High Field HTS SMES Coil

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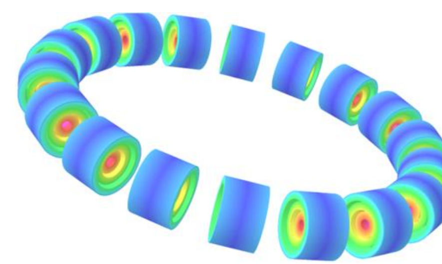


Overview

From our sponsor:

… ARPA-E's mission is to catalyze and accelerate the creation of transformational energy technologies by making high-risk, high-reward investments in their early stages of development

This presentation summarizes an aggressive R&D where

We demonstrated a higher field and a higher operating temperature energy storage coil than proposed before …

- **12.5 T SMES coil operating at 27 K**

SMES SYSTEM Proposal

ABB | BROOKHAVEN NATIONAL LABORATORY | SuperPower Inc. | UNIVERSITY of HOUSTON

Superconducting Magnet Energy Storage System with Direct Power Electronics Interface

Project Goal:

- **Competitive, fast response, grid-scale MWh superconducting magnet energy storage (SMES) system**

Team member major contributions:

- **ABB:** ***Power electronics, Lead***
- **BNL:** ***SMES coil and Superconducting switch***
- **SP:** ***2G HTS manufacture and improved production***
- **UH:** ***Wire manufacturing process research***

Focus of the Presentation

Technology for High field HTS SMES coil

– **Design, construction and test results**

- For economic viability of a large scale energy storage system, cost of coated conductor must come down significantly (smart designs can help)
- The technology developed could already be applied to special purpose storage system and other applications

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)

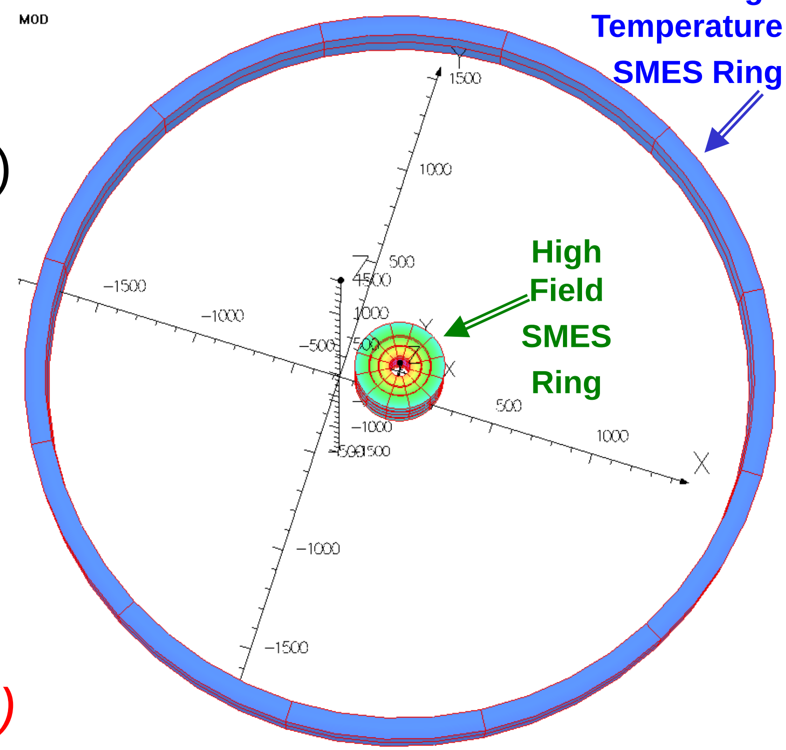
Our analysis on HTS option:

Presently conductor cost dominates the cryogenic cost by an order of magnitude

High field HTS could be game changer:

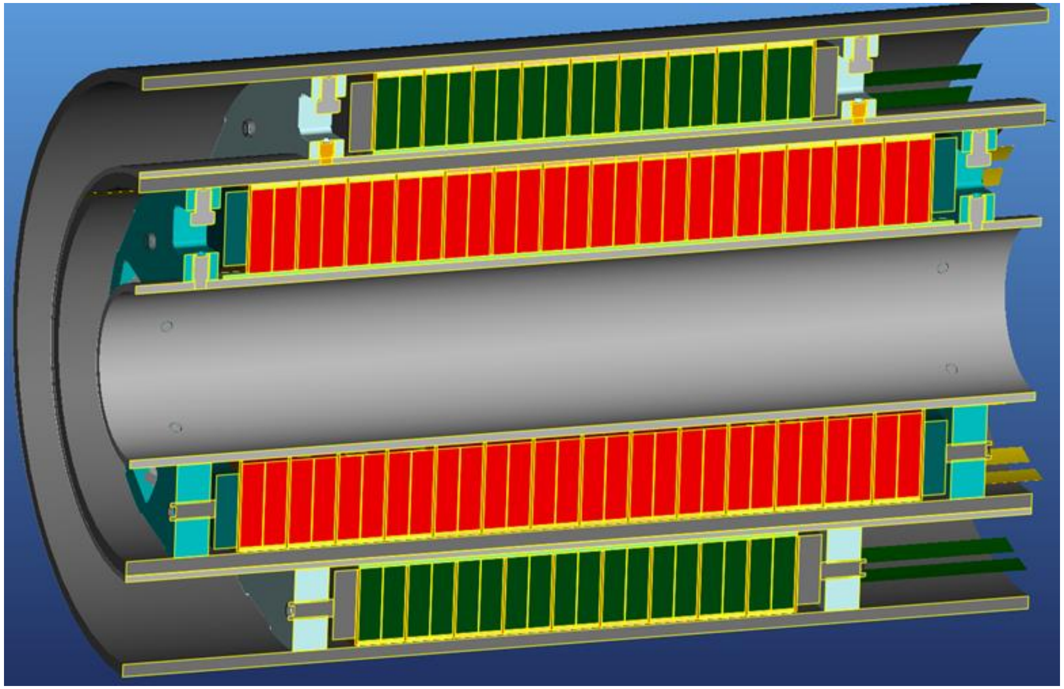
✓ Very high fields: 25-30 T (E α B^2)

❖ Only with HTS *(high risk, high reward)*



➢ **Also: A medium field and medium temperature option (a new record 12.5T@27K demonstrated, thanks to arpa-e)**

The Basic Demo Module



Aggressive parameters:

Field: 25 T@4 K (more than ever)

Bore: 100 mm (large)

Hoop Stresses: 400 MPa (>2X)

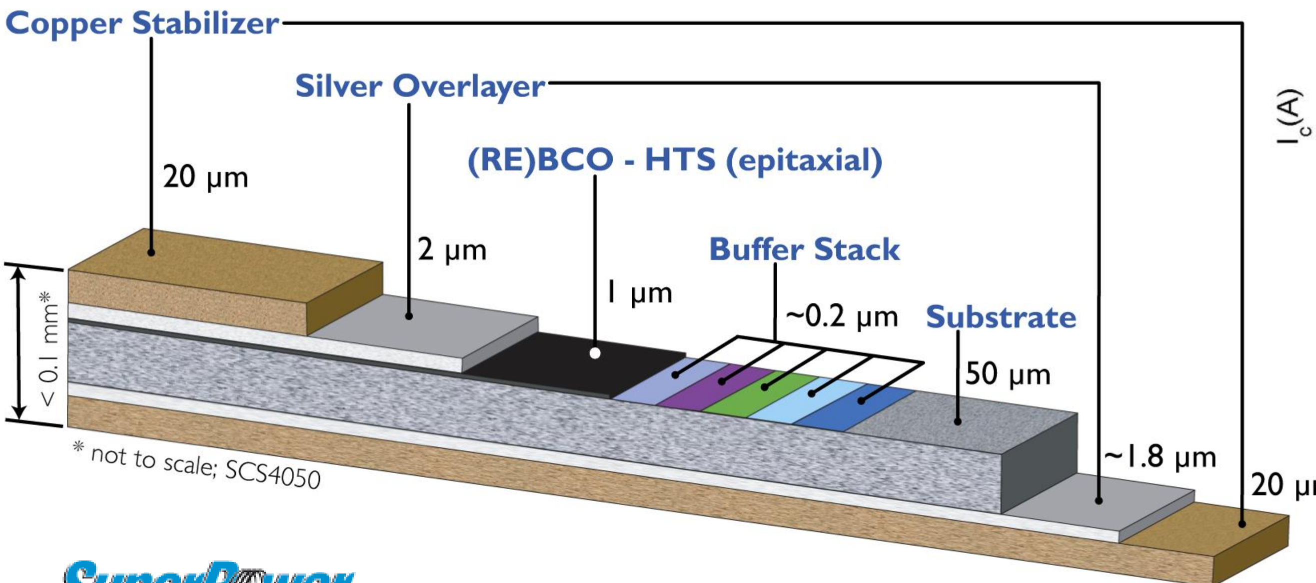
Conductor: ReBCO (evolving)

Conductor – ReBCO Tape

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

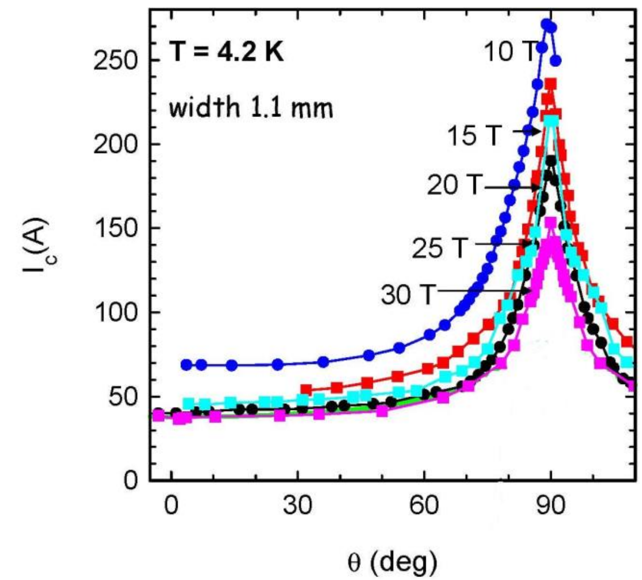
arpa·e CHANGING WHAT'S POSSIBLE



SuperPower Inc. A Furukawa Company

HTS tape: angular dependence

Measurements at NHMFL (earlier sample)



