Design, Construction and Testing of a Large Aperture High Field HTS SMES Coil

R. Gupta, M. Anerella, P. Joshi, J. Higgins,
S. Lakshmi, W. Sampson, J. Schmalzle, P. Wanderer

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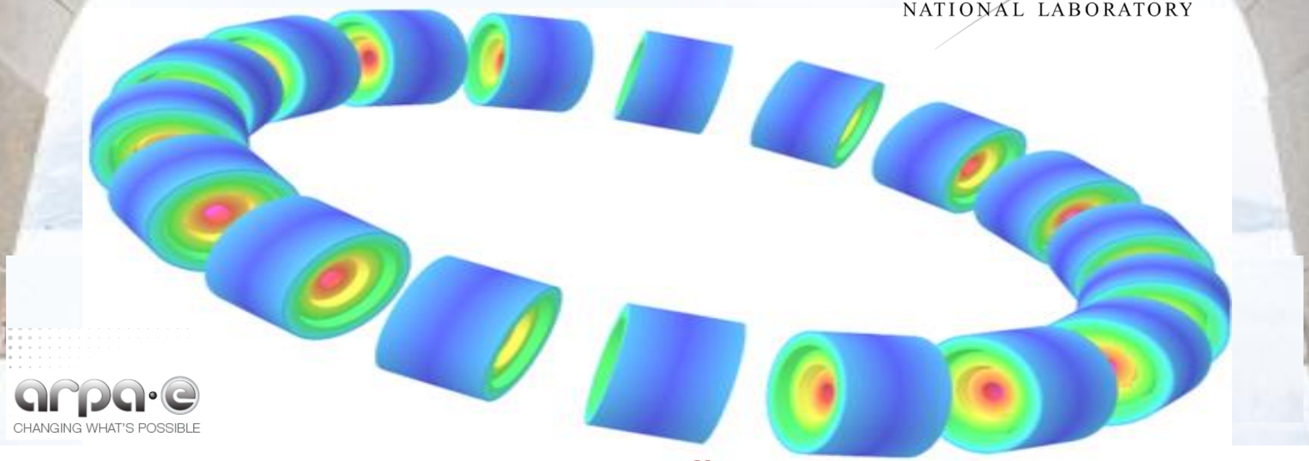

Overview

- Strategy for HTS based Superconducting Magnetic Energy Storage (SMES) Systems
- Design, Construction and Testing of SMES Coil
- Ground Breaking Results
- Summary – take away for future
- Acknowledgment

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Superconducting Magnet Division

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)**

Significant attempts:

LTS: 5 T, 4 K (BPA, USA)

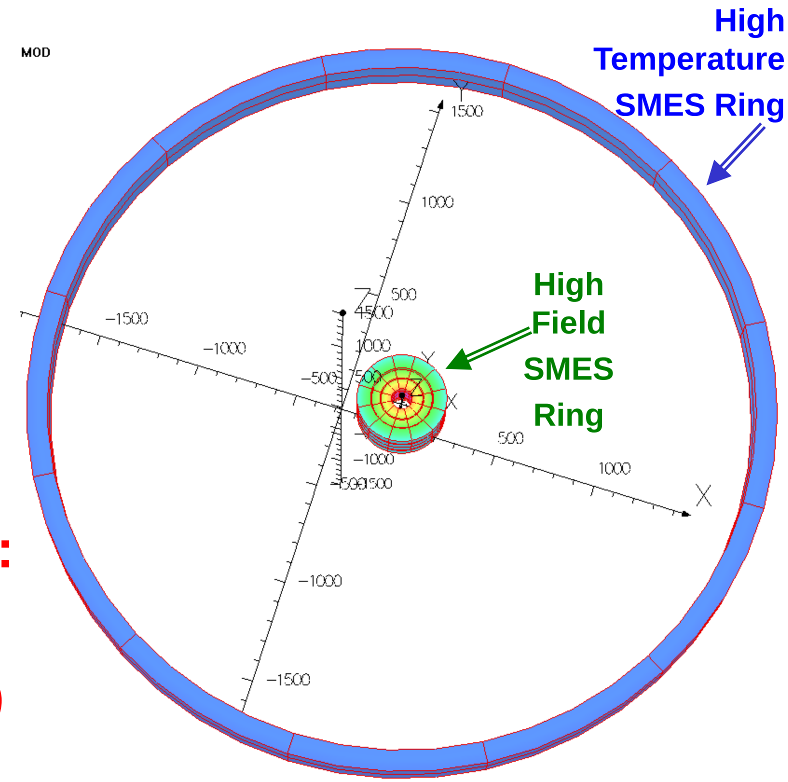
HTS: Medium field, high temperature

Cost analysis of HTS option:

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

High field 4 K HTS could be game changer:

- ✓ Very high fields: 25-30 T (E α B^2)
  - ❖ Only with HTS *(high risk, high reward)*

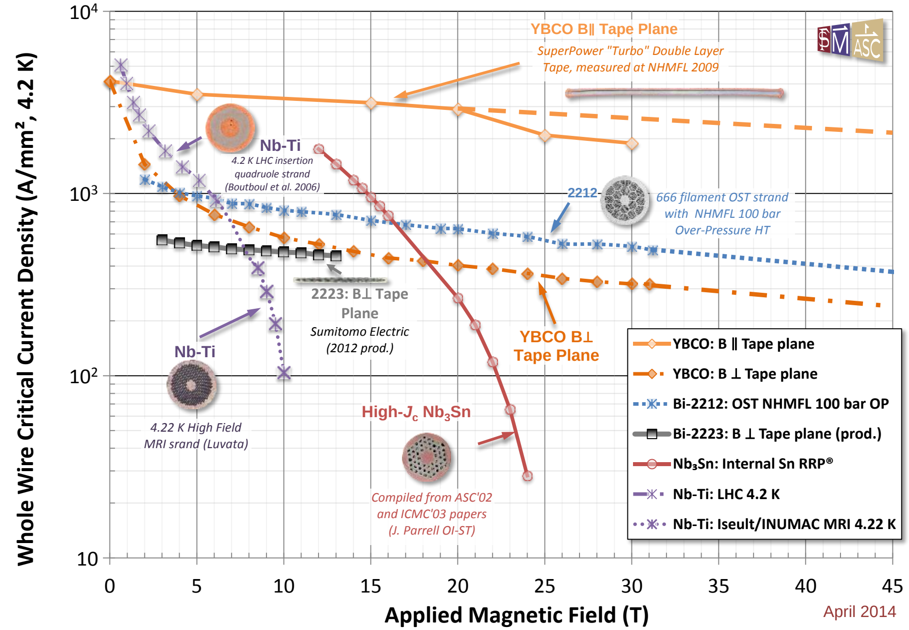


➢ **Also interesting: Medium field, medium temperature option (depending on the application and the future cost of HTS)**

Cost Considerations of HTS SMES for GRIDS

For large applications, amount of HTS used drives the cost. To reduce YBCO cost:

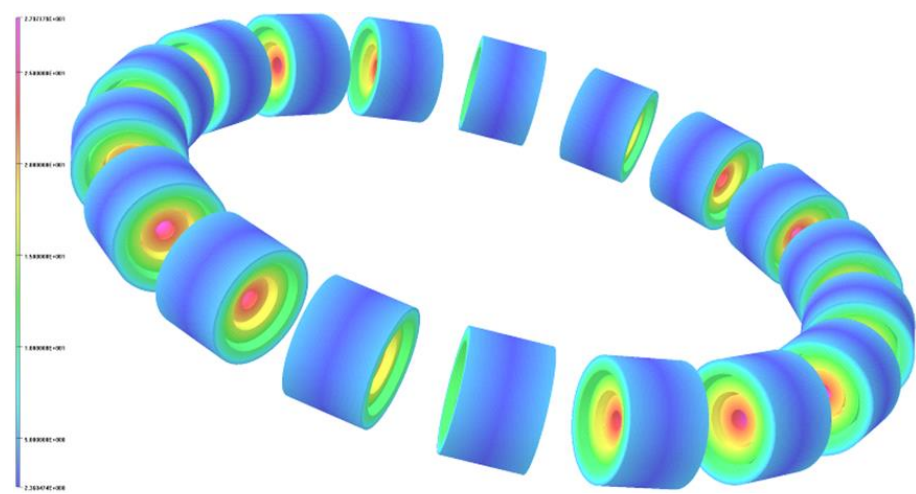
- **Design for field favorable direction (torus)**
- **Develop high field technology**
  - ➢ **In HTS, critical current falls slowly**
  - ➢ **Energy increases rapidly (as B^2)**



25-30 T large bore magnets would be really interesting but

High field HTS magnets pose huge challenges

- ➢ **Large stresses**
- ➢ **Quench protection**
- ➢ **New conductor**



Nothing like this has ever been done before !

