Very High Field HTS and Superconducting Magnets

Ramesh Gupta
Brookhaven National Laboratory (BNL), USA
(for BNL staff and collaborators from PBL and SMES Team)

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Overview

- **HTS in High Field Superconducting Magnets**
  - **Opportunities and Challenges**
- **HTS Magnet Programs at BNL**
  - **We work on a variety of magnet types (solenoid, dipoles, etc.). The focus of this presentation is on very high field solenoids.**
  - **A15^{+} T HTS solenoid already designed, built and tested; and a more ambitious 20-25 T goal in 2013 in multiple programs**
  - **Ultimate target: ~40 T in a hybrid design (HTS+LTS)**
- **Summary**

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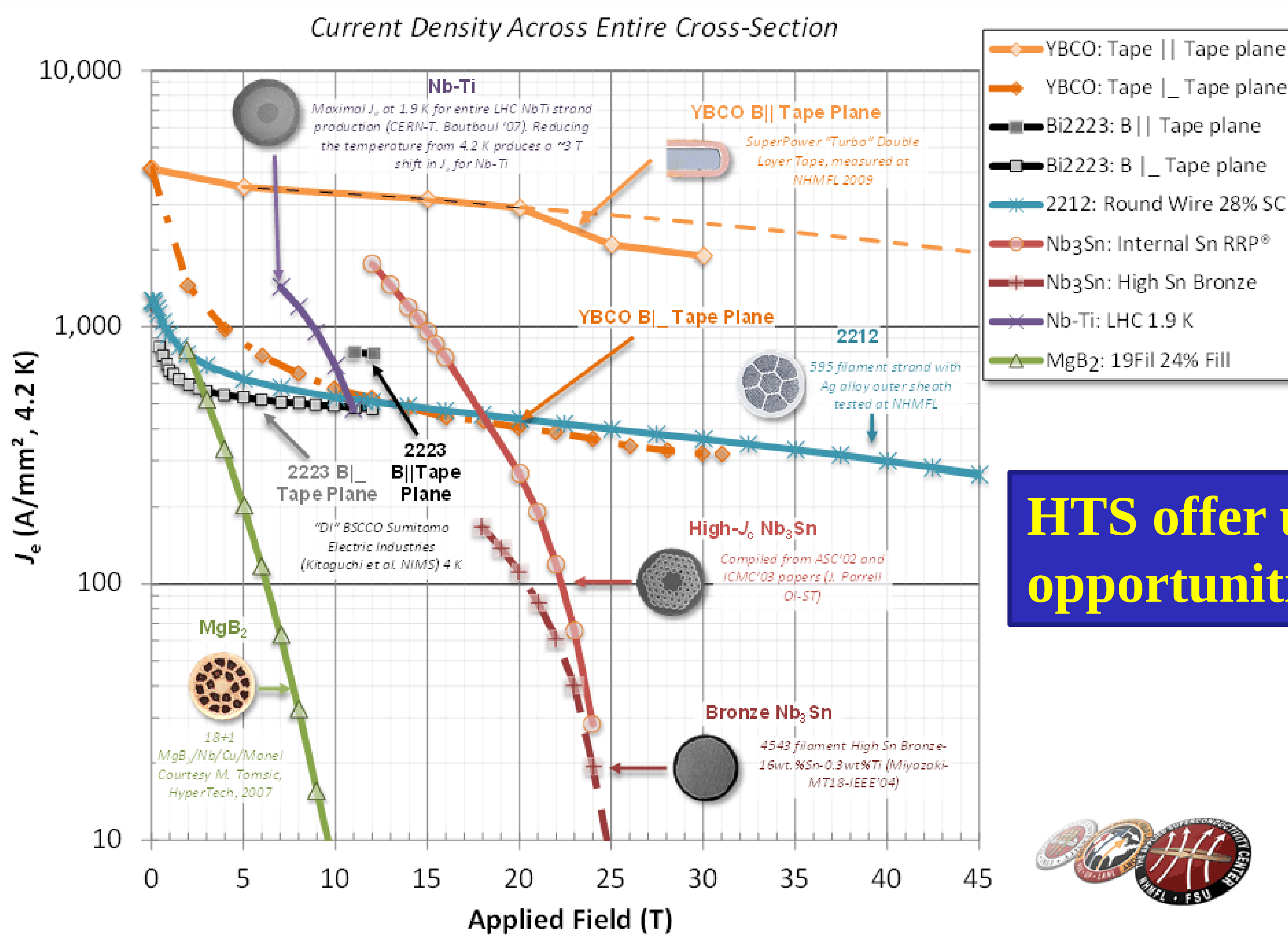
Modern Superconductors for Very High Field Magnets



Courtesy:
P. Lee, NHMFL

HTS offer unique opportunities

High Field Superconductor (HTS)

- **The development of High Temperature Superconductor (HTS) as the High Field Superconductor (HFS) is the key to all ongoing very high field magnet development programs**
- **High strength HTS (e.g., with Hastelloy substrate from SuperPower) are very attractive for high field applications**
- **Progress in conductor to date has been impressive. There is even more room for progress – even higher Ic and more uniform Ic**
- **But conductor is only the beginning. There are several challenges in making very high field magnets out of them**

Challenges with HTS for High Field Superconducting Magnets

- Anisotropic electrical properties for YBCO or tape conductor
- Mechanical properties (more so for 2212 but for YBCO also)
- Quench protection : a major issue for HTS
- Containment (mechanical) structure
- Conductor cost

More discussion later with progress made in some of these areas

HTS Magnet Programs at BNL

- Brookhaven National Laboratory (BNL) has been active in HTS conductor, coil and magnet R&D for over a decade. The level of effort has been significant:
  - Received over 50, 000 meters of HTS (normalized to 4 mm tape)
  - Built well over hundred coils and a large number of magnets
  - Used all – Bi2212, Bi2223, YBCO, MgB_2 - in round wire and tape form
- Magnet R&D on a wide range of programs:
  - Low field, high temperature (unique and sometime cost-effective)
  - Medium field, medium temperature (baseline design of a major machine)
  - High Field, low temperature ← ← ← focus of this presentation

These variety of programs help develop a wider understanding and cross solutions

High Field Solenoid Programs

- **Ongoing programs:**
  - ❑ **~25 T High Energy Density SMES**
  - ❑ **~40 T Solenoid for Muon Accelerator Program**
- **Other future possibilities:**
  - ❑ **NMR**
  - ❑ **???**
  - ❑ **???**

Motivation for High Field HTS SMES

High Temperature (~65 K) Option: Saves on cryogenics (Field ~2.5 T)

High Field (~25 T) Option: Saves on Conductor (Temperature ~4 K)

Some previous/other work:

LTS: ~5 T (~4 K operation)

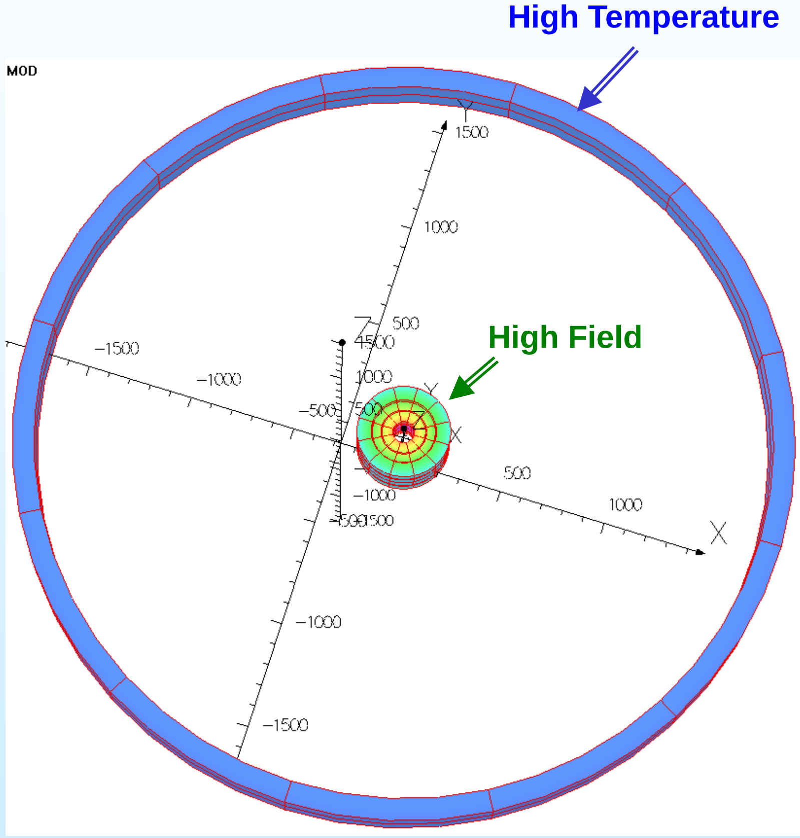
HTS: few to several Tesla (20 K or more)

Our analysis on HTS option:

Conductor cost dominates the cryogenic cost by an order of magnitude

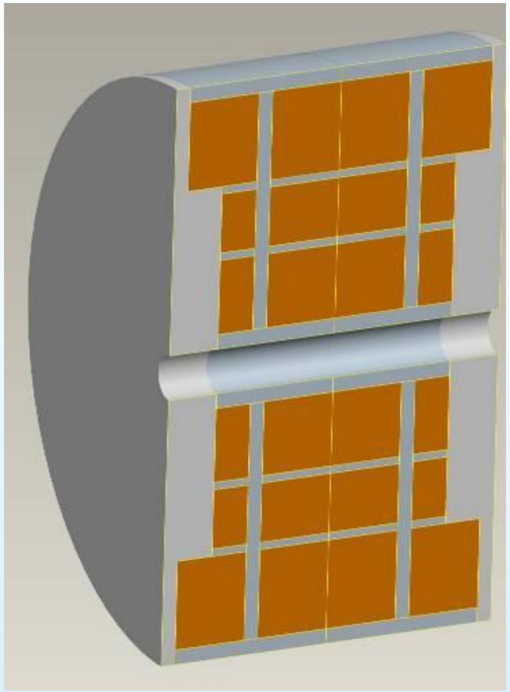
An aggressive option:

- Ultra high fields ~25 T
  - ✓ Only possible with HTS
  - ✓ High risk and high reward program

