Superconducting
Magnet Division

High Field Solenoid Magnets

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- **Summary of HTS magnet program at BNL**
  - Design, construction and test results
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- **Summary/Outlook for CAPP high field solenoid**

Motivation for High Field Solenoid (slides from Yannis Semertzidis)

What's there to improve over ADMX?

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L$$

- B^2, energy density
- Q, resonator quality factor
- B-field/resonator volume V
- Ampl. noise/physical temperature, S/N

21

(CAPP) Axion dark matter plan

- We have started an R&D program with BNL for new magnets: goal 25T; then 35T. Currently all axion experiments are using <10T.
- Based on high T_c cables (including SuNAM, a Korean high T_c cable company). ~5 year program.

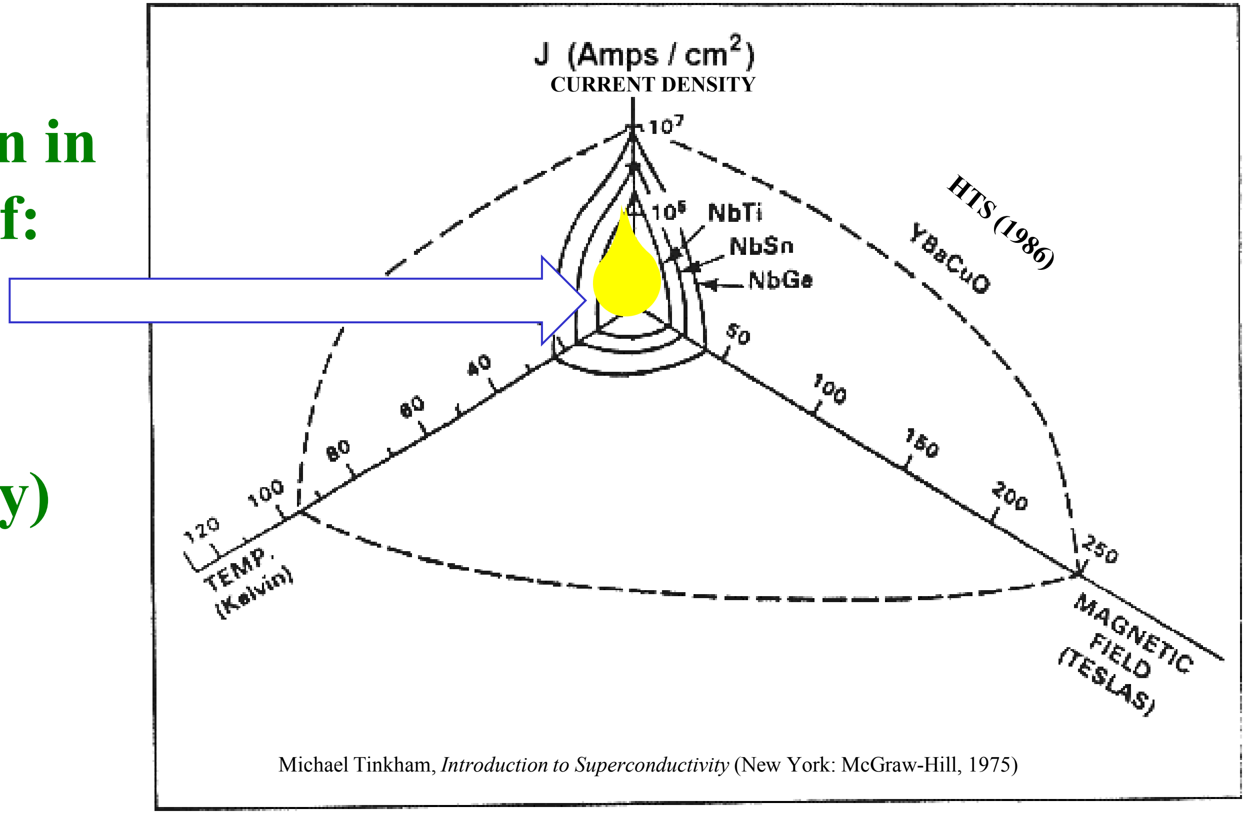
B-field possibilities

- Magnetic field B:
  - Develop 25T magnet.
  - 35T magnet based on high T_c.

Phase space for Superconducting Magnets

Superconductor in magnets must remain in the captive volume of:

- **Field**
- **Temperature**
- **Current (density)**



Phase Diagram

Conventional superconductors (NbTi and Nb_3Sn) generally operate at 4 K and applications rely on liquid helium for cooling

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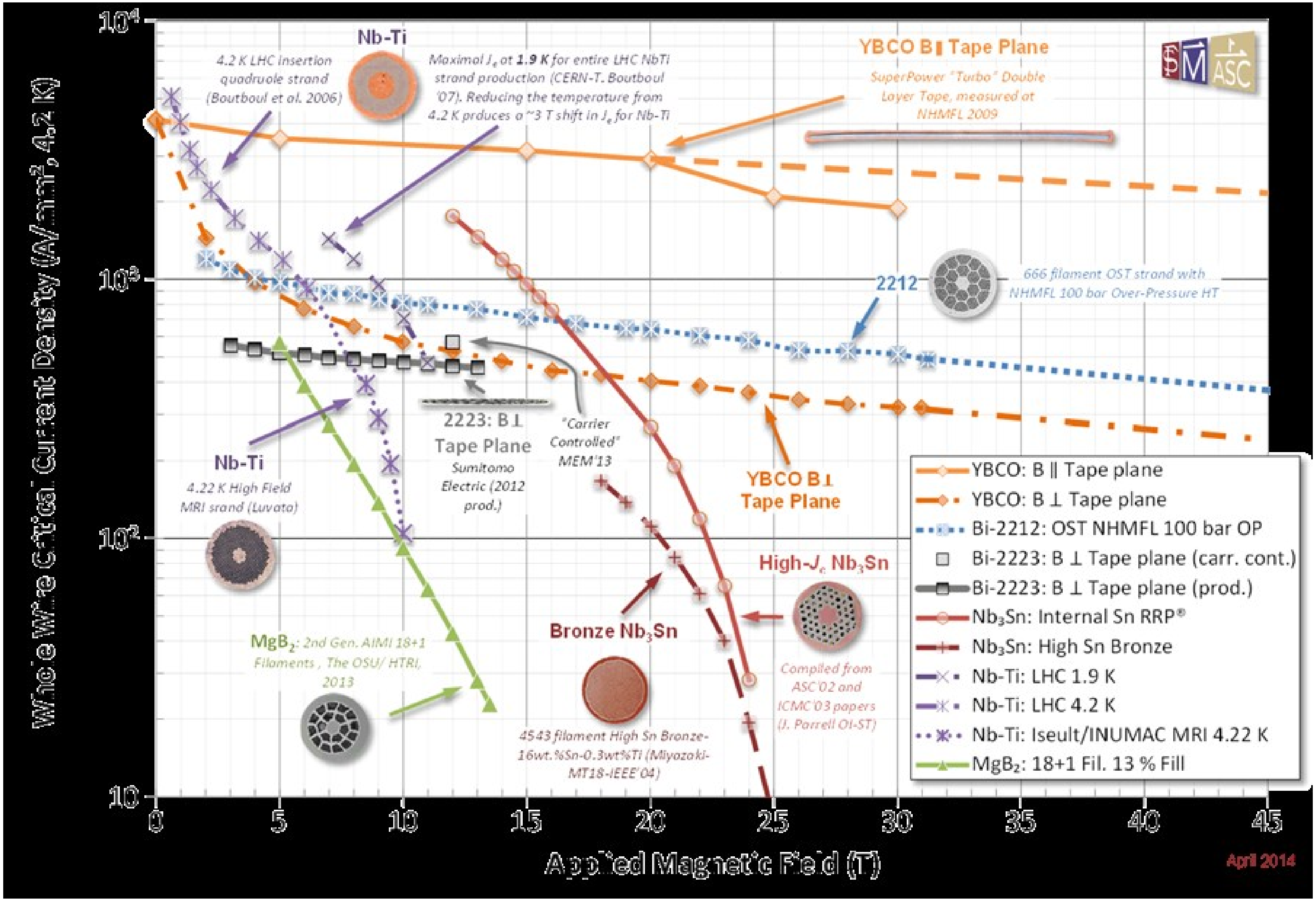
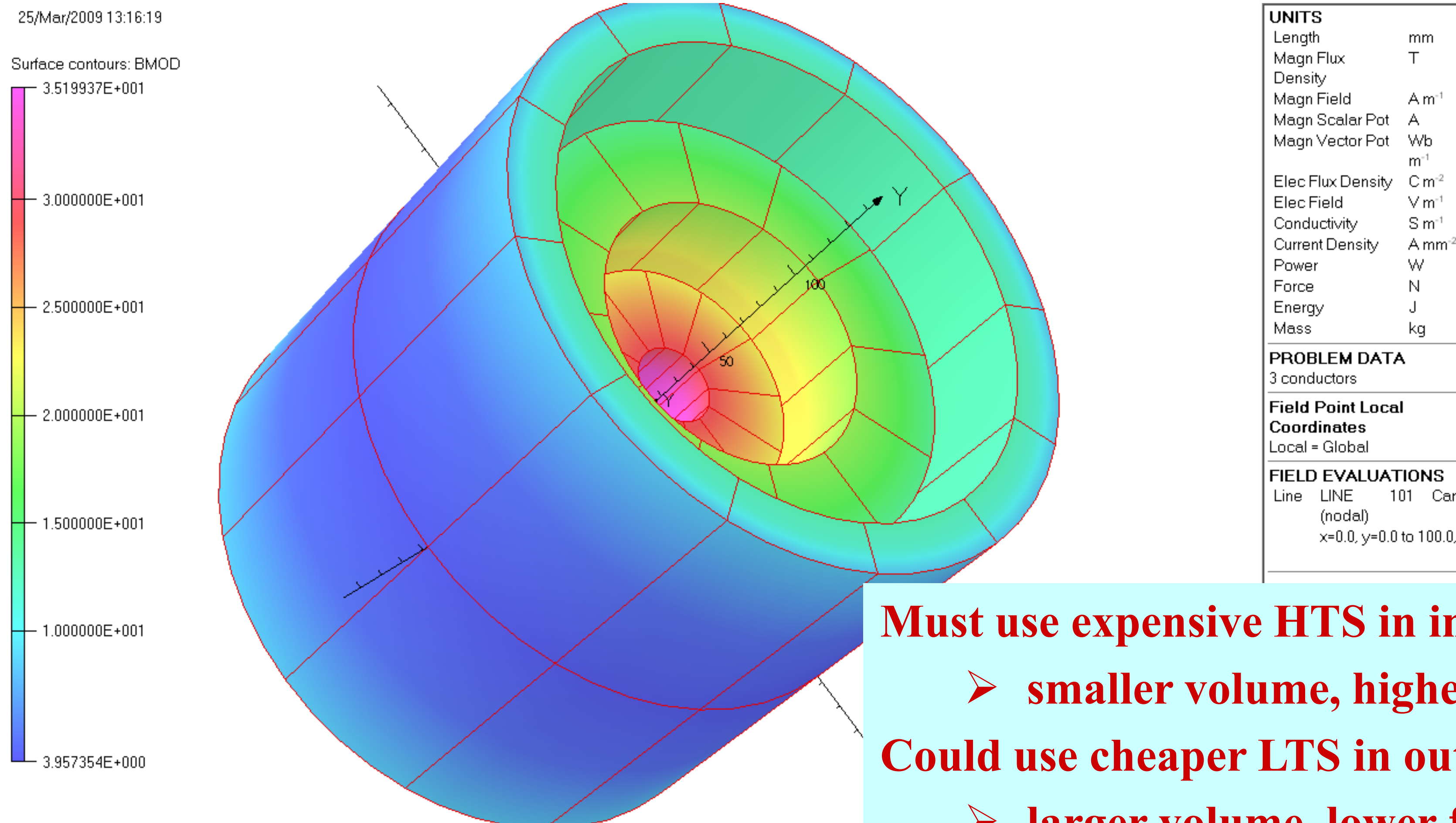
High Temperature Superconductors (HTS) are also High Field Superconductors (HFS)



A 35 T Hybrid (HTS/LTS) Design



Must use expensive HTS in inner

- ➢ smaller volume, higher field

Could use cheaper LTS in outer

- ➢ larger volume, lower field

❖ **HTS is the driver; however, HTS/LTS hybrid may eventually be more realistic on cost consideration, if the operation can be at ~4K**

HTS Magnet Programs at BNL (1)

- BNL has been active in developing HTS technology for well over a decade.
- We have used all types of HTS
  - Bi2212 (tape and Rutherford cable)
  - Bi2223
  - MgB_2
  - YBCO (Second Generation)
- We have used about 50 km of HTS (normalized to the standard 4 mm tape equivalent) for various programs.
- We have designed, built and tested a large number of HTS coils and magnets at a temperature range of ~4 K to ~80 K.

