HTS SMES Coil for Large Energy Storage

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William (Bill) Sampson

W. Sampson is given the highest honor in applied superconductivity.

IEEE Council on Superconductivity Award for Significant and Sustained Contributions to Applied Superconductivity (2010)

FIFTH WEEK – SUPERCONDUCTING MAGNETS

Chairman: W.B. SAMPSON, Brookhaven National Laboratory

Bill Sampson's week on superconducting magnets was the most popular of the Summer Study. Superconducting magnets were described, from the huge affairs under construction for large bubble chambers to miniature units suitable for transport of particle beams. It was during this week that Peter Smith of the Rutherford Laboratory brought forward his suggestions for stabilizing superconducting magnets and for reducing ac losses. These ideas already have inspired programs in a number of laboratories; thus far Smith appears to have been correct in all of his predictions.

From 1968 Brookhaven Summer Study on Superconducting Devices and Accelerator

SYNCHROTRON POWER SUPPLIES USING SUPERCONDUCTING ENERGY STORAGE

P.F. Smith
Rutherford Laboratory
Chilton, Berks., England

I. INTRODUCTION

The possibility of using energy storage in superconducting coils as the

LEFT: Chairman W.B. Sampson with P.F. Smith of the Rutherford Laboratory. RIGHT: M. Morpurgo of CERN discusses a point with D. Bruce Montgomery of the Francis Bitter National Magnet Laboratory.

http://www.bnl.gov/magnets/staff/gupta/Summer1968/

Overview

Chosen Option : High Field HTS-based SMES

- First and foremost: Why this choice from technology point of view?
- How does this compare with other options?
  - A brief review of various options
- Challenges involved
  - Experience with technology
  - Preliminary analysis

Role of Magnet Division at BNL and Relevance to Developing a New SMES

- We develop, design, build, test and maintain magnets for various facilities
- We look at all options : NbTi, Nb_3Sn and now HTS.
- A particular technology and design is chosen to reduce system cost, maximize the performance and reliability (as appropriate). Mostly it is cost, cost, cost...
- Our primary mission is not to just develop a new technology (which we do time to time to break new grounds), but generally to implement the chosen technology to a particular application as most of our funding come from specific projects.

- In this regard, we see many similarities in what we do for accelerator magnets versus what we need to do for developing a new SMES design. That is, take a fresh look based on technologies available now or are on or near the horizon to see if they can be developed to implement economically them in a real device.

SMES Options

- NbTi SMES (say 5 T) option has been considered for many decades.
- We can build a coil with that technology today. In fact, we are currently designing and building two 2.5 meter solenoids (6 T operating, over 7 T quench). Two, together will have stored energy of 3.8 MJ. The solenoid geometry can be modified to say a toroidal geometry to store over 3.4 MJ target energy for SMES.

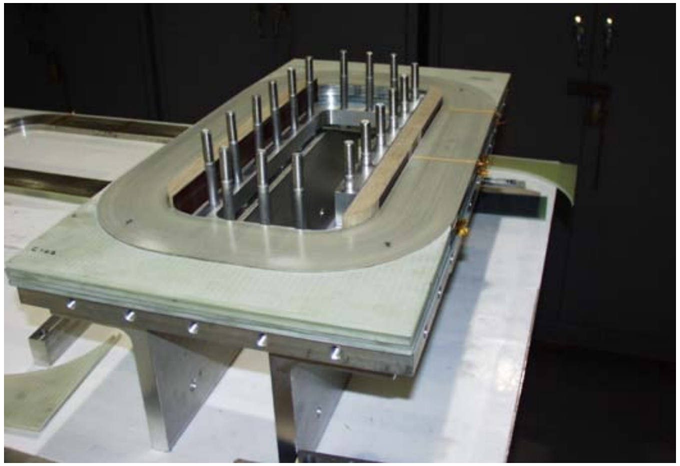
- However, SMES based on existing technology has not been able to make a splash into the market place. We are looking at all technological options for whole system (including the coils) to possibly change that situation.
- Superconducting coils play a major role in defining cost, parameters, etc. of the Superconducting Magnetic Storage System, just as does in accelerator magnets.
- Hence it is worthwhile looking into the options that have become available now which were not available earlier.

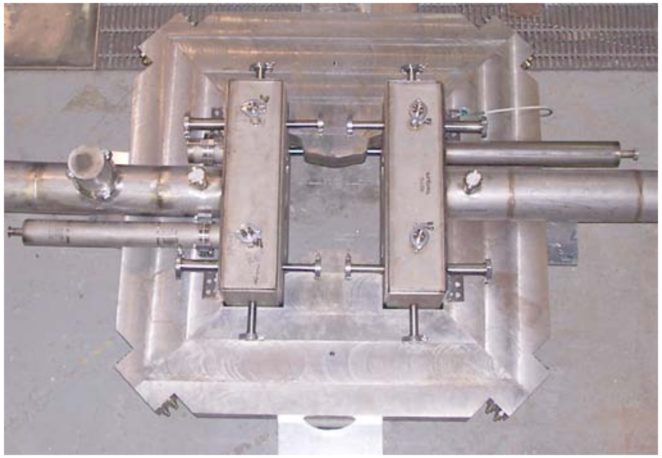
- In conductor area, the new option is High Temperature Superconductor (HTS).

Energy Storage as a Function of Temp. (in HTS Coils Built and Tested at BNL)

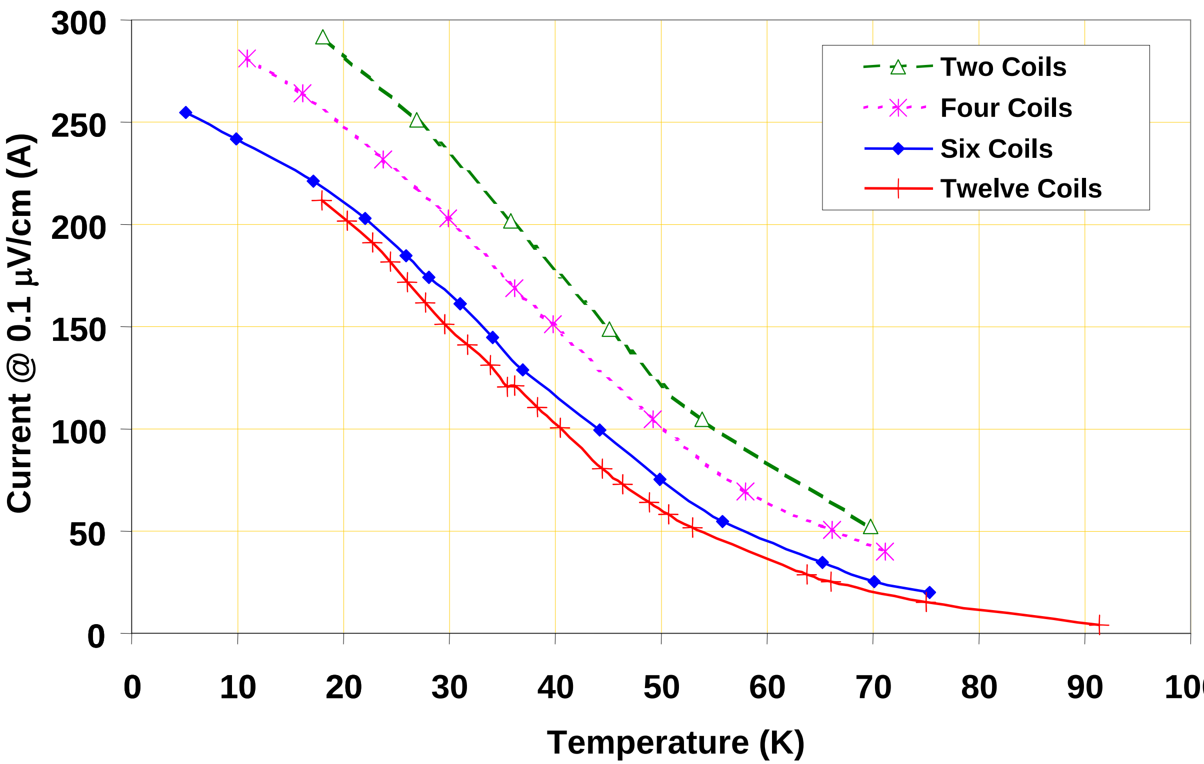
HTS coils can operate over a wide temperature range : 5 K – 77 K

➢ **Operating cost is lower at higher temp. where cryo-coolers also become efficient**





➢ **However, energy storage (proportional to I^2) can be much higher at lower temperature.**