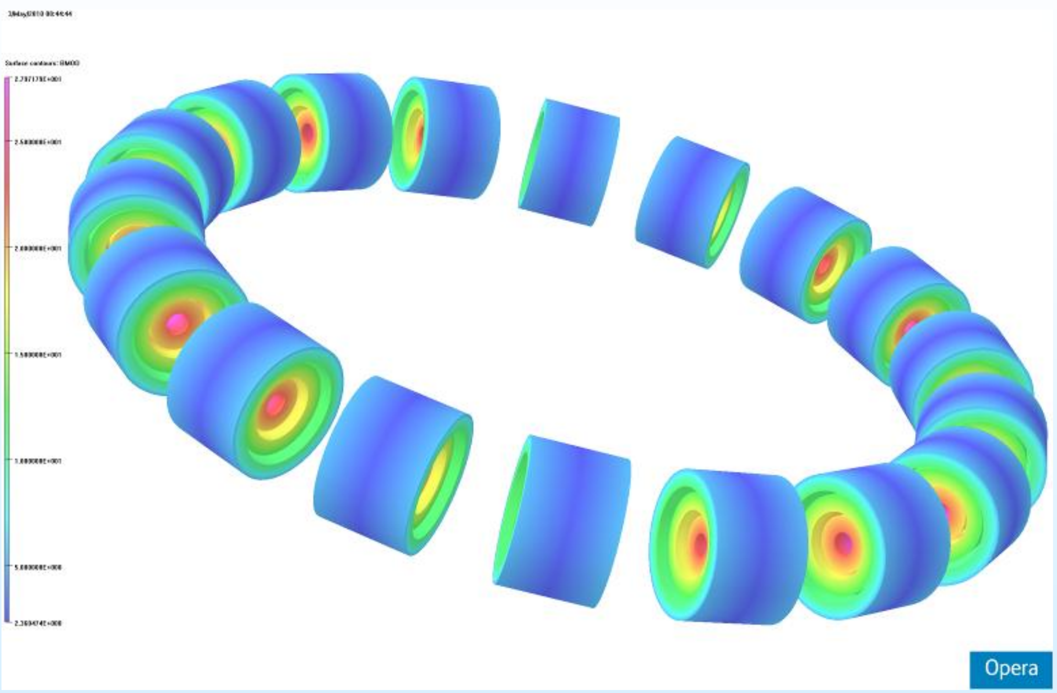


Partnership between BNL, SuperPower and ABB

Concept of GRID Scale (GJ scale) Superconducting Energy Storage



Concept of a single Unit

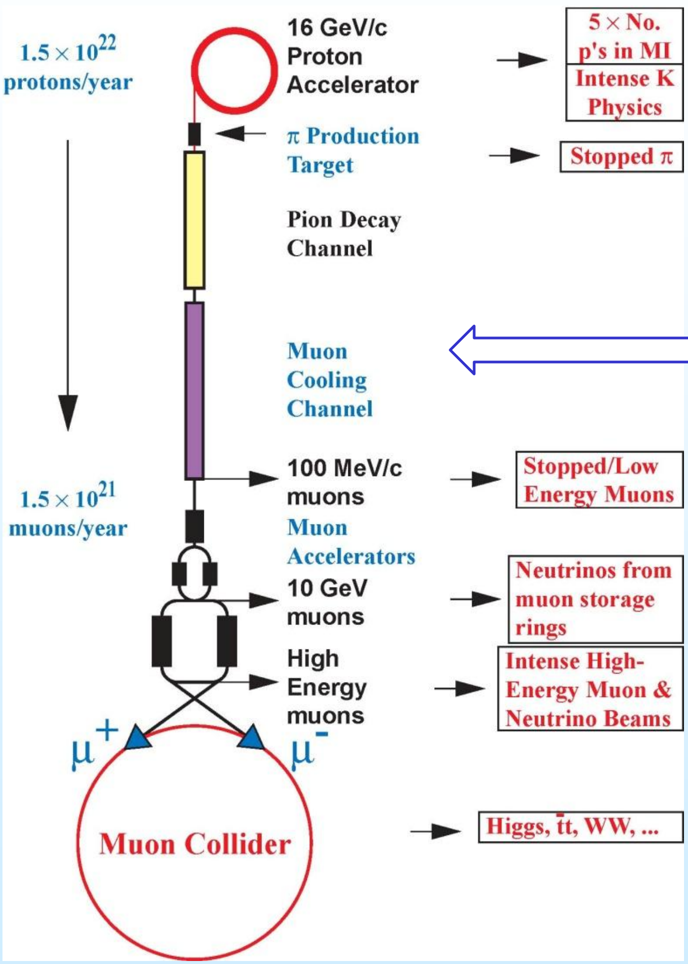


Concept of Number of units in a toroidal SMES system

Participants: ABB (Lead), SuperPower/Furukawa and BNL

- Funded by arpa-e as a “high risk, high reward” project.

High Field Solenoid for Proposed Muon Collider



Courtesy: Bob Palmer

Muon collider:

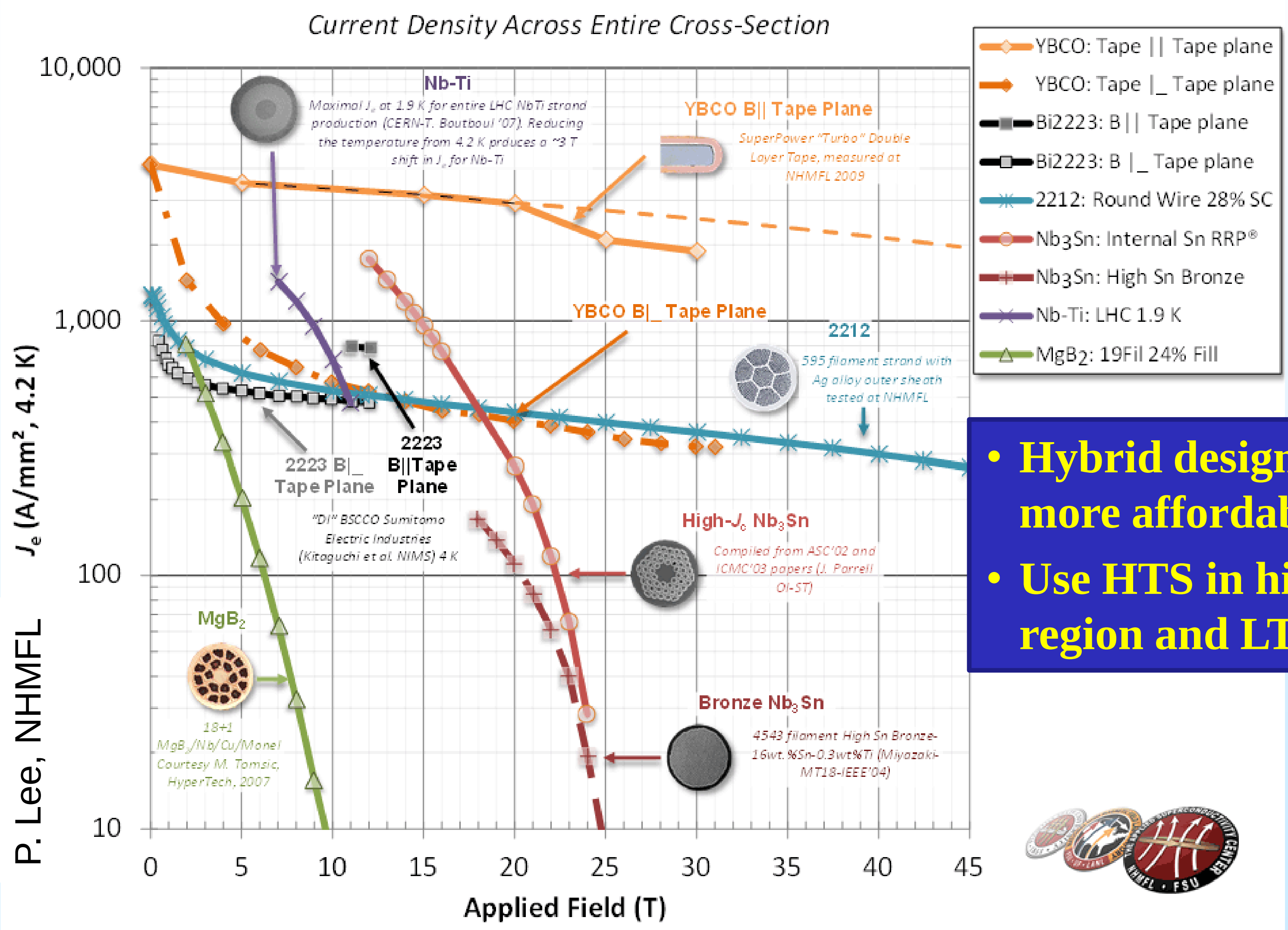
- An exciting and challenging machine

One key challenge:

- High field (~40 T) solenoid for cooling
  - ➢ Resistive magnet would use enormous electro power (**hundreds of MW)**
  - ➢ Even a combination of resistive and superconductive magnets will consume large power

✓ **Need superconducting magnets and use of HTS for such high field is essential**

Modern Superconductors for Very High Field Magnets



Courtesy: P. Lee, NHMFL

- **Hybrid design offers a more affordable solutions**
- **Use HTS in higher field region and LTS in lower**

30-40 T Technology Demo Magnet

Design consisted of several coils (HTS and LTS)

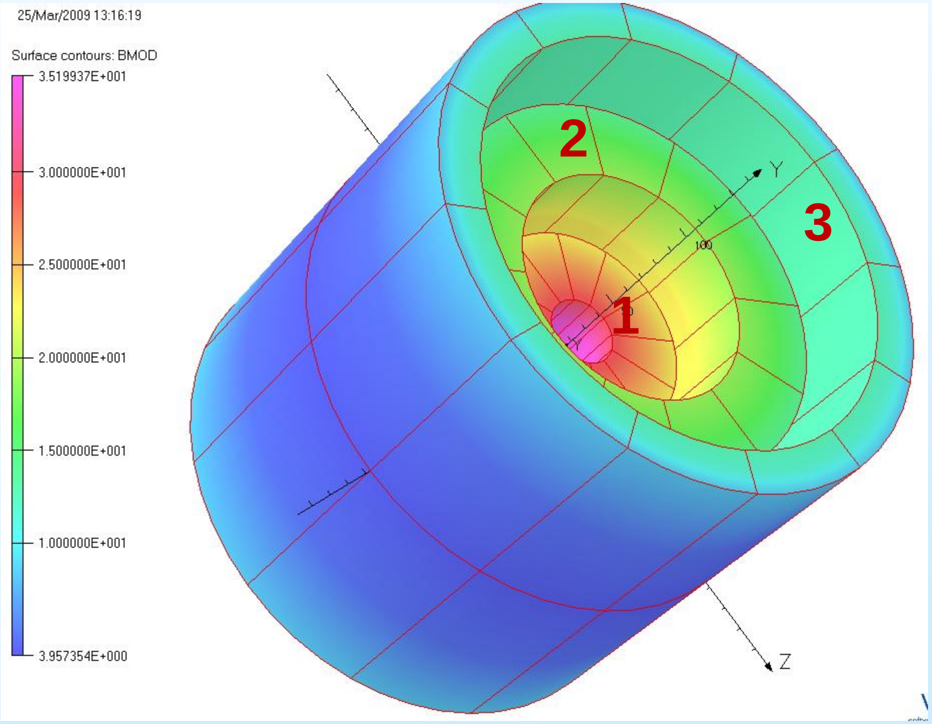
1. 10-15 T HTS insert coil (~25 mm aperture)
2. 10-12 T HTS midsert coil (~100 mm aperture)
3. 6-15 T LTS coil(s) - NbTi for 6-8 T; and/or Nb_3Sn for 12-15 T

20-25 T All HTS Coils (1 & 2):

addresses challenges with high field HTS solenoids

30-40 T All Superconducting Solenoid (1, 2 and 3+):

addresses challenges with high field superconducting solenoids



Funding Status of 30-40 T Solenoid

This technology is being primarily developed under a series of US DOE SBIR (Small Business Innovative Research Program) with BNL (a national lab) collaborating with PBL, Inc. (an industry.)

