ReBCO-based High Field Solenoids for MAP

Ramesh Gupta

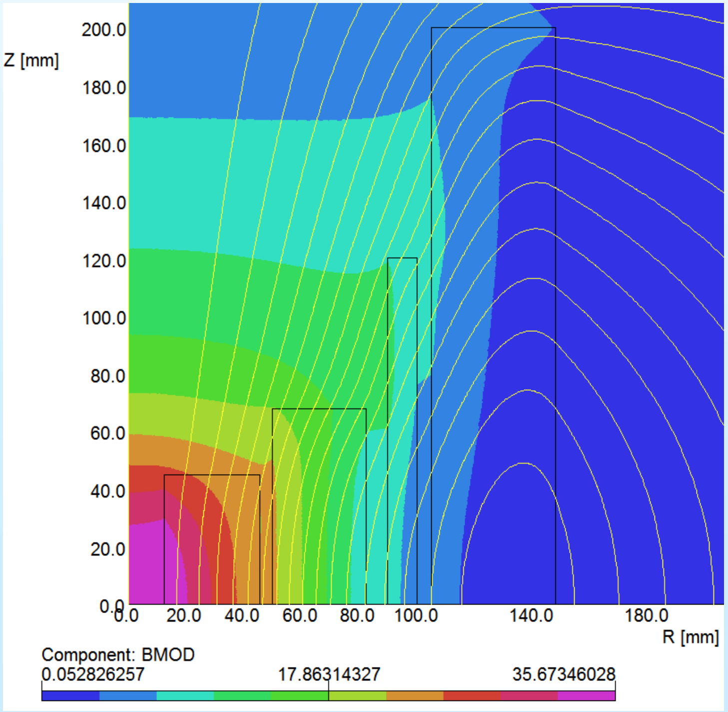
February 22, 2013

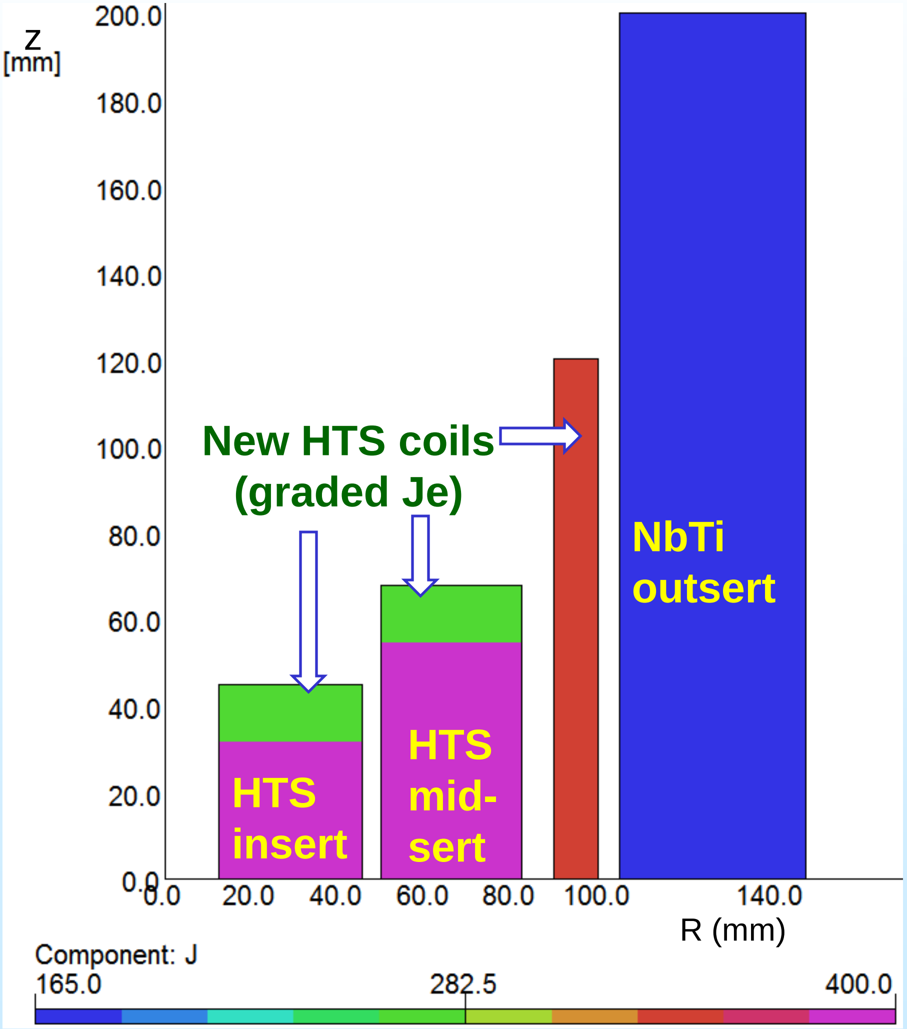
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

Pathway to a 35 T Solenoid

➢ **We propose to develop technology and demonstrate a ~35 T solenoid in 5 years.**

It takes advantage of existing coils, hardware and contributions from various programs and collaborators (highly leveraged).





