Muon Collider Magnet Development in USA

Ramesh Gupta
Brookhaven National Laboratory
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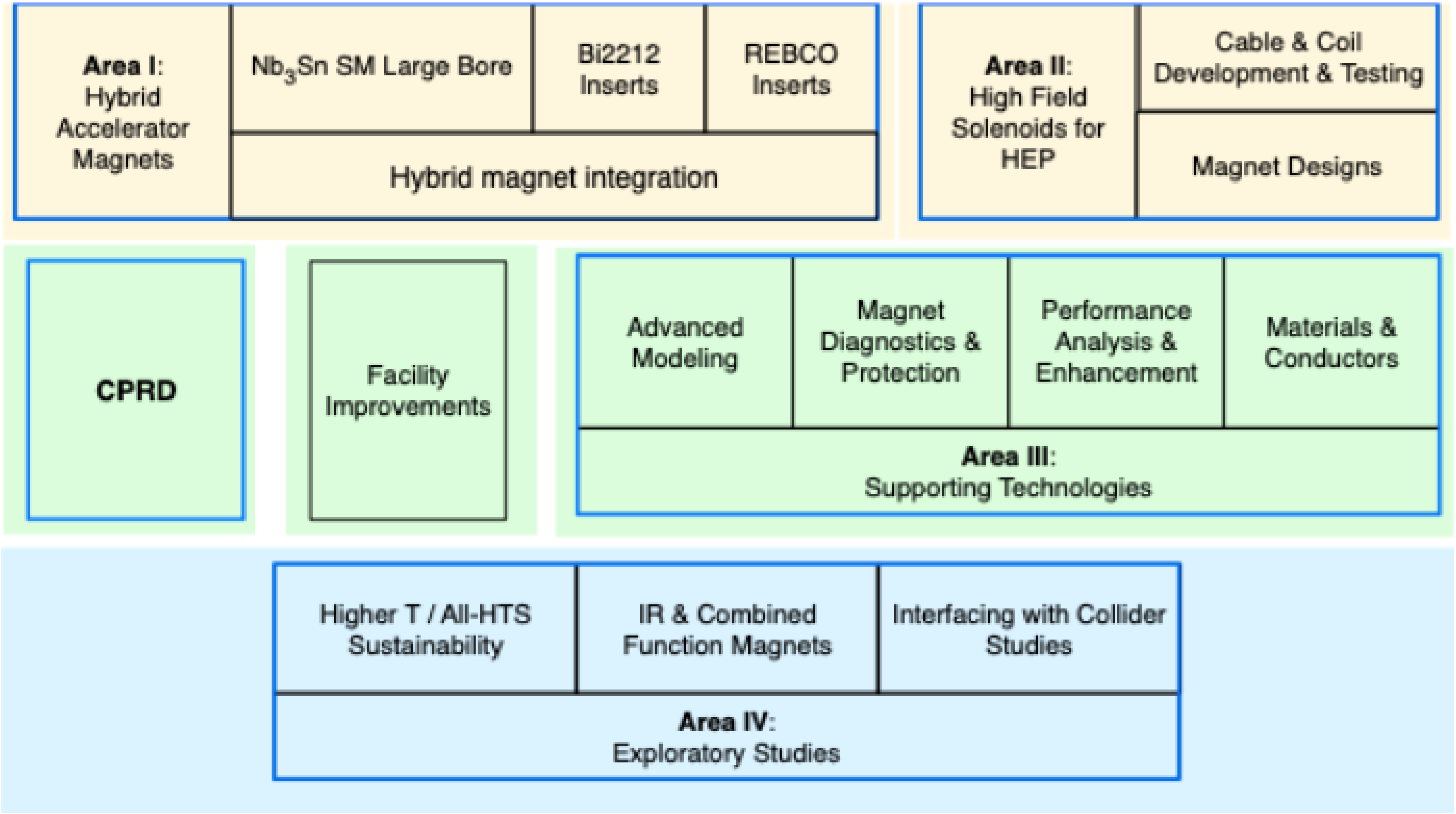
Introduction

- There has been a significant magnet R&D program in USA across various institutions (national labs, universities, and small companies via SBIR/STTR grants) that was directly focused on the specific needs of the muon collider magnets before the interruption.
- Though a formal well defined magnet R&D program on muon colliders has not restarted yet, there are significant ongoing programs in US that are strongly related to the needs of the muon collider.
- This presentation will be a very rapid tour to give an idea of wide-ranging magnet R&D in US (both past and/or just started) related to muon colliders. It contains slides from various institutions. As such, this presentation is not intended to reflect any programmatic view.