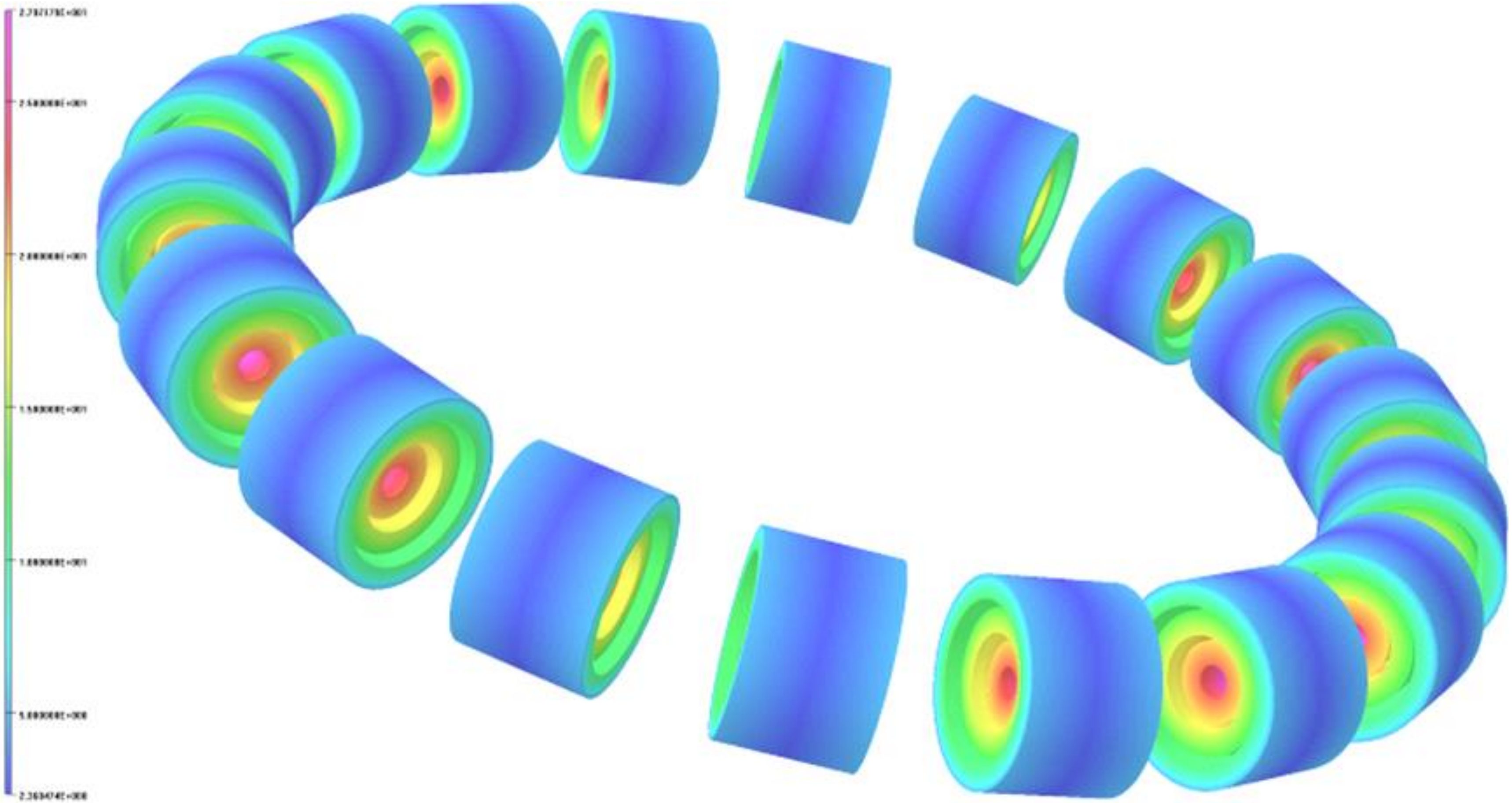
<u>SMES specs (12 mm)</u>:

>700 A@4K

(at any angle)

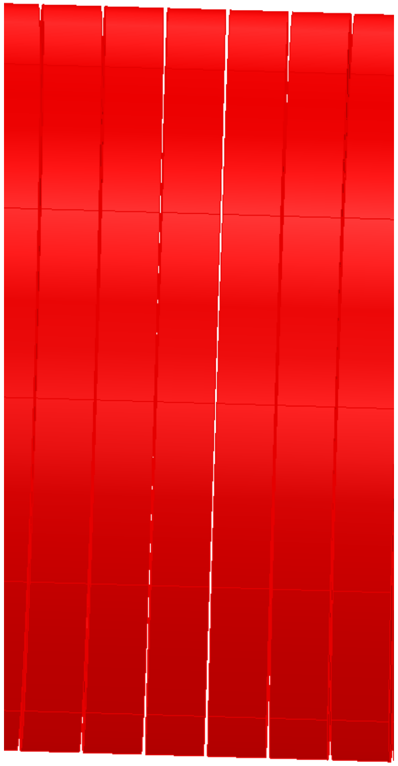
12 mm wide ReBCO tape with high strength hastelloy substrate

Large Scale SMES Concept (1)



- **A torus would consist of a large number of solenoid module**
- **Field becomes parallel => less amount of conductor required**

Large Scale SMES Concept (2)

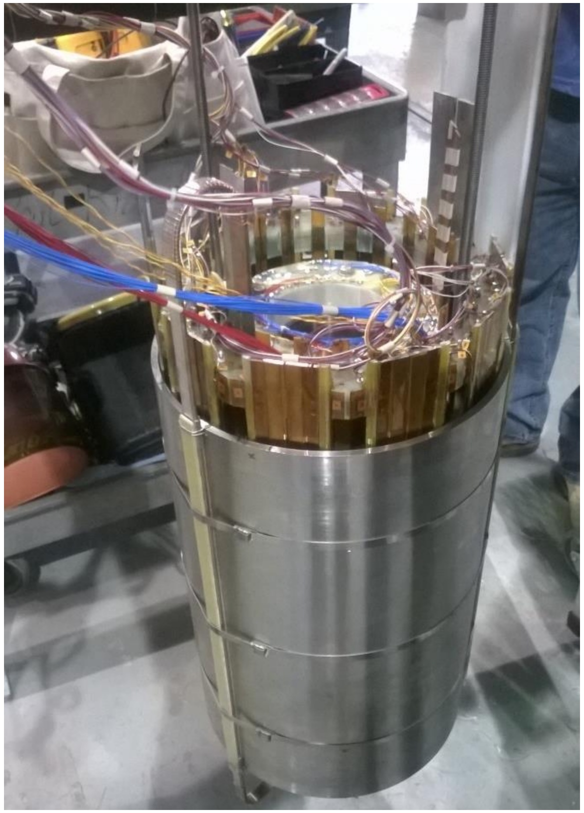


GJ scale GRID storage system that can fit in a room!

- **Moreover, a small $B_{\perp}$ (<0.5 T) for a large $B_{//}$ (30 T) means a major reduction in conductor cost (~1/5 with an optimized HTS)**

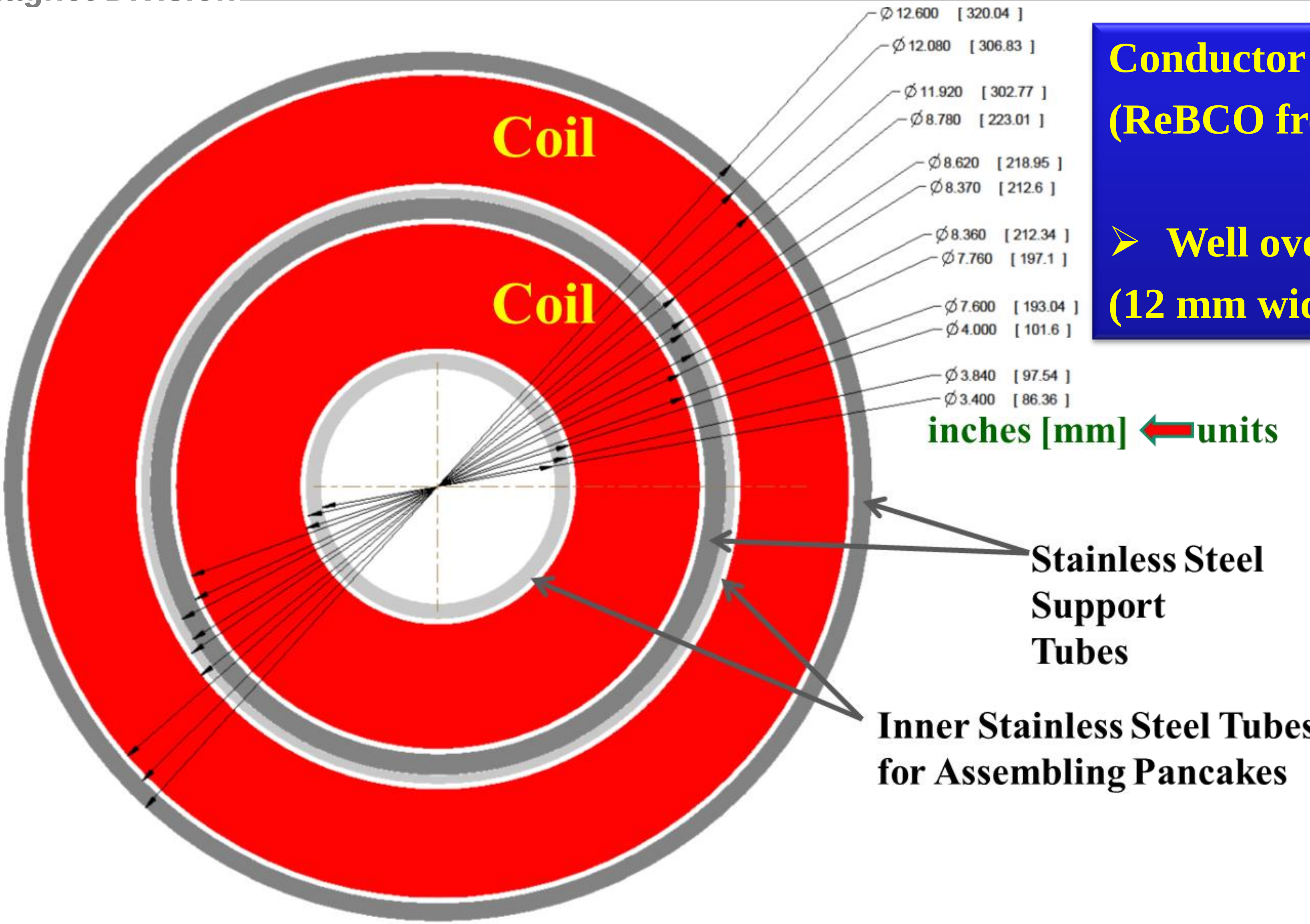
Design Parameters of BNL Demonstration Coil

