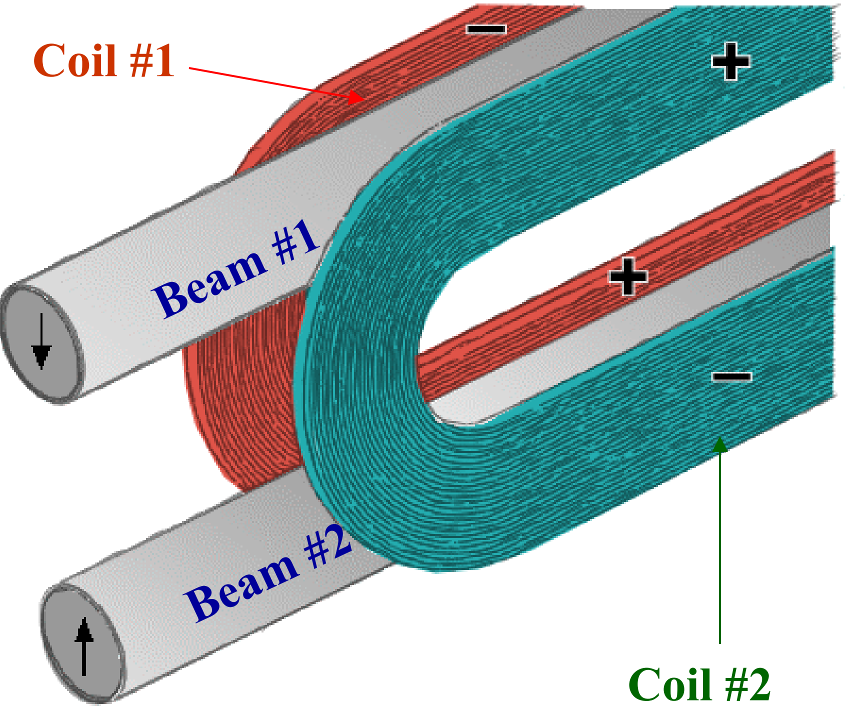


High Field Magnet for Accelerators



Common Coil Design

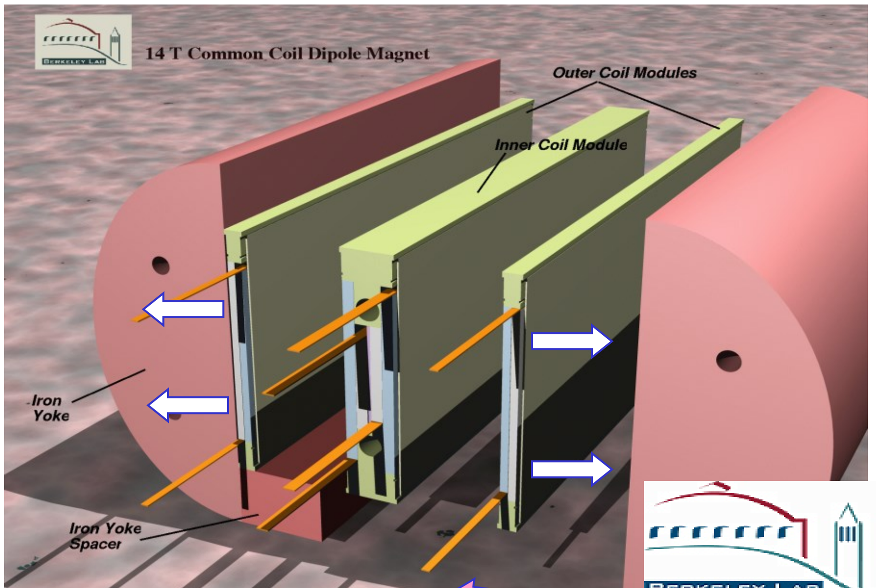
- **Simple 2-d geometry with large bend radius (no complex 3-d ends)**
- **Conductor friendly (suitable for brittle materials – can do both Wind & React and React & Wind with LTS and HTS)**
- **Compact (compared to single aperture LBL's D20 magnet, half the yoke size for two apertures)**
- **Special coil geometry (suitable for large Lorentz forces at high fields)**
- **Efficient and methodical R&D due to simple & modular design**
- **Minimum requirements on expensive tooling and labor**
- **Successfully built at LBL, BNL & FNAL**
- **Lower cost magnets expected**

