HTS Activities and Recent Progress at BNL

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HTS Magnet Program at BNL

- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – solenoid, racetrack, cosine theta, curved coils
- Number of HTS coils/magnets designed built & tested:
  - Well over 150 HTS coils and well over 15 HTS magnets
- Type of HTS used:
  - Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape
- Amount of HTS acquired:
  - Over 50 km (4 mm tape equivalent)
- Our recent activities have been largely on magnets with ReBCO

Completed HTS Magnet Programs

- 25 mm aperture 16 T HTS solenoid (SBIR)
- 100 mm aperture 9 T HTS solenoid (SBIR)
- 100 mm aperture "12.5 T @27 K" HTS SMES solenoid (arpa-e)
- HTS quadrupole for RIA/FRIB (Collaboration with MSU)
- Bi2223 HTS tape common coil dipole (funded by DOE)
- Bi2212 Rutherford cable Common Coil Collider Dipole (DOE)
- HTS solenoid for Energy Recovery Linac (BNL project)
- HTS magnet for NSLS (BNL Project)
- Cosine theta dipole with 4 mm YBCO/ReBCO tape (SBIR)
- Cosine theta dipole with 12 mm YBCO/ReBCO tape (SBIR)
- And a few others

Current HTS Magnet Programs

- High Field HTS solenoid for IBS, Korea (Work for Others)
- High field collider dipole (Phase II STTR)
- Curved ReBCO tape dipole (Phase II SBIR)
- MgB_2 solenoid (Phase II SBIR)
- High field open HTS midplane dipole and Novel dipole design (Phase I SBIR)
- HTS solenoid for Energy Recovery Linac (BNL project)

A wide variety of applications and collaborative work is the nature of our HTS magnet program

A Brief Review of Select HTS Magnet Programs

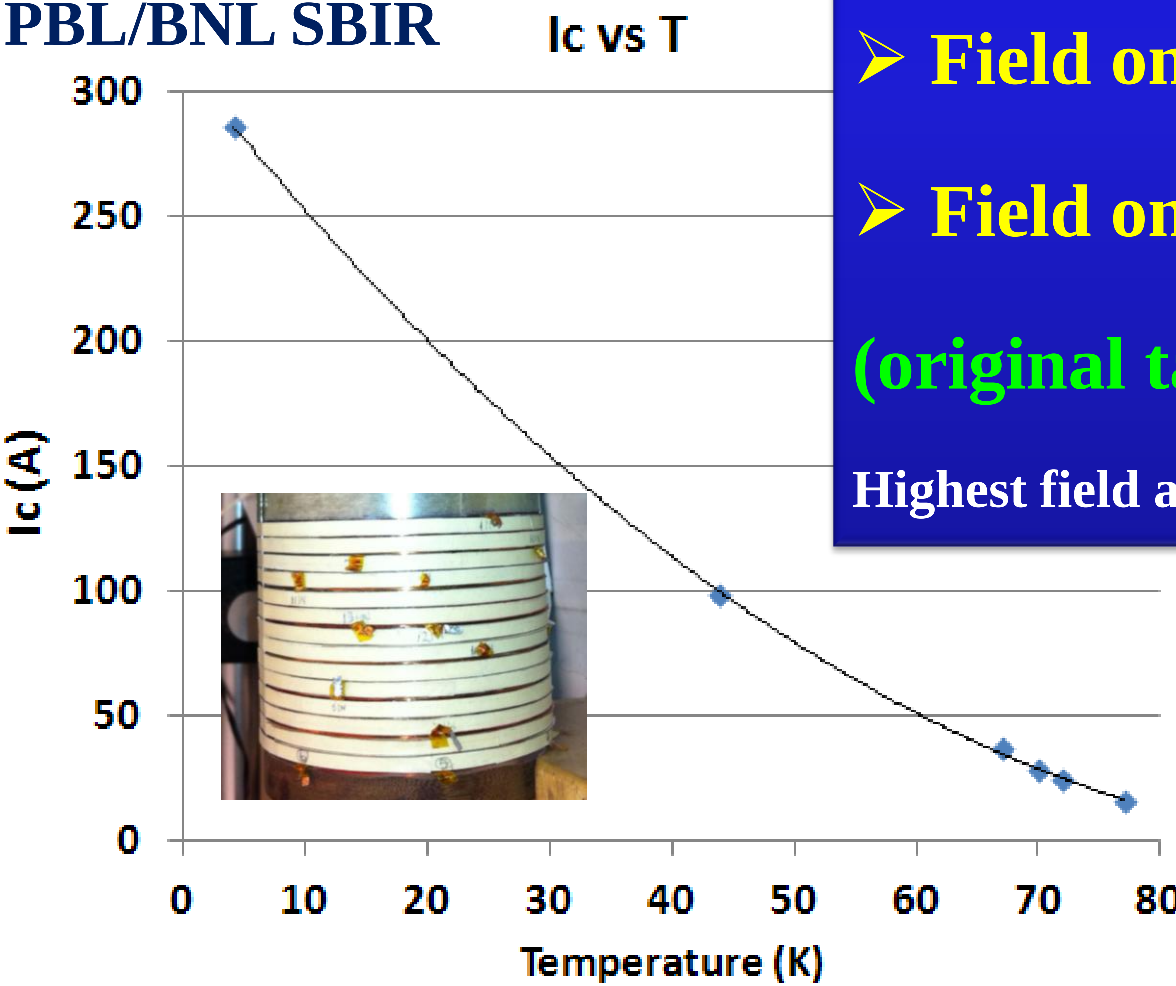
1. High Field Large Stress (~400 MPa) HTS Solenoids
2. High Radiation/Energy Deposition Quadrupoles

Common Features:

SS tape insulation, either to deal with large stresses or to provide radiation resistant insulation and help in quench protection

16 T HTS Solenoid
(plus a wide range of operating temperature)

PBL/BNL SBIR



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

(original target: 10-12T)

Highest field all HTS solenoid at that time

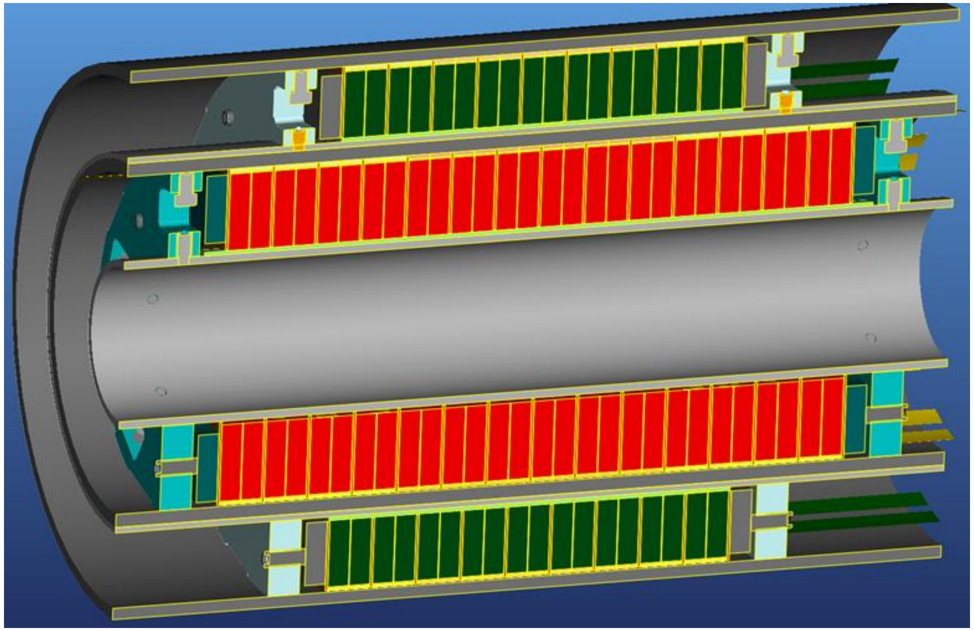
Overall J_o in coil:
>500 A/mm^2 @16 T

Insert solenoid: 14 pancakes, 25 mm aperture


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
BROOKHAVEN
arpa-e
High Field HTS SMES Coil
R. Gupta, ..., BNL
Seoul, S. Korea
Oct 19, 2015

The Basic Demo Module

Aggressive parameters:



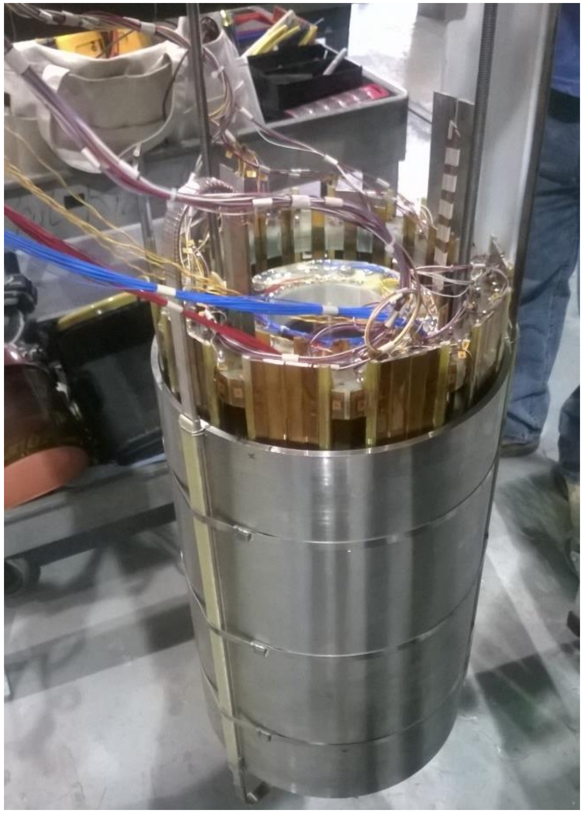
- Field: 25 T@4 K
- Bore: 100 mm
- Stored Energy: 1.7 MJ
- Hoop Stresses: 400 MPa
- Conductor: ReBCO