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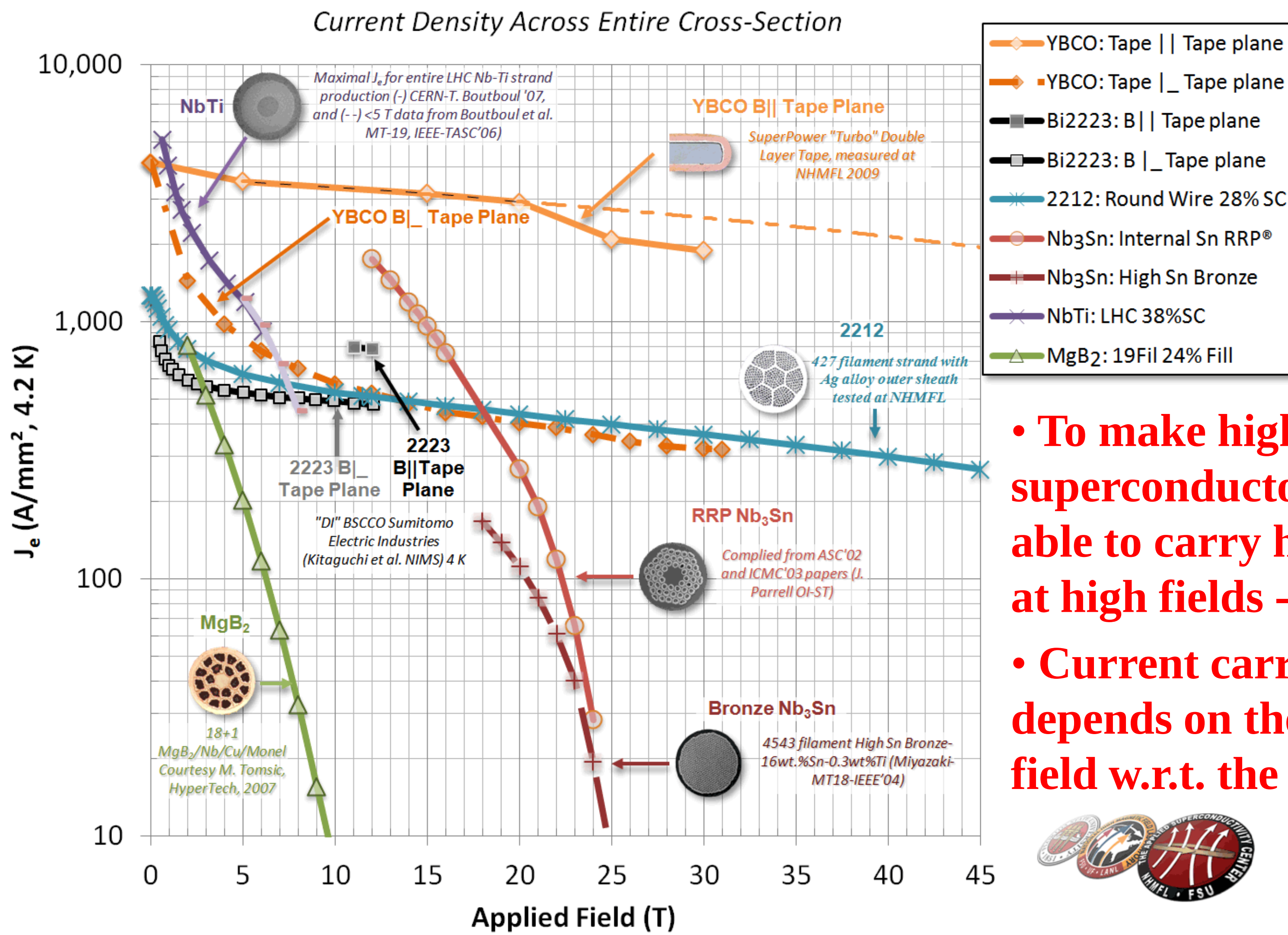
Critical Current of Various Conductors at 4 K as a Function of Field

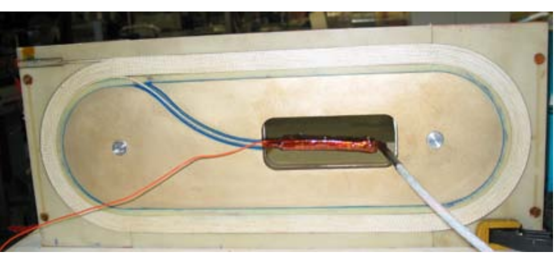


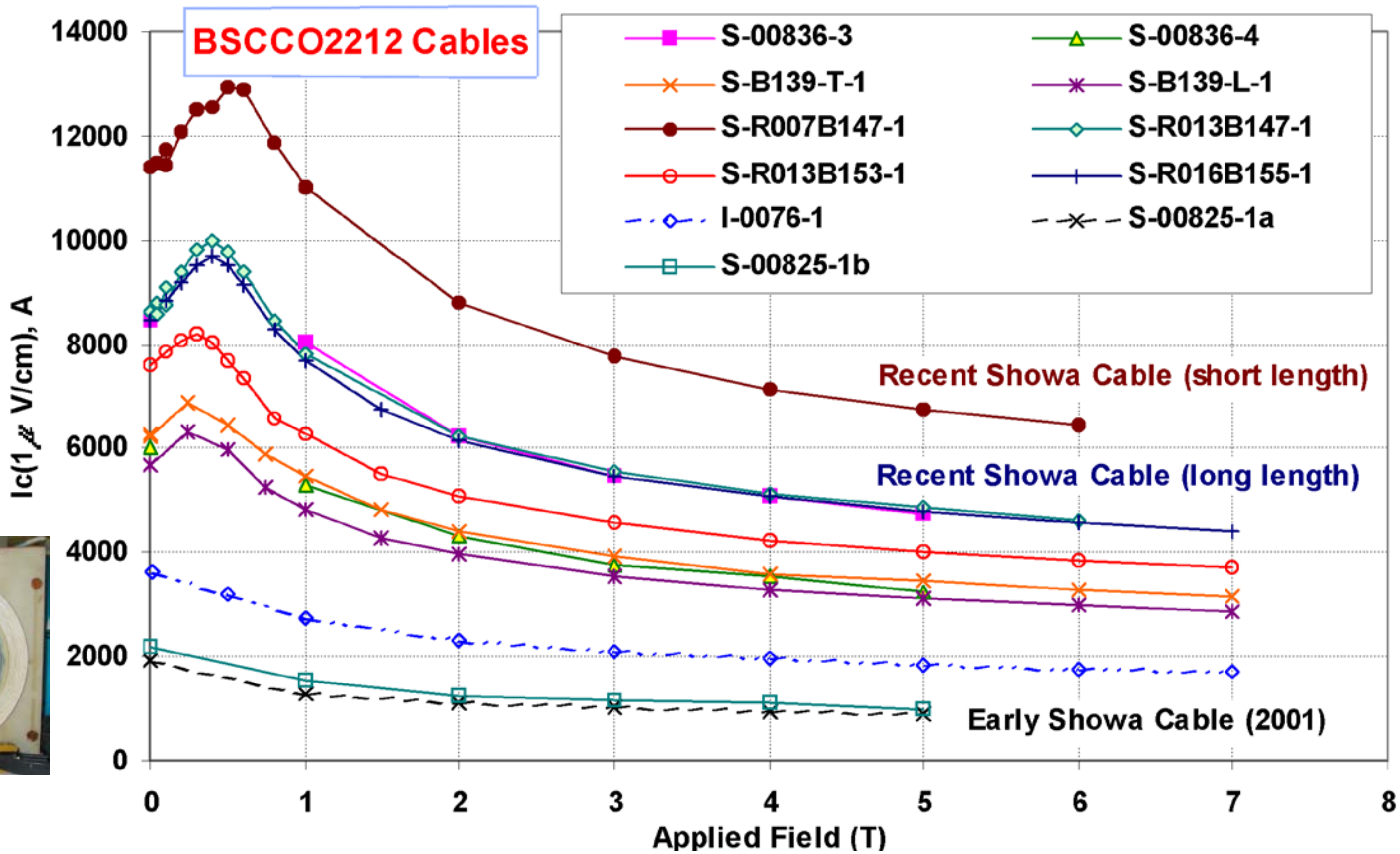
We have made coils with all conductors

- To make high field SMES, superconductor must be able to carry high currents at high fields -YBCO can.
- Current carrying capacity depends on the direction of field w.r.t. the tape surface.

4K Test of SMES Cable (from Japan) and Coils made from that at BNL

- Bi2212 wire (1G HTS) and high Ic cable was developed in Japan for SMES
- BNL collaborated as there was a mutual interest – coils can be considered as prototype for both SMES and accelerator magnets operating at ~4 K
- It proves that HTS can carry high currents at high fields in cable and in coils





Intermediate Temperature Option

- Other option is operating at intermediate temperature (say 20 K)

- BNL has tested special cable for American Superconductor Corporation at 20 K (as a part of mutually beneficial collaboration) which were consisted of several 1G (Bi2223) tapes and was likely intended for such HTS SMES

HTS SMES

- HTS has opened new options. It allows high temperature operation which can save on cryogenic cost and allow cost effective use of cryo-coolers.
- Other advantage of HTS is that temperature needs to be controlled to only within a few K rather than few tenth of a K in NbTi. This simplifies the cryogenic system, reduces its cost and makes it more robust and forgiving.

- HTS also opens the possibility of very higher field SMES as capability of HTS to carry high current at high fields makes ultra high field magnets possible.
- Higher field allows higher energy density ($E \propto B^2$). Higher energy density makes the overall coldmass smaller which apart from offering a better technical solution also reduces the cost of building and operating the cryogenic system.
- However, Ultra High Field (UHF) create larger stresses on conductor due to Lorentz forces and may create significant degradation in conductor performance.
- 2G HTS (particularly high strength YBCO available from SuperPower now), can handle much larger stresses over 1G HTS (Bi2212, Bi2223).

- The major concern, however, remains the high cost of HTS wire.

