HTS Activities and Recent Progress at BNL

Ramesh Gupta
Brookhaven National Laboratory
Upton, NY 11973 USA

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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, curve 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 (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 (Phase I SBIR)
- High radiation HTS Quadrupole for FRIB (Collaboration)
- 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

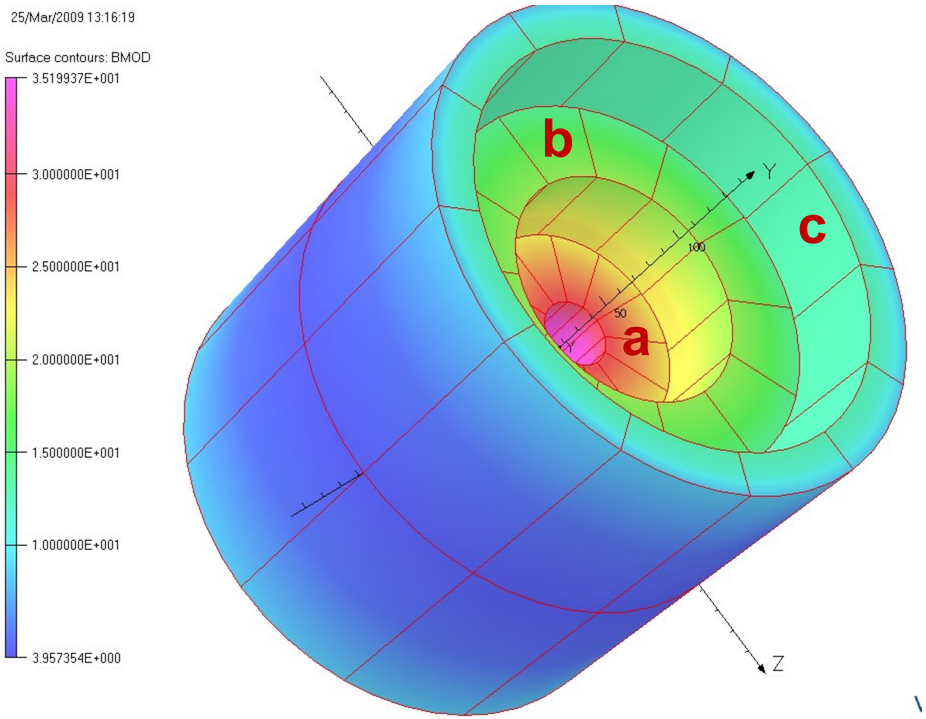
1. High Field Large Stress (~400 MPa) HTS Solenoids
2. High Radiation/Energy Deposition Quadrupoles

Common Features:

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

Path to a 30-40 T Solenoid

Goal: Develop high field solenoid for Muon Cooling



Several coils (build and test in their own structure, then combine):

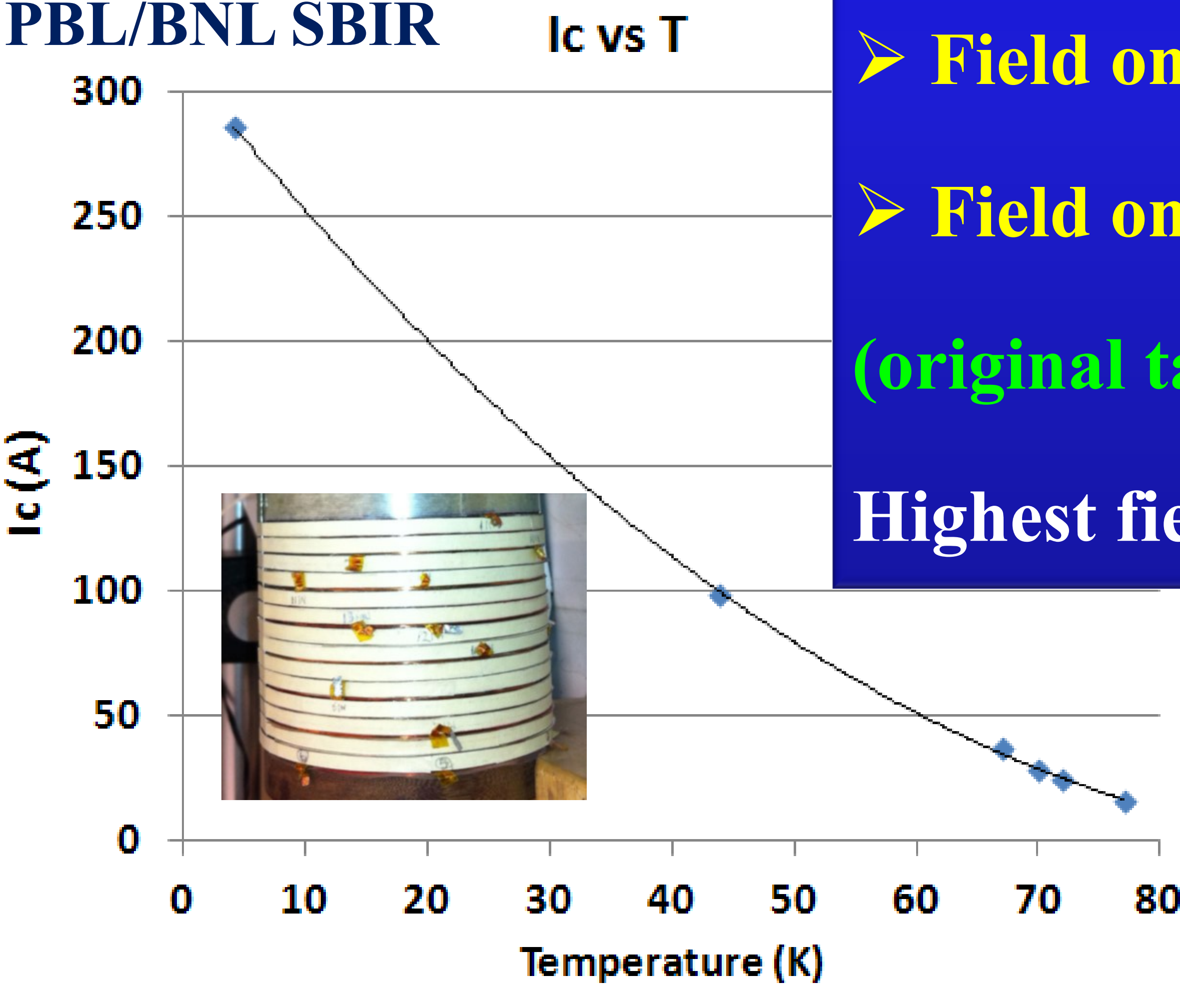
a) >12 T HTS solenoid (insert): 25 mm, 14 pancakes, 4 mm tape

b) >10 T HTS (midsert): 100 mm, 24 pancakes, 4 mm tape

c) >10 T LTS (outsert): NbTi and/or Nb_3Sn cable

16T HTS Solenoid
(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

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

Insert solenoid: 14 pancakes, 25 mm aperture

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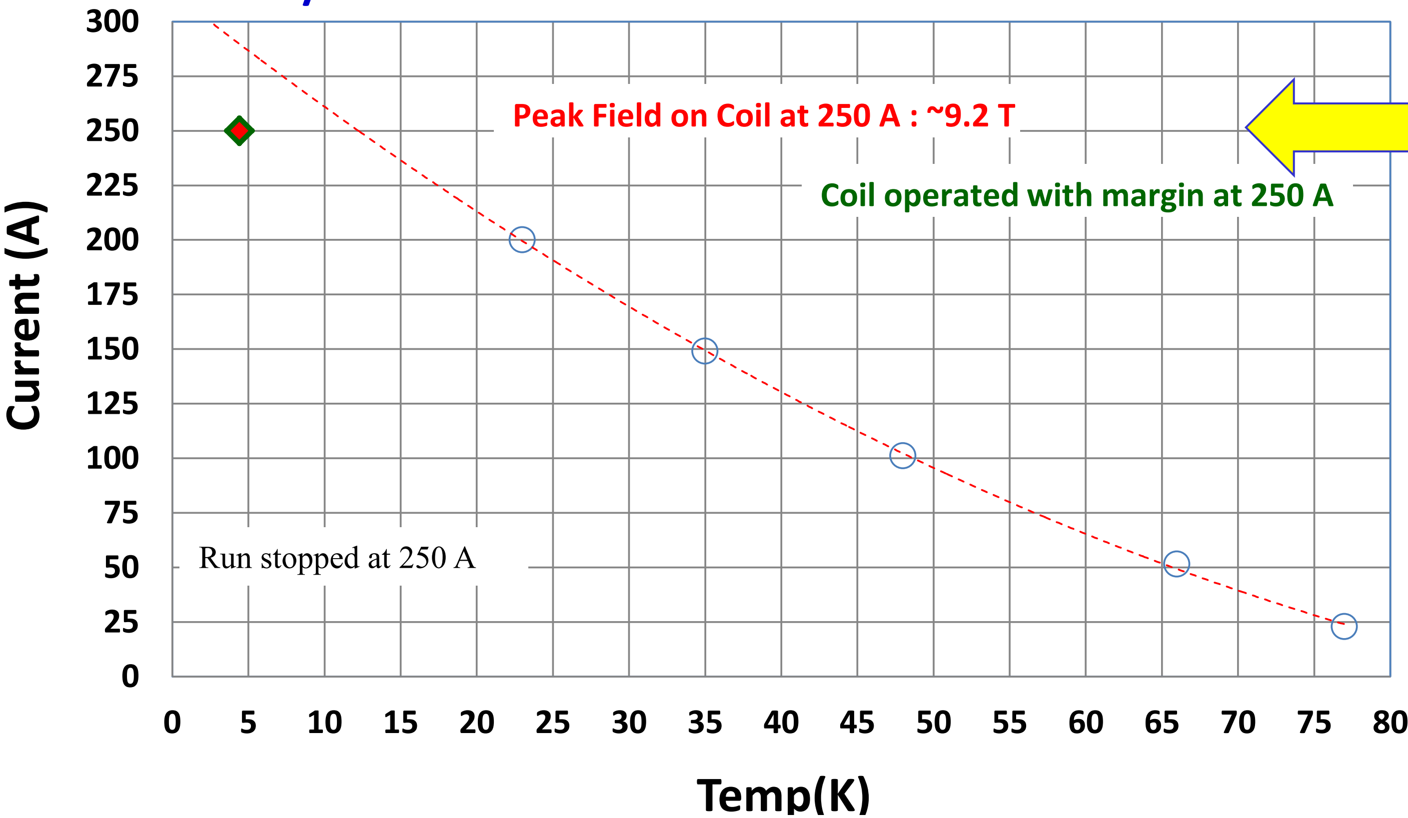
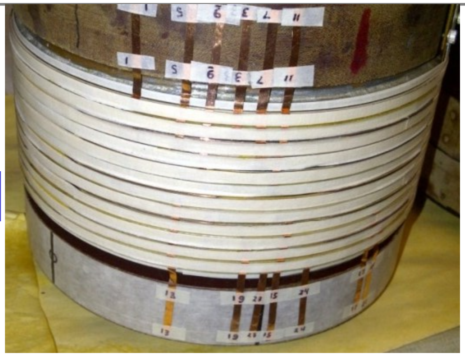
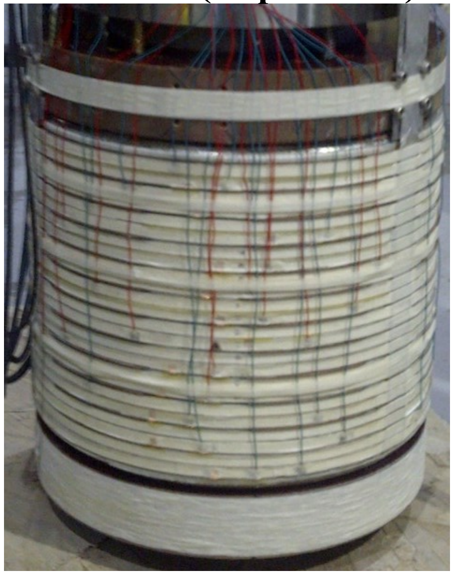
Large Aperture High Field HTS Magnet (a wide range of operating temperature)

PBL/BNL 100 mm HTS Solenoid Test for Muon Collider





Half midsert (12 pancakes)

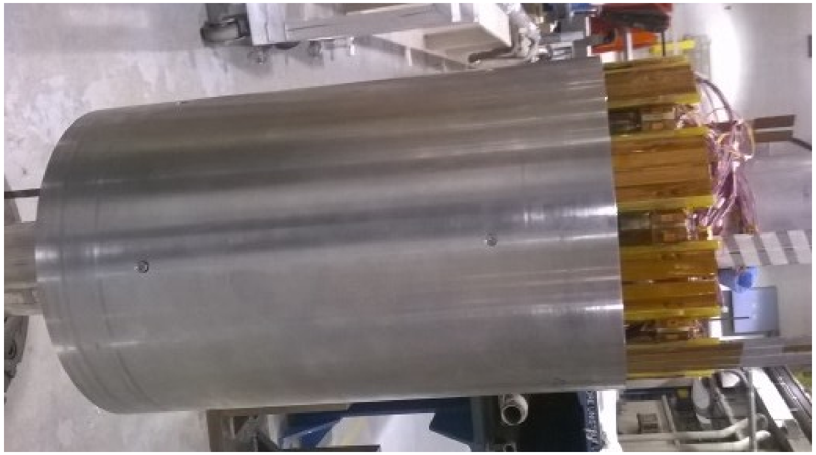


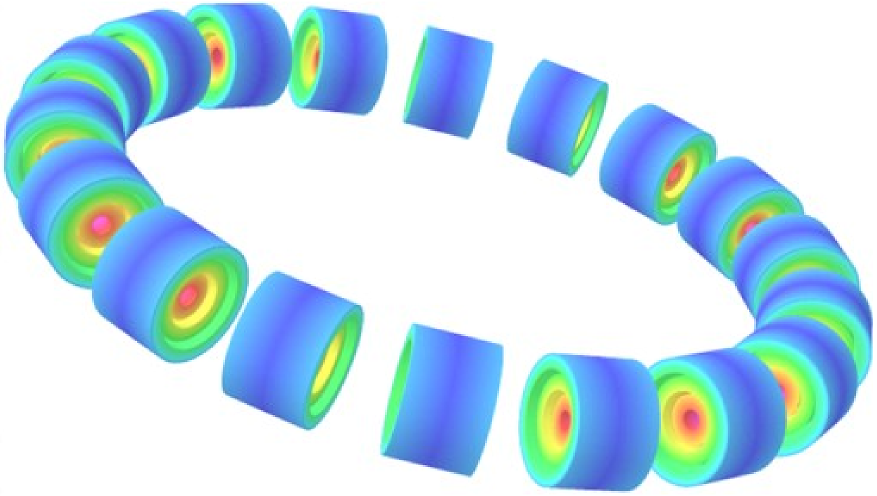
Full midsert (24 pancakes)