Unique Opportunity

… 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

Such missions provide a unique opportunity

- **Even partial success breaks new grounds**

arpa·e CHANGING WHAT'S POSSIBLE ARPA-E: Advanced Research Project Agency - Energy

Superconducting Magnet Energy Storage System with Direct Power Electronics Interface

funded by arpa·e CHANGING WHAT'S POSSIBLE

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*

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

Focus of the Presentation

Technology for High field HTS SMES coil

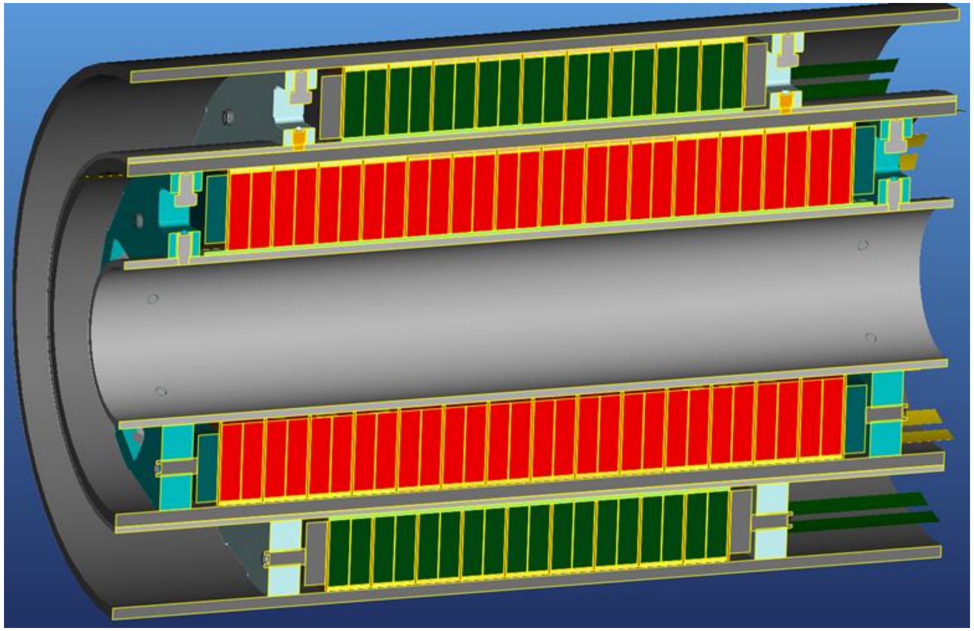
– Design, construction and test results

- For economic viability of a large scale energy storage system, cost of HTS must come down significantly

- The technology developed and demonstrated as a part of this project could already be applied to special purpose storage system and other applications

The Basic Demo Module

Aggressive parameters:



- Field: 25 T@4 K
- Bore: 100 mm
- Stored Energy: 1.7 MJ
- Hoop Stresses: 400 MPa
- Conductor: ReBCO

Amount of ReBCO used: >6 km, 12 mm wide

Significant use of HTS in a high field application

Guiding Principles

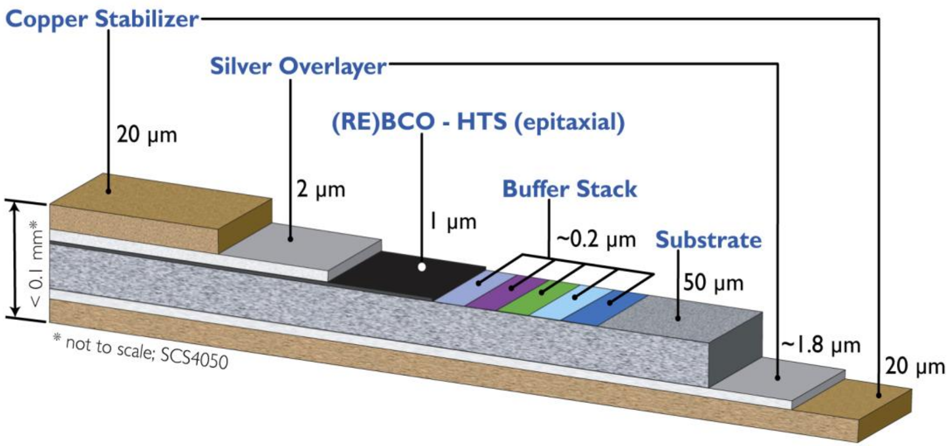
- High strength ReBCO tape with advanced pinning (SuperPower)
- Co-wind with stainless steel insulating tape for high strength
  - Stainless steel insulation also helps in quench protection
- Subdivide structure to keep stress accumulation within limit
- Use copper discs for uniform cooling and to reduce thermal strain
  - Copper discs also help in rapid energy extraction *after quench*
- Advanced quench protection system
- Strong QA with several intermediate tests (R&D conductor)
  - ✓ Each pancake was tested at 77 K
  - ✓ Intermediate high current 4 K tests

Conductor Specifications

SuperPower Inc. A Furukawa Company

12 mm wide tape with Hastelloy substrate

- ❑ Formal specs at 77 K
- ❑ Informal specs at 4 K

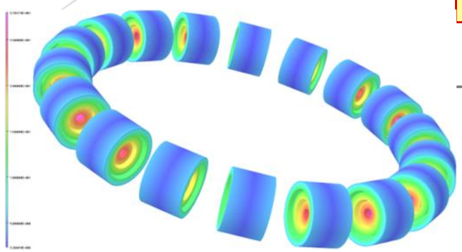


- Minimum I_c (@4K, 8T) : 700 A (irrespective of angle)
  - ➢ Significant variation in performance found

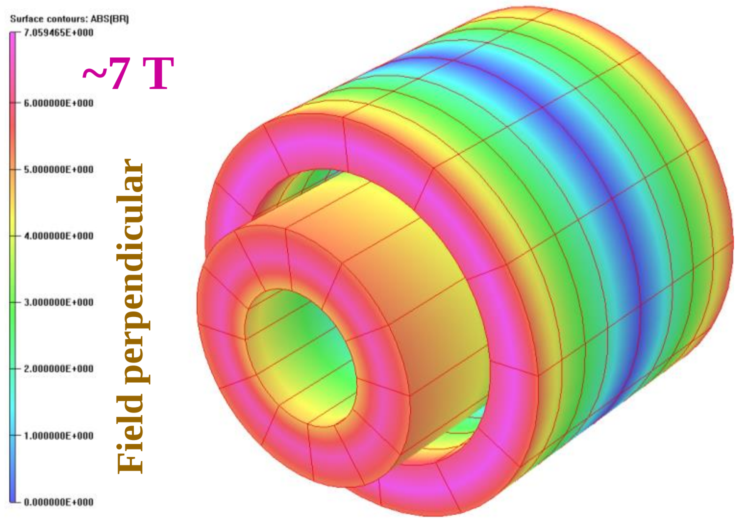
Cu: 65 µm and 100 µm

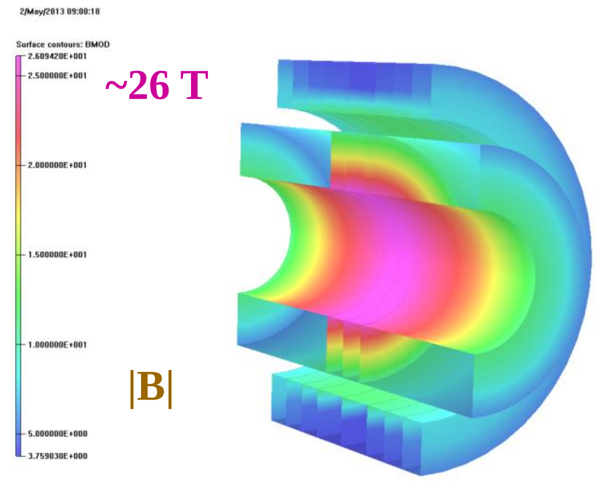
➢ Two values for electrical and mechanical grading

Design Optimization of Demo Module

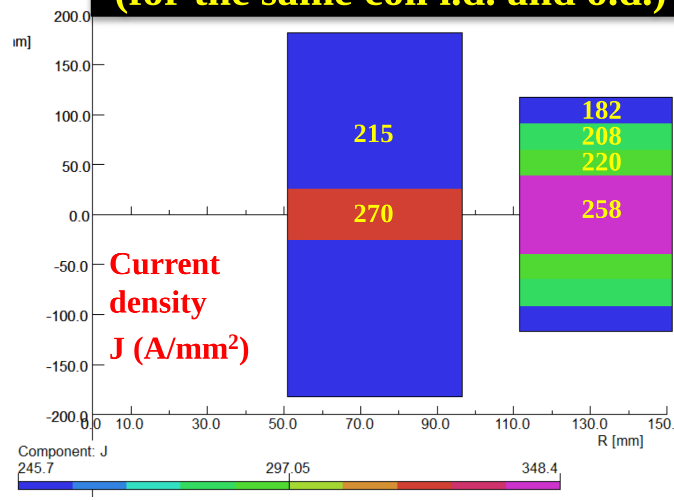


- In torus, field is primarily parallel in ends (higher I_c)
- In demo, outer coils are made shorter for that





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



Coil winding adjusted for grading:

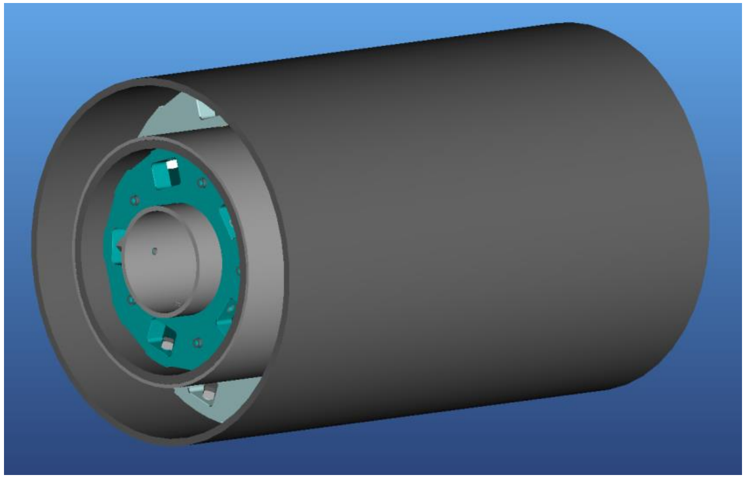
- Cu thickness in HTS tape (65 and 100 μm)
- SS tape thickness (65 and 100 μm)