HTS Magnet Programs at BNL (2)

- HTS magnet R&D on a wide range of programs:
  - High B, low T (similar to what is needed at CAPP/IBS)
  - Medium B, medium T (similar to what is needed at RISP/IBS)
  - High T, low B (many applications, only with HTS)
- We also have major program on magnets with conventional Low Temperature Superconductors (LTS) – NbTi and Nb_3Sn
- These varieties of programs help each other in developing a wider perspective while optimizing designs and sharing resources

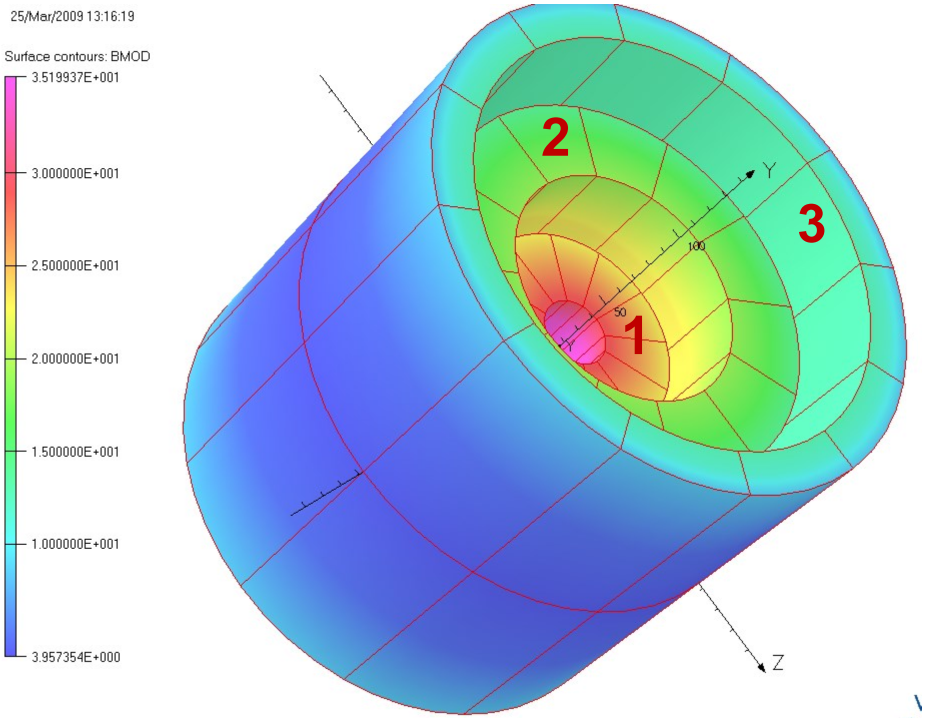
High Field HTS Solenoid Programs (1)

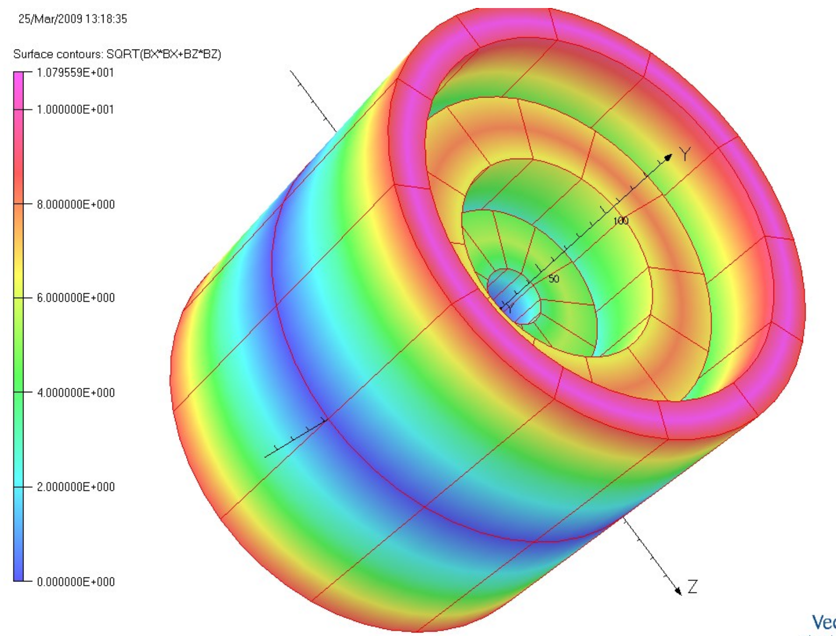
BNL/PBL Collaboration for Muon Accelerator Program (MAP)

Path to 30+ T Solenoid

Modular R&D approach consisting of three coils:

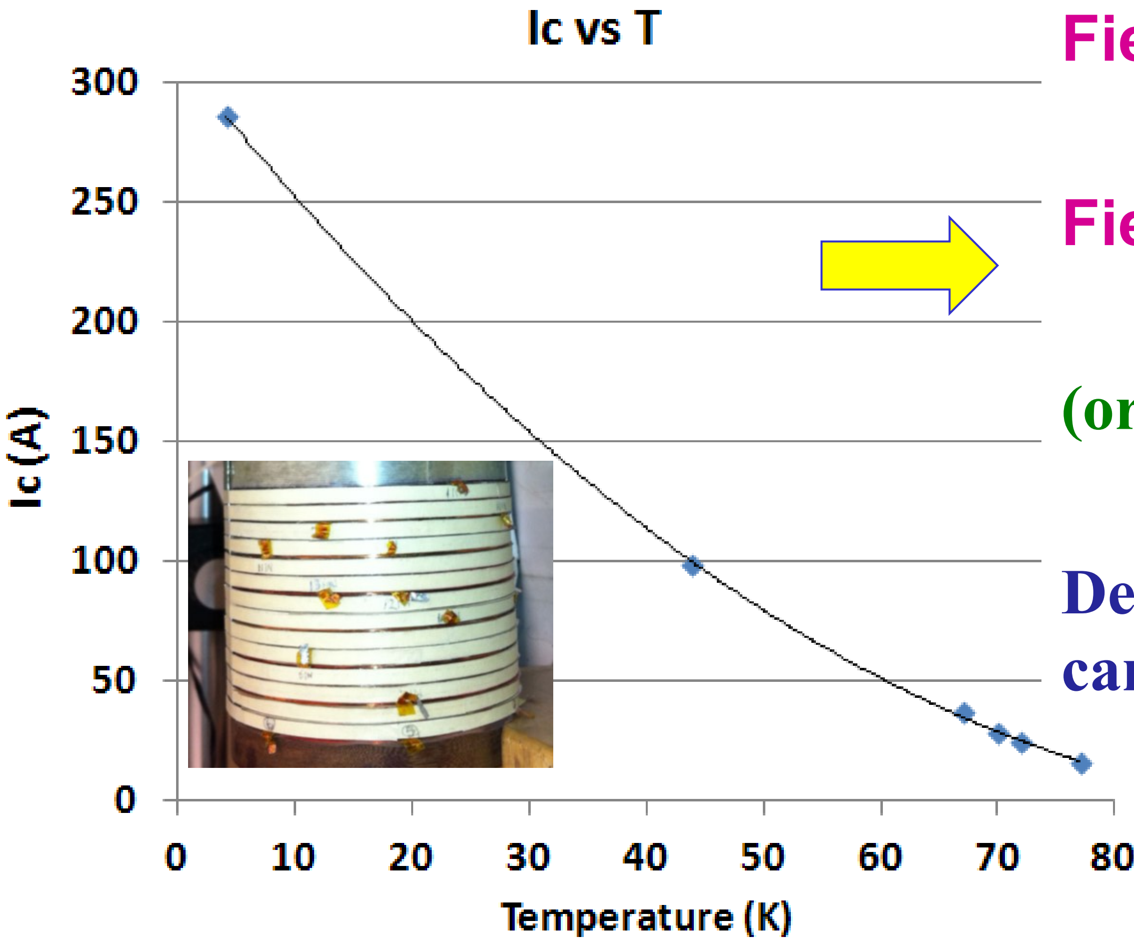
1. Design >12 T HTS; Demonstrated ~16 T
2. >10 T HTS solenoid; Demonstrated in ½ coil >6 T (>9 T peak)
3. >8 T LTS; Demonstrated ~7 T in a separate BNL program





Field Perpendicular

High Field HTS Solenoid Test Results (magnet #1 - insert)



Field on axis:
- over 15 T

Field on coil:
- over 16 T

(original target was 10-12 T)

Demonstration that HTS can create high fields

Overall J_o in coil:
> 500 A/mm^2 at 16 T
(despite anisotropy)

~25 mm PBL/BNL solenoid, 14 pancakes, 700 meters of HTS from SuperPower

NbTi (or Nb3Sn) Outer Solenoid

Parameters	Value
Wire, bare	1.78 mm X 1.14 mm
Wire, insulated	1.91 mm X 1.27 mm
Wire I_c specification (4.2 K, 7 T)	>700 A
Turn-to-turn spacing (axial)	1.98 mm
Turn-to-turn spacing (radial)	1.42 mm
Number of layers (main coil)	22 (11 double layers)
Additional trim layers in ends	4 (2 double layer)
Length of additional trim layers	173 mm on each end
Coil inner diameter	200 mm
Coil outer diameter	274 mm
Coil length	2360 mm
Yoke length	2450 mm
Maximum design field	6 T
Current for 6 T	~440 A
Peak Field on the conductor @ 6 T	~6.5 T
Computed Short Sample @4.2 K	~7.0 T
Stored energy @ 6 T	~1.4 MJ
Inductance	~14 Henry
Yoke inner diameter	330 mm
Yoke outer diameter	454 mm
Operating field (on the axis)	1 T to 6 T
Relative field errors on axis	$<6 \times 10^{-3}$

- **Two NbTi solenoids were built and tested to 6.6 T for BNL/RHIC e-lens (test stopped 10% above design field)**
- **Nb_3Sn will give higher field but require reaction facilities (ReBCO comes pre-reacted)**

High Field HTS Solenoid Programs (2)

Superconducting Magnetic Energy Storage (SMES)

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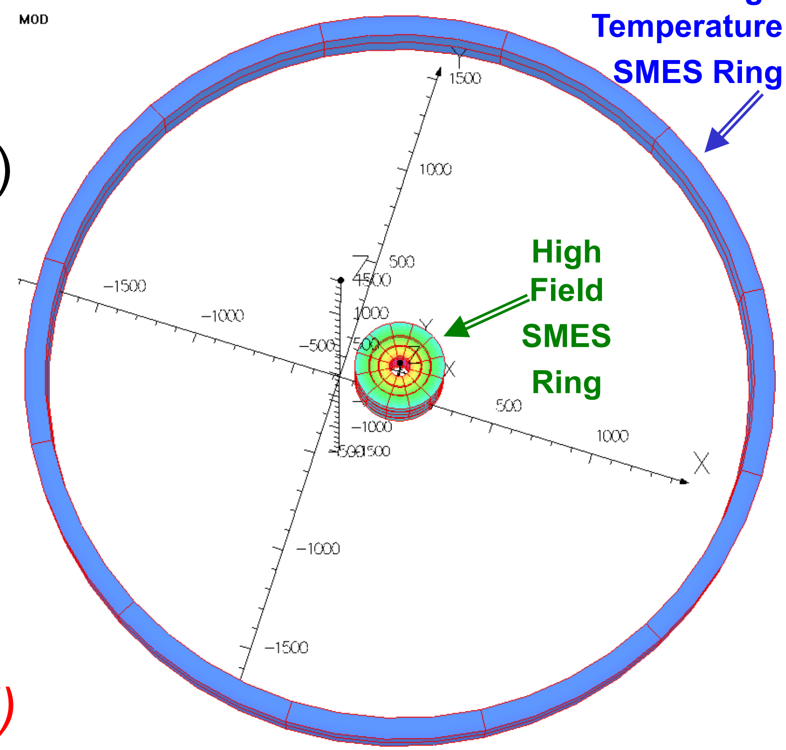
SMES Options with HTS