- **Half midsert** operated at **250 A @4 K (6.4 T field on axis, 9.2 T peak field on coil**

HTS Insert + midsert designed to generate ~22 T and with Nb_3Sn outsert ~35 T

High Field HTS SMES Coil





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)

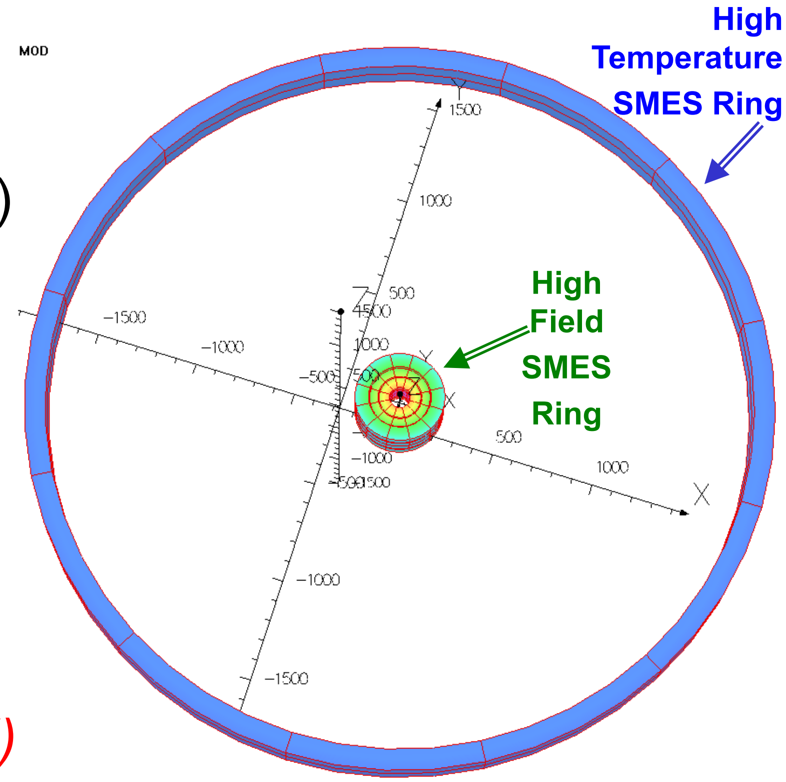
Our analysis on HTS option:

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)

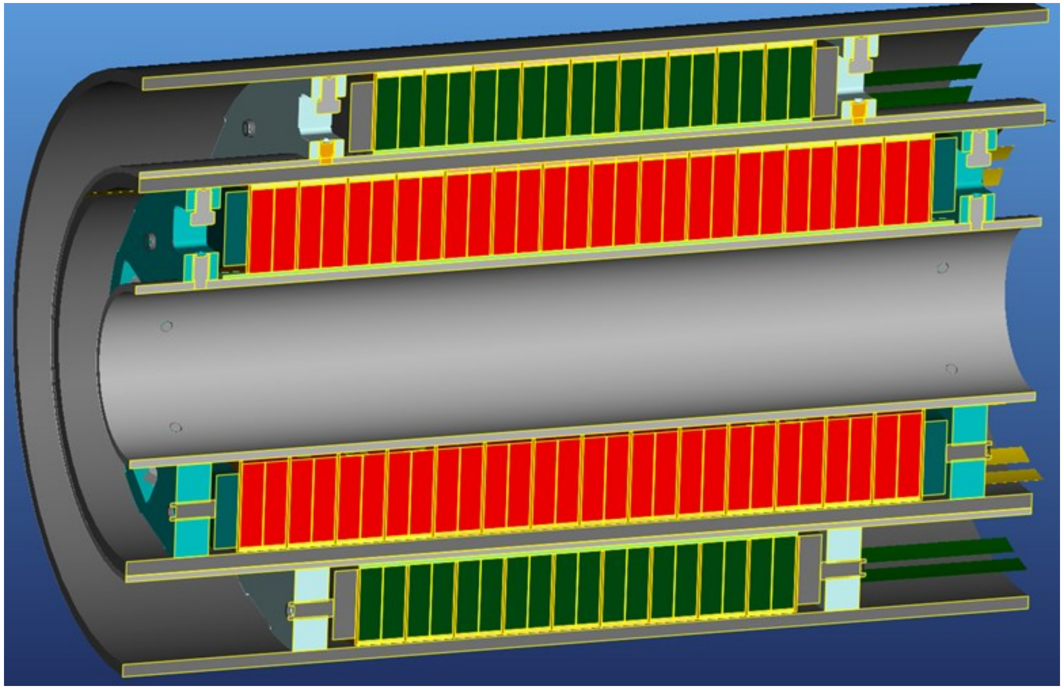
❖ Only with HTS *(high risk, high reward)*



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

The Basic Demo Module

High Risk, High Reward R&D funded by arpa-e



Aggressive parameters:

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

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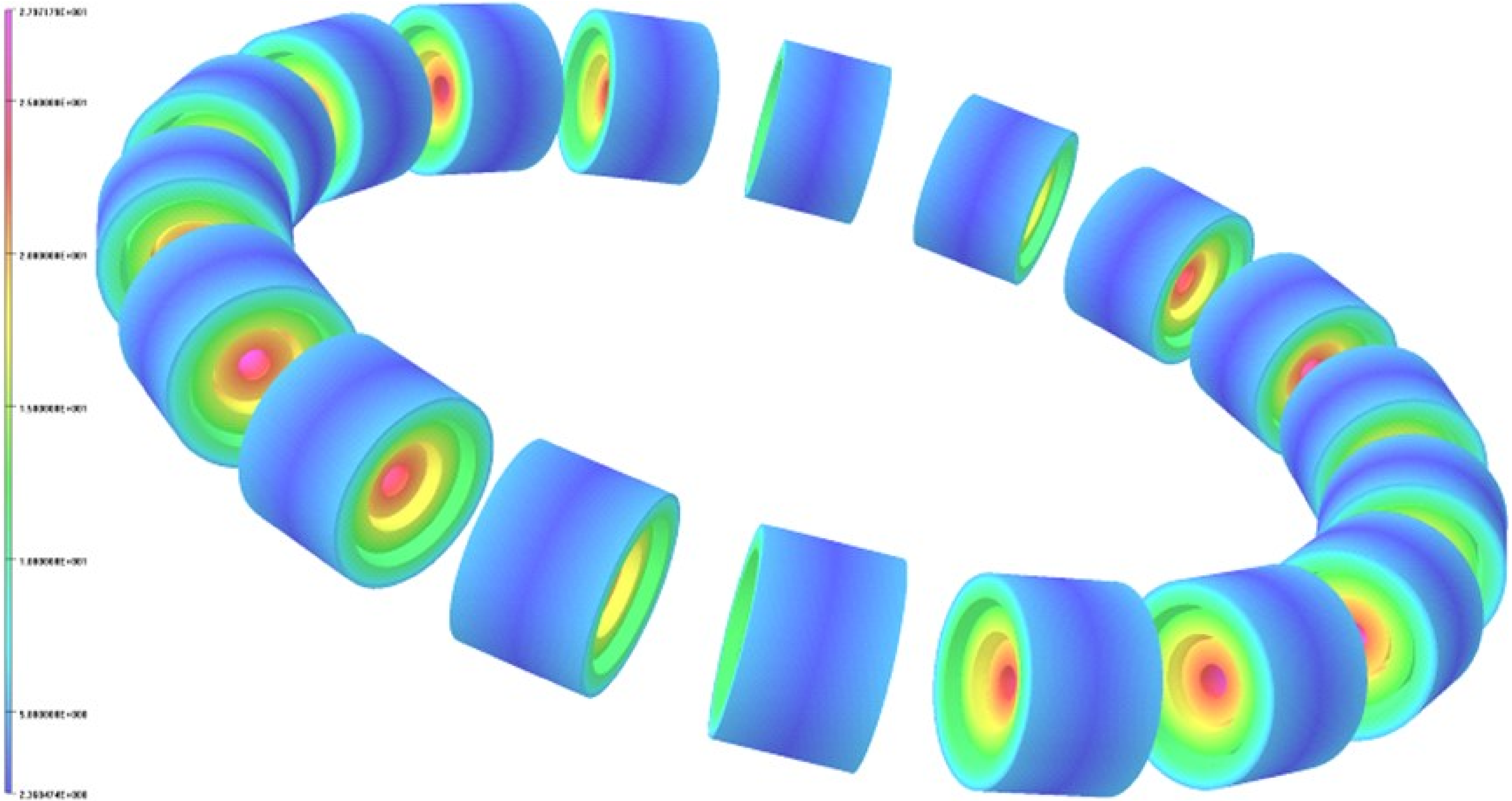
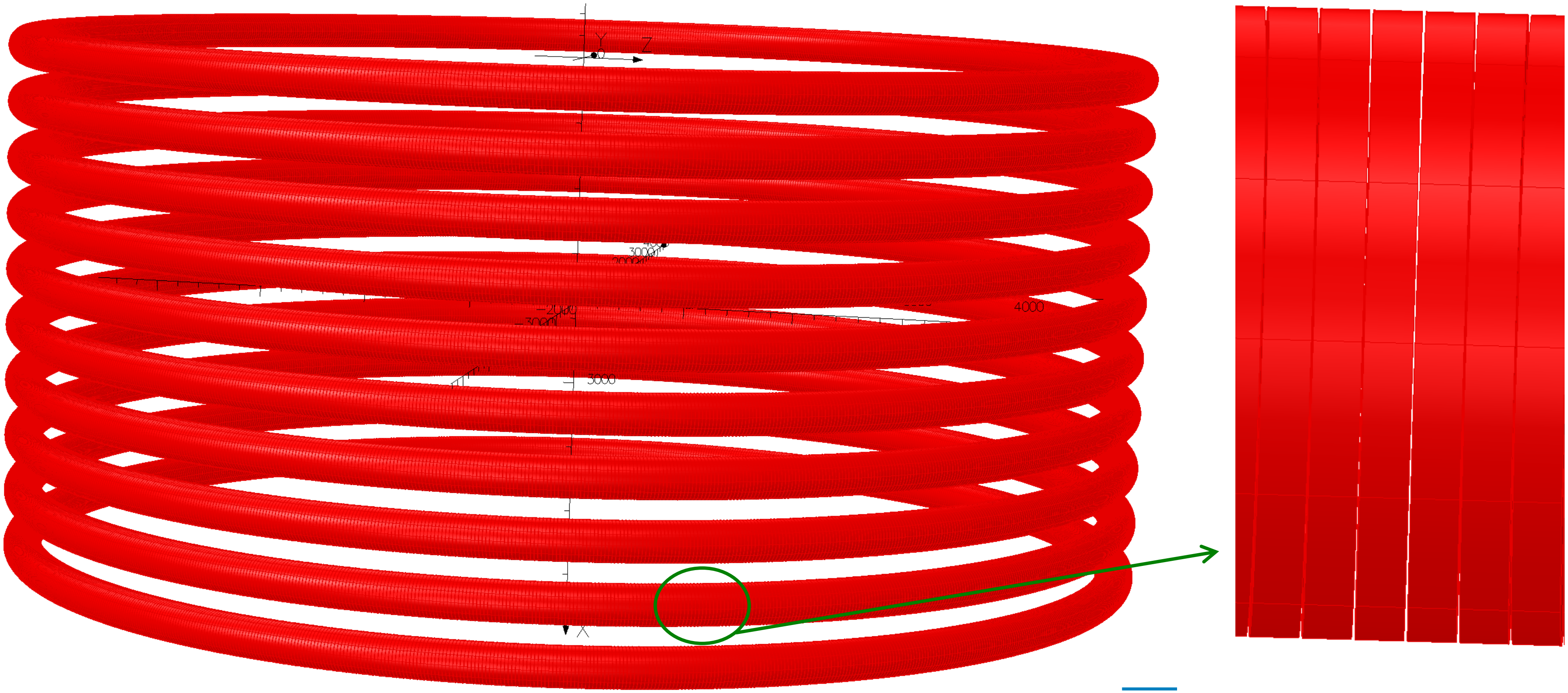
Large Scale SMES Concept (1)



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

Large Scale SMES Concept (2)

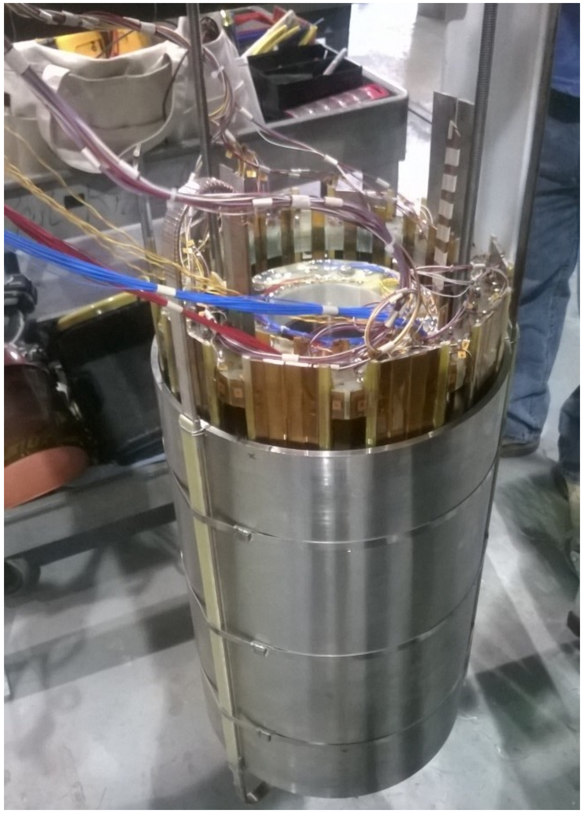


GJ scale GRID storage system that can fit in a room!