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

Significant use of HTS in a high field application

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

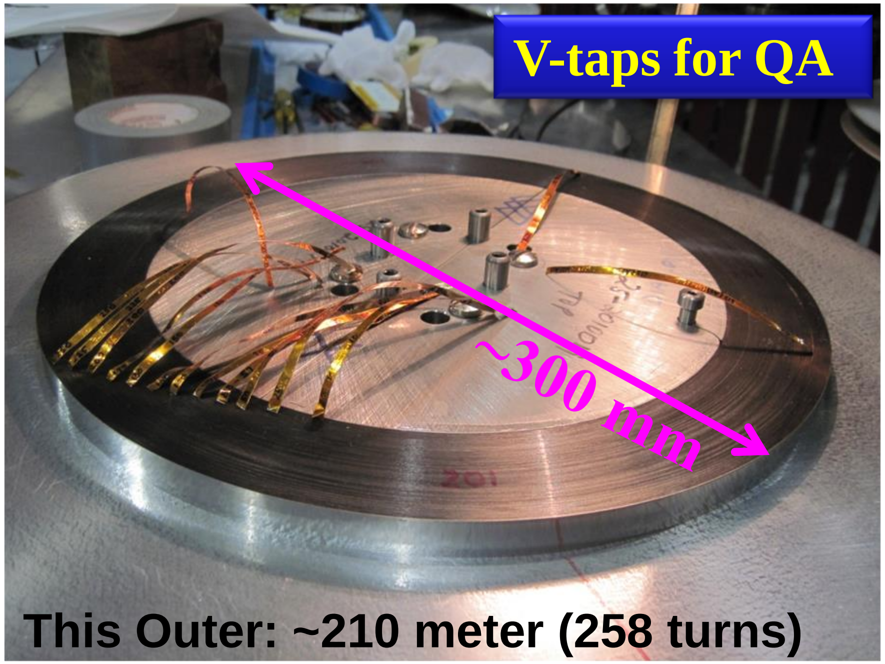


High field and big radius create large stresses (~400 MPa)

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

HTS Single Pancake



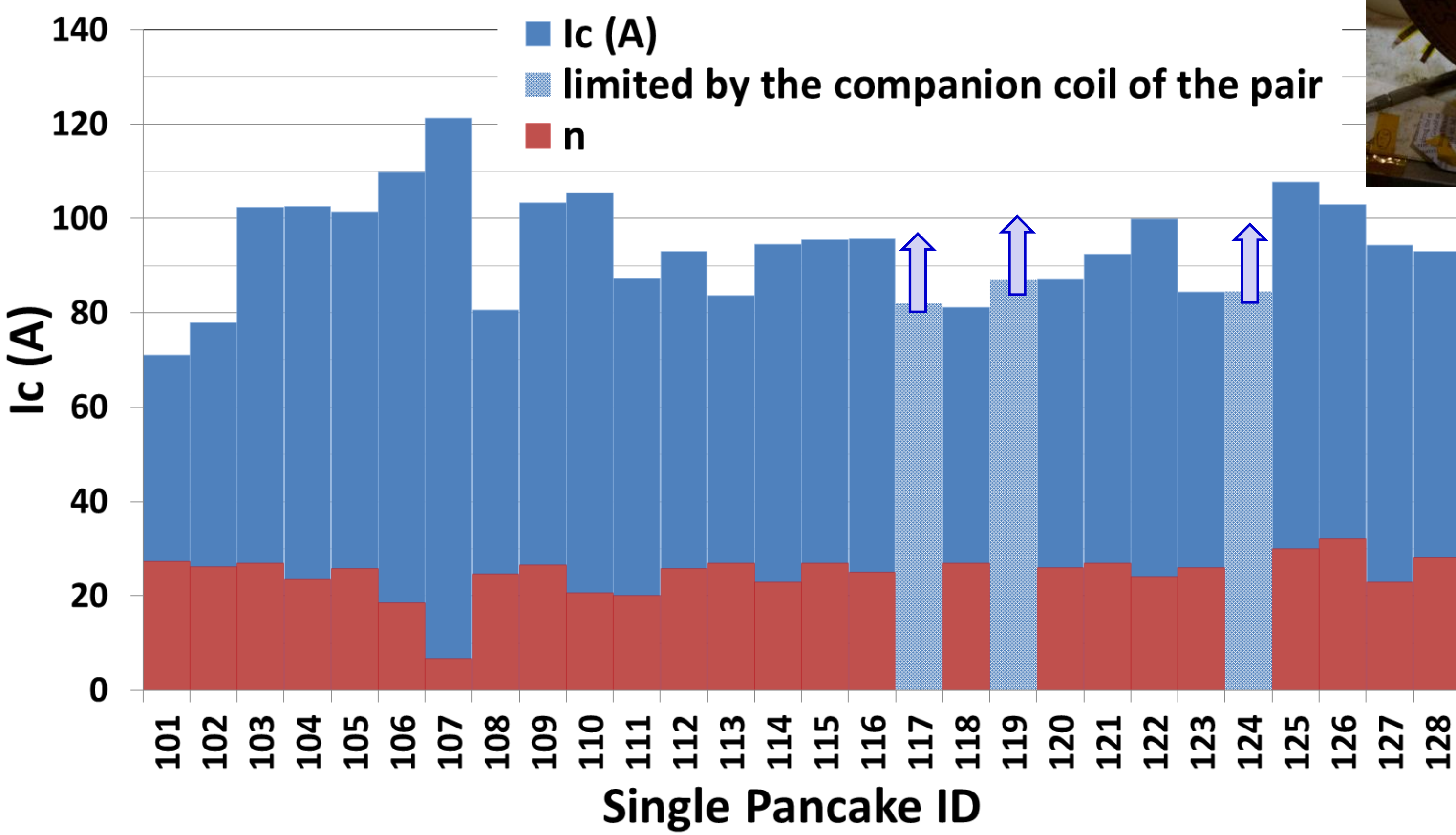
HTS is not a production conductor yet and it was treated that way

- **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)

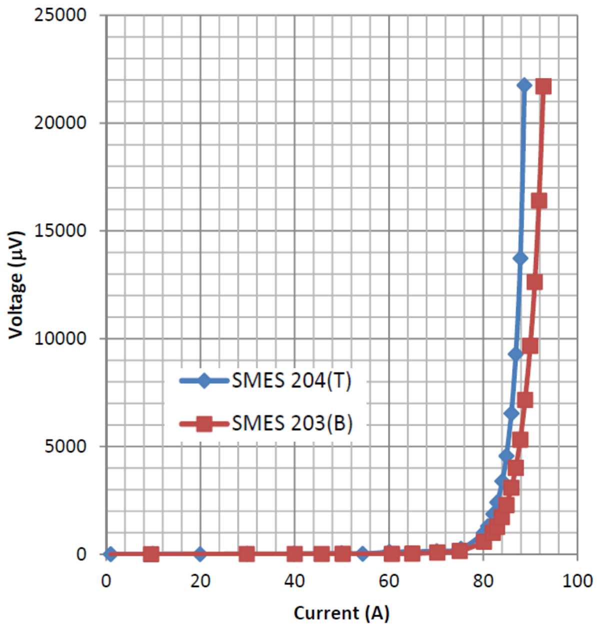
Critical current (@1 μV/cm)



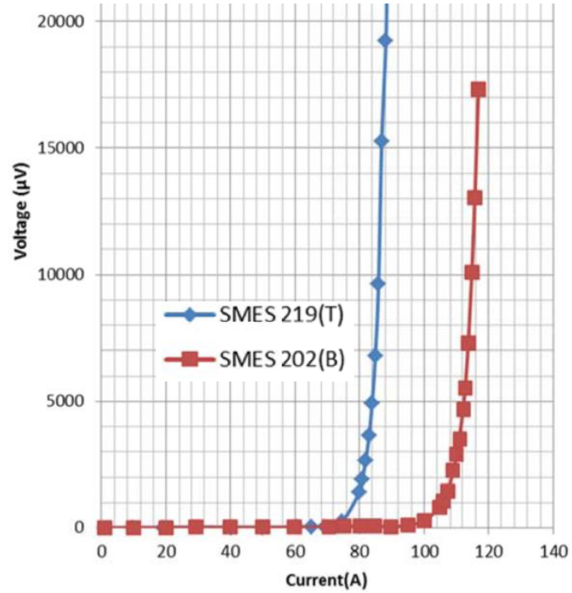
Two single pancakes powered in series

Double Pancake 77 K QA Test

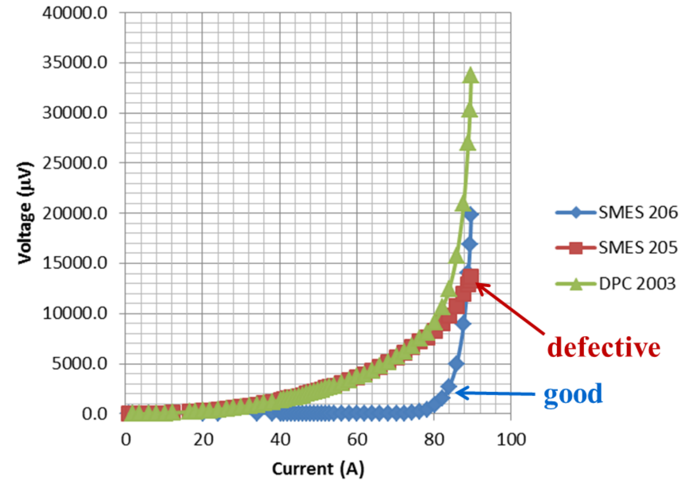
2 pancakes with similar critical currents