(more copper in ends; more SS in center)

End Result : Improved performance

- Reduced $B_\perp$ and better mechanical structure

Mechanical Structure

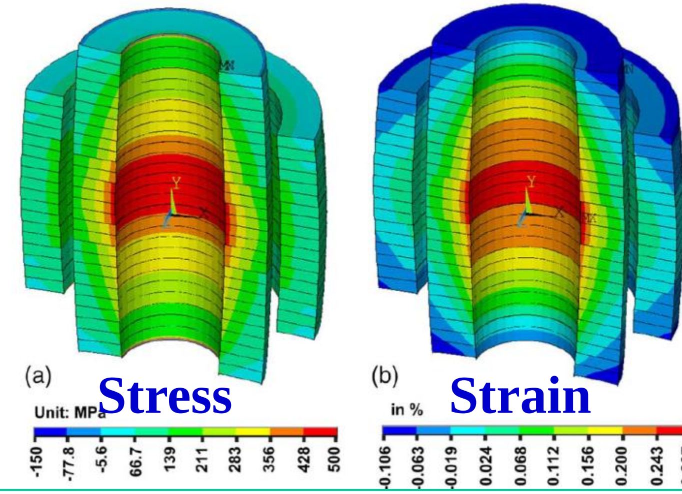


Stress

< 500 MPa

Strain

< 0.3%



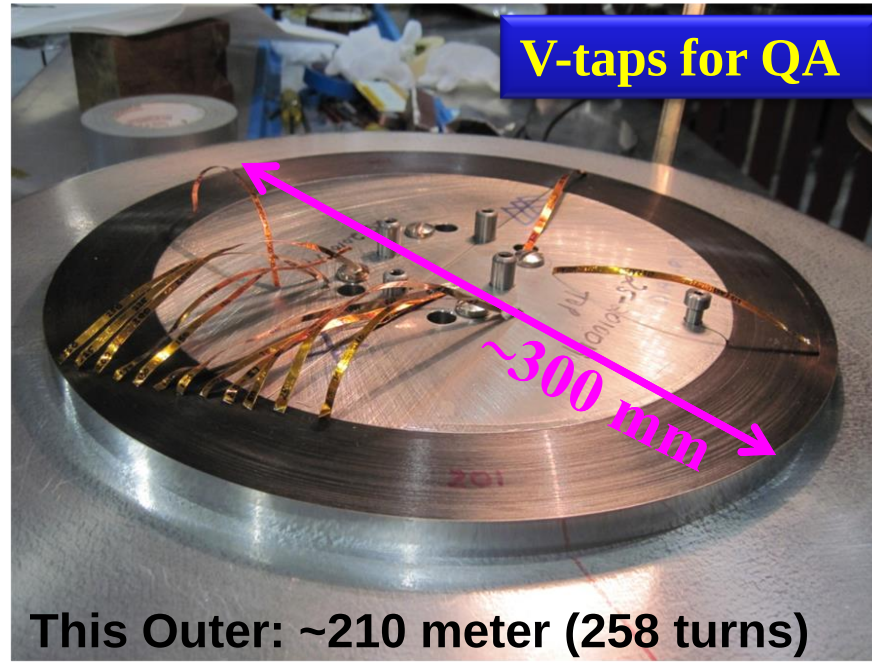
S.L. Lalitha and R.C. Gupta, "The Mechanical Design Optimization of a High Field HTS Solenoid"@ASC2014
Same principle as in PBL/BNL solenoid for Muon collider

- **Stainless steel tubes to contain the hoop stress**
- **The magnet was radially divided in two coil layers (inner and outer) with stainless steel tubes in between to reduce stress build up**
- **Use high strength conductor - ReBCO with Hastelloy substrate from SuperPower**
- **Co-winding with metallic insulation (Stainless Steel) rather than inorganic (Kapton) to increase the modulus of the coil**
- **Stainless steel thickness increased in the middle (high stress) area**
- **Parameters to keep the stress & strain (hoop and axial) below the conductor limit**

Coil Construction

(and quality assurance)

HTS Single Pancake



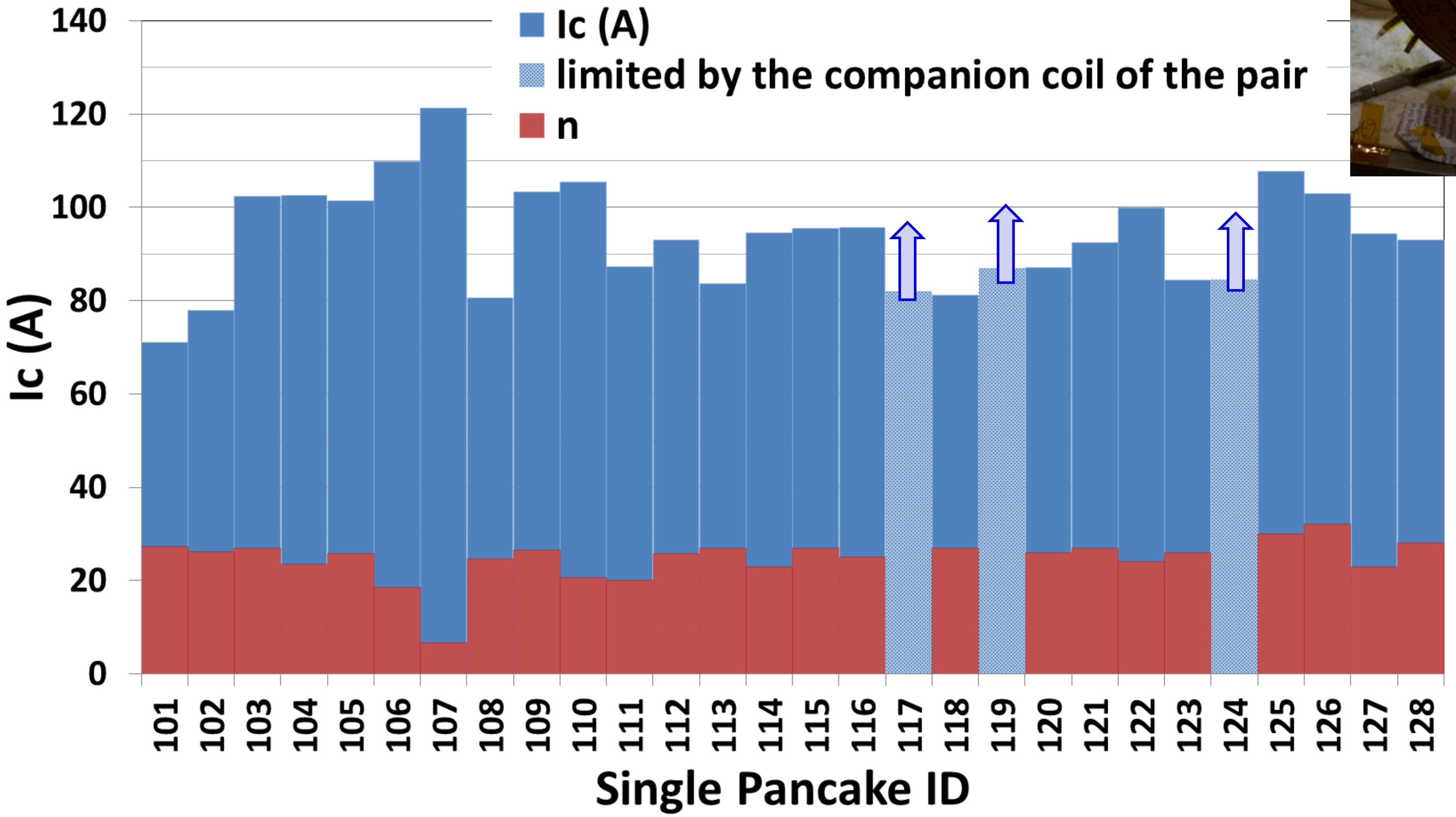
HTS is not a production conductor yet and it was treated that way

- **Conductor inspected physically during the coil winding**

- **Each coil was tested at 77 K with many v-taps to find significantly lower performing sections, if any**

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

Critical current (@1 μV/cm)



Two single pancakes powered in series

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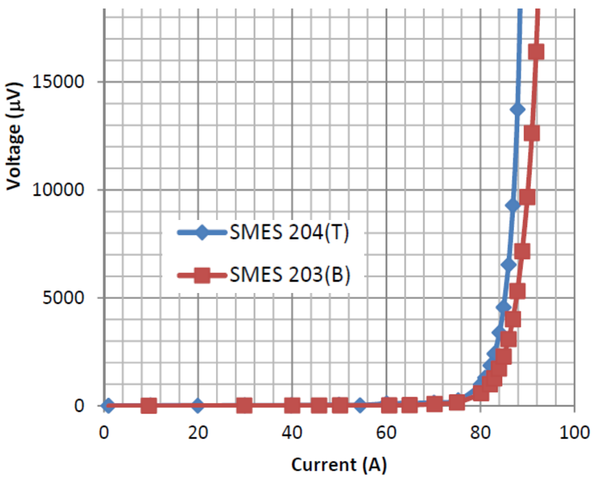
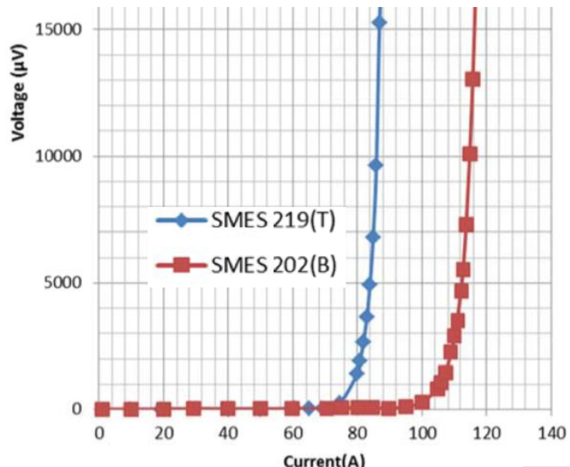
Double Pancake 77 K Test Results (3 types)