- **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

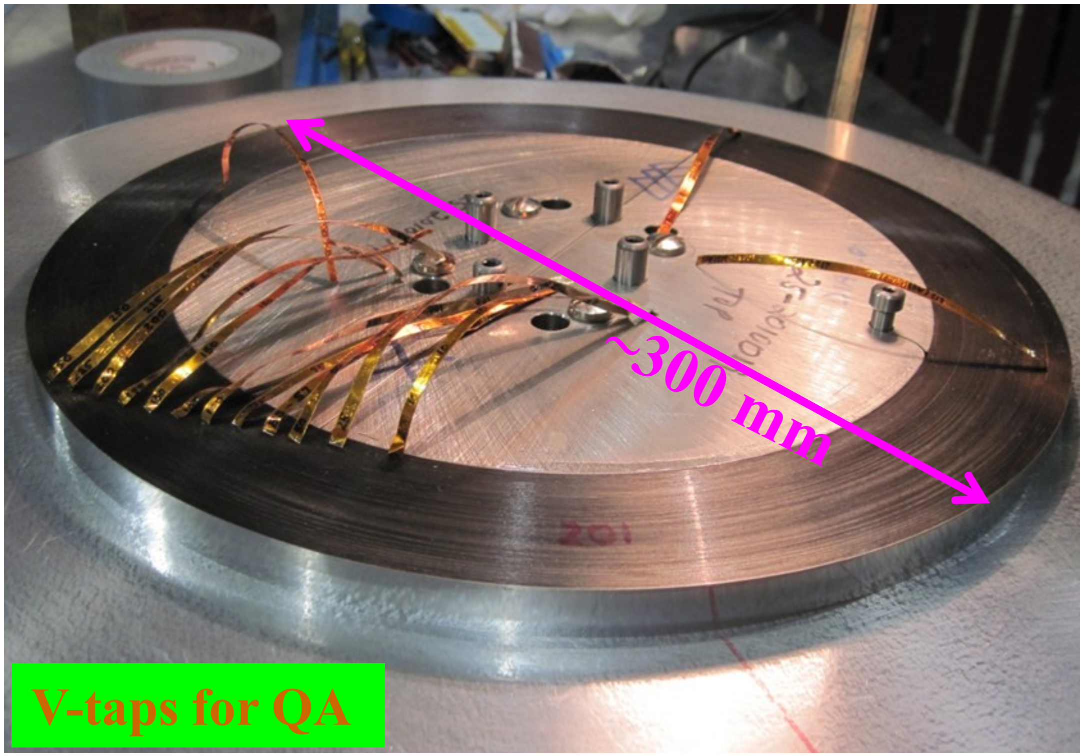


High field and big radius create large stresses (~400 MPa)

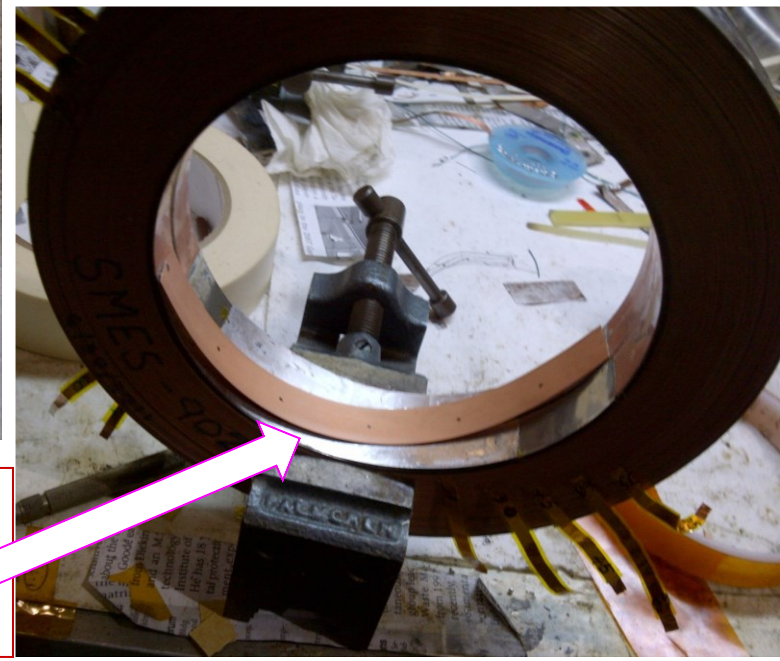
HTS Coil Winding

HTS Pancakes

~210 meter i.d., 12 mm tape, 258 turns



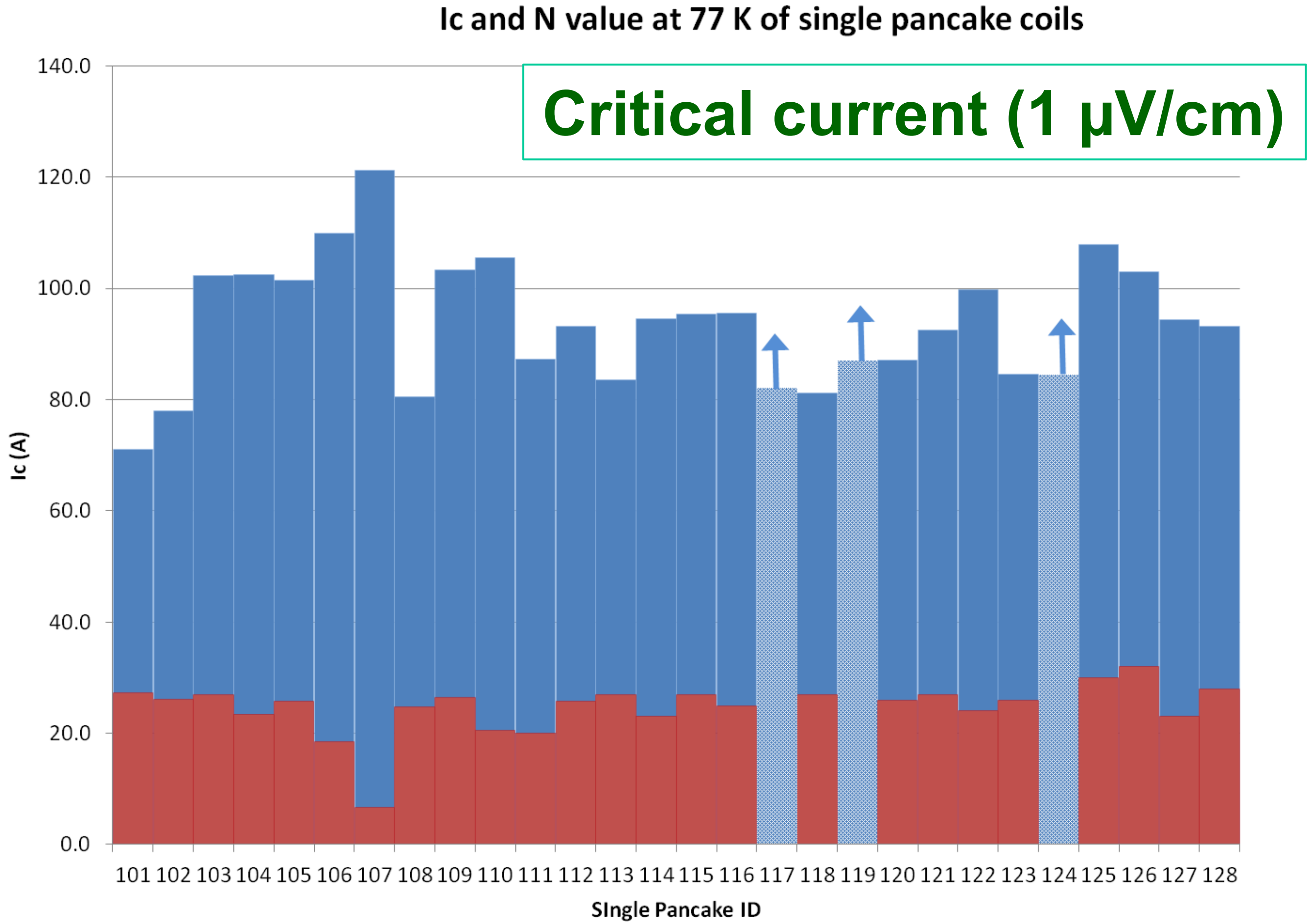
- High strength HTS tape, co-wound with SS tape (for insulation and added strength)
- Thickness of SS tape and copper on HTS adjusted to optimize the performance



Two Pancakes Connected with Spiral Splice Joint

77 K Pre-Test of Pancakes (inner)

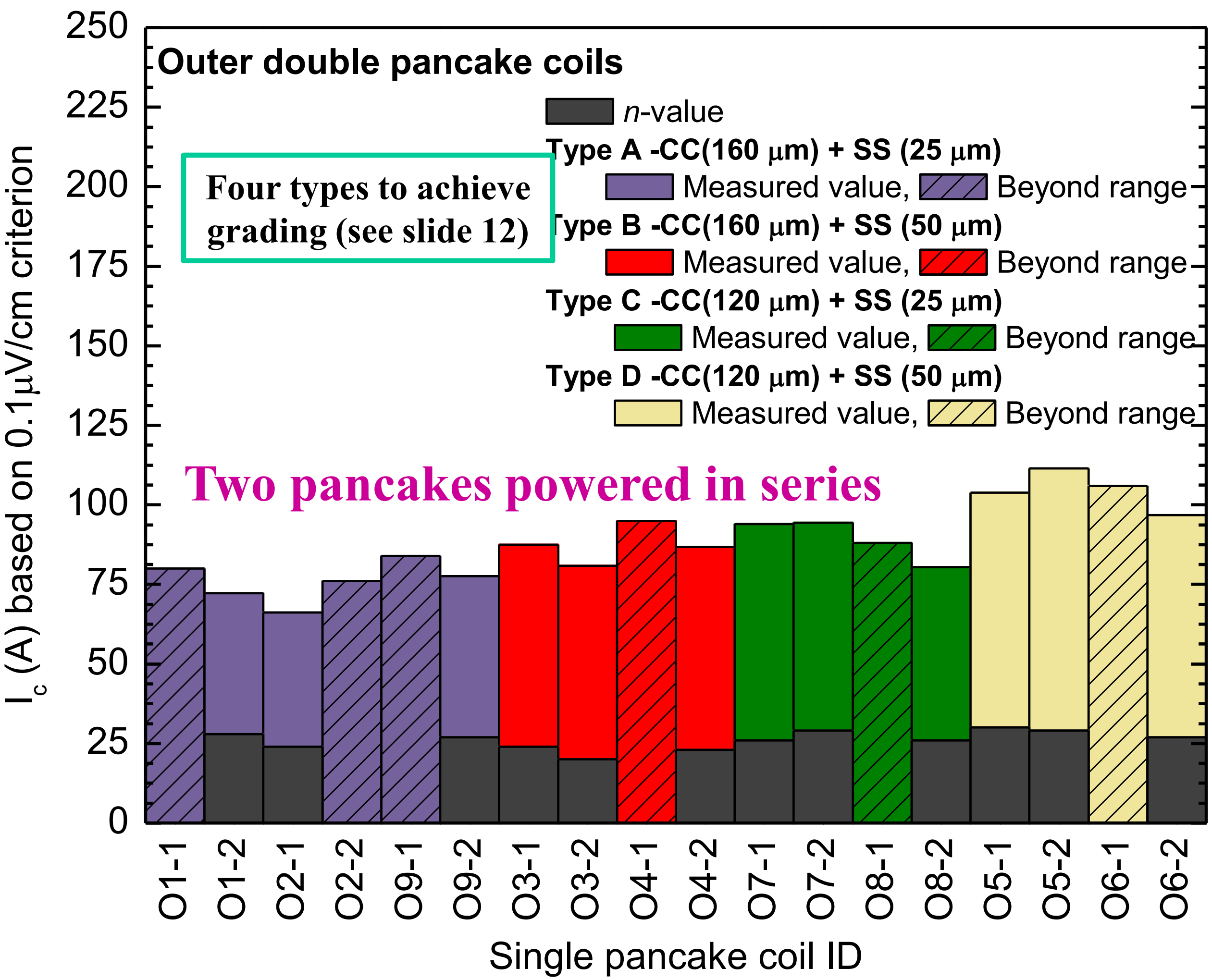
All pancakes are individually pre-tested at 77 K for QA check (a unique benefit of HTS)

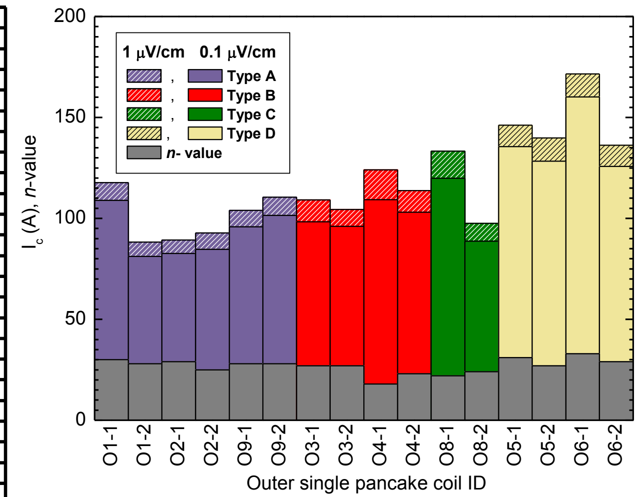


Two single pancakes powered in series.

