BROOKHAVEN NATIONAL LABORATORY

Superconducting
Magnet Division

Brookhaven HTS Solenoids

Ramesh Gupta

April 13, 2018

ADMX Magnet Workshop

Friday, April 13, 2018 from **08:30** to **17:10** (US/Central)
at **Wilson Hall (Hornet's Nest)**

Relevance of BNL High Field HTS Magnet Program to ADMX

- ADMX needs large aperture, high field solenoid. Next upgrade must use High Temperature/Field Superconductors.
- For a decade, BNL has been working on high field HTS solenoids.
- For about five years, BNL HTS program has been dedicated to the large aperture, high field HTS solenoids for Axion search.
- Prior to that BNL worked on high field HTS solenoid for SMES with many parameters similar to those needed for Axion search.
- BNL would be glad to offer its experience with large aperture, high field HTS solenoids to the development of ADMX program.

HTS Solenoids Projects at BNL

- 25 mm aperture, ~16 T HTS solenoid (SBIR)
- HTS solenoid for Energy Recovery Linac (BNL)
- MgB_2 solenoid (SBIR)
- HTS solenoid for SRF cavity (BNL project)
- 100 mm aperture, ~9 T HTS solenoid (SBIR)
- 100 mm aperture, 25 T HTS SMES solenoid (arpa-e)
- 100 mm aperture, ~11 T solenoid with SuNAM HTS (IBS)
- 100 mm aperture, 25 T HTS solenoid for Axion search (IBS)

Focus of this presentation will be on the BNL experience with the high field HTS solenoids

Other HTS Magnet Projects at BNL

- HTS quadrupole with 1G Bi2223 for RIA (DOE/NP)
- HTS quadrupole with 2G ReBCO HTS FRIB (MSU/FRIB)
- 1G Bi2223 HTS tape common coil dipole (DOE/HEP)
- 1G Bi2212 Rutherford cable common coil Dipole (DOE/HEP)
- Cosine theta dipole with 4 mm 2G YBCO/ReBCO tape (SBIR)
- Cosine theta dipole with 12 mm 2G YBCO/ReBCO tape (SBIR)
- Curved 2G ReBCO tape dipole (Phase II SBIR)
- HTS novel dipole design overpass/underpass ends (SBIR)
- High field HTS/LTS hybrid collider dipole (Phase II STTR)
- HTS/LTS hybrid common coil dipole with CORC® cable (SBIR)

A wide ranging magnet program with ~200 coils and ~20 magnets built using over 60 km of HTS (4 mm tape equivalent)

BSCCO: Bismuth strontium calcium copper oxide ReBCO: Rare earth Barium Copper Oxide

High Field Magnets for the Axion Search Experiments and for the Hadron Colliders (1)

- **High field magnets are needed both for the next generation Axion search experiments and for the next generation high energy hadron colliders.**
- **Axion search experiments are essentially looking for very high field solenoids whereas hadron colliders for the very high field dipoles and quadrupoles.**
- **The target field for the next generation Axion search experiments is 25 – 40 T whereas the target field for the next generation colliders is 15 – 20 T.**
- **Use of HTS is must for the next generation Axion search experiments, whereas the use of HTS is optional for the next generation colliders (and in fact HTS is not a part of the base line design).**

High Field Magnets for the Axion Search Experiments and for the Hadron Colliders (2)

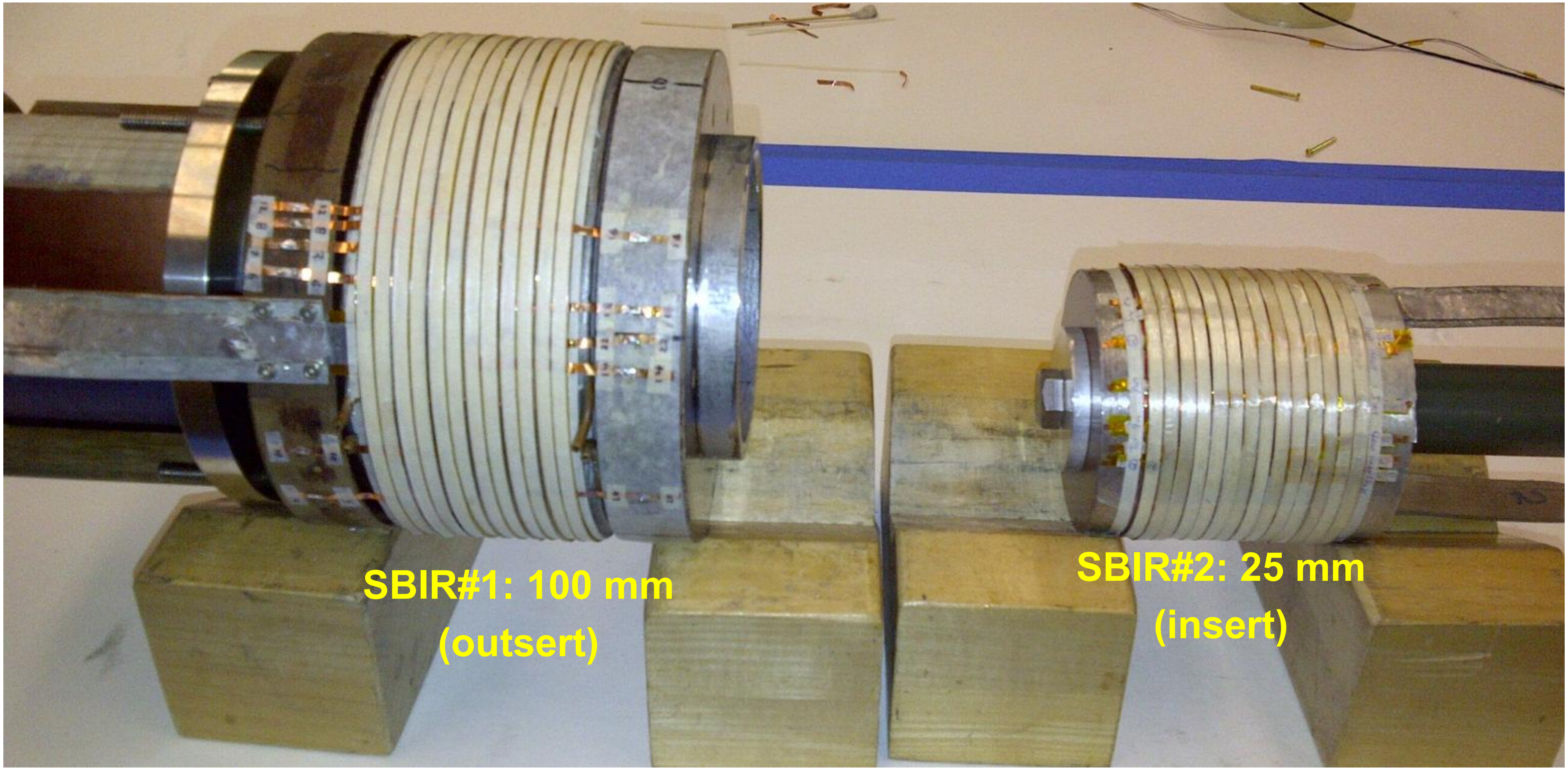
- Field quality requirements are only 10^{-2} for the Axion search experiments whereas they are typically 10^{-4} for hadron colliders. This plays a significant role on the choice of conductors and in the choice of certain technologies.
- The maximum stresses on the conductor is of the order of ~500 MPa in the Axion solenoids whereas it is of the order of ~200 MPa in collider magnets.
- The ramp rate could be much lower and need not be well controlled in the Axion search solenoids as compared to that in the collider magnets.
- Number of dipoles needed for the next generation collider is of the order of tens of thousand as compared to a few for Axion search experiments. It has bearing on the magnet R&D budgets and the timeline.

High Field HTS Solenoids

R&D with PBL (SBIR funded)

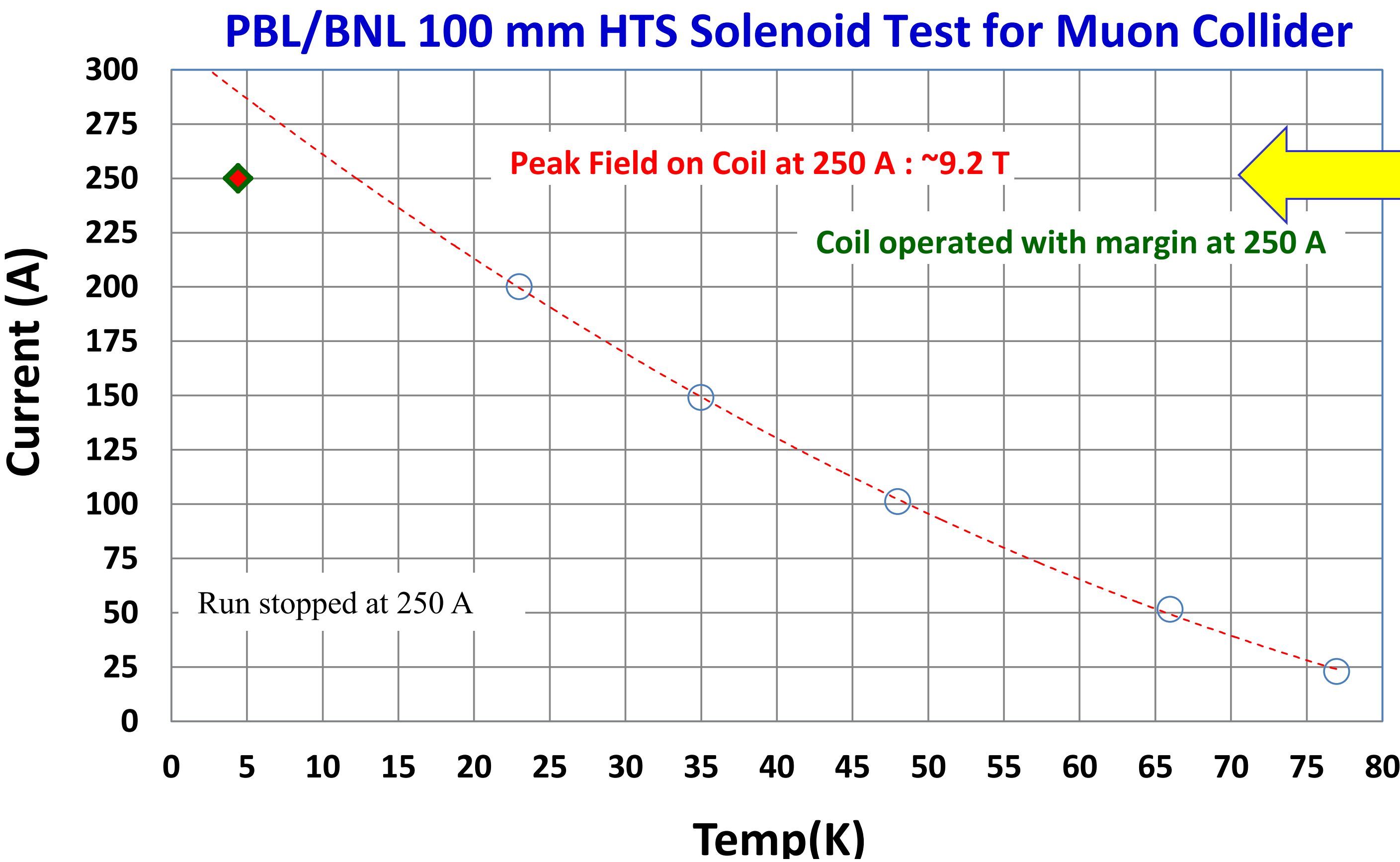
PBL: Particle Beam Lasers, Inc.

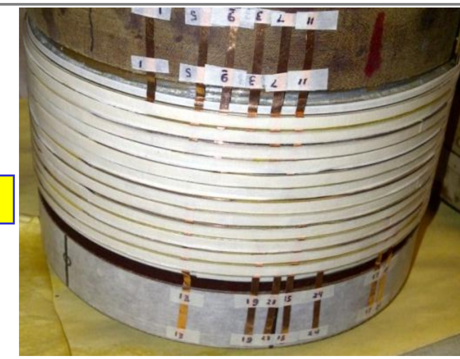
High field HTS solenoid R&D at BNL started with SBIR work with PBL



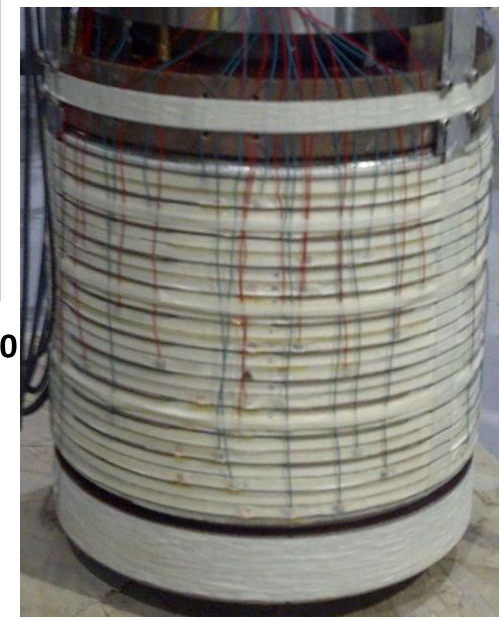
Conductor used: High strength, ~4 mm wide 2G ReBCO HTS tape from SuperPower

SBIR #1: 100 mm Outsert





Half midsert (12 pancakes)



Full midsert (24 pancakes)

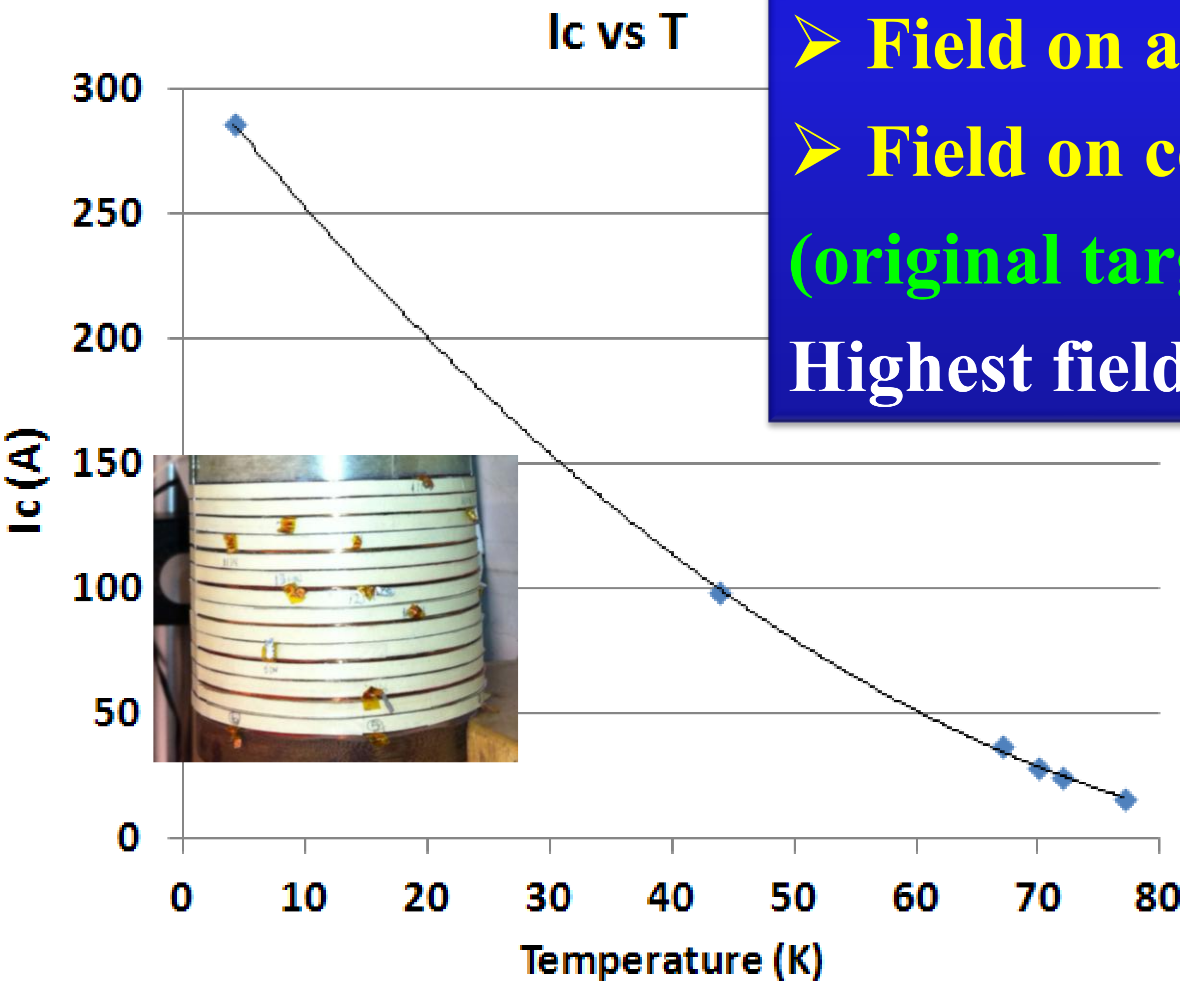
- **Half midsert operated at 250 A @4 K (6.4 T field on axis, 9.2 T peak field on coil**
- **Design value for full midsert: 220 A for 10 T**