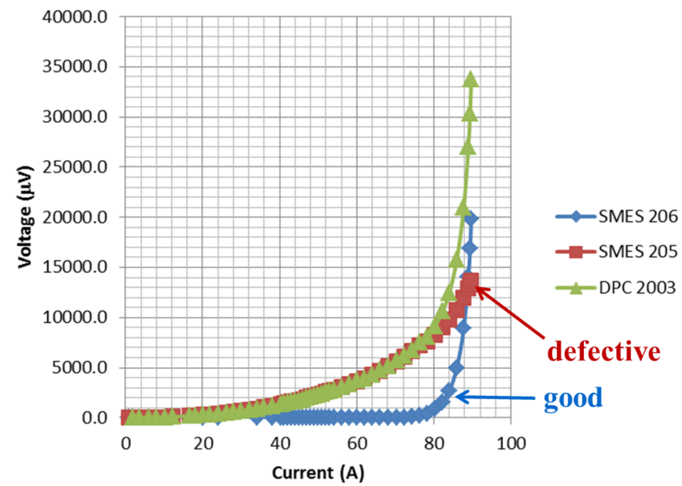
Pancakes with similar critical currents (I_c)

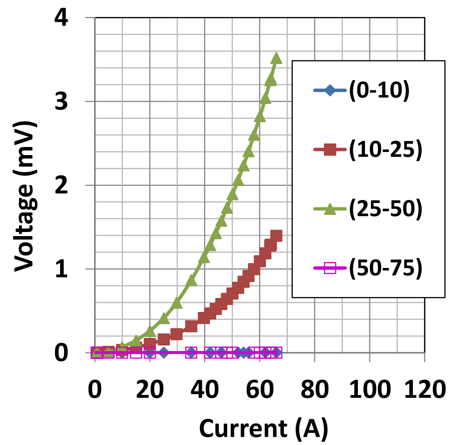


Pancakes with different Ic



One pancake good and the other pancake defective



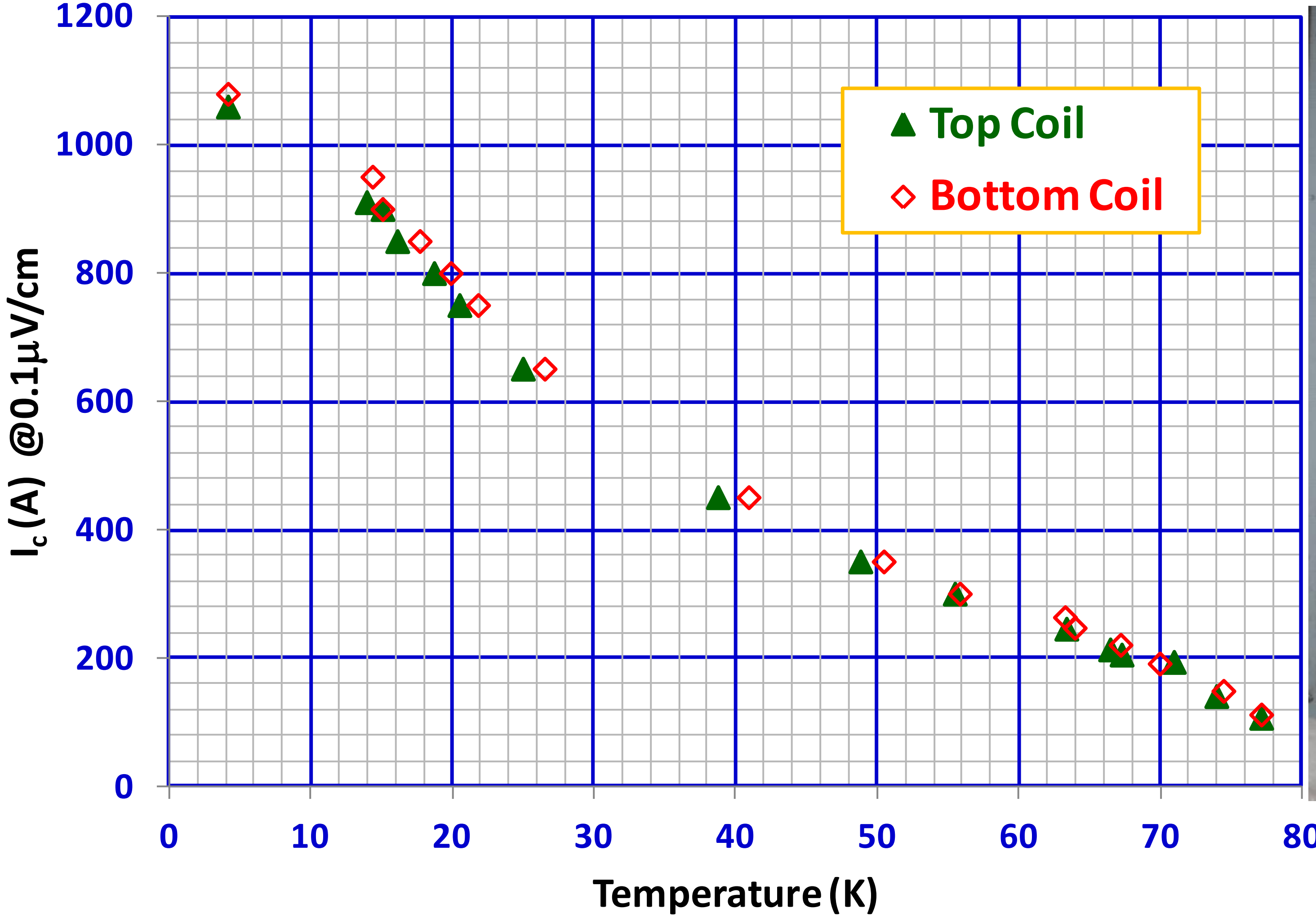


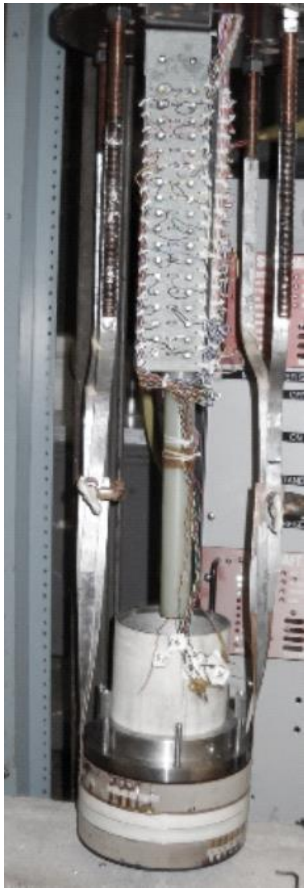
- **V-taps isolated the bad sections**
- **Importance of 77 K QA Test**