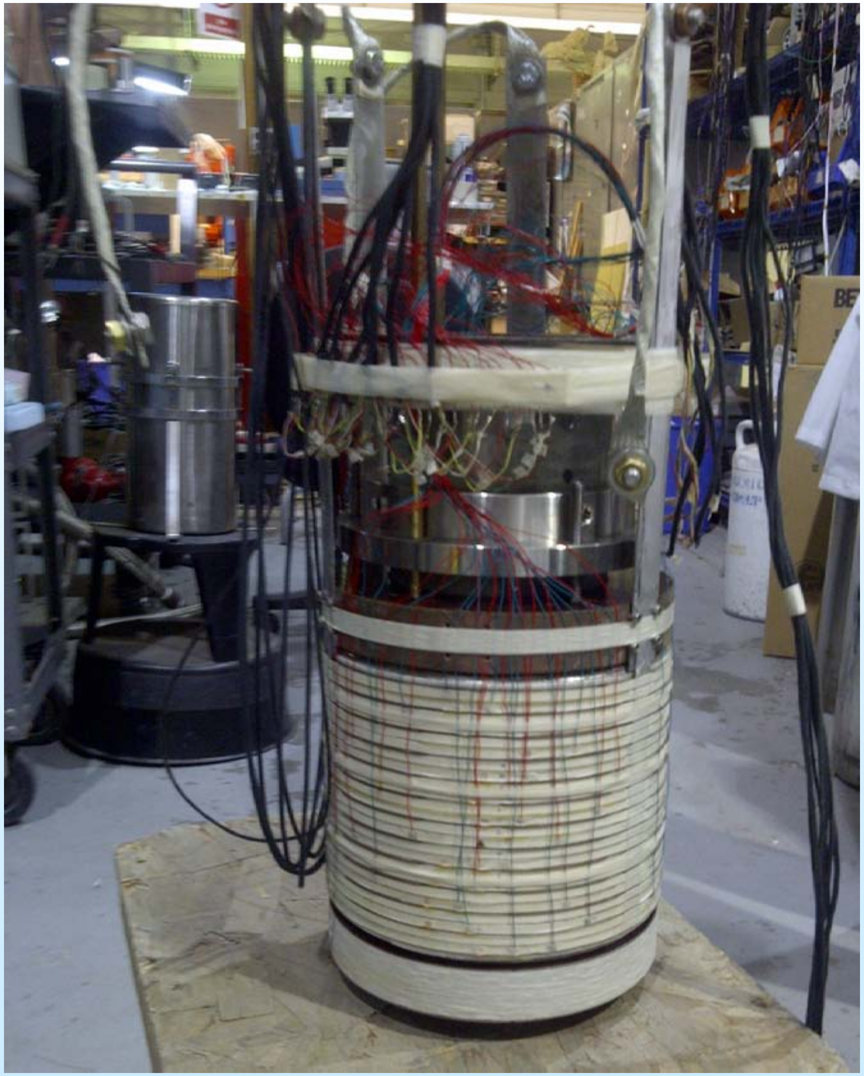
Overview of the Proposed R&D Program for ReBCO based High Field Solenoid

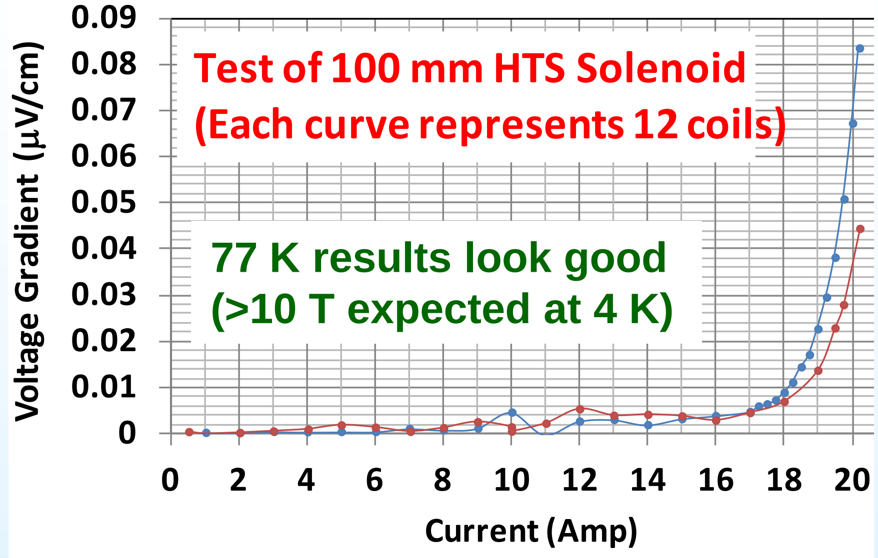
- **Task I (continuing from previous years)**
  - Complete test of HTS 10+T, 100 mm midsert (SBIR funded)
  - Develop quench protection hardware to protect this coil during 4 K test (some hardware module provided by PBL, and part of tech labor provided by MAP)
- **Task II (expected from 100k$ FY13 funding from MAP)**
  - Replace 25 mm insert pancakes (labor from MAP, conductor from SuperPower)
  - Combine insert and midsert to demonstrate >20 T (up to 25 T?) HTS solenoid
- **Task III (Phase I with estimated funding of $400k in FY14)**
  - Design, build and test NbTi outsert (design and construction of NbTi solenoid is leveraged by successful test and existing infrastructure of e-lens solenoid for RHIC).
- **Task IV (Phase II with longer term funding from MAP)**
  - Demonstration of ~30 T solenoid when HTS insert and midsert are combined with NbTi
  - Build additional HTS coils (this can be done in parallel to Phase I or can be Phase 1a)
  - Demonstration of ~35 T superconducting solenoid with additional HTS coils
  - A more complete engineering design with required analysis
  - Quench protection R&D and examination of various options
  - Ongoing conductor specification with existing magnet

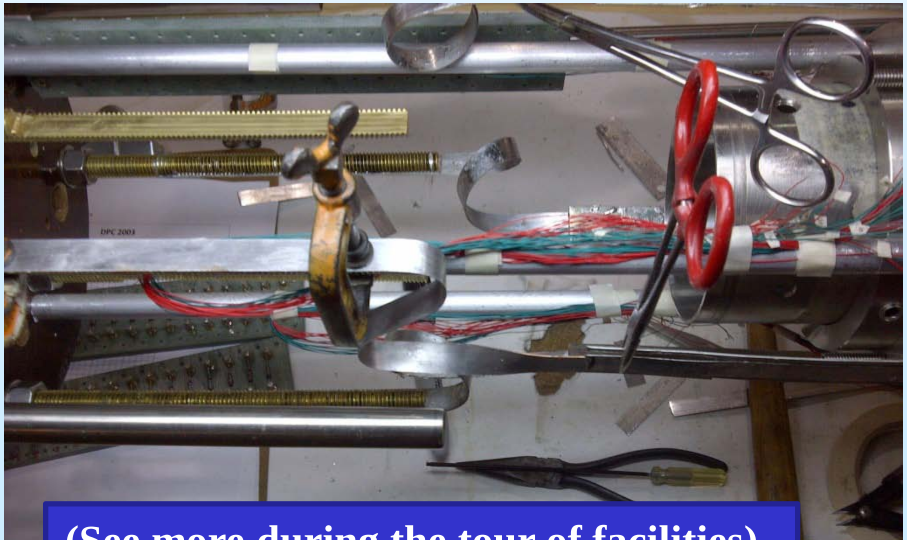
Next Few Slides Gives Overview of the Tasks

(Technical discussion in the session after the tour of the facilities)

Task #1 : 4K Test of Midsert (expected in March)







(See more during the tour of facilities)

Task #2 : 20+T with Insert

(See more during the tour of facilities)

- We plan to replace bad pancakes with conductor from SuperPower
- Out of fourteen pancakes, bottom four are found bad, then next two and top four are found good.
- We hope that other four, which are in between, are good. We will verify that and replace if necessary.
- We hope to get back 15+ T in this solenoid
- We will fix the thermal issues by better cooling through copper discs and slower cool-down
- We will integrate the two (insert plus midsert) together and hope to get 20-25 T

➢ **This will be a major achievement and everyone (MAP, BNL and PBL) should benefit from it, as it redefines the field**

Task #3: 7 T Outsert NbTi Solenoid

Motivation for NbTi Solenoid rather than Test at NHMFL

•When we looked at all aspects of testing 20+T coils in the background field of NHMFL resistive solenoid, it became clear that it was not a simple task.