- ➢ **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

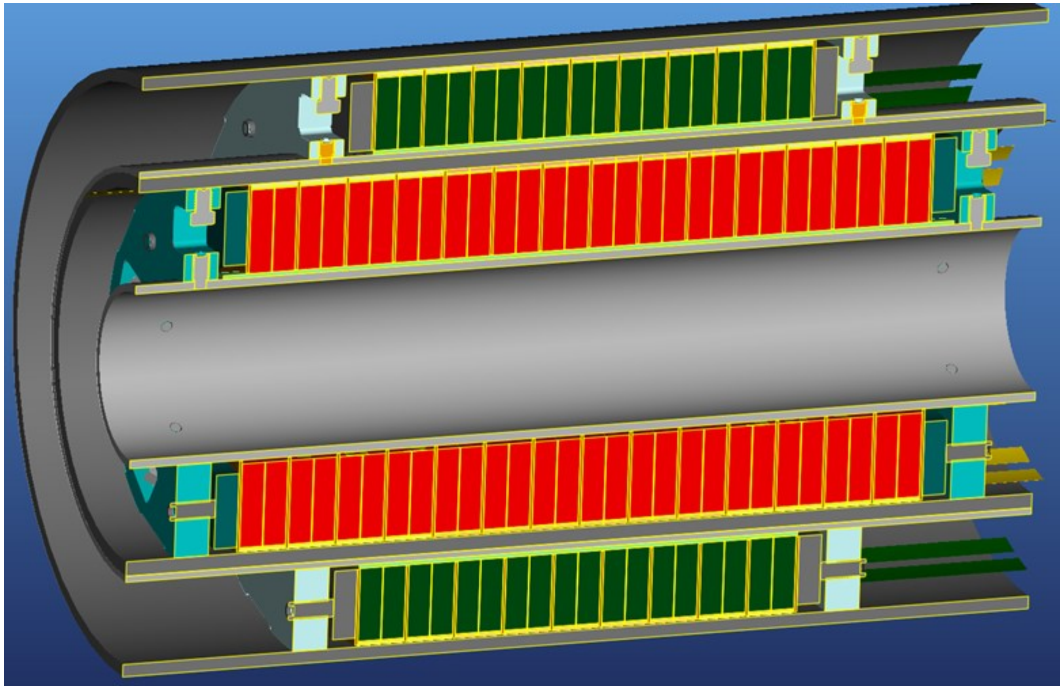
High field HTS could be game changer:

✓ 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:

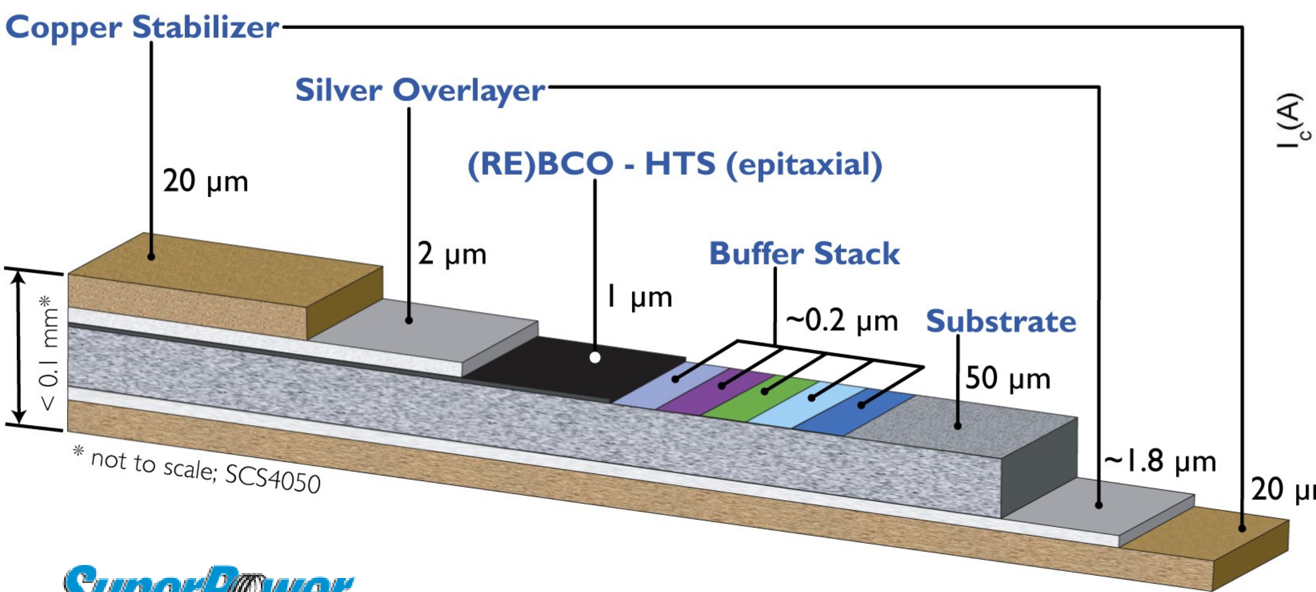
Field: 25 T@4 K (more than ever)

Bore: 100 mm (large)

Hoop Stresses: 400 MPa (>2X)

Conductor: ReBCO (evolving)

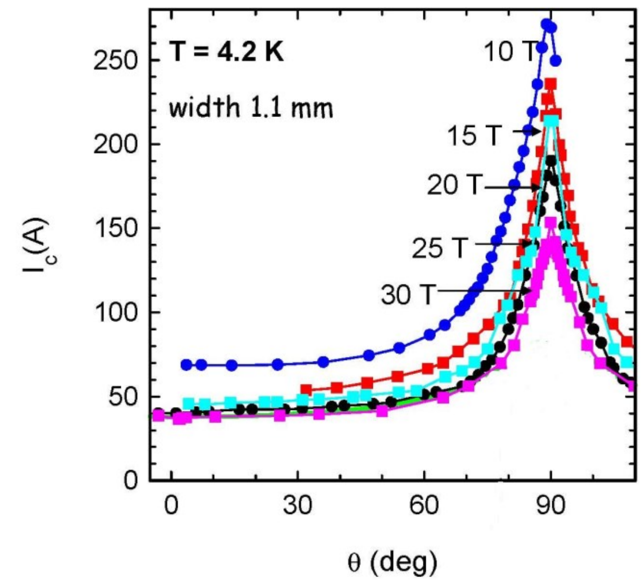
Conductor – ReBCO Tape



SuperPower Inc. A Furukawa Company

HTS tape: angular dependence

Measurements at NHMFL (earlier sample)



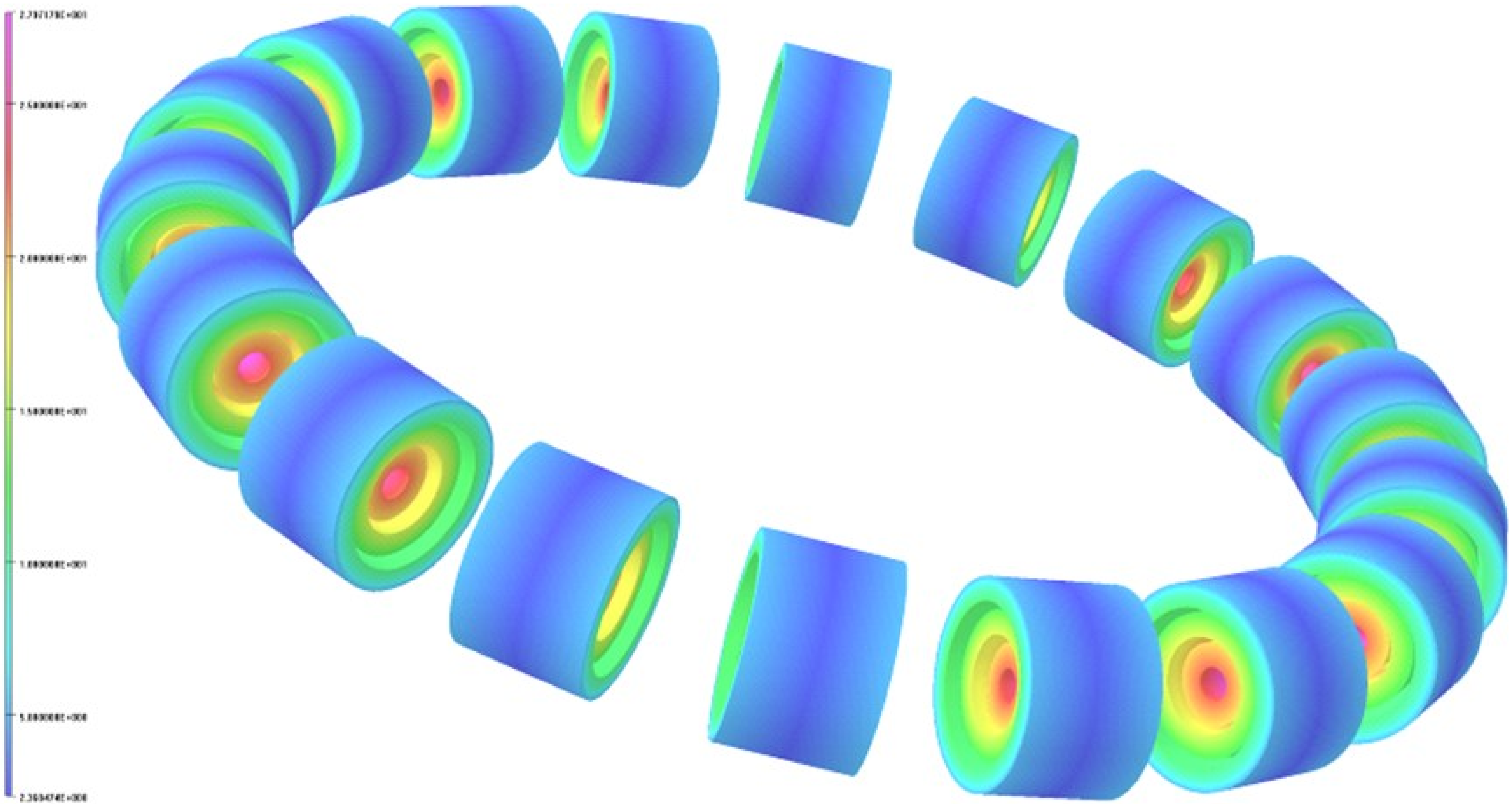
<u>SMES specs (12 mm)</u>:

>700 A@4K

(at any angle)

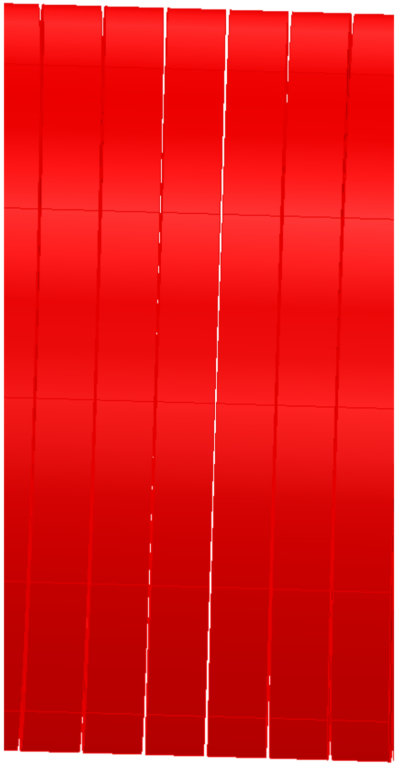
12 mm wide ReBCO tape with high strength hastelloy substrate