SBIR #2: 25 mm Insert

- Field on axis: 15.7 T
- Field on coil : 16.2 T

(original target: 10-12T)

Highest field at that time (2012)



Overall J_o in coil: >500 A/mm^2 @16 T

Insert solenoid: 14 pancakes, 25 mm aperture

High Field HTS Solenoids

SMES (ARPA-E funded)

Note: The basic requirements of the IBS solenoids for Axion search are nearly the same as they were for the SMES HTS solenoid

Unique Opportunity

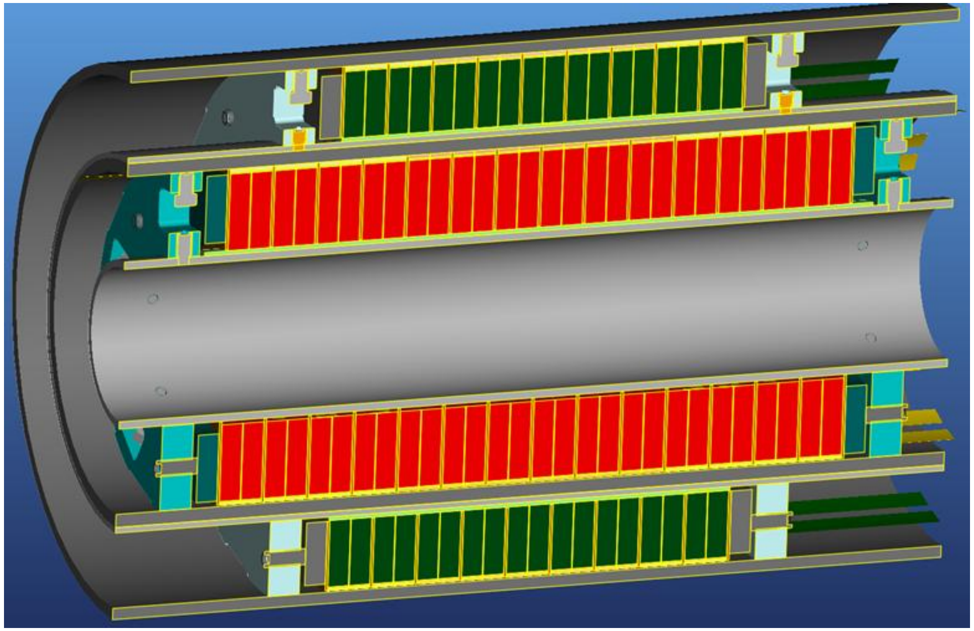
… ARPA-E's mission is to catalyze and accelerate the creation of transformational energy technologies by making high-risk, high-reward investments in their early stages of development

Such missions provides a unique opportunity *"despite a constrained budget & schedule"*

Target: 25 T HTS solenoid in 3 years

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

Major Parameters of the HTS High Field SMES Solenoid



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

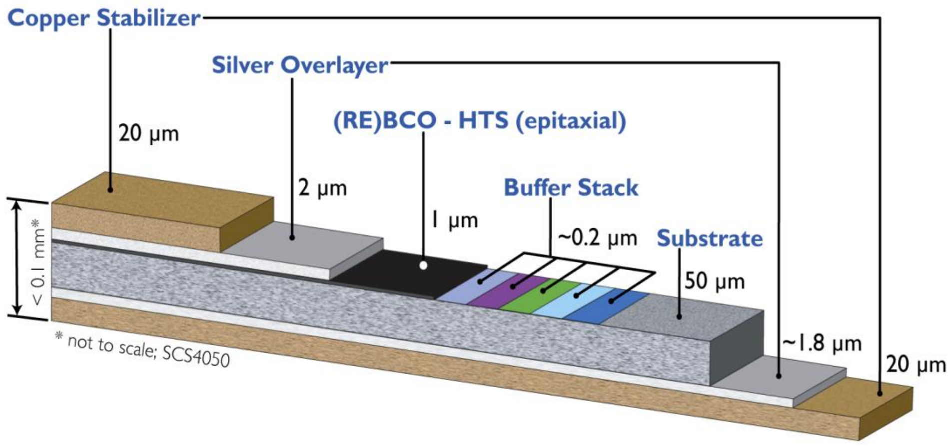
Amount of ReBCO used: >6 km, 12 mm wide

Significant use of HTS in a high field application

Conductor Specifications

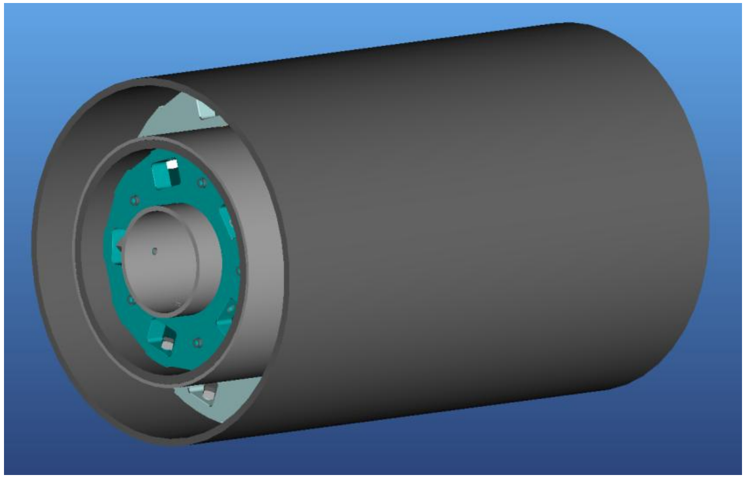
SuperPower Inc. A Furukawa Company

12 mm wide tape with Hastelloy substrate



- Minimum I_c (@4K, 8T) : 700 A (irrespective of the angle)
- Electro-mechanical properties graded (next slide)

The Basic Mechanical Structure

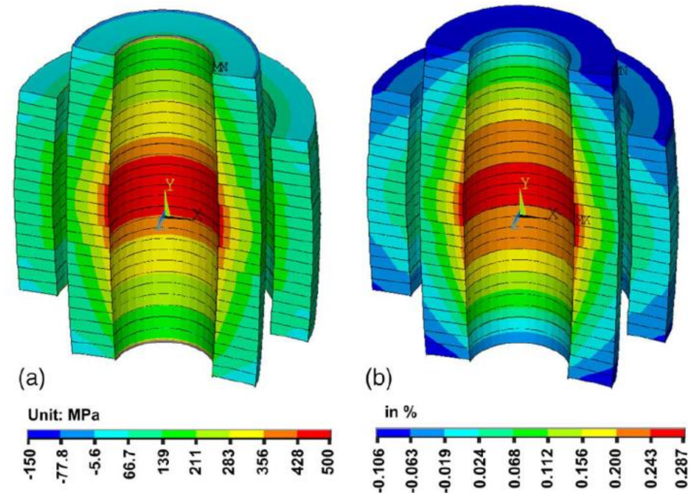


Stress

< 500 MPa

Strain

< 0.3%



Stress **Strain**

- **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**
- **Stress and strain (hoop and axial) are kept below the conductor limit**

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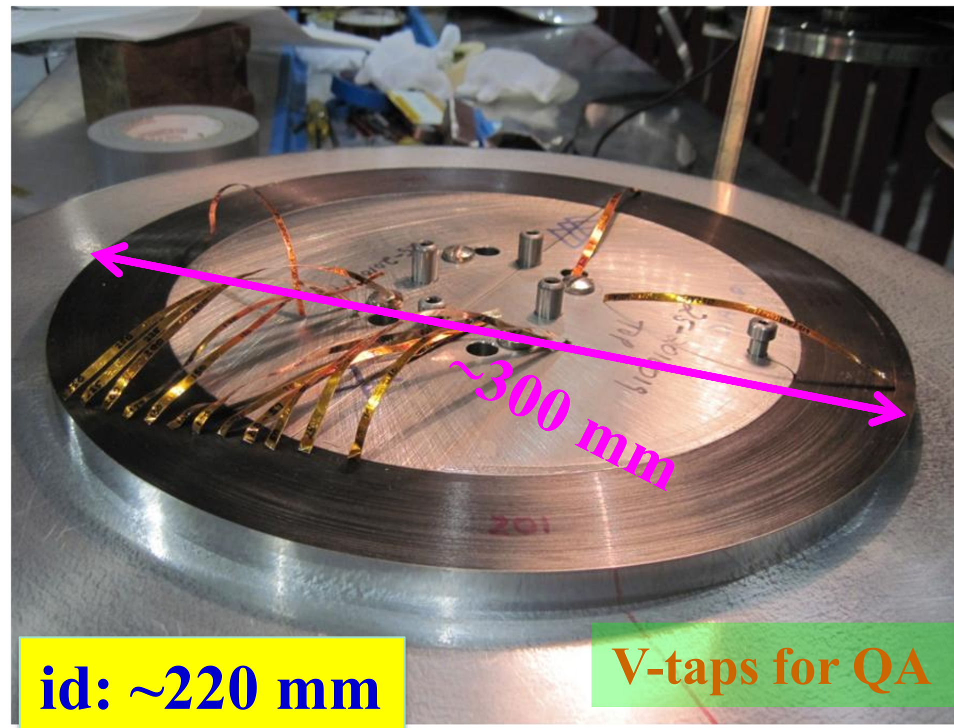
HTS Pancake Coil Winding

Winding Machine

High strength HTS tape co-wound with SS tape

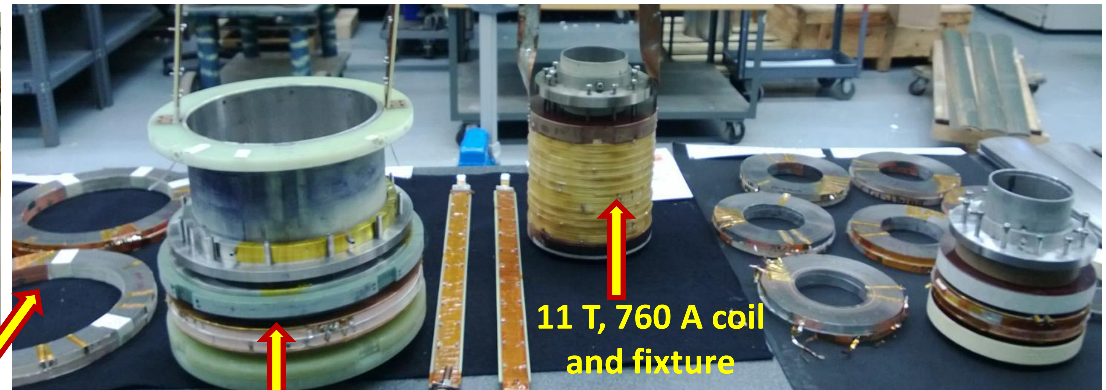
Single pancake (outer)



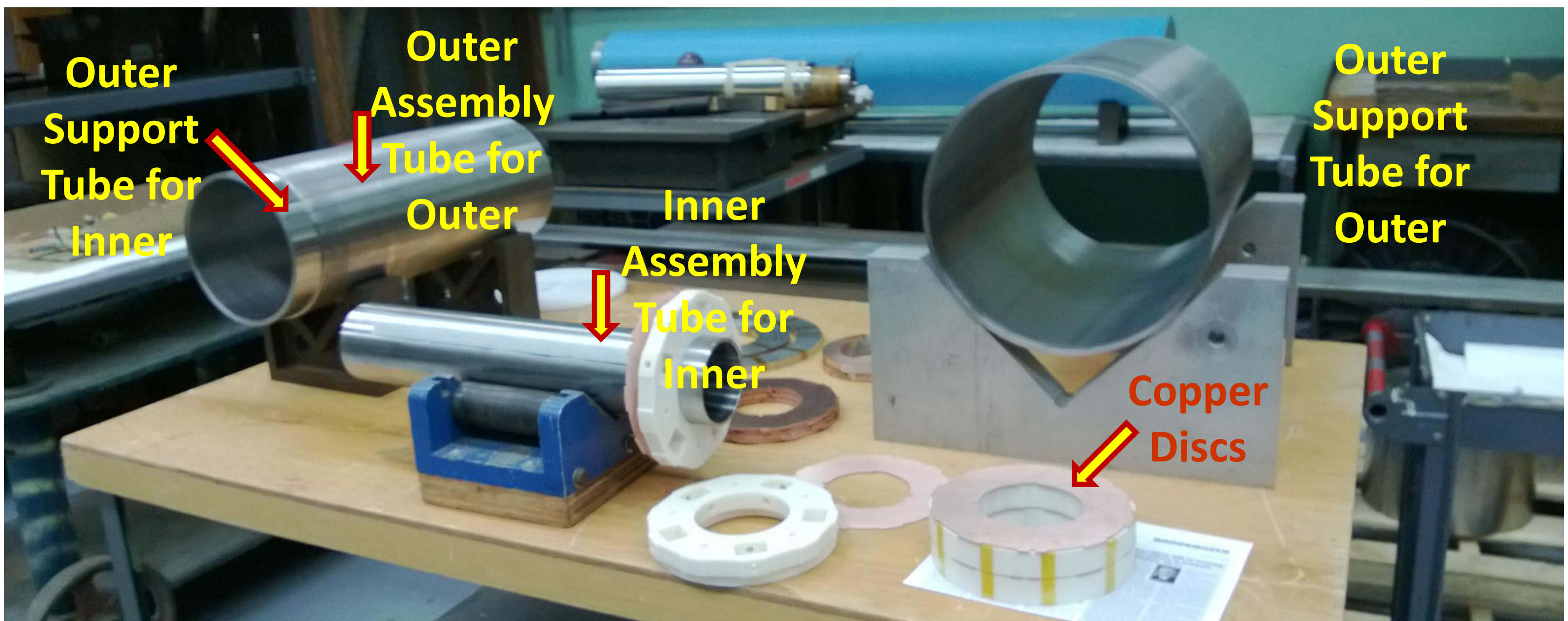
Conductor used per pancake:
~210 m, 12 mm tape (258 turns)

Coils, Test Fixtures and Support Structure

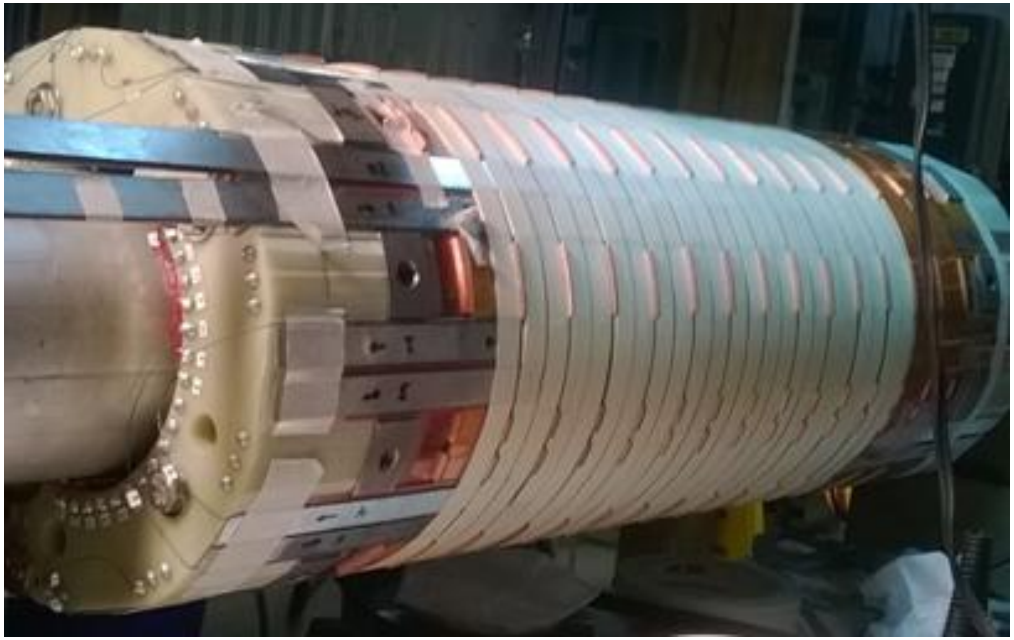
Pancake coils: inner and outer



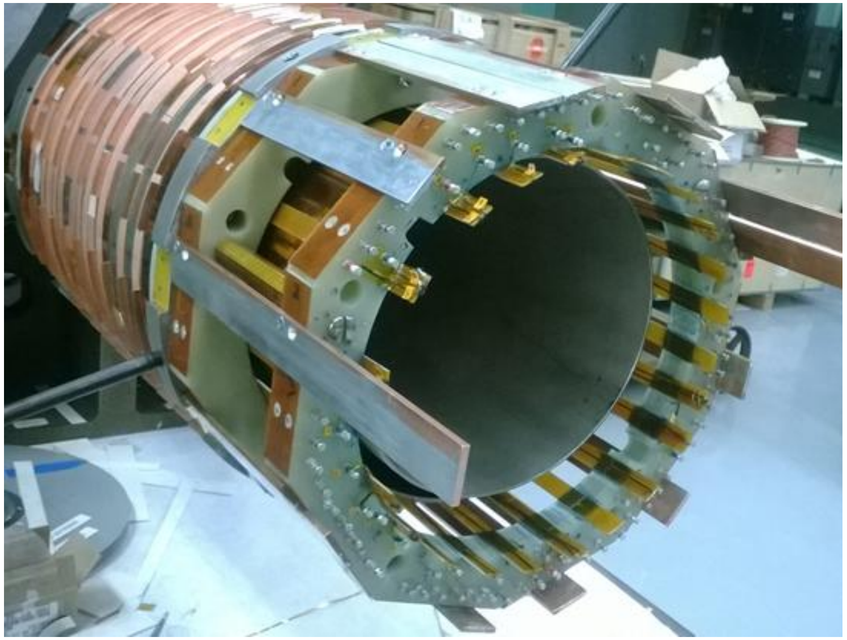
77 K Test Fixture for outer



Inner and Outer Coils Assembled



Inner Solenoidal Coil
(102 mm id, 194 mm od)
28 pancakes



Outer Solenoidal Coil
(223 mm id, 303 mm od)
18 pancakes

- **Multiple leads to bypass a possibly weaker performing pancakes (in pair to balance Lorentz forces)**