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



High field and big radius create large stresses (~400 MPa)

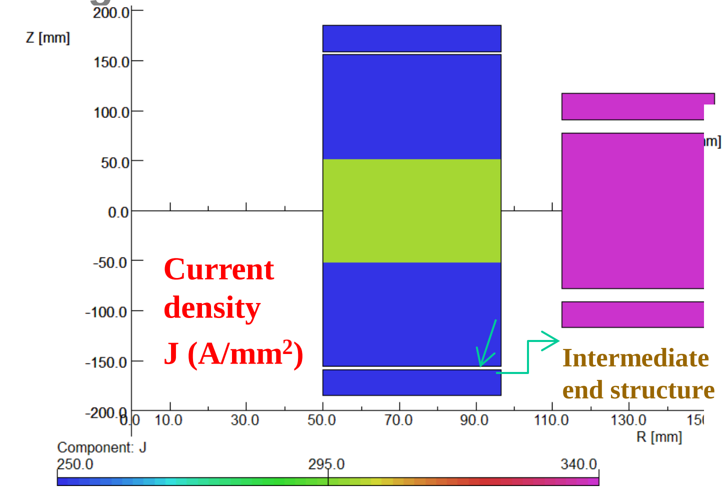
Cross-section of Coil and Support Tube

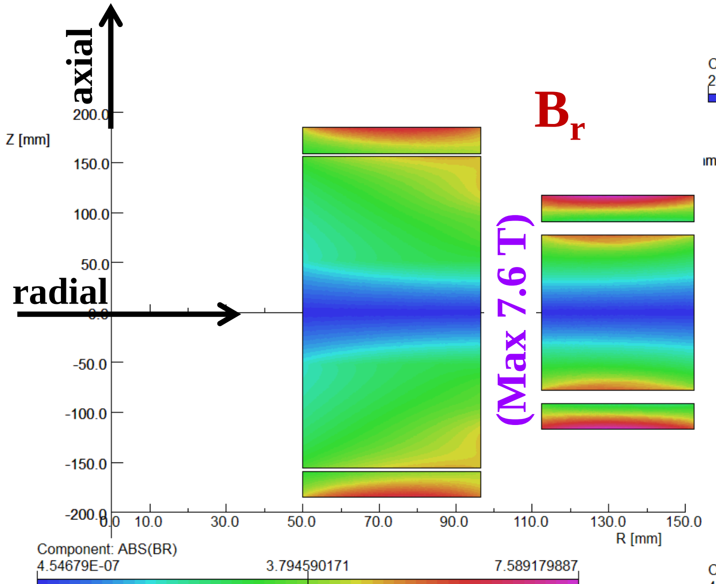


Conductor used (ReBCO from SP):

- Well over 6 km (12 mm wide tape)

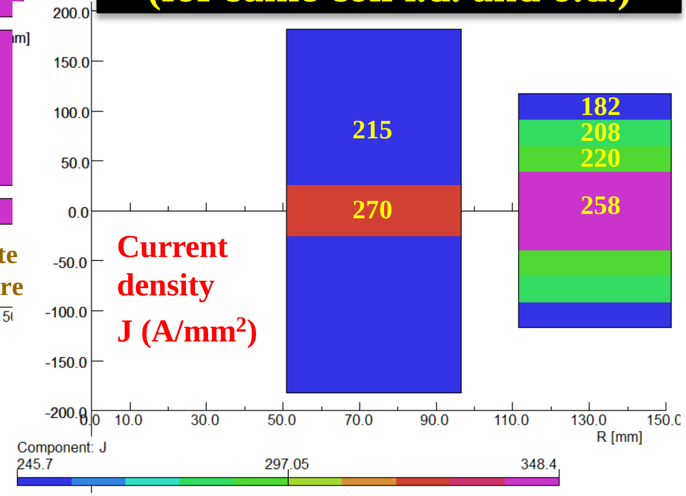
Grading to Optimize Magnetic and Mechanical Design

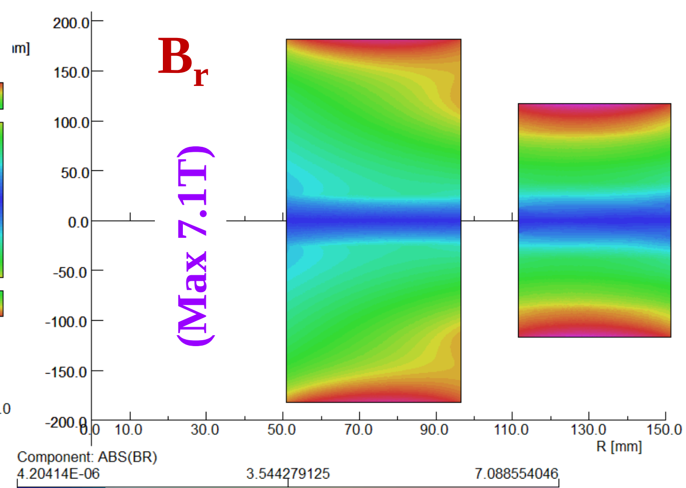




Initial 1.7 MJ Design

Number of turns per pancake (for same coil i.d. and o.d.)





Optimized 1.7 MJ Design

Adjusted for grading:

- Cu thickness in HTS tape (65 and 100 μm)
- SS tape thickness (65 and 100 μm)

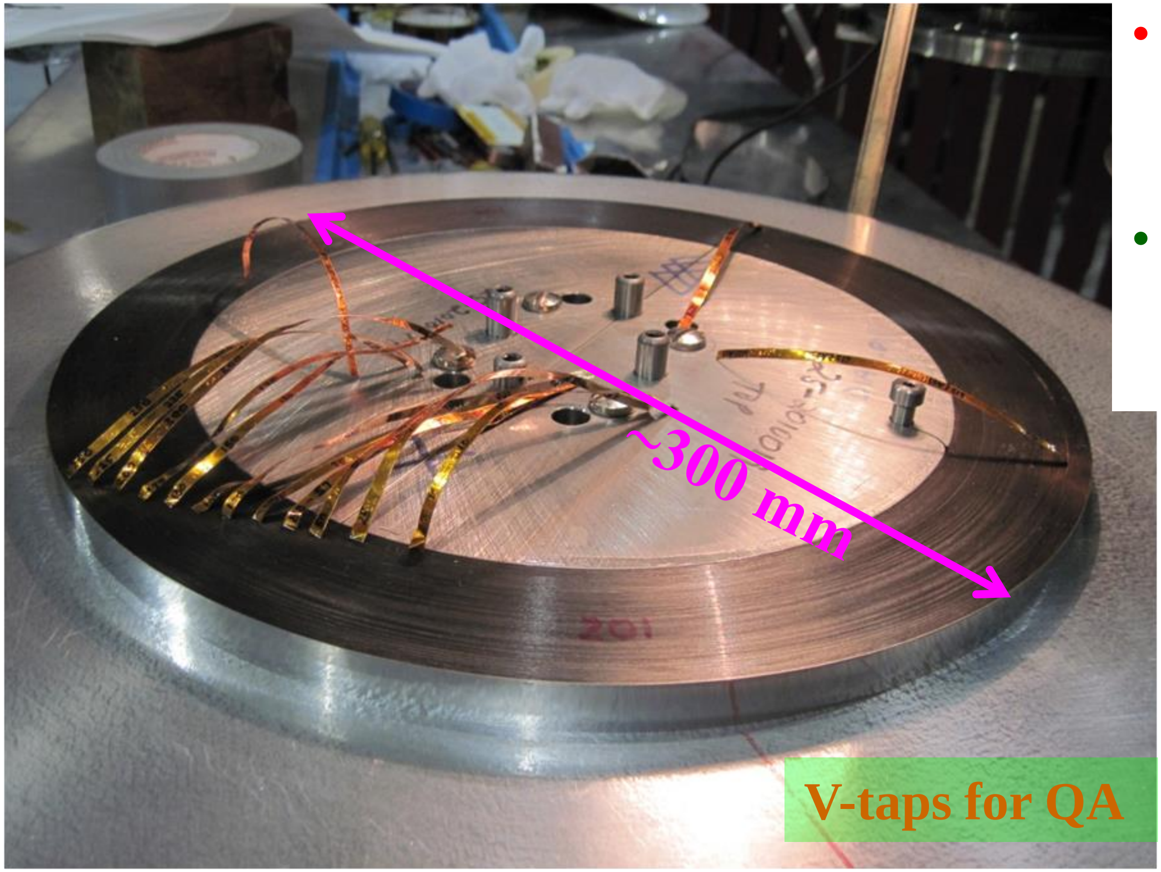
(more copper in ends; more SS in center)

End Result:

✓ Improved performance

➢ Better mechanical structure and reduced Bperp

HTS Single Pancake

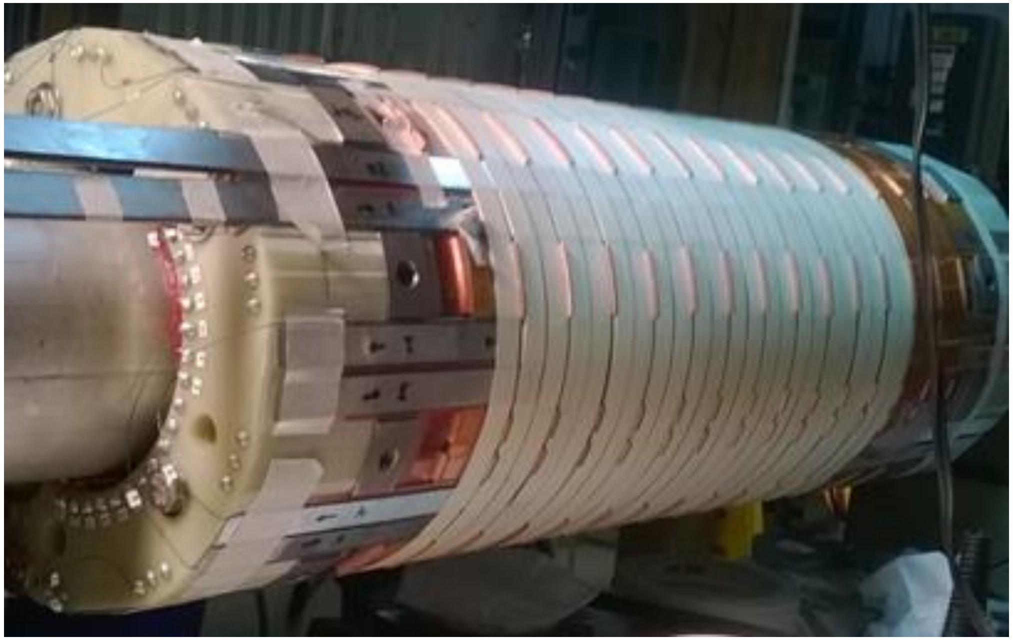


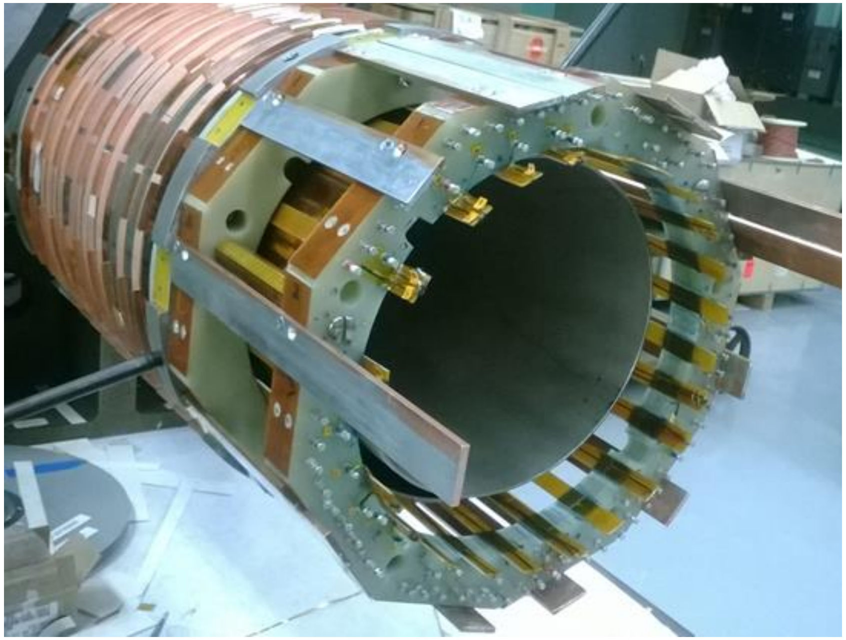
- High strength HTS tape, co-wound with SS tape (for insulation and added strength)
- Thickness of SS tape and copper on HTS adjusted to optimize the performance

Outer: ~210 meter 12 mm tape (258 turns)

Two Pancakes Connected with Spiral Splice Joint

Inner and Outer Coils Assembled





Inner Coil

(102 mm id, 194 mm od)

28 pancakes

Outer Coil

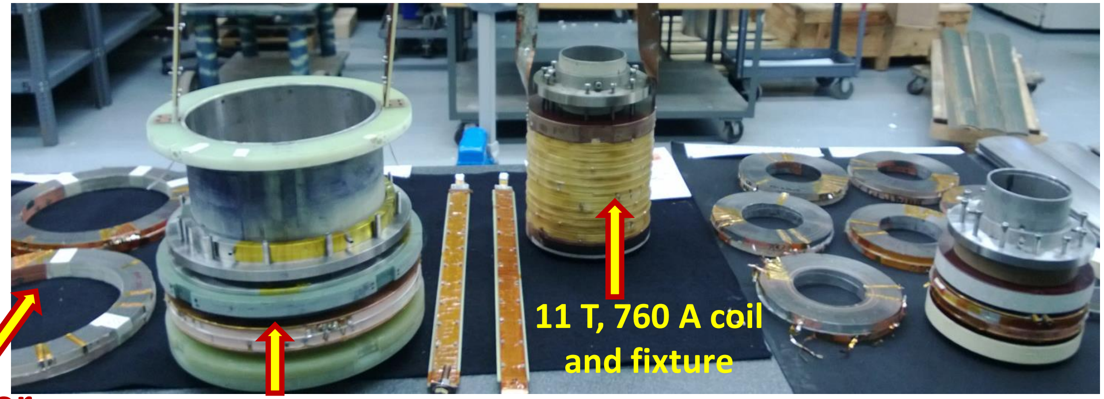
(223 mm id, 303 mm od)

18 pancakes

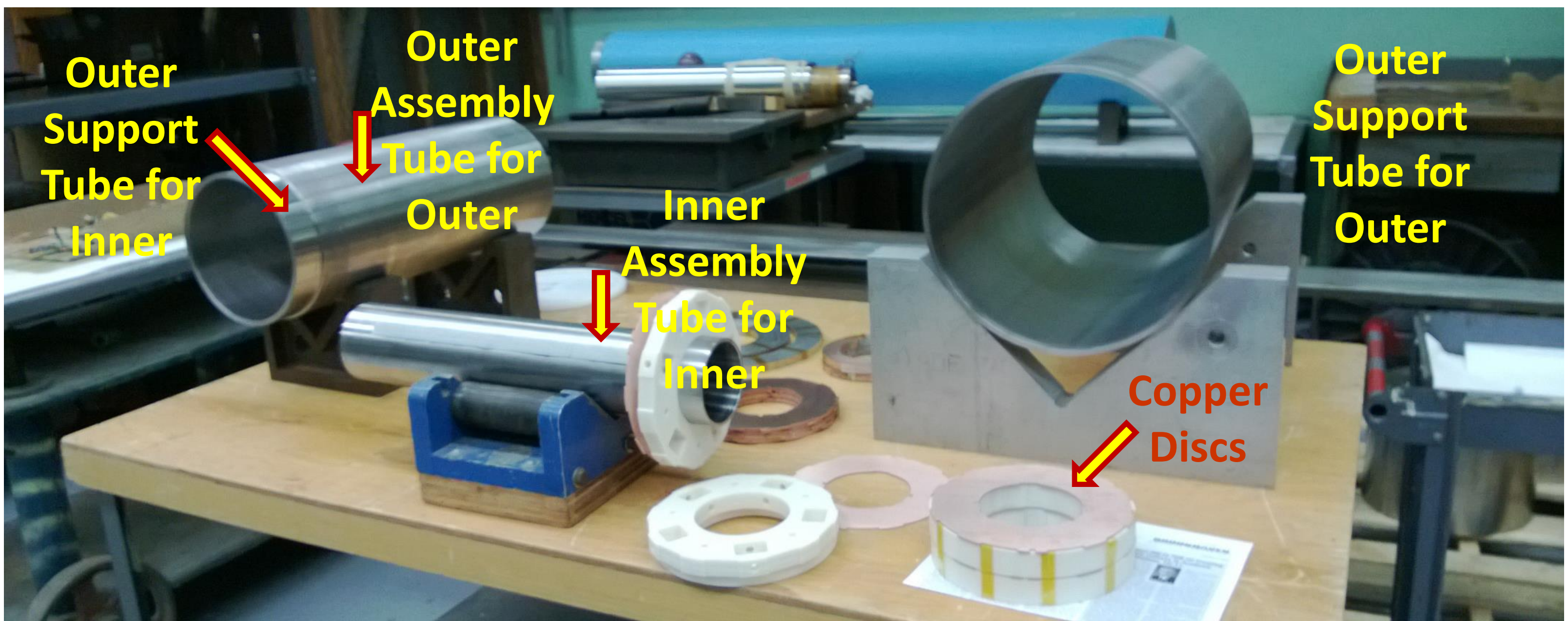
Total: 46 pancakes

Coils, Test Fixtures and Support Structure

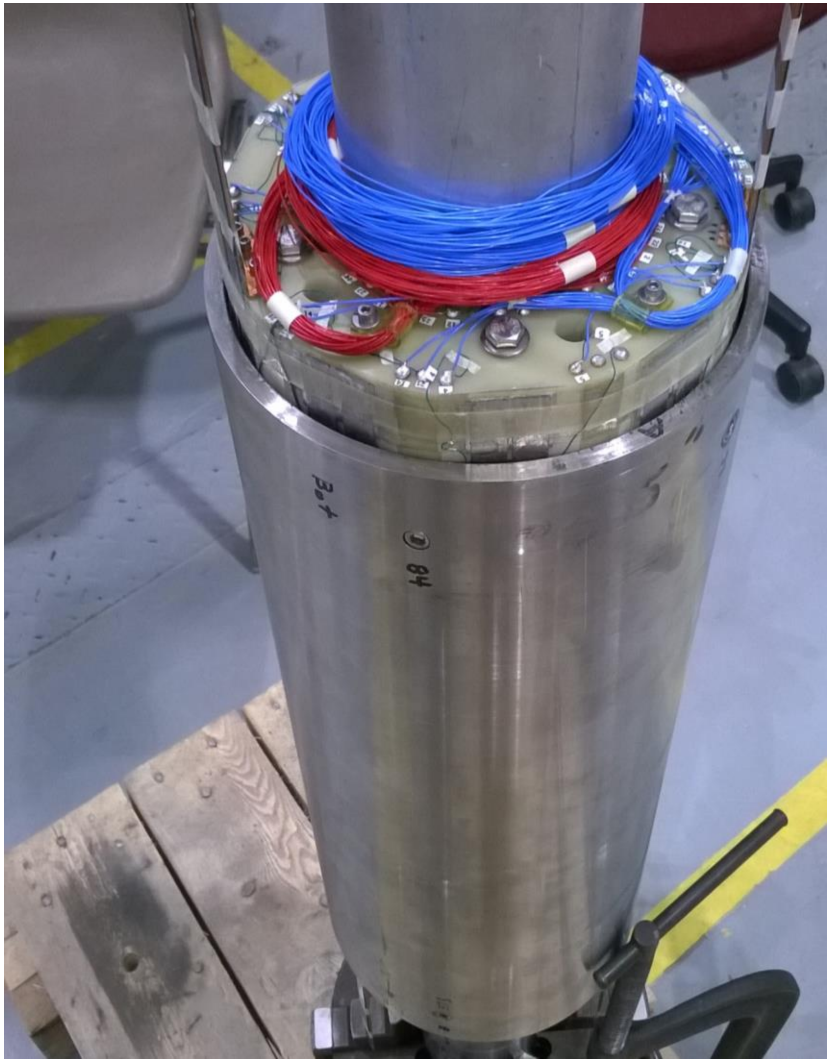
Pancake coils: inner and outer



77 K Test Fixture for outer



Inner and Outer Coils



Inner (in support tube)