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 of the Basic Module

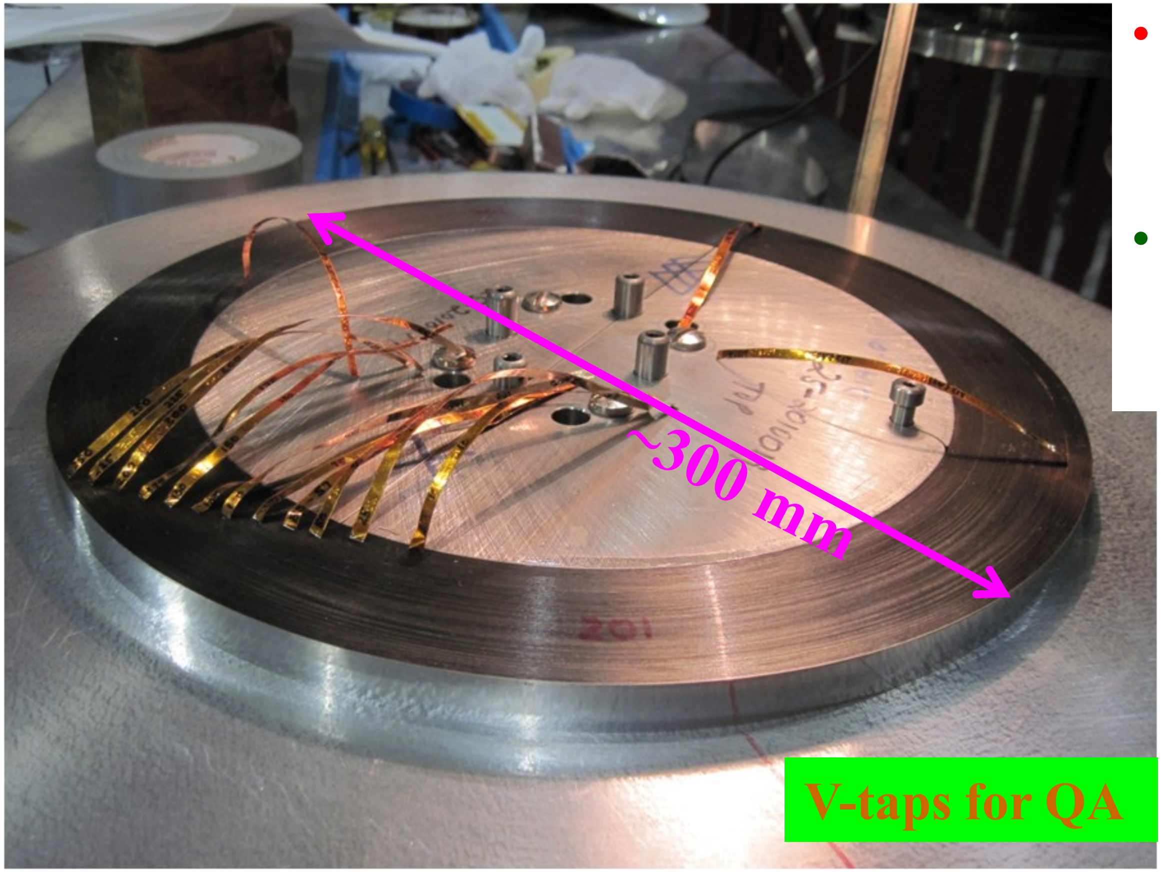
The High Field Solenoid

Parameters of the SMES Solenoid

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

Very Similar Design and Technologies that are needed for CAPP/IBS solenoid

HTS Single Pancake

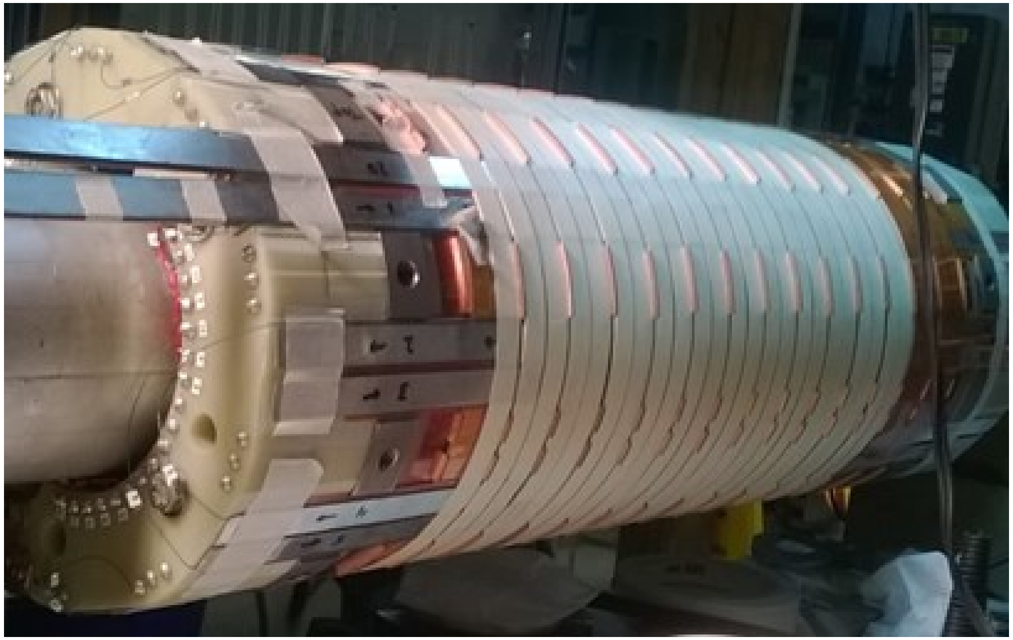


- High strength HTS tape, co-wound with SS tape (for insulation and added strength)
- Thickness of SS tape and copper on HTS adjusted to optimize the performance

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

Two Pancakes Connected with Spiral Splice Joint

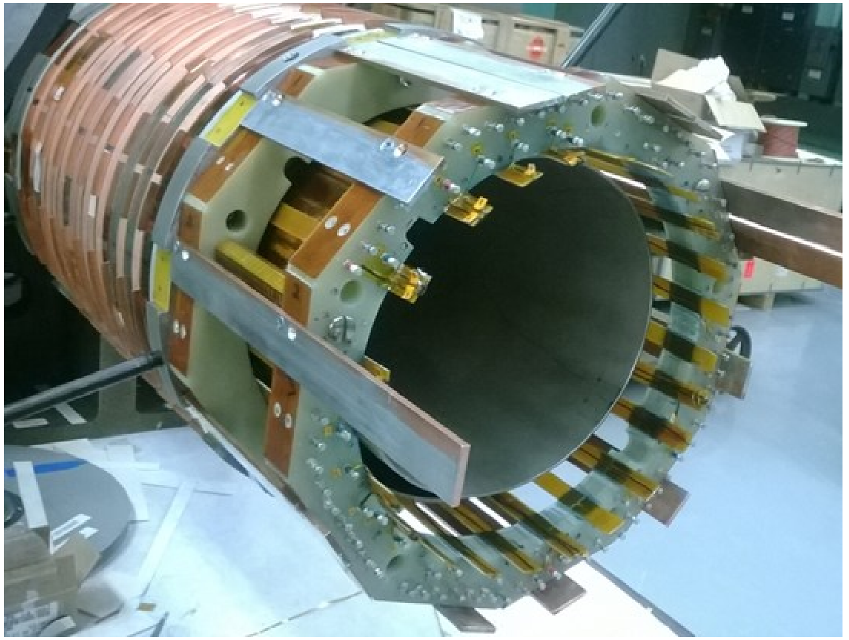
Inner and Outer Coils Assembled



Inner Coil

(102 mm id, 194 mm od)

28 pancakes



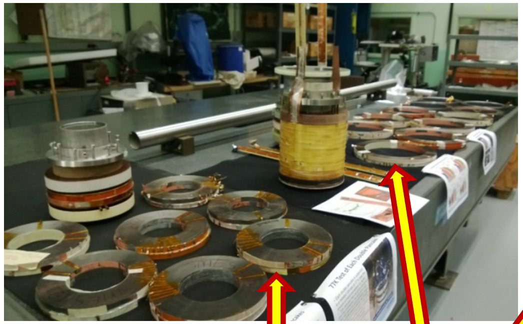
Outer Coil

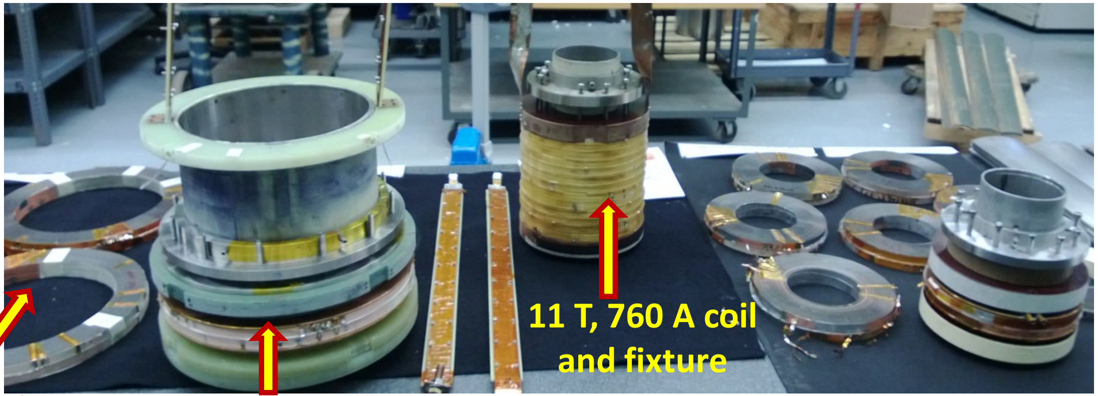
(223 mm id, 303 mm od)

18 pancakes

Total: 46 pancakes

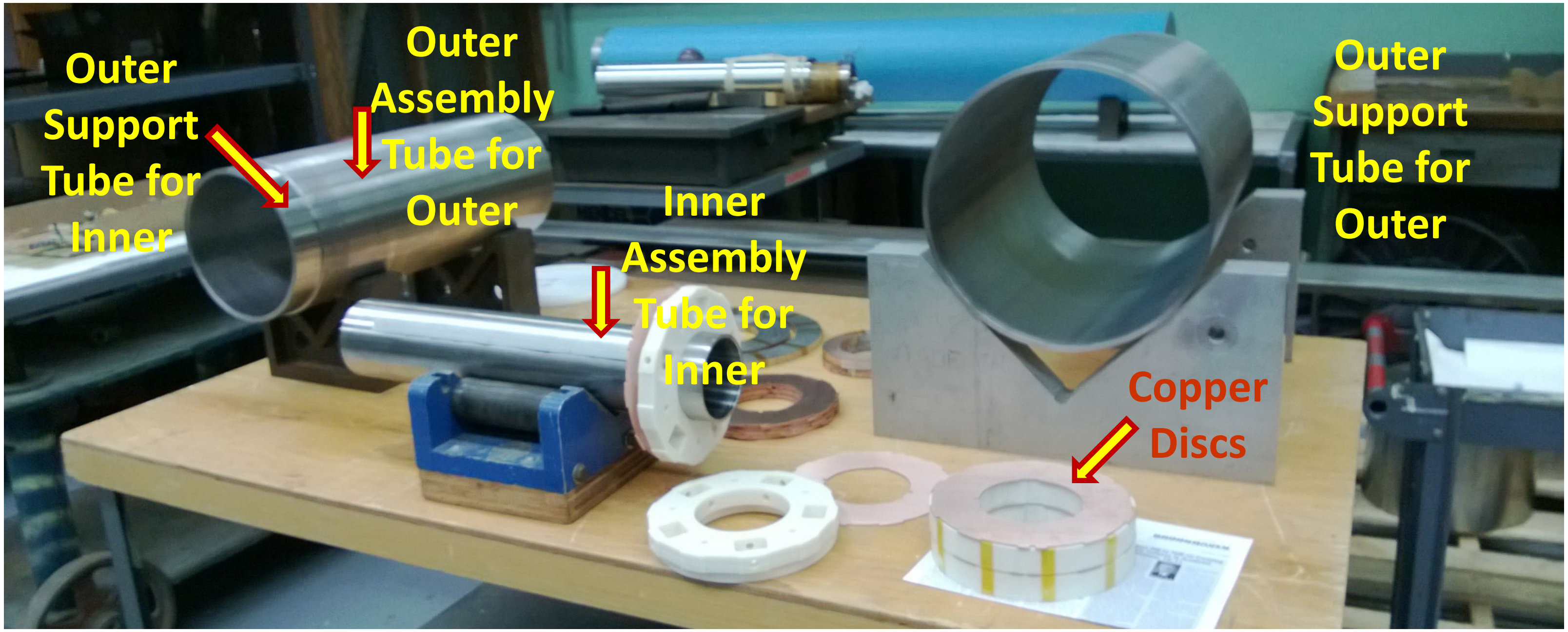
Coils, Test Fixtures and Support Structure



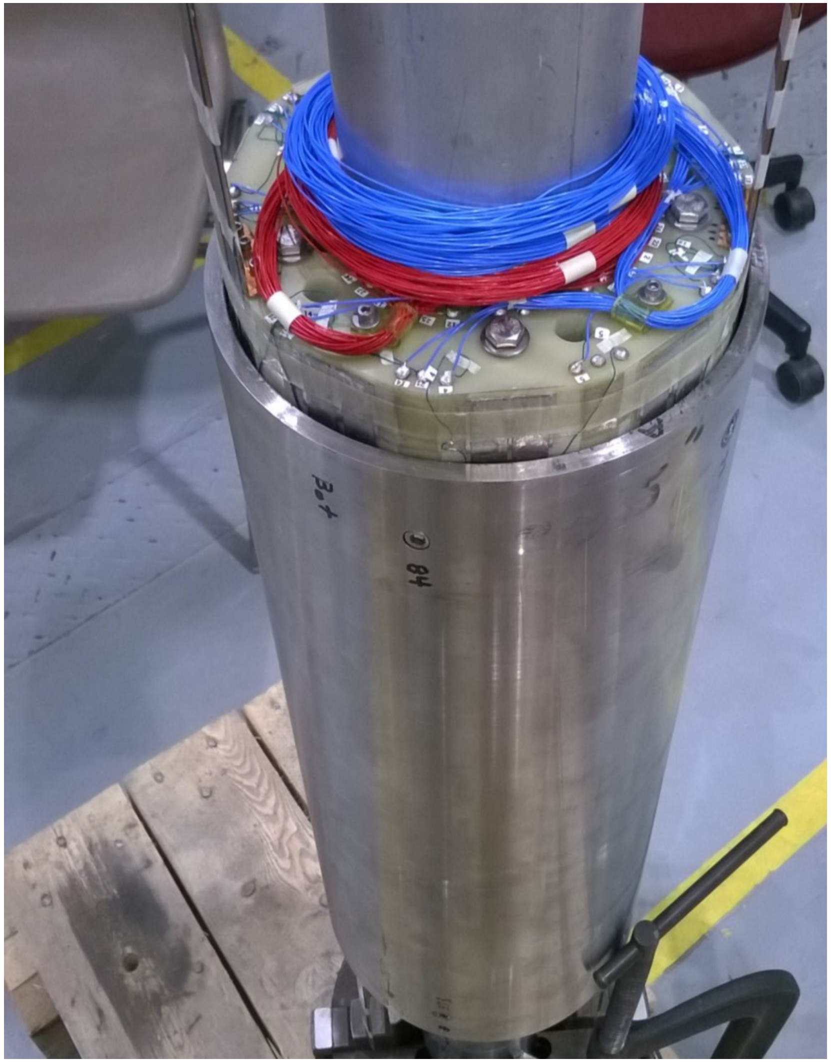


Pancake coils: inner and outer

77 K Test Fixture for outer



Inner and Outer Coils



Inner (in support tube)