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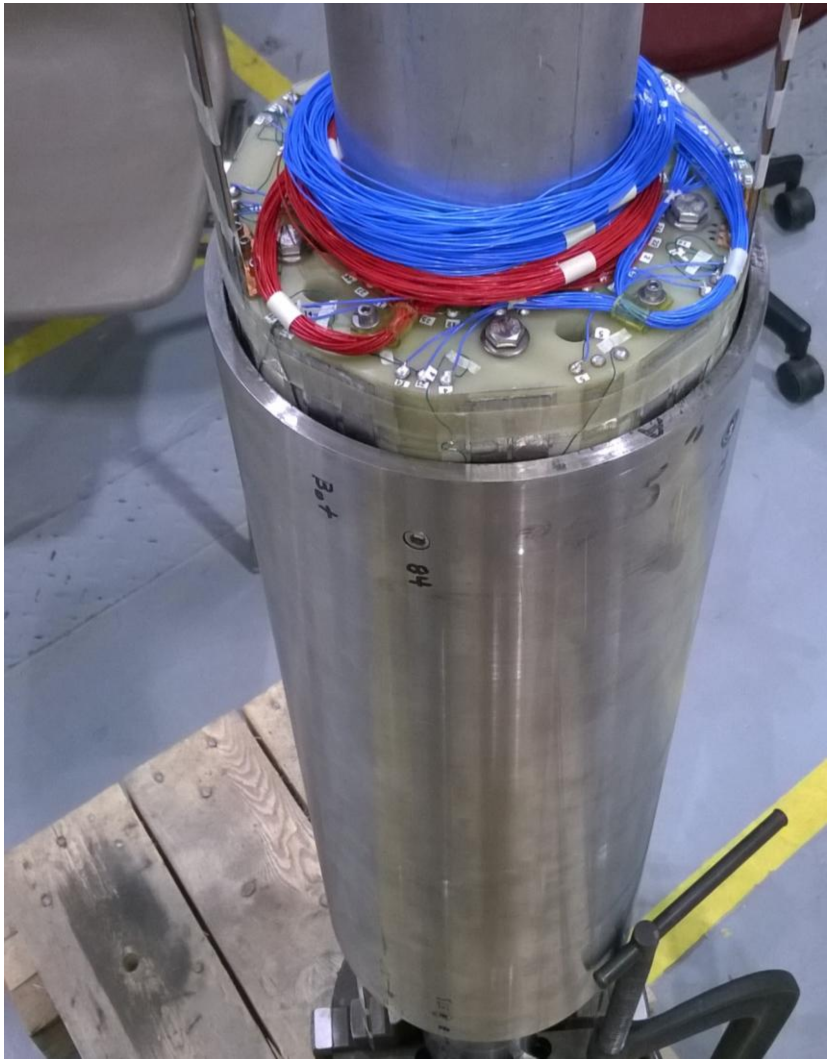
Inner and Outer Coils



Inner (in support tube)

Outer (prior to support tube)

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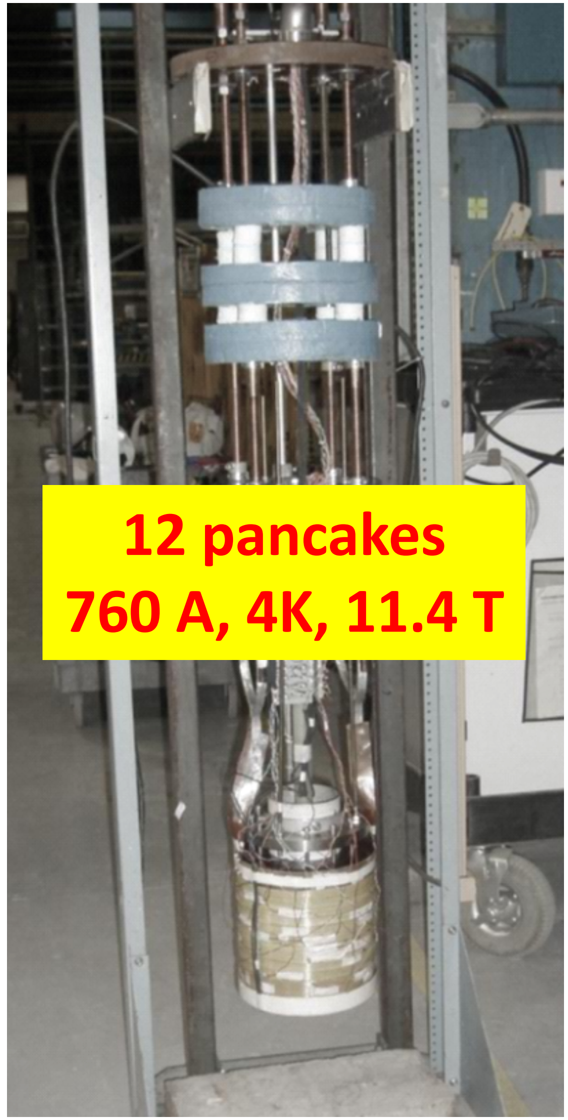
Final Assembly

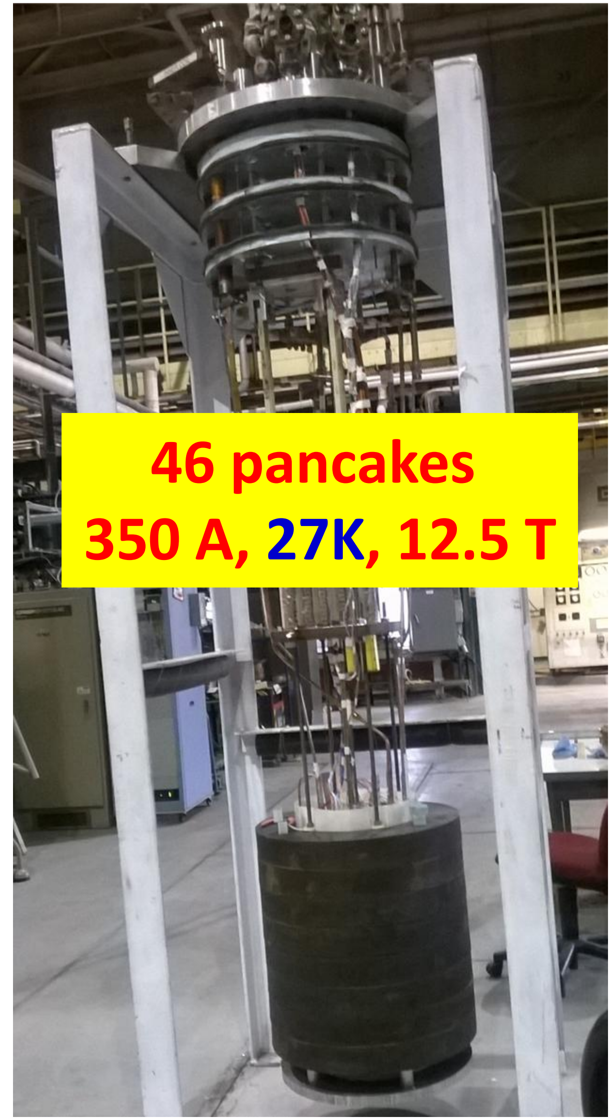
Outer inserted over inner coil

SMES coil in iron laminations

Test Results

Low Temperature, High Field Tests

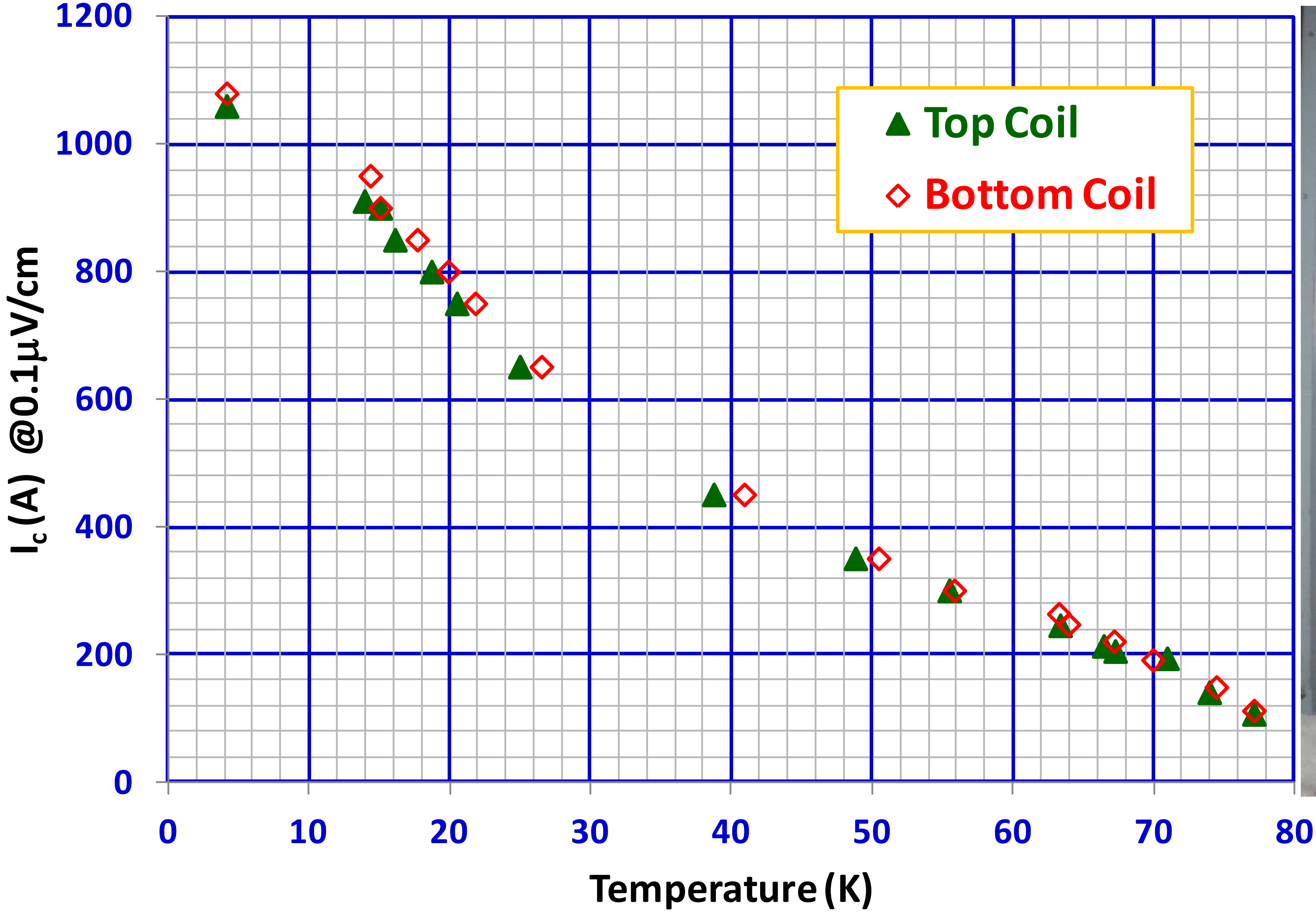


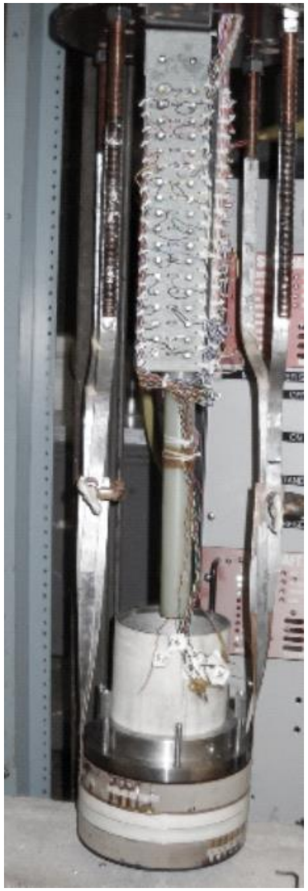


Peak fields higher

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)

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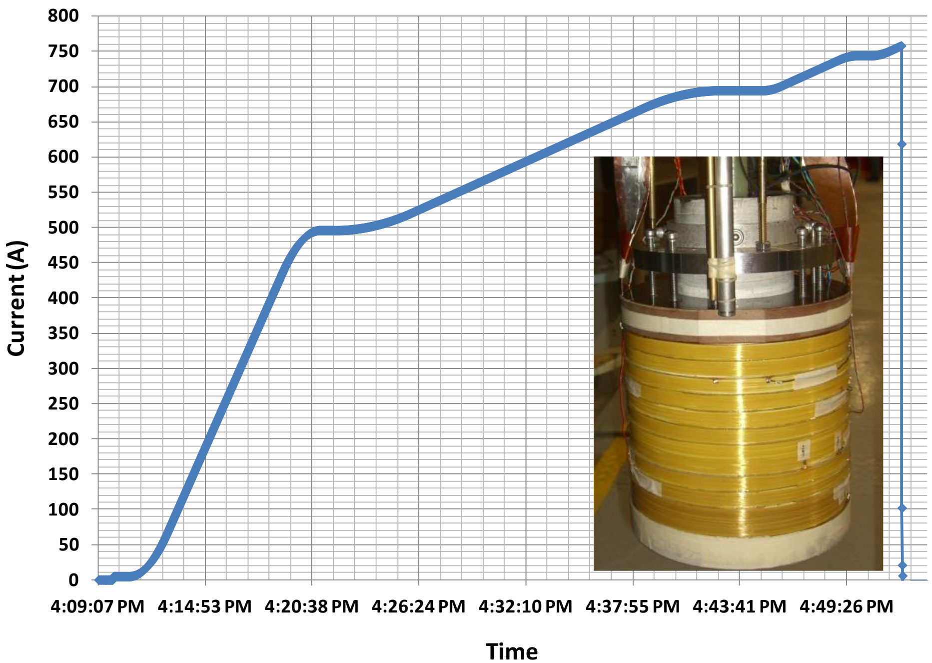
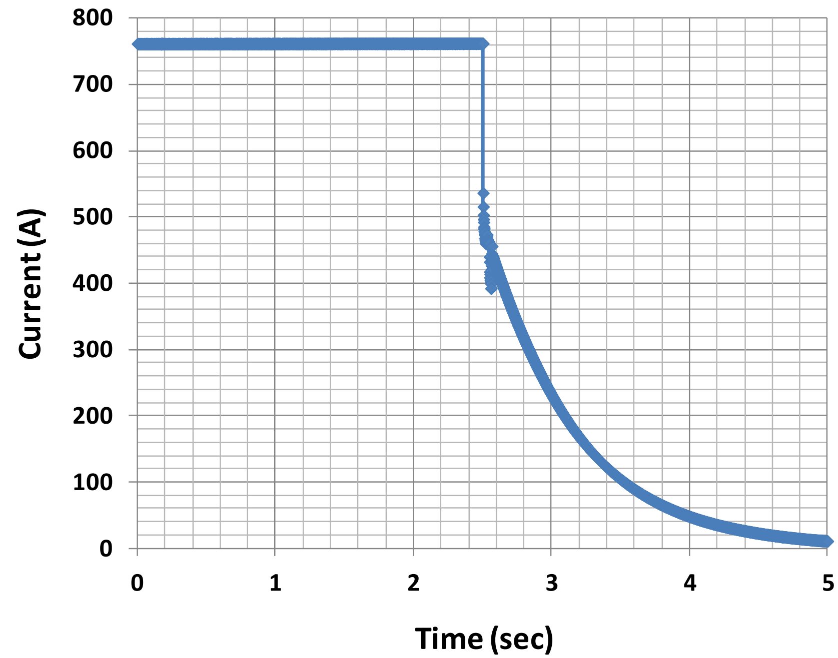
12 Pancake Coil Test