77 K Test of a Series of Outer Pancakes (mechanical and electrical properties adjusted)

Adjustment in SS tape thickness and amount of Cu on HTS tape





Each pancake powered alone

Higher I_c in coil at 77K , doesn't necessarily translate in to a higher I_c at 4K

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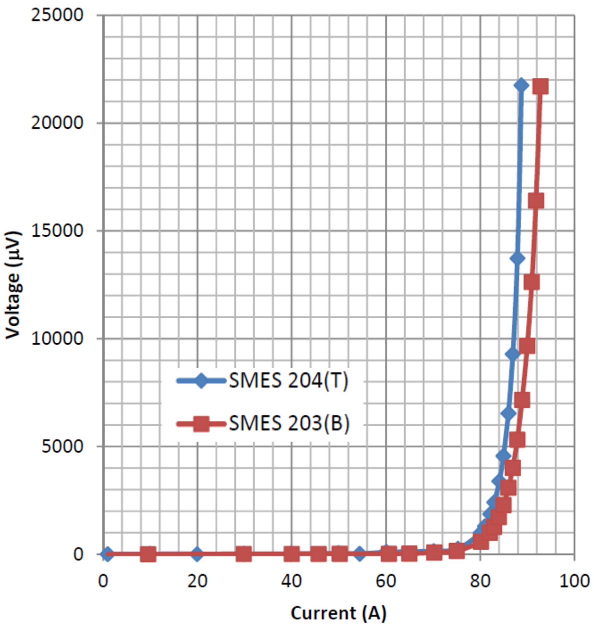
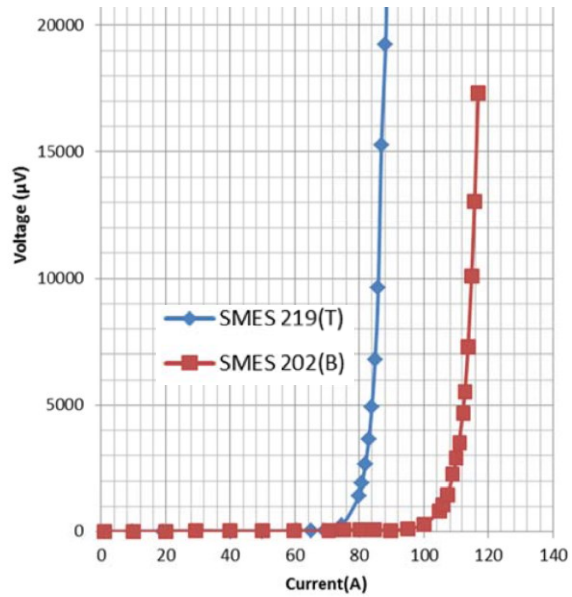
Double Pancake 77 K QA Test

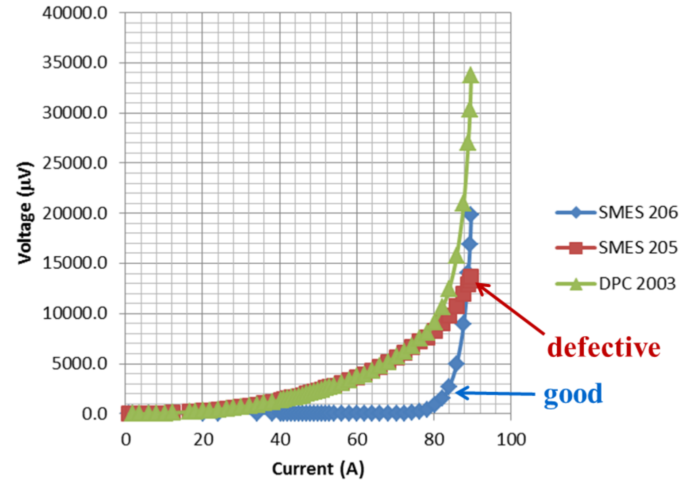
2 pancakes with similar critical currents

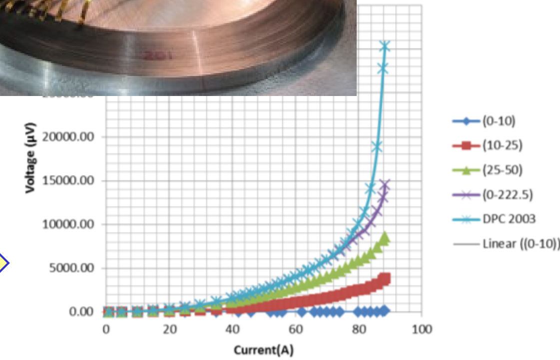


2 pancakes with very different critical current



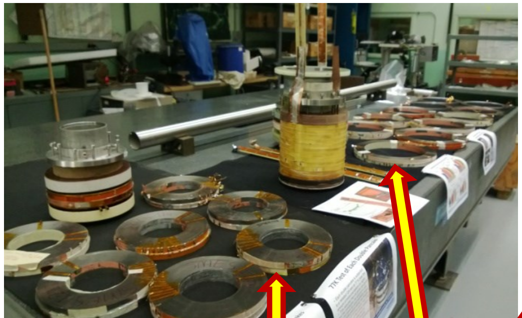
one pancake good and other pancake defective

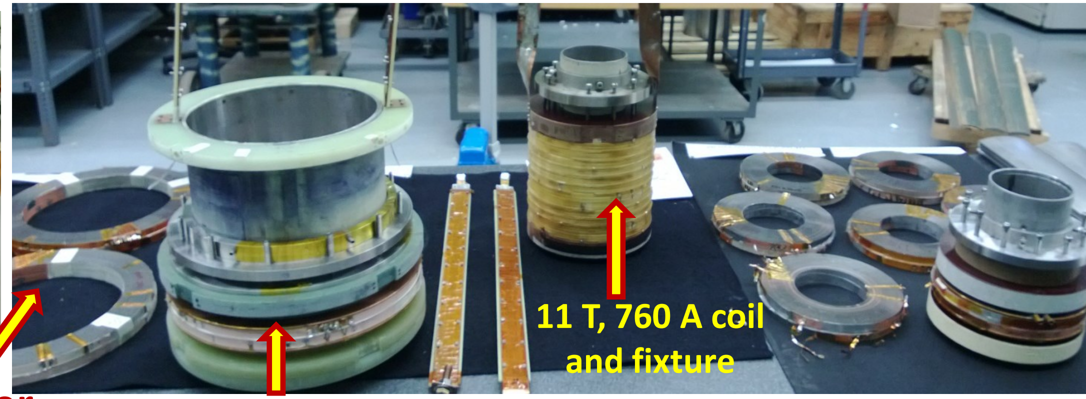




Note: Thorough 77 K test of each pancake was an important part of a series for QA

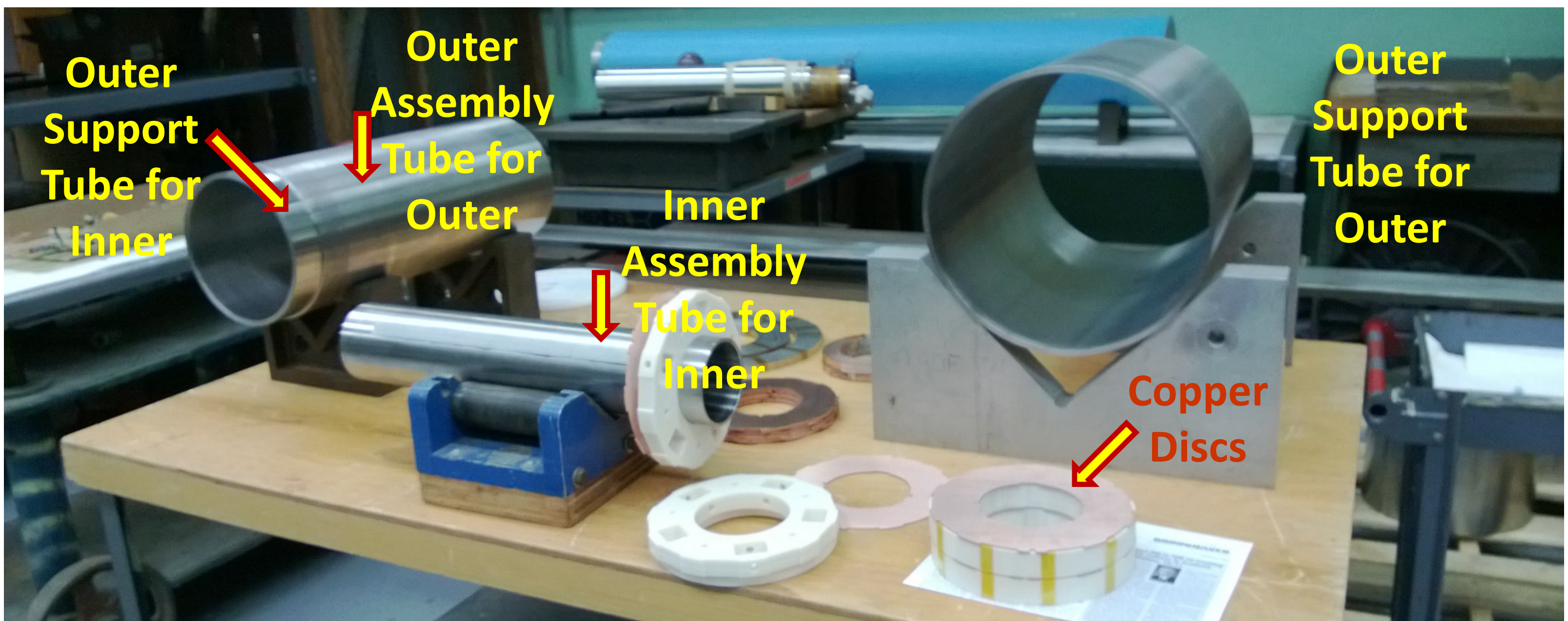
Coils, Test Fixtures and Support Structure



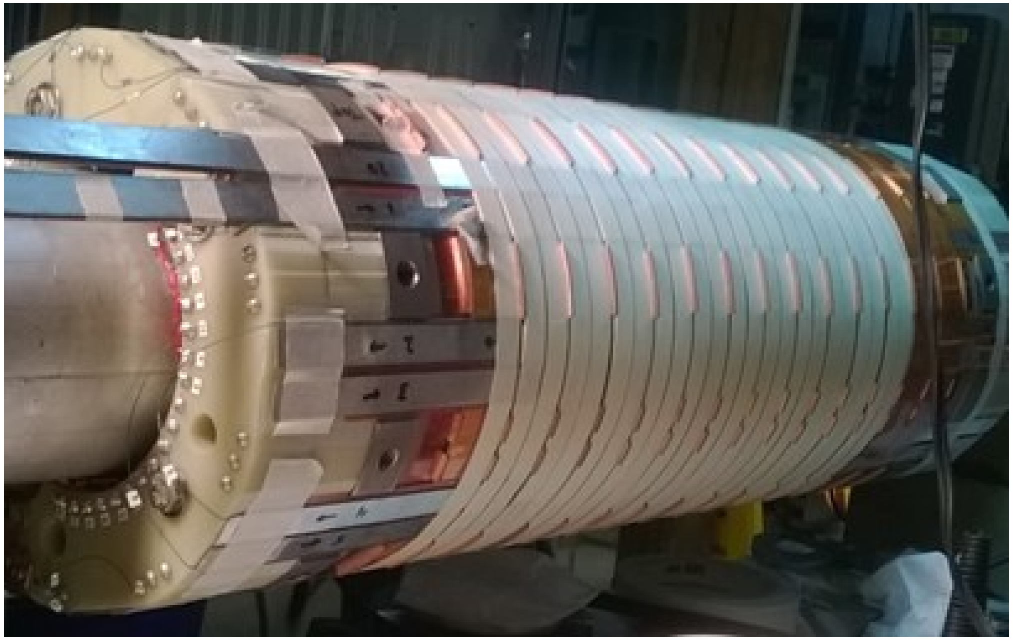


Pancake coils: inner and outer

77 K Test Fixture for outer



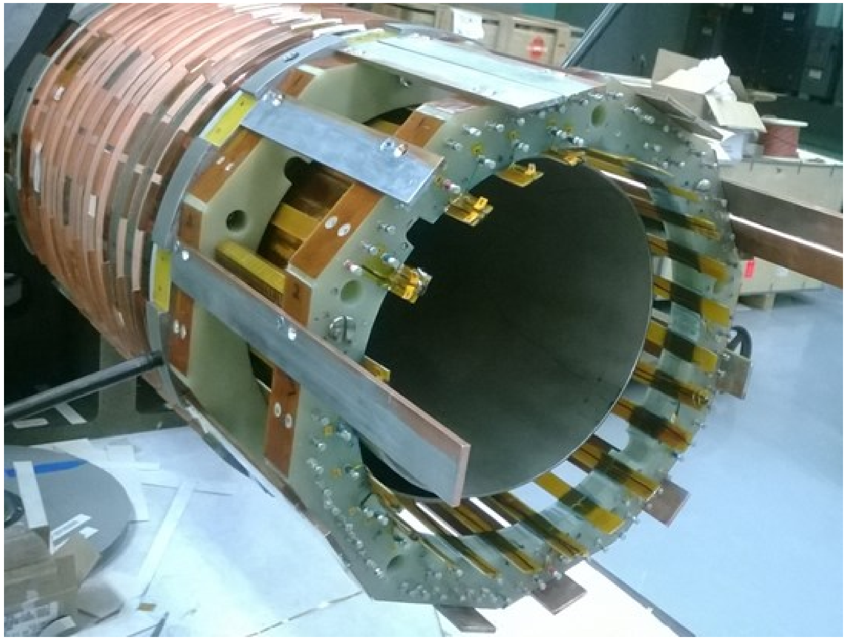
Inner and Outer Coils Assembled



Inner Coil

(102 mm id, 194 mm od)

28 pancakes



Outer Coil

(223 mm id, 303 mm od)