Outer (prior to support tube)

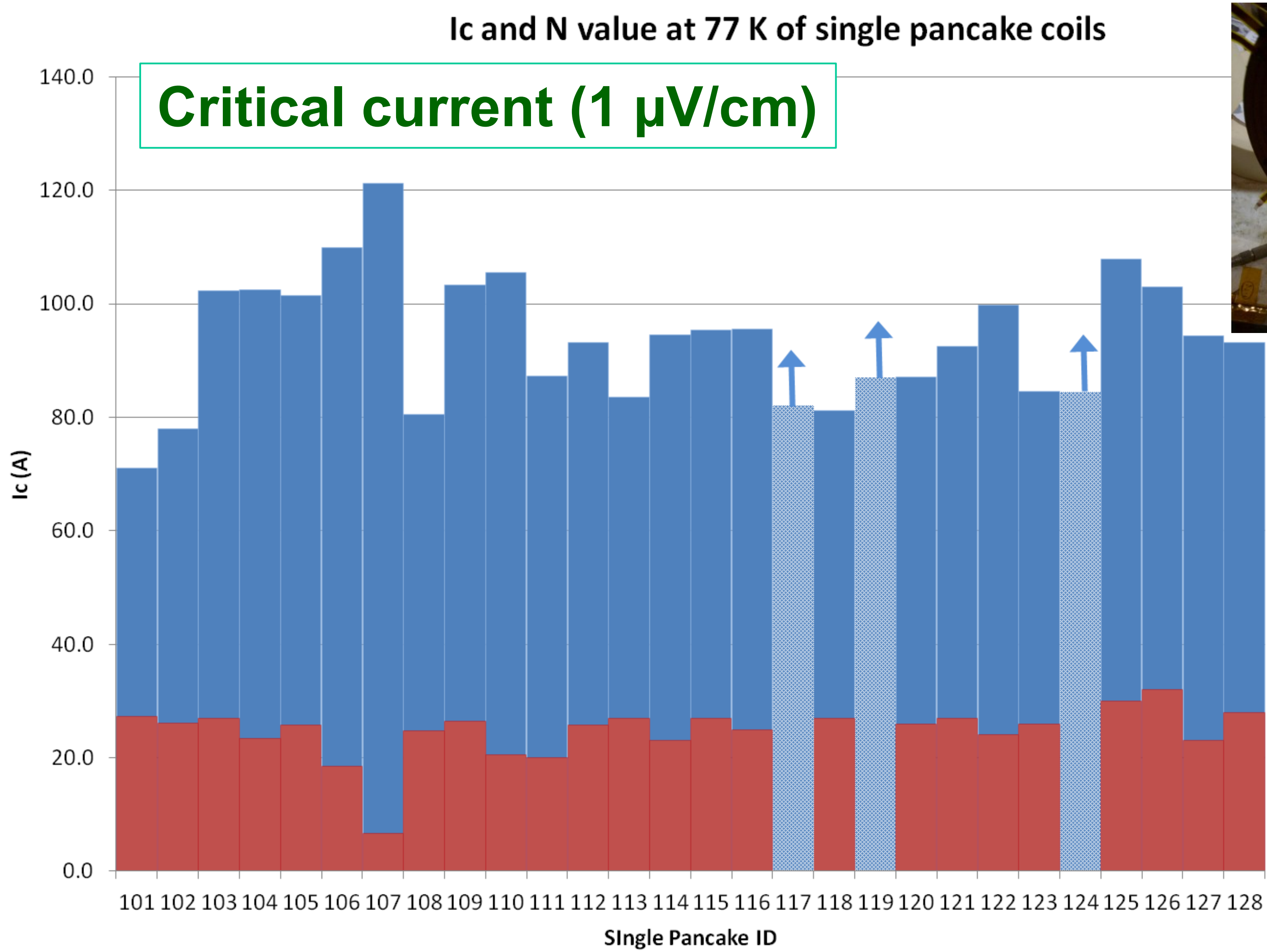
Final Assembly

Outer inserted over inner coil

SMES coil in iron laminations

Test Results

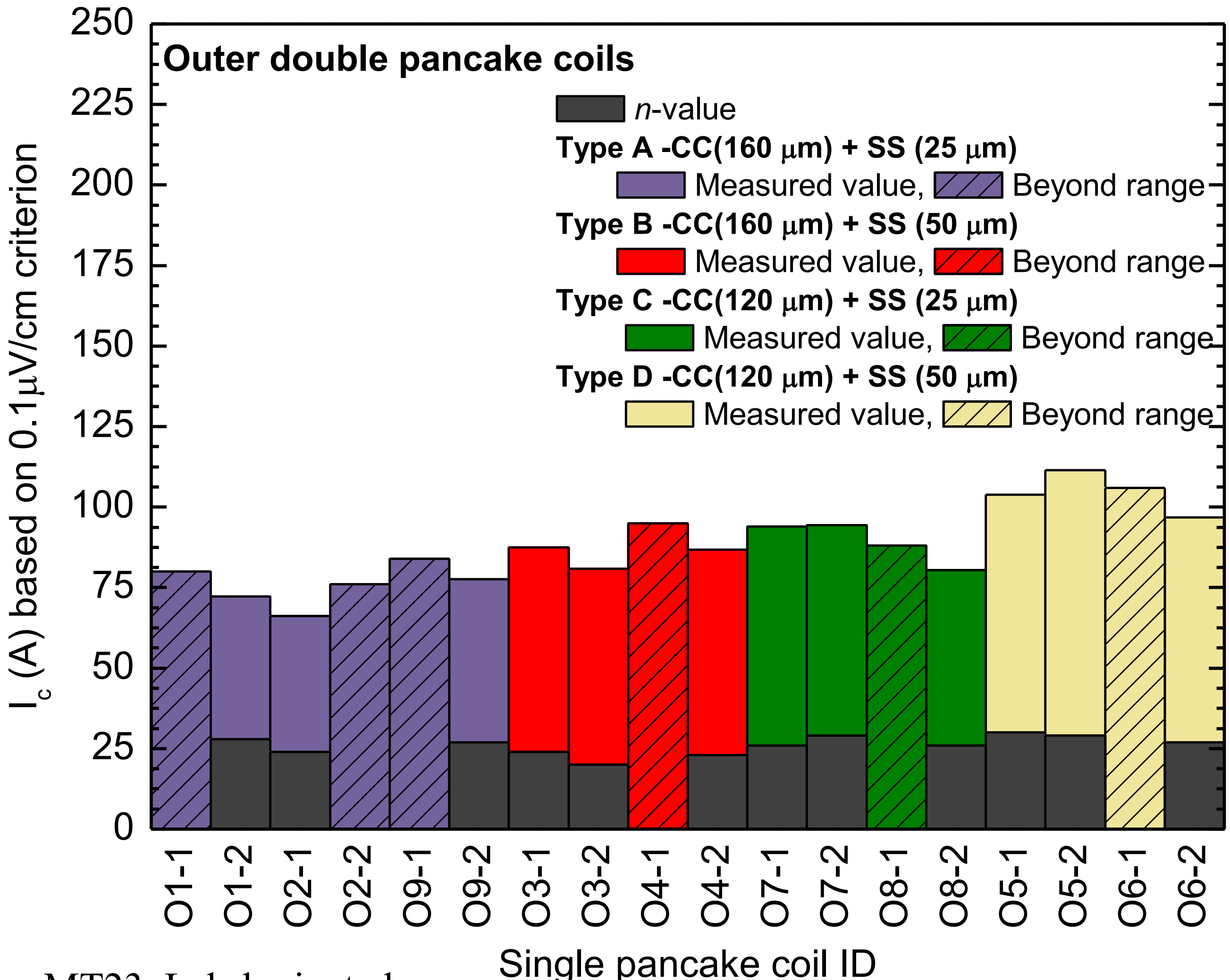
77 K Test of a Series of Double Pancakes (inner)



Two single pancakes powered in series.

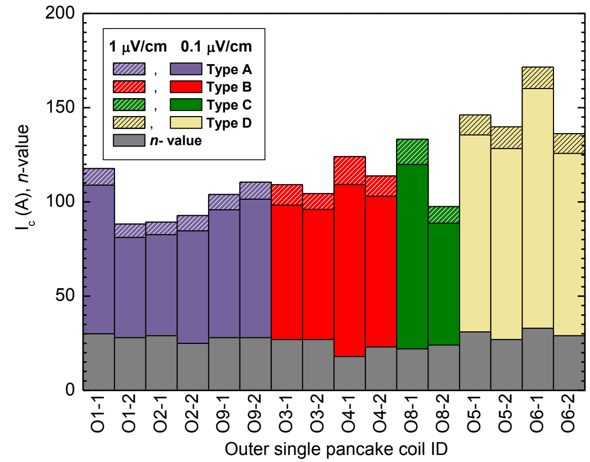
77 K Test of a Series of Double Pancakes (outer)

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)

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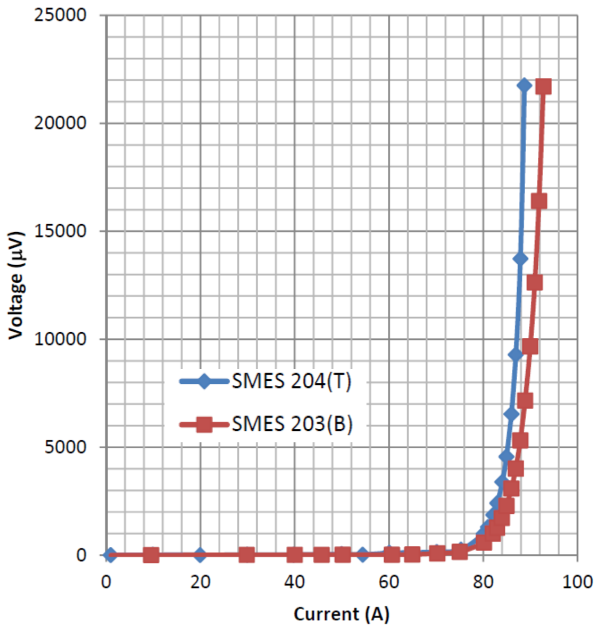
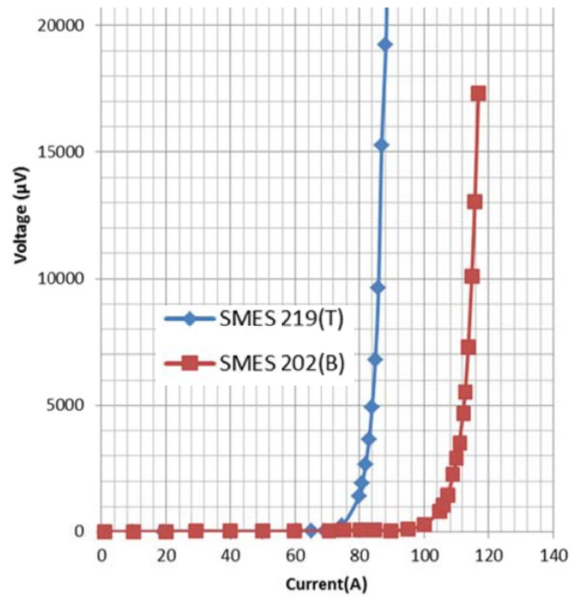
Double Pancake 77 K Test