3.4 MJ HTS SMES Options

- **Option A: Low Field (2.5 T), High Temperature (~65 K)**
- **Option B: High Field (28 T), Low Temperature (~5 K)**

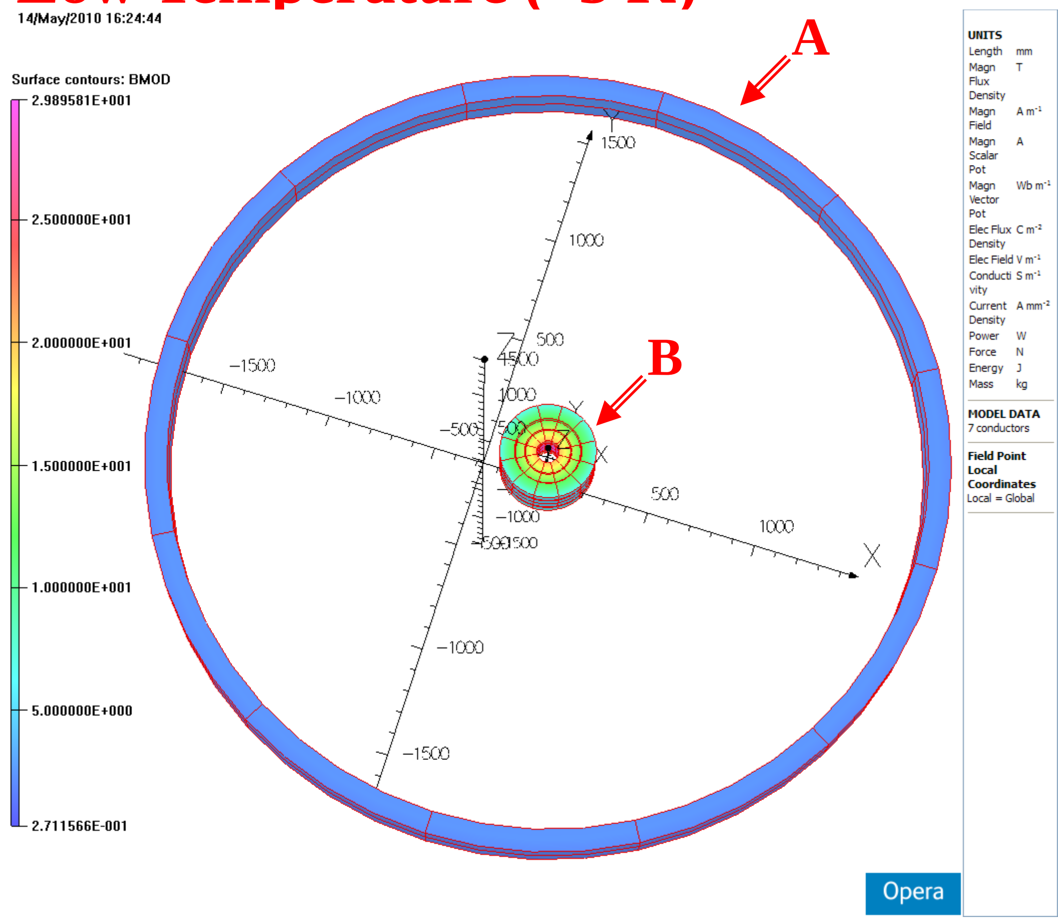
➢ **Option A saves on cryogenic cost but put higher cost on conductor**

➢ **Option B saves on conductor cost but put higher cost on cryogenic**

➢ **We started with Option A, but it requires 10 times more conductor than that required in Option B.**

➢ **Since conductor cost (~10 million $ in option A) dominates the cryogenic cost; we chose option B (~1 million $).**

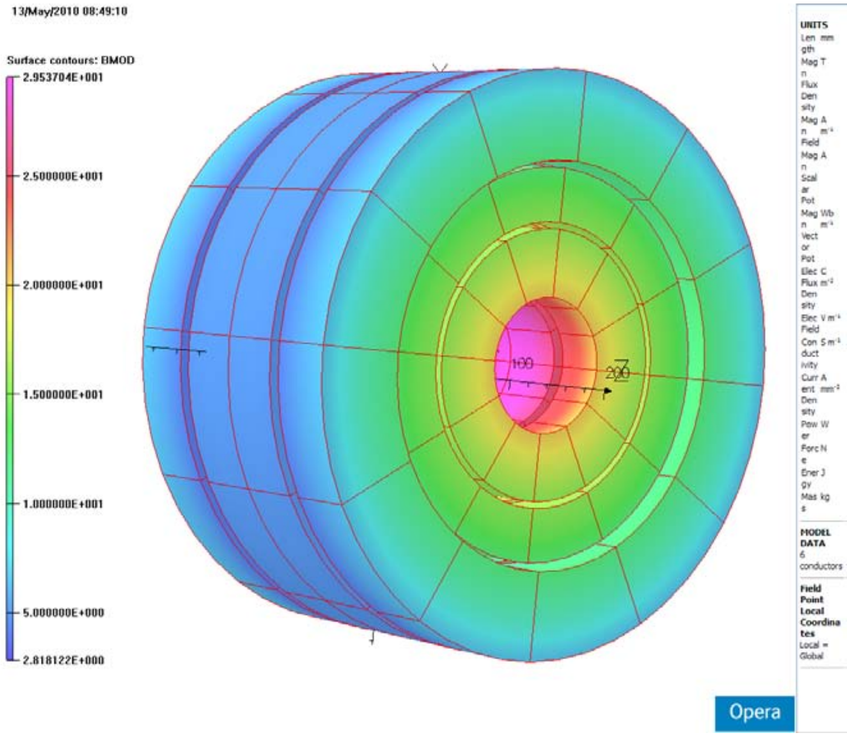
➢ **Moreover, we can test option B at BNL without expensive cryostat, etc.**



Given the funding limitations, this arpa-e proposal is feasible for Option B only

High Field HTS SMES Coil

- **Concept paper was for 30 T field and no segmentation of coil.**
- **A preliminary analysis found that large Lorentz forces can cause significant stress/strain degradation of the conductor.**
- **SuperPower YBCO is strong and can tolerate over 700 MPa stress on wide face.**
- **This is much better than 1 G conductor.**
- **However, on the axial direction 2G is about an order of magnitude worse.**
- **Coil segmentation is necessary to keep stress/strain from accumulating.**

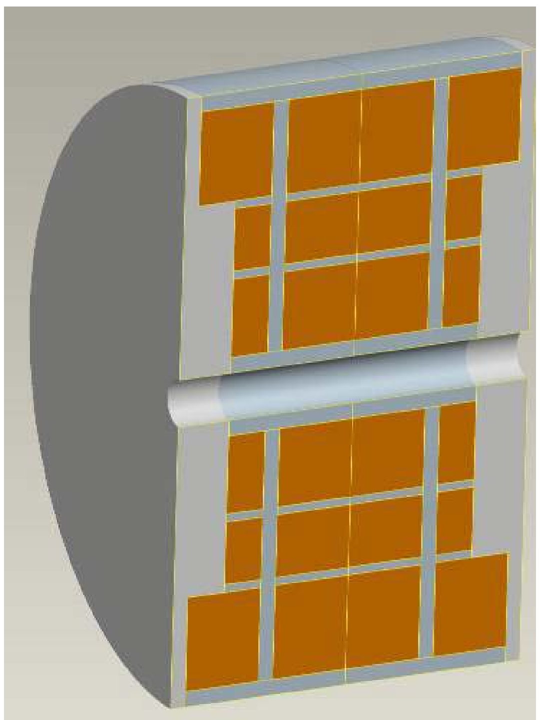


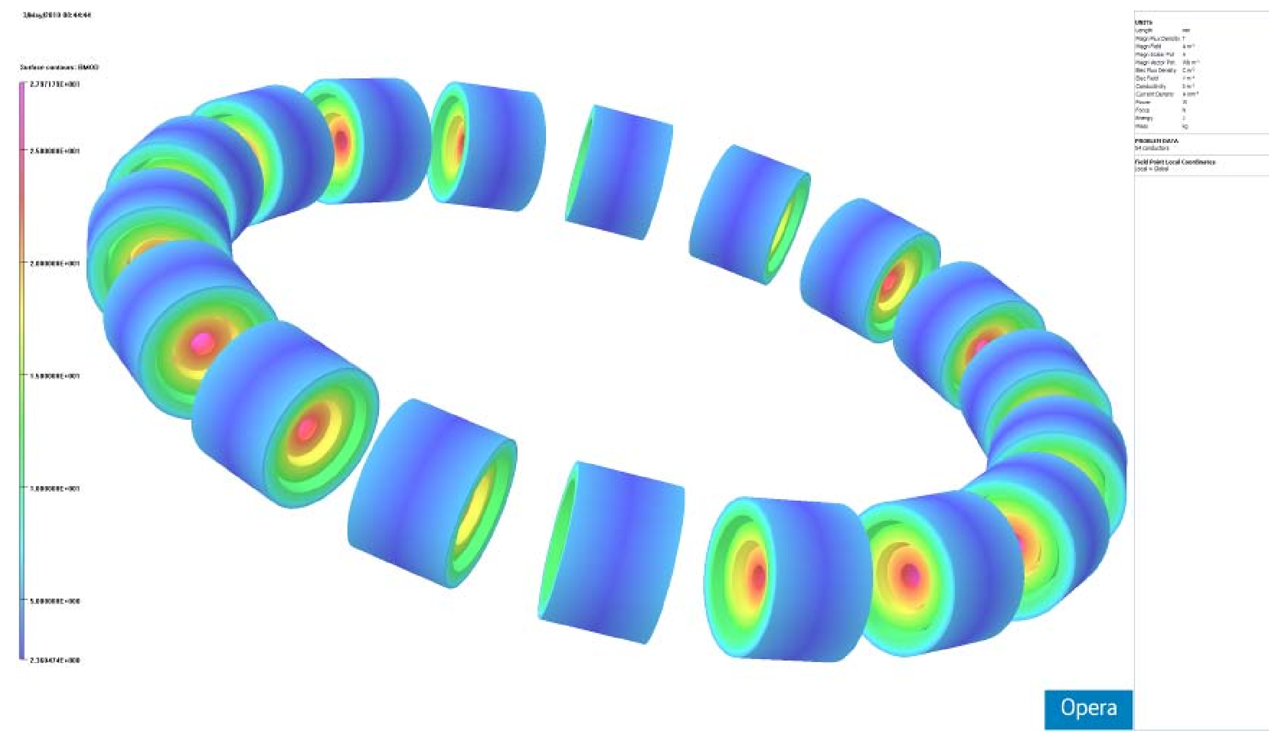
➢ **Current design for 3.4 MJ stored energy is based on 28 T central field. It has three segments in radial direction and three in axial direction.**