18 pancakes

Total: 46 pancakes

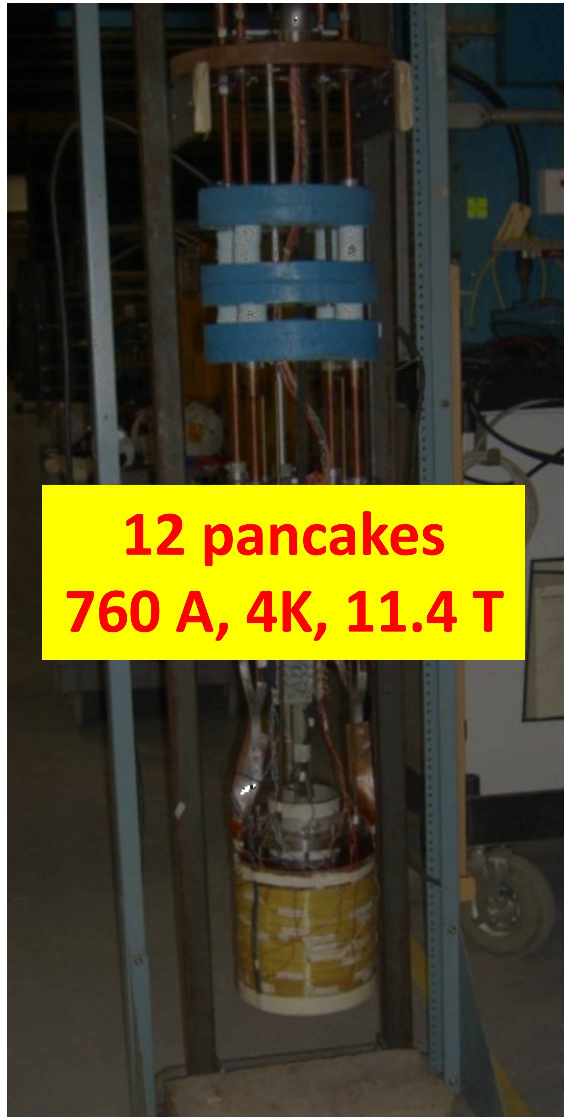
Final Assembly

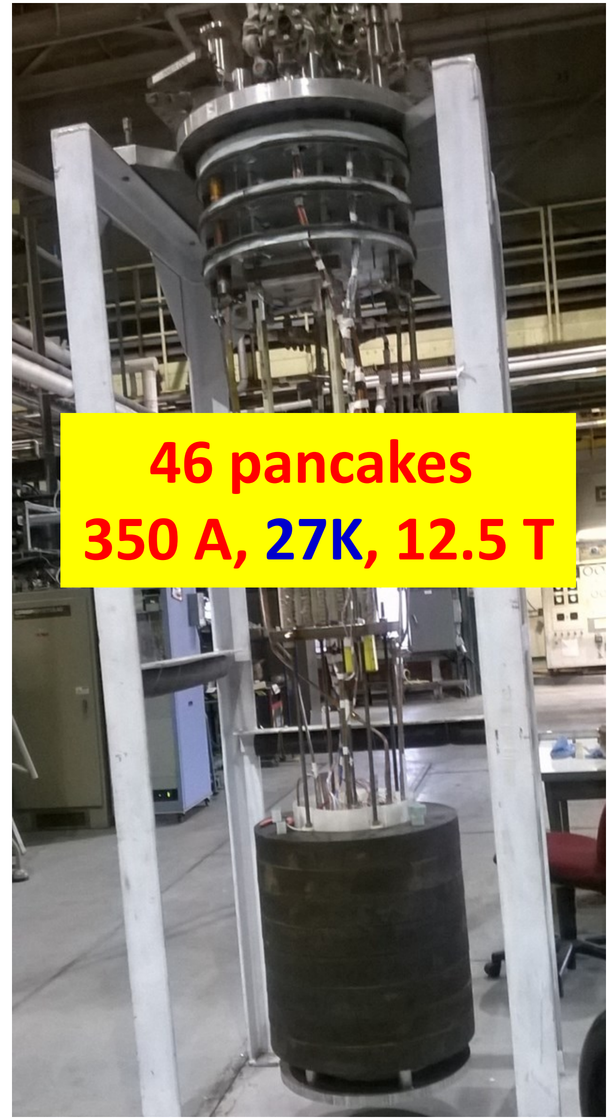
Outer inserted over inner coil

SMES coil in iron laminations

Low Temperature Test Results

HTS SMES Coil High Field Tests

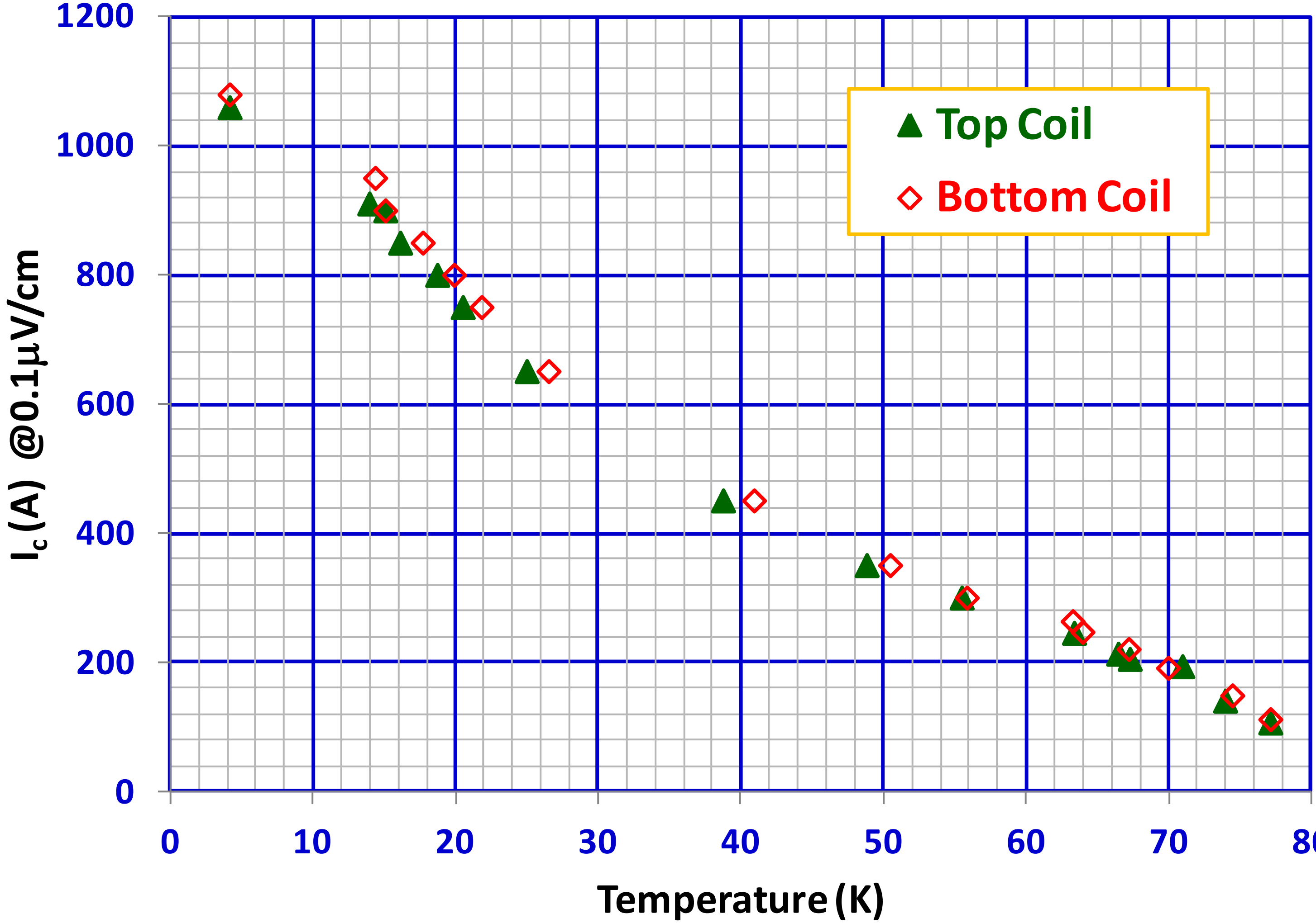


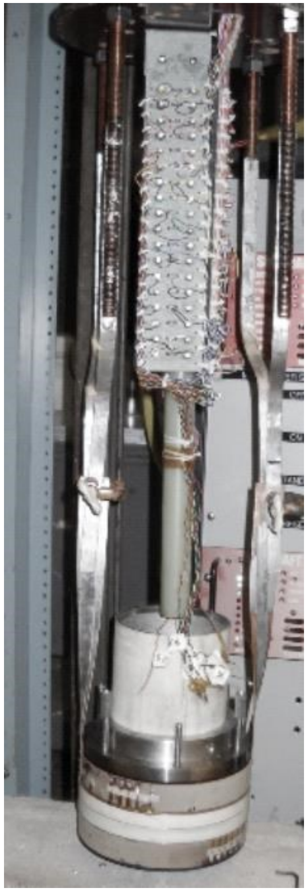


Peak fields higher

Double Pancake Coil Test
(a wide range of operating temperature)

Nominal design current: ~700 A

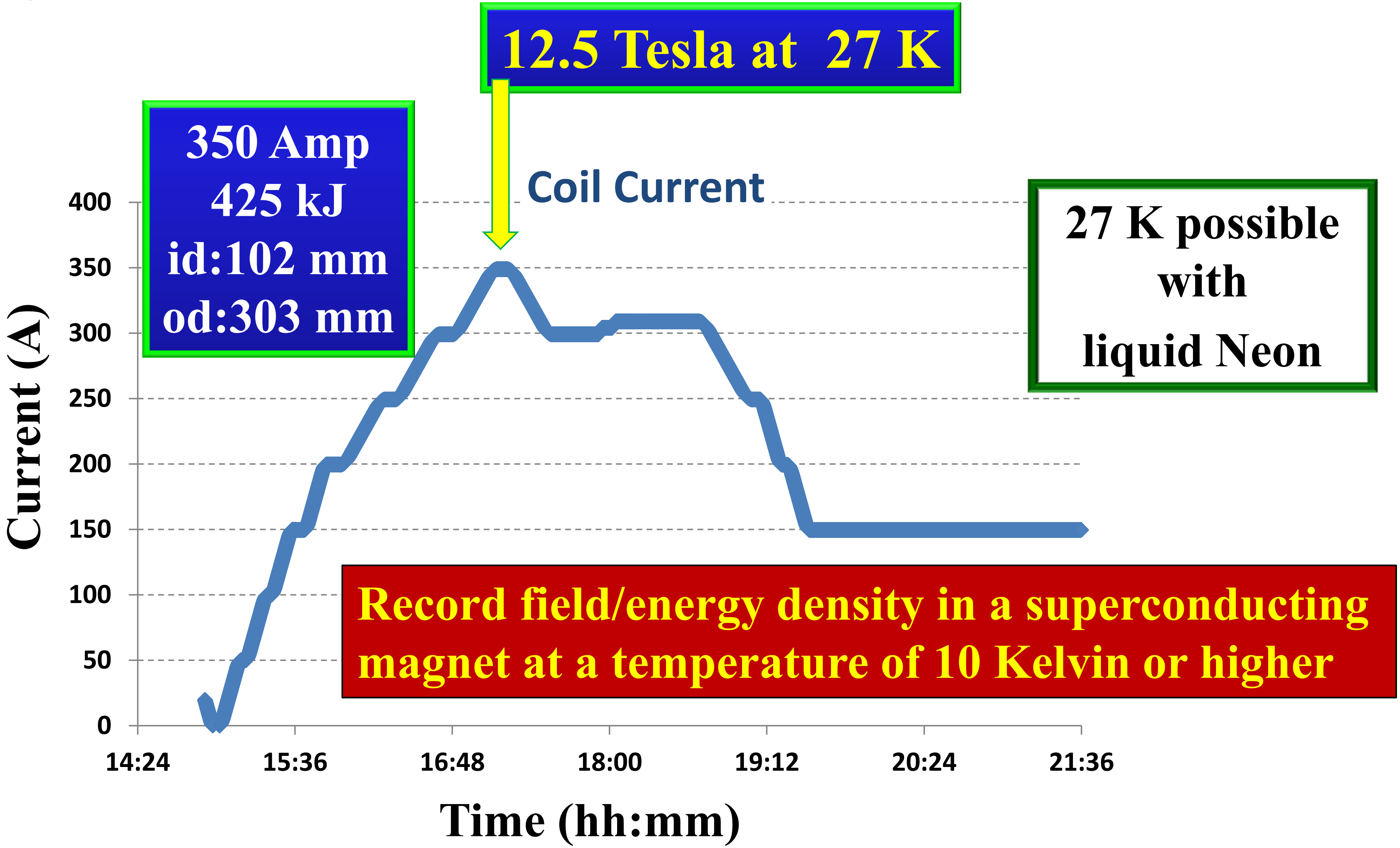




Ramp rate up to 10 A/s

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

SMES Coil Run on 5/21/14



HTS Quadrupole for RIA/FRIB

RIA: Rare Isotope Accelerator

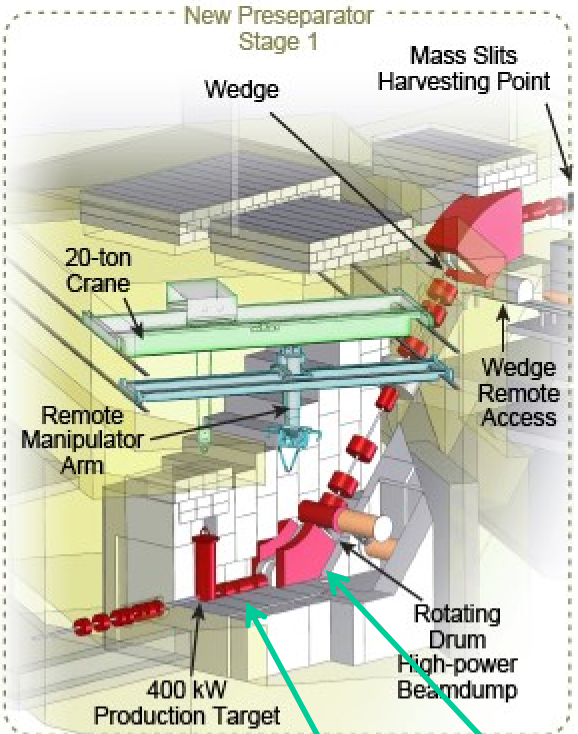
FRIB: Facility for Rare Isotope Beams

Radiation Tolerant HTS Quad for the Fragment Separator Region of FRIB

To create intense rare isotopes, 400 kW beam hits the production target.