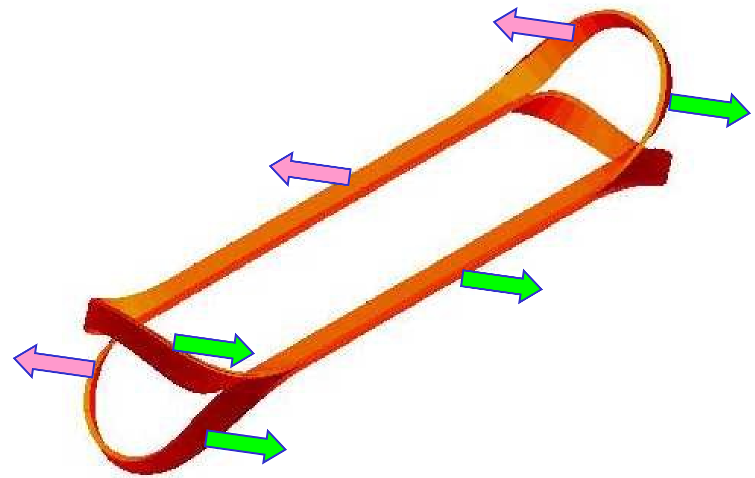


Main Coils of the *Common Coil Design*

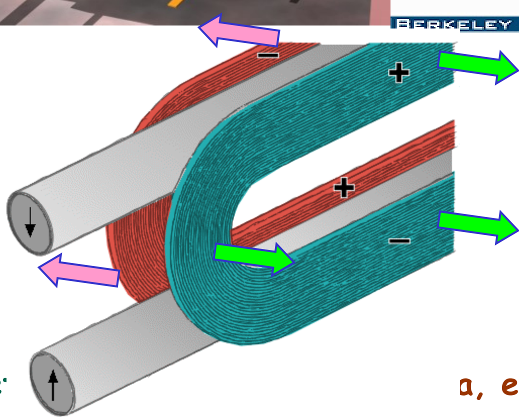
Common Coil Design in Handling Large Lorentz Forces in High Field Magnets

In common coil design, a racetrack coil can move as a block, without straining the conductor in the ends and thus minimize causing quench or damage.