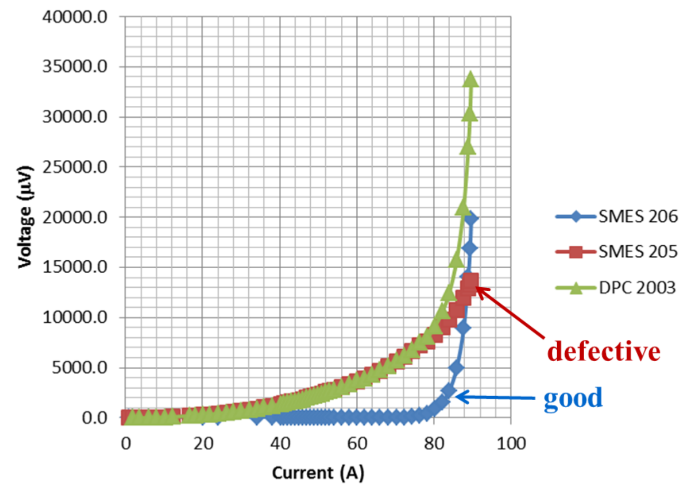
2 pancakes with similar critical currents

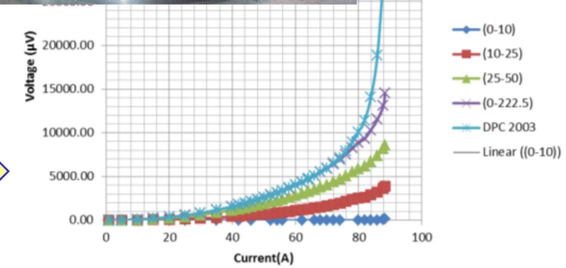


2 pancakes with very different critical current



one pancake good and other pancake defective





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

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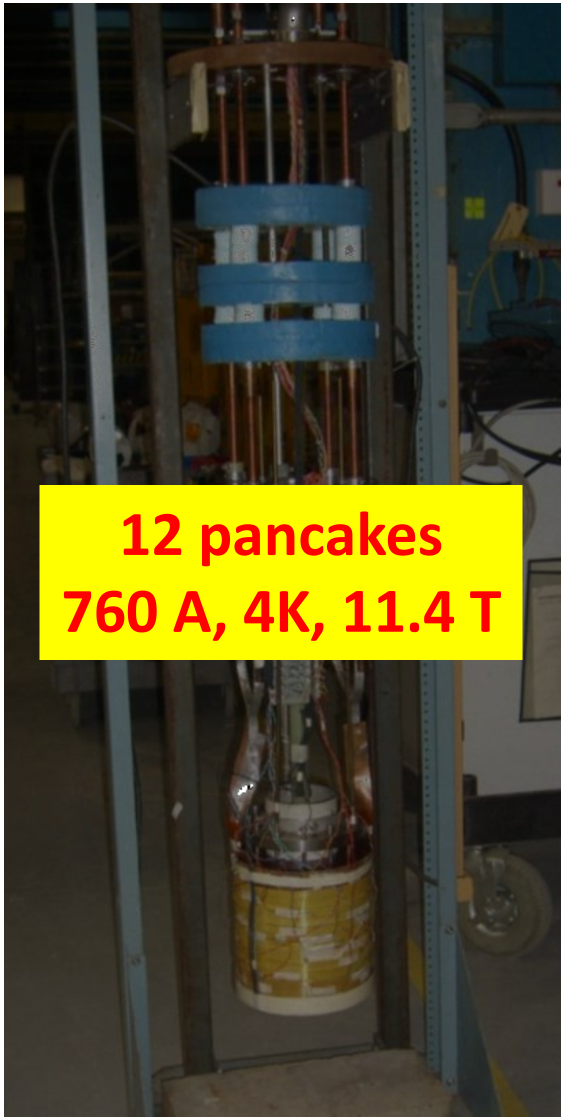
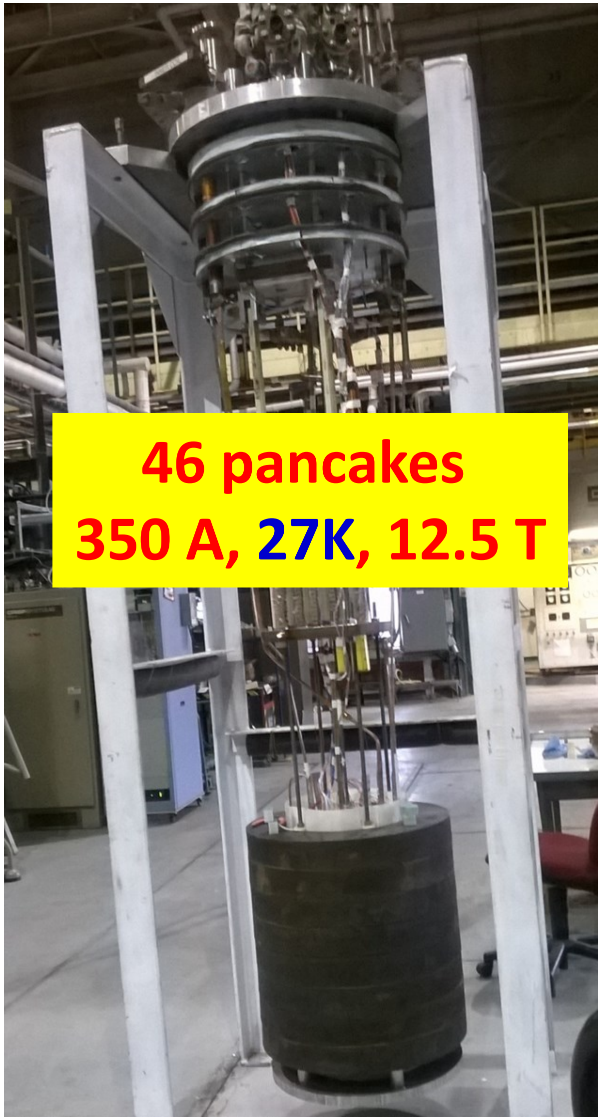
HTS SMES Coil High Field Tests





Peak fields higher

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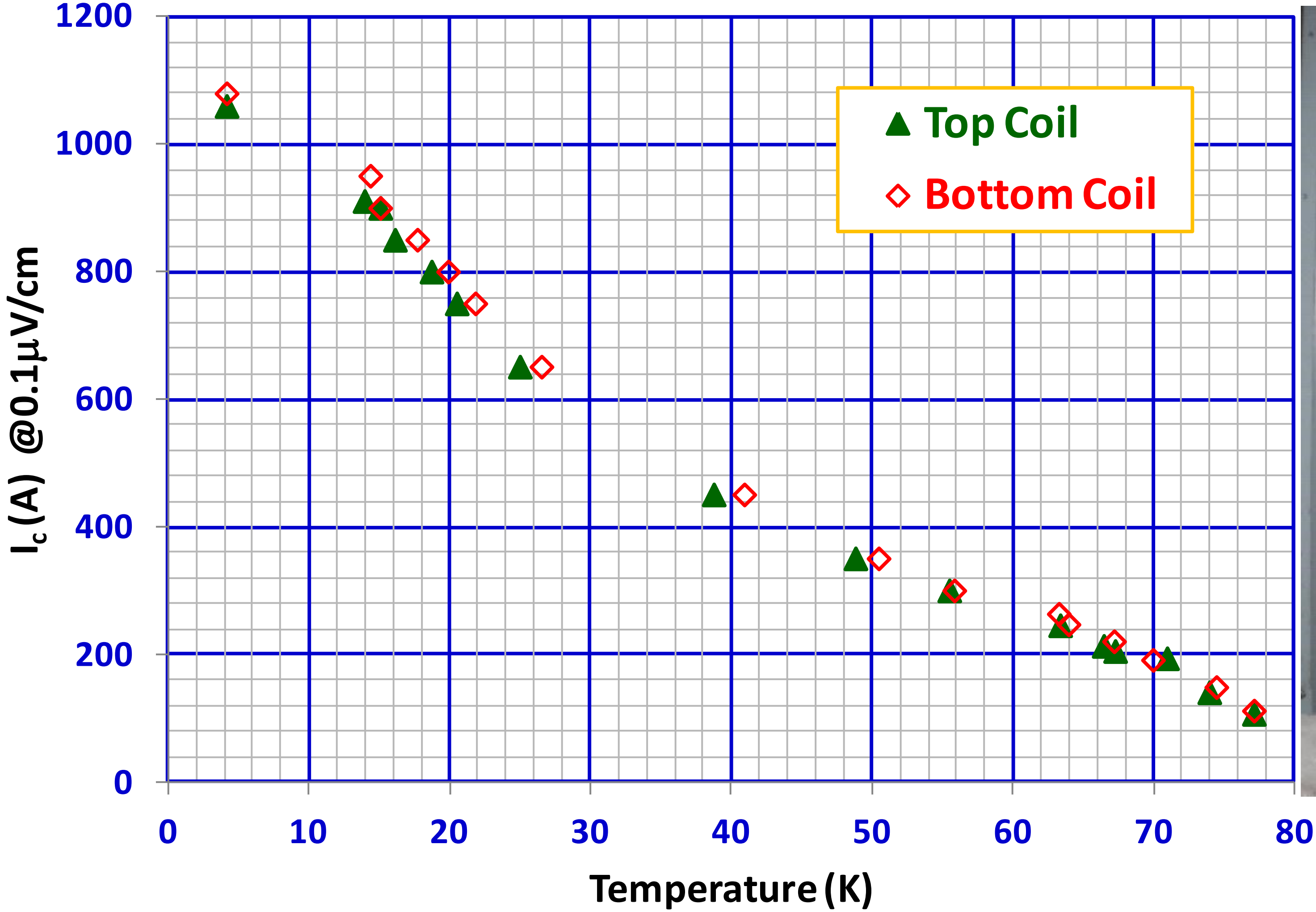
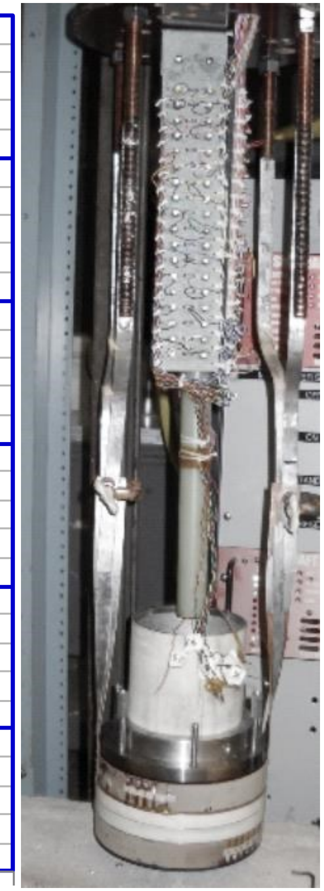
Double Pancake Coil Test