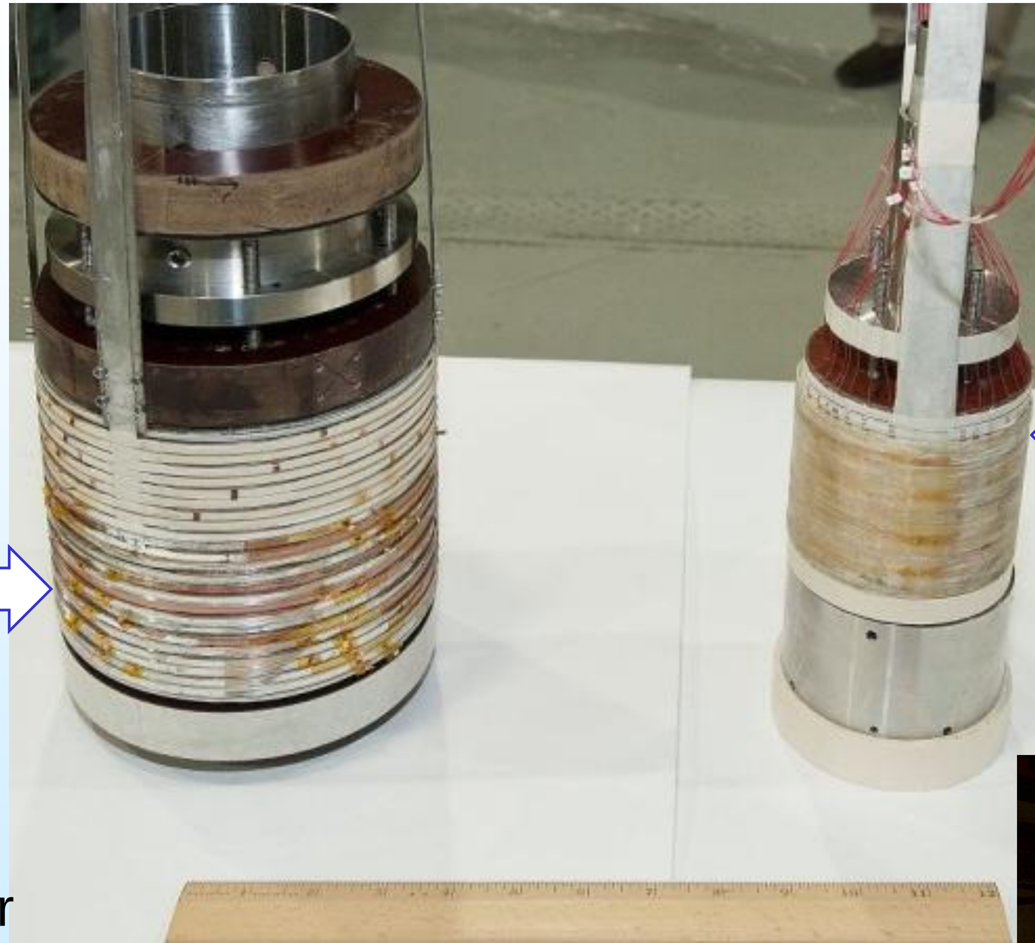
Funding Status:

1. **HTS insert solenoid : Funded**
2. **HTS midsert solenoid : Funded**
3. **LTS outsert : Not yet funded for construction**

Courtesy: Bob Palmer

PBL/BNL High Field HTS Solenoids

10+ T,100 mm HTS solenoid (midsert) with 24 pancakes for full length solenoid (ready for test)



15+ T, 25 mm HTS solenoid (insert) with 14 pancakes already tested

Record Field

Half length 100 mm with 12 pancakes already tested and reached 6+ T on axis (9+ T peak)

Coils made with ~4mm HTS tape from SuperPower

Use of high strength HTS is critical to the success

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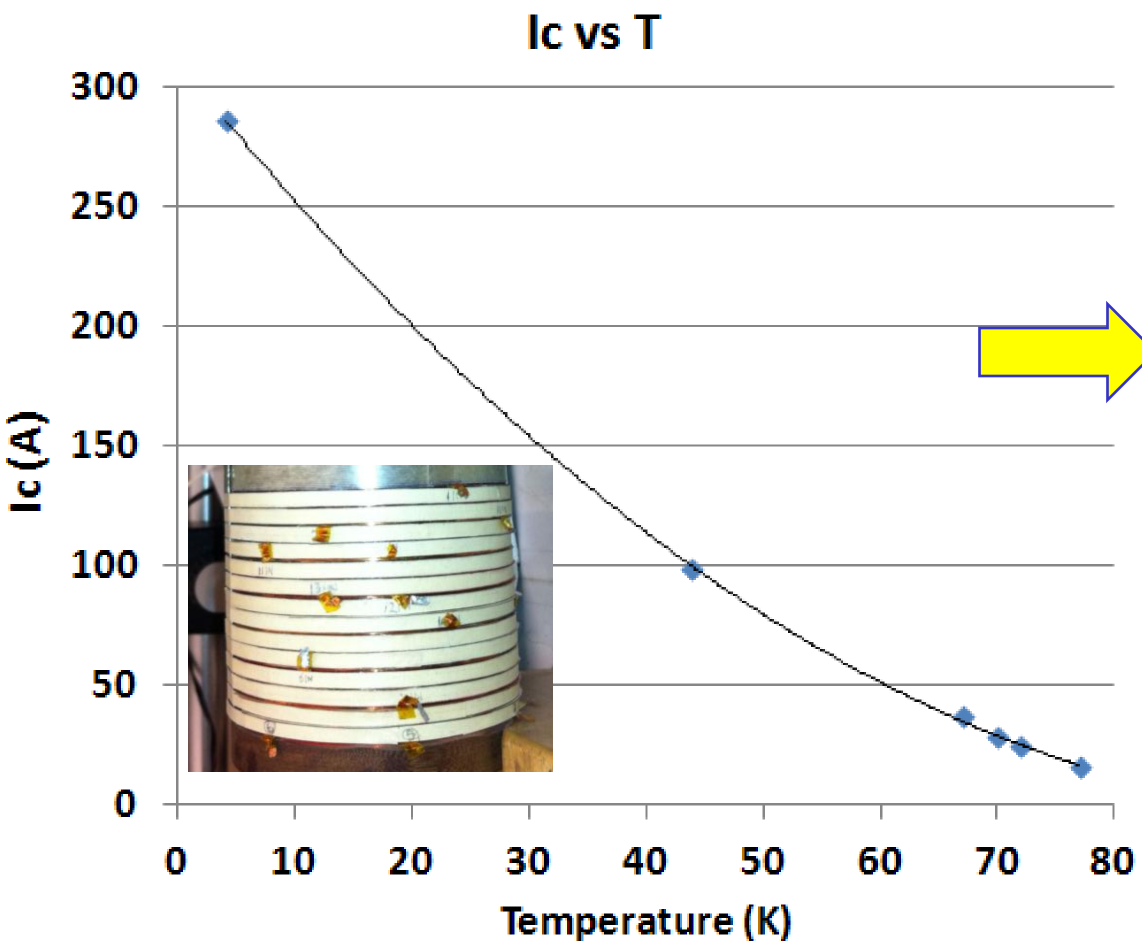
High Field HTS Solenoid Test Results (magnet #1 using SuperPower HTS)



Field on axis:

- **over 15 T**

Field on coil:

- **over 16 T**

(original target was 10-12 T)

Real demo of 2G HTS to create high field

- **Highest field ever in an all HTS solenoid**

Overall J_o in coil:

>500 A/mm^2 at 16 T

(despite anisotropy)

14 pancake coils with ~25 mm aperture

- **Note: Benefit of HTS – large operating range**

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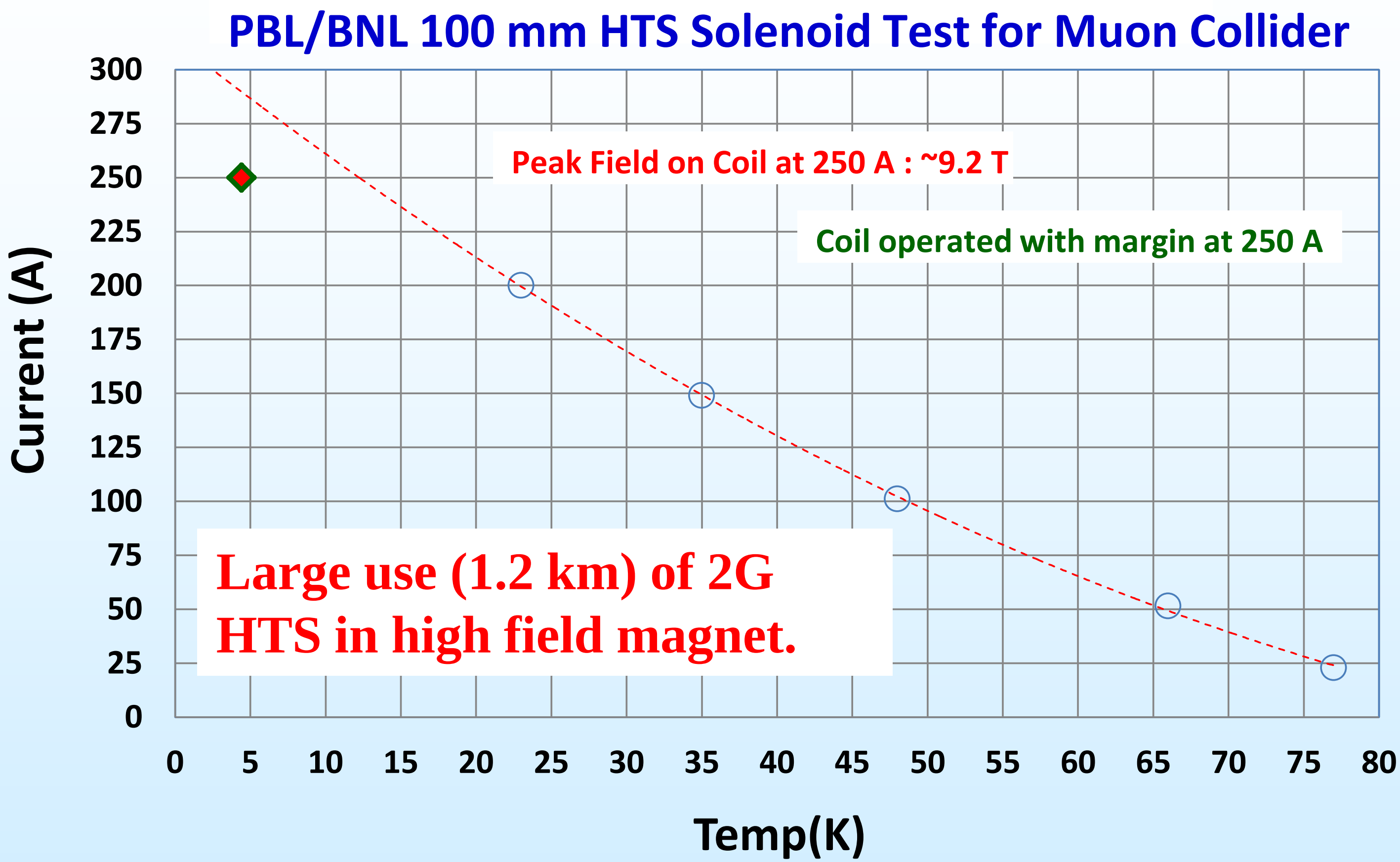
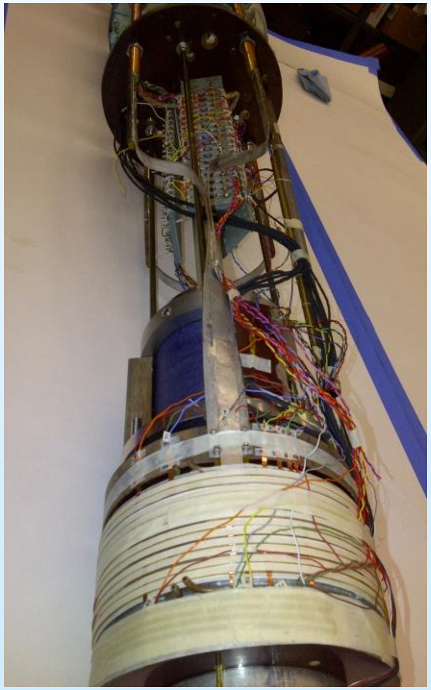
Test Results of HTS Solenoid #2 (½ Midsert, 12 coils instead of 24)