Overall System Design

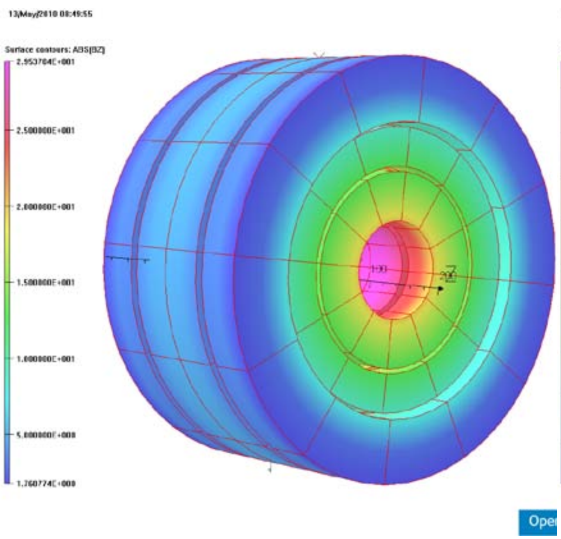
- A structure to minimize stress accumulation
- A possible layout of large energy storage system with low fringe field

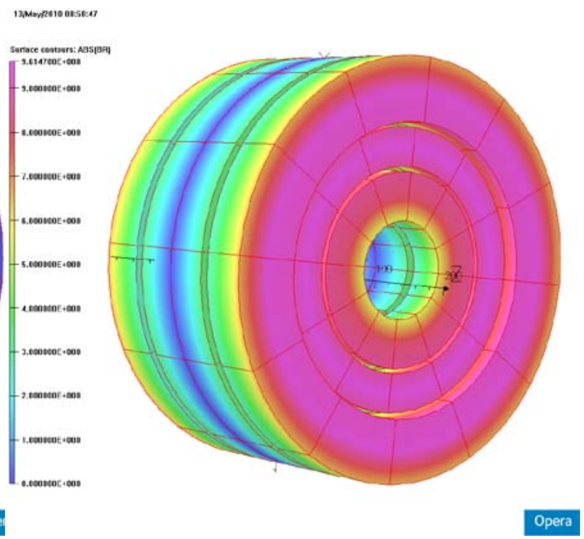
Design Field	28 T (target)
Inner Diameter	100 mm
Outer Diameter	432 mm
Length	220 mm
Current at Design Field	~600 A
Conductor	~12 mm wide ~100 micron YBCO from SuperPower
Stored Energy	~3.4 MJ
Inductance	~18.8 Henry
Conductor usage	~11 km

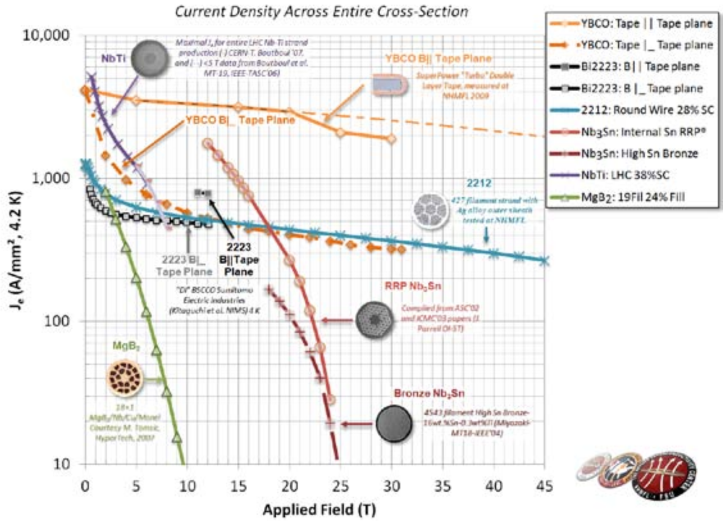




Magnetic Analysis of 3.4 MJ, 28 T Solenoid



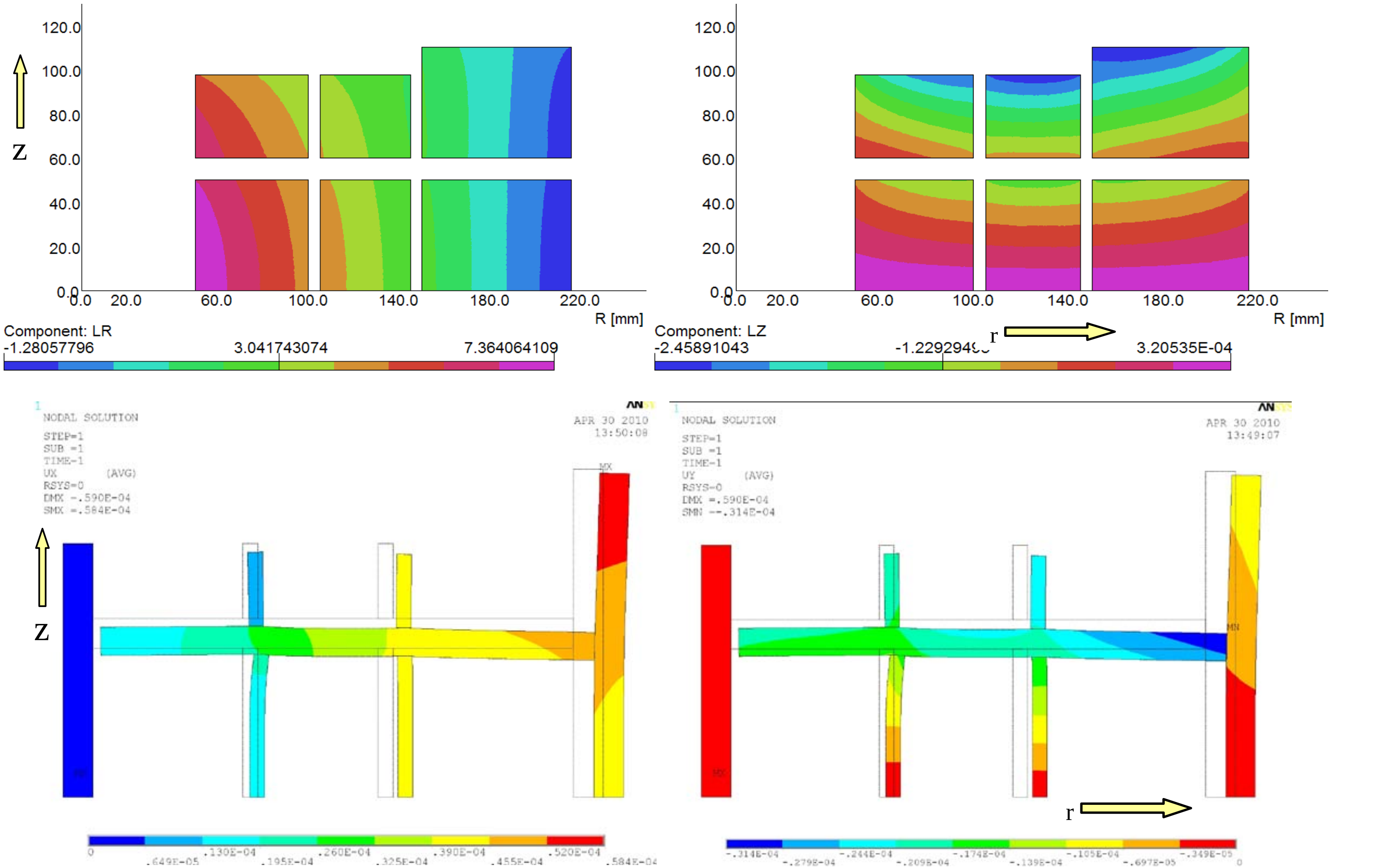




Components of the field on the surface solenoid (field parallel to the wide surface on left and field perpendicular on middle).