High Current Intermediate Tests

Double Pancake Coil Test

Nominal design current: ~700 A





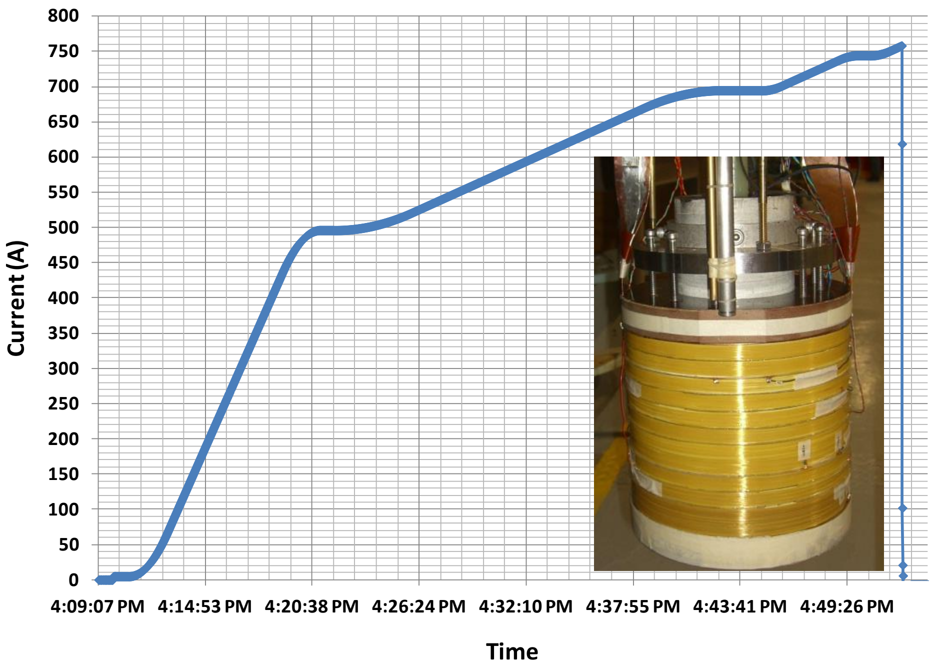
Ramp rate up to 10 A/s

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

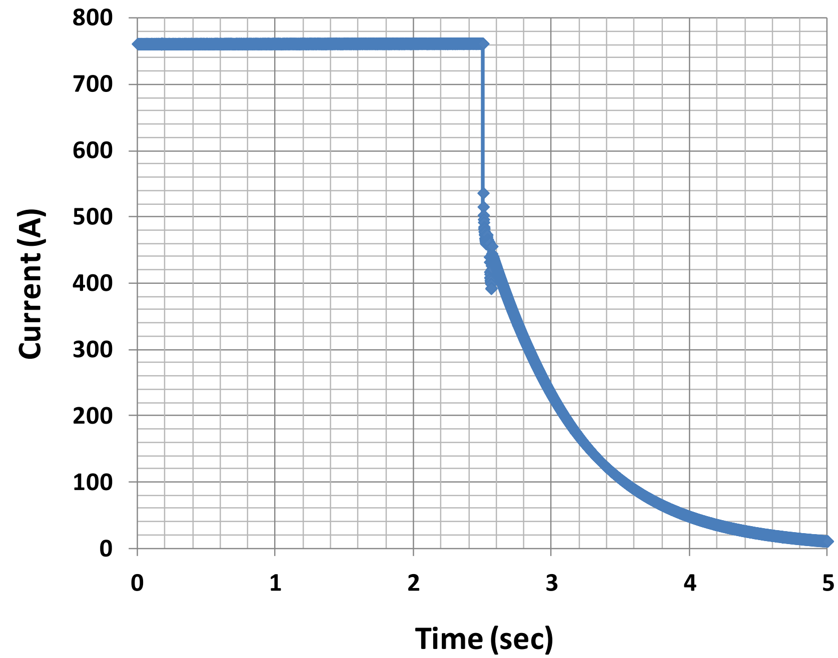
12 Pancake Coil Test

11.4 T in 100 mm bore

Charge



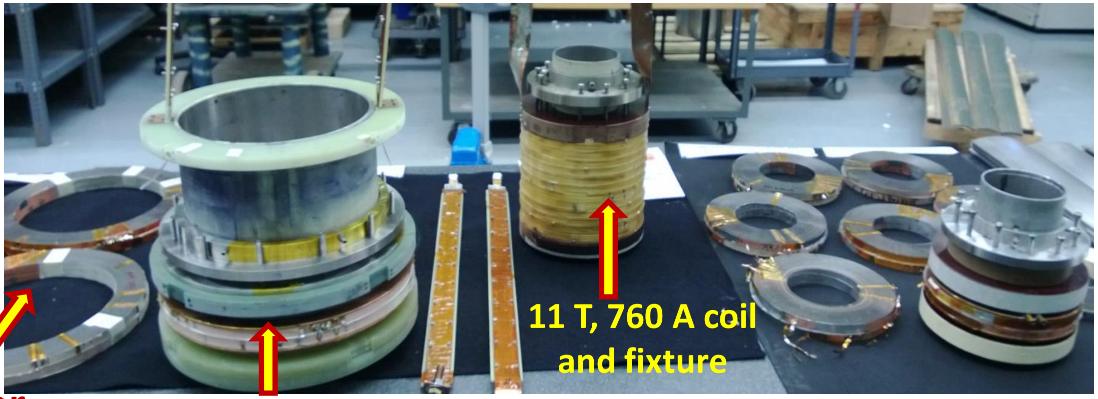
Quench



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

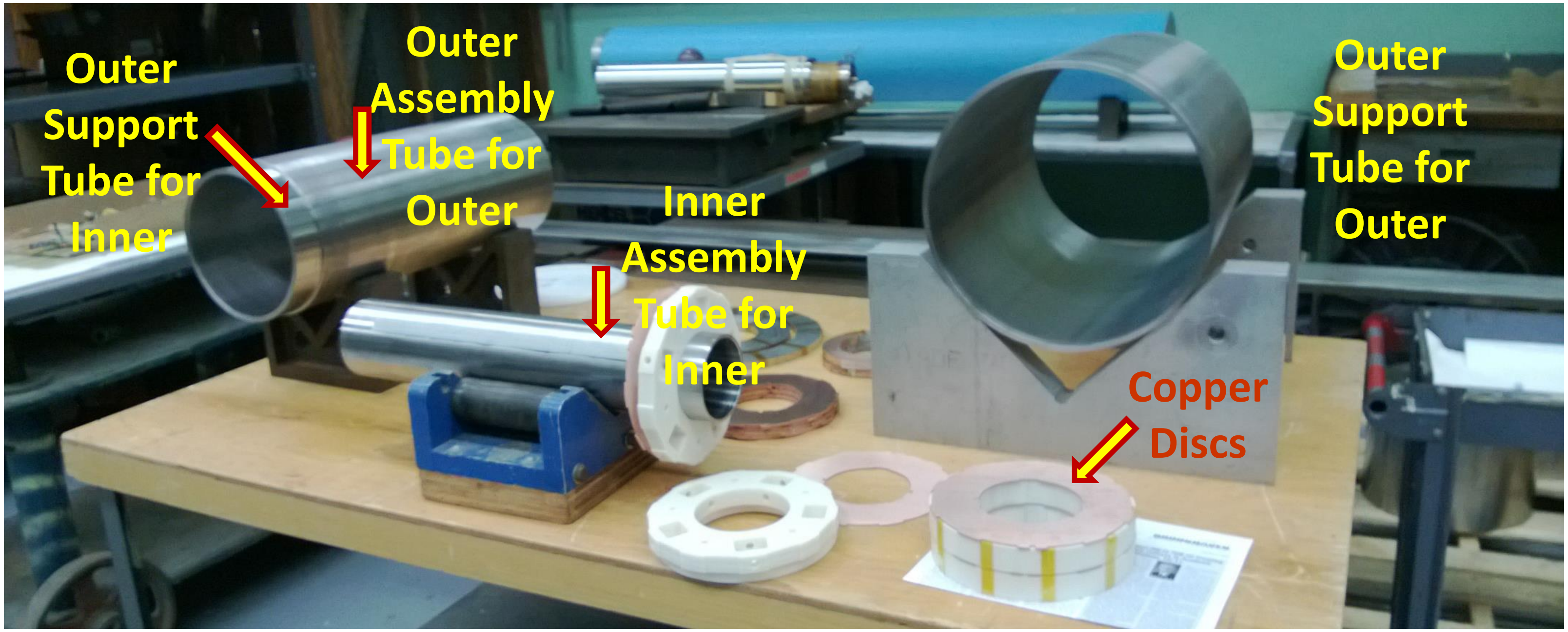
Final SMES Coil

Coils, Test Fixtures and Support Structure



Pancake coils: inner and outer

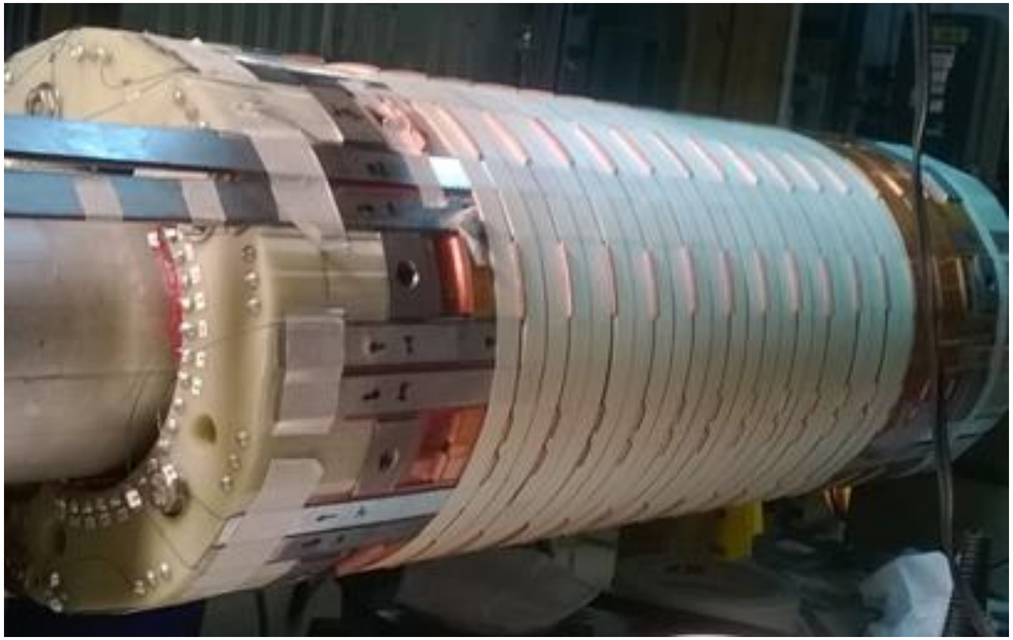
77 K Test Fixture for outer



Special Considerations

- **Tasks were challenging – no such device with design parameters near this (25 T, 100 mm, new R&D conductor) ever built.**
- **The program was on the fast track (3 years) with a limited R&D and a limited funding.**
- **This was not a normal technology development program with a series of tests planned. Project limits permitted one attempt only.**
- **Conductor was showing a significant variation in properties. One weak link in over 6 km conductor had a potential of limiting the performance of the entire system.**
- **We installed additional current leads to electrically bypass a weaker performing coil, if needed. The idea was to demonstrate maximum achievable field in one test run with minor adjustments.**