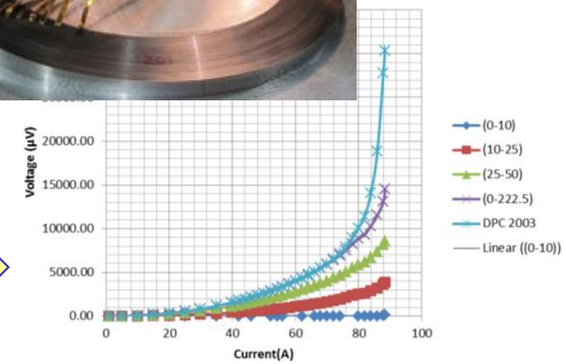


2 pancakes with very different critical current



one pancake good and other pancake defective

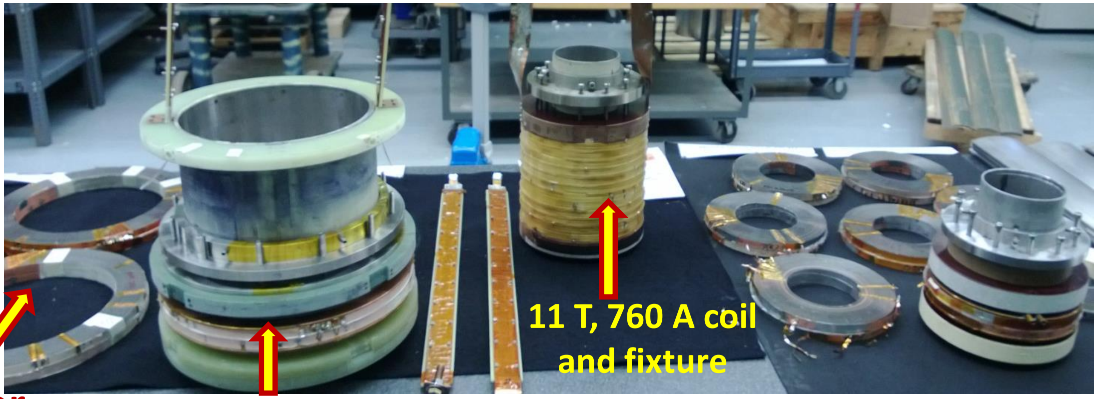




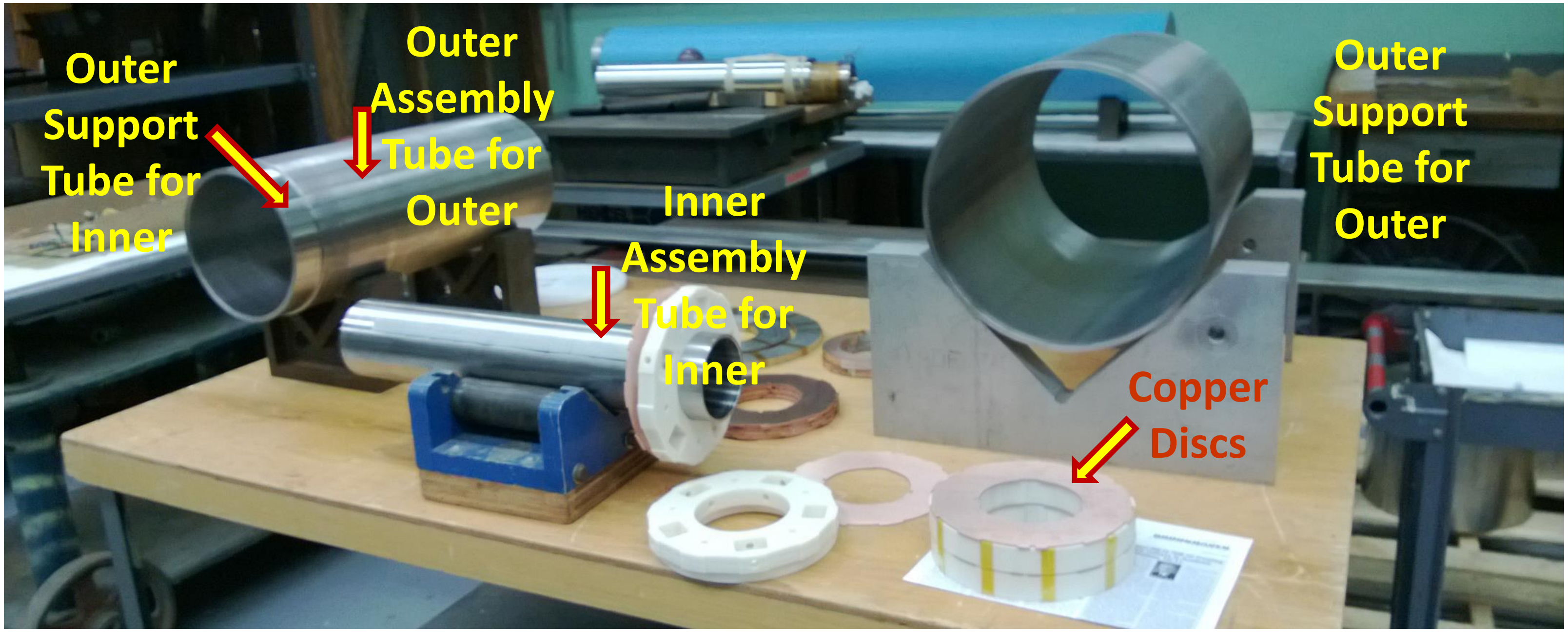
Note: Thorough 77 K test of each pancake was an important part of a series for QA

Coils, Test Fixtures and Support Structure

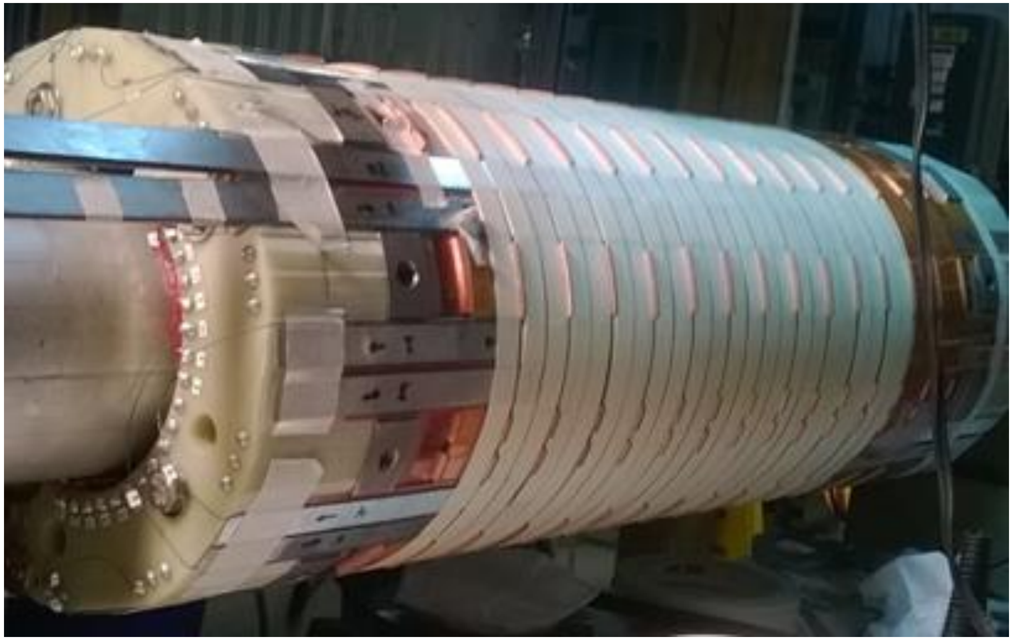
Pancake coils: inner and outer



77 K Test Fixture for outer



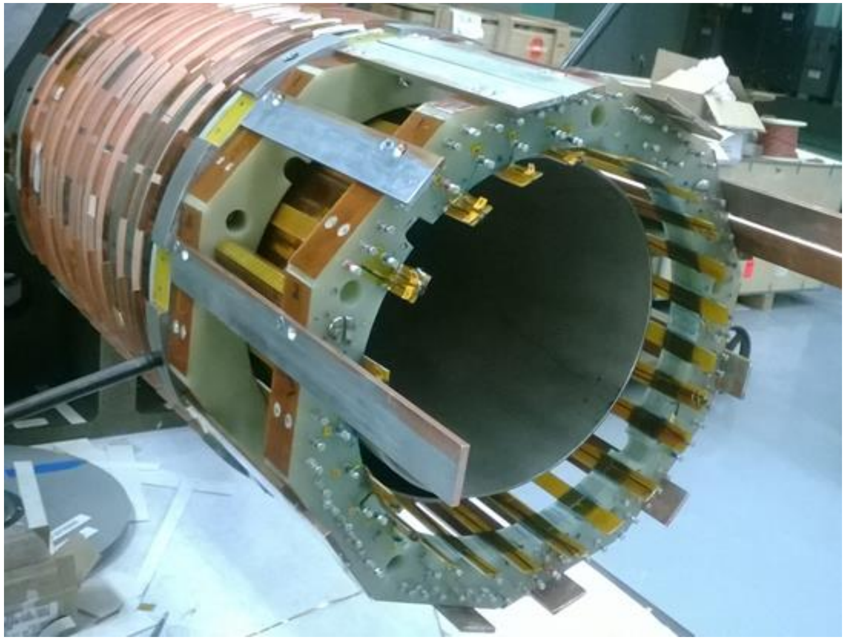
Inner and Outer Coils Assembled with Bypass Leads