250 A ==>

6.4 T on axis

9.2 T peak field on coil



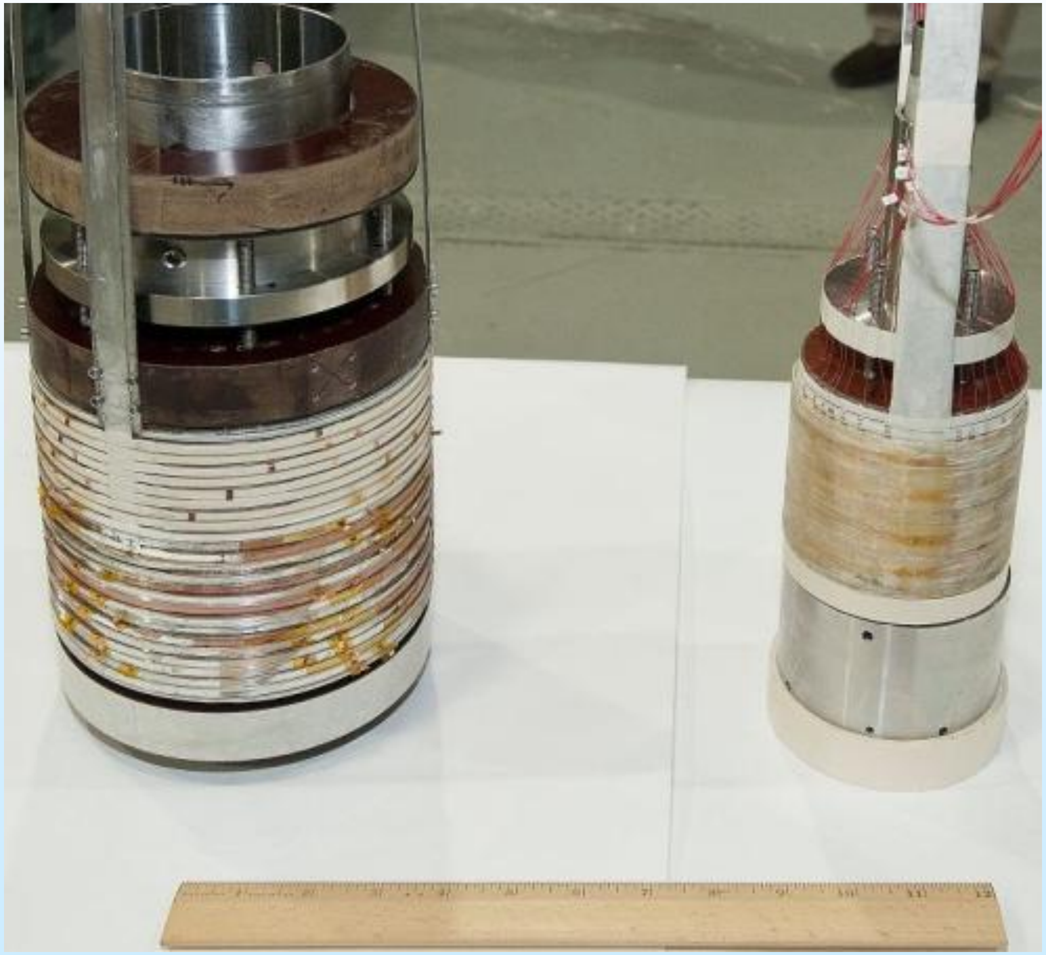
Coil could have reached above 10 T peak (original target), but was not ramped up to protect electronics of that time.

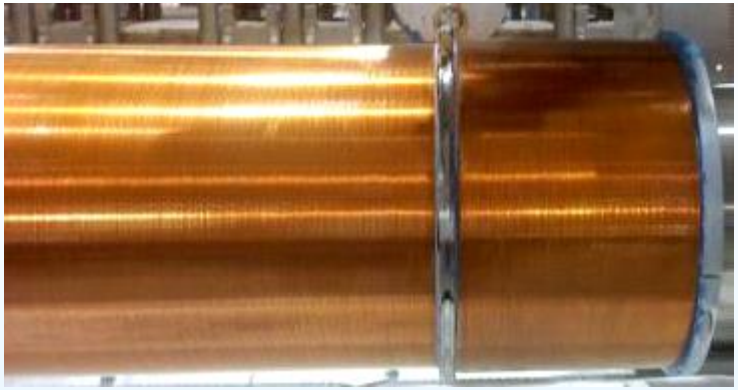
Full solenoid with 24 pancakes should create >10 T on axis.

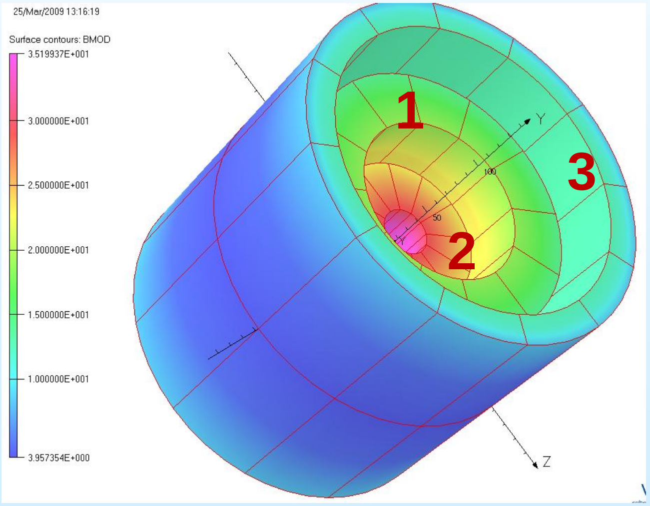
SuperPower HTS

Status of High Field MAP Solenoids

Two HTS coils together made with SuperPower HTS is expected to create 20-25 T, if successful







~30 T with NbTi outer

(40 T with Nb_3Sn or more HTS)

Challenges with High Field HTS Magnet Technology

Discussion on two selected topics:

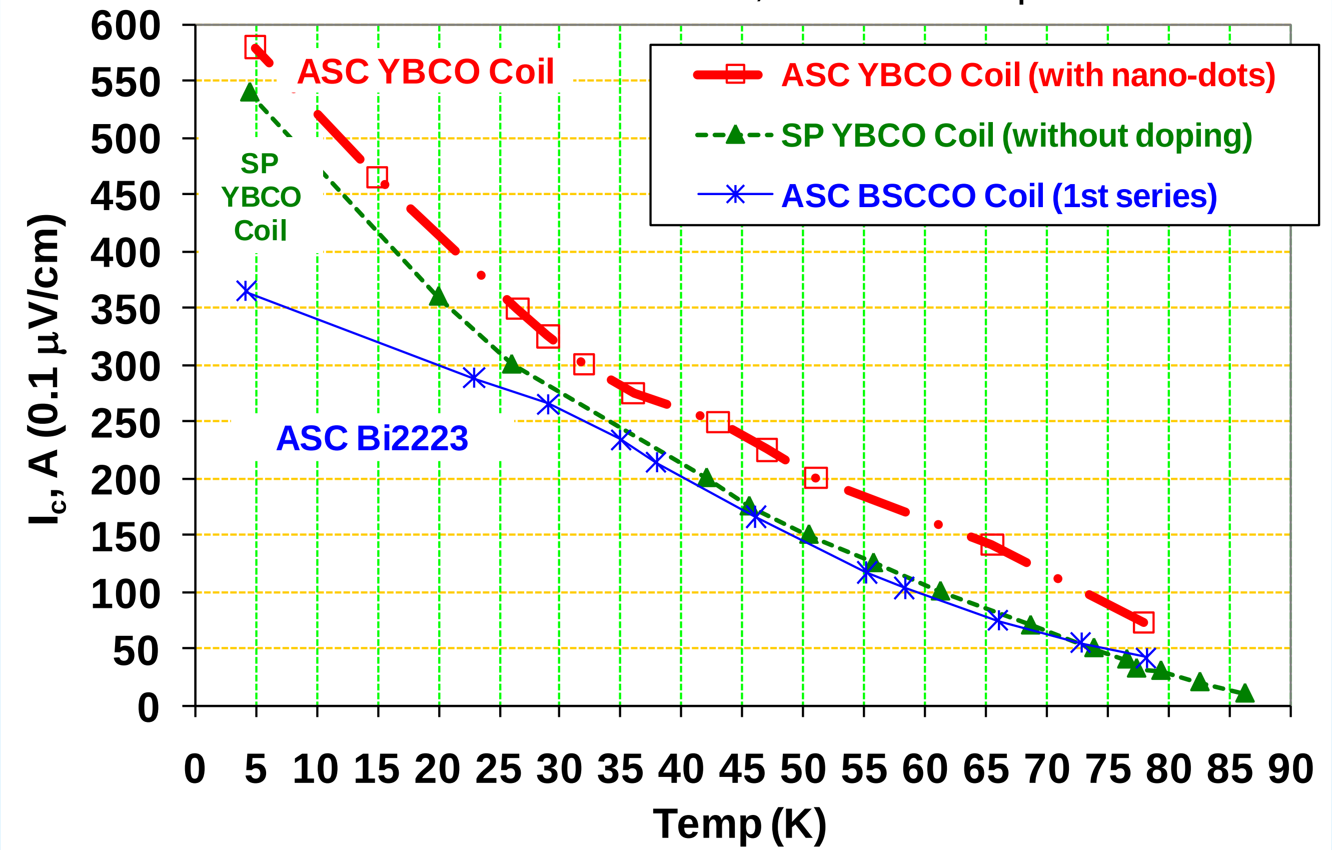
- Quench Protection
  - Slow quench propagation velocities
  - Coil may get degraded even before one detects quench
- Mechanical Properties
  - Stress /strain tolerance important in high field magnets
  - Asymmetric properties of tape (just as magnetic)

High Current Test of 4 mm Tapes

During the initial R&D period, coils with 2G HTS tape from ASC (~0.4 mm X 0.3 mm) and SuperPower (0.4 mm X 0.1 mm) were built and tested

Coil built with 4mm tape purchased ~5 years ago

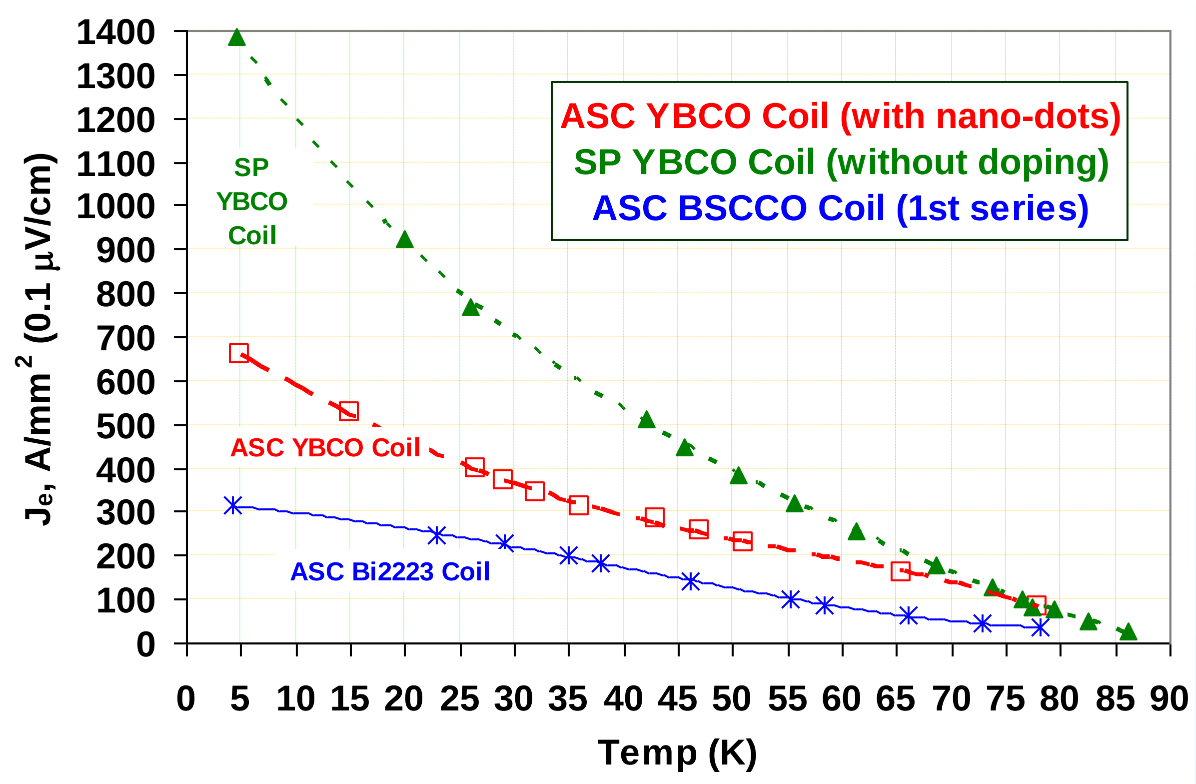
Max current: 540 A and 580 A; coils remain protected



Low Temp Performance of FRIB Coils (R&D during technology development period)

Tape width: ~ 4 mm; Length used in single coil ~100 meter

Copper thickness: SuperPower ~ 0.045 mm; ASC ~ 0.1 mm



If coils go normal (momentarily or thermal runaway, etc.).