Magnets in the fragment separator region are exposed to unprecedented radiation and heat loads. HTS can efficiently remove that at elevated temperatures.

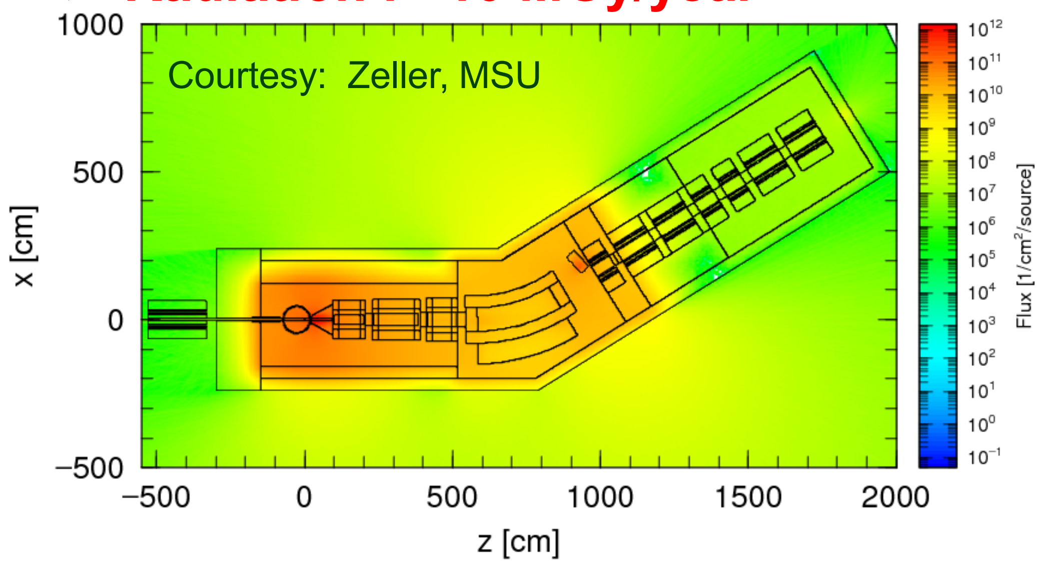
Courtesy: Al Zeller, FRIB/MSU



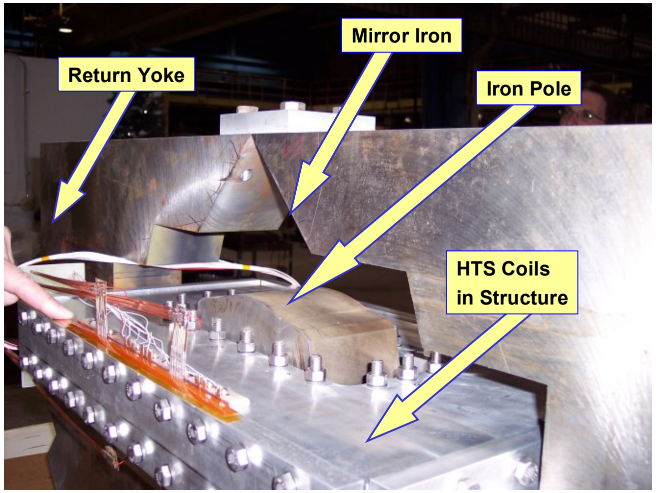
Radiation resistant
Pre-separator quads and dipole

Exposure in the first magnet itself:

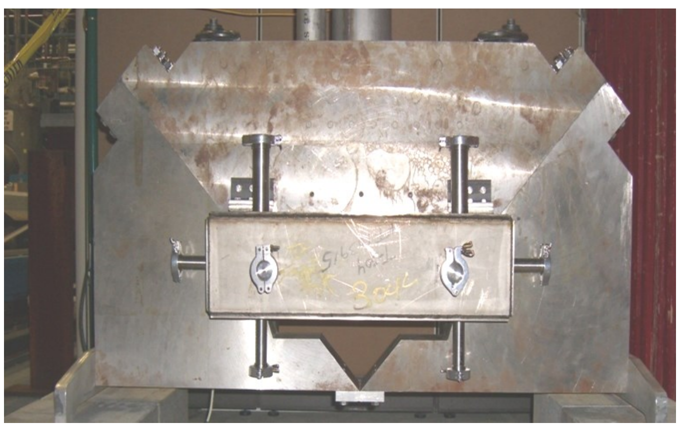
- **Head Load : ~10 kW/m, 15 kW**
- **Fluence : 2.5 x10^{15} n/cm^2 per year**
- **Radiation : ~10 MGy/year**



First Generation HTS Quad for FRIB

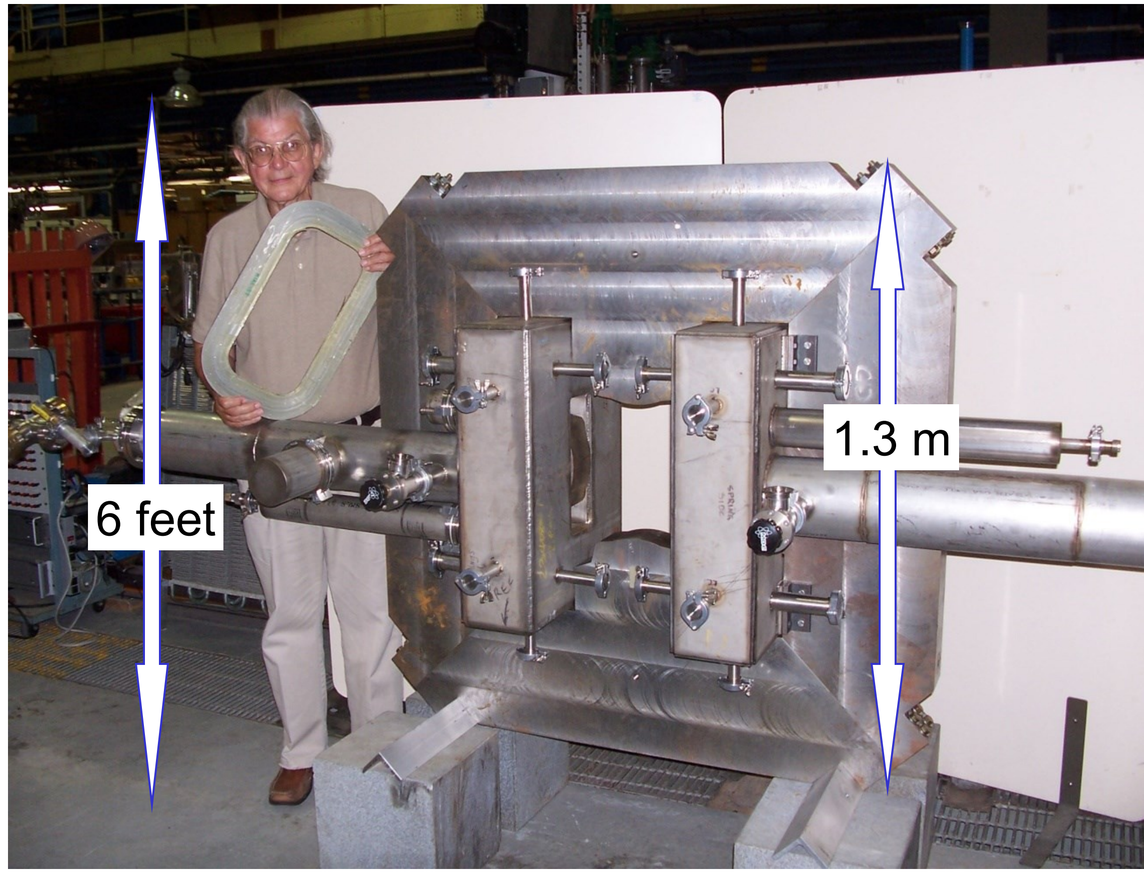


Mirror cold iron

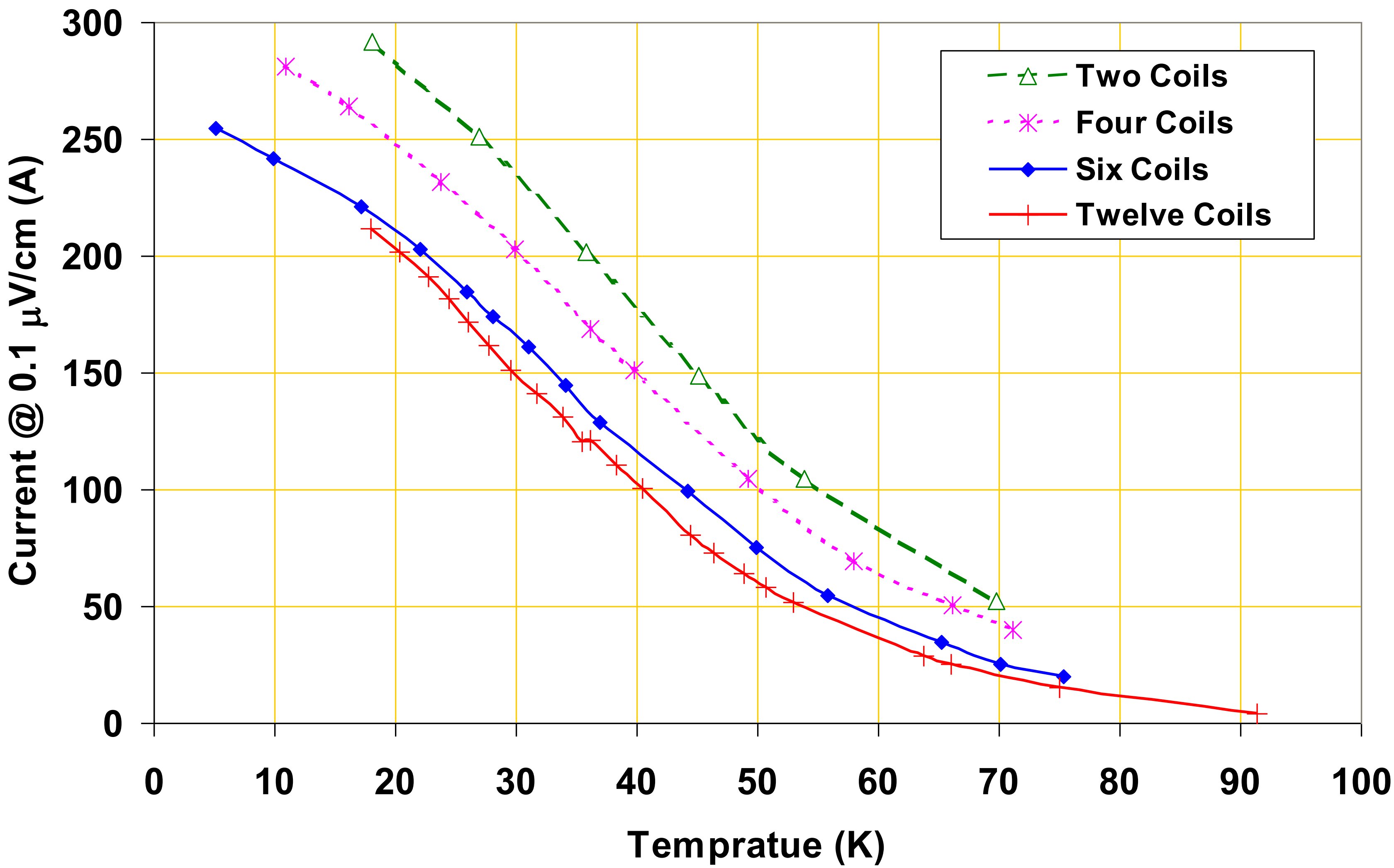


Mirror warm iron

Warm Iron Design with Bi2223 HTS



First Generation HTS Quad Test (operation over a large temperature range)