11.4 T in 100 mm bore

Charge

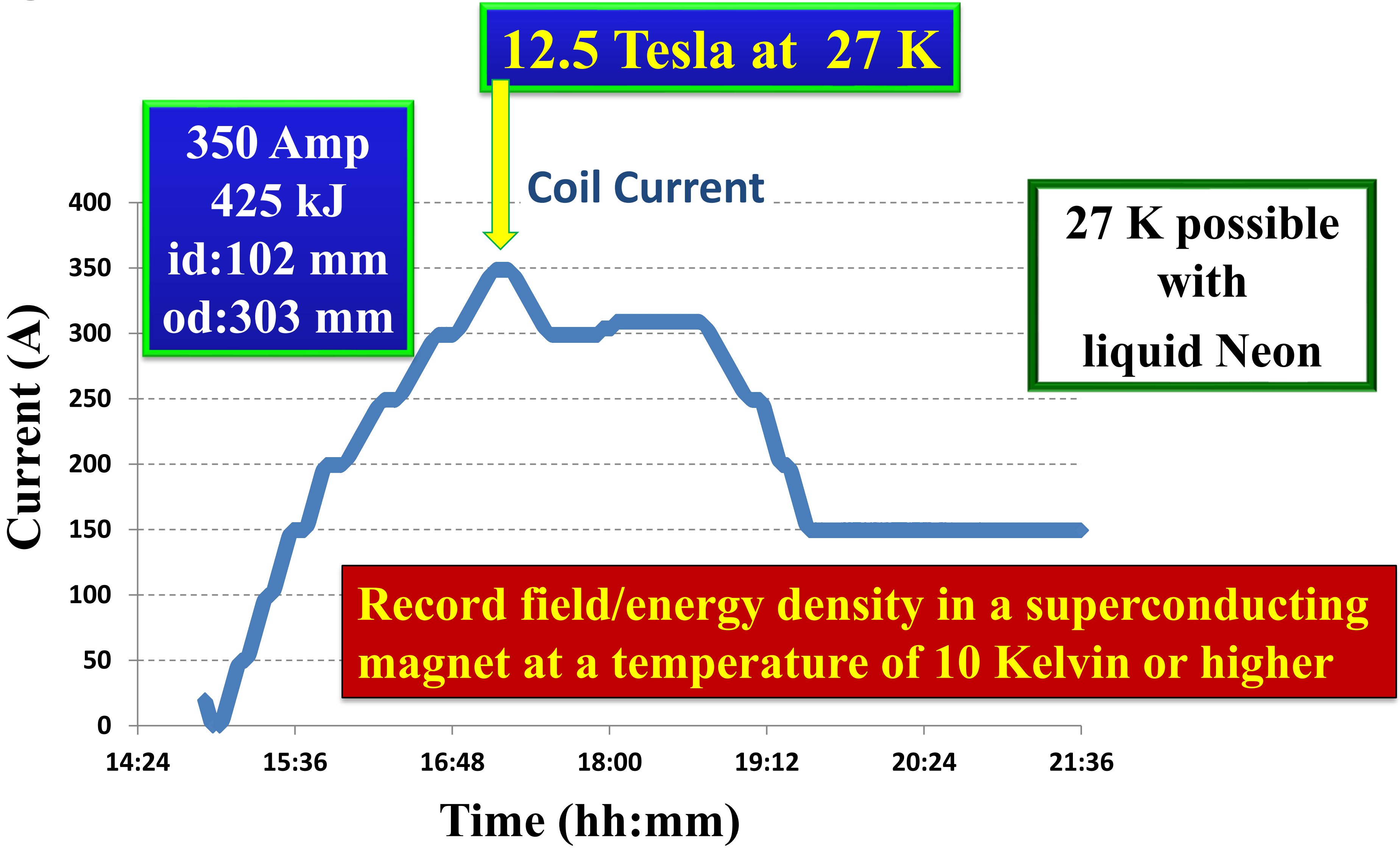


Quench



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

SMES Test at Intermediate Temperature
Critical Current Reached at 27 K



Summary of the Final Magnet Test

- The ambitious design goal: 25 T, 100 mm HTS solenoid in a short period.
- It created a new record at an intermediate temperature: 12.5 T at 27 K.
- During one test, the system tripped at a much lower fields than powered before.
- This trip resulted in arcing between two current leads in the inner coil. These leads were not part of the normal magnet construction. They were added to bypass a potentially weaker coil; ended up causing a problem instead.
- The current lead issue is not related to the high field HTS magnet technology.
- Only one test was allowed despite a challenging magnet with an R&D conductor.

A high risk, high reward program on a tight schedule, even though didn't reach the design field, it still created a record performance advancing the technology.

High Field HTS Solenoids

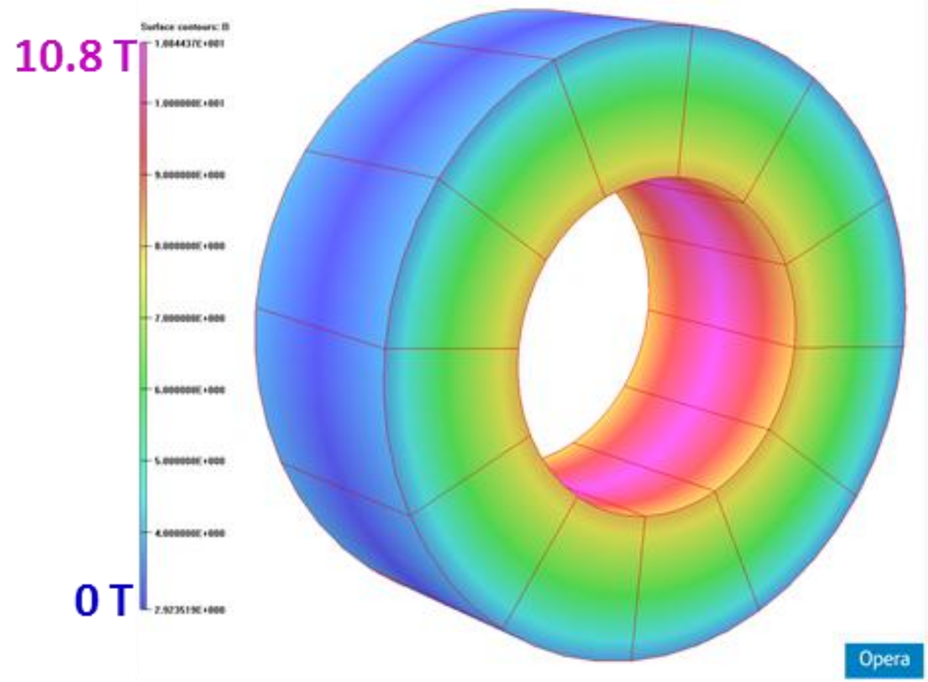
Axion Search (IBS funded)

- **Phase I : ~100 mm coil id, 10 T solenoid with HTS SuNAM (completed)**
- **Phase II: 100 mm bore id, 25 T HTS solenoid (in progress)**

Case examined earlier: 35-40 T with Nb_3Sn outsert from Oxford (still a possibility?)

CAPP/IBS Phase I HTS Solenoid

- **Peak Field : 10.8 T**
- **Aperture : 100 mm**
- **Stored Energy : 66 kJ**
- **Temperature : 4.2 K**
- **Number of Turns: 1881**
- **Number of Pancakes : 6**
- **Conductor: 12 mm wide HTS Tape from SuNAM**
- **Insulation: Stainless Steel**



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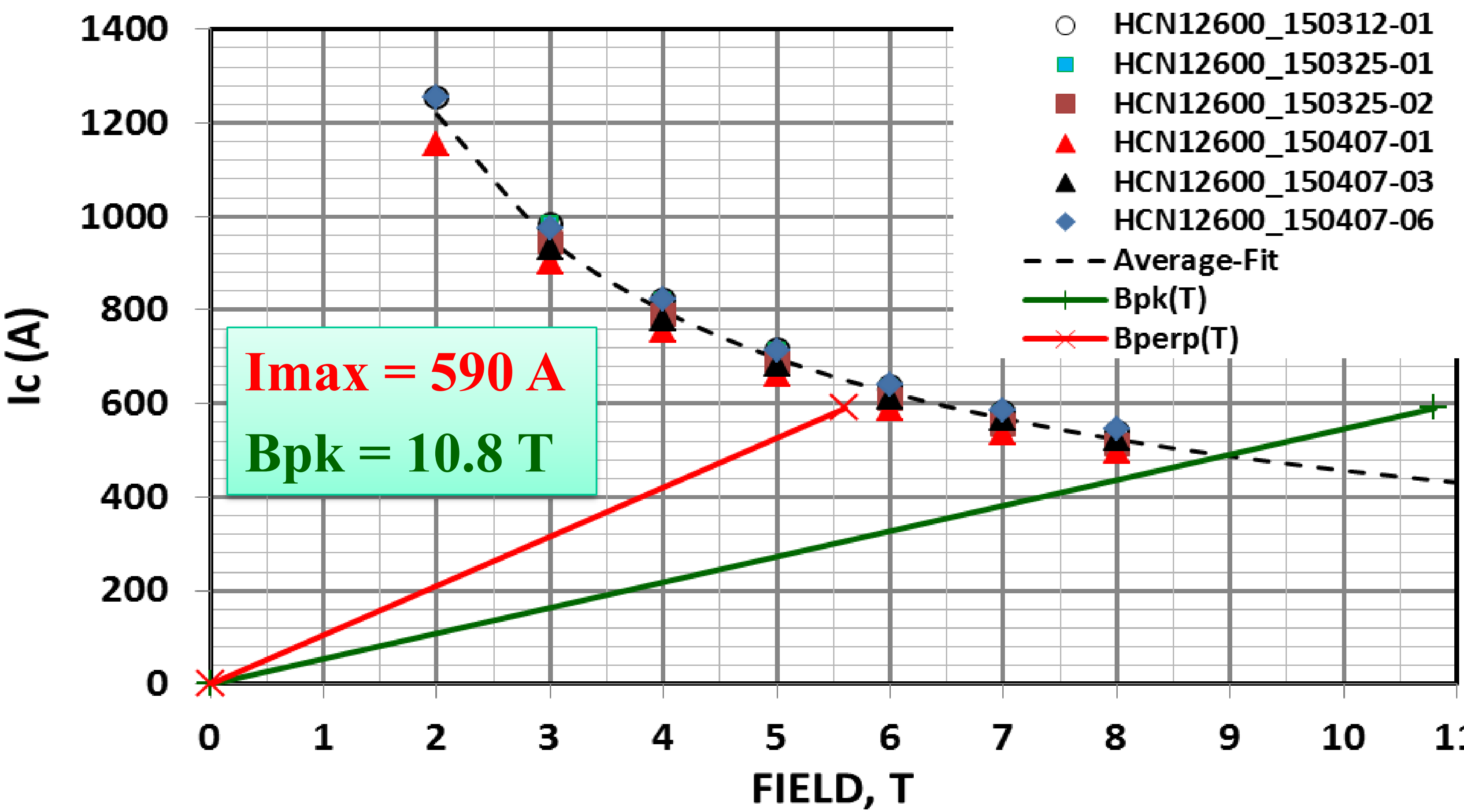
Test Results of the IBS HTS Solenoid



Performance is primarily limited by perpendicular component.
The target peak field > 10 T was reached with SuNAM Tape.

100 mm, 25 T HTS Solenoid

A Review of the Basic Requirements

- High Field : 25 T (must use HTS)
- Large Volume: 100 mm bore, +/-100 mm long

  Stresses: J X B X R
- Field quality: ~10%
- Ramp-up time: up to 1 day

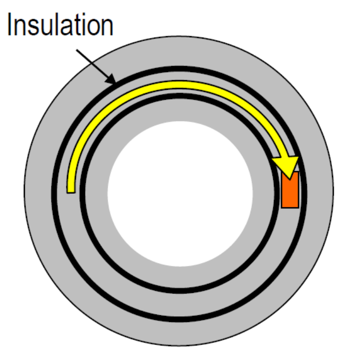
  Relaxed field quality and slow charging
- User magnet: robust design, large Margin

These requirements (particularly the reliability, rather than high risk, high reward) made a significant impact on the design choices.

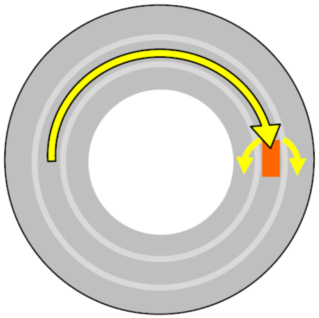
No Insulation Approach to Magnet Protection (slides courtesy S. Hahn)

No-Insulation HTS Winding Technique

INS: Difficulty in Protection



NI: "Quench Current Bypass"



- Slow normal zone propagation in HTS
  - ➔ Slow quench detection
- Larger enthalpy (stability margin) of HTS
  - ➔ Difficulty in "activate-heater" protection

- "Automatic bypass" of quench current through turn-to-turn contacts

REF: S. Hahn, D. Park, J. Bascuñán, and Y. Iwasa, "HTS Pancake Coil without Turn-to-Turn Insulation," *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 1592 – 2011.

S. Hahn
<shahn@fsu.edu>

No-Insulation HTS Magnet
WAMHTS-3, Lyon, France (September 11, 2015)

No Protection Device: No-Insulation HTS Magnets

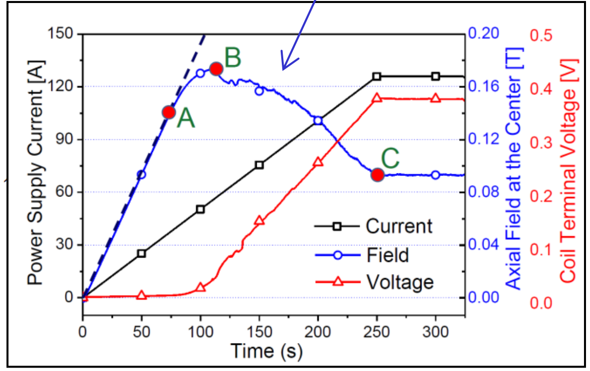
Seungyong Hahn

Applied Superconductivity Center
National High Magnetic Field Laboratory
Department of Mechanical Engineering
Florida State University

WAMHTS-3
Lyon, France

September 11, 2015

A decrease in field implies that more and more turns are getting shorted



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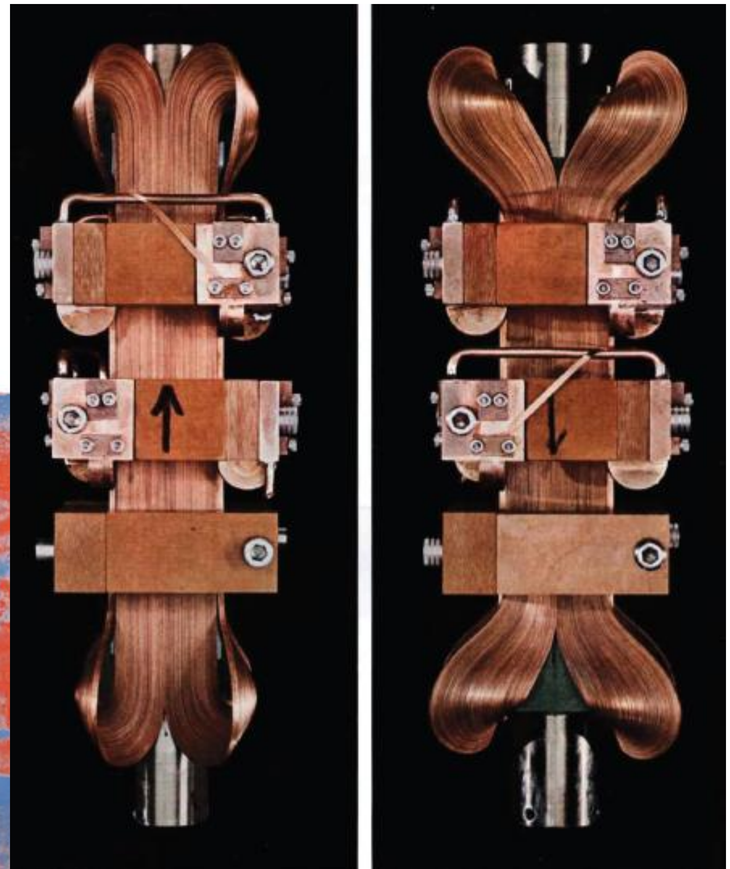
Fifty Years of "No-Insulation" Superconducting Tape Magnets

Bill Sampson BNL (1967)



SUPERCONDUCTING MAGNET was designed by one of the authors (Sampson) as a prototype of a class of magnets that will be used to focus the beam of protons from the 33-billion-electron-volt accelerator at the Brookhaven National Laboratory. The device, called a rectangular quadrupole magnet, consists of four mutually perpendicular current sheets made of superconducting niobium-tin ribbon encased in copper. The direction of the current (*pointed black arrows*) is opposite on adjacent sheets, two of which are visible in these two side views. The magnet is shown approximately actual size. When it is in use, it is immersed in liquid helium.

Nb$_3$Sn Tape Quadrupole (still available to touch)

Advances in Superconducting Magnets

In the past five years superconducting magnets have developed from a laboratory curiosity into the most practical means of generating intense magnetic fields for a growing number of research projects

by William B. Sampson, Paul P. Craig and Myron Strongin

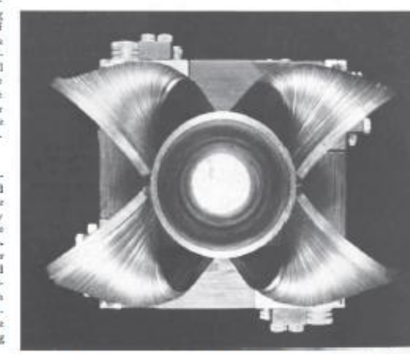
Five years ago superconducting magnets were a laboratory curiosity. An adequate supply of superconducting wire was available, and experimental magnets capable of generating fields as high as 70,000 gauss had been built and operated successfully [see "Superconducting Magnets," by J. E. Kunzler and Morris Tanenbaum; SCIENTIFIC AMERICAN, June, 1962]. Nevertheless, numerous technical difficulties remained, and in spite of their widely recognized potential such magnets were held to be economically impractical for most purposes in competition with conventional electromagnets.