Critical current density of various superconductors is shown as a function of field on right [ASC-NHFML, Florida].

Mechanical Analysis

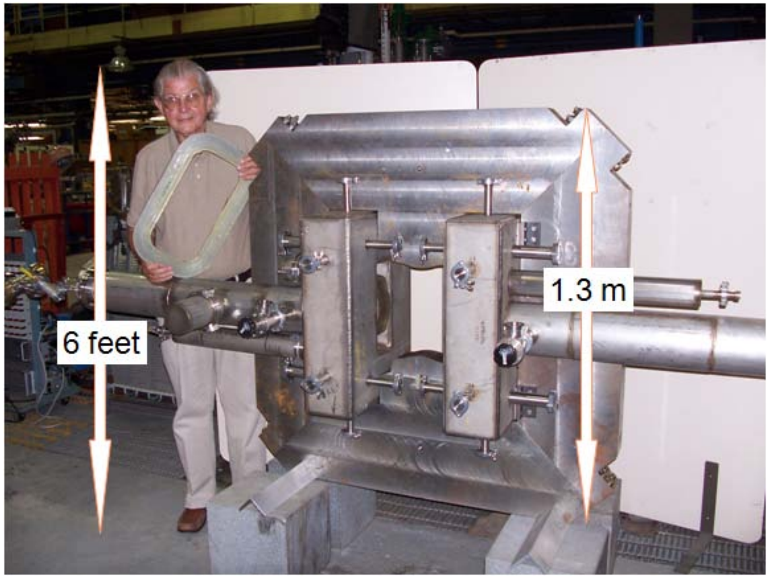


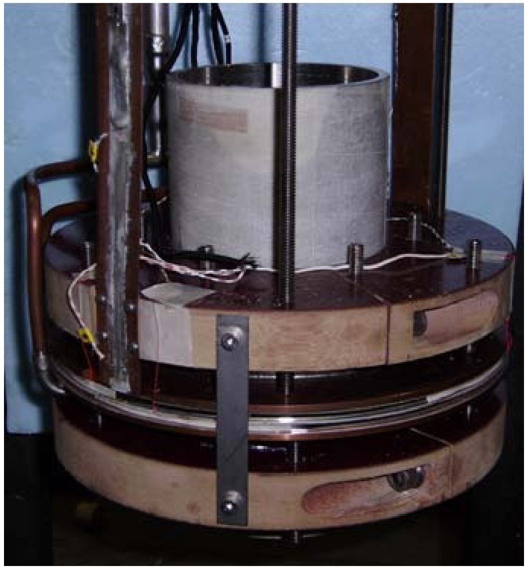
Review of HTS projects at BNL which provides sound basis of this proposal

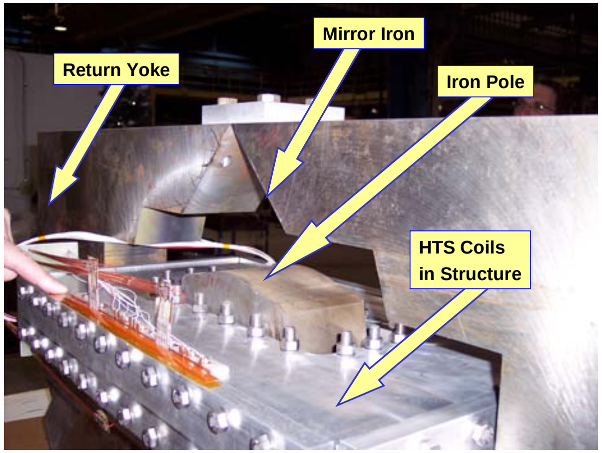
BNL has developed and is involved in developing several HTS magnets that play a key role in various devices.

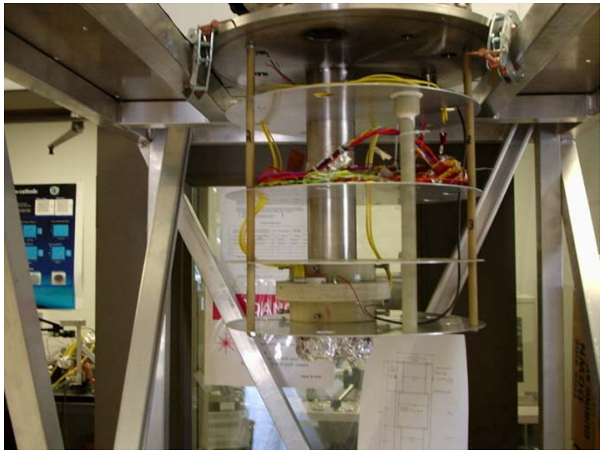
Select few will be presented. Slides will be glanced very rapidly - more discussion during the tour.

HTS Magnet Technology at BNL









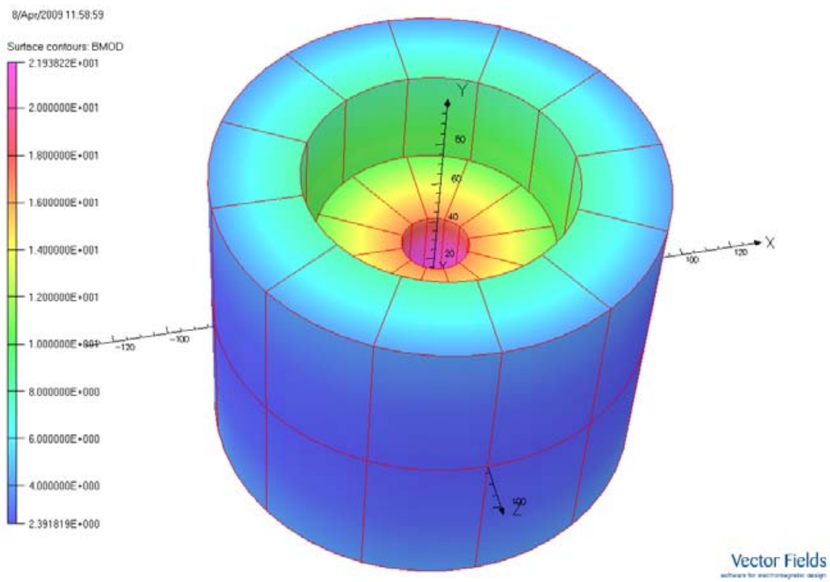
A few examples of HTS magnets successfully built and tested at BNL over the last decade

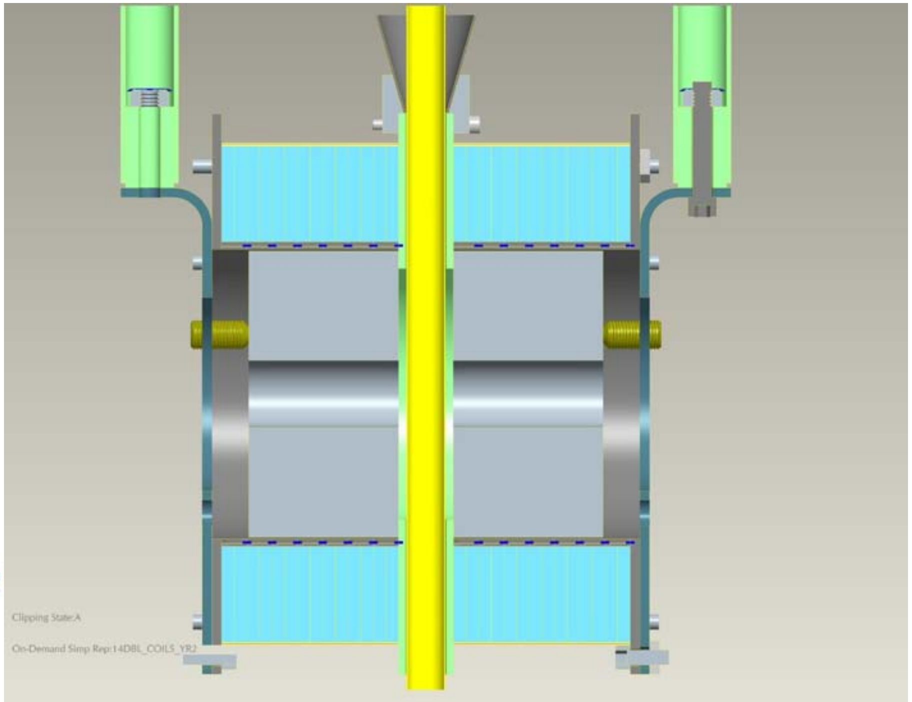
High Field HTS Solenoid

Solenoid coils in the 20+ T SBIR (now under construction):

1. ~10 T outsert YBCO solenoid (i.d. ~100 mm, o.d. ~165 mm, L ~128 mm)

2. YBCO ~12 T YBCO insert (i.d. = 25 mm, o.d. = 95 mm, L ~64 mm)





This provides a reasonable foundation to designing and building the proposed 28 T SMES Coils.