• One had to consider the off-centric forces, protecting NHMFL solenoid and various fault scenarios

• Taking BNL's advanced quench protection system at Florida and matching it with their system was another complication

• It turns out that building a NbTi background field solenoid with existing parts, infrastructure will be simpler and more cost-effective.

• Moreover it becomes part of a demonstration of a high field (~35 T) solenoid test rather than a background field coil test.

• We choose NbTi solenoid dimensions such that it could be tested in a smaller dewar that does not require running expensive infrastructure.

NbTi Solenoid based on Several Existing Components and Proven Design

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	$<6 \times 10^{-3}$

(See more during the tour of facilities)

- **Two of these solenoids were recently tested to 6.6 T (test stopped 10% above design field)**
- **Design, technology and some leftover material available for use**

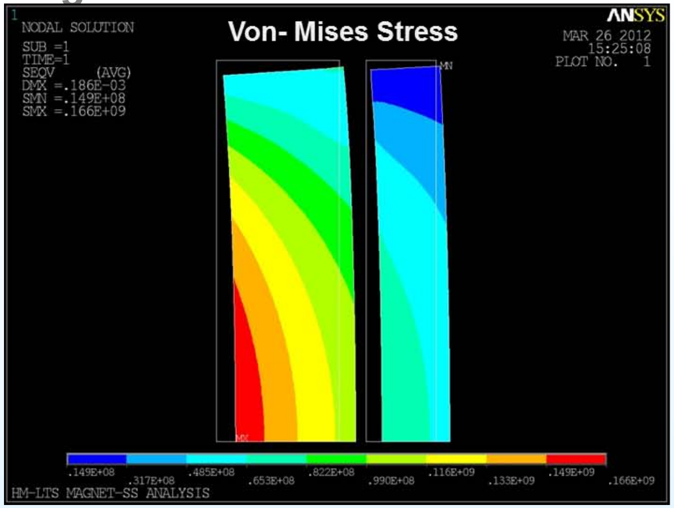
Tasks#4 or Phase II

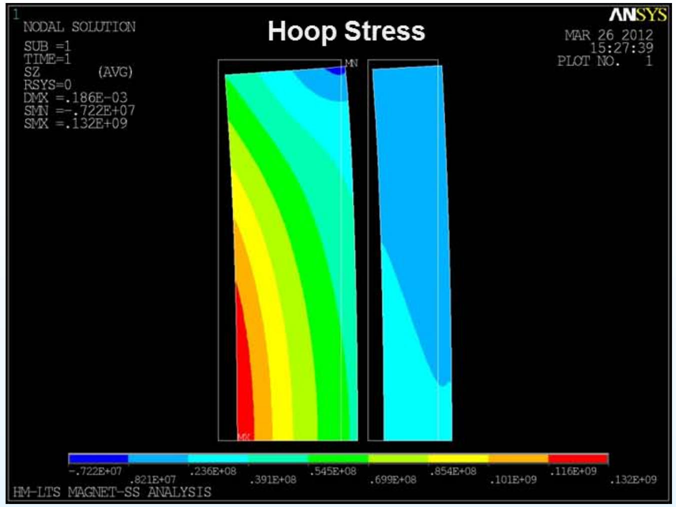
(Brief overview of various aspects of the long term R&D and engineering needed for developing technology and demonstration of 35 T)

Magnet Engineering

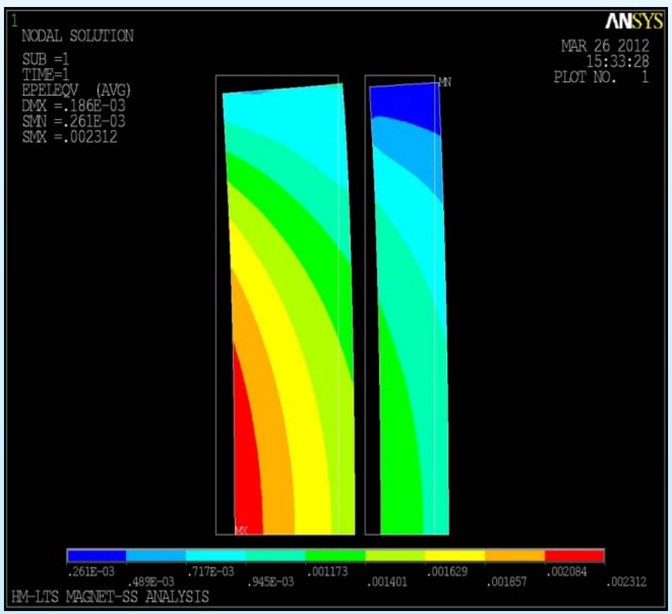
- Because of limited funds, very little magnet engineering has been carried out in SBIR programs.
- In SBIR program, we chose an approach where funds were used in most effective way to open and show the possibility.
- In MAP program, we have to demonstrate the technology.
- Therefore, as we move to the next phase, we have to significantly increase both magnet engineering and magnet analysis.