Inner Coil

(102 mm id, 194 mm od)

28 pancakes



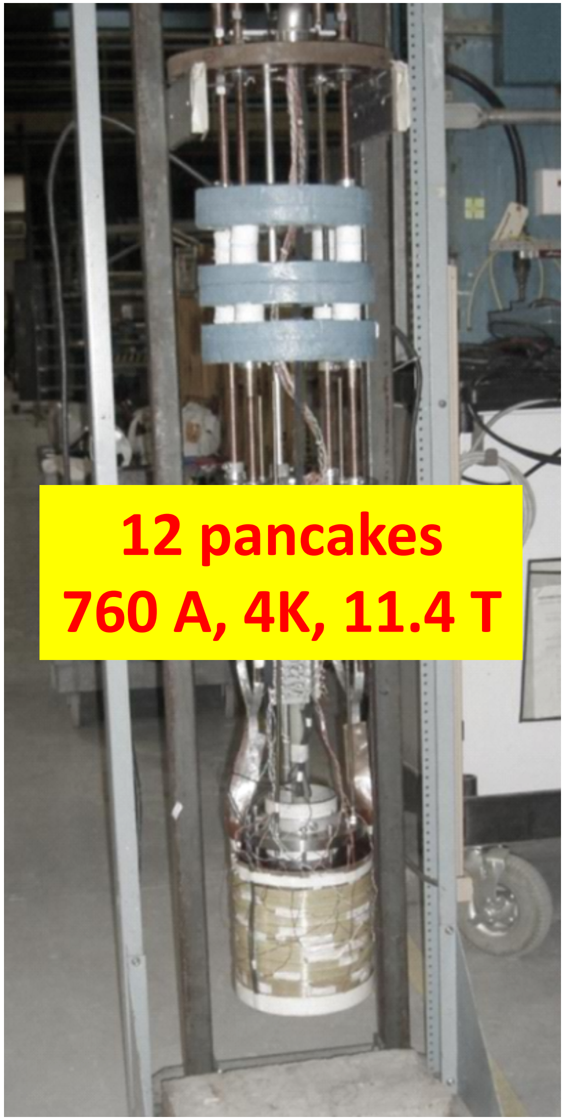
Outer Coil

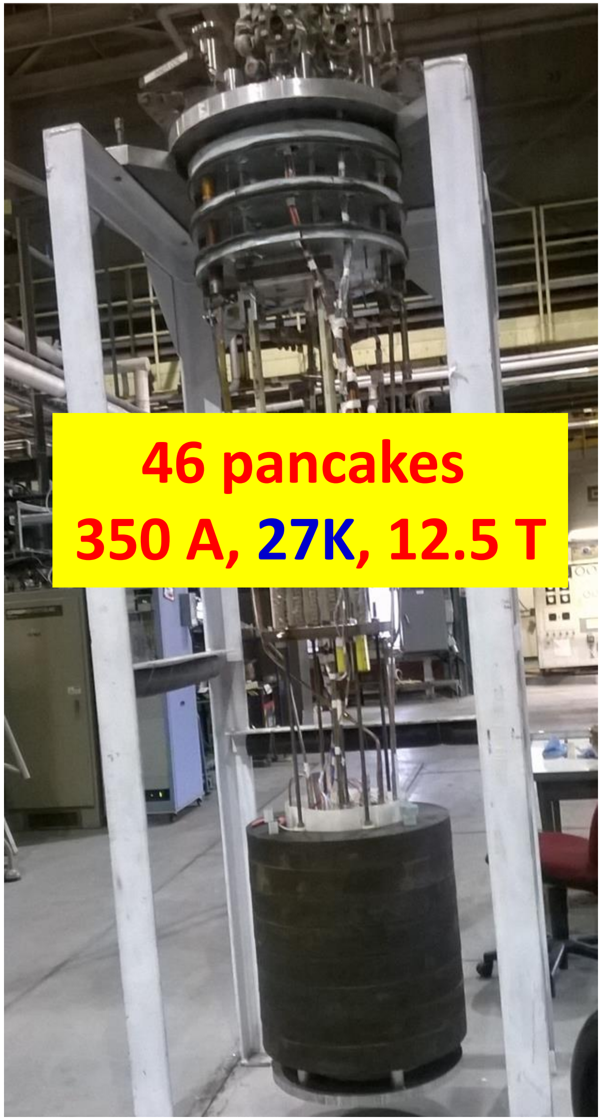
(223 mm id, 303 mm od)