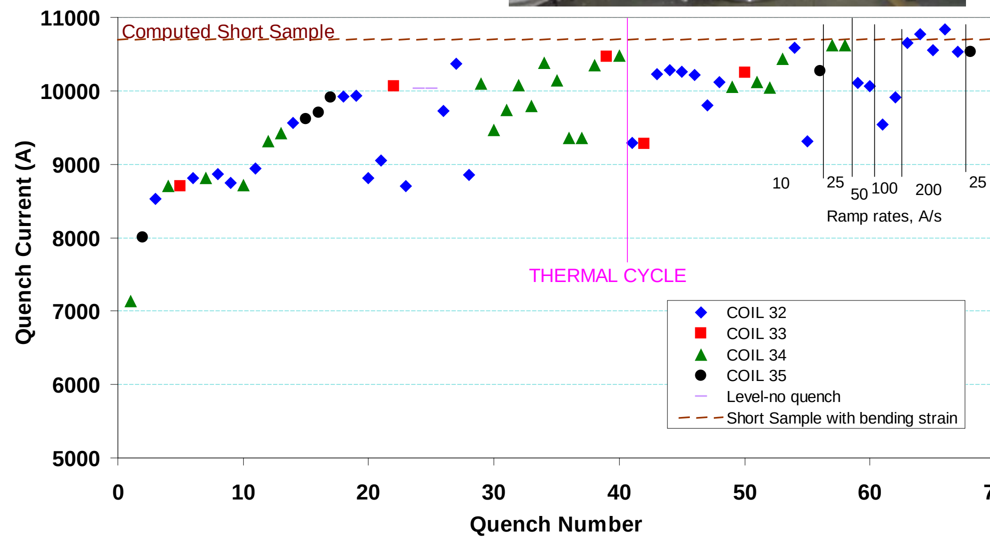
Coils for 20 T Solenoid

13 coils have been built and tested

High Field Nb_3Sn Common Coil Dipole

- **High Field Nb_3Sn React & Wind Magnet**
- **Design & Technology Developed for HTS**

I_c=10.8 kA
B_{pk}=10.7 T
B_{ss}=10.2 T



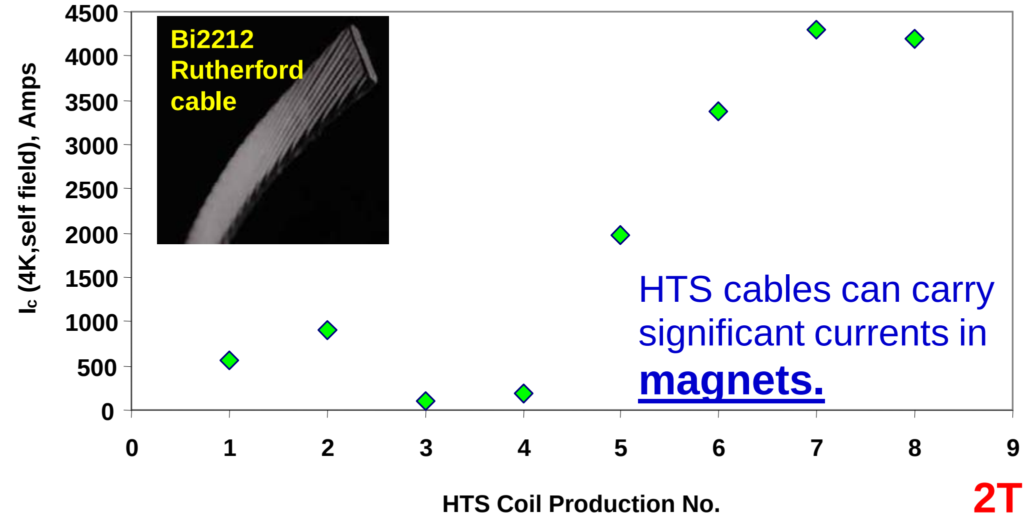
Common Coil Dipole with Bi2212 Cable Developed Primarily for Japanese SMES

Coils and Magnets built at BNL with Rutherford Bi2212 Cable

Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm²)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing Common coil configuration	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands		900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand) 74 mm spacing Common coil	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag		182	177 [80]	0.045
CC012 DCC008	0.81 mm wire, 18 strands	Hybrid Design 1 HTS, 2 Nb_3Sn	1970	212 [129]	0.66
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb_3Sn	3370	215 [143]	0.95
CC026 DCC014	0.81 mm wire, 30 strands	Hybrid Common Coil Design 2 HTS, 4 Nb_3Sn coils (total 6 coils)	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands		4200	272 [212]	1.84

Earlier coils
<1 kA (~2001)

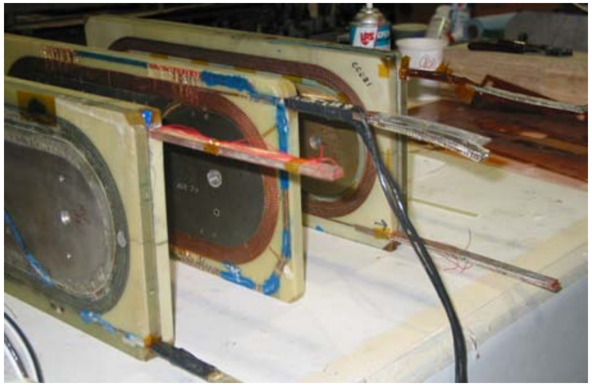
Later coils
4.3 kA (2003)

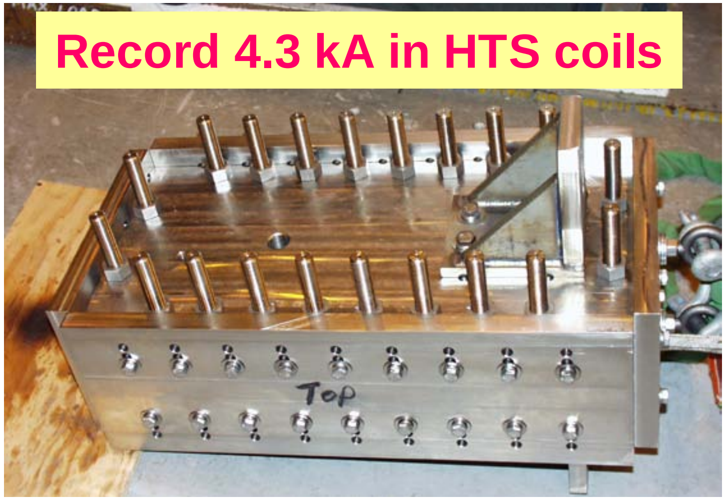


2T

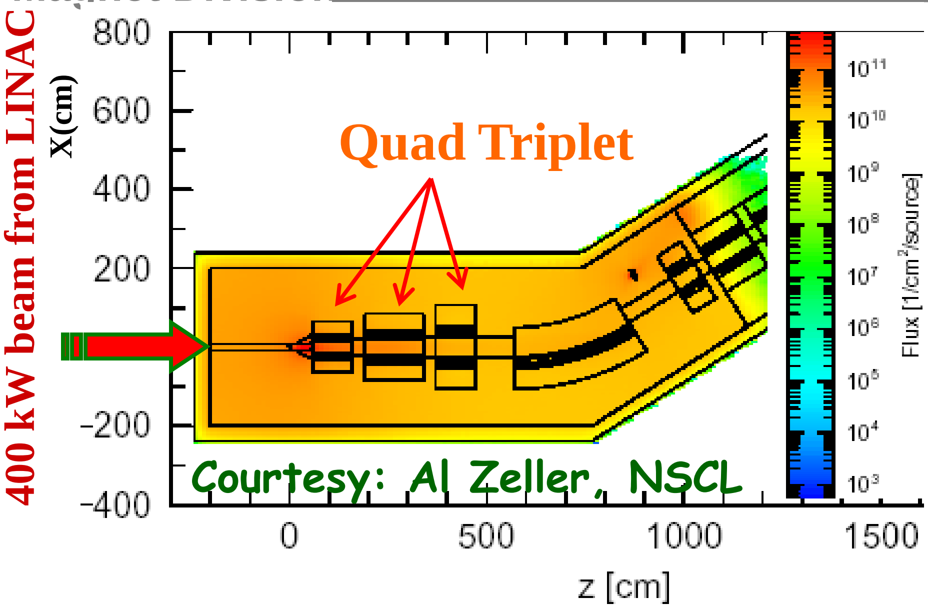
Racetrack Bi2212 (1G HTS) coils

(consider prototype for accelerator magnets or SMES)

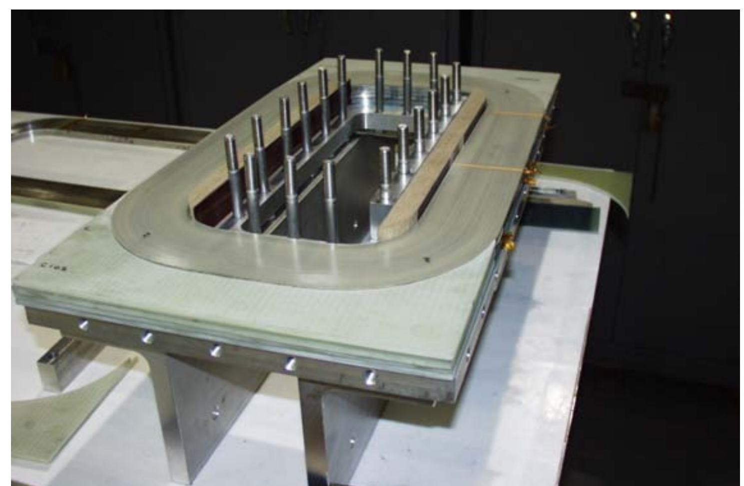




HTS Magnets For FRIB



- Facility for Rare Isotope Beams (FRIB) is the proposed ½ billion+ dollar facility.
- Up to 400 kW of beam power hits the target producing a variety of isotopes.
- Magnets are subjected to extremely high level of radiation and heat loads.
- ~15 kW of the above is deposited in the first quadrupole itself.
- 2G HTS magnets can remove these large heat loads at ~50 K instead of ~4K - over an order of magnitude more efficient.