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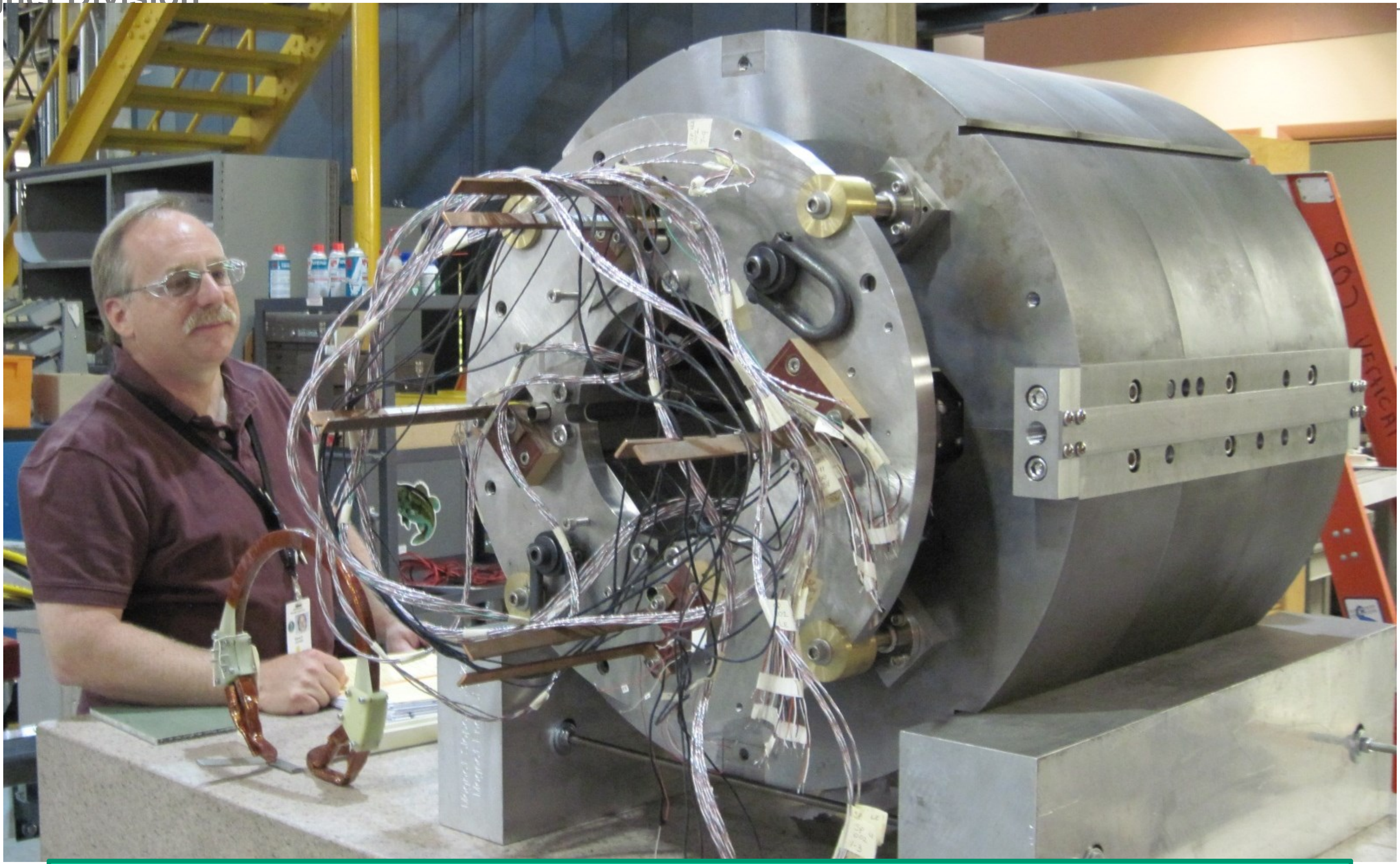
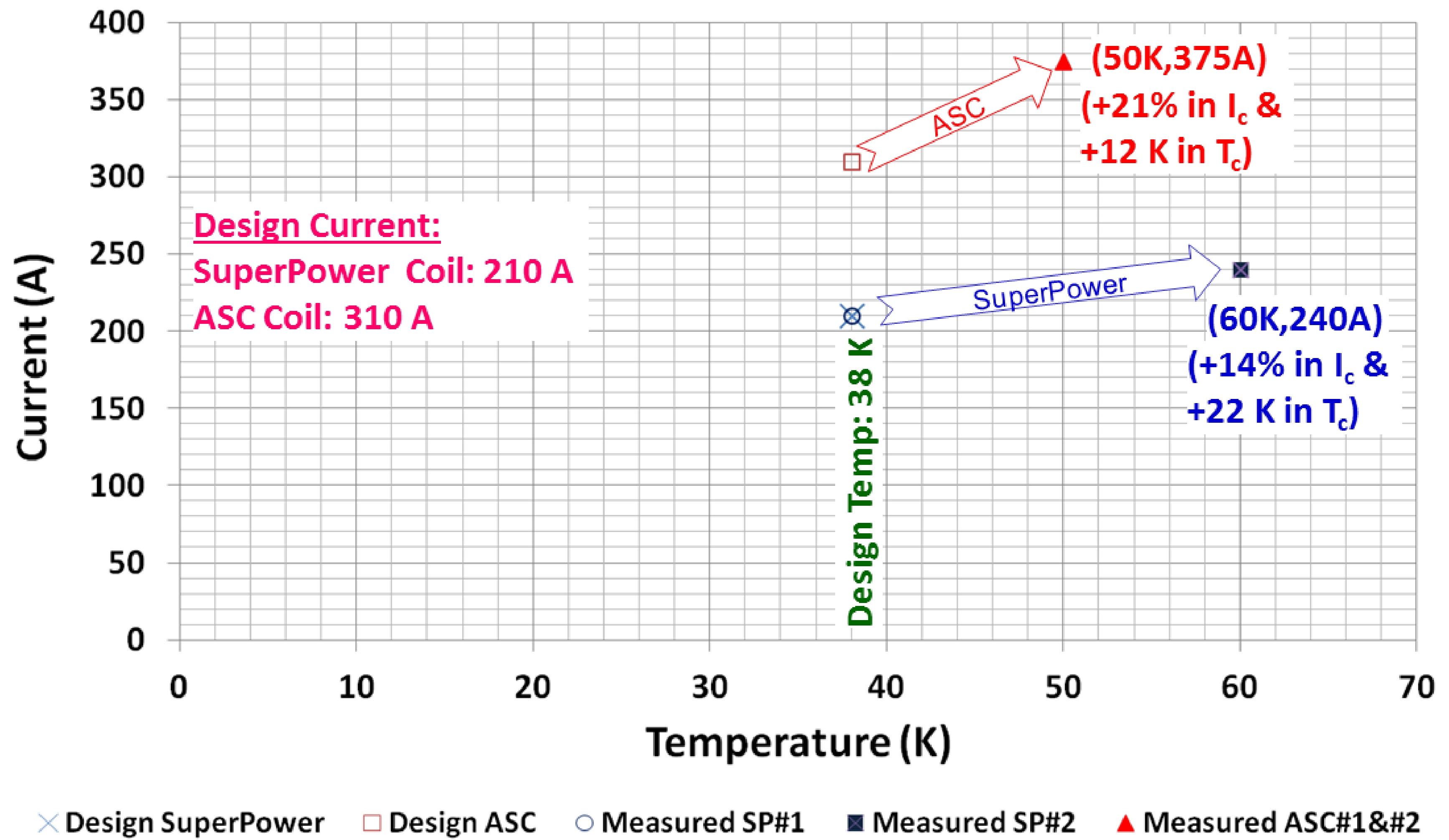
Second Generation HTS Quad for FRIB Fragment Separator Region



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.

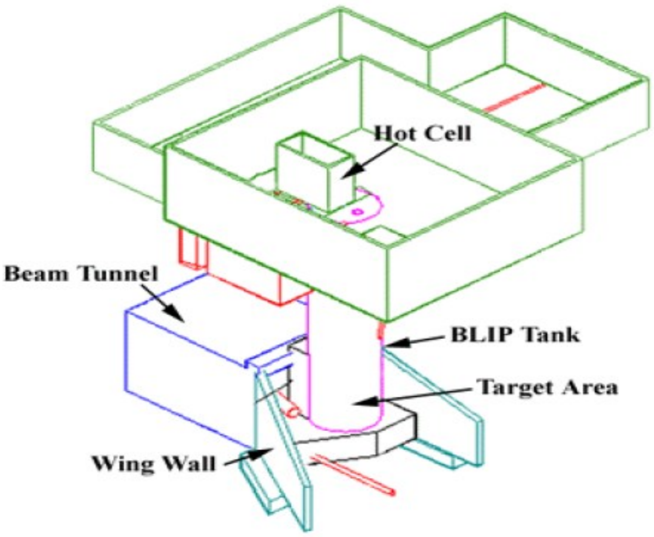


Figure 3. BLIP Beam Tunnel and Target Schematic

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.

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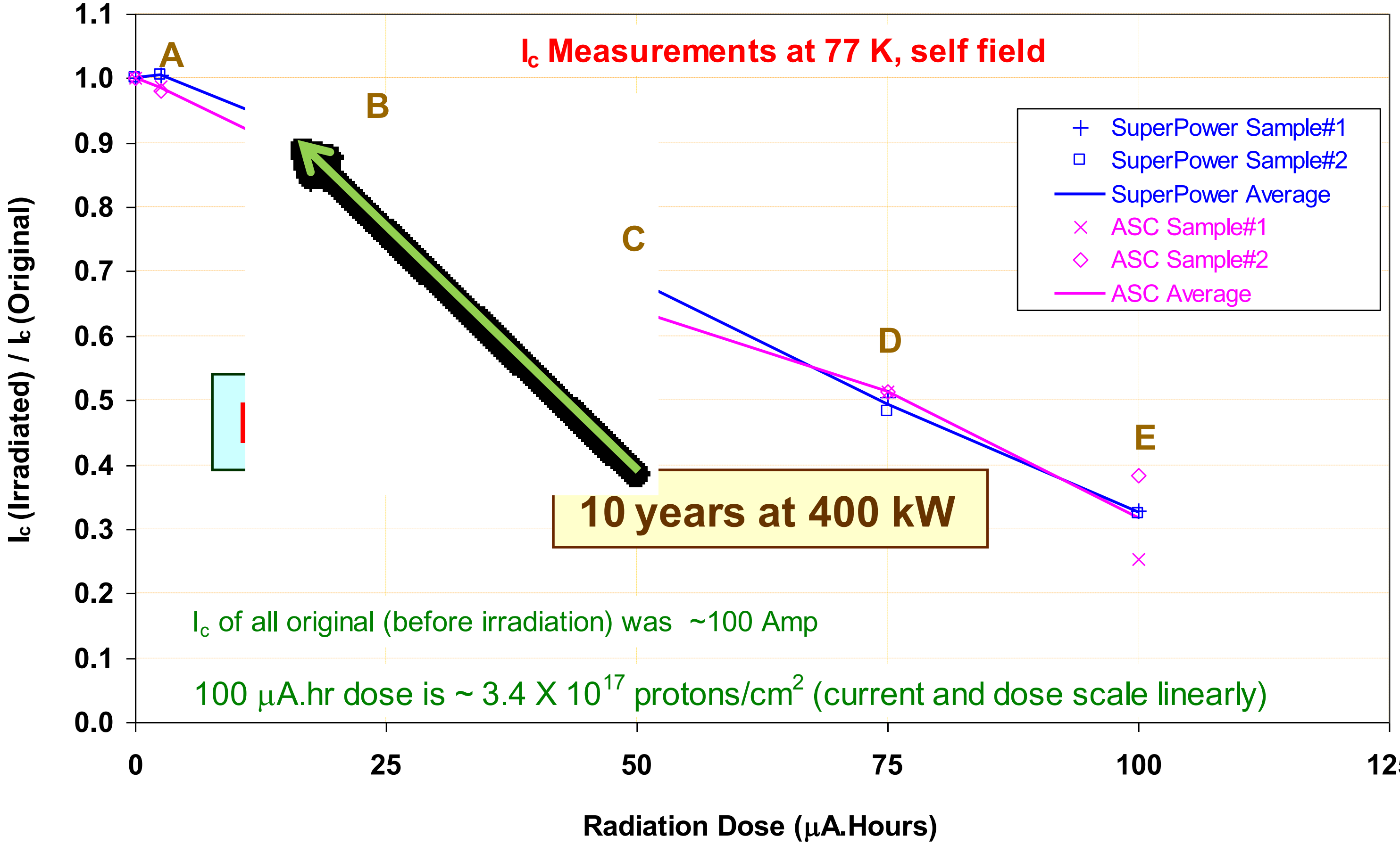
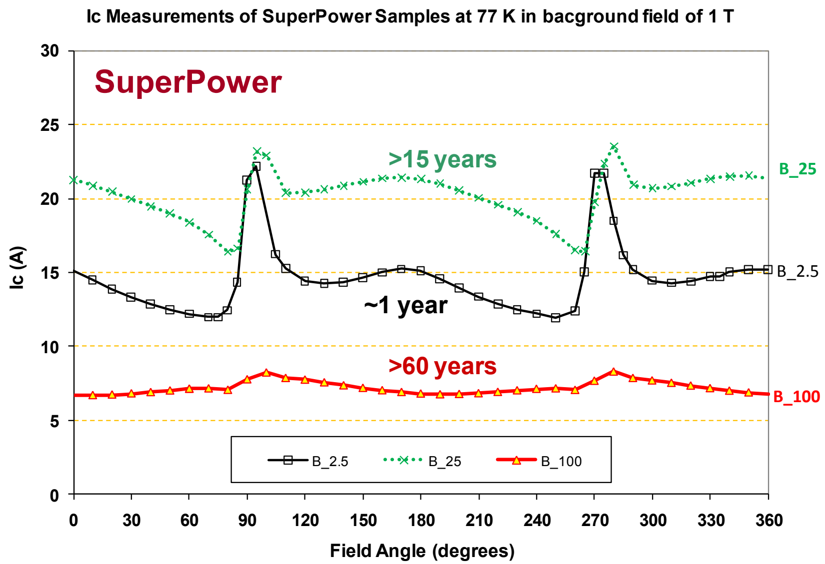
Impact of Irradiation on 2G HTS

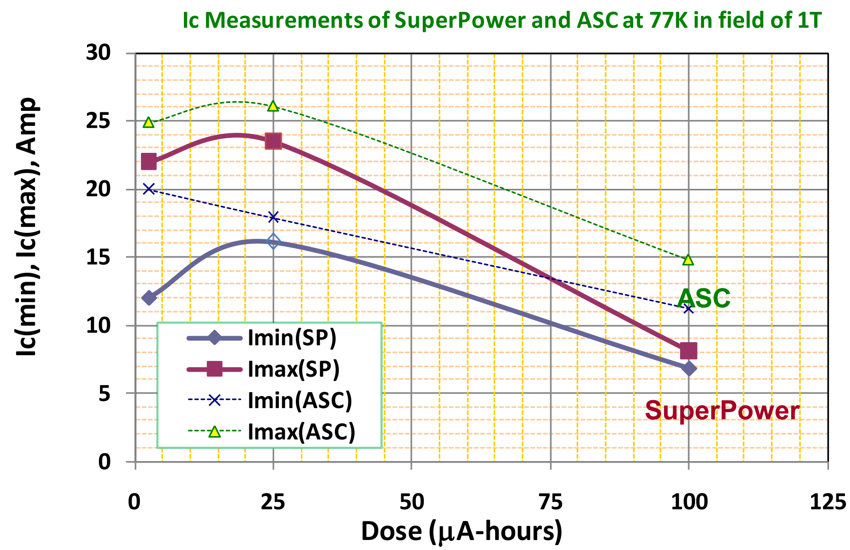
Radiation Damage Studies on YBCO by 142 MeV Protons by G. Greene and W. Sampson at BNL (2007-2008)