- Copper current density in ASC coil : ~1500 A/mm^2
- Copper current density in SuperPower coil : ~3000 A/mm^2

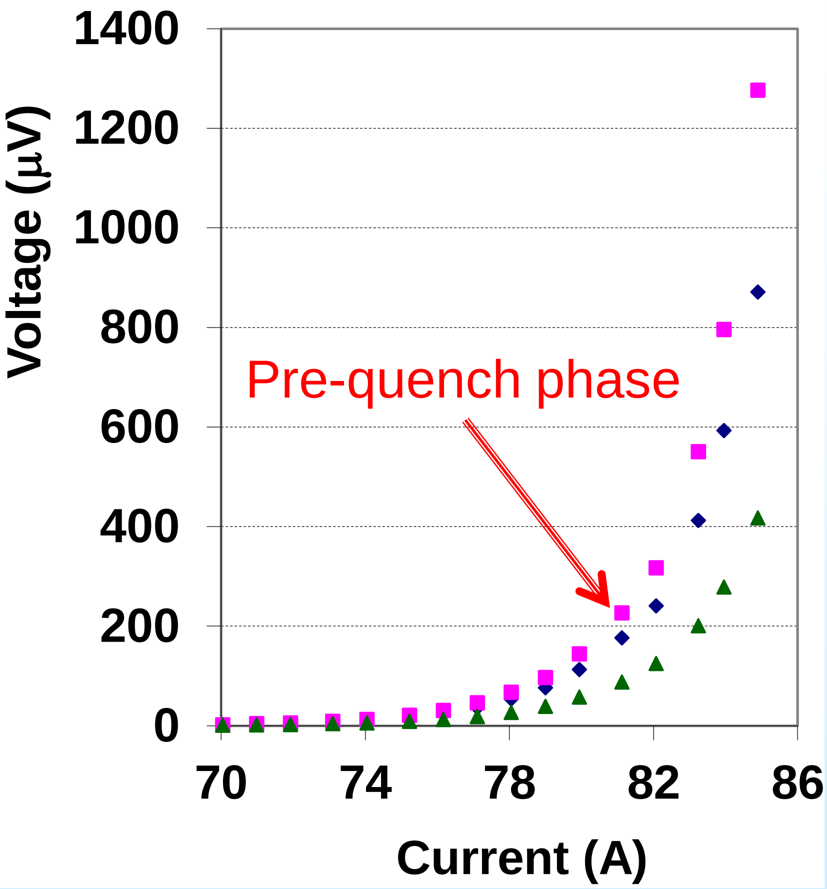
Coil remained protected (we usually don't allow such high Jcu in LTS magnets)

These numbers are amazing ...

- ***May be too demanding for protection and should be avoided in real applications.***

BNL Quench Protection Strategy

- Quench protection in high field HTS magnets is one of the biggest challenges of the field.
- We have developed a unique approach to overcome this challenge.
- Use problem (things happening slowly) to our advantage.
- Detect the longer pre-quench phase of HTS (where coil can be operated safely) and initiate the action for protection.
- ***This requires detecting small resistive voltage in presence of large noise and inductive voltages – challenge in large systems.***
- ***BNL has made significant advances in electronics to detect start of this pre-quench phase well below 1 mV rather than 50-100 mV.***



Use quench protection heaters as the final line of defense

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Advanced Quench Detection System Developed at BNL

- Advance quench protection electronics detects quench fast and extract energy quickly.
- This requires development of low noise, fast electronics with large isolation voltage.

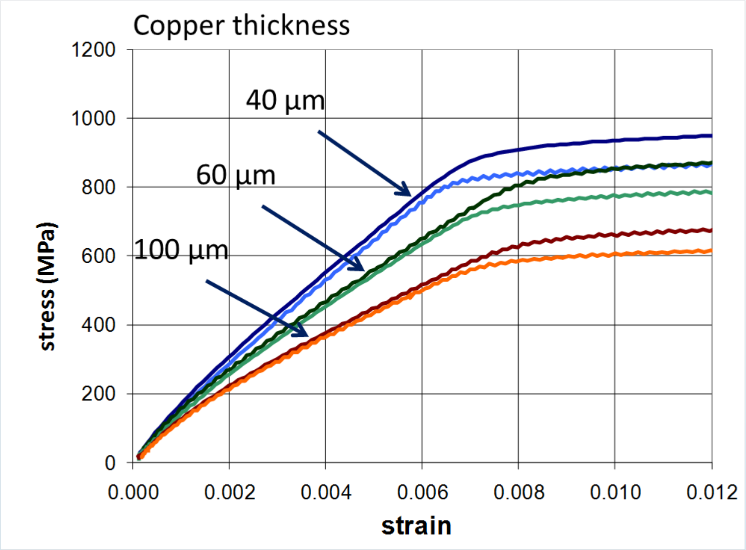
Mechanical Properties of HTS

- HTS tapes (such as 2G tape with Hastelloy substrate) have inherently higher stress and strain tolerances and are particularly suitable for high field solenoids

- However, even these 2G tape have relatively lower stress tolerance on the narrower face (question how much). Question is how much?

Mechanical Properties of High Strength HTS from SuperPower

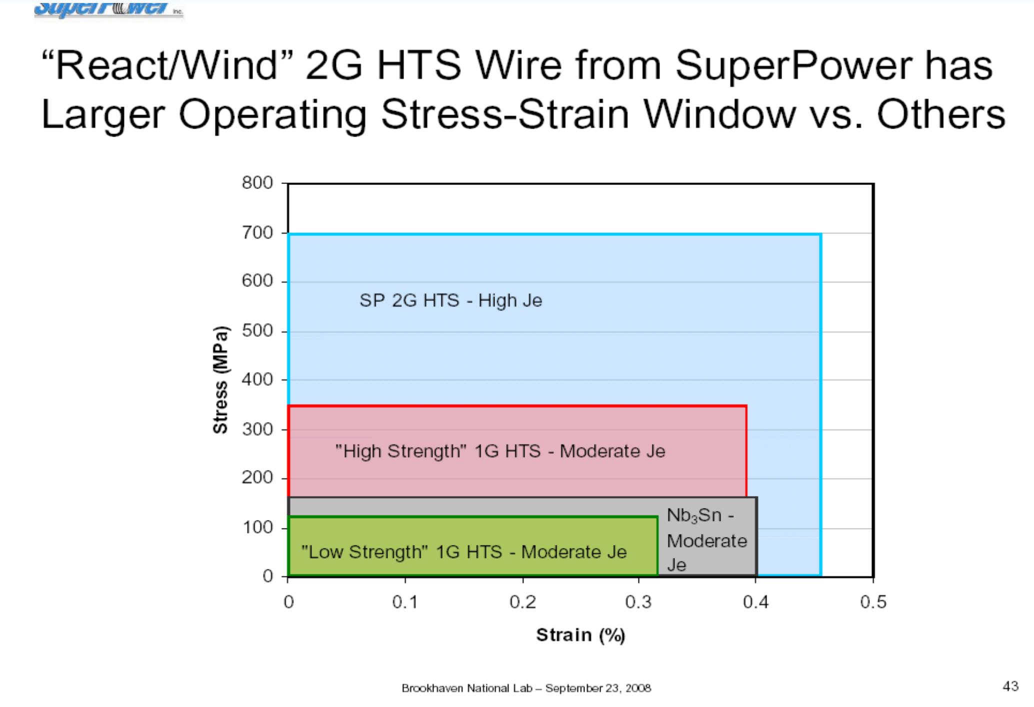
Conductor Stress-Strain at 77K and 4 K with Various Copper Thickness



Significant softening of the stress-strain curve with added copper due to reduced modulus and yielding of the copper.

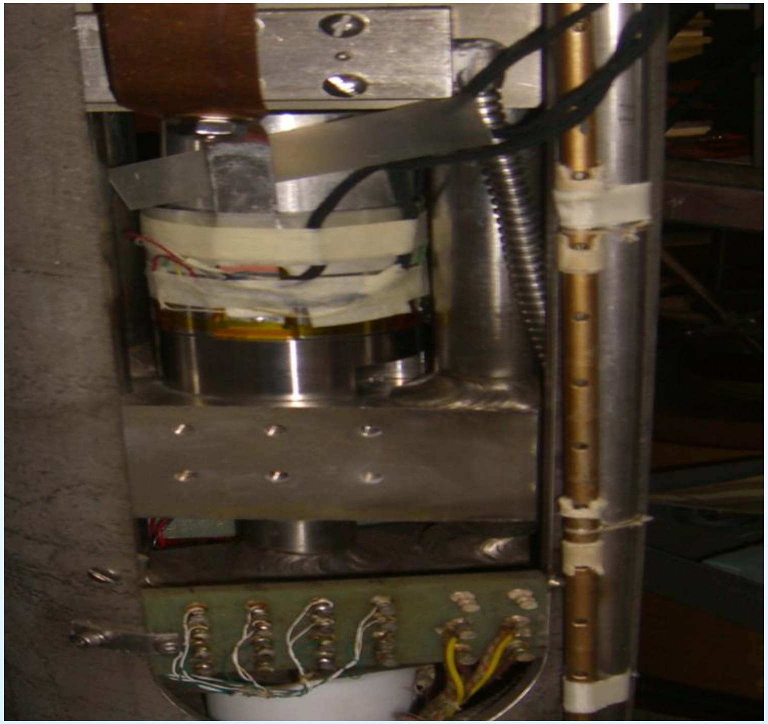
High Strength HTS from SuperPower/ Furukawa tested at Florida, USA