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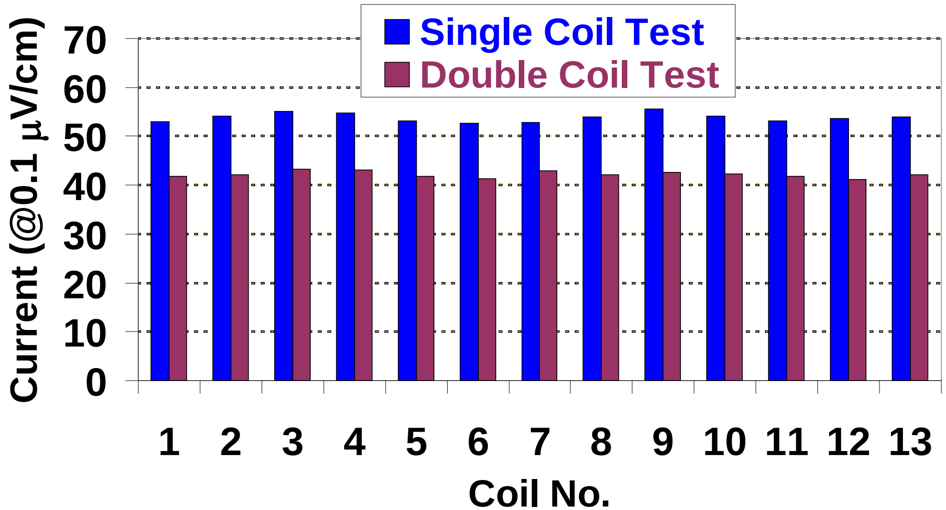
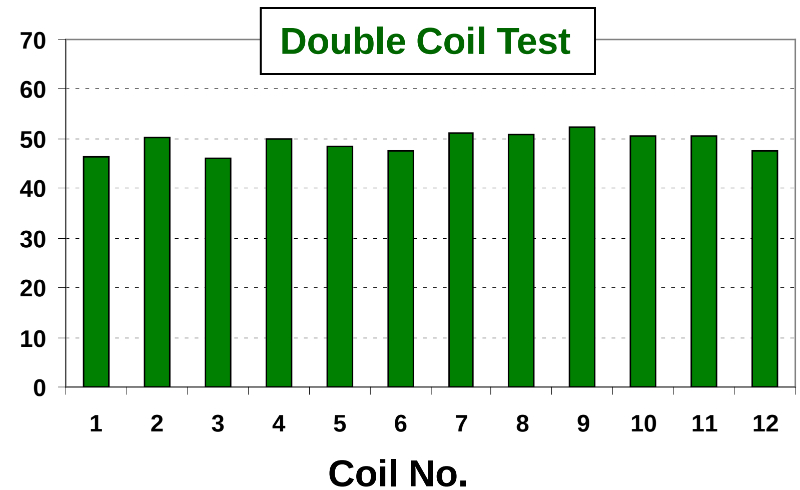
LN_2 (77 K) Test of 1G HTS Coils

13 Coils made earlier tape
(Nominal 175 turns with 220 meters)



12 Coils made with newer tape
(150 turns with 180 meters)

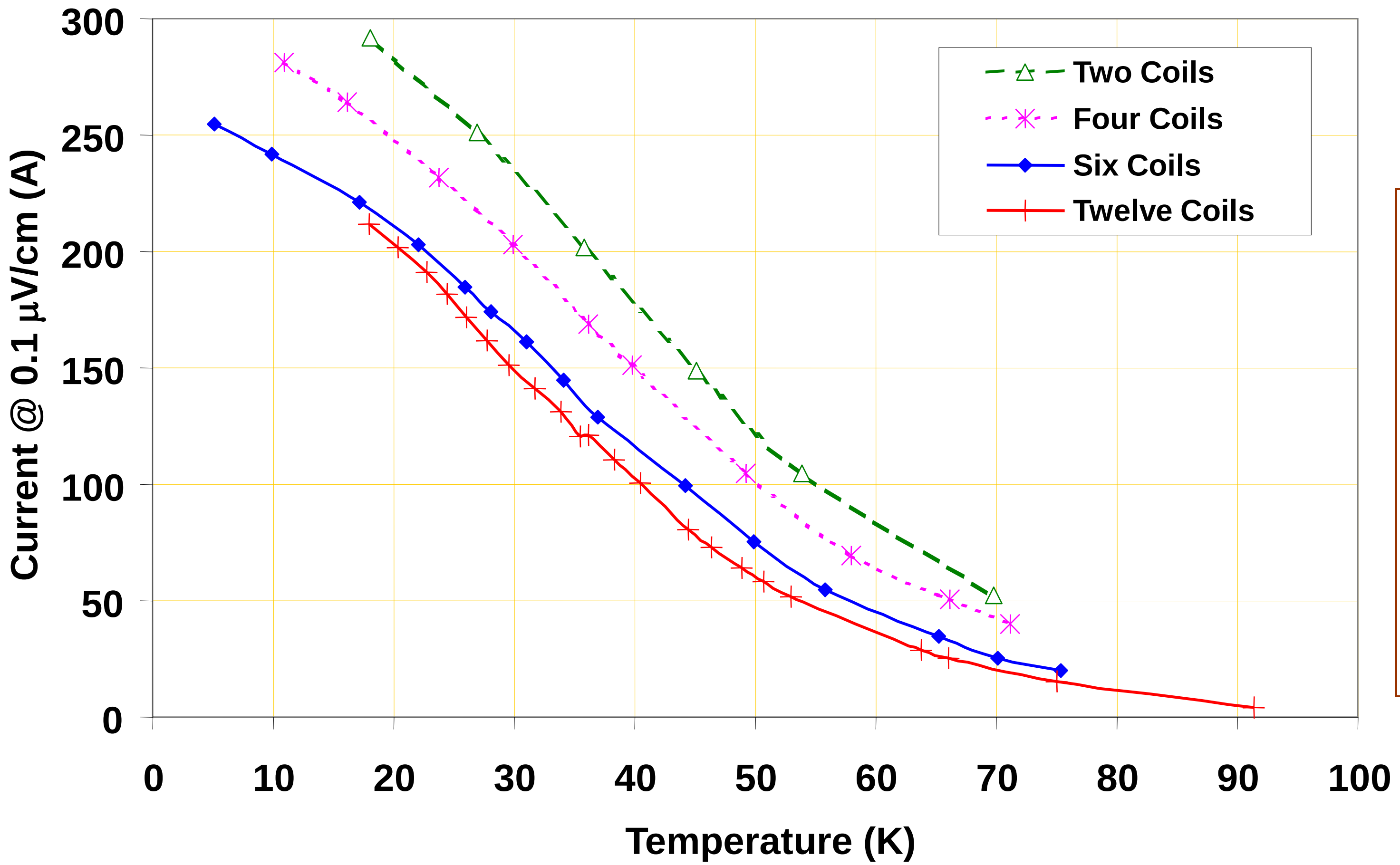


Coil performance generally tracked the conductor performance pretty well.

Note: A uniformity in performance of a large number of HTS coils made with commercially available superconductor (ASC)

– It shows that the HTS technology is now maturing !

Coil Performance as a Function of Temperature



More coils create more field and hence would have lower current carrying capacity

A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

Summary

- High field HTS option provides a promising option to SMES.
- We are eager to participate in this exciting opportunity.
- We have worked with all conductors that helps us in making a more informed decision.
- We not only develop technologies but build devices that go in to real machine.
- We bring a unique experience and technological perspective to the program.

Extra Slides

Stored Energy and Quench Protection

• The goal of this proposal is to ultimately build a large stored energy device.

• The goal of the current R&D demo device is to design, build and protect a solenoid with stored energy over 3 Mega Joule.

• Protecting superconducting coils with large stored energy is a major issue in any such proposal. However, HTS magnets have a major quench protection issue even for small devices.

• Therefore, developing a quench protection system for HTS with large stored energy will be a significant part of the proposal.

Superconducting Magnet Division - Resources

- Superconducting Magnet Division is currently consisted of ~40 persons with Peter Wanderer as Acting Head.