Outer (prior to support tube)

Final Assembly

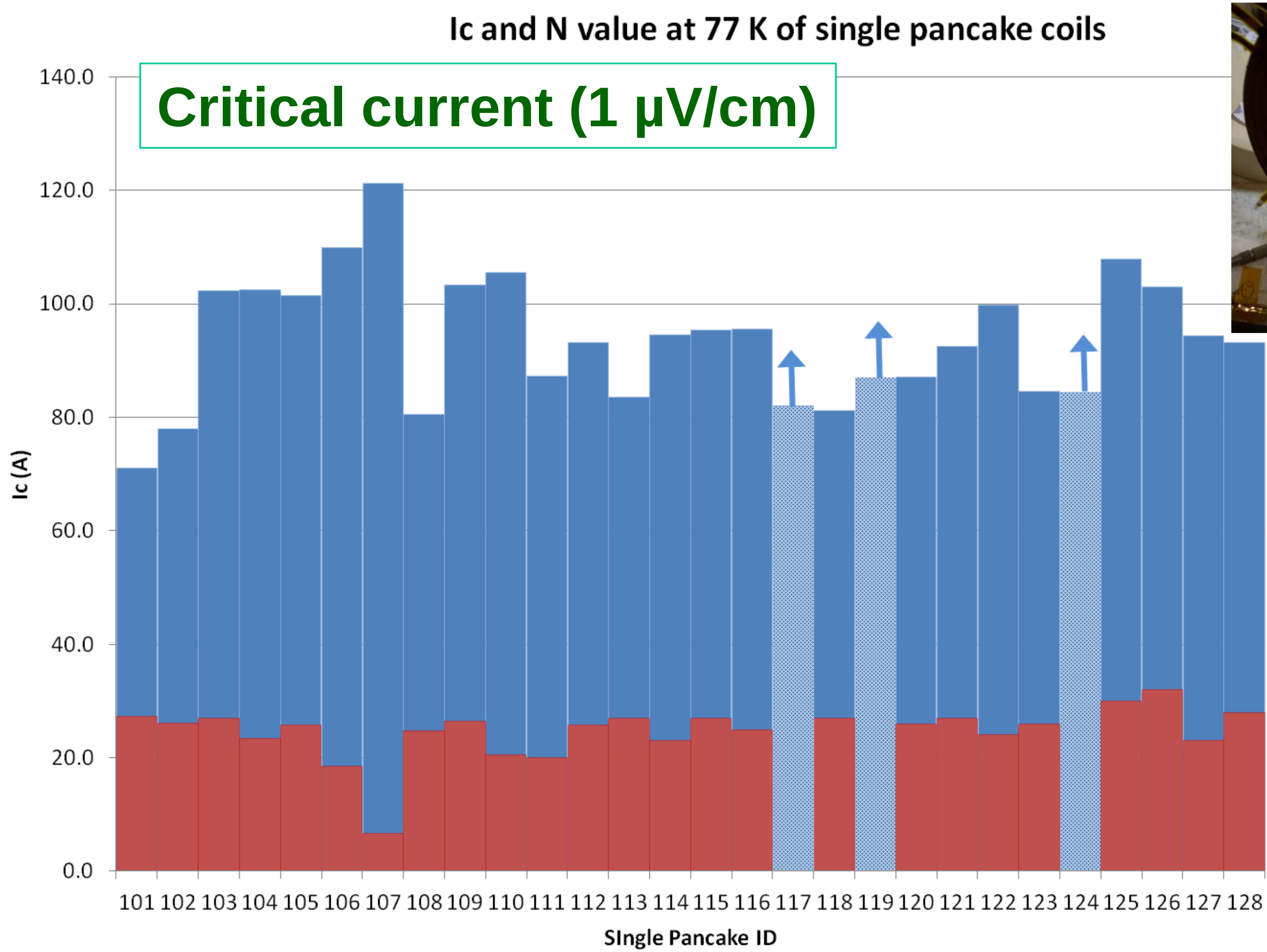
Outer inserted over inner coil

SMES coil in iron laminations

Test Results

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

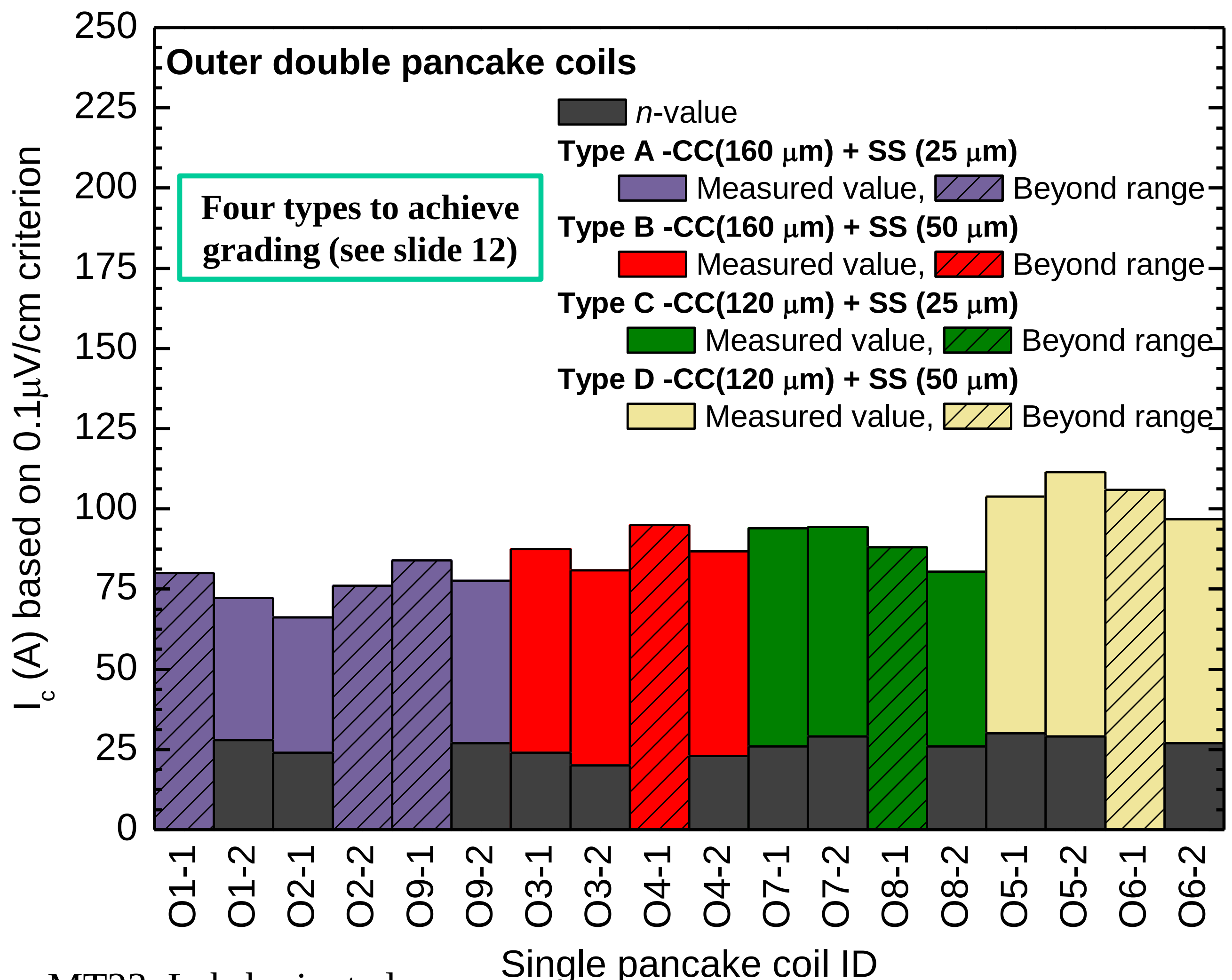
Critical current (1 μV/cm)



Two single pancakes powered in series.

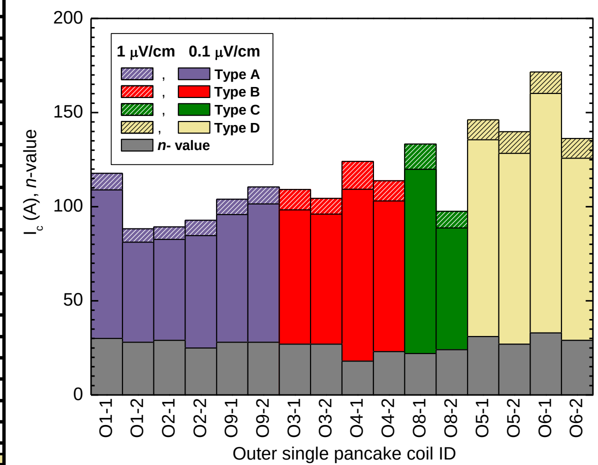
77 K Test of a Series of Double Pancakes (outer)

Two pancakes powered in series



MT23, Lakshmi, et al

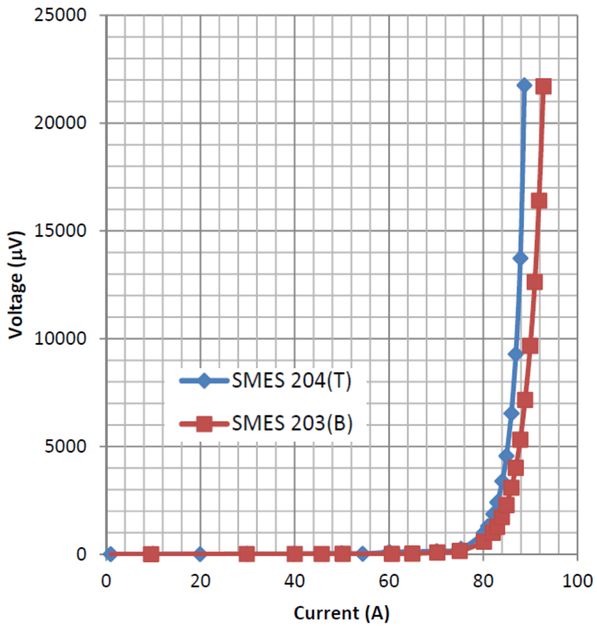
Single pancakes powered alone



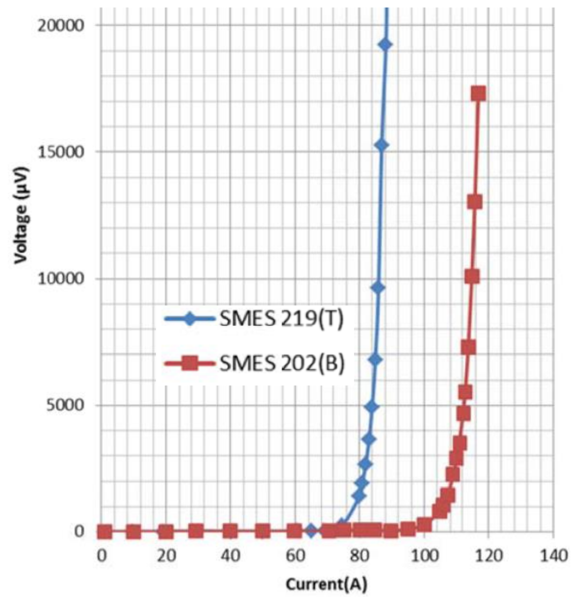
Higher I_c in coil at 77K , however, doesn't necessarily translate in to a higher I_c at 4K (present conductor)