High Strength HTS are important for high field magnets

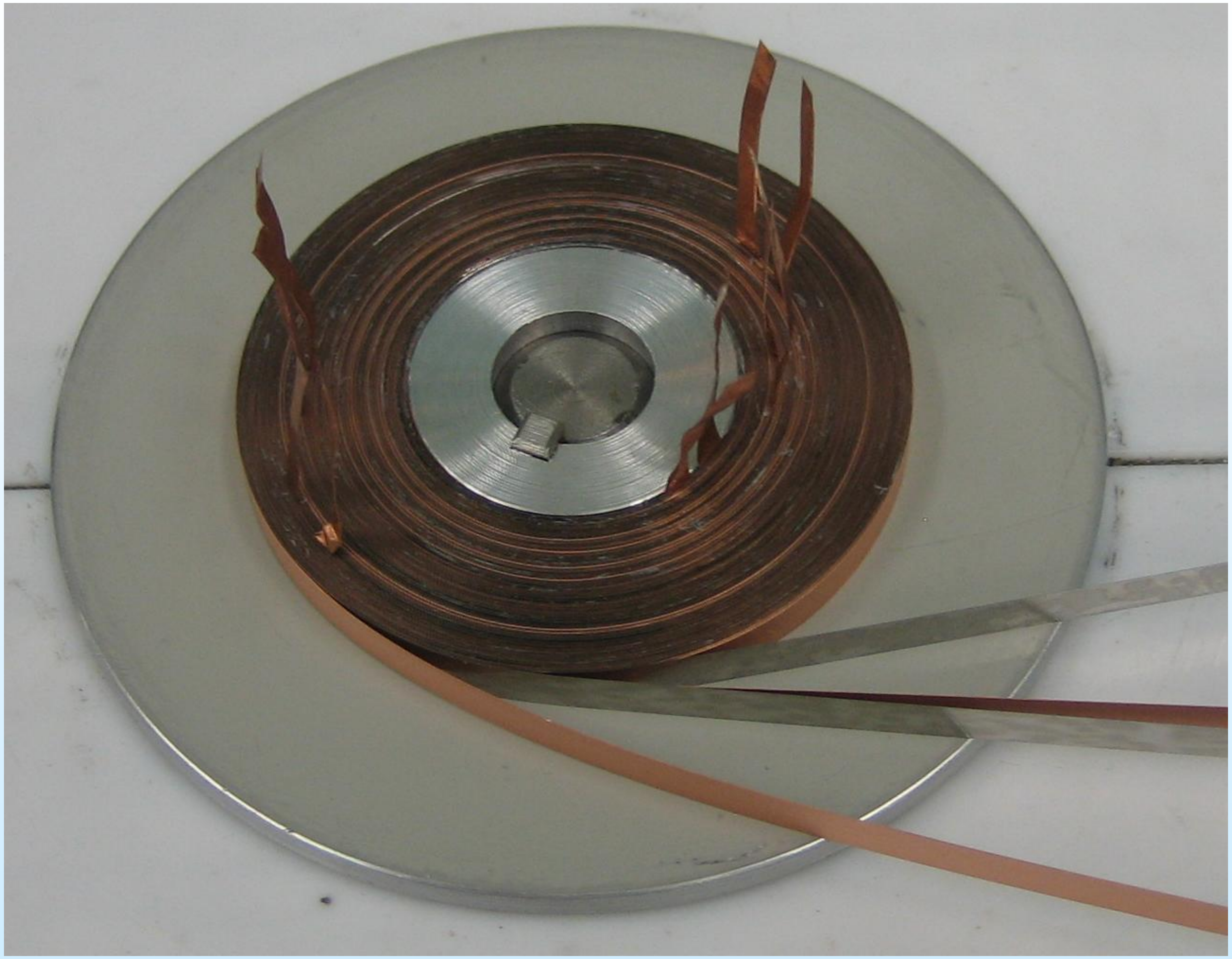


But what happens on the narrow face?

Measurements to Study the Influence of Stress on the Narrow side of HTS Tape



Bi-filar Coil for Axial Loading



Load is applied on the narrow face.

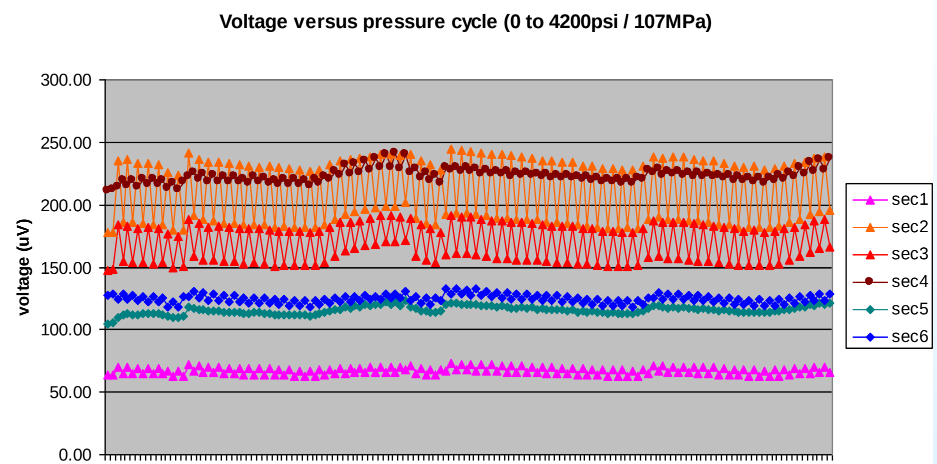
Bi-filar winding is chosen to minimize the influence of magnetic field on Ic.

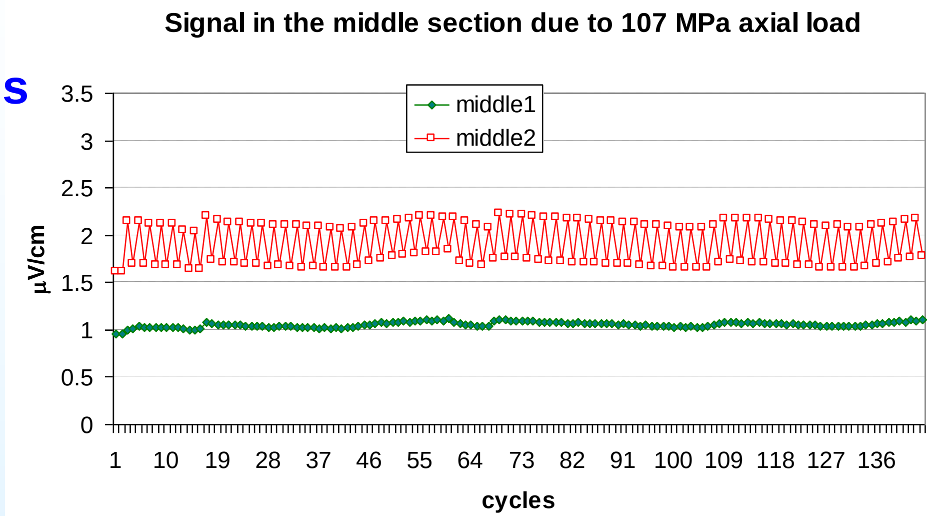
Maximum load applied: 107 MPa (max in current designs ~100 MPa)

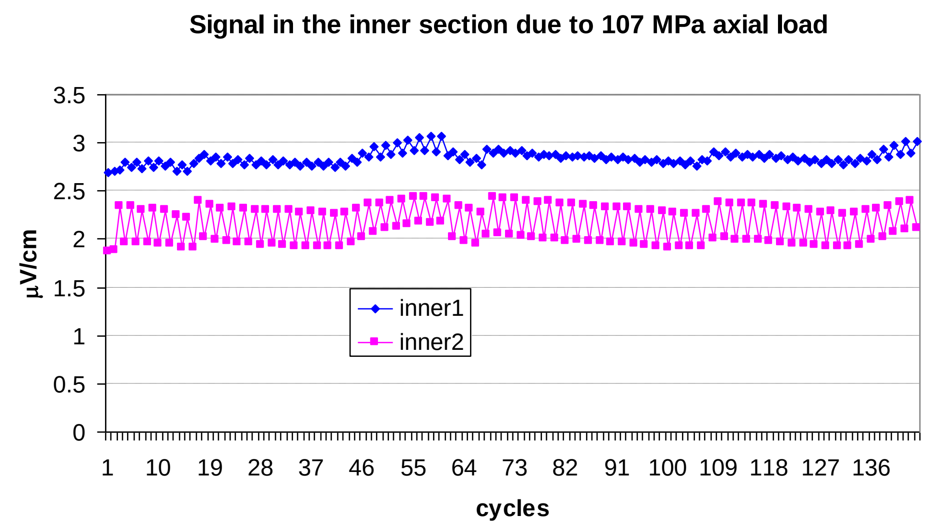
The test was carried out in real situation: the coil remain cold

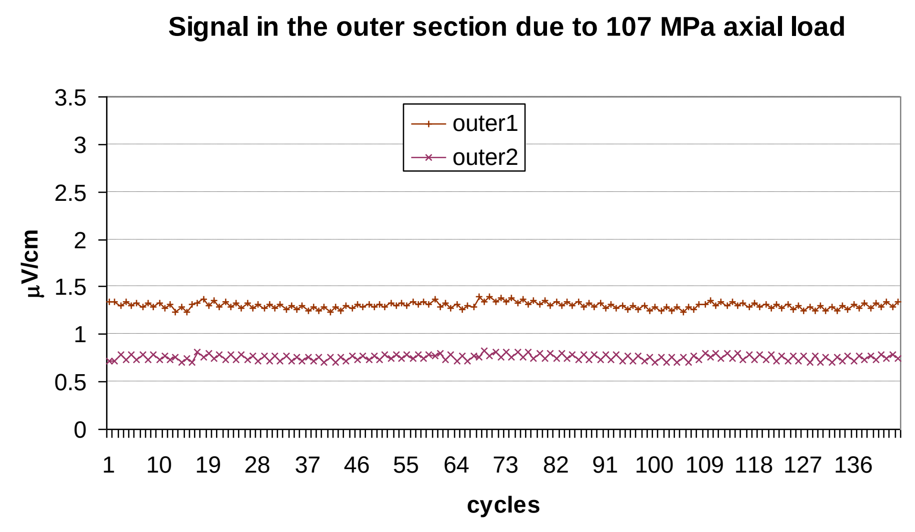
Influence of ~107 MPa Pressure on the Narrow Face of Conductor in 2G HTS Coil

Load ON, Load OFF. Measure change in voltage in ~100 cm (1 m) long six sections









~0.5% reversible change in Ic

Other High Field Geometries

HTS Dipole and Quadrupole

- High field (>20 T) cosine theta magnet technology with complex ends
- The proposed energy and luminosity upgrade of LHC at CERN will require high field dipole and quadrupole magnets
- Hybrid designs with HTS inner

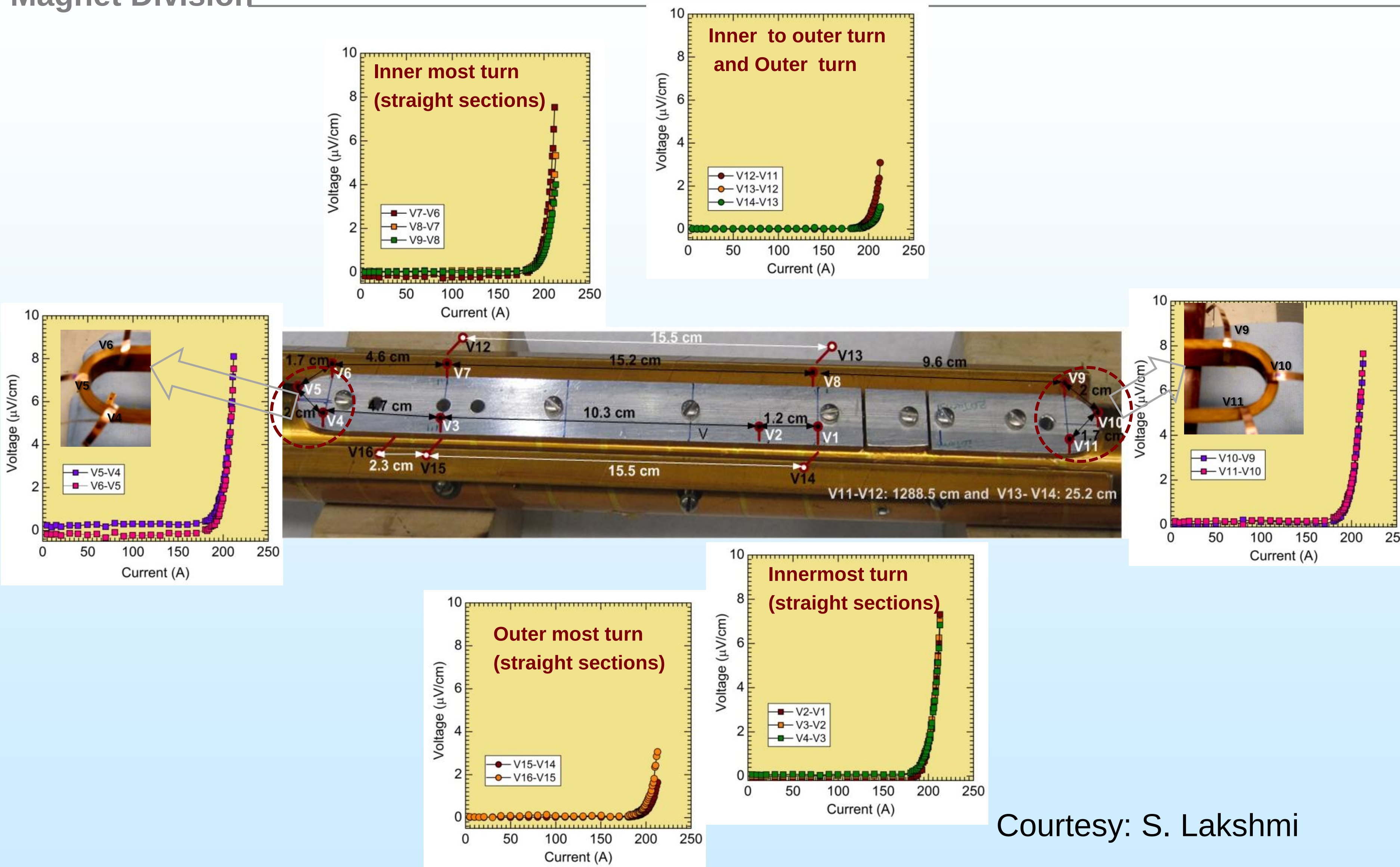
Dipole NbTi Magnet (BNL)