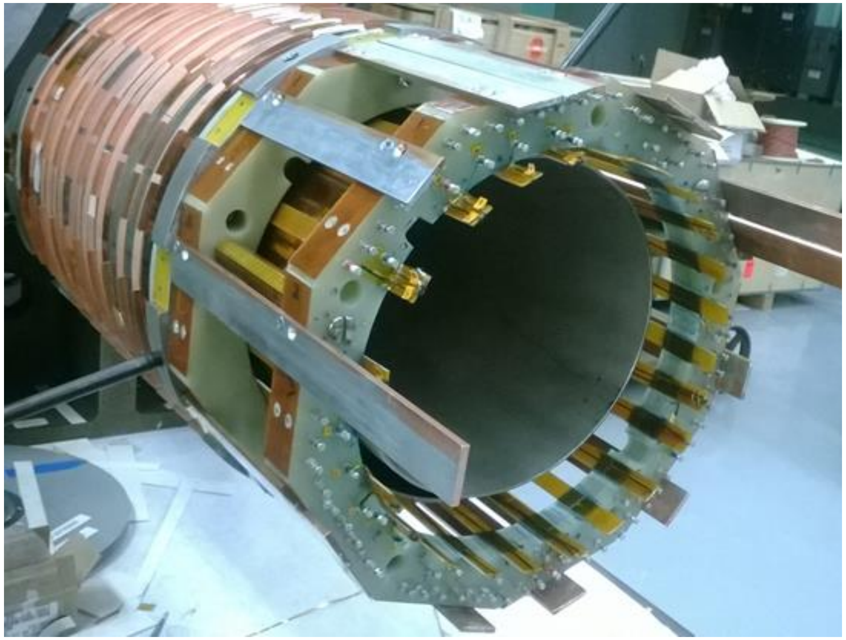
Inner and Outer Coils Assembled with Bypass Leads



Inner Coil

(102 mm id, 194 mm od)

28 pancakes



Outer Coil

(223 mm id, 303 mm od)

18 pancakes

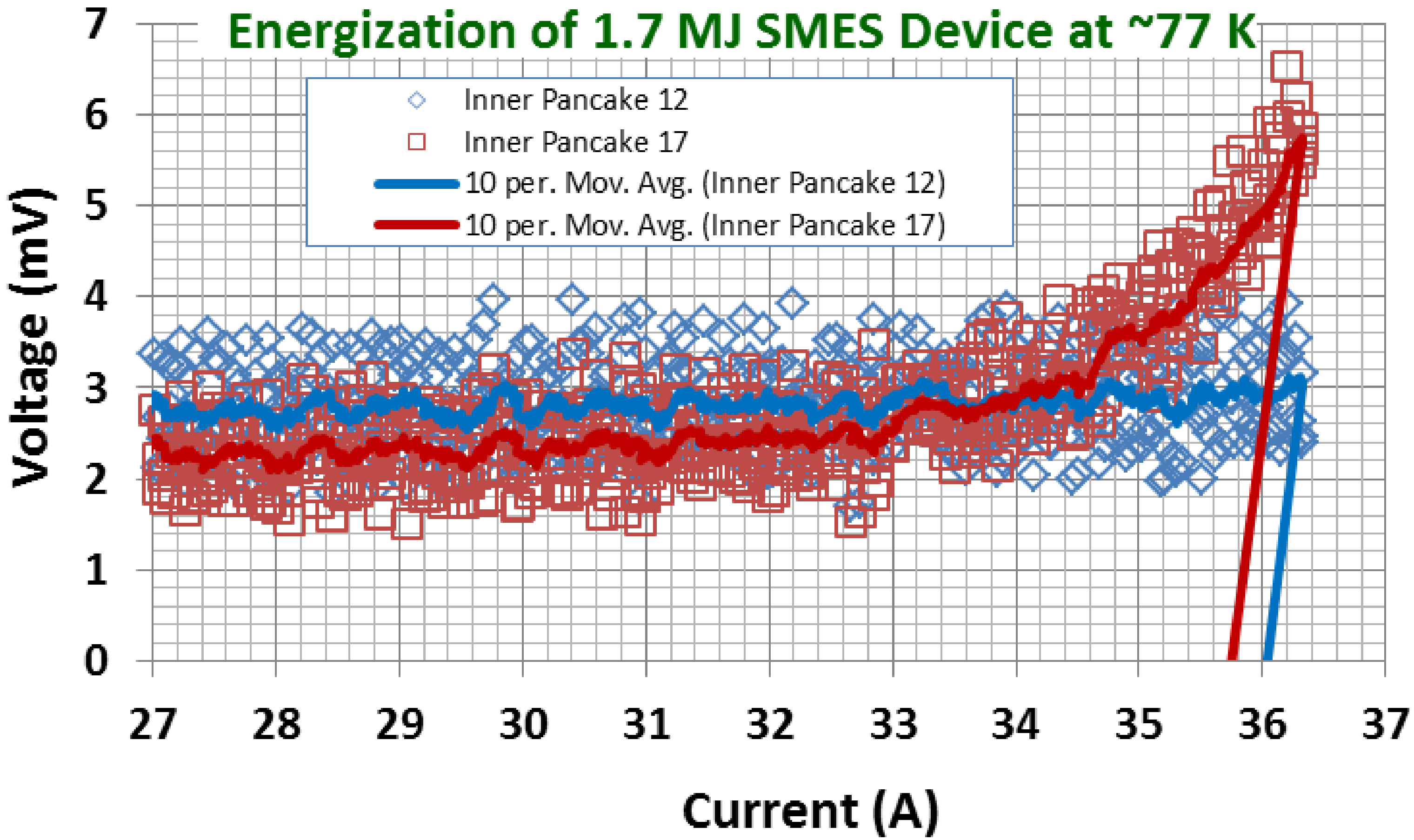
Total: 46 pancakes

Final Assembly

Outer inserted over inner coil

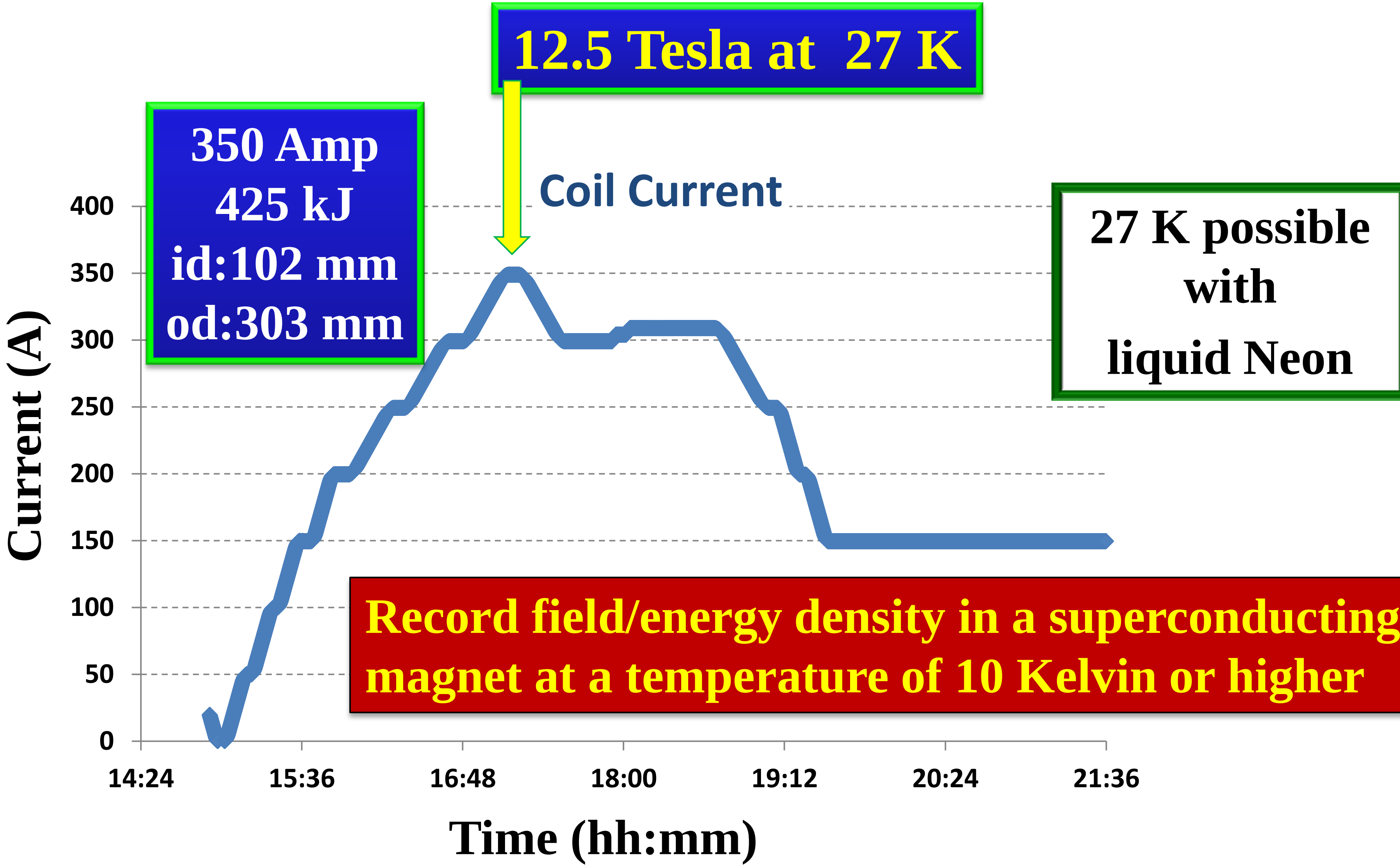
SMES coil in iron laminations

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 Test @50%
Critical Current Reached at 27 K



Record field/energy density in a superconducting magnet at a temperature of 10 Kelvin or higher

An Incident During the Test

- The ambitious design goal was: 1.7 MJ at ~700 A with 25 T at 4 K.
- We ramped the unit several times between 20-80 K. The test run at 350 Amp - 12.5 T at 27 K was already a record demonstration.
- During one such tests, the system tripped due to a data entry error at ~165 A – well below the current the coil was powered earlier.
- This trip resulted in arcing between two current leads in the inner coil and some damage. This was not part of the normal magnet construction. These leads were added to bypass weaker coil.
- The issue is not related to the high field HTS SMES technology.
- The coil still has the potential to reach higher fields after repair.