Double Pancake 77 K Test

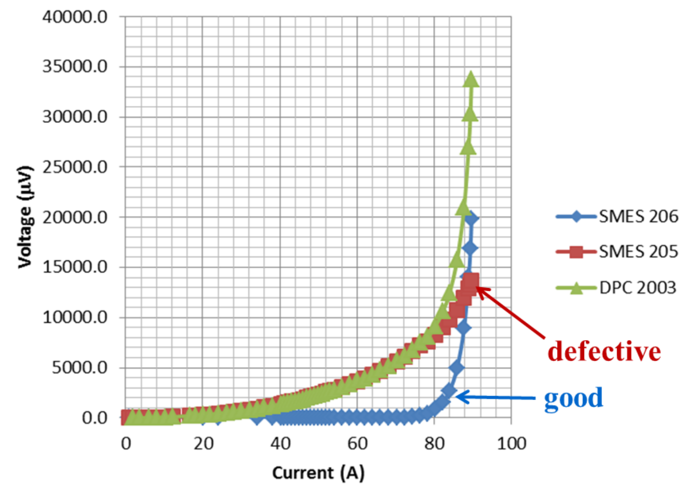
2 pancakes with similar critical currents

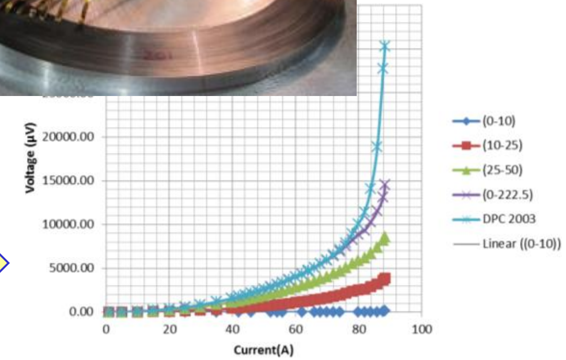


2 pancakes with very different critical current



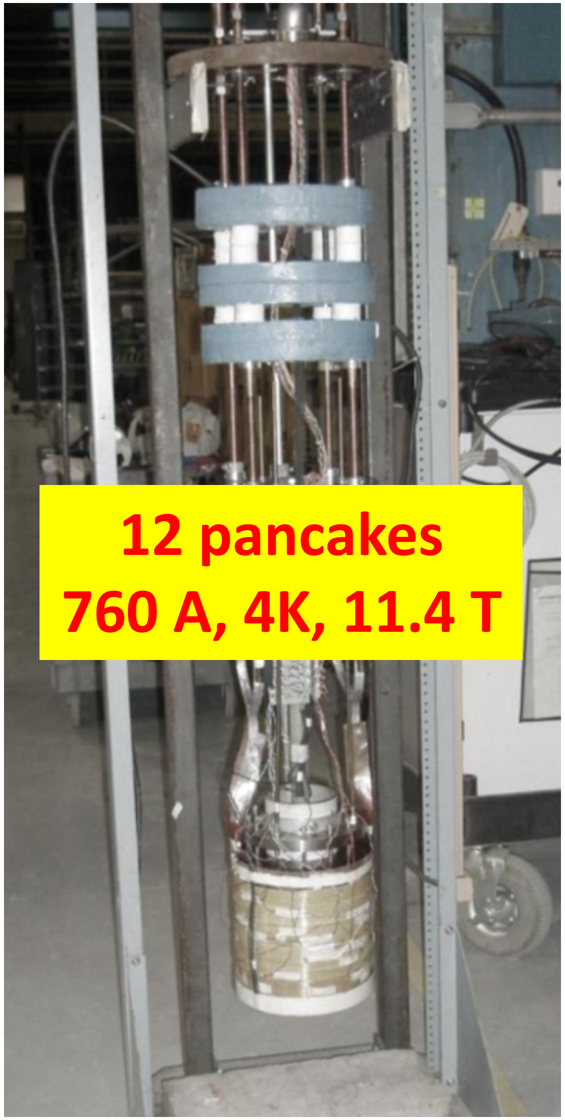
one pancake good and other pancake defective

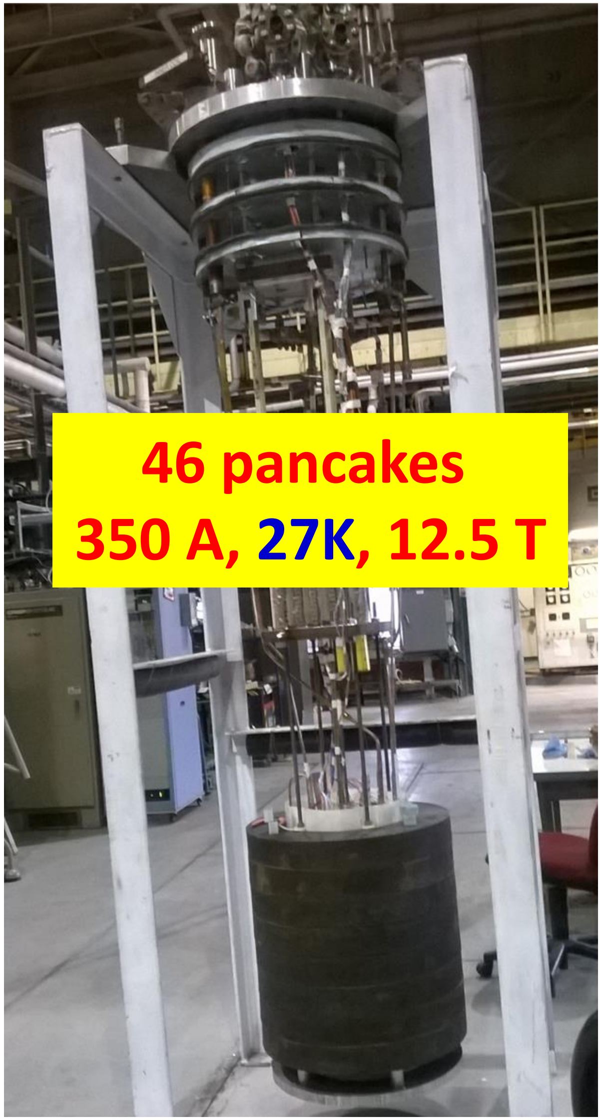




Note: Thorough 77 K test of each pancake was an important part of a series for QA