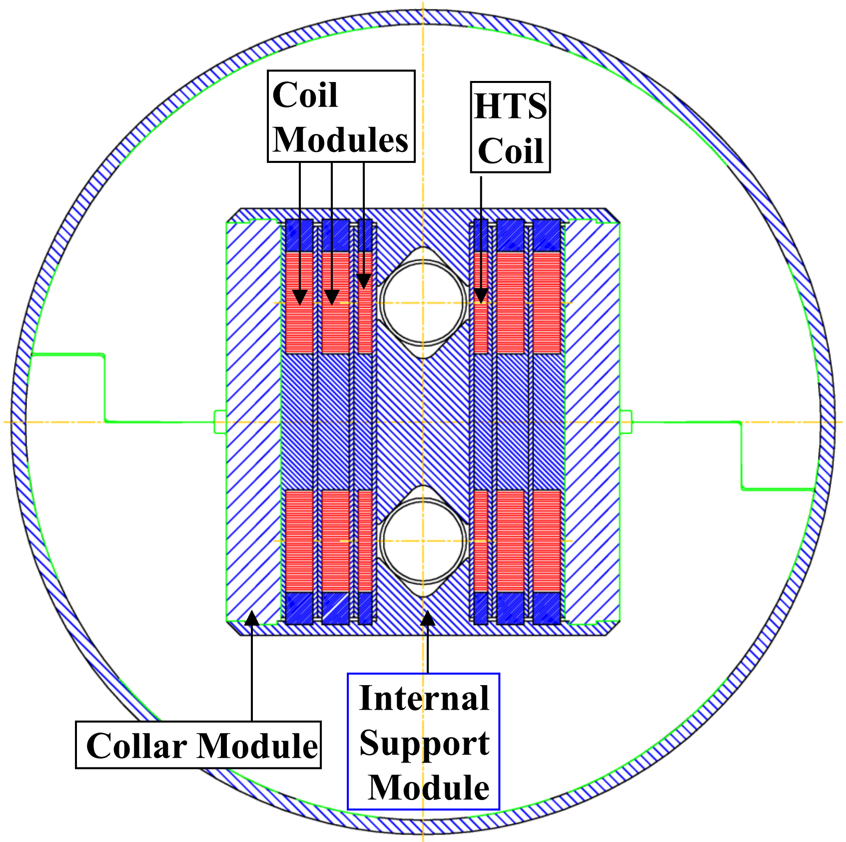
Horizontal forces are larger



In cosine theta or conventional block coil designs, the coil module cannot move as a block. Therefore, Lorentz forces put strain on the conductor at the ends which may cause premature quench.