Areas of Interest to US Magnet Development Program (USMDP)

Next generation magnet R&D (most topics should help muon collider)



HTS and the Muon Collider

- High temperature superconductors (HTS), though still R&D conductors, have come a long way. An unprecedented funding from the fusion industries has made a major impact. **We must take advantage of that.**
- Like in fusion, HTS can make a significant impact on the design and performance of the muon colliders. This is due to their unique ability to (a) withstand high energy loads, (b) operate at high temperatures (20 K or more instead of 2-4 K), and (c) their ability to generate high fields.
- Single-tape based coils built in past pose many issues. We must learn to take advantage of the HTS cables such as those being developed by fusion industries. The conventional magnet designs, however, are not always compatible with them. We should look at the alternate designs.

Summarizing magnet needs for potential future colliders

Courtesy: Steve Gourlay

- **In general . . .**
  - High field dipoles– up to 17T (and perhaps 20 – 24T)
  - Large aperture interaction region quadrupoles
  - Sustainability → higher operating temperatures
- **Muon Collider (in addition to above)**
  - Large apertures (~ 160mm)
  - (Very) fast ramping magnets
  - Large aperture, high field solenoids (> 30T)
  - Operation in high radiation, high heat load environment

Open Midplane Dipole may significantly reduce aperture

→ Need to ramp up R&D NOW!

This presentation will summarize* the major work performed in previous years or work underway now, related to muon colliders at various US institutions (in alphabetic order)

*Not a complete list; apologies for omissions.

Muon Collider Magnet R&D at BNL

(includes R&D performed with PBL under SBIR/STTR)

- HTS solenoids (also a recent BNL LDRD)
- Radiation and energy depositions studies
- Dipole design concepts for muon colliders

BNL has built and tested over 150 HTS coils using over 50 km equivalent of 4 mm HTS tape

Previous Programs at BNL that Benefits Muon Collider R&D

- **SBIR/STTR Awards to Particle Beam Lasers, Inc. (PBL):**

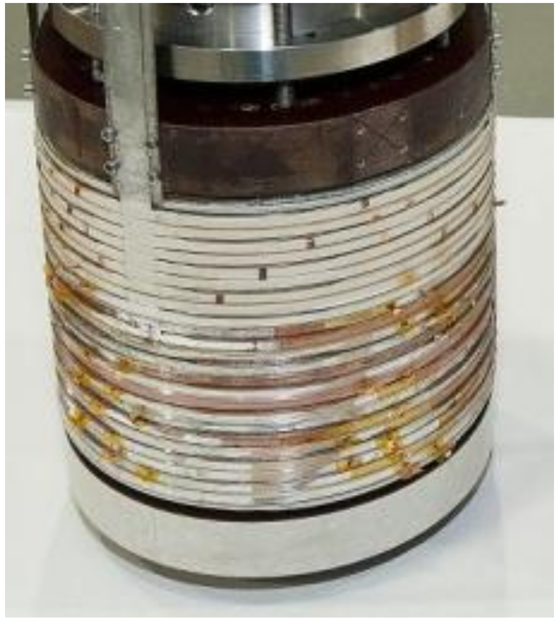
1. Overpass/Underpass Coil Design for High-Field Dipoles. Phase I
2. Quench Protection for a Neutron Scattering Magnet. Phase I
3. HTS Solenoid for Neutron Scattering. Phase I
4. Dipole Magnet with Elliptical and Rectangular Shielding for a Muon Collider. Phase I
5. Magnet Coil Designs Using YBCO High Temperature Superconductor (HTS). Phase I
6. Innovative Design of a High Current Density Nb_3Sn Outer Coil for a Muon Cooling Experiment. Ph I
7. Study of a Final Cooling Scheme for a Muon Collider Utilizing High Field Solenoids: Cooling Simulations and Design, Fabrication and Testing of Coils. Phase II
8. Study of a Muon Collider Dipole System to Reduce Detector Background and Heating. Phase I
9. Design of a Demonstration of Magnetic Insulation & Study of its Application to Ionization Cooling. Ph I
10. Study of a Final Cooling Scheme for a Muon Collider Utilizing High Field Solenoids. Phase I
11. A 6-D Muon Cooling System Using Achromat Bends and the Design, Fabrication and Test of a Prototype High Temperature (HTS) Solenoid for the System. Phase II

- **HTS solenoid (MI - Metal Insulation) for SMES (arpa-e)**
- **HTS solenoid (NI - No insulations) for Axion search (IBS, Korea)**
- **HTS coils plus radiation and energy deposition studies (FRIB)**

PBL/BNL HTS 16 Tesla Solenoid (Record in 2012)

(Testing at higher operating temperature is important to muon collider)