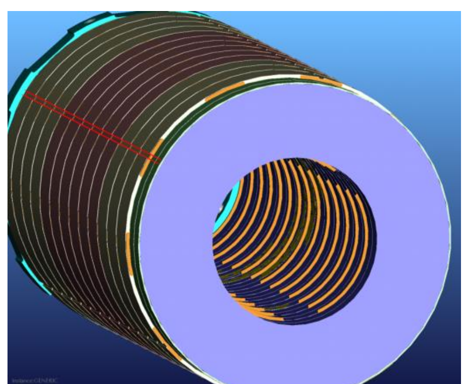
Quench Protection

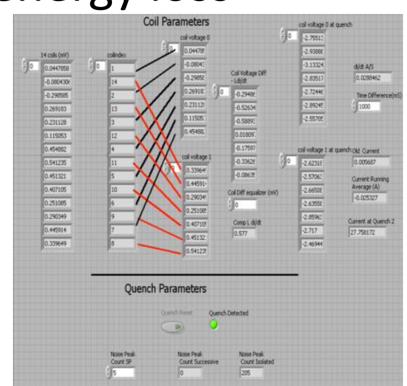
Quench Protection Strategy at BNL

BNL has relied on a multi-prong approach for quench protection in a large number of HTS coils/magnets built and tested to date

1. Stainless steel (metallic) turn-to-turn insulation to spread energy after the quench
2. Inductively coupled copper disks to transfer energy instantaneously out of HTS coils, heat up coils and reduce current to provide extra margin at a critical time
3. Sensitive electronics to detect resistive voltage quickly at the pre-quench phase
4. Fast energy extraction with electronics that can tolerate high voltage stand-off
5. Quench heaters, used in LTS magnets, could be used in HTS also (used at NHMFL)

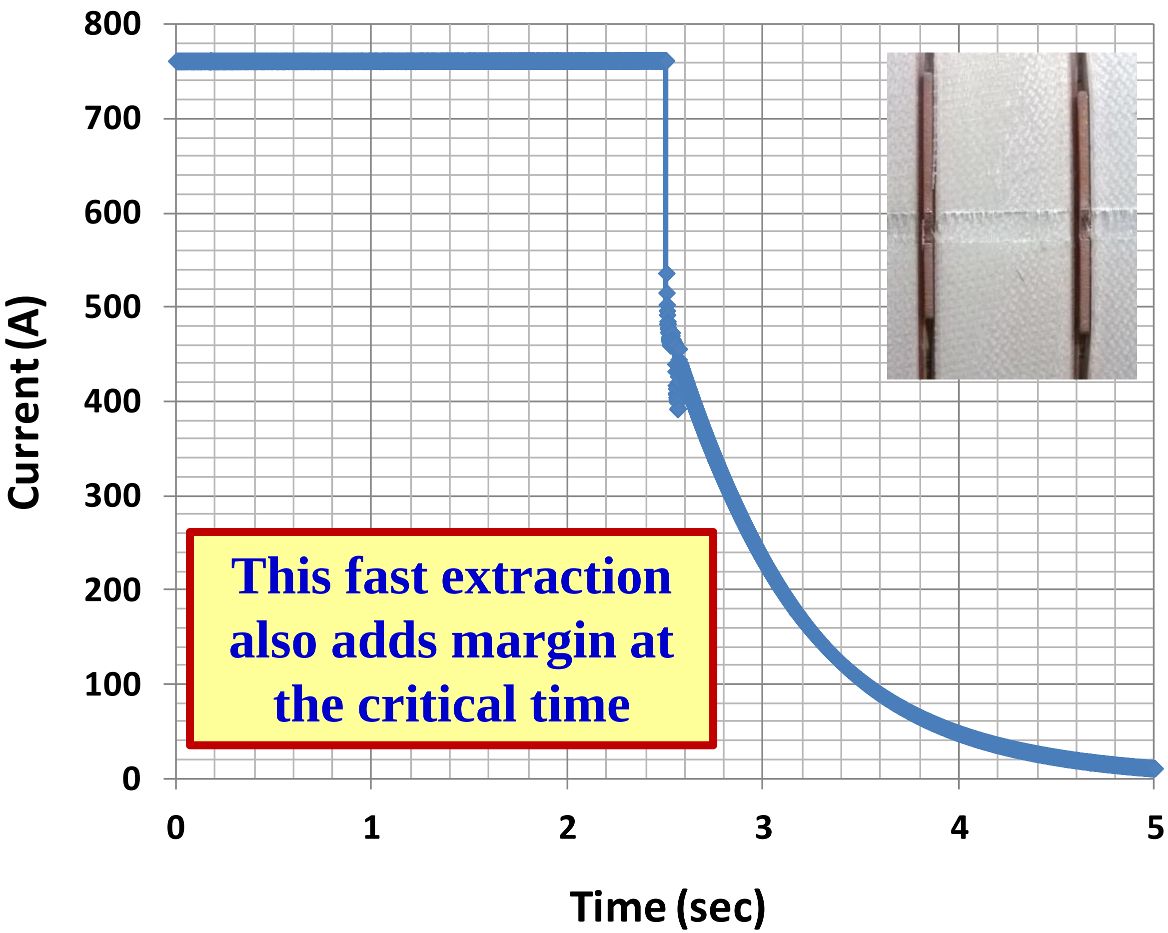
Note: Some of above methods are associated with energy loss



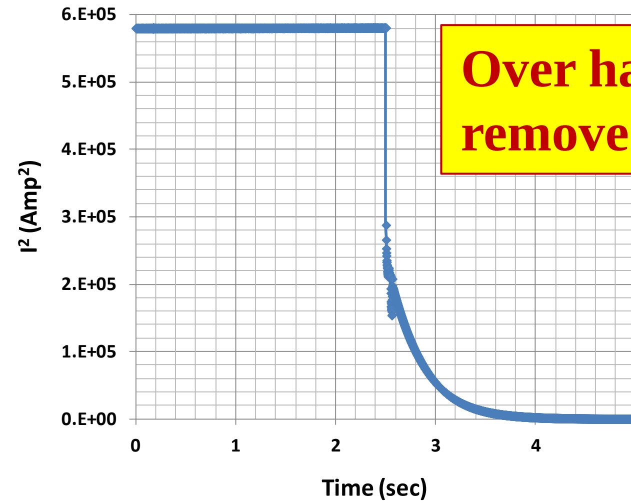


Copper Discs for Energy Extraction

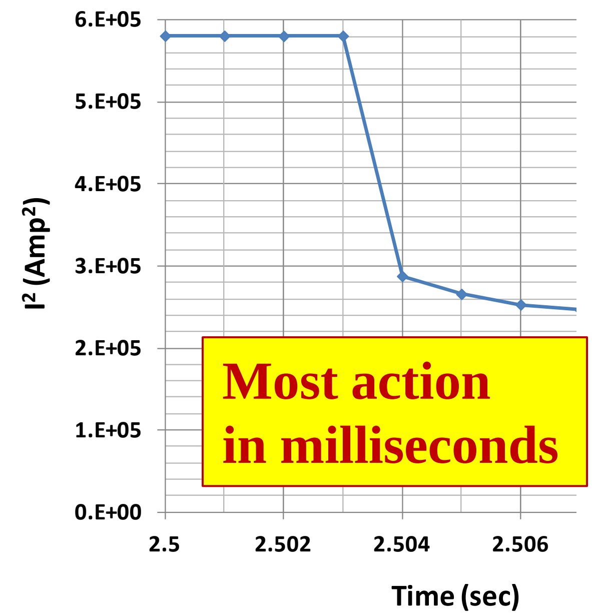
Inductively coupled cooper discs between two double pancakes



This fast extraction also adds margin at the critical time



Over half removed



Most action in milliseconds

SUMMARY

- ARPA-E SMES provided a unique opportunity for using a large amount of HTS (over 6 km, 12 mm wide SuperPower high strength ReBCO tape) in a demanding 4 K, high field magnet application.
- The goal of achieving 25 T, in a significant aperture (~100 mm) superconducting magnet with large hoop stresses (~400 MPa) and new material was too aggressive to be met in one attempt only.
- Demonstration of a 12.5 T SMES coil at 27 K is highly promising. It exceeded all previous demonstrations. This development should encourage special applications of medium field HTS SMES.
- The incident which terminated the test doesn’t reflect a limit of high field HTS technology. There is still significant potential.