Possible Layout of Common Coil Designs

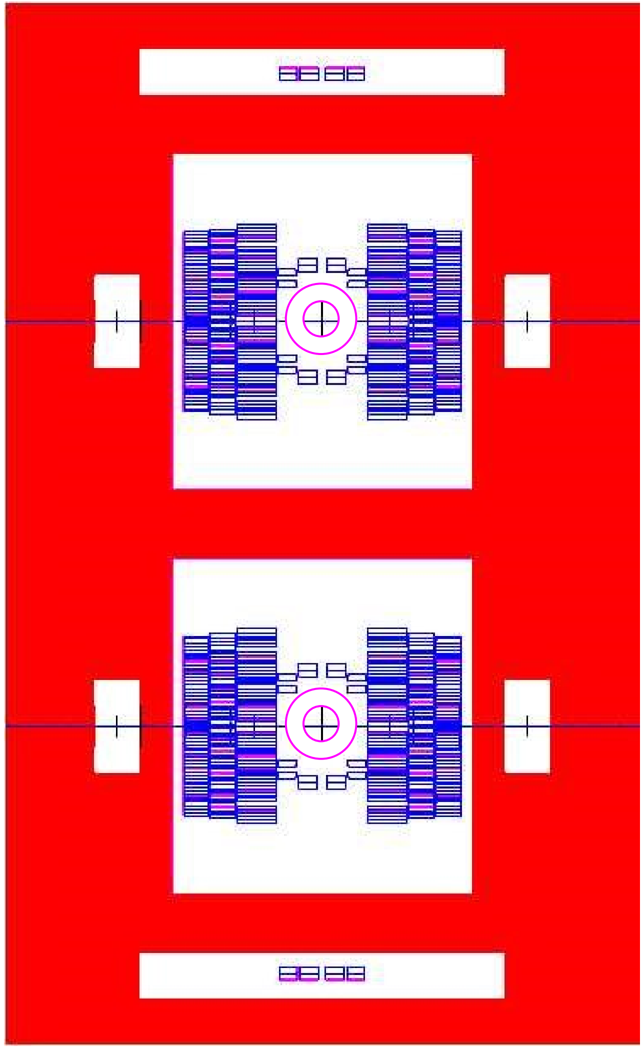
R&D Magnet



Vary aperture after the coils are made

- **a unique feature in R&D magnets**
- **lower separation, higher field**

15 T Field Quality Magnet



A good field quality magnetic design is demonstrated

15 T design is based on Nb_3Sn conductor with $J_c = 2200\ A/mm^2$ @(12T, 4.2K)

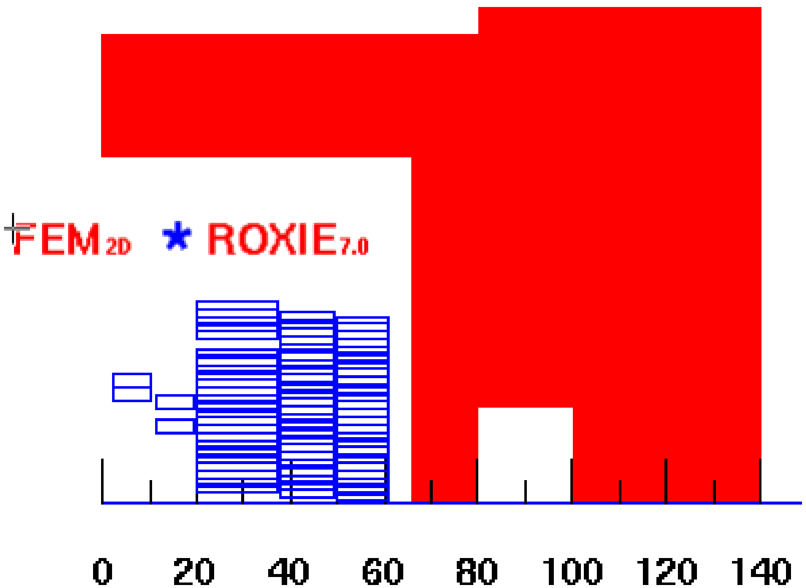
More horizontal space for structure will need a minor iteration

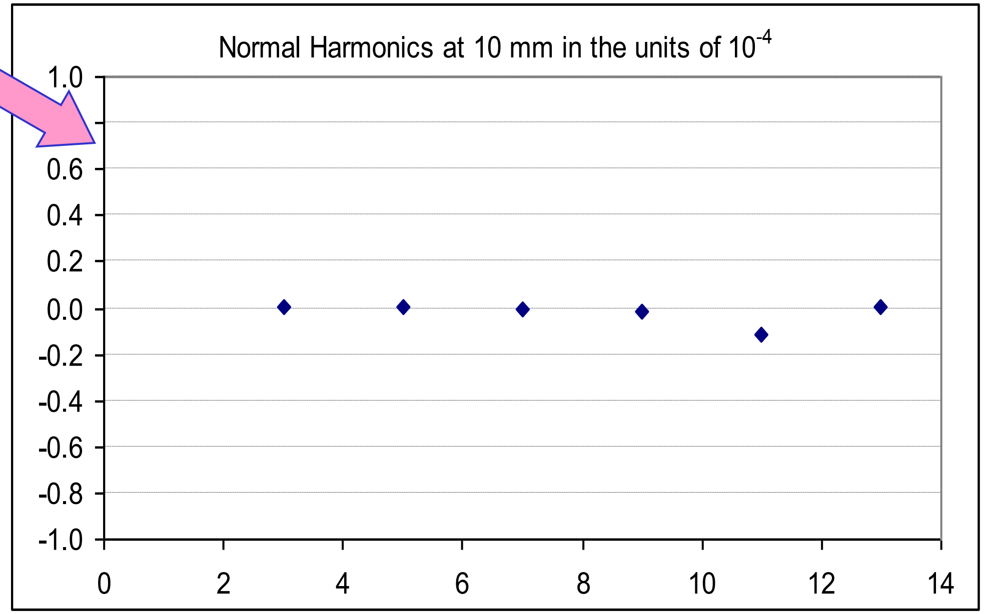
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Demonstration of a Good Field Quality in Geometric Harmonics

Typical Requirements:
~ part in 10^4, we have part in 10^5





(from 1/4 model)