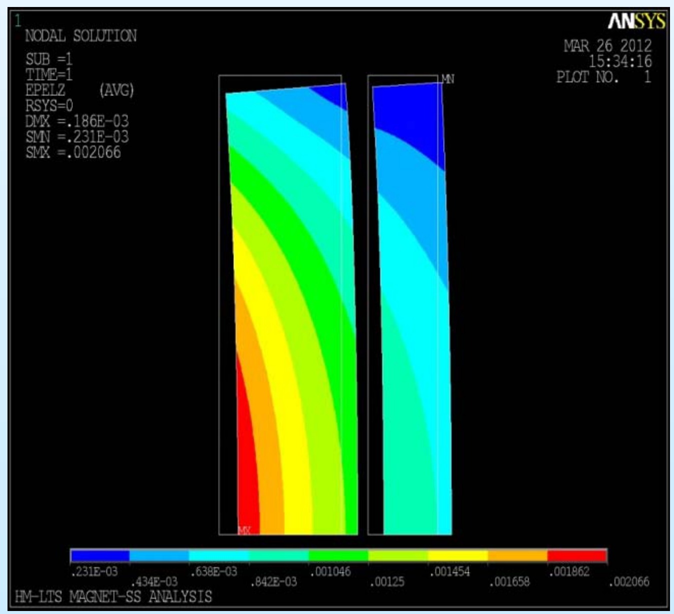
Mechanical Analysis





Von Mises and hoop stress in distribution from ANSYS in an LTS solenoid design





Courtesy:
S. Lakshmi

Von Mises and hoop strain in distribution in an LTS solenoid design from ANSYS

Advanced Quench Detection System

Construction of the second quench detection module is partly supported by MAP. **Thanks.** **More work needed.**

(See more during the tour of facilities)

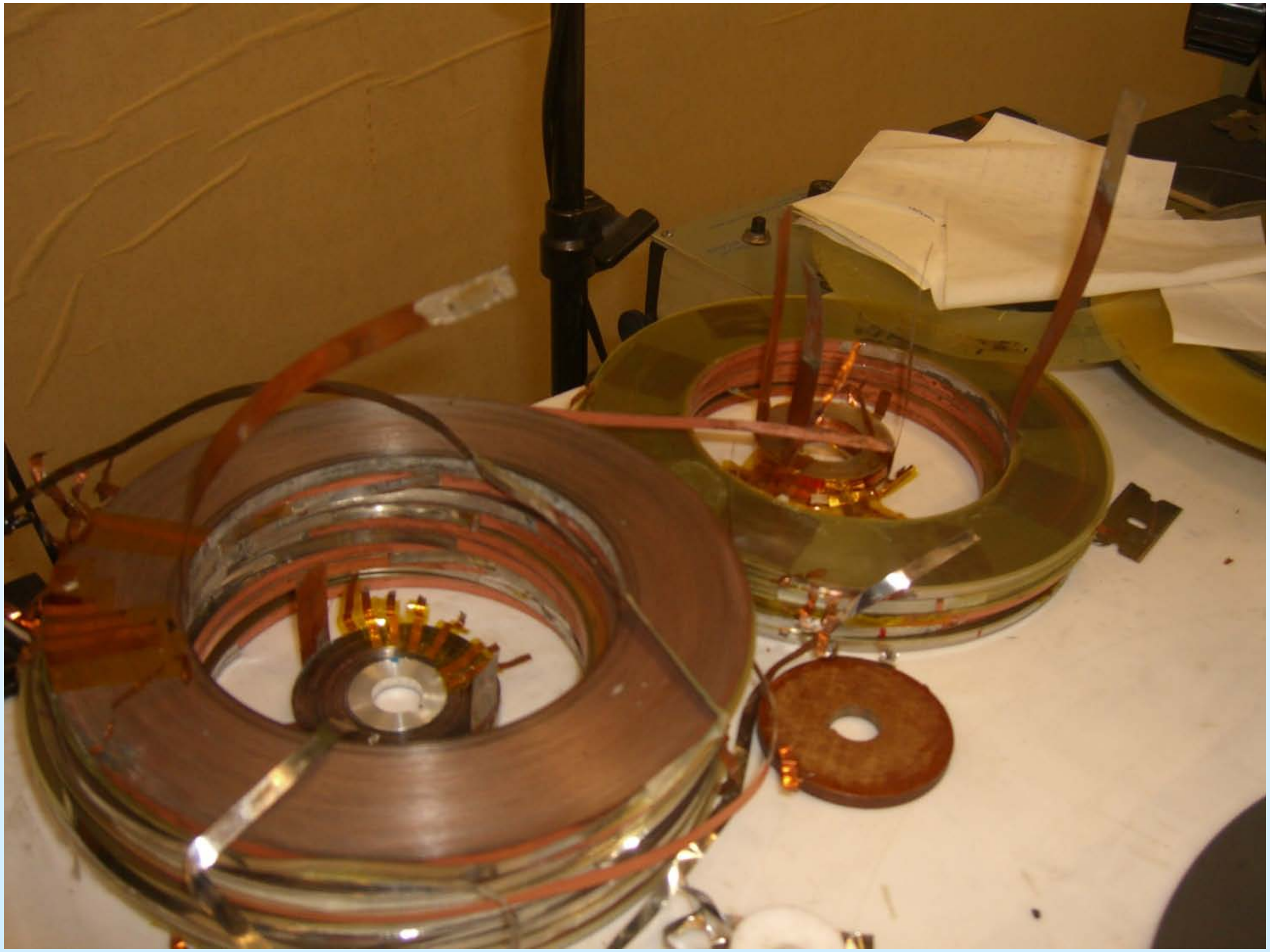
NI FPGA based Quench Detector

NI PXIe based Data Logger

NI PXI based Data Logger

NI FPGA based Quench Detector

Quench Studies in HTS Coils



Carryout various quench related studies in single pancake, double pancake and bi-filar coils.

In these studies coil can be run to beyond safe value (and possibly get destroyed) to find out what the limit is