Quadrupole Nb_3Sn Magnet
(Courtesy: Bill Sampson, BNL)

Cosine theta prototype magnets built and tested in BNL using LTS materials

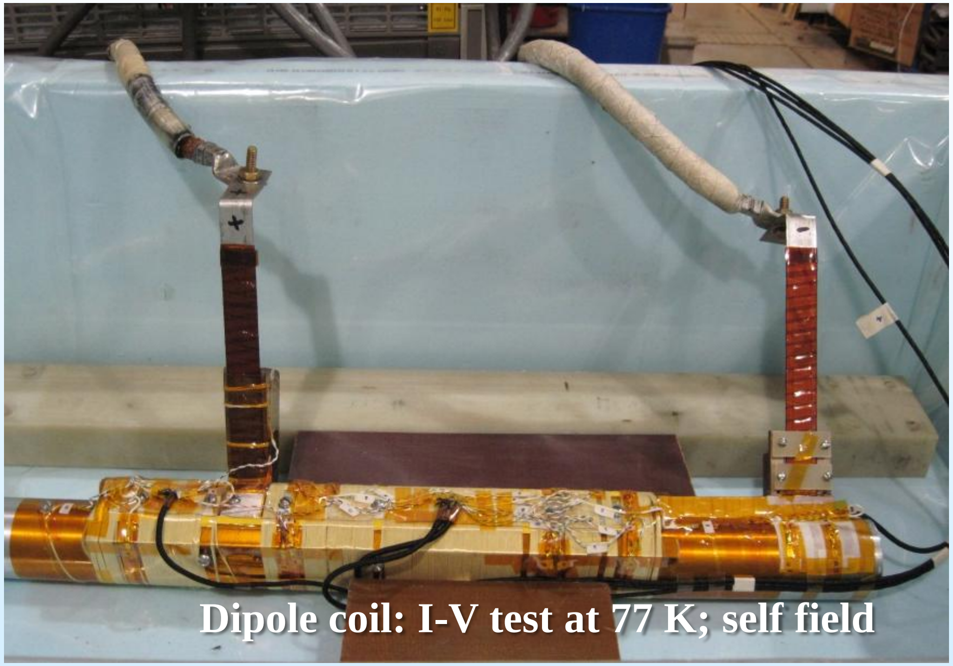
Courtesy: S. Lakshmi

Several V-taps for Detailed Examinations



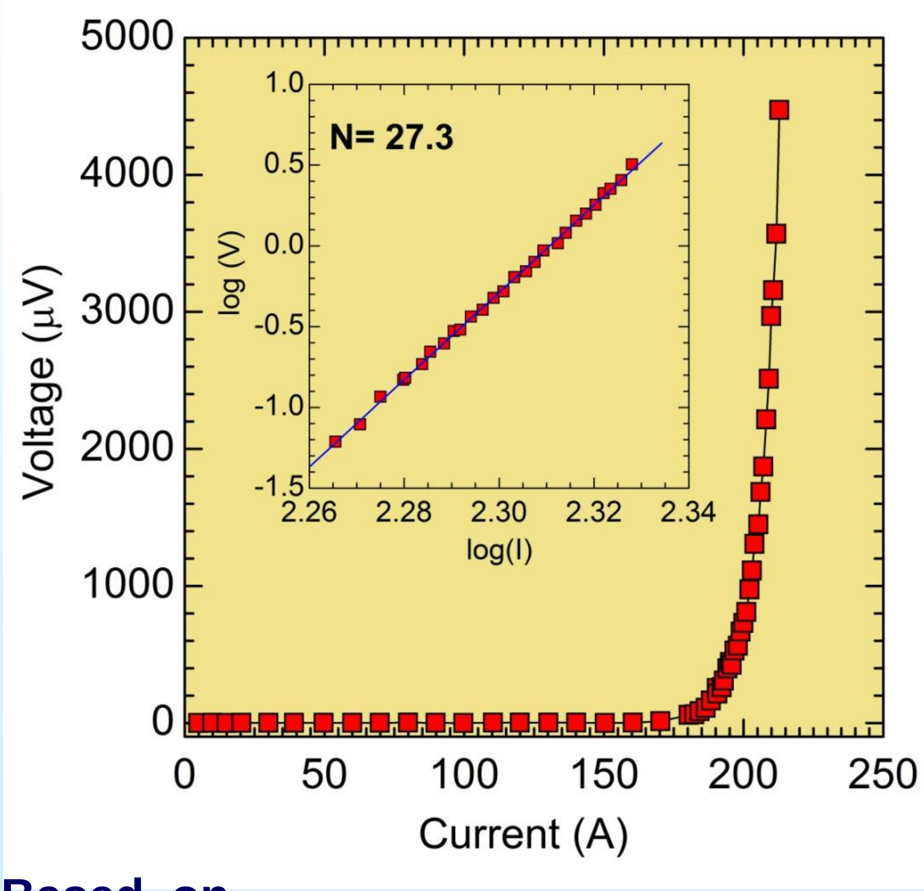
Courtesy: S. Lakshmi

Test Results at 77 K



Courtesy: S. Lakshmi

Y axis represents the end-to end voltage in the coil block (V1-V16)



Based on

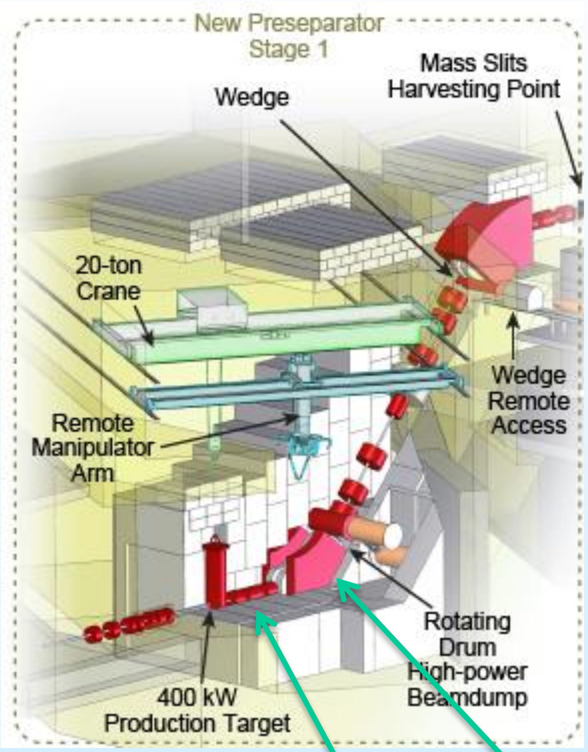
1μV/cm criterion: Ic= 204 A

0.1μV/cm criterion: Ic= 187.8 A

Other Significant HTS Magnet Development at Medium Fields

Magnets for the Fragment Separator of Facility of Rare Isotope Beams

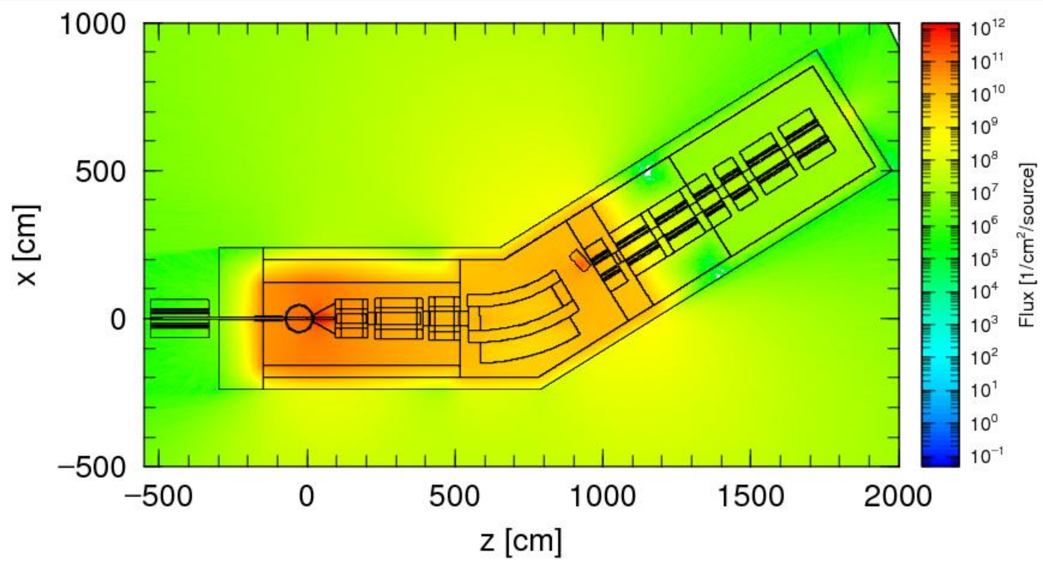
Large Radiation and Heat Loads in Fragment Separator Region Magnets



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**



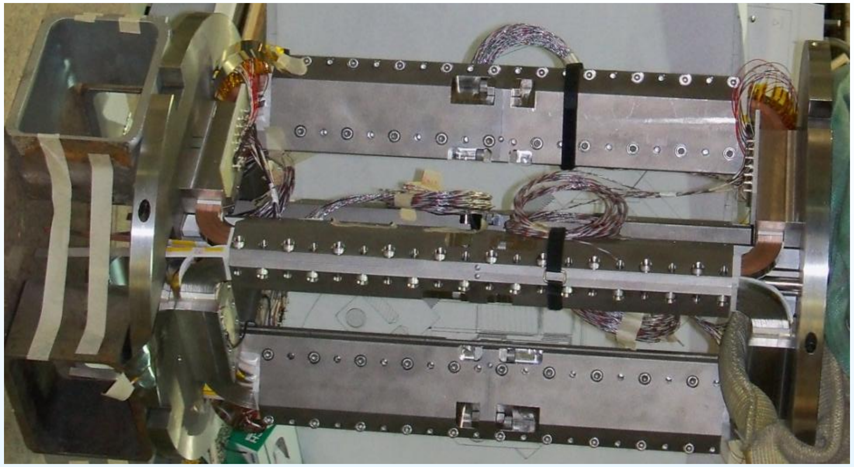
Copper or NbTi Magnets don't satisfy the requirements