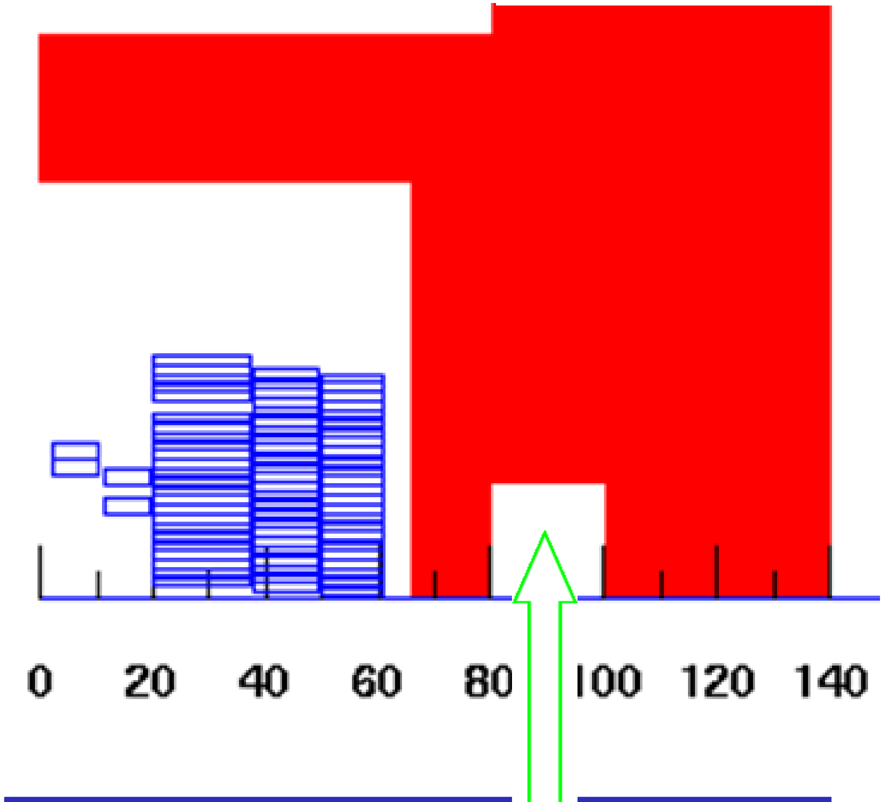
MAIN FIELD: -1.86463 (IRON AND AIR):

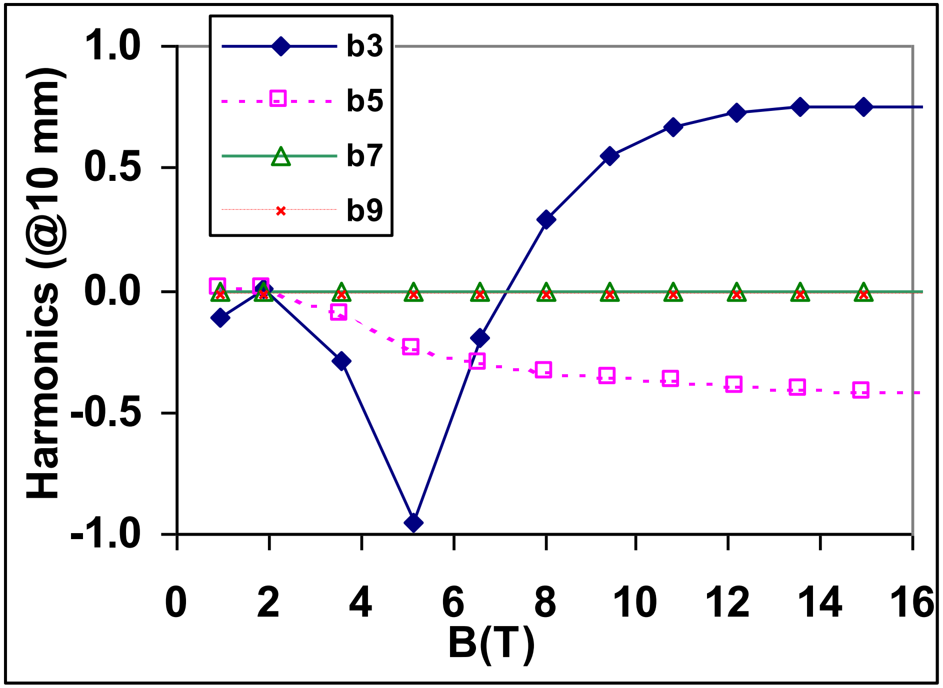
b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	0.00000
b13:	0.00932	b14:	0.00000	b15:	0.00140
b16:	0.00000	b17:	-0.00049	b18:	0.00000

Horizontal coil aperture: 40 mm

Demonstration of a Good Field Quality in Saturation-induced Harmonics

Maximum change in entire range: ~ part in 10^4 (satisfies general accelerator requirement)