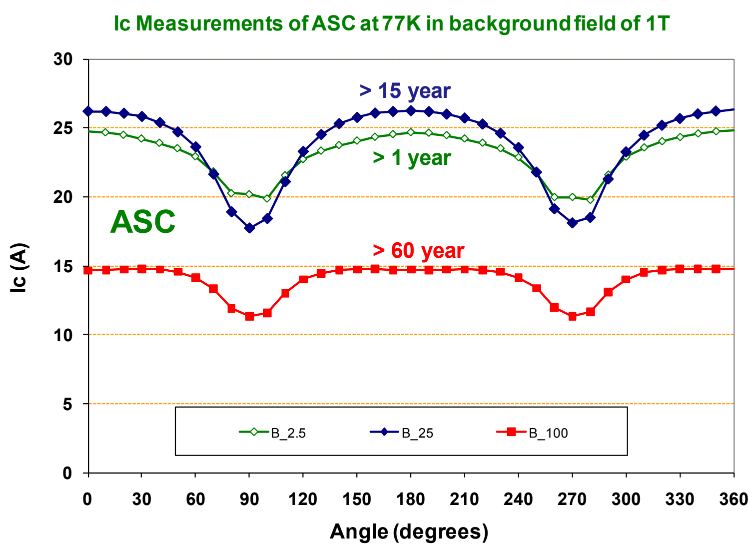
YBCO is at least as much radiation tolerant as Nb_3Sn is

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





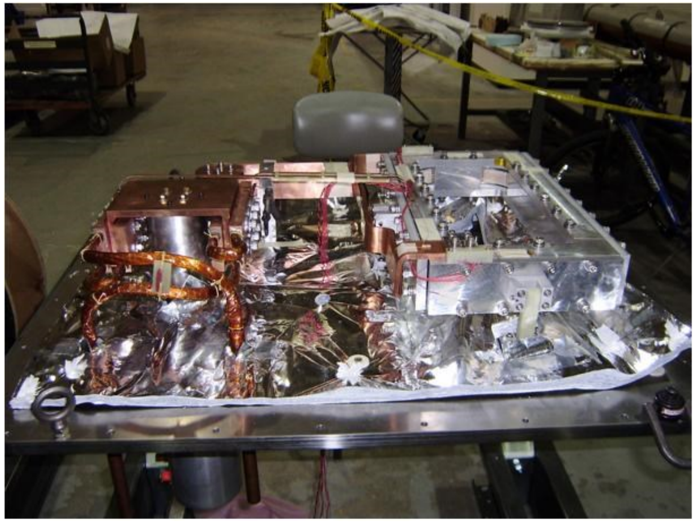
Minimum and maximum values of I_c are obtained from the graphs on the right

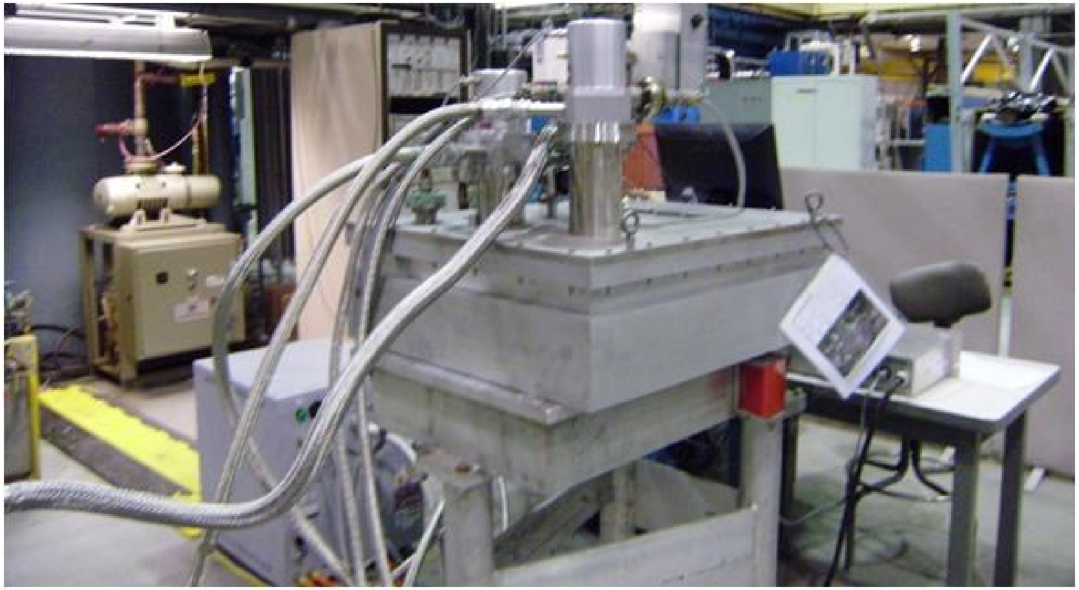


- While the SuperPower and ASC samples showed a similar radiation damage pattern in the absence of field, there is a significant difference in the presence of field (particularly with respect to the field angle).
- HTS from both vendors, however, show enhancement to limited damage during the first 10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

Cryo-cooler based HTS Coil R&D

- Coils reached <40 K (goal was 40 to 50 K)
- 25 W at 50 K can be removed by a number of cryo-coolers





3d and Curved HTS Coils

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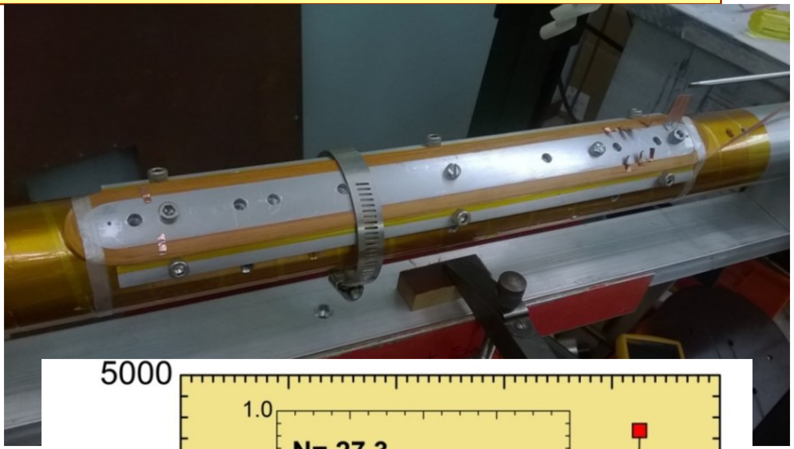
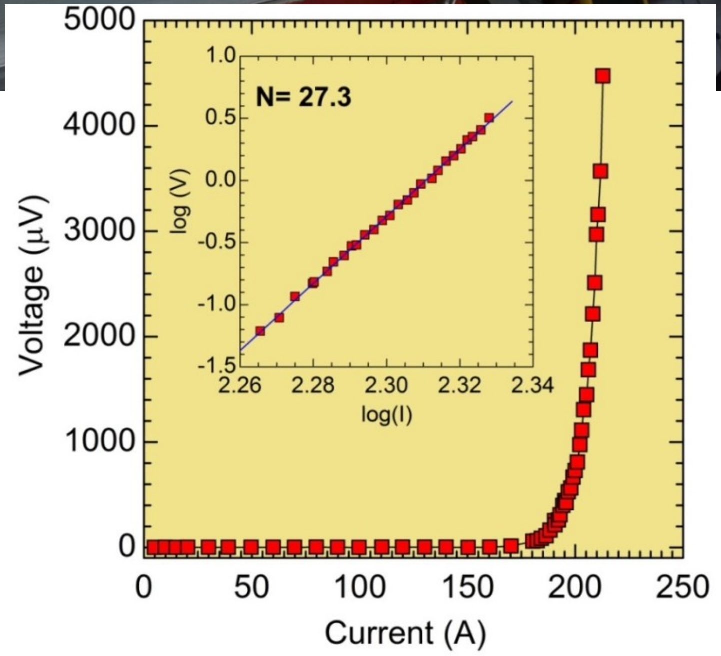
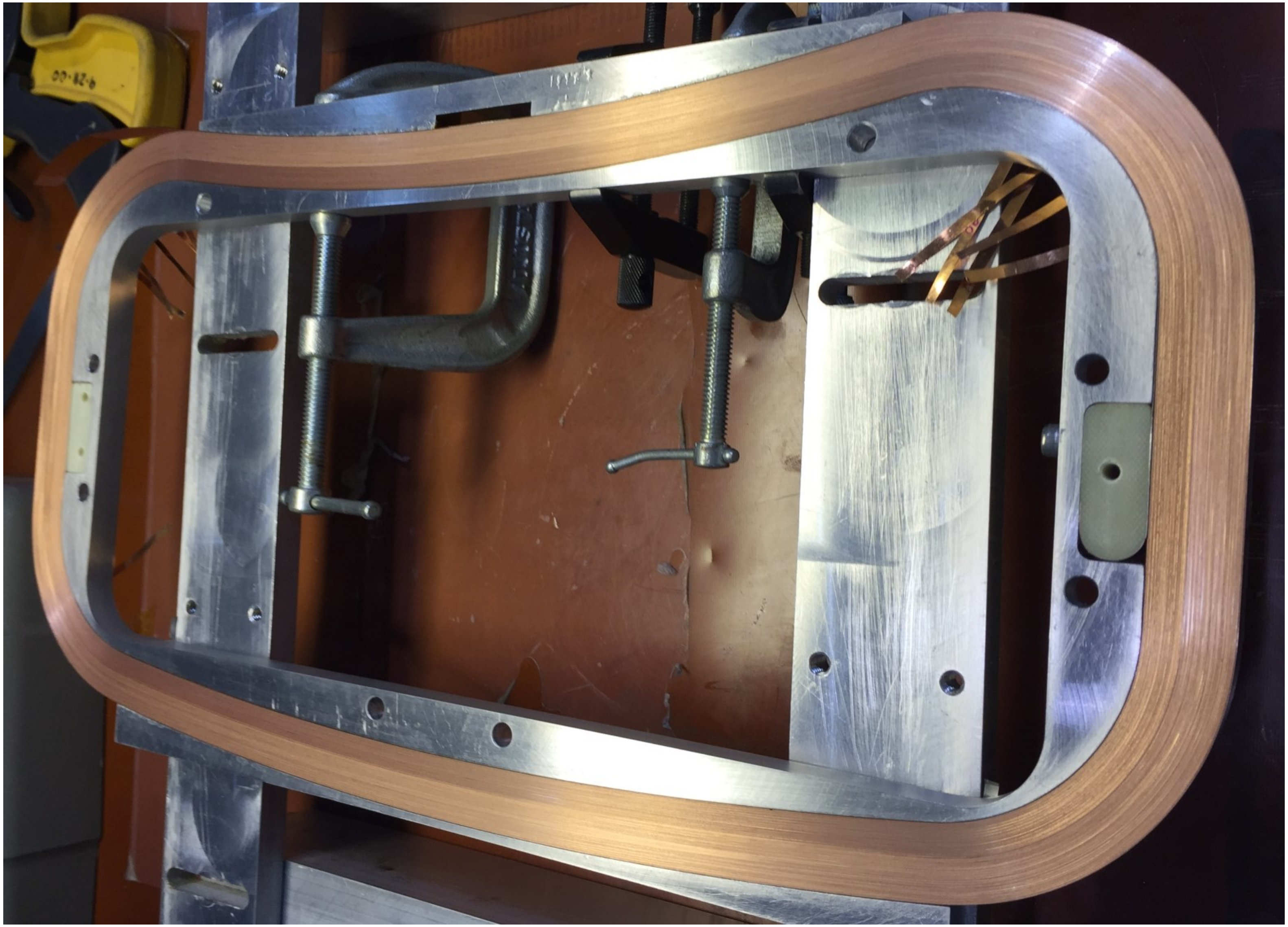
Cosine (θ) Coil with Complex Ends PBL/BNL (two) STTR





No measurable degradation

Curved HTS Coil



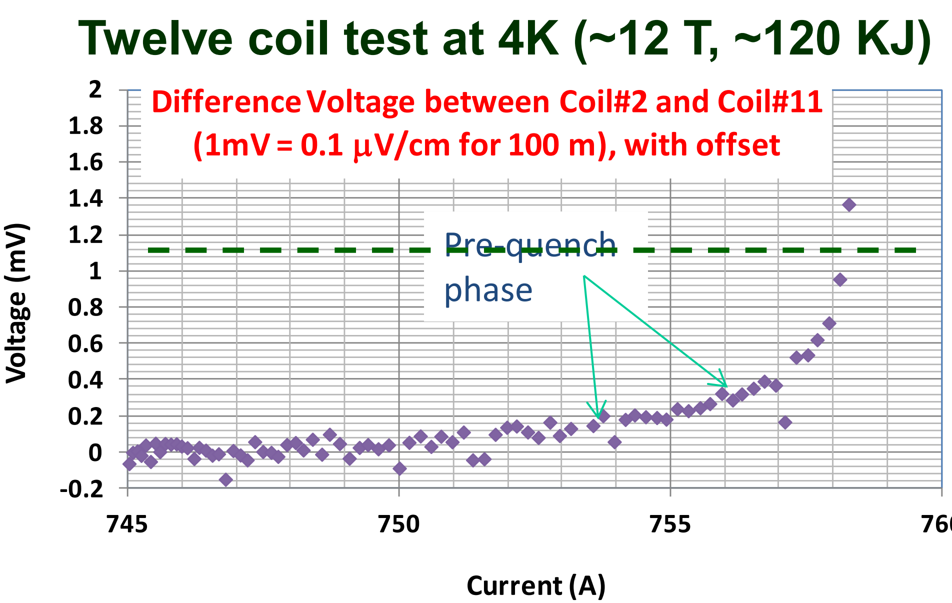
Quench Protection

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.**



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 PPPL in this possible ground breaking application of HTS magnets in fusion technology.**