Today this situation has changed drastically. Considerable progress has been achieved in the past few years in the design and fabrication of superconducting magnets. For a substantial number of applications superconducting magnets now perform better and more economically than comparable conventional magnets. Moreover, it seems probable that in the not too distant future the growing need for stronger and cheaper magnetic fields in many areas of science and technology will be filled by superconducting magnets.

At the Brookhaven National Laboratory we are engaged in building and testing superconducting magnets for use primarily in the fields of high-energy physics and solid-state physics. We have also begun to use such magnets for specific experiments in these fields. Other investigators have recently speculated on some potential uses of superconducting magnets in space research. Although the space applications seem much further in the future, they do not require any unreasonable extension of existing knowledge.

The most important property of superconducting materials from the point of view of a magnet designer is their complete lack of resistance to an electric current at temperatures near absolute zero. This property, discovered by the Dutch physicist Heike Kamerlingh Onnes in 1911, makes it possible in principle to build an extremely strong magnet that requires no input of power. (Permanent iron magnets also produce magnetic fields with no power input, but the strongest fields they can attain are only about 10,000 gauss.) The vast amount of power consumed by a conventional high-field electromagnet appears in the form of heat as a result of electrical resistance in the current-carrying coils. This power input produces no useful work and must be carried away by some cooling agent, usually large quantities of water. At the National Magnet Laboratory in Cambridge, Mass., continuous fields as strong as 250,000 gauss have been achieved with a conventional electromagnet, but the electric power consumed by the magnet is about 16 million watts—approximately the power requirement for a town of 15,000 inhabitants [see "Intense Magnetic Fields," by Henry H. Kolm and Arthur J. Freeman; SCIENTIFIC AMERICAN, April, 1965].

Since there is no electrical resistance in the current-carrying coils of a superconducting magnet, no power is dissipated as heat, and strong fields can be



END VIEW of the superconducting quadrupole magnet on the opposite page shows the rectangular array of current sheets around the bore, which is slightly more than an inch across.

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However, no-insulation coils were made for different reasons

Design Choices

- No Insulation
  - Takes benefit of relaxed field quality and slow charging time
  - Most reliable quench/defect forgiveness scheme in HTS magnets
- Single Layer
  - Two layers may create unbalanced force condition between the two layers, particularly for "No Insulation" option
- Conductor: High Field, High Strength 2G ReBCO Tape
- Critical current margin (generous): ~50%
  - High performance needed at high fields @ 4 K
- Stress/strain margin (generous): ~50%
  - Multi-width option increases maximum stress (NOT acceptable here)

Conductor for 25 T, 100 mm HTS Solenoid for IBS

- Essentially all major 2G HTS vendors (foreign and domestic) already meet the critical current requirements with a sufficient margin.
- The design is limited by the mechanical properties. We didn't use higher J_c (though available), as that increases stresses.

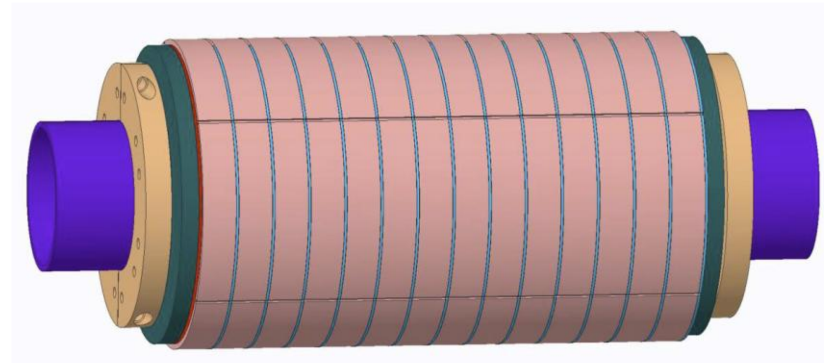
We are buying the conductor with the lowest spec (and the lowest cost) as this will still gives a 50% margin →

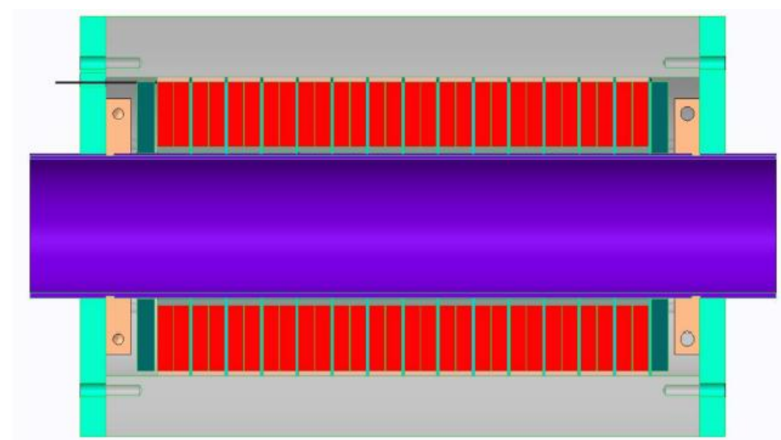
Quoted	Reference	Target
12mm	12mm	4mm
4K, 8T	77K, sf	30K, 2T
675	300	289
775	350	332
875	400	375
975	450	418

(backup slide for more on conductor)

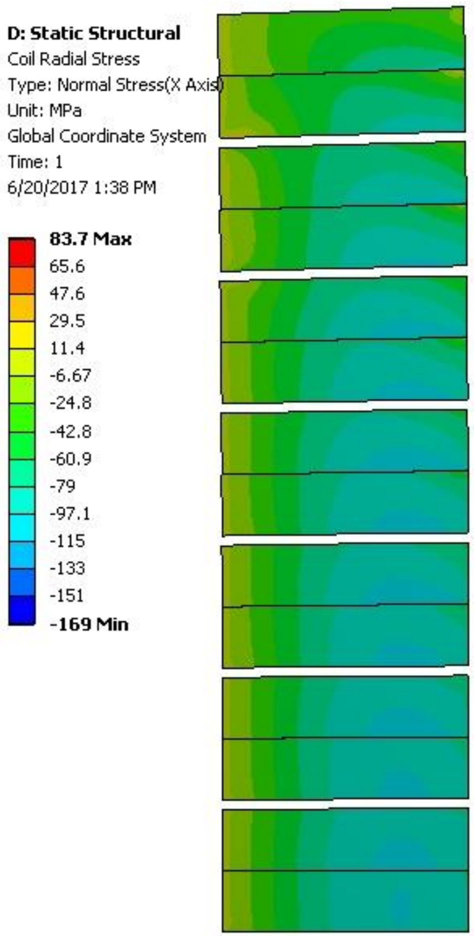
Major Parameters of the HTS Solenoid for IBS

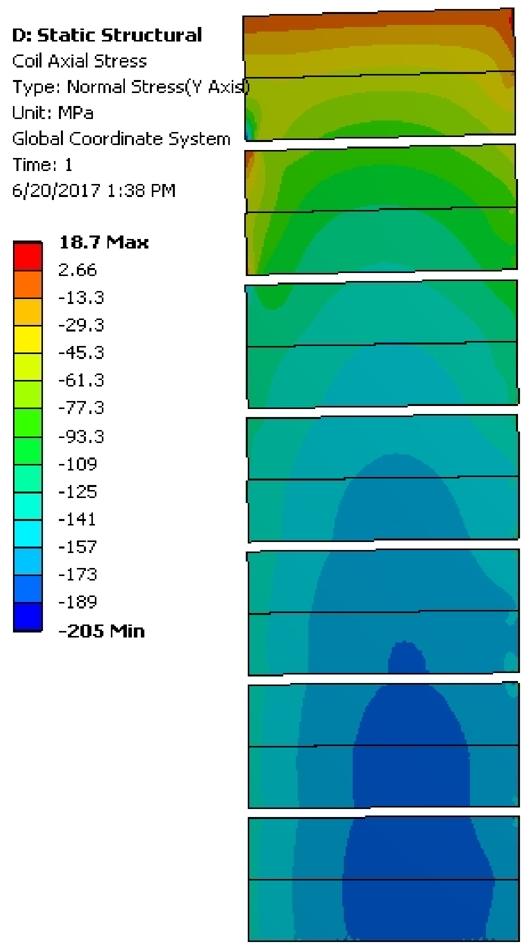
- Field: 25 T@4 K
- Single Layer
- Cold Bore: 100 mm
- Coil i.d.: ~118 mm
- Coil o.d.: ~214 mm
- Conductor: 12 mm wide ReBCO
- Current: ~450 A
- Current Density: ~490 A/mm^2
- Stored Energy: ~1.6 MJ
- Max. Hoop Stress: ~500 MPa

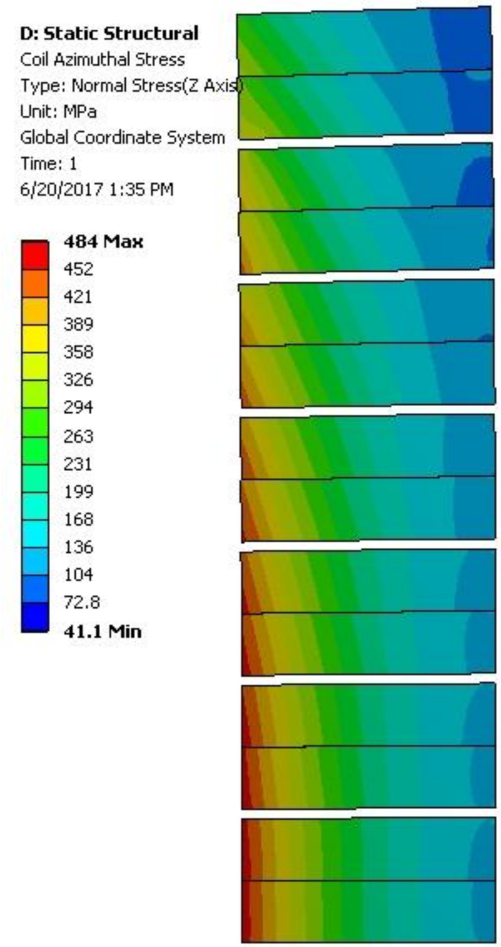




Coil Stresses (MPa) @ 4 K, 25 T







484 MPa Max Stress

-100 MPa Max Stress

-205 MPa Max Stress

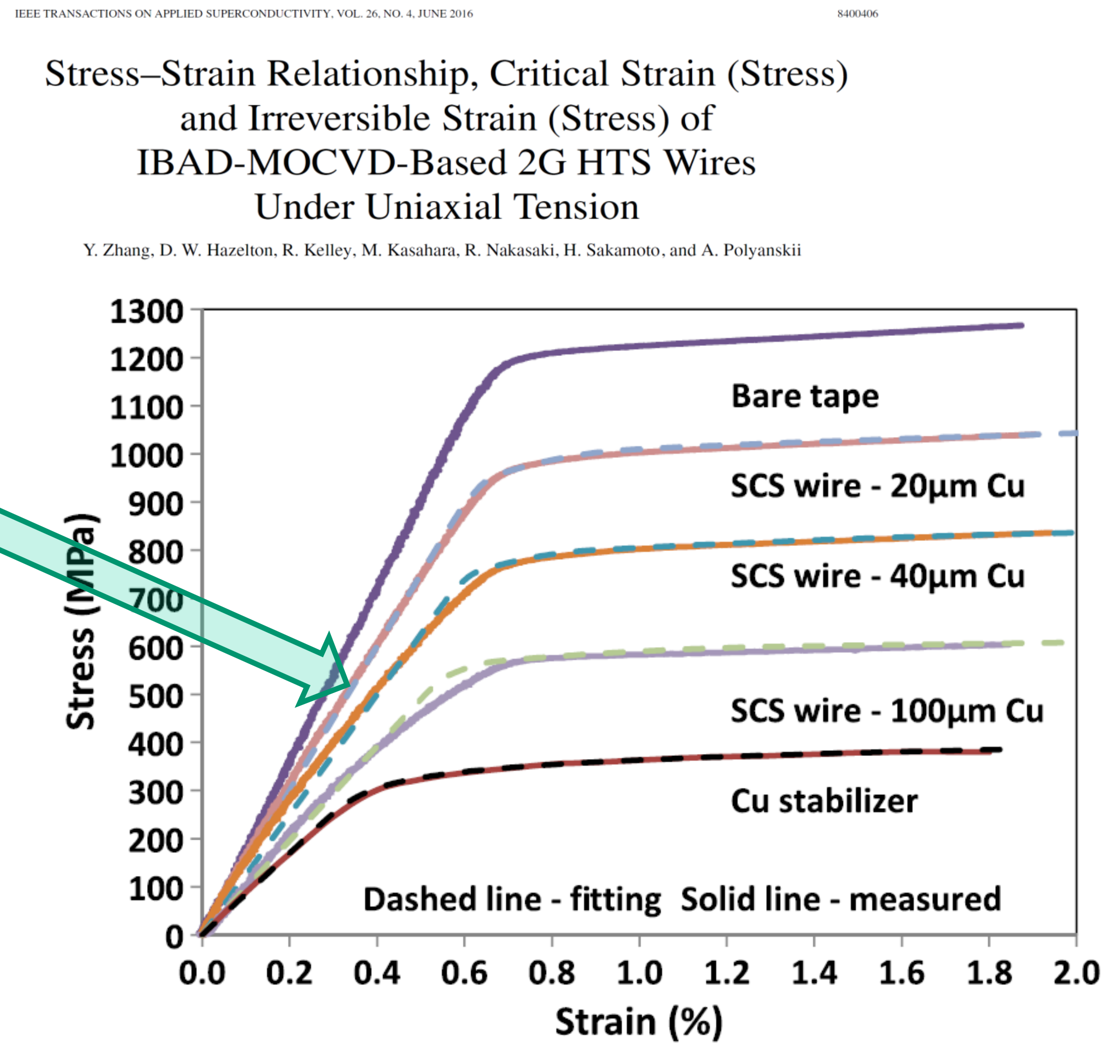
Azimuthal

Radial + **Axial** +

Mechanical Properties of the Conductor

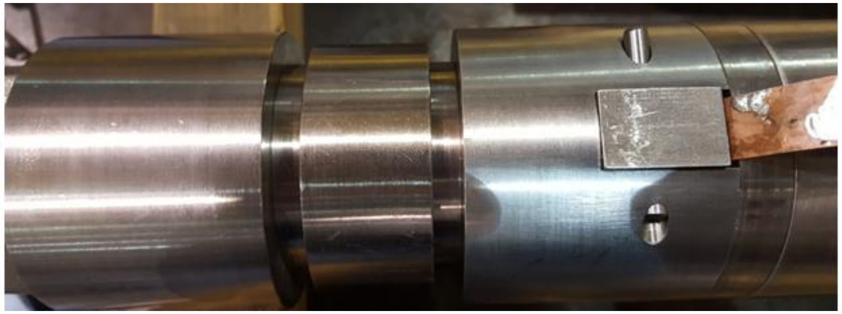
Requirement of Azimuthal stresses of ~500 MPa is met with 2G Tape having 50 micron Hastelloy and 20 micron Copper

Meeting requirement of ~200 MPa on the narrow side of the tape needed to be checked as no such data was available

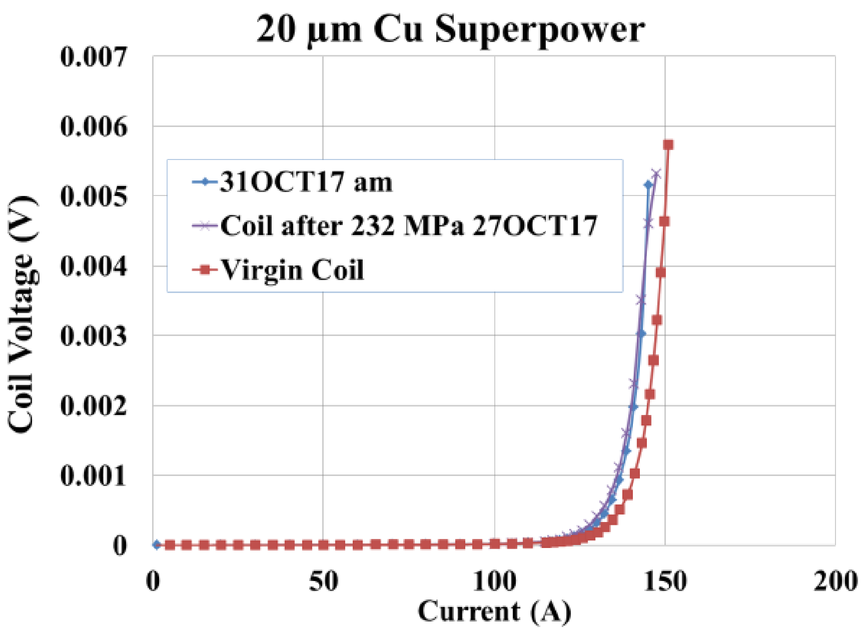


Courtesy: SuperPower

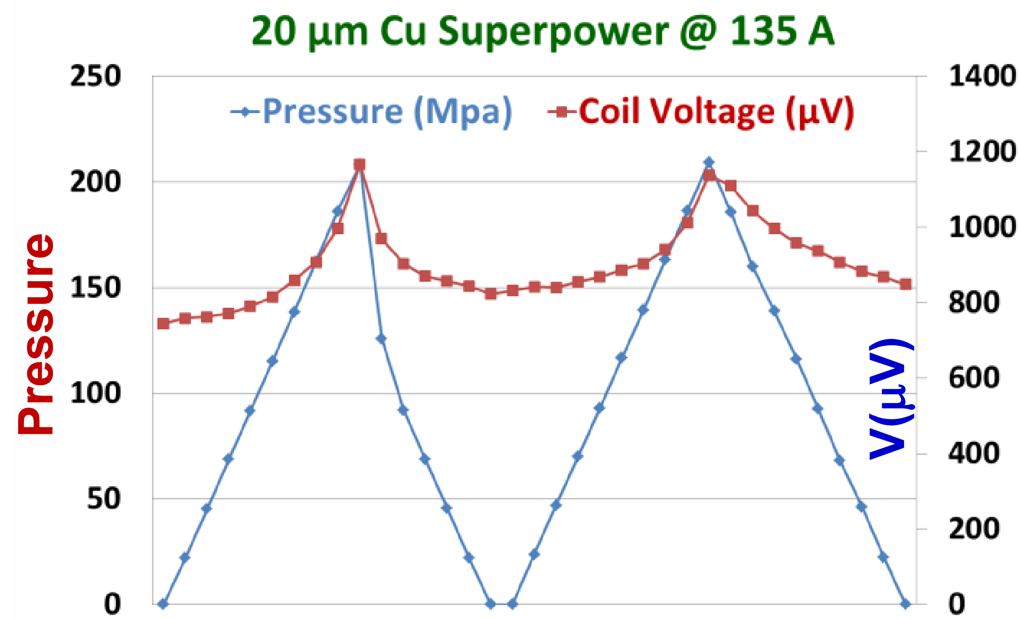
Apparatus to Apply and Measure High Pressure on the Narrow Face of the Conductor and the Coil