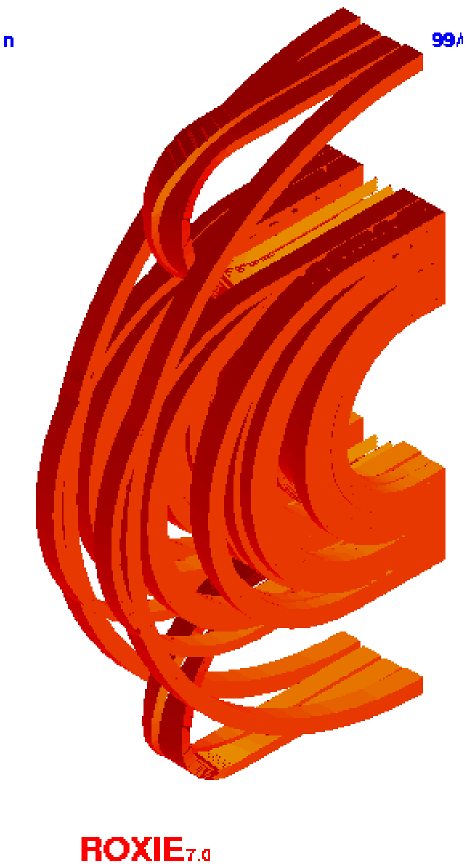
Use cutouts at strategic places in yoke iron to control the saturation

Low saturation-induced harmonics (within 1 unit)

Demonstration of a Good Field Quality in End Harmonics

End harmonics can be made small in a common coil design.

(Very small)

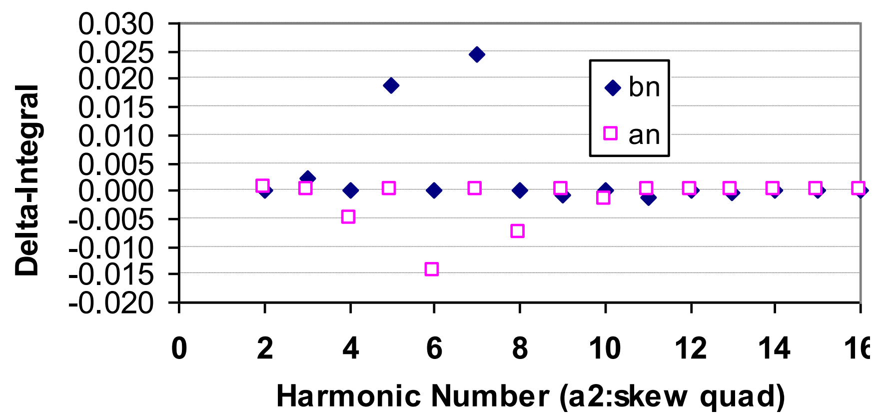


End harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

Contribution to integral (a_n,b_n) in a 14 m long dipole (<10^{-6})