18 pancakes

Total: 46 pancakes

HTS SMES Coil High Field Tests

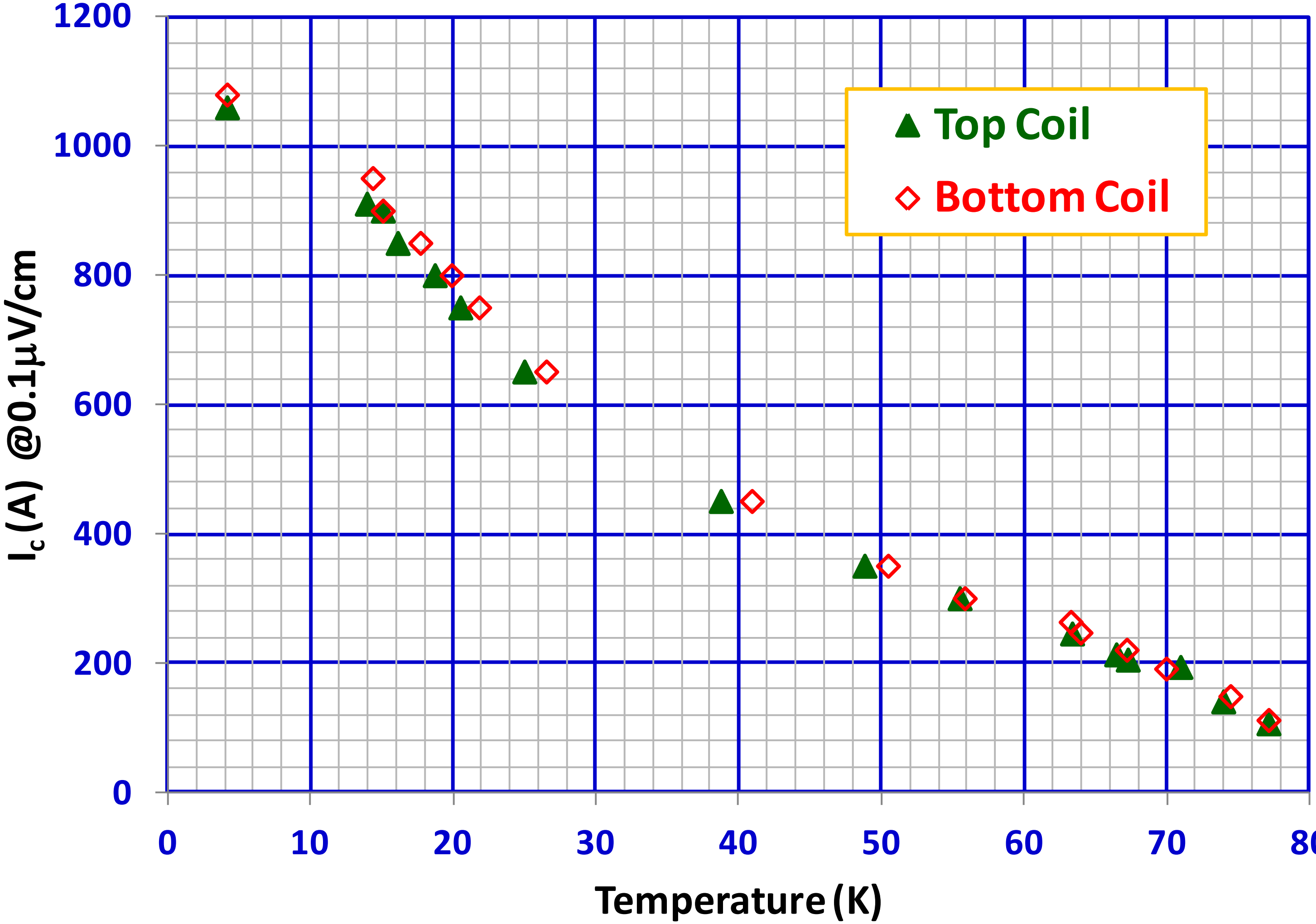


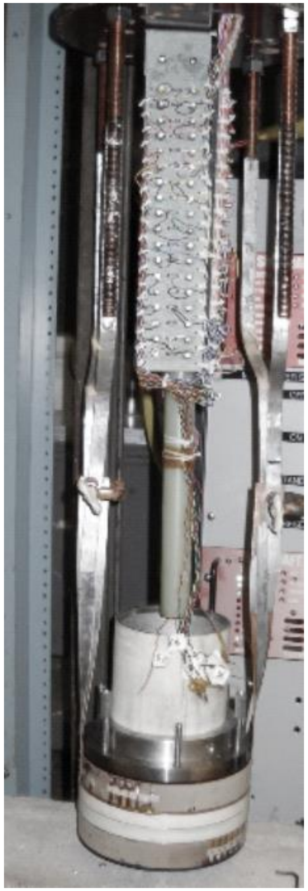


Peak fields higher

Double Pancake Coil Test

Nominal design current: ~700 A





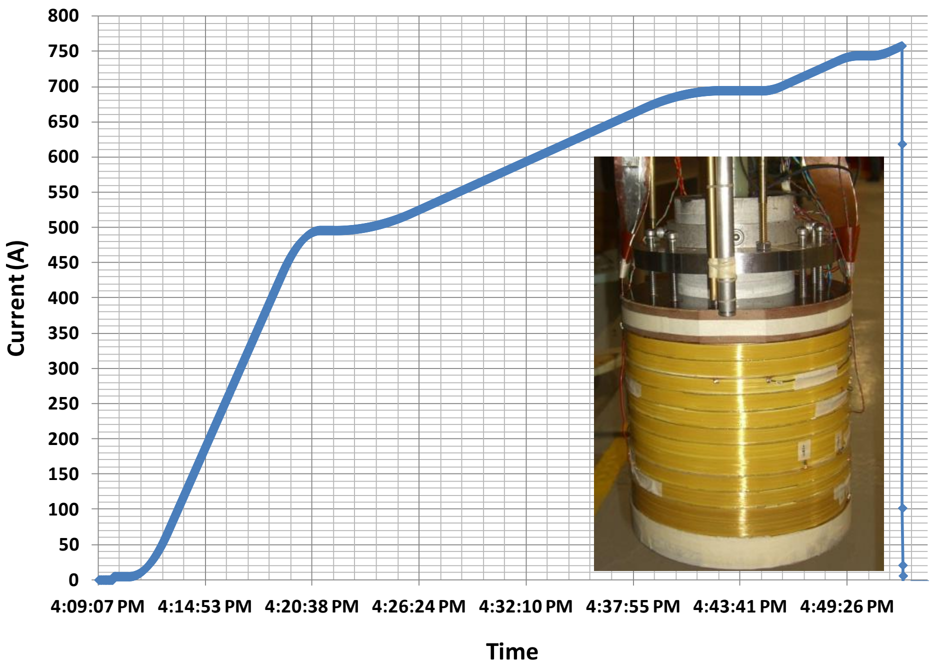
Ramp rate up to 10 A/s

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

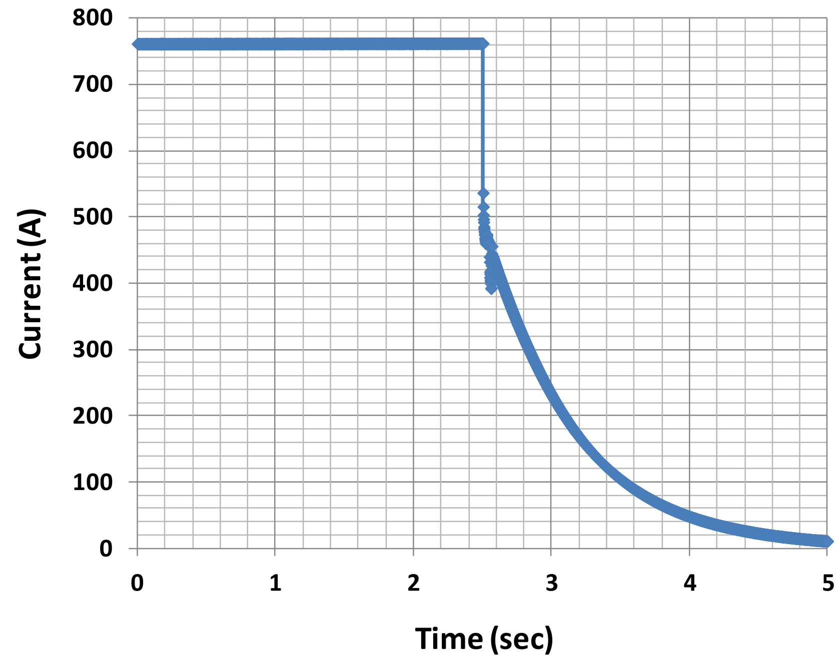
12 Pancake Coil Test

11.4 T in 100 mm bore

Charge

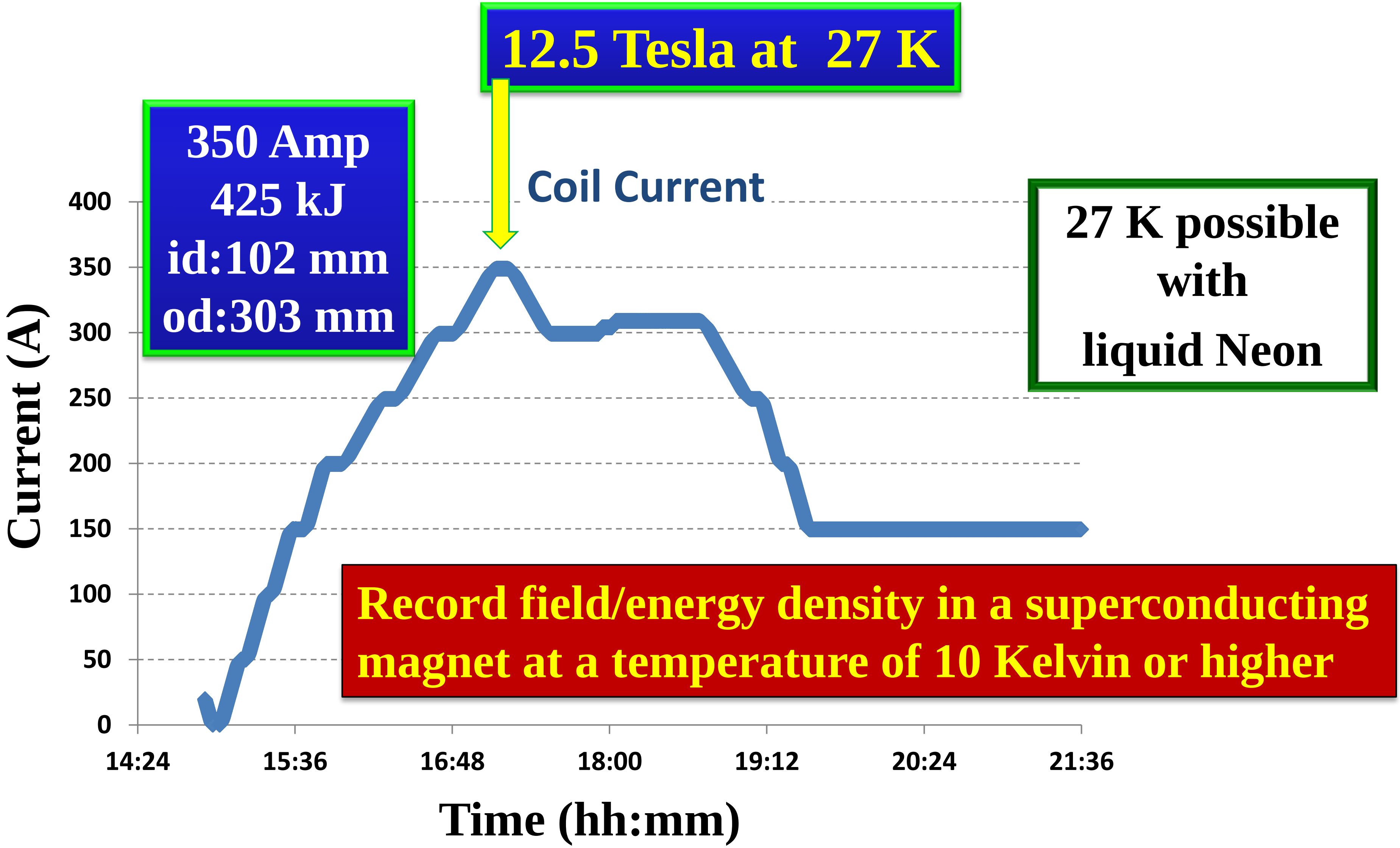


Quench



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

SMES Coil Test @50%
Critical Current Reached at 27 K