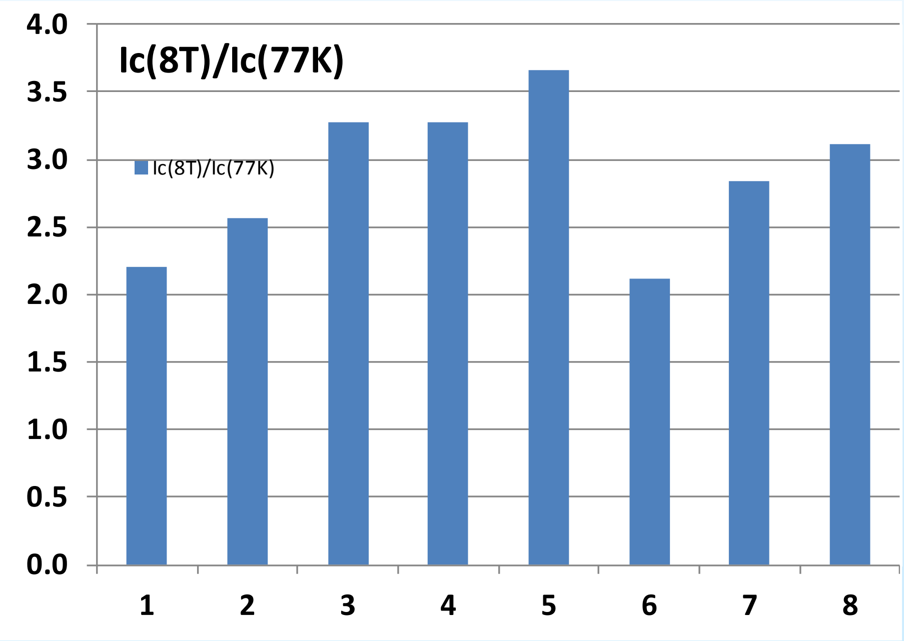
4 K in-field measurement of HTS Tape

- HTS vendor typically measure performance at 77 K, self-field
- We find a large variation in scaling between 77 K and 4K, in field
- We need to monitor it and know this scaling for the conductor used in making magnet

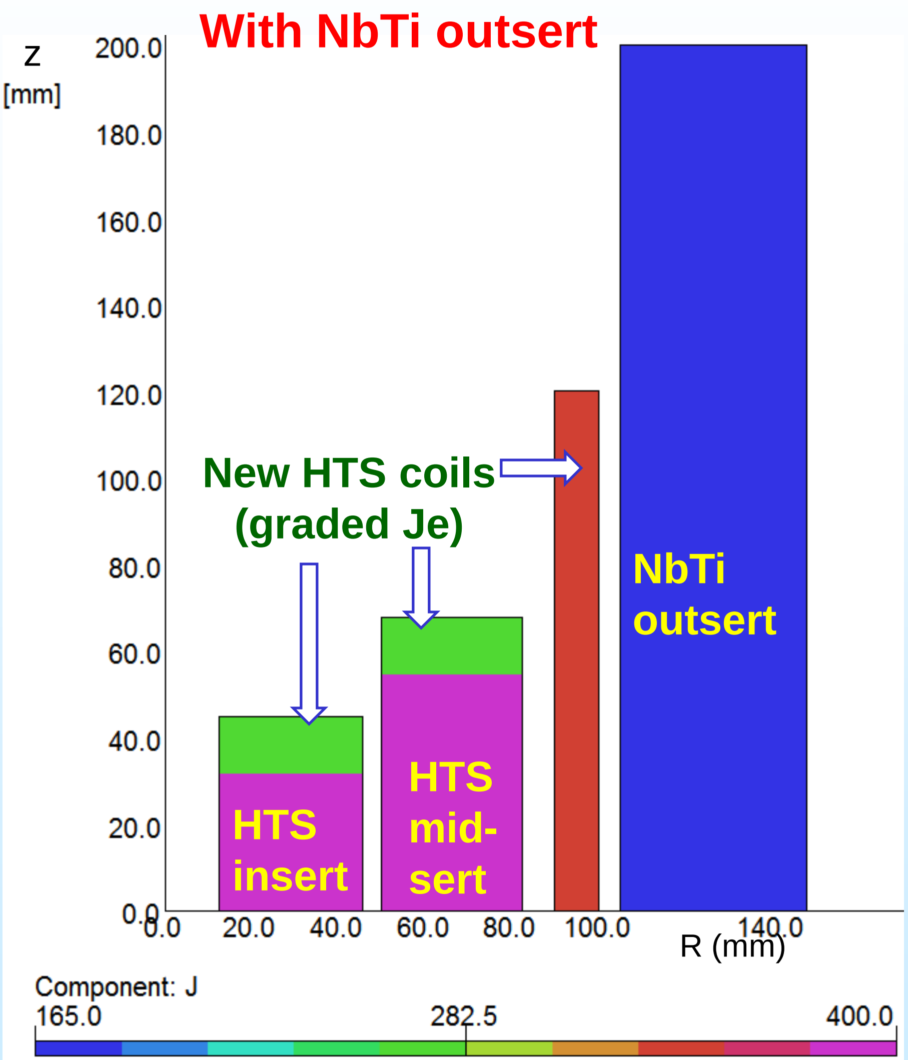
(See more during the tour of facilities)

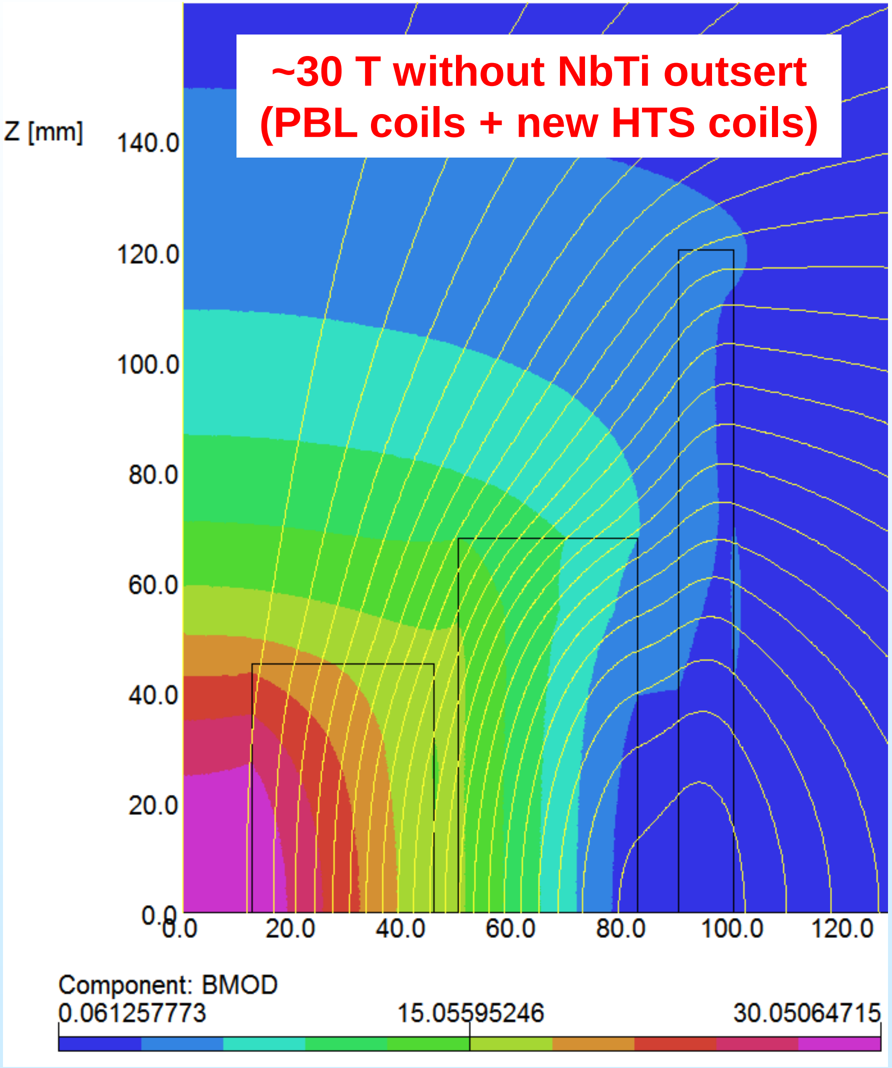
For measuring performance in field parallel