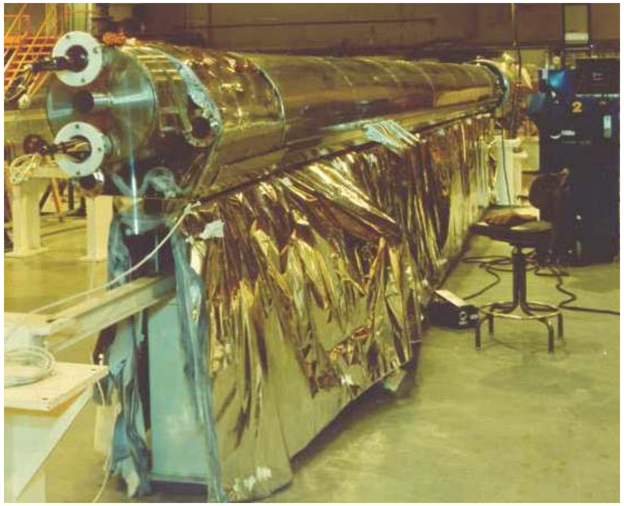
- It has all resources necessary to develop a variety of superconducting magnets - from testing superconductor to designing, building and testing the completed magnet
  - Personnel resources include: engineers (mechanical, electrical and cryogenic), scientists, technicians, designers and support staff.
  - Facilities include: conductor testing, coil winding, magnet assembling and number of cryogenic test stations for magnets.

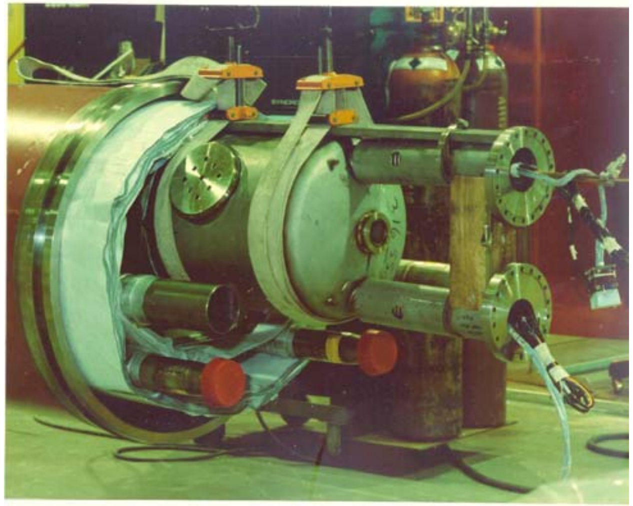
Support to BNL and Collaborators

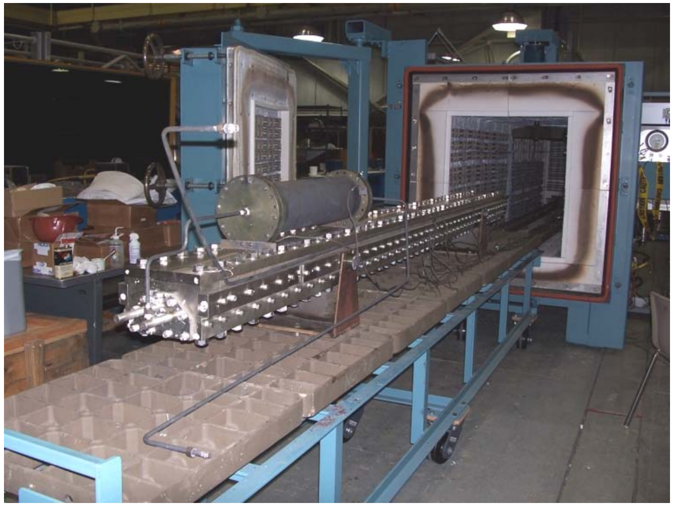
- BNL management has identified “magnets” as one of the five core competencies needed for the laboratory.
- The Superconducting Magnet Division (SMD) contributes to three of the four major activities at BNL.
- It supports existing facilities (including RHIC, a 3.8 km long superconducting machine) and those under construction (for example NSLS II).
- Magnet Division is part of several national and international collaborations. It has contributed key magnets to several international facilities (LHC, DESY, KEK, BEPC, etc) and currently working on more.
- Magnet Division is working with several scientific and industrial partners (collaboration, work for others, SBIR).

Magnet Construction and Test

(more during the magnet division tour this afternoon)







Some of them have large stored energy

Variety of Conductors and Magnets

Conductors

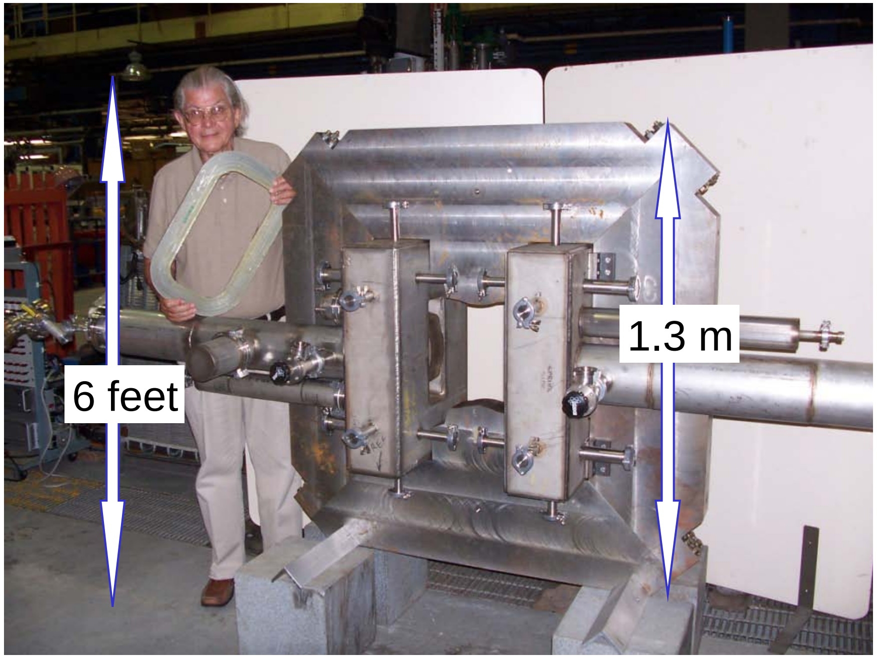
- NbTi : used in all machine magnets (including RHIC with 3.8 km circumference)
- Nb3Sn: used in many R&D magnets
- MgB2: R&D coil
- HTS: First generation (1G) HTS (Bi 2212, Bi 2223) and second generation (2G) HTS (YBCO) – used in many state-of-the-art R&D magnets

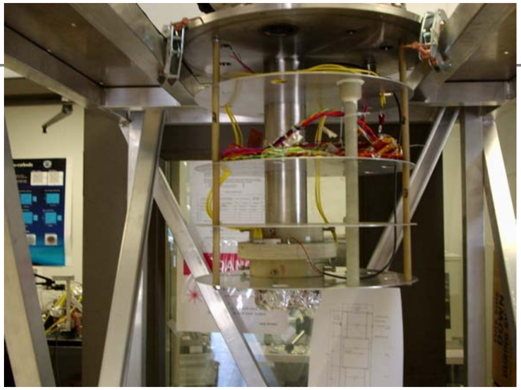
Magnets

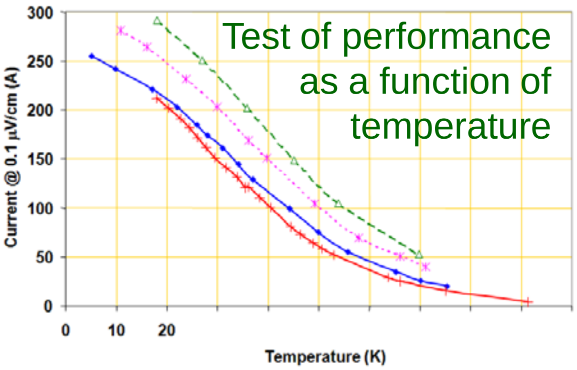
- Dipoles (<1 m to 10+ m long): Made with NbTi, Nb3Sn and HTS (range in strength <1 T to 10+ T)
- Quadrupoles: NbTi & HTS
- Sextupole, helical and corrector magnets: NbTi
- Solenoids:
  - 6 T (>7 T quench), 2.5 meter long NbTi, over MJ stored energy
  - low field HTS
  - high field HTS (20 T, now under construction), over MJ stored energy

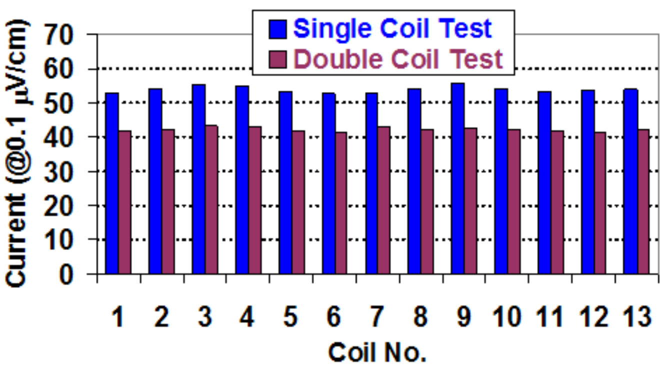
This vast experience helps us decide what is most suitable for which application.

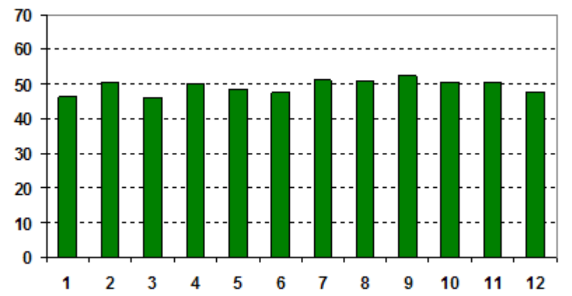
Variety of HTS Magnets











Test of a series of coils (>30 made so far)