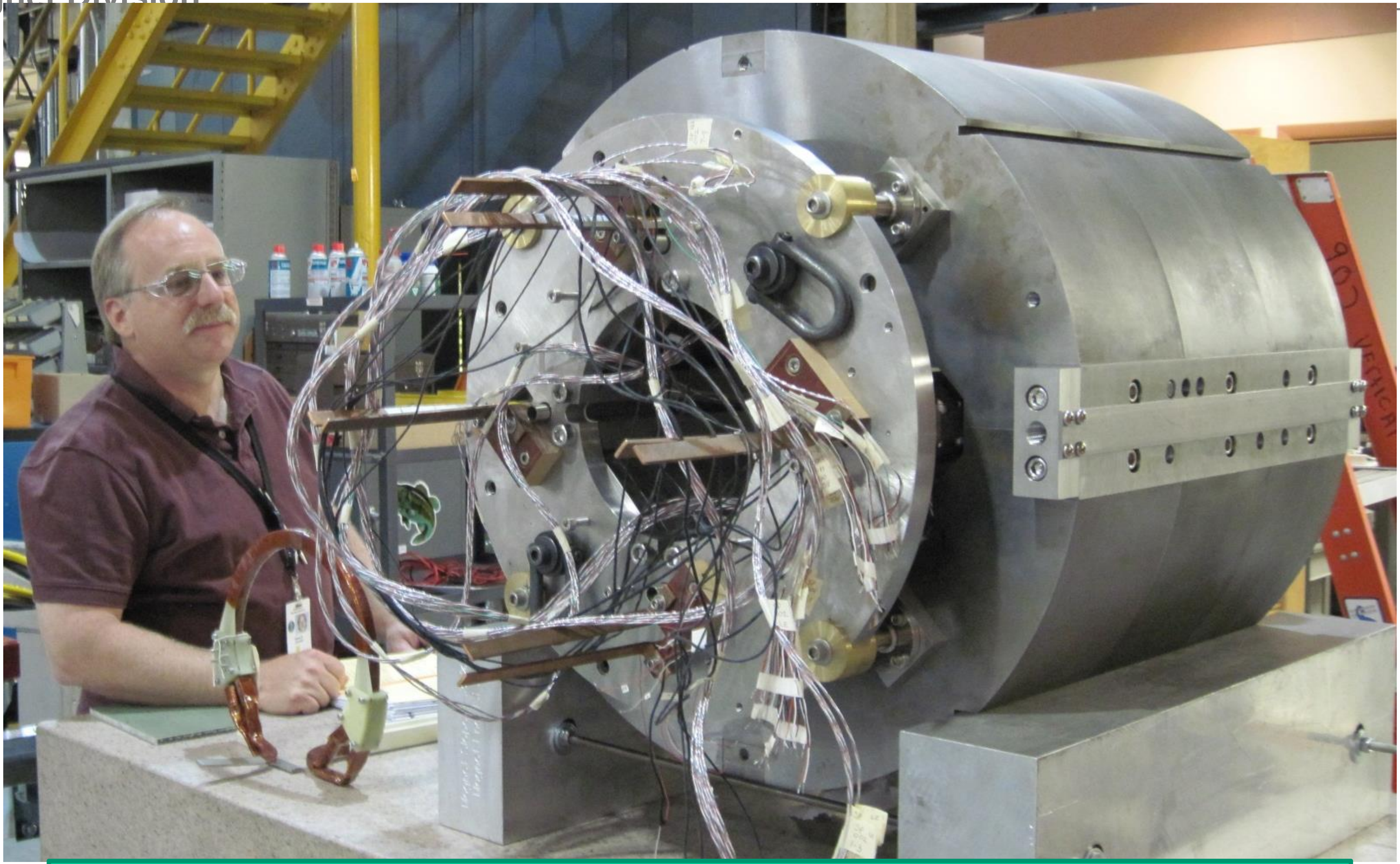
An Incident During the Test

- 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.

HTS Quadrupole for FRIB

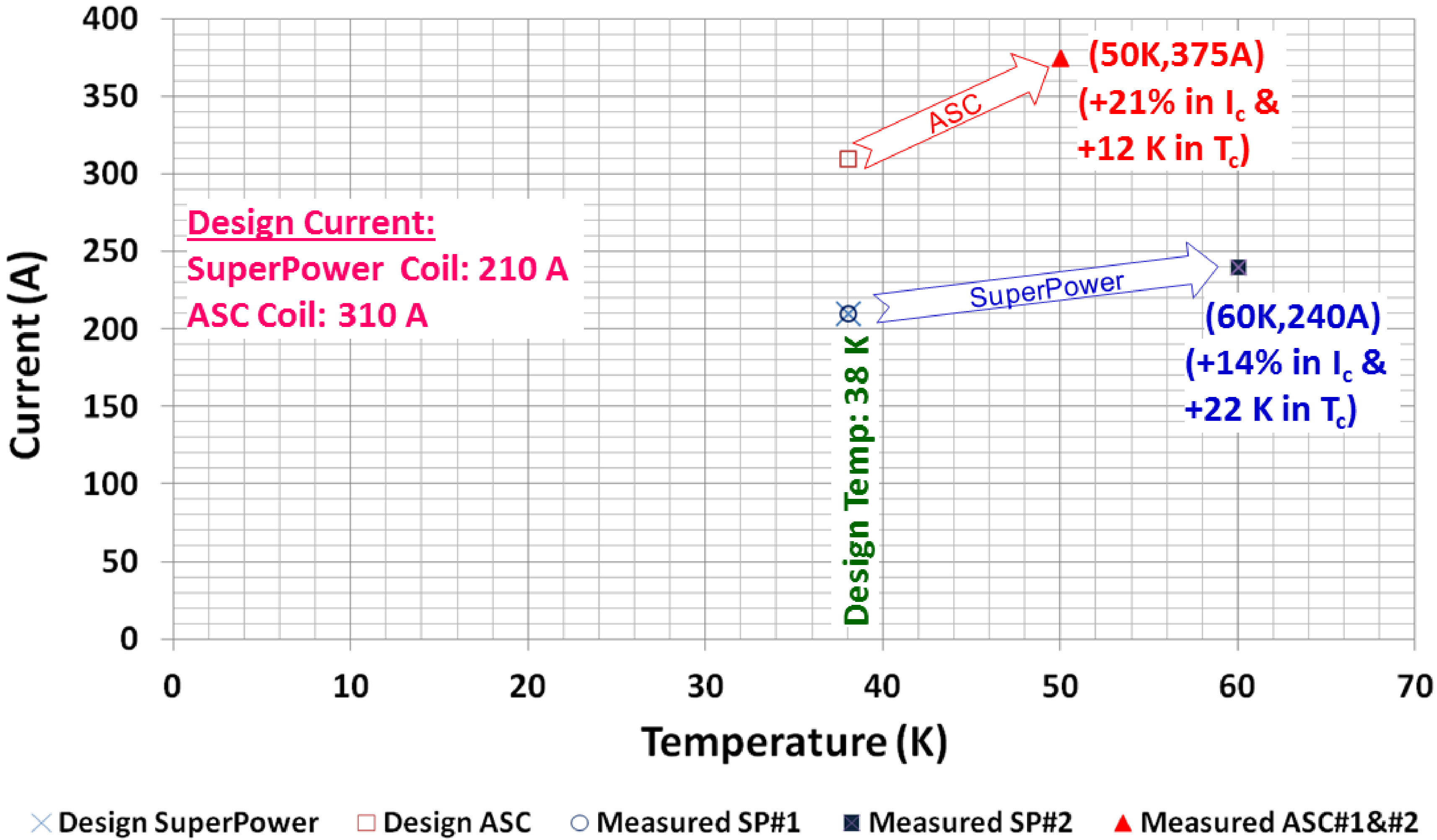
FRIB: Facility for Rare Isotope Beams

Second Generation HTS Quad for FRIB Fragment Separator Region



YBCO/ReBCO from two vendors ASC and SuperPower

Large Temperature Margins (only possible with HTS)



HTS provides robust operation against local and global heat loads

Radiation Damage Studies of 2G HTS (YBCO)

Figure 2. The BLIP facility.

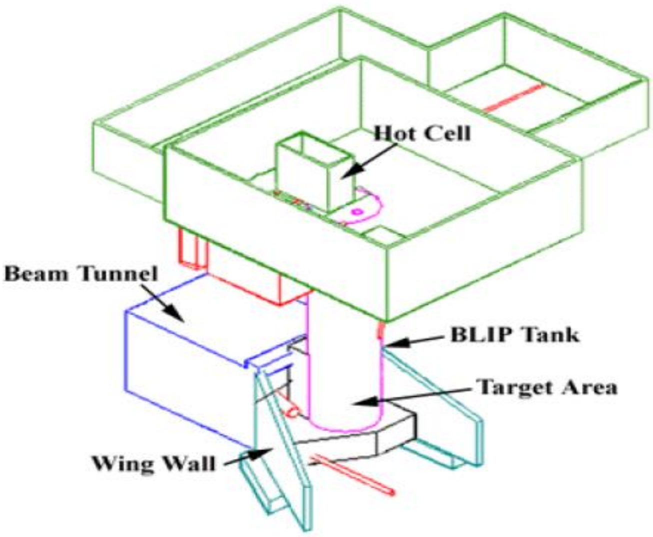
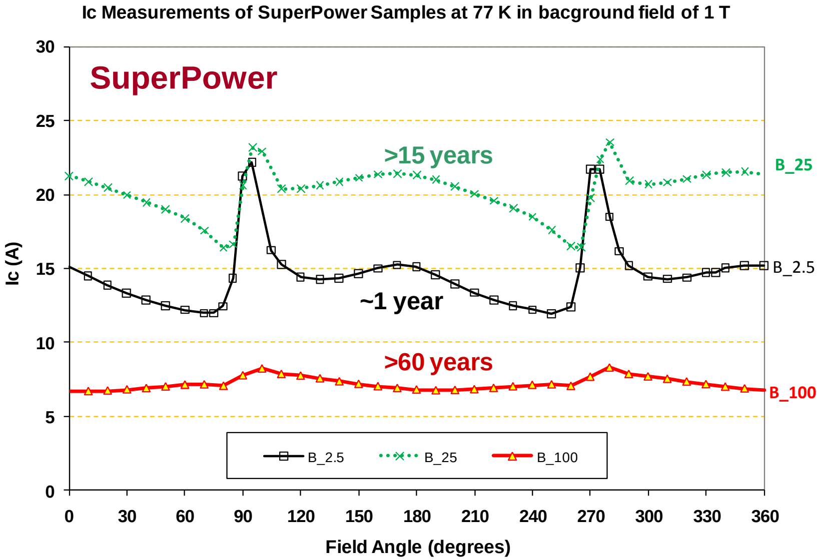