Measured field perpendicular scaling (Ghosh)



Phase 1a (more HTS coils)





HTS J_e higher by 6%

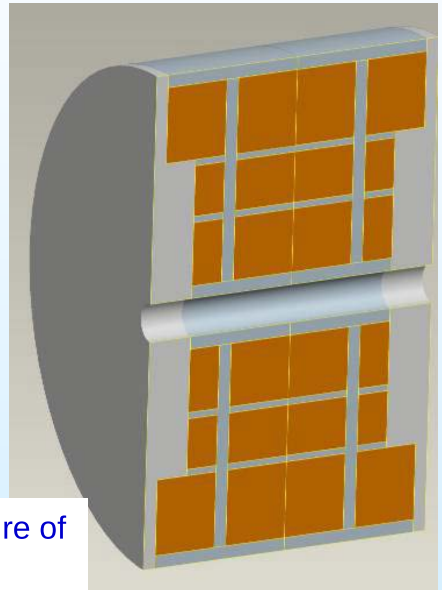
Other Significant Programs at BNL on High Field HTS Solenoids

Superconducting Magnetic Energy Storage (SMES)

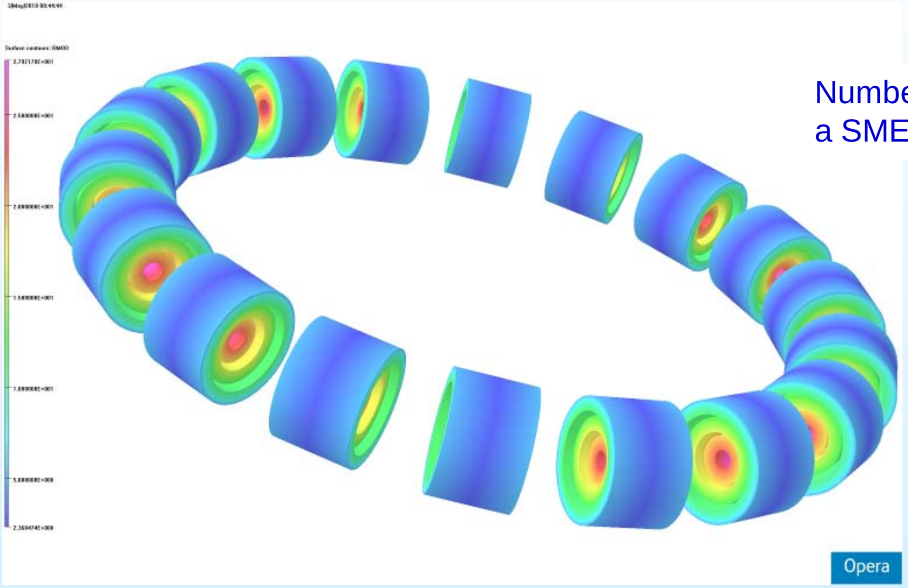
High field, large aperture, HTS solenoid with ambitious targets:

Key Target Parameters: 25 T, 100 mm, 2.5 MJ, 12 mm YBCO

Figures from the original proposal (current version is different)



Basic structure of a single Unit



Number of units in a SMES system

Participants: ABB, USA (Lead), SuperPower (Schenectady and Houston), and BNL (Material Science and Magnet Division)

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

Many challenges still remain but so far we have been getting good test results.

Leverage and Synergy (?) with Other Future HTS Programs

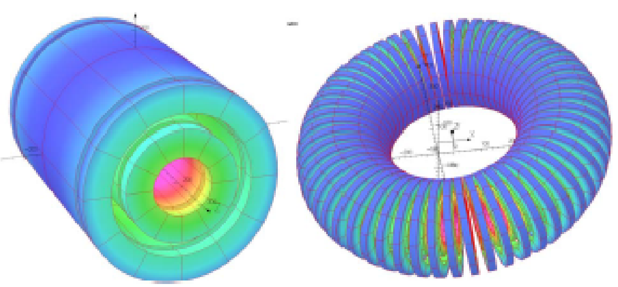
Slide Presented by D. Hazelton of SuperPower @ ISS2012

SuperPower Inc. A Furukawa Company

Army Research Lab – SMES for Micro-Grid

SuperPower Inc. A Furukawa Company — BROOKHAVEN NATIONAL LABORATORY — m tech Laboratories — UNIVERSITY of HOUSTON

- Funding: US Army Research Laboratory $4.2 M of $7M funded to date
- Project timeline: 3 yrs., 2012 - 2015
- Partners:
  - **SuperPower Inc**: project lead, 2G HTS wire, coil development
  - **Brookhaven National Lab**: SMES coil
  - **MTech Labs:** power electronics
  - **University of Houston**, TcSUH: low ac loss material development



- Objective: Build upon the developments achieved in the ARPA E-SMES project with HTS superconductors and adapt those developments to the Army's tactical Microgrid application (lower voltage).
  - Model, design and fabricate a 2.5MJ class tactical Microgrid SMES
  - Modify 2G HTS MJ ARPA E-SMES coil to meet the tactical Microgrid requirements
  - Develop robust quench protection and switching components
  - Investigate methods to reduce ac losses through superconductor tape design
- Relevance:
  - High power and high energy storage in a compact device enables a power solution for remote areas.
  - Build on ARPA E investment in SMES technology to provide a practical application in real world environments.

SA-21 ISS2012 – Tokyo, Japan – December 4, 2012 14

The plan is to apply technology developed for ARPA-E SMES, to a project for Army Research Lab.

However, the geometry and operating temperatures may become different.