HTS SMES Coil High Field Tests

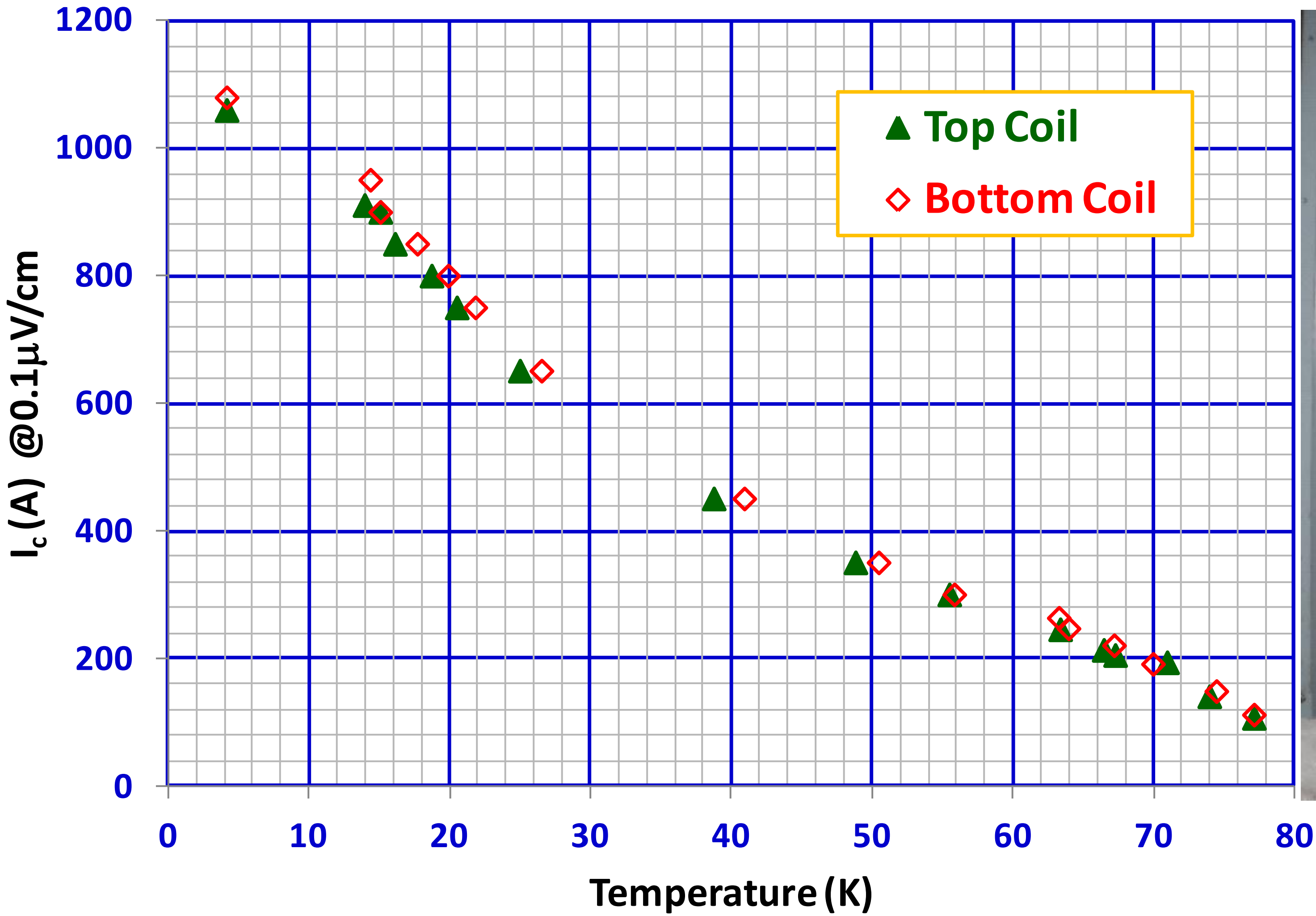


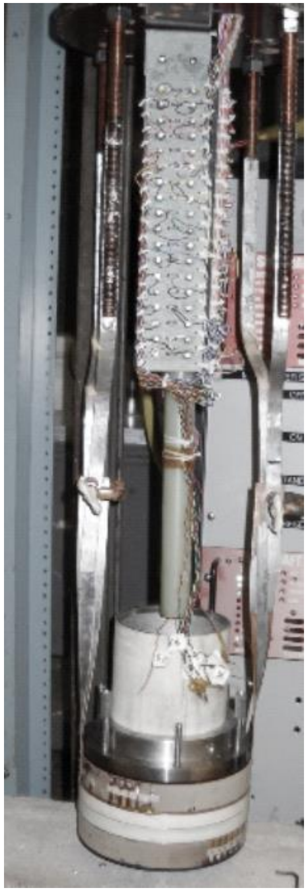


Peak fields higher

Double Pancake Coil Test

Nominal design current: ~700 A





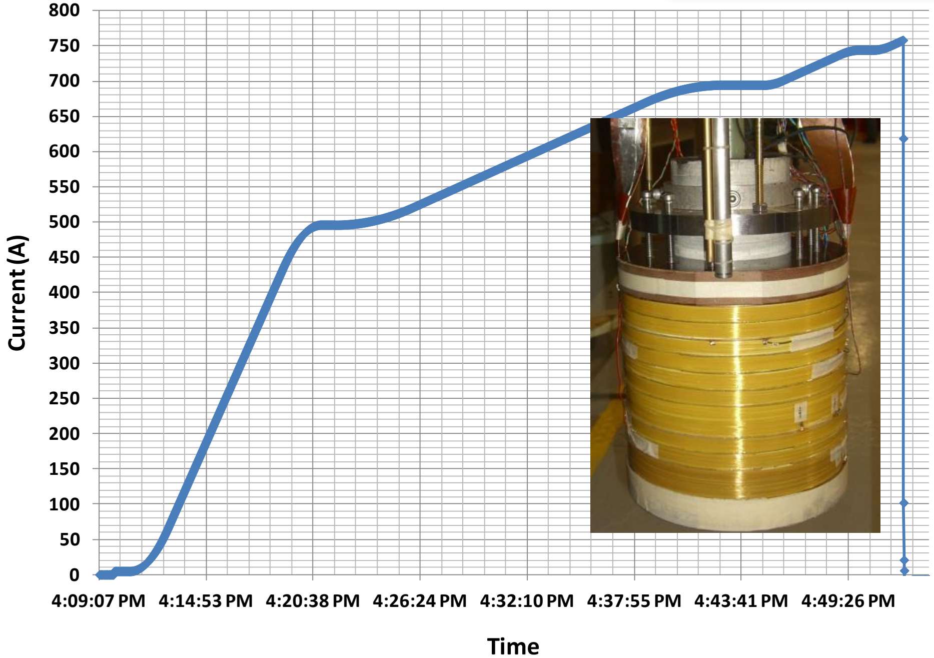
Ramp rate up to 10 A/s

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

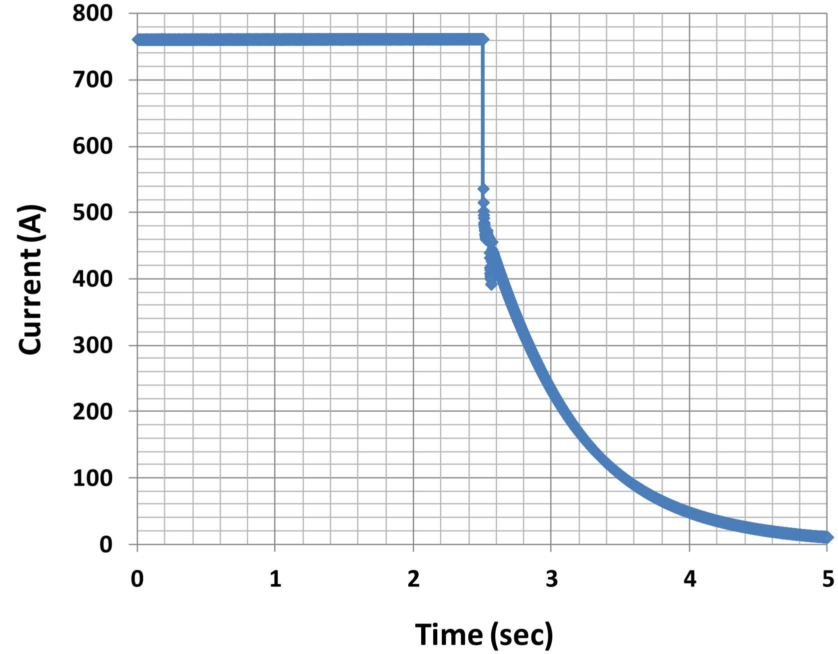
12 Pancake Coil Test

11.4 T in 100 mm bore

Charge

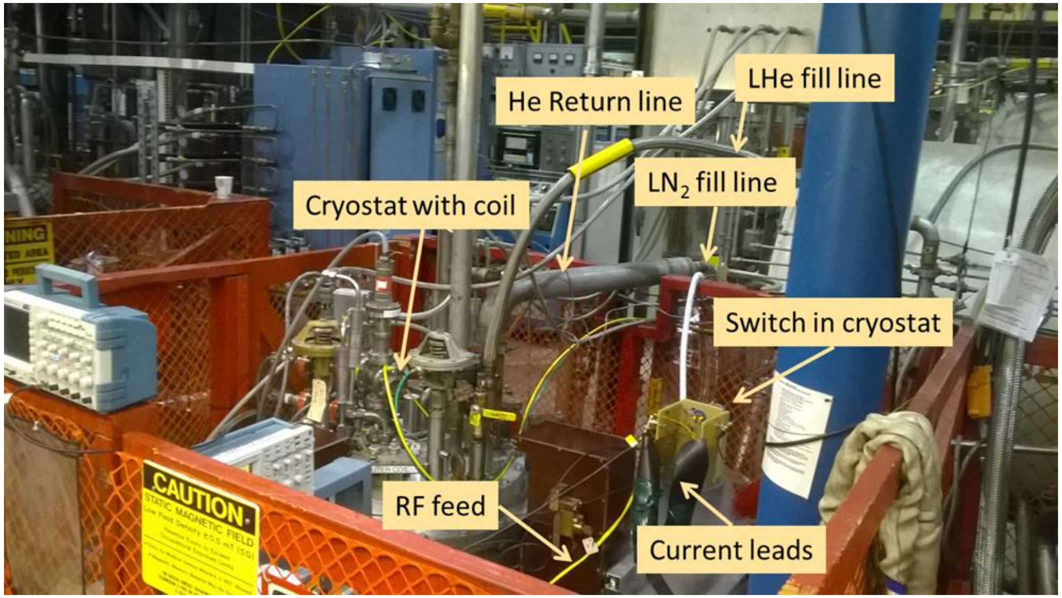


Quench

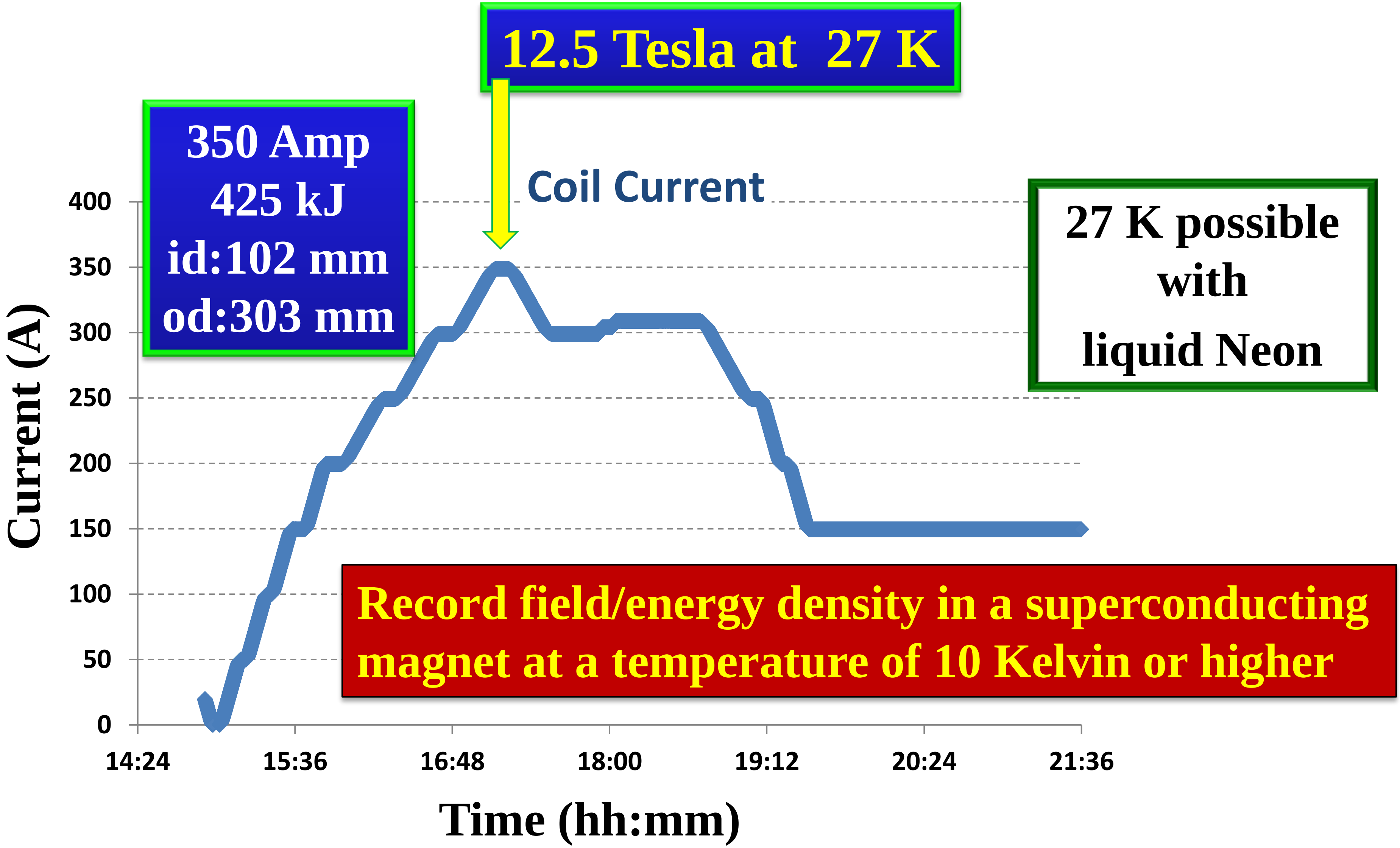


- Energy (~125 kJ) extracted and dumped in the external resistor.
- 77 K re-test (after quench) showed that the coil remained healthy.