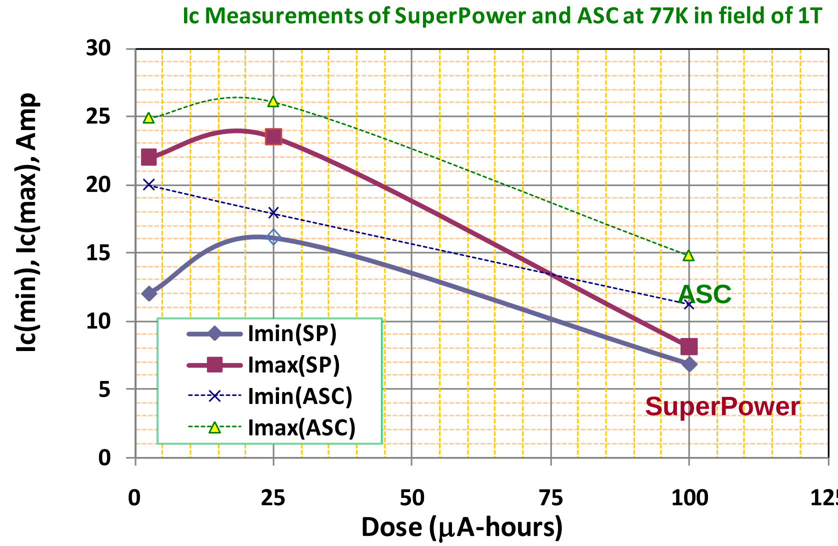
Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

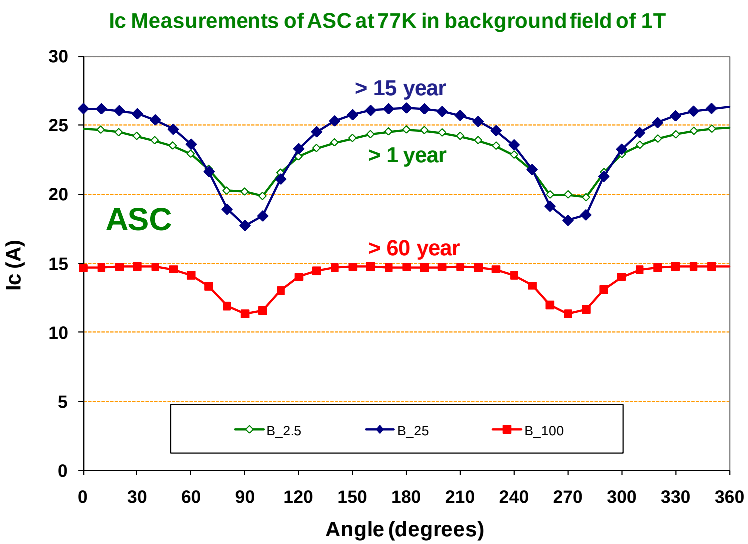
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 μA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

Radiation Damage from 142 MeV protons in SP & ASC Samples (measurements at @77K in 1 T Applied Field)



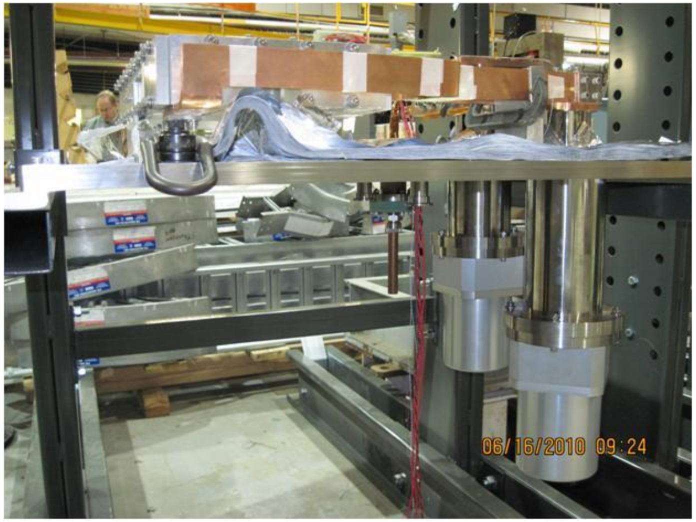


Minimum and maximum values of I_c are obtained from the graphs on the right

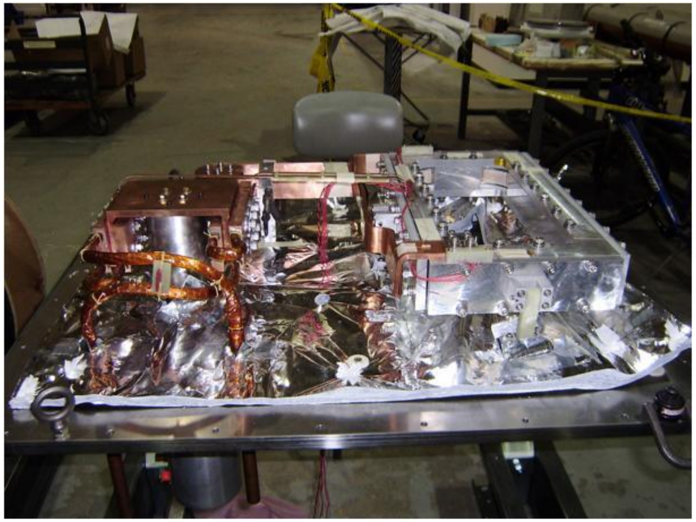


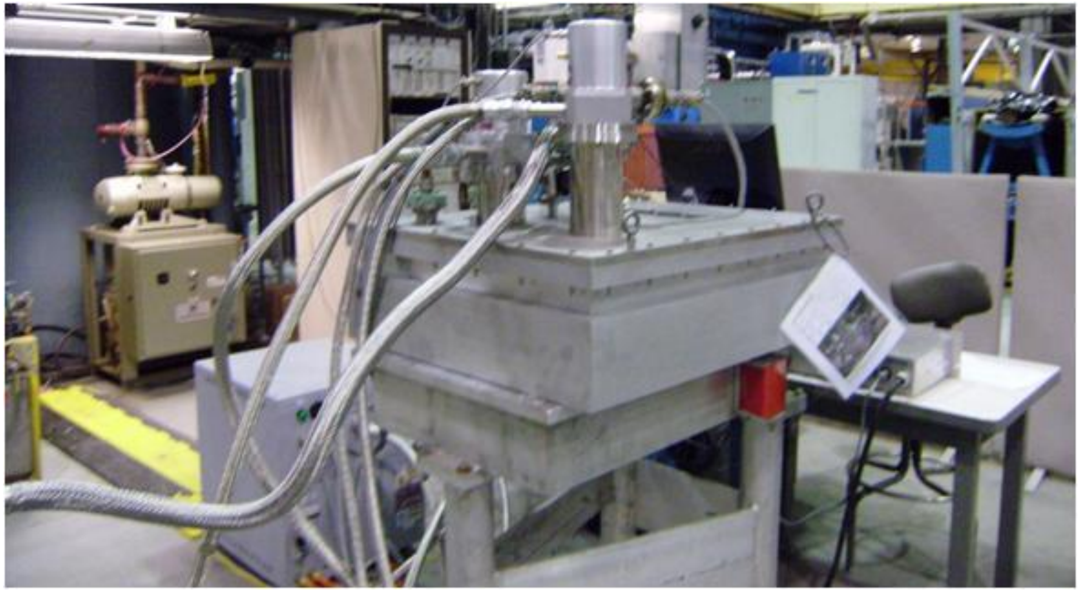
- **While the SuperPower and ASC samples showed a similar radiation damage pattern in the absence of field, there is a significant difference in the presence of field (particularly with respect to the field angle).**
- **HTS from both vendors, however, show enhancement to limited damage during the first 10 years of FRIB operation (good news)!!!**