Nominal design current: ~700 A





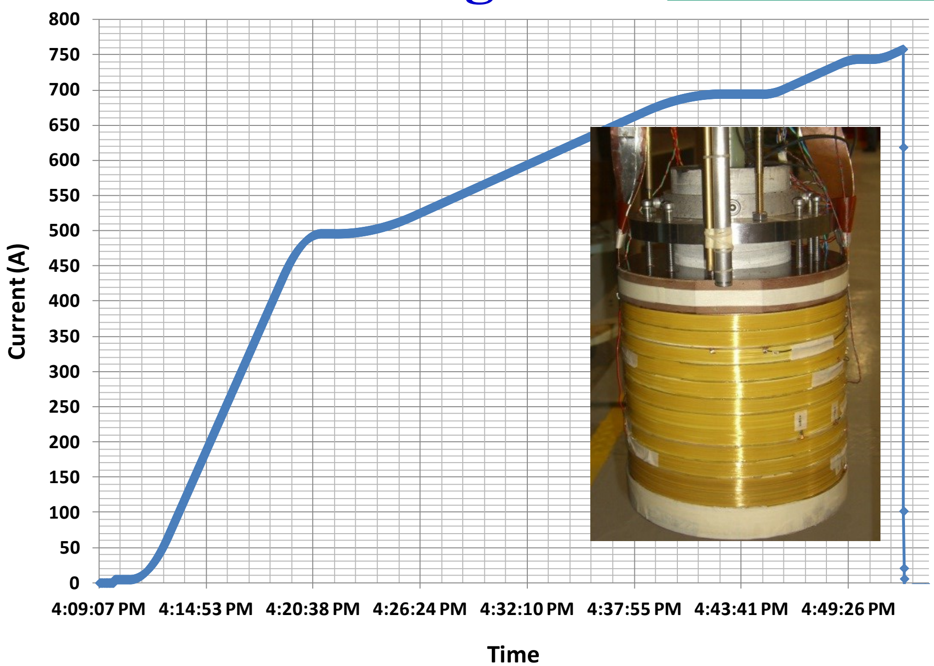
Ramp rate up to 10 A/s

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

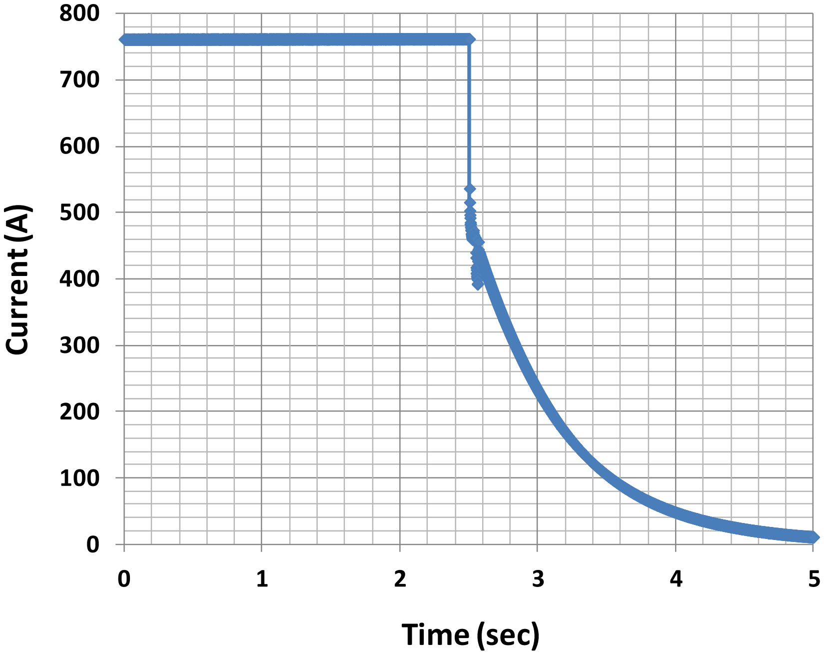
12 Pancake Coil Test

11.4 T in 100 mm bore

Charge

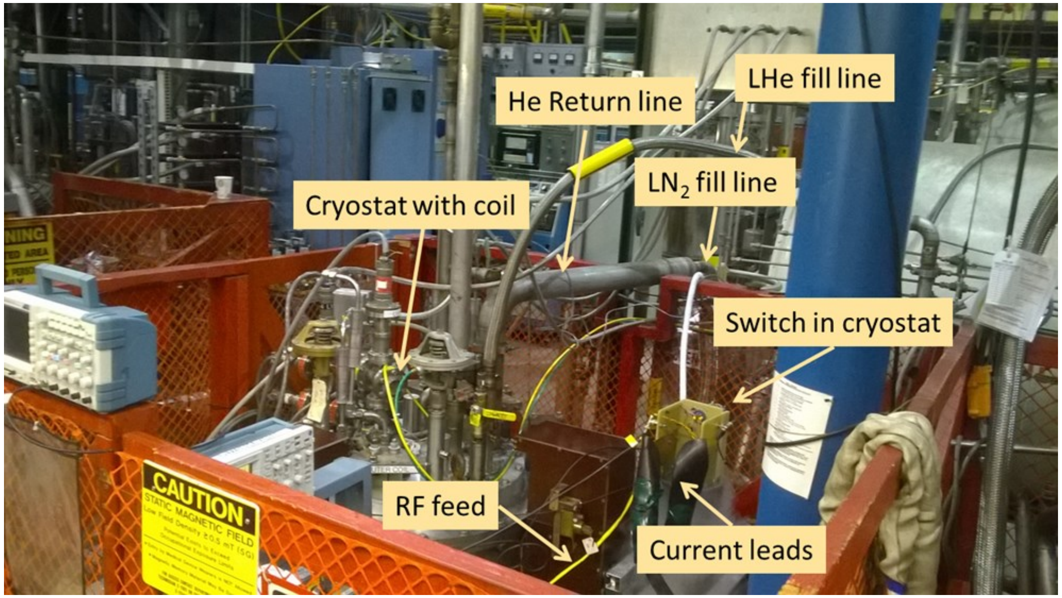


Quench

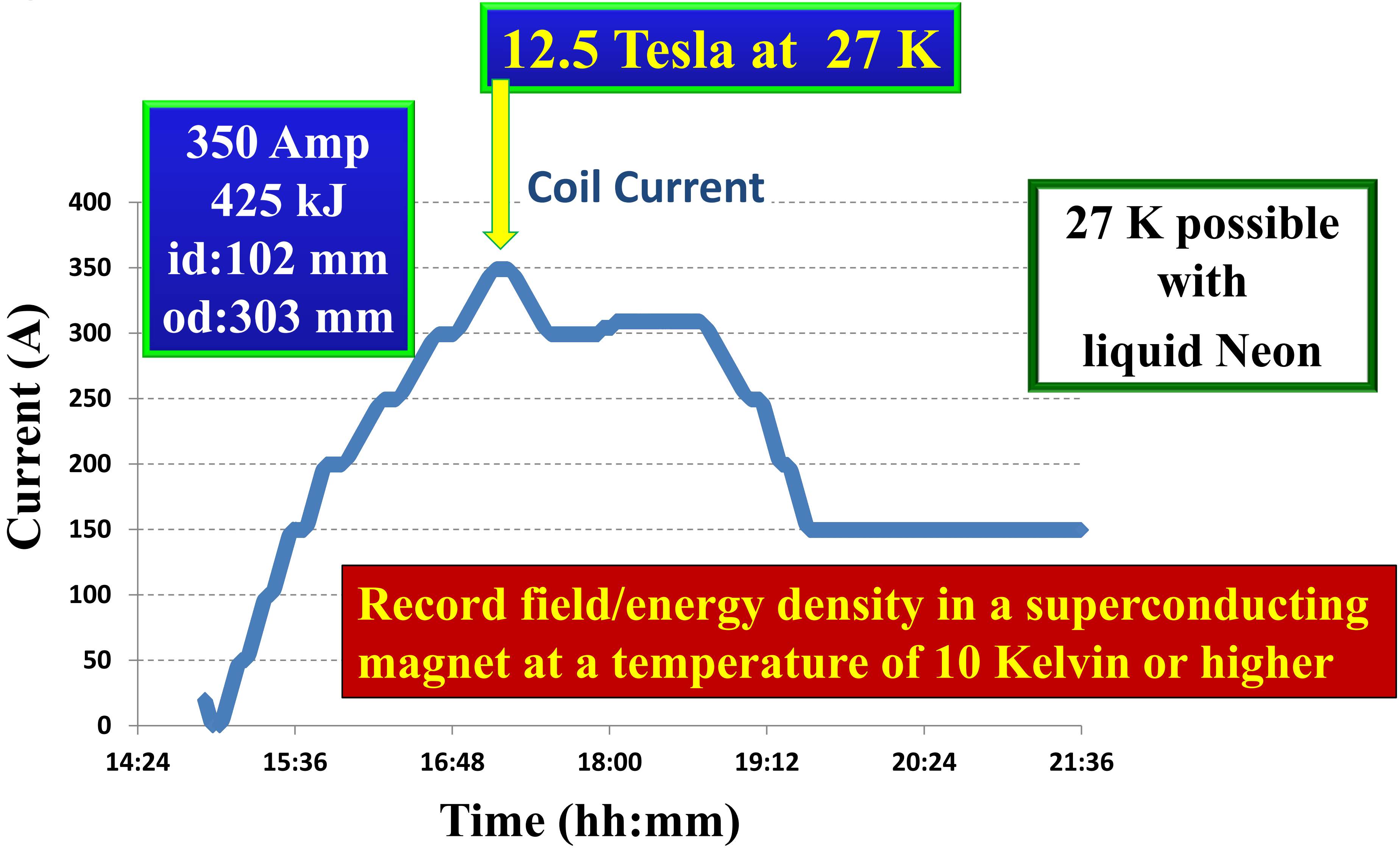


- Energy (~125 kJ) extracted and dumped in the external resistor.
- 77 K re-test (after quench) showed that the coil remained healthy.

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 coil still has the potential to reach higher field after repair.**

4 mm wide SuNAM- ReBCO Tape Critical Current Measurements at field and 4.2 K

Test Set-up for I_c Measurements

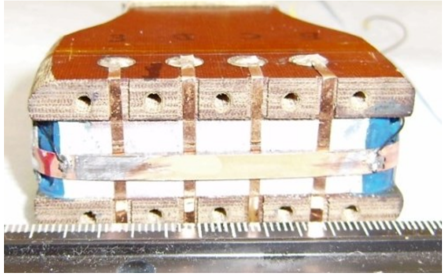
Field Parallel

B-Field

- Samples are mounted on ITER-type barrels for I_c measurements in // field. Typical length used 0.5 m
- Measurements in //-field at 4.2 K using either a 12 T or 16 T solenoid magnet to provide background field
- For H-parallel to ab-plane: using SS barrel holder V-tap separation of 47 mm total length 235 mm.
- H-perpendicular to ab-plane: using U shaped sample V-tap separation 10 mm; total length 30 mm