Measurement of the Load on the Narrow Face of HTS Tape (50 μm Hastelloy, 20 μm Copper from SP)



First Test



Repeated Cycles

Meets the requirements of ~200 MPa on the narrow side

Tapes with 40 and 65 microns copper and from other vendors were also examined

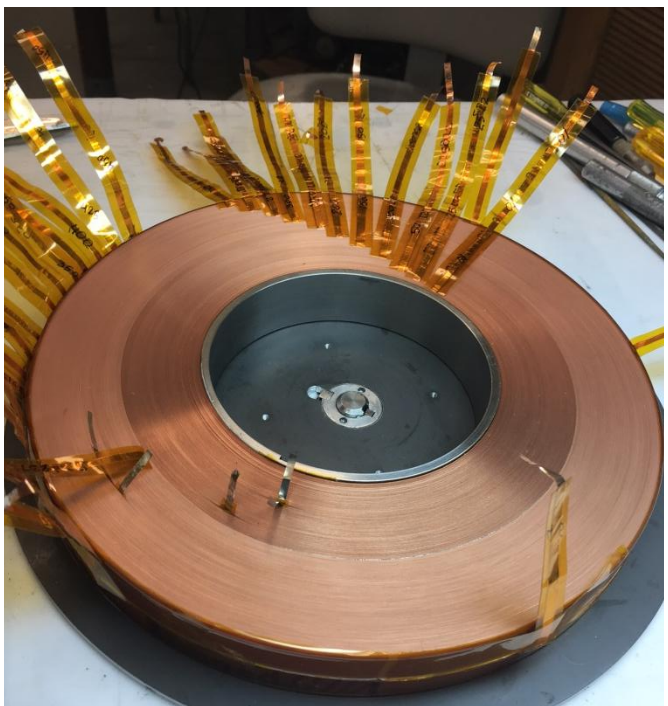
No Insulation Coil Construction and Test Results

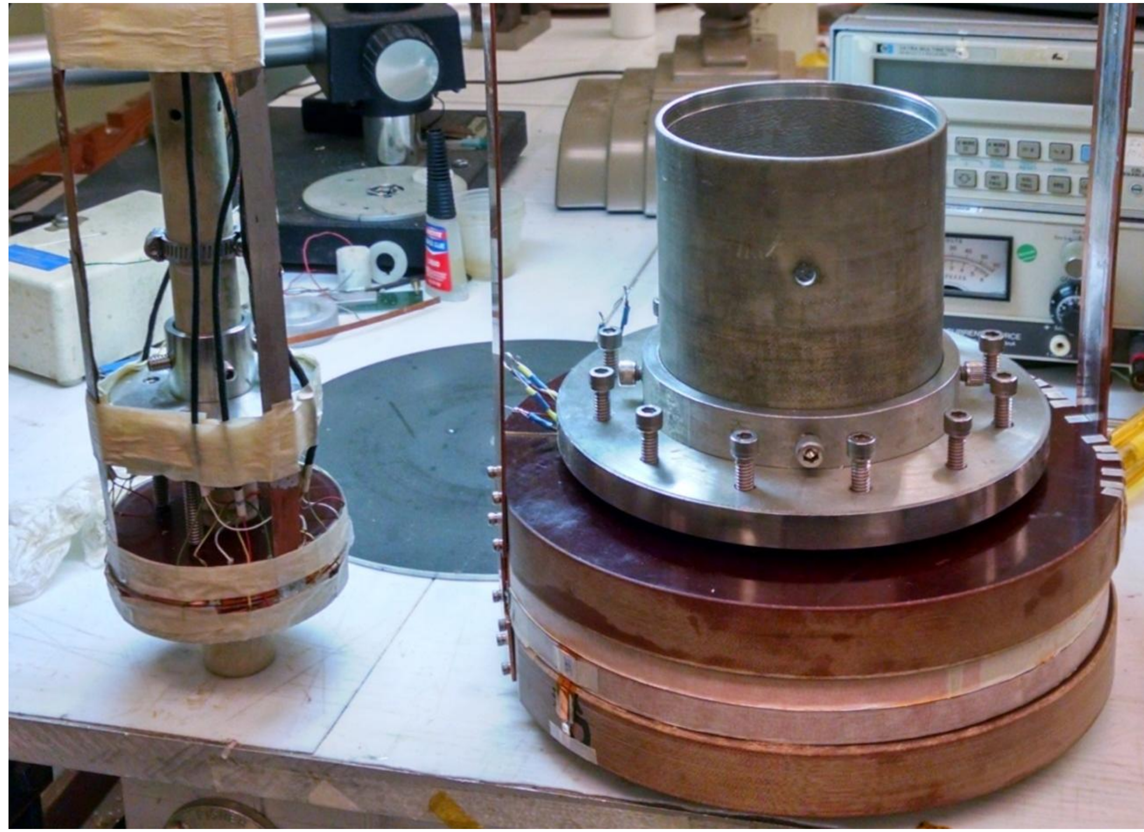
- No Insulation protection has been demonstrated to be robust in many coils.
- No such data, however, is available for big coils (100 mm or more i.d.) at 4K.
- Since this is a critical part of providing a reliable magnet, we decided to do a series of early tests on the full scale double pancake coil to avoid any surprise.

No Insulation Double Pancake Coils

Early experience with a big "NI" coil wound with ~550 m of 12 mm wide ReBCO tape

- i.d. = 100 mm
- o.d. = 220 mm
- Turns = 971

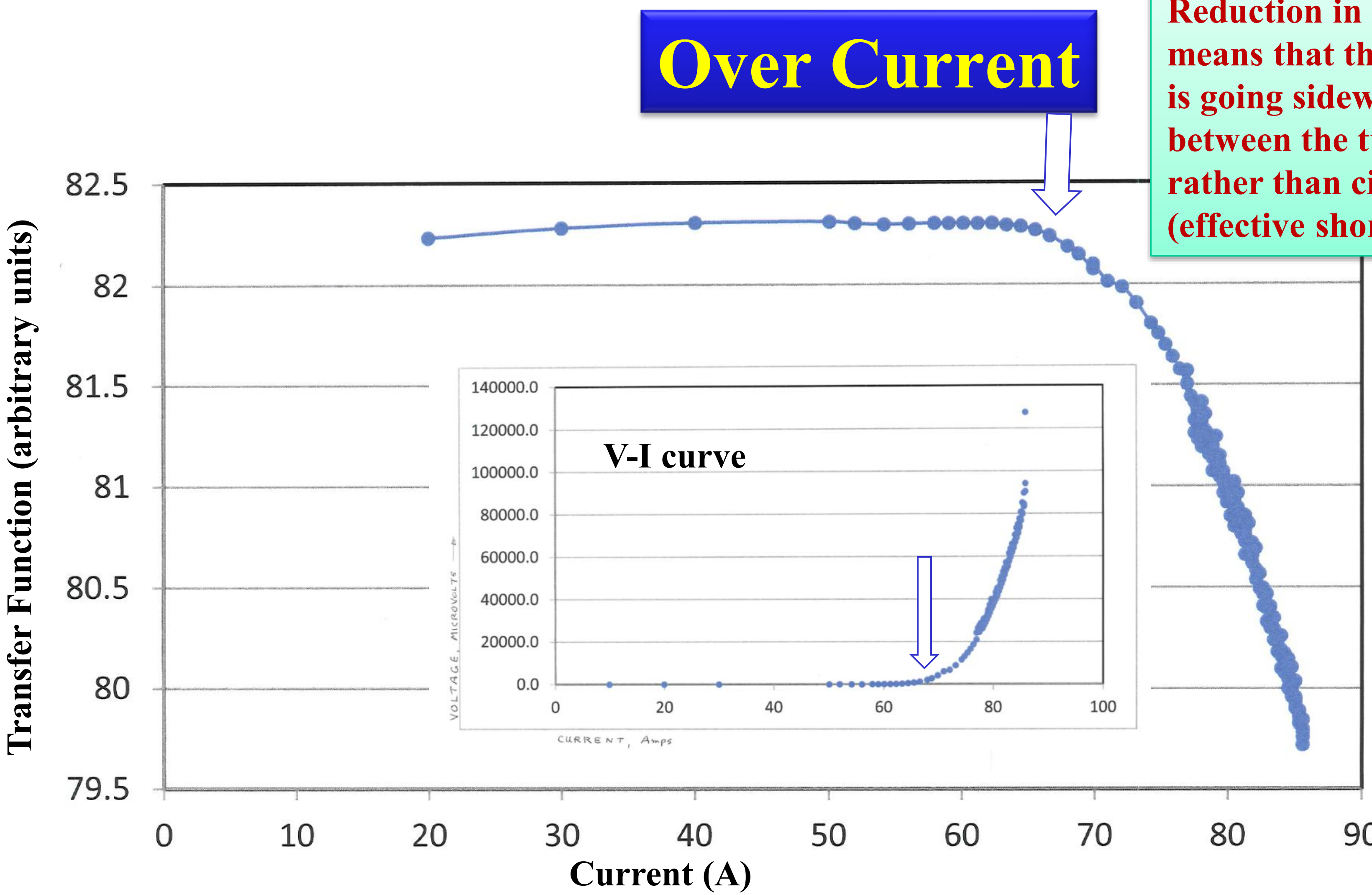




Significant instrumentation:

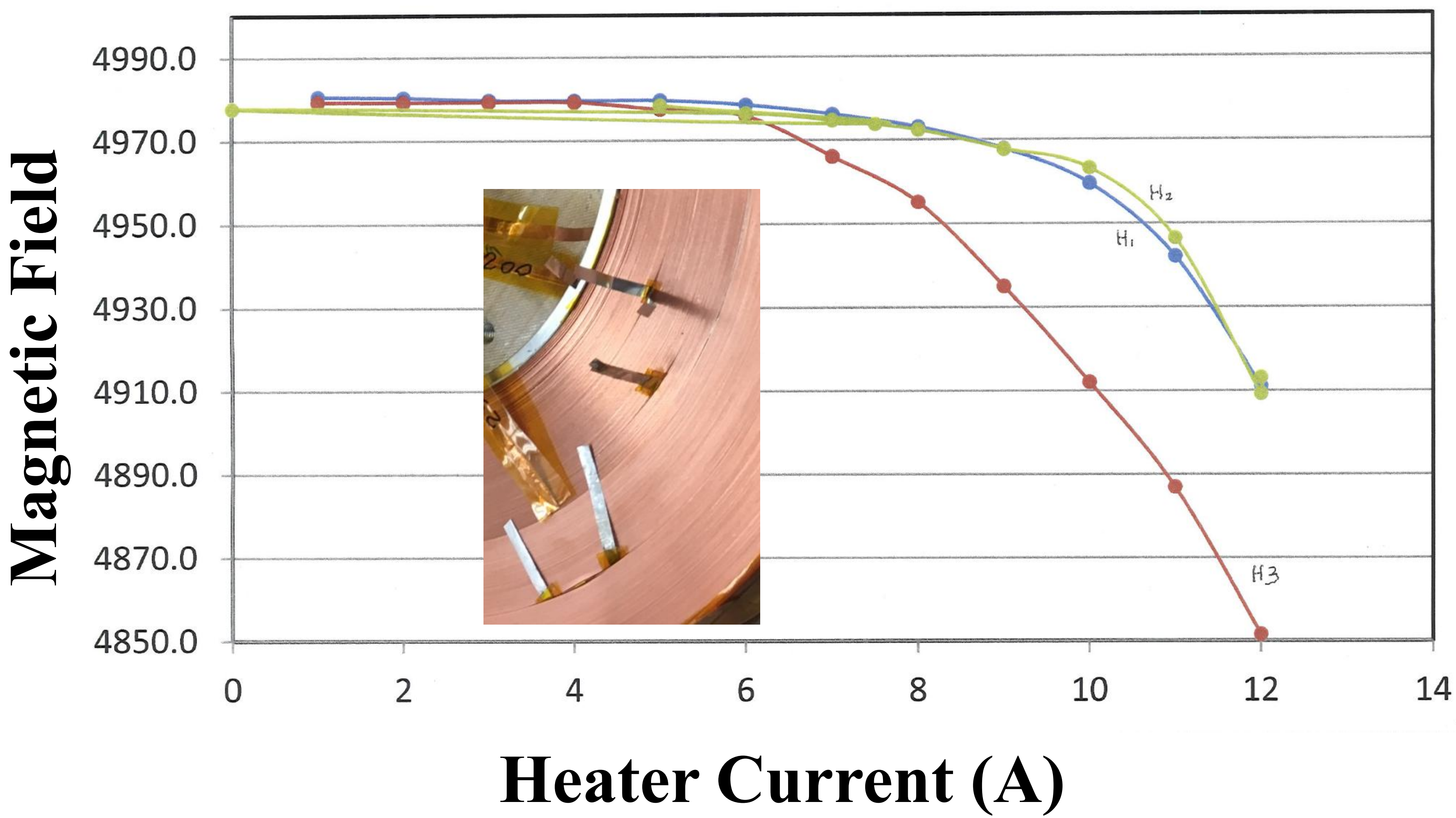
- A large number of v-taps
- Three heaters (for controlled simulation of defects)

Transfer Function Vs. Current in No Insulation Coils

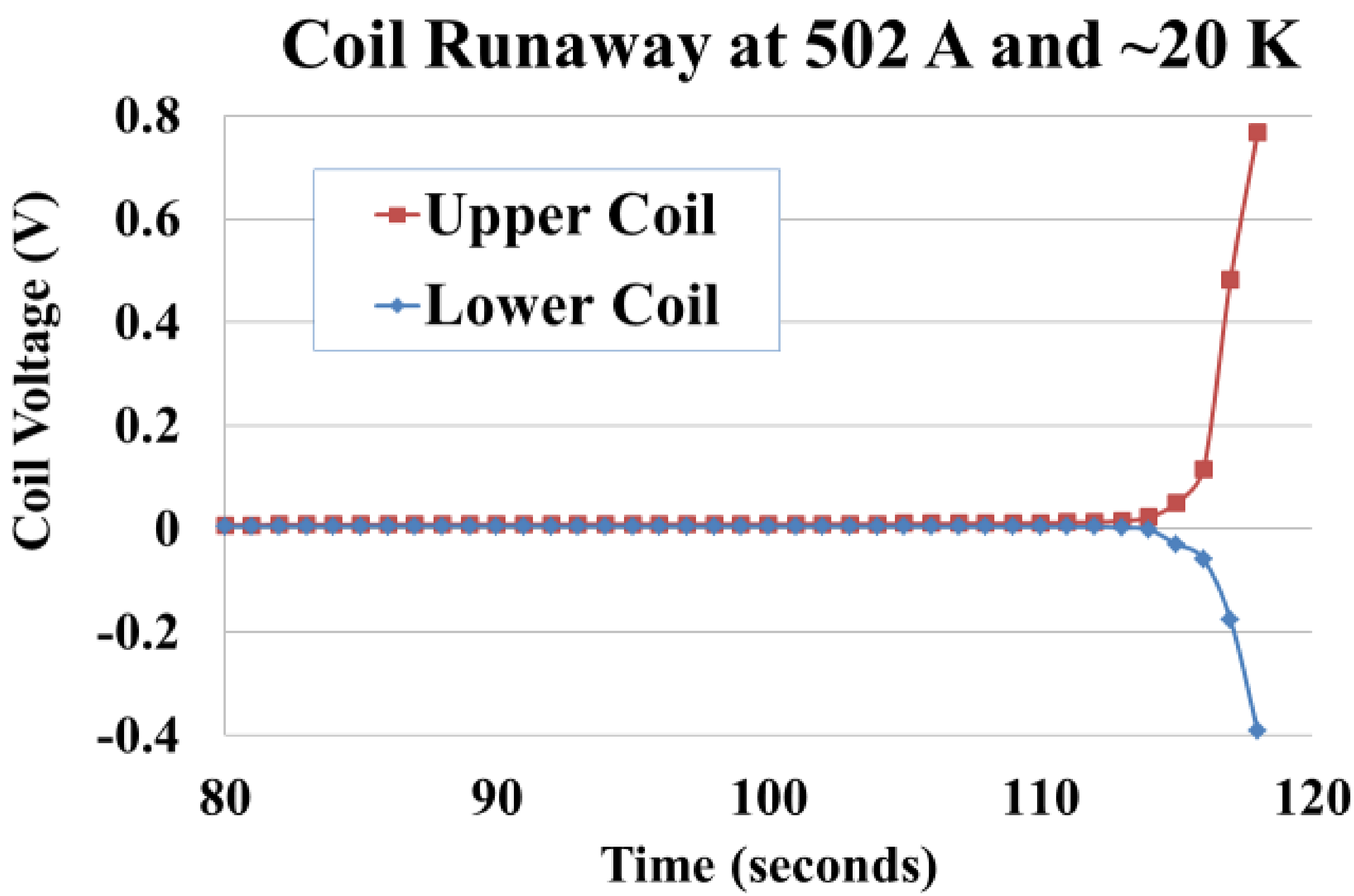


Reduction in T.F. means that the current is going sideways between the turns rather than circulating (effective short)