Cryo-cooler based HTS Coil R&D



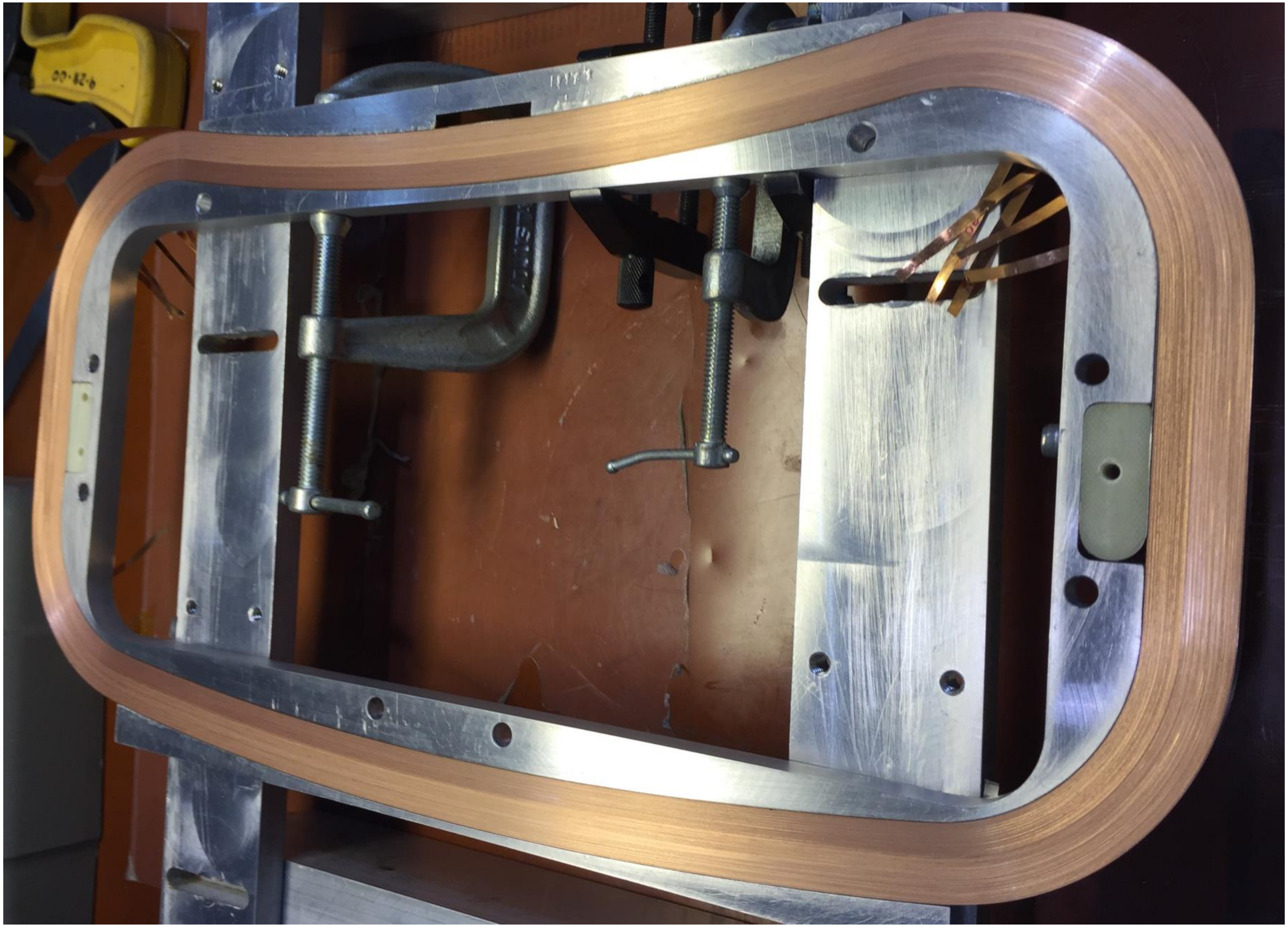
- Coils reached <40 K (goal was 40 to 50 K)
- Cryo-coolers turn-on at 5 pm in the evening before leaving and coils cooled at 8:30 am in the morning.
- Cryo-coolers removed a significant heat efficiently removed at 50 K.



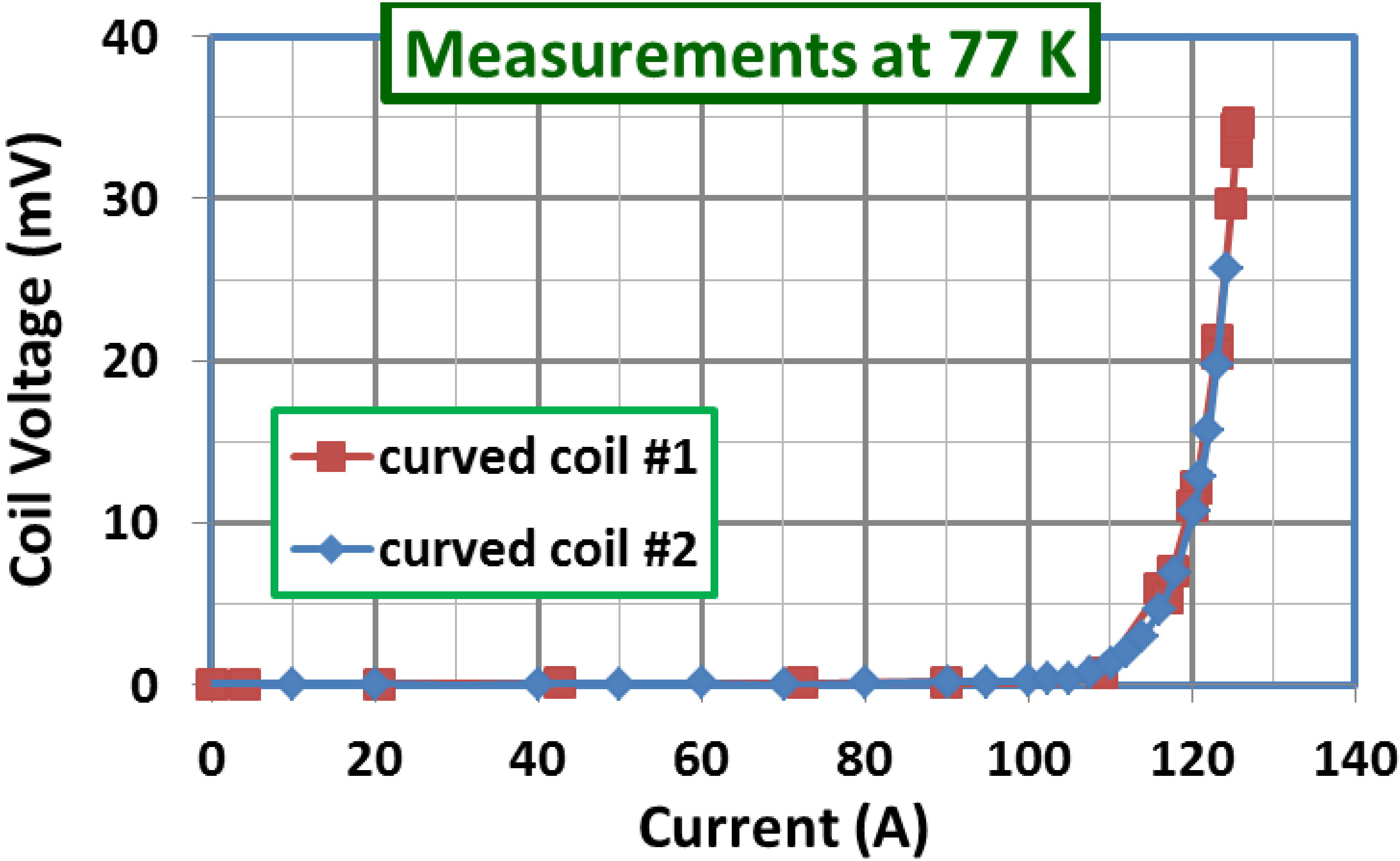


Curved HTS Coils

Curved HTS Coil




MUONS INC.
DBC-1001
DBC- 002


Measurements at 77 K
curved coil #1
curved coil #2
Coil Voltage (mV)
40
30
20
10
0
0
20
40
60
80
100
120
140
Current (A)

Quench Protection

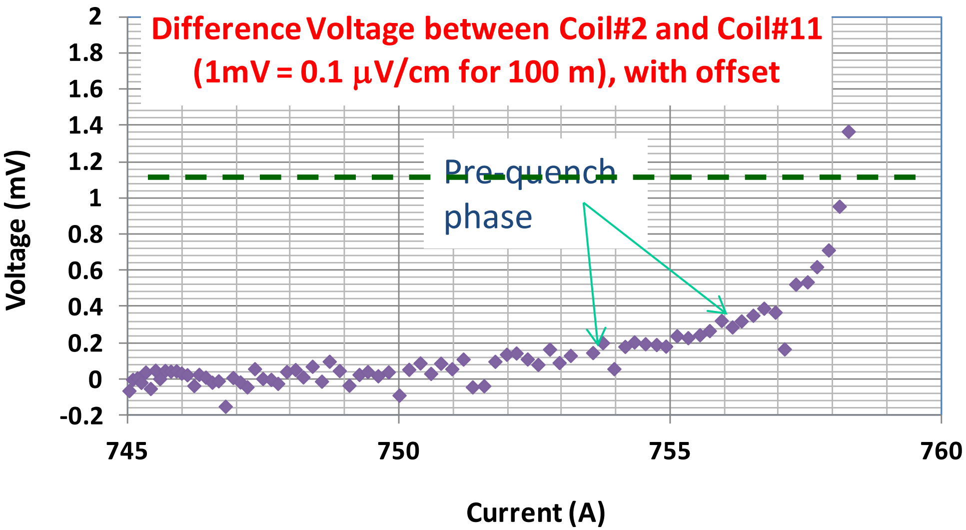
BNL HTS Quench Protection Strategy

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. Co-winding with stainless steel tape helps in quench protection.**

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



SUMMARY

- BNL has worked on a variety of HTS magnets covering a wide range and a variety of geometries with a number of collaborators.
- In addition to HTS, BNL has expertise with NbTi and Nb_3Sn magnets which will be helpful in developing the entire system.
- BNL is the only US laboratory with a large operating superconducting accelerator complex - Relativistic Heavy Ion Collider (RHIC). This gives a very useful perspective and support to superconducting magnet program.
- We are looking forward to working with MIT in this possible ground breaking application of high field HTS magnet technology in fusion energy research.