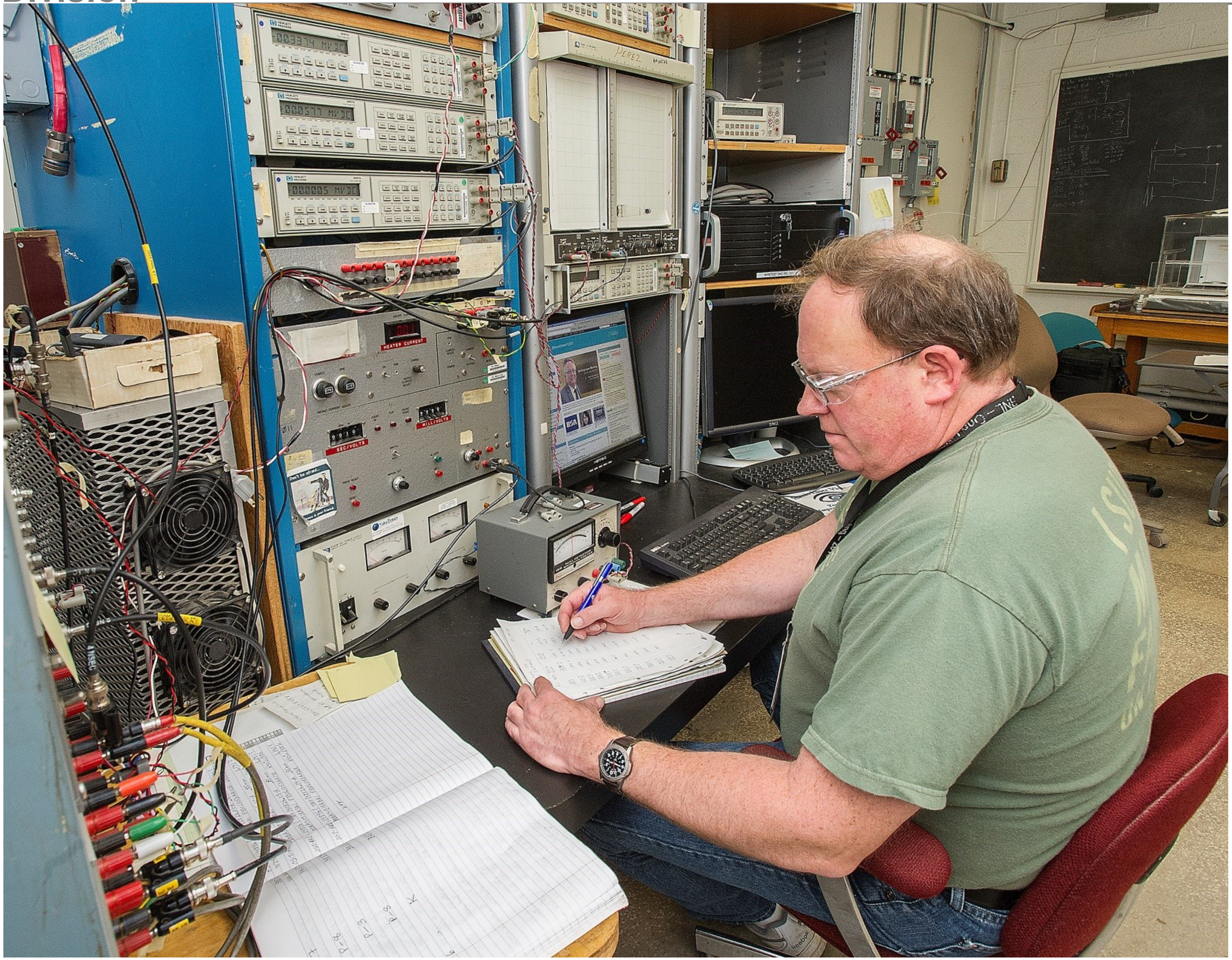
Field Perpendicular

B

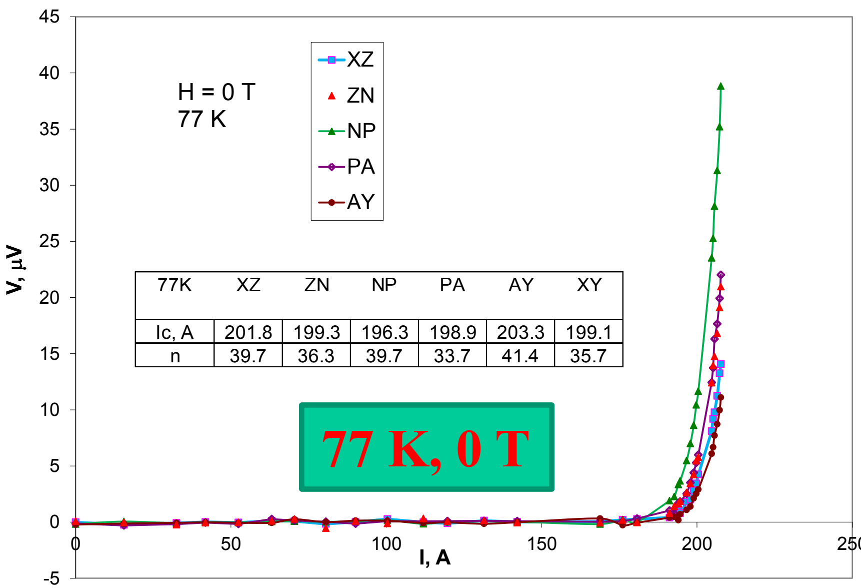


Pictures of Conductor Test Station

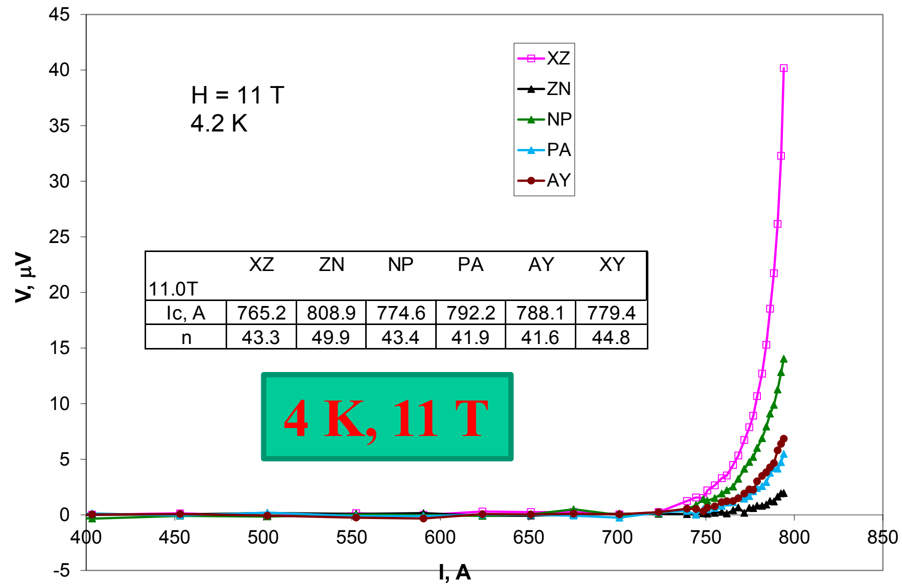
Pictures of Conductor Test Station



V-I curves for the sections at 77 K and at 11 T, 4.2 K (field parallel)



77K	XZ	ZN	NP	PA	AY	XY
Ic, A	201.8	199.3	196.3	198.9	203.3	199.1
n	39.7	36.3	39.7	33.7	41.4	35.7



11.0T	XZ	ZN	NP	PA	AY	XY
Ic, A	765.2	808.9	774.6	792.2	788.1	779.4
n	43.3	49.9	43.4	41.9	41.6	44.8

~200 A

~770 A

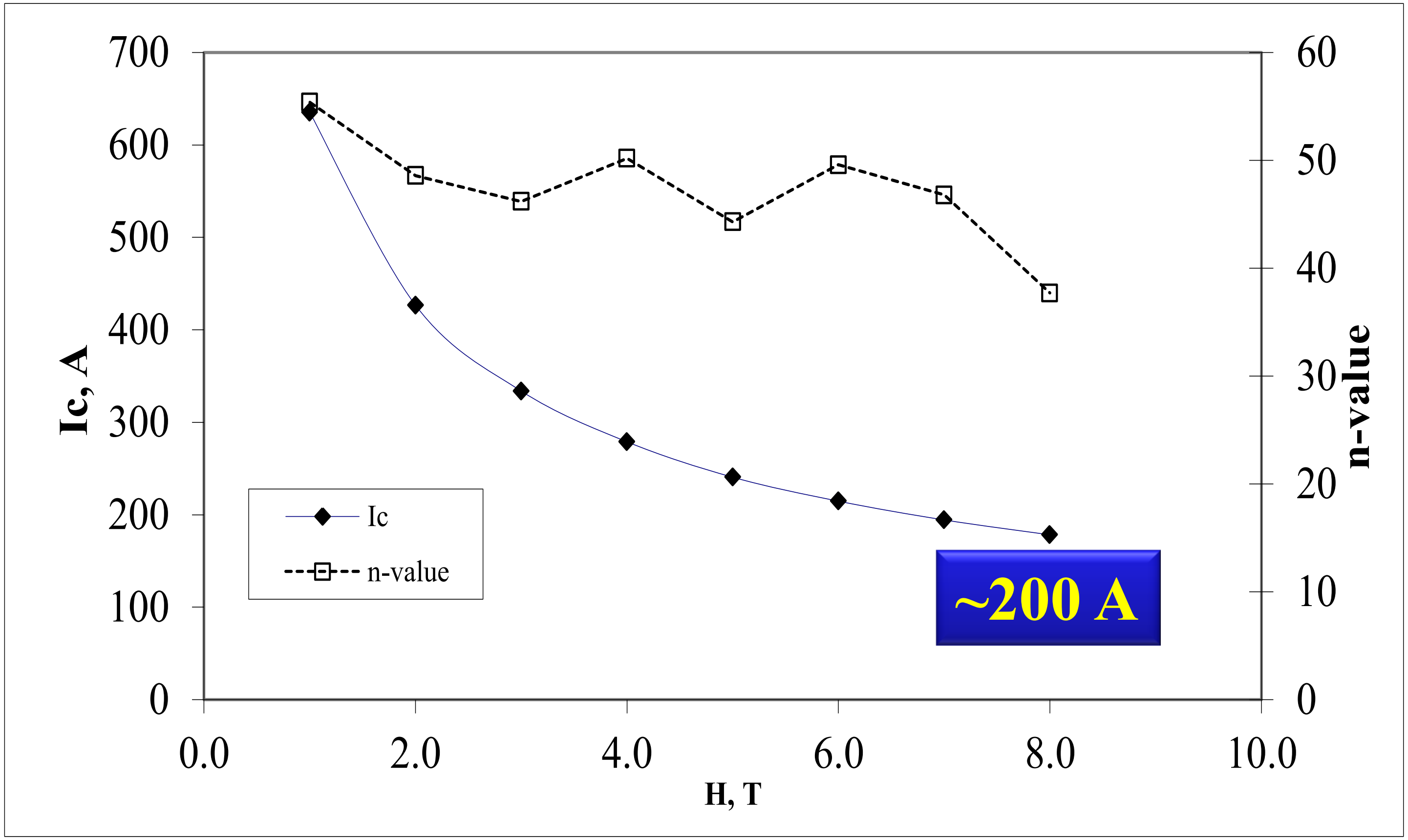
Ratio of Ic(11T, 4.2K) and Ic(77K, SF) for all the sections

I_c(11T,4.2 K) / I_c(77K, SF)	XZ	ZN	NP	PA	AY	XY
	3.79	4.06	3.95	3.98	3.88	3.91

The different sections look fairly uniform

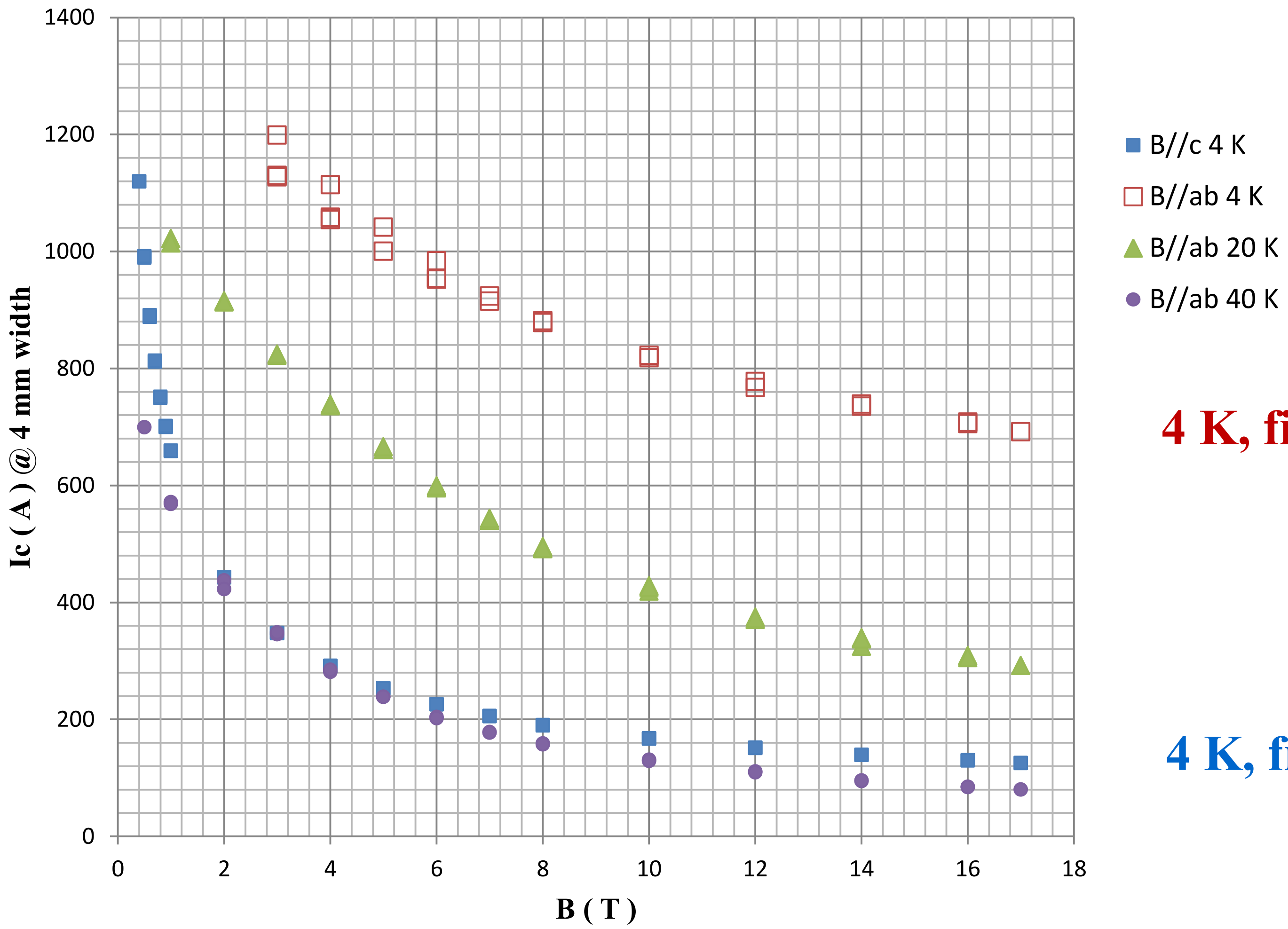
BNL Test

Test Summary SuNAM Sample (field perpendicular)



BNL Test

In-field performance of SuNAM HCN04200 (measured at Grenoble)



4 K, field parallel

4 K, field perpendicular

Recent Results from SuNAM

- Recent results (21 T test) from SuNAM show that the conductor is good for high field solenoids
- They were able to overcome somewhat poor in-field performance by grading the coil with different width tapes used in the design
- However that significantly increased the amount of conductor required (700 meter in BNL 16 T magnet vs 11.4 km in 21 T)
- It is known that SuNAM produces one of the best conductor for 77 K, self-field application. The mechanical properties of the conductor are good for high field applications as well (with additional reinforcement by SS tapes as used in BNL designs). However, the lift factor for in-field 4K critical current performance significantly lags behind the competitor currently
- SuNAM continues to make remarkable progress and there is no reason why this (high field performance) would not improve over time
- For now, a smart mixture of SuNAM (most part) and SuperPower (some part) should be interesting

SUMMARY (1)

- 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.

SUMMARY (2)

- By coincidence, the 100 mm, 25 T solenoid design (fully engineered, developed for a completely different project,) is directly applicable to CAPP
- If no changes in the design are made, the magnet can be built quickly
  - Change in length is allowed as that can be accomplished by stacking more or less number of pancakes
- SuNAM conductor could be used for most part except for the pancakes in the ends
- We are excited and ready to see our work being used in a real application at CAPP