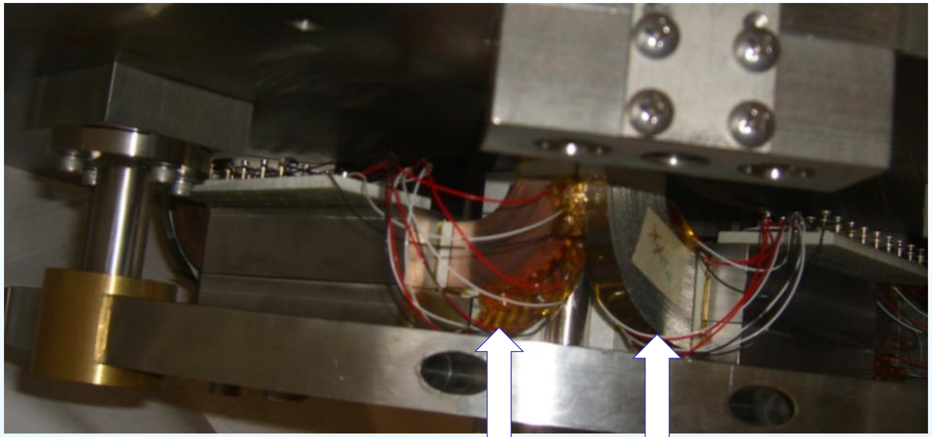
HTS Magnets For FRIB

- **HTS offers a unique solution for challenging environment of FRIB magnets with unprecedented energy and radiation loads.**
- **Because of large thermal margins HTS magnets can operate reliably and can remove large heat loads efficiently at ~40 K.**

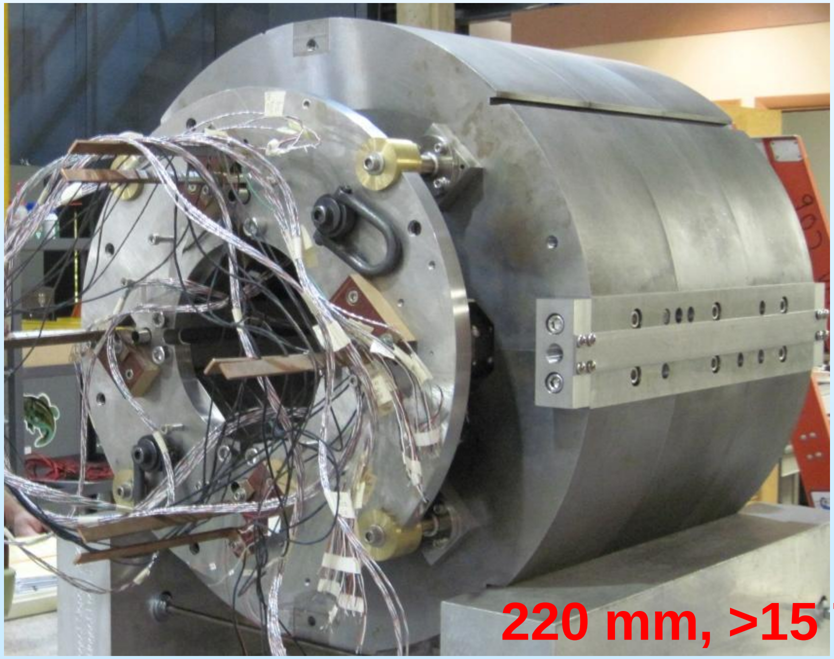
➢ **HTS magnets are now the baseline design for the quadrupole and dipole magnets in the fragment separator region of FRIB.**

FRIB HTS Quadrupole

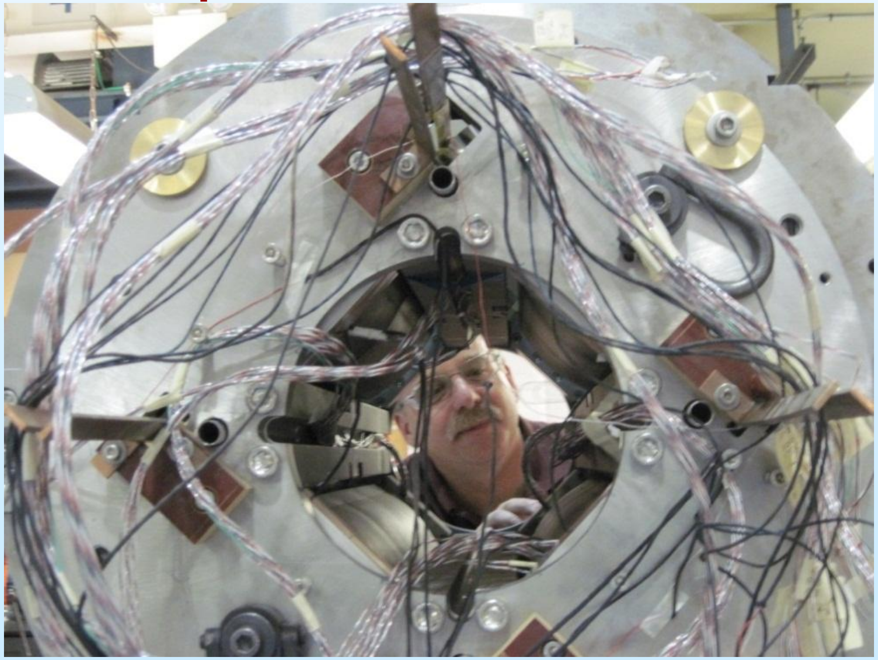




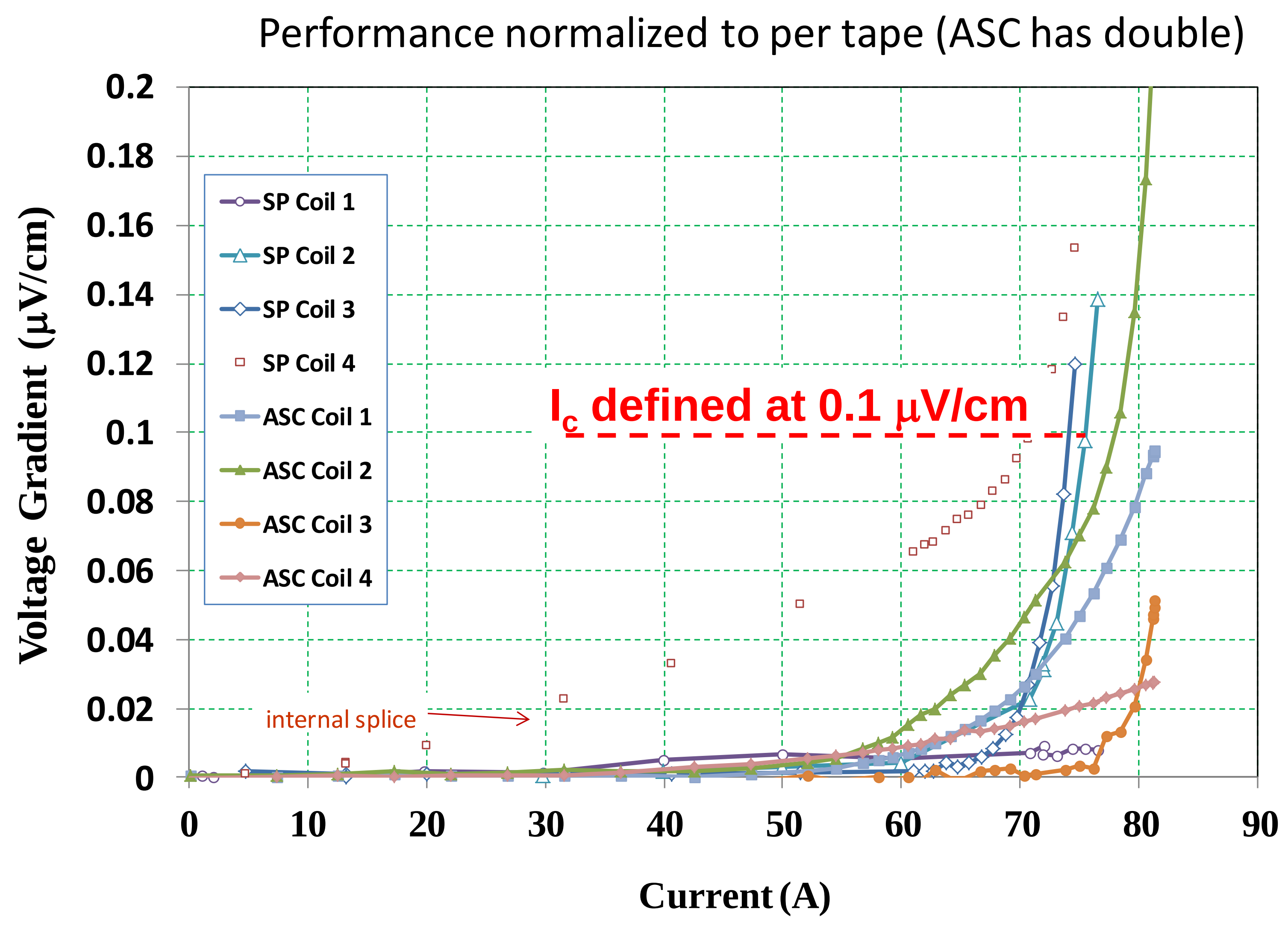
SuperPower ASC



220 mm, >15 T/m



Coils in FRIB Quad Structure @77 K
(made with 2G HTS from SuperPower and ASC)



~330 meter 12 mm used in each of four SuperPower coil and

~215 meter 12mm double tape used in each of four ASC coil

Performance at ~40 K is more relevant

Summary

- High field all HTS solenoids can now be successfully built using a significant amount of conductor (~2 km)
- Maximum field on coil >16 T, overall current density (J_o) in coil >500 A/mm^2 – new record for the technology
- We still have a lot to demonstrate and many challenges to overcome
- However, the impact of these two results of all HTS solenoid (and other high field insert coil test at NHMFL) is obvious
- We are now at the verge of revolutionizing the superconducting magnet technology – reaching higher field as never possible before
- Stay tuned for more results in coming years from around the world. We hope that 30-40 T solenoids will become a reality.

Back-up Slides

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Original Design Parameters (as presented at ASC2010)

Target Design field (optimistic)	~22 T
Number of coils (radial segmentation)	2 self supporting
Stored Energy (both coils)	~110 kJ
Inductance (both in series)	4.6 Henry
Nominal Design Current	~220 A
Insulation (Kapton or stainless steel)	~0.025 mm
J_e (engineering current density in coil)	~390 A/mm^2
Conductor	2G ReBCO/YBCO
Width	~4 mm
Thickness	~0.1 mm
Stablizer	~0.04 mm Cu

Midsert

~~Outer~~ Solenoid Parameter

Inner diameter	~100 mm
Outer diameter	~160 mm
Length	~128 mm
Number of turns per pancake	~240 (nominal)
Number of Pancakes	~~28 (14 double)~~ 24 (12)
Total conductor used	2.8 km
Target field generated by itself	~10 T

Inner Solenoid Parameter

Inner diameter	~25 mm
Outer diameter	~90 mm
Length	~64 mm
Number of turns per pancake	~260 (nominal)
Number of Pancakes	14 (7 double)
Total conductor used	0.7 km
Target field generated by itself	~12 T
External Radial support (overband)	Stainless steel tape

- ❑ **This was thought to be a very ambitious proposal!!!**
- ✓ **We have achieved >60% (6^+ T) with only half outer**
- ✓ **We have already exceeded inner by over 25% (15^+ T)**