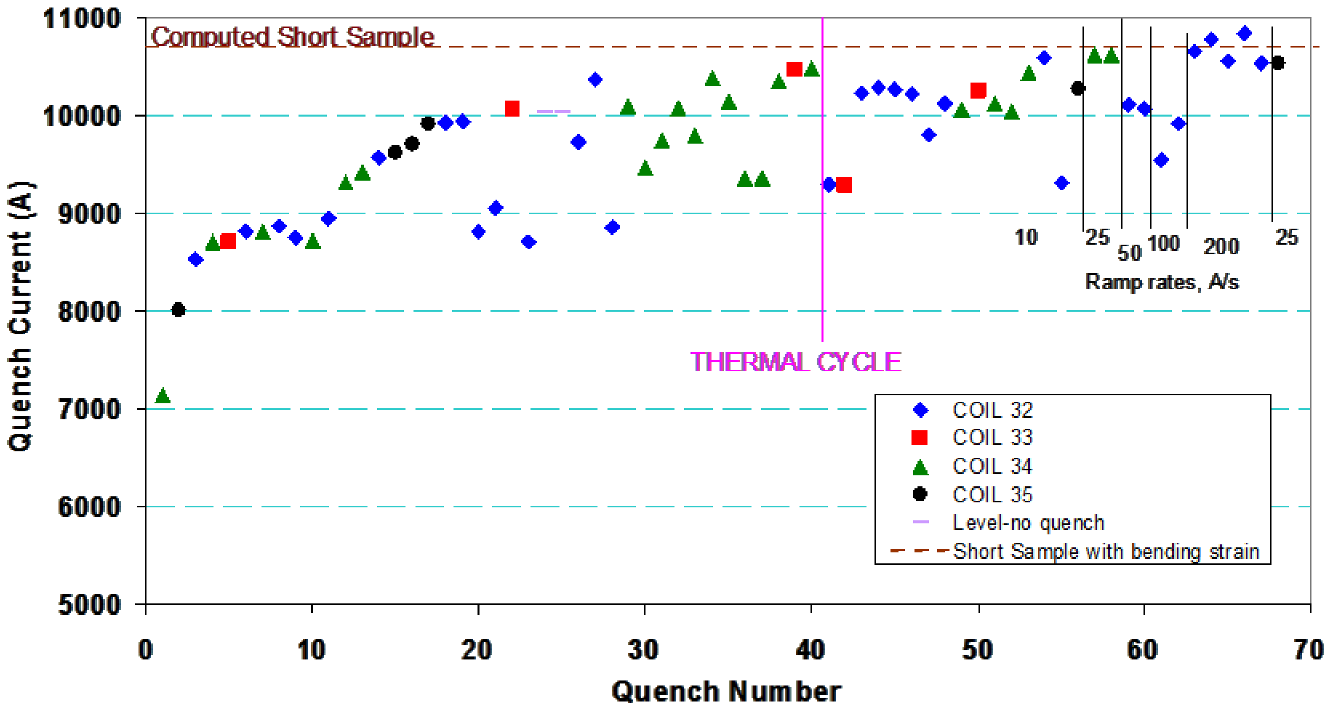
n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000



BNL Nb_3Sn React & Wind Common Coil Dipole DCC017

Large open space for insert coil testing

Performance of Common Coil Dipole (despite large deflections)



I_c=10.8 kA
B_{pk}=10.7 T
B_{ss}=10.2 T

- Slightly exceeded the computed short sample
- Practically no vertical or horizontal pre-load

- Magnet reached short sample after a number of quenches
  √ Reasonable for the first technology magnet
- The geometry can tolerate large horizontal forces and deflections
  - ➢ important for high field magnets
  - ➢ computed horizontal deflection/movement of the coil as a whole ~200 μm

Common Coil Design for FCC

- One can obtain as good field quality (geometric, saturation, ends) in common coil as in any design. Field quality would depend on the construction errors and conductor properties
- Common coil can handle large forces (and deflections associated with it) without causing internal strain on the conductor because the coil moves as a whole
- BNL, LBL and FNAL have built Nb_3Sn based on this design with several positive experience
- It offers both choices – "wind & react" and "react & wind"
- A simpler geometry opens the door for lower cost construction
- Thus the common coil design offers an interesting possibility for high performance, lower cost magnets

SUMMARY

Two R&D programs with significant possible potential:

1. **Several aspects of arpa-e high field HTS SMES can be directly applied to FCC magnet R&D**
2. **Common coil design offers a potential for higher performance lower cost high field magnets**

Extra Slide

Concluding Remarks

- HTS have a potential for generating high fields that were not possible before in superconducting magnets.
- High field coils with a large amount of ReBCO tape have been built and record performances achieved.
- HTS conductor is still in R&D stage. We took the approach that use the limited resources and opportunities to demonstrate the potential. Positive results should create interest and more funding.
- Even though the progress has been rapid (in the scale of superconducting magnet technology), particularly given that the conductor is still in R&D phase, still much remains to be done.
- To realize the true potential of HTS as HFS, we will require a specifically focused and funded program.
- Common coil design offers a potential for low cost, high performance magnets for the next high energy collider.