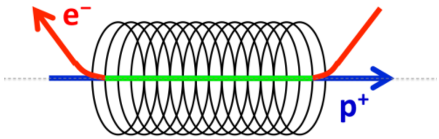
That would reduce synergy with MAP but a general support is helpful.

Summary and Discussion

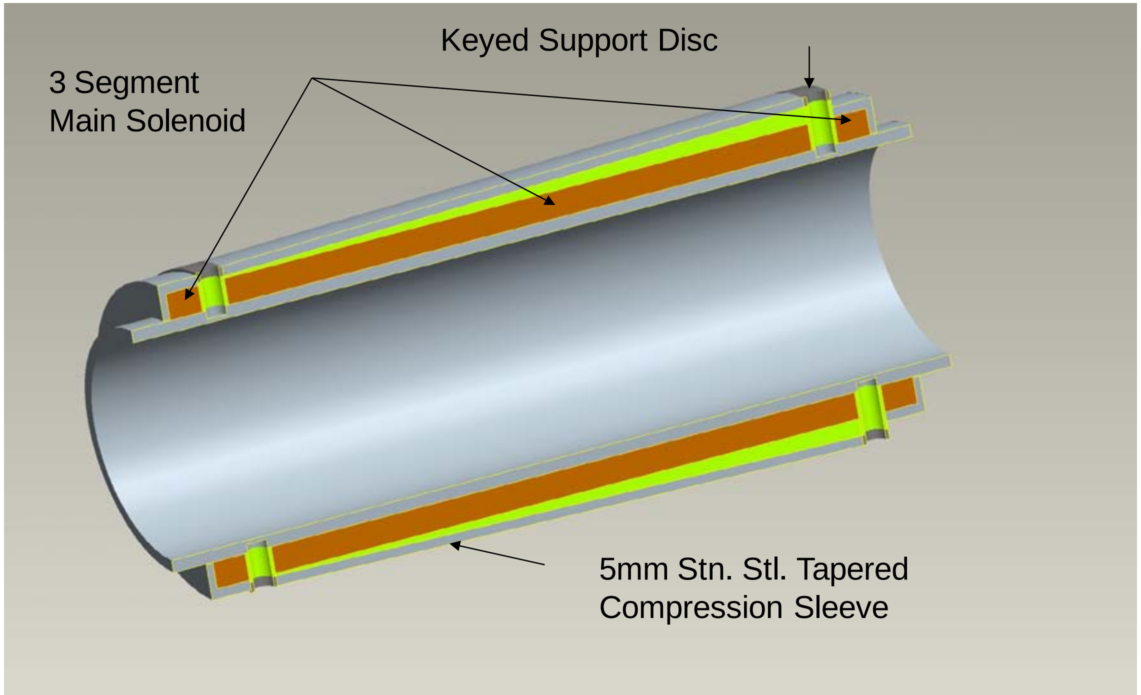
- **Task I (continuing from previous years)**
  - Complete test of HTS 10+T, 100 mm midsert (SBIR funded)
  - Develop quench protection hardware to protect this coil during 4 K test (some hardware module provided by PBL, and part of tech labor provided by MAP)
- **Task II (expected from 100k$ FY13 funding from MAP)**
  - Replace 25 mm insert pancakes (labor from MAP, conductor from SuperPower)
  - Combine insert and midsert to demonstrate >20 T (up to 25 T?) HTS solenoid
- **Task III (Phase I with estimated funding of $400k in FY14)**
  - Design, build and test NbTi outsert (design and construction of NbTi solenoid is leveraged by successful test and existing infrastructure of e-lens solenoid for RHIC).
- **Task IV (Phase II with longer term funding from MAP)**
  - Demonstration of ~30 T solenoid when HTS insert and midsert are combined with NbTi
  - Build additional HTS coils (this can be done in parallel to Phase I or can be Phase 1a)
  - Demonstration of ~35 T superconducting solenoid with additional HTS coils
  - A more complete engineering design with required analysis
  - Quench protection R&D and examination of various options
  - Ongoing conductor specification with existing magnet

Extra Slides

Radial Force Restraint

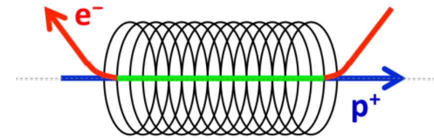


- Outward pressure (hoop stress) from 24 MN Lorentz forces.
- Radial forces can be restrained by 6 mm of material stressed (hoop) to 40,500 psi with coil energized.
- Resulting stress in support tube (pressure vessel) is 17,000 psi. Required strain for S.S. tube is 0.014.
- S.S. Tube heated to 80 degree C will give the required interference.
- Tube has 10 mm radial taper.