Preparation for the Final Test



SMES Coil Run on 5/21/14



Status of ARPA-E SMES Coil

- **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 earlier magnet test current.**
- **This trip resulted in damage to a few current leads in the inner coil. It appears that there was arcing, perhaps during shut-off.**
- **Since the test was not limited by the field performance, the SMES coil still has the potential to reach higher field after repair.**

Quench Protection

BNL HTS Quench Protection Strategy

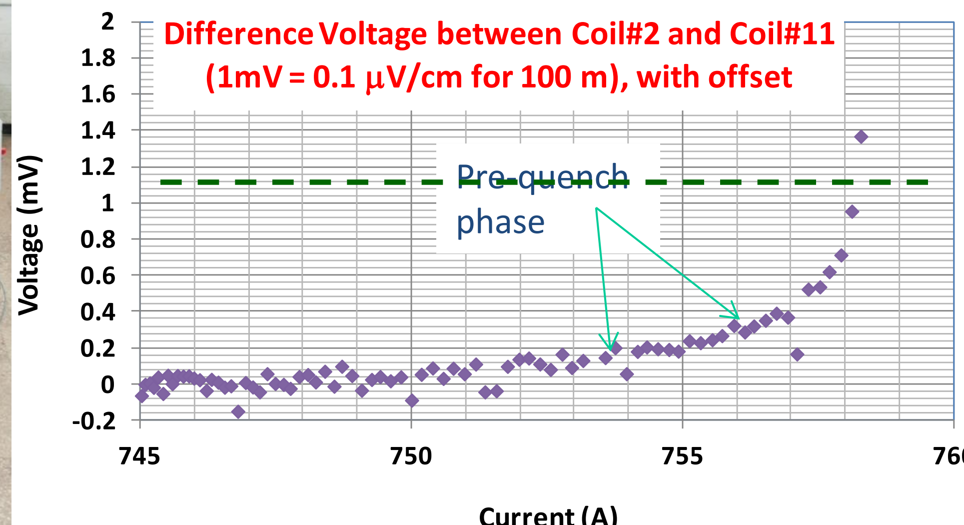
Superconducting Magnet Division

A multi-pronged strategy developed and used at BNL in various HTS programs:

- **Detect early and react fast with an advance quench protection system**

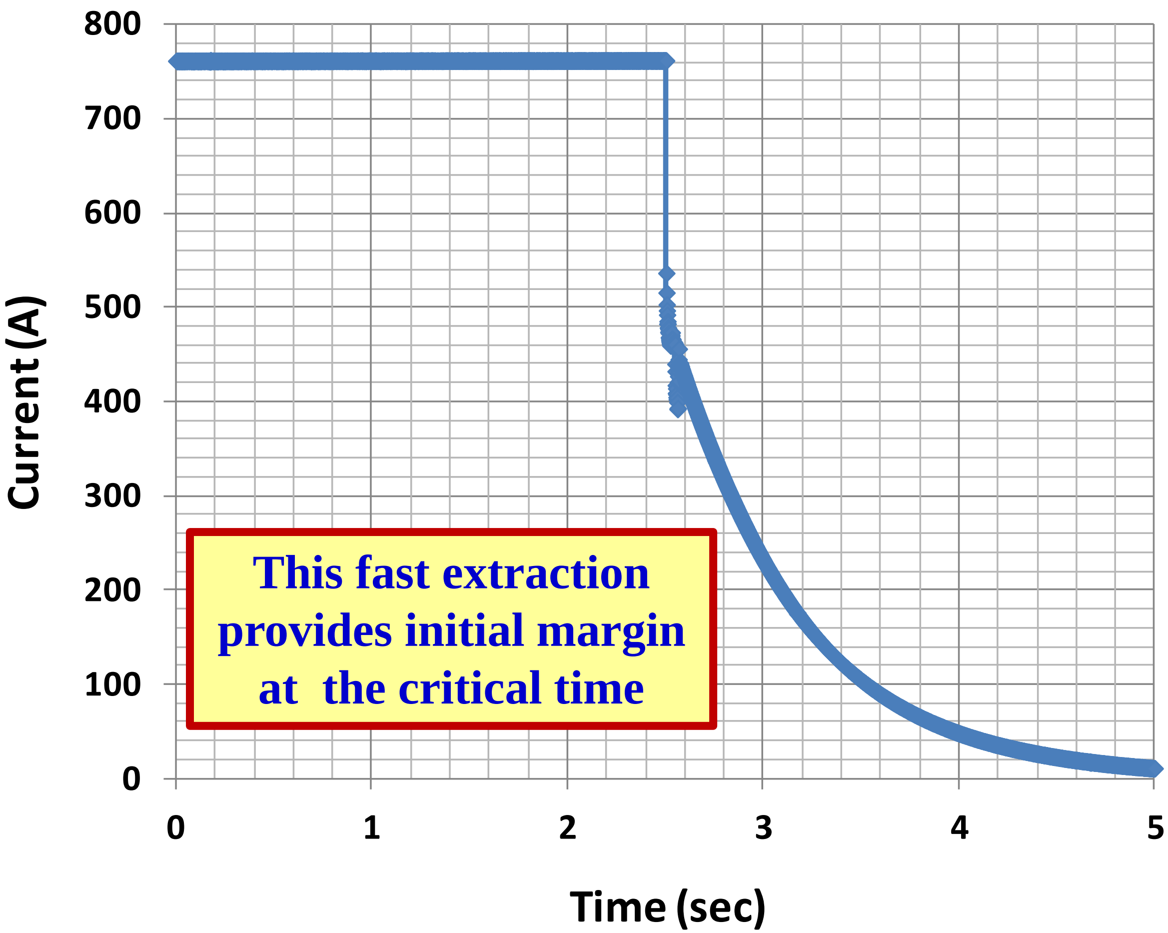
1. **Developed an advanced low-noise electronics and noise cancellation scheme to detect pre-quench voltage (phase) where HTS coils can operate safely**
2. **Fast energy extraction with electronics to handle high isolation voltage (>1kV)**
3. **Use inductively coupled copper discs for fast energy extraction**
   - **Drawback: additional energy loss during charging and discharging**

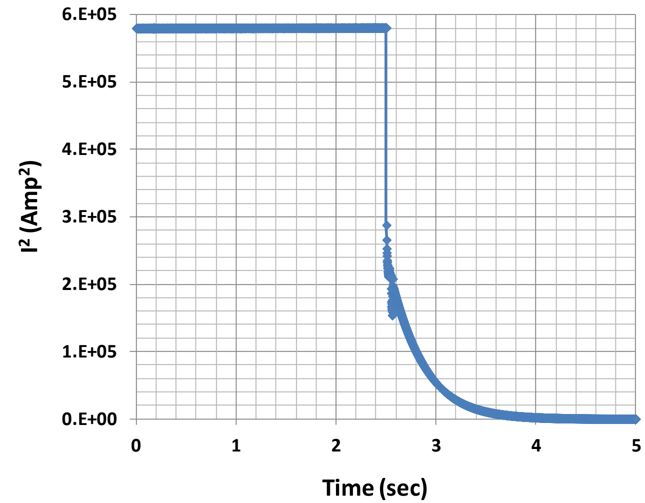
Twelve coil test at 4K (~12 T, ~120 KJ)

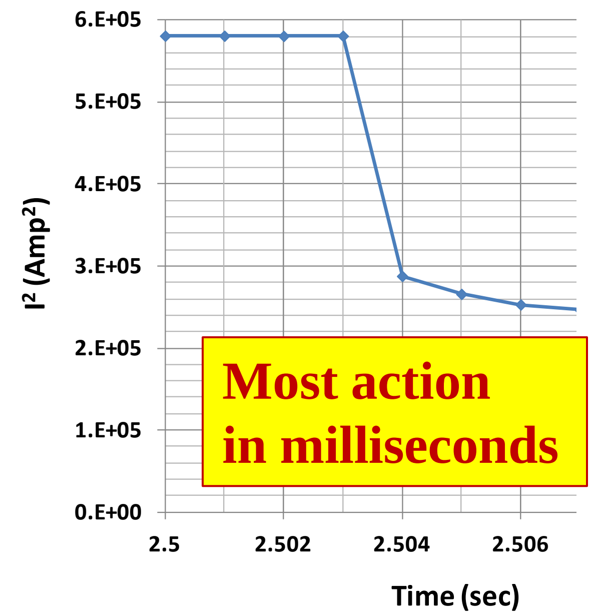


Copper Discs for Energy Extraction

Inductively coupled cooper discs between two double pancakes







SUMMARY

- **Even though we didn't reach the aggressive design goal of 25 T, in a big aperture (~100 mm) superconducting magnet with large hoop stresses (~400 MPa) in the first attempt, we did learn several things in the process beside creating new records.**
- **This provided a significant experience in using a large amount of coated conductor (over 6 km of 12 mm wide tape) in a demanding 4K, high field and a high stress application.**
- **Demonstration of a 12.5 T SMES coil at 27 K is a promising application of the coated conductor. The earlier most ambitious proposal was for 11 T at 20 K by Chubu Electric and Furukawa.**
- **The experience and technologies developed should also be useful in other applications, such as in NMR, ADMX, accelerators, etc.**