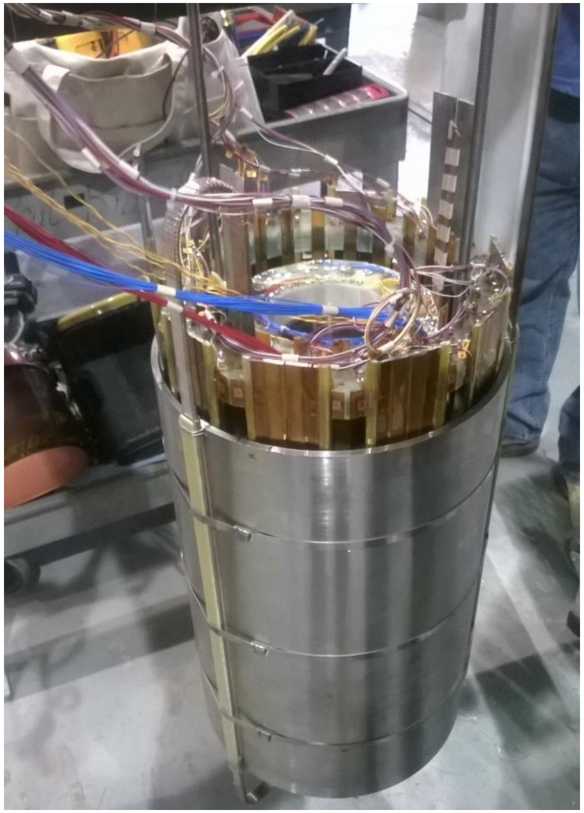
Acknowledgement

- **ARPA-E for providing funding for this "high-risk, high reward" R&D.**
- **VR V. Ramanan (PI for the SMES project) and Eddy Aelozolia of ABB for convertor and providing administrative support.**
- **BNL management for strong support to the development of quench protection system and success of the overall program.**
- **Qiang Li for initiating this collaboration. Qiang Li and Vyacheslav Solovyoy for the superconducting switch.**
- **BNL technicians Glenn Jochen, Sonny Dimaiuta, William McKeon, Ray Ceruti and high school/undergraduate student Eric Evangelou for winding HTS coils and helping in assembling and testing the SMES.**
- **Drew Hazelton (SuperPower) and Venkat Selvamanickam (University of Houston) for expertise and feedback on the High Temperature Superconductor.**

Backup Slides

Design Parameters of BNL Demonstration Coil

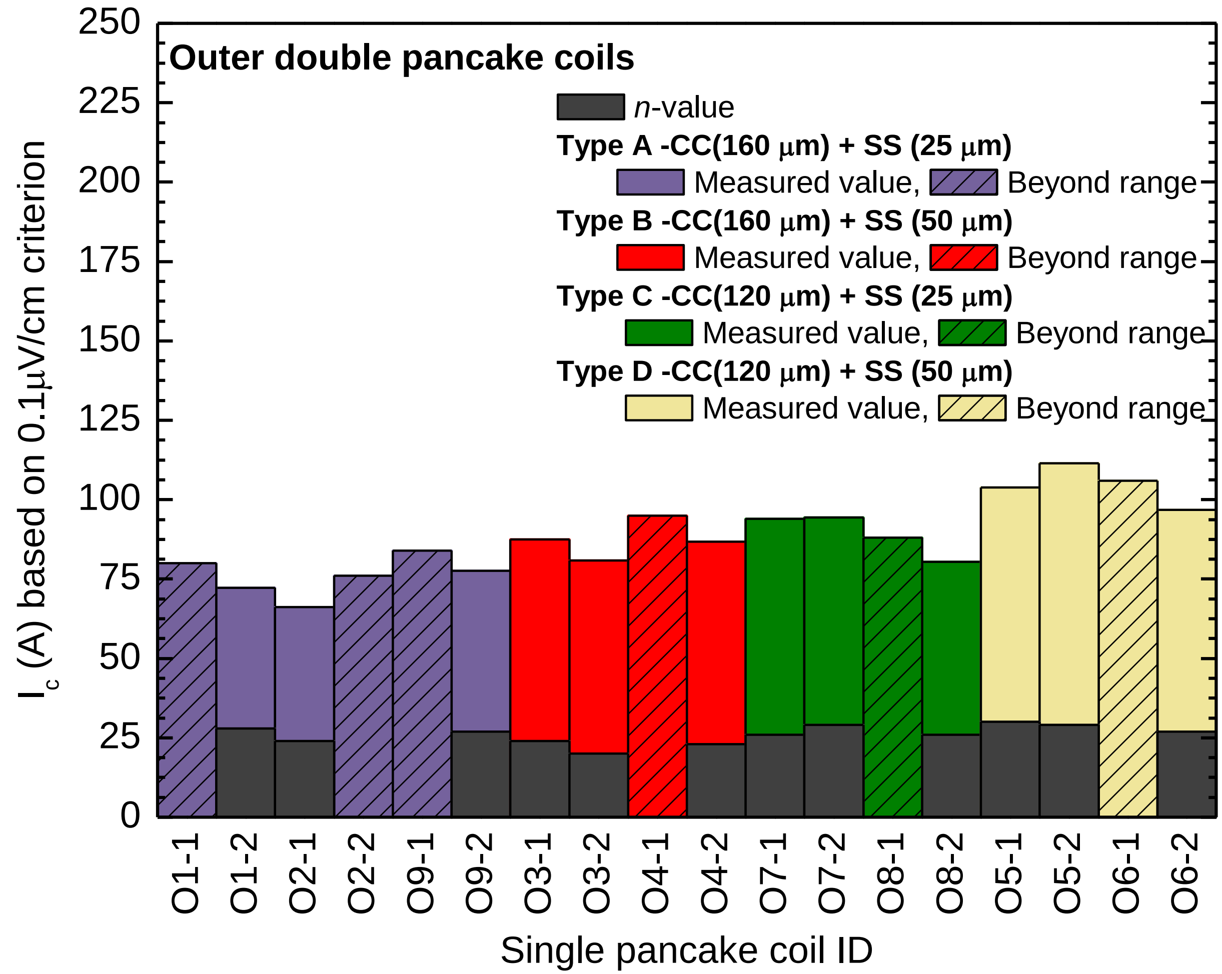
Stored Energy	1.7	MJ
Currrent	700	Amperes
Inductance	7	Henry
Maximum Field	25	Tesla
Operating Temperature	4.2	Kelvin
Overall Ramp Rate	1.2	Amp/sec
Number of Inner Pancakes	28	
Number of Outer Pancakes	18	
Total Number of Pancakes	46	
Inner dia of Inner Pancake	102	mm
Outer dia of Inner Pancake	194	mm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

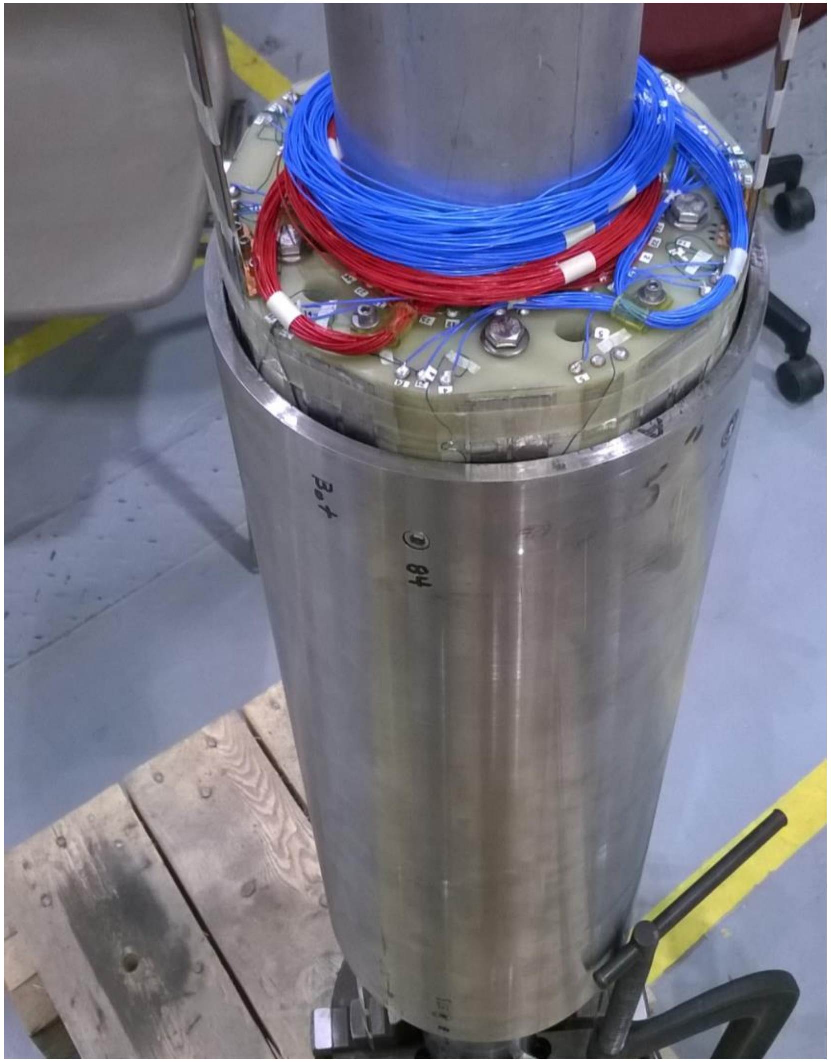
77 K Test of a Series of Double Pancakes (outer)

HTS coils are 100% cold tested at 77 K as a standard QA in all HTS Magnet programs at BNL



S.L. Lalitha, W.B. Sampson and R.C. Gupta, "Test Results of High Performance HTS Pancake Coils at 77 K," presented @MT23

Inner and Outer Coils



Inner (in support tube)

Outer (prior to support tube)

Preparation for the Final Test