Simulated Defects with Heaters

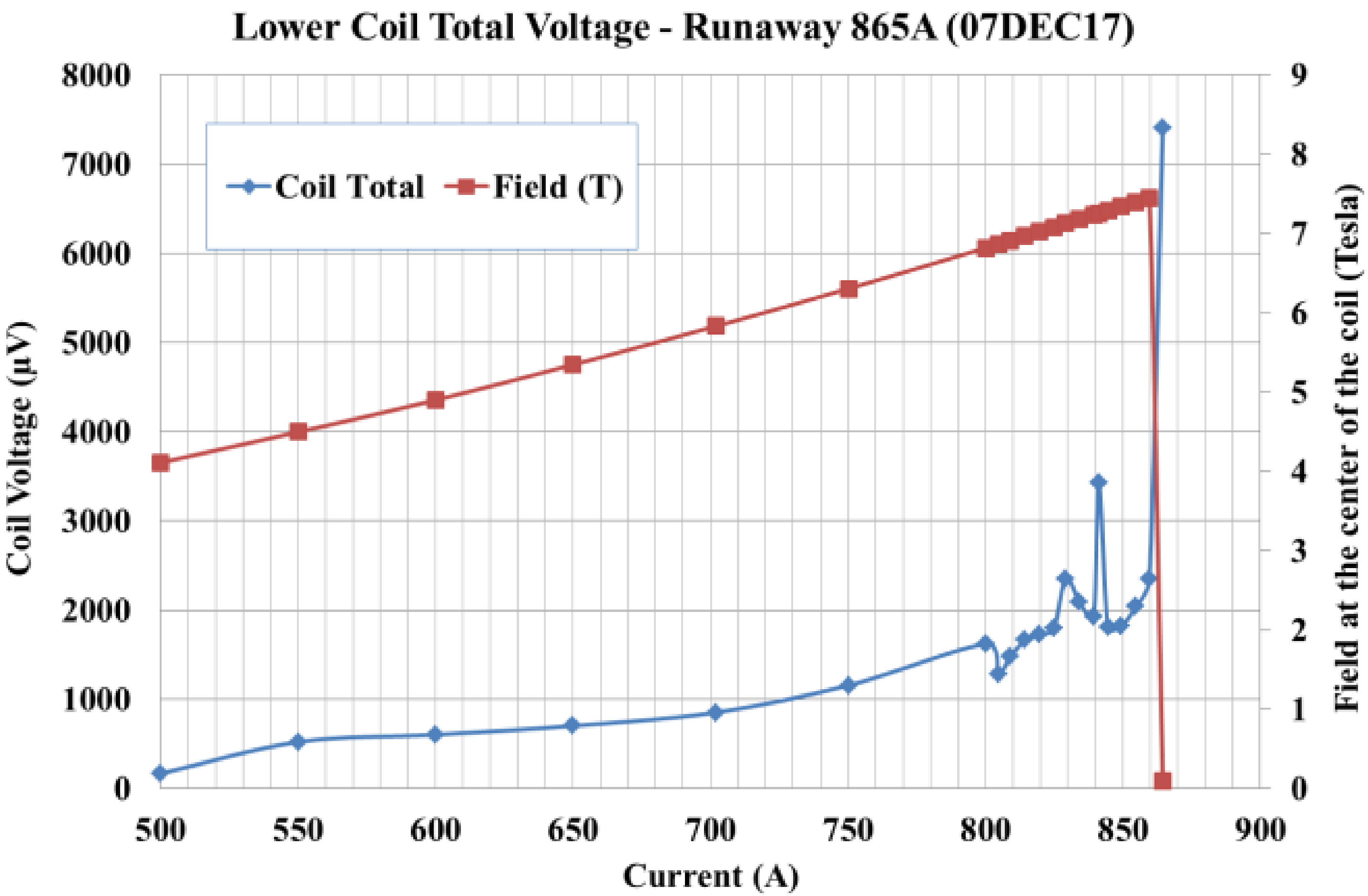


Test at Intermediate Temperature (20 K)



- Coil was allowed to runaway unprotected.
- Normal HTS coil would probably have been damaged.

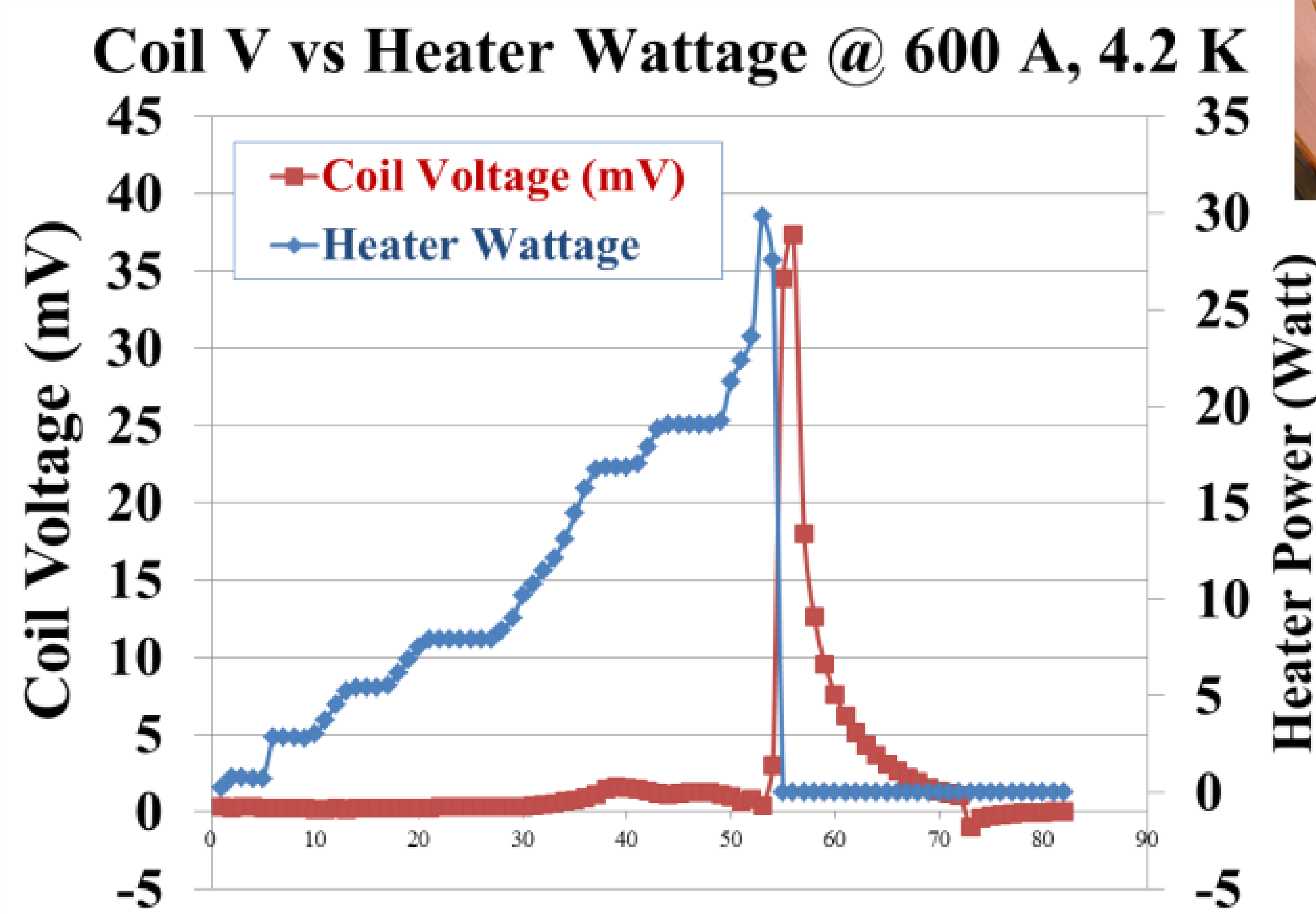
Test of Large Double Pancake Coil at 4 K

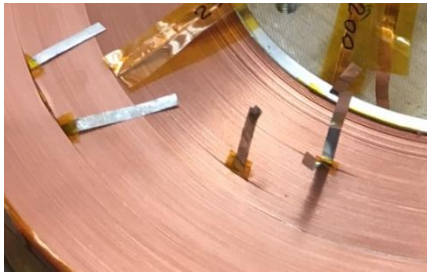


Further tests found no damage in coil

Peak field 11.2 T

Simulation of Large Local Defects (~30 W)





No degradation in the performance of the coil observed during further tests

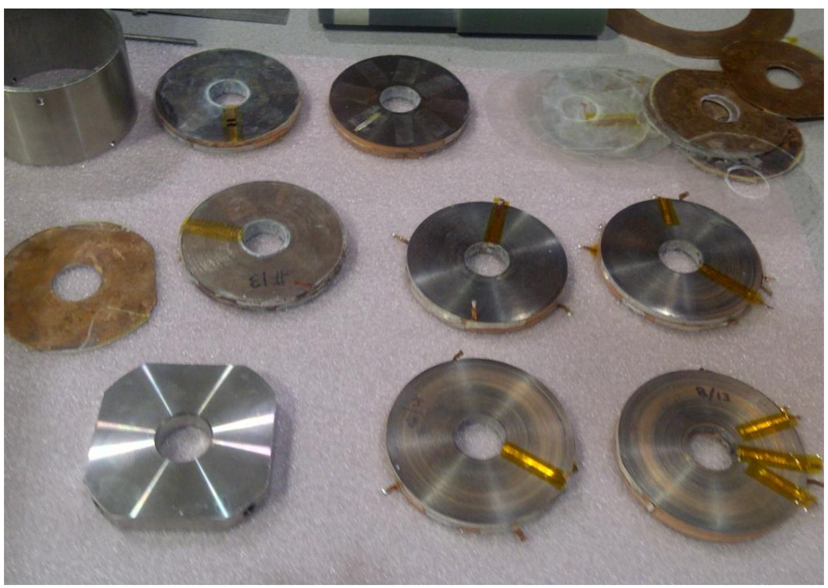
SUMMARY

- **Conductor specifications for such a high field, large aperture solenoid are primarily driven by the mechanical requirements. We already have HTS with sufficient critical current for such applications.**
- **No-insulation option offers the possibility of a reliable high field solenoid for ADMX.**
- **With about 200 HTS coils made using 60 km, 4 mm tape equivalent conductor, BNL has significant experience with the HTS magnet technology and in particular with the large aperture, high field HTS solenoids.**
- **Experience with a relatively large bore HTS and high field solenoids for SMES and IBS should directly help high field HTS solenoid development for ADMX.**
- **There is likely to be synergy in the magnet R&D needed for ADMX with the HTS solenoid being built for IBS.**

Backup Slides

Basic Design and Construction

- Pancakes coils are made with high strength 2G HTS from SuperPower, Inc.
- HTS tape is co-wound with Stainless Steel (SS) tape providing Metallic Insulation (MI). SS tape (instead of kapton, etc.) is used to handle hoop stress and to help in quench protection
- Cu discs are used between the double pancakes to reduce thermal gradient during cool-down of large assembly. Cu discs play a crucial role in quench protection
- No epoxy impregnation (only surface painted)
- A large number of v-taps for extensive 77 K QA testing



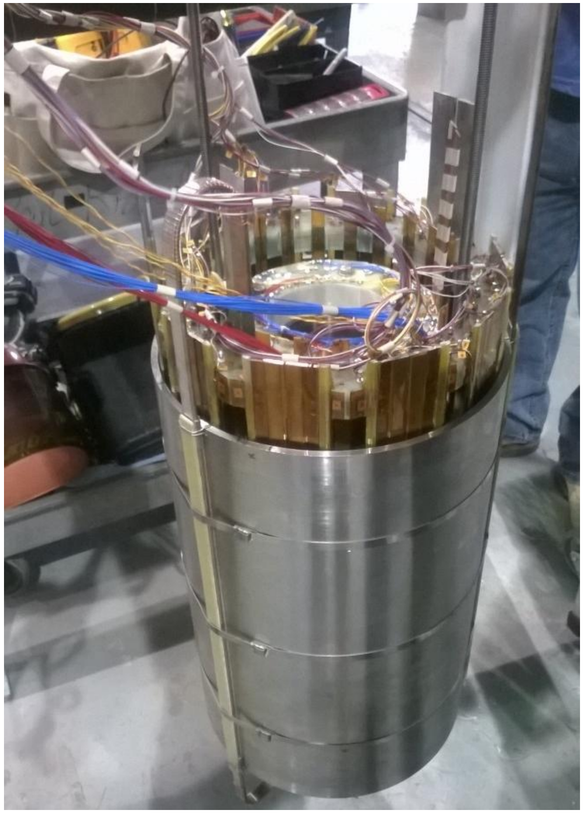
Pancakes

Insert solenoid

Midsert solenoid

Design Parameters of SMES 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



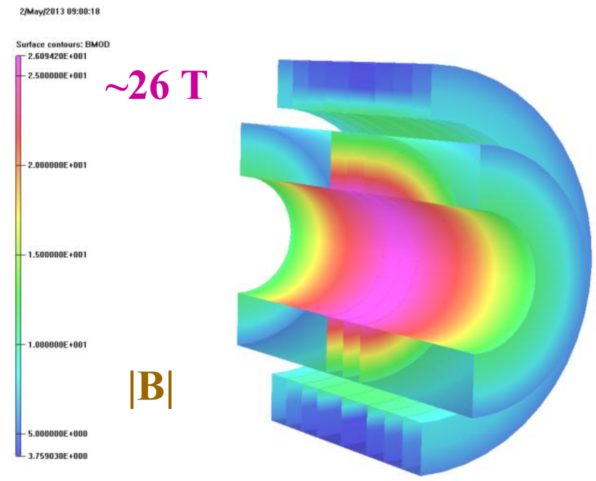
High field and big radius create large stresses (~400 MPa)

Basic Design of the SMES Solenoid

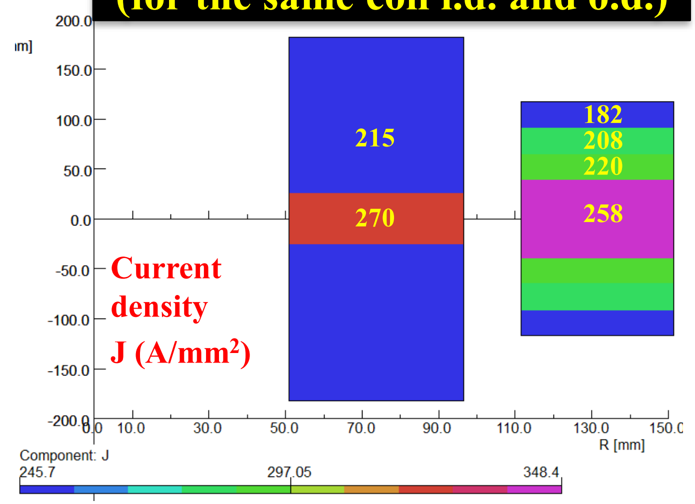
<u>**Coil winding adjusted for grading:**</u>

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

(more copper in ends; more SS in center)