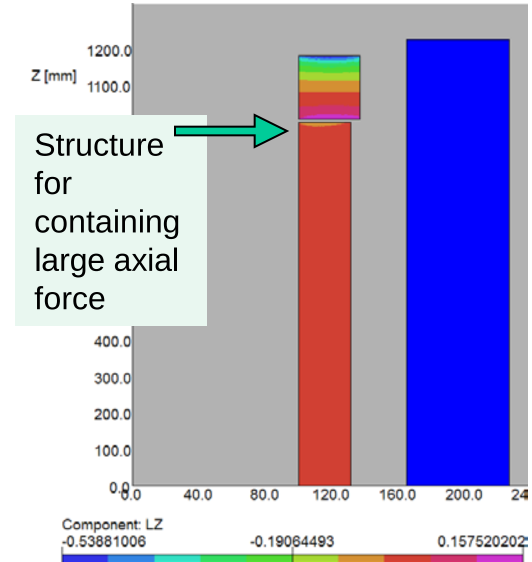


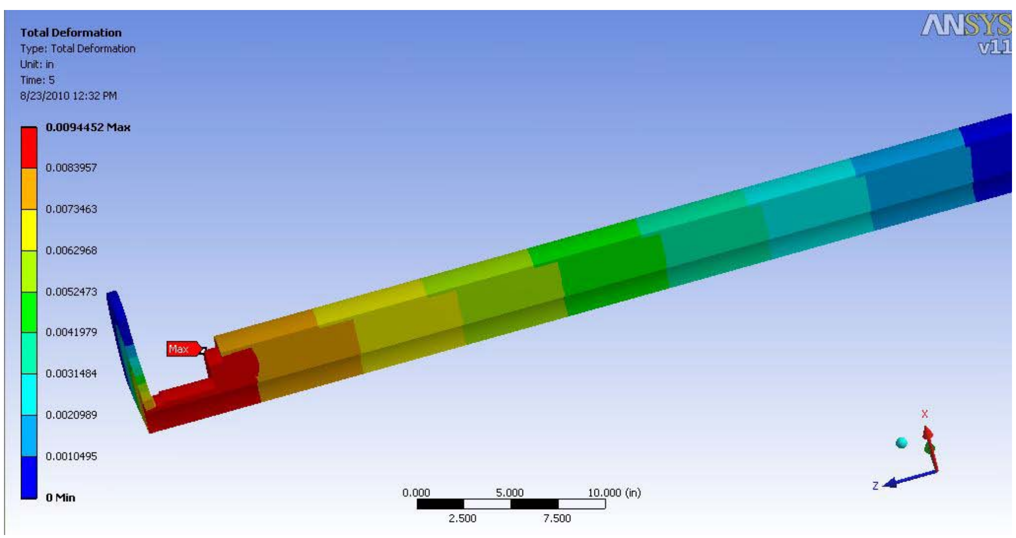
Courtesy: A. Marone

Axial force containment

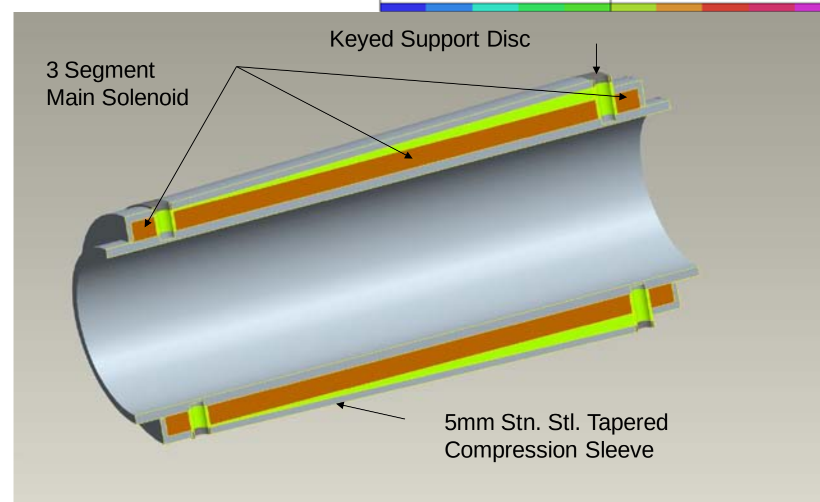


- Insert structure towards the end of the coil to contain forces
- Coil is wound continuously through the end structure to keep axial forces contained throughout (during quench).
- The axial forces exerted by the outer solenoid sections are transferred around the center section.
- The keyed support discs transfer the load to the support tube and the compression sleeve.

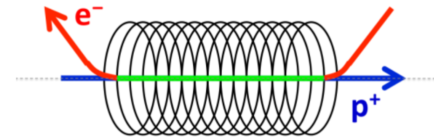




Courtesy: A. Marone



Magnet Mechanical Design Overview



17 separate circuits / max. current:

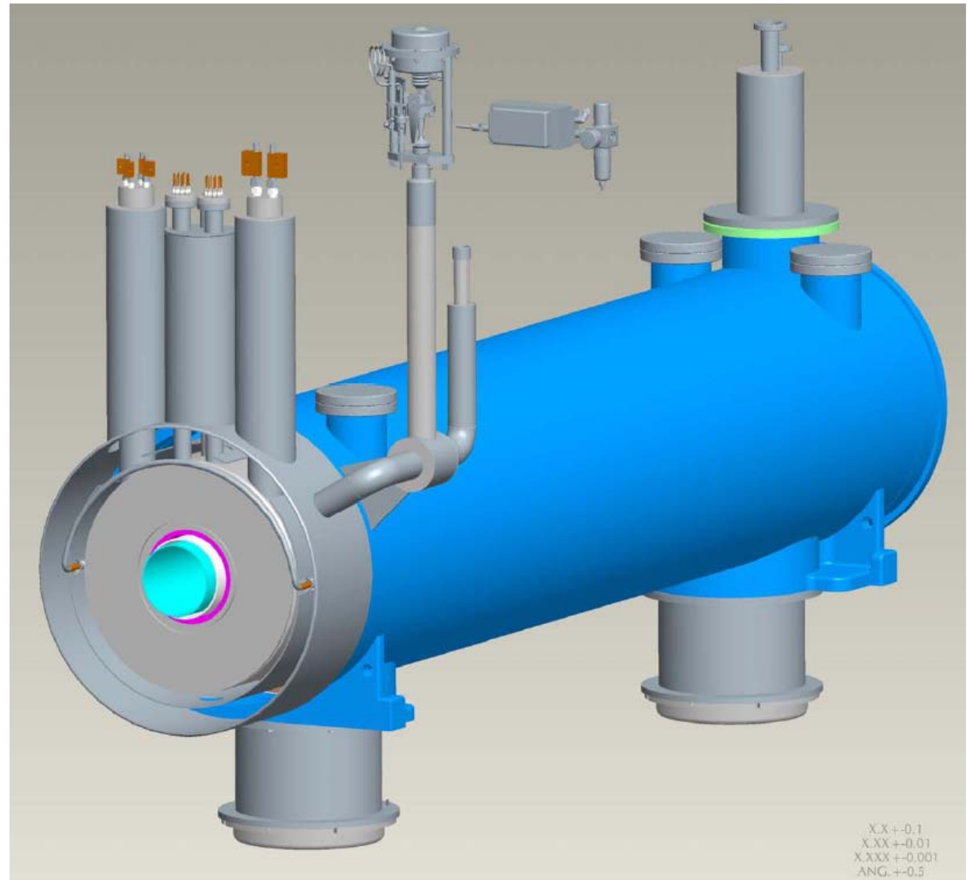
- 1 main solenoid / 460A
- 2 fringe field solenoids / 47A
- 2 anti-fringe field solenoids / 33A
- 5 0.5m vertical correctors / 26A
- 5 0.5m horizontal correctors / 26A
- 1 2.5m vertical corrector / 34A
- 1 2.5m horizontal corrector / 34A

Quench protection via cold diodes

Helium vessel cooled by liquid bath from RHIC supply

Outer heat shield actively cooled from 4K boil-off, inner shield conductively cooled

RHIC support posts / cryostat



Courtesy: M. Anerella