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

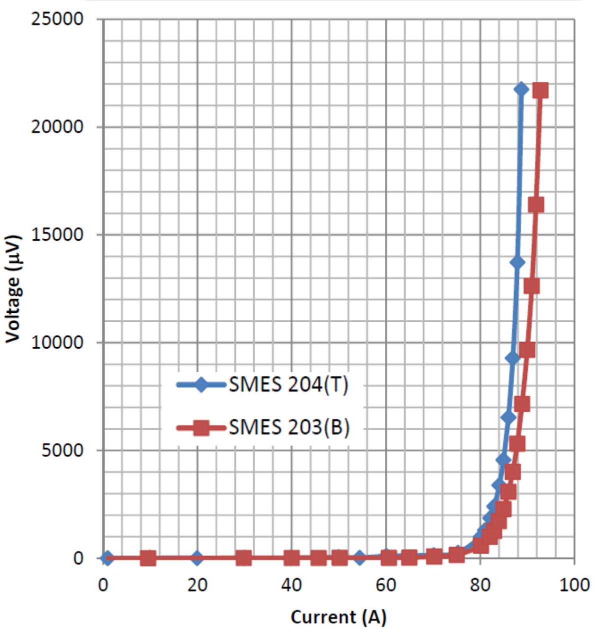


<u>**End Result : Improved performance**</u>

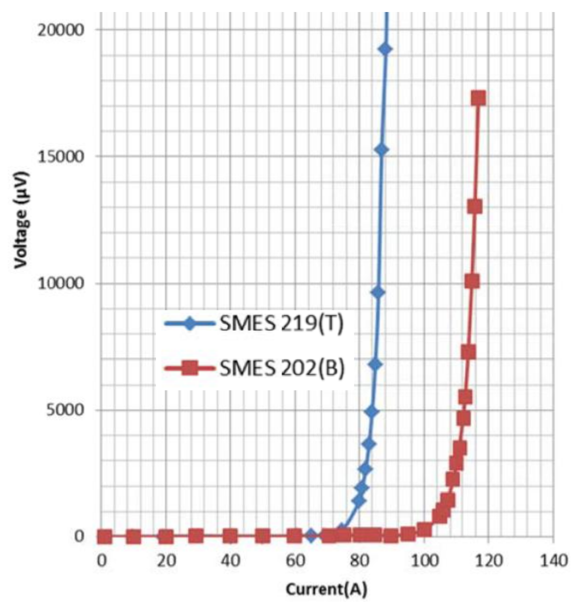
➢ **Reduced $B_\perp$ and better mechanical structure**

77 K QA Test of Double Pancake Coils

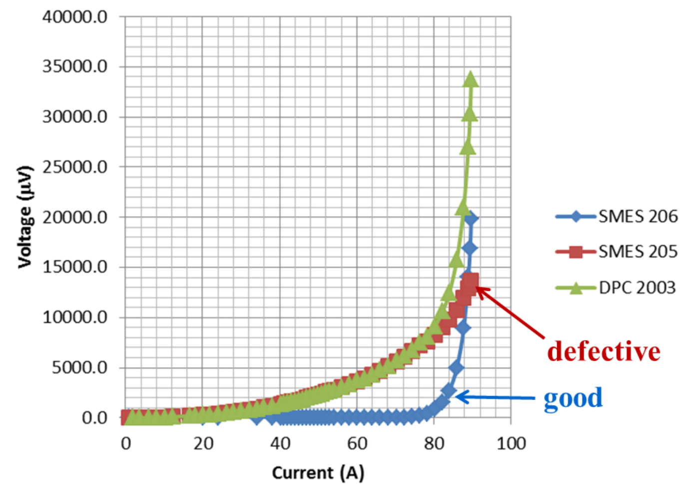
2 pancakes with similar critical currents

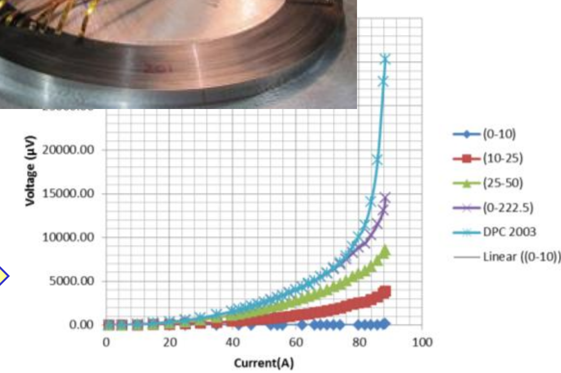


2 pancakes with very different critical current



one pancake good and other pancake defective



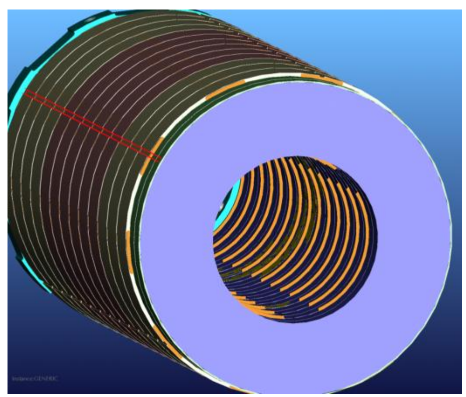


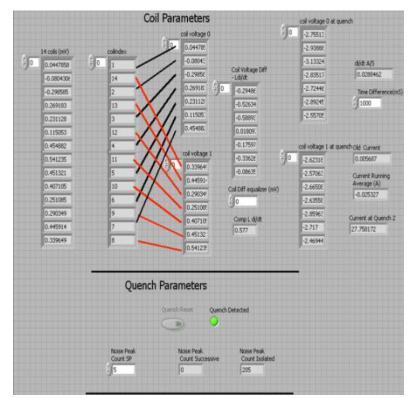
Note: Thorough 77 K test of each pancake was an important part of a series for QA

Quench Protection Strategy for SMES

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

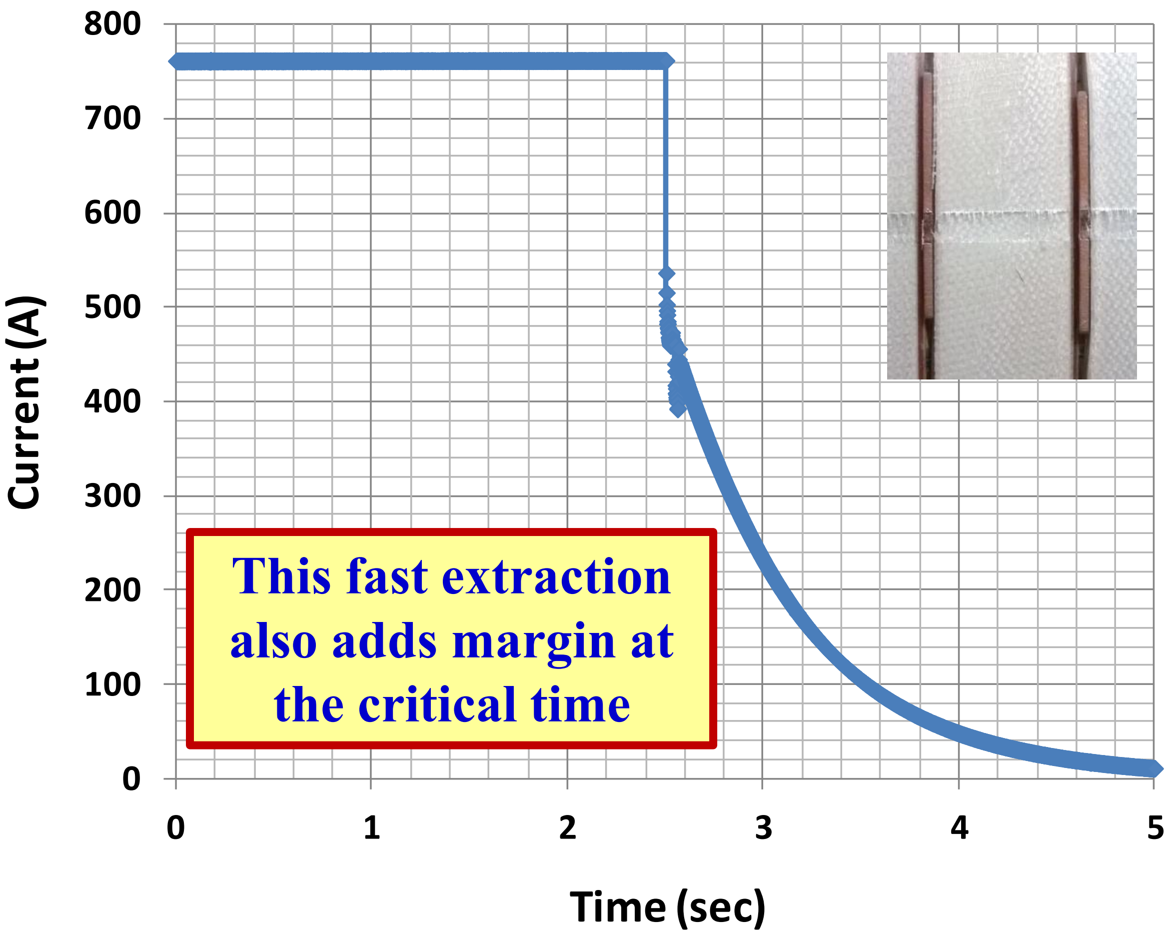
1. Stainless steel (metallic) turn-to-turn insulation to spread energy after the quench
2. Inductively coupled copper disks to transfer energy instantaneously out of HTS coils, heat up coils and reduce current to provide extra margin at a critical time
3. Sensitive electronics to detect resistive voltage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

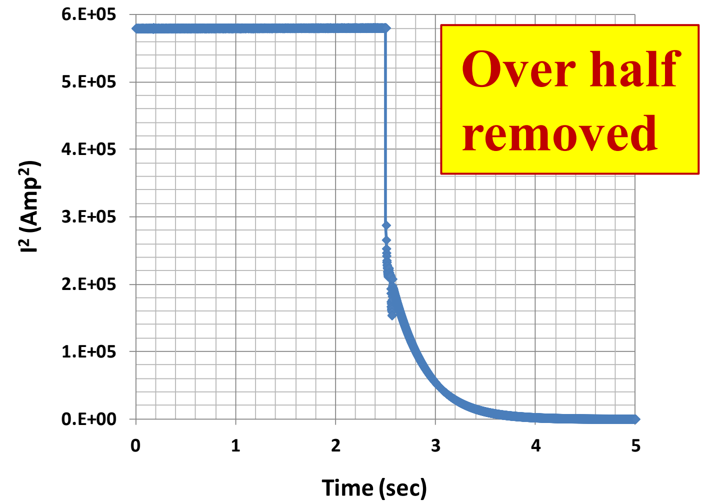


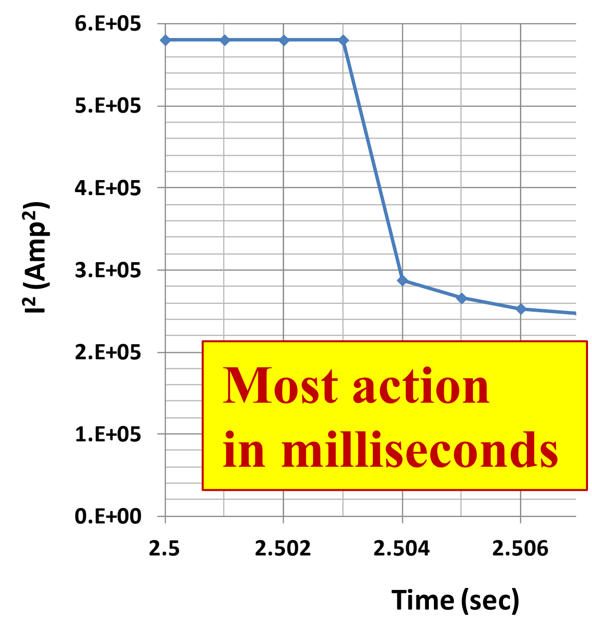


Copper Discs for Energy Extraction

Inductively coupled copper discs between two double pancakes





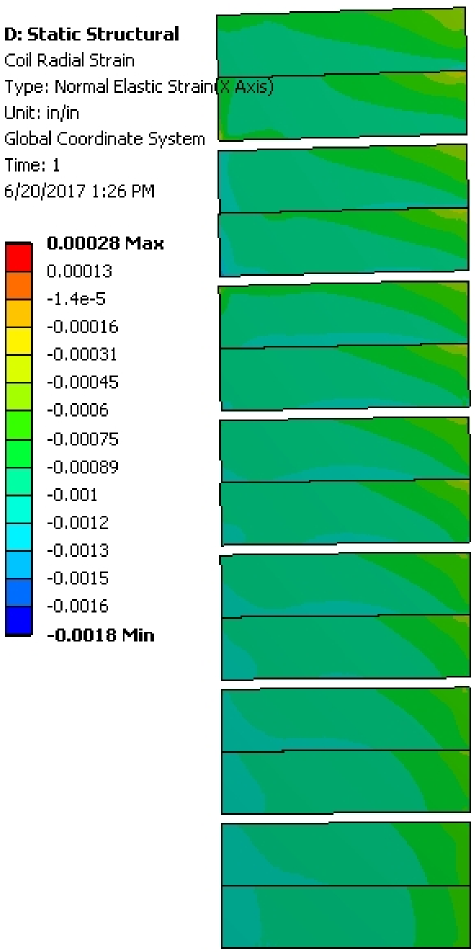


Conductor Selection

Considerations in selecting the conductor:

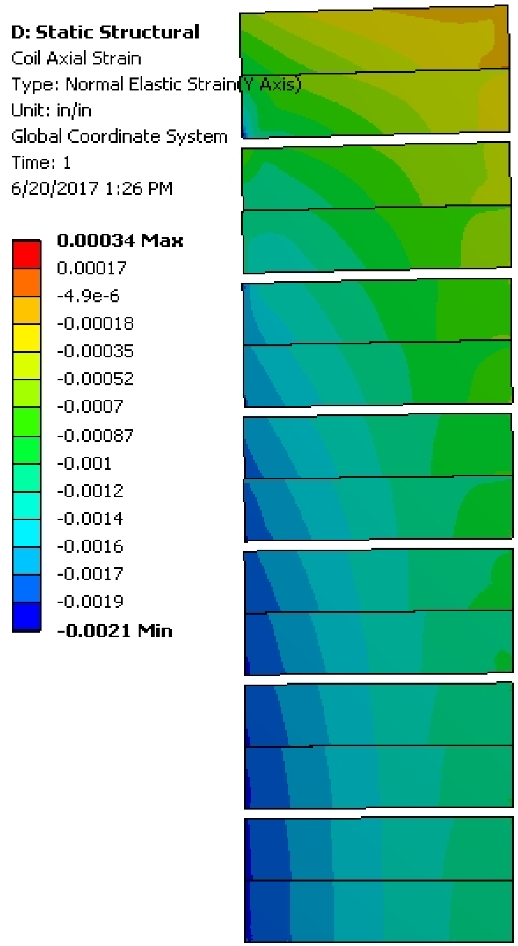
- ❑ Width of the tape : 2 mm to 12 mm
  - ✓ 12 mm gives larger current, smaller impact of local defect and fewer coils
- ❑ Choice of substrate: Hastelloy, SS, Ni and others
  - ✓ Hastelloy for the best mechanical properties
- ❑ Amount of copper : 20 micron to 100 micron
  - ✓ 20 micron gives the best mechanical properties; modelling to continue
- ❑ Critical current at high field: depends on the manufacturer
  - ✓ Need good (4K, high field) performance rather than (77K, self field)
- ❑ Previous delivery of similar conductor to BNL or elsewhere
  - ✓ Quotations from several conductor manufactures from around the world

Orthogonal Coil Strains @ 4 K, 25 T



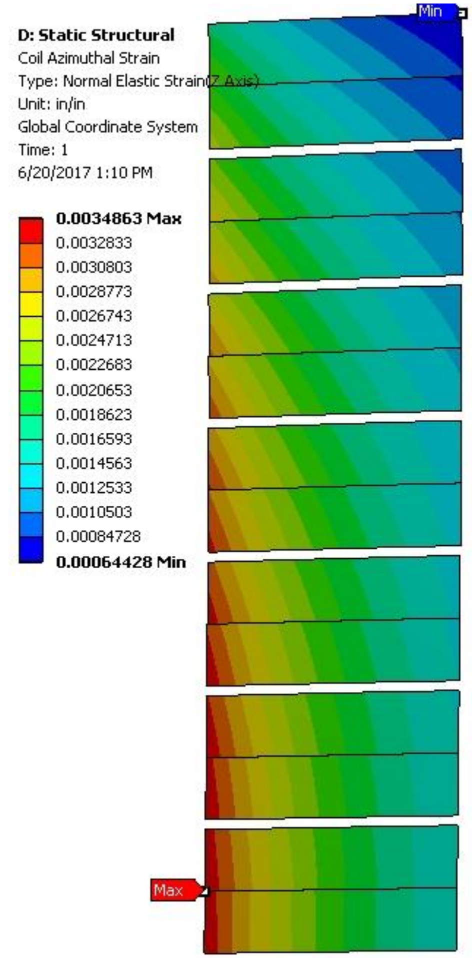
-.10% Max Strain

Radial +



-.21% Max Strain

Axial +



.35% Max Strain

Azimuthal

Conductor for 25 T, 100 mm HTS Solenoid for IBS

- Essentially all major 2G HTS vendors (foreign and domestic) already meet the critical current requirements with a sufficient margin.
- The design is limited by the mechanical properties. We didn't use higher J_c (though available), as that increases stresses.

Quoted	Reference	Target
12mm	12mm	4mm
4K, 8T	77K, sf	30K, 2T
675	300	289
775	350	332
875	400	375
975	450	418

We are buying the conductor with the lowest spec (and the lowest cost) as this will still gives a 50% margin (→ row 675 / 300 / 289)

In reality, the margin will be even higher as SuperPower makes the conductor in the similar way. Also we can sort based on the location and (30K, 2T) measurements

Moreover, most places field is parallel => higher margin

(backup slide for more on conductor)

New Apparatus to Apply 300 MPa Load on the Narrow Side (design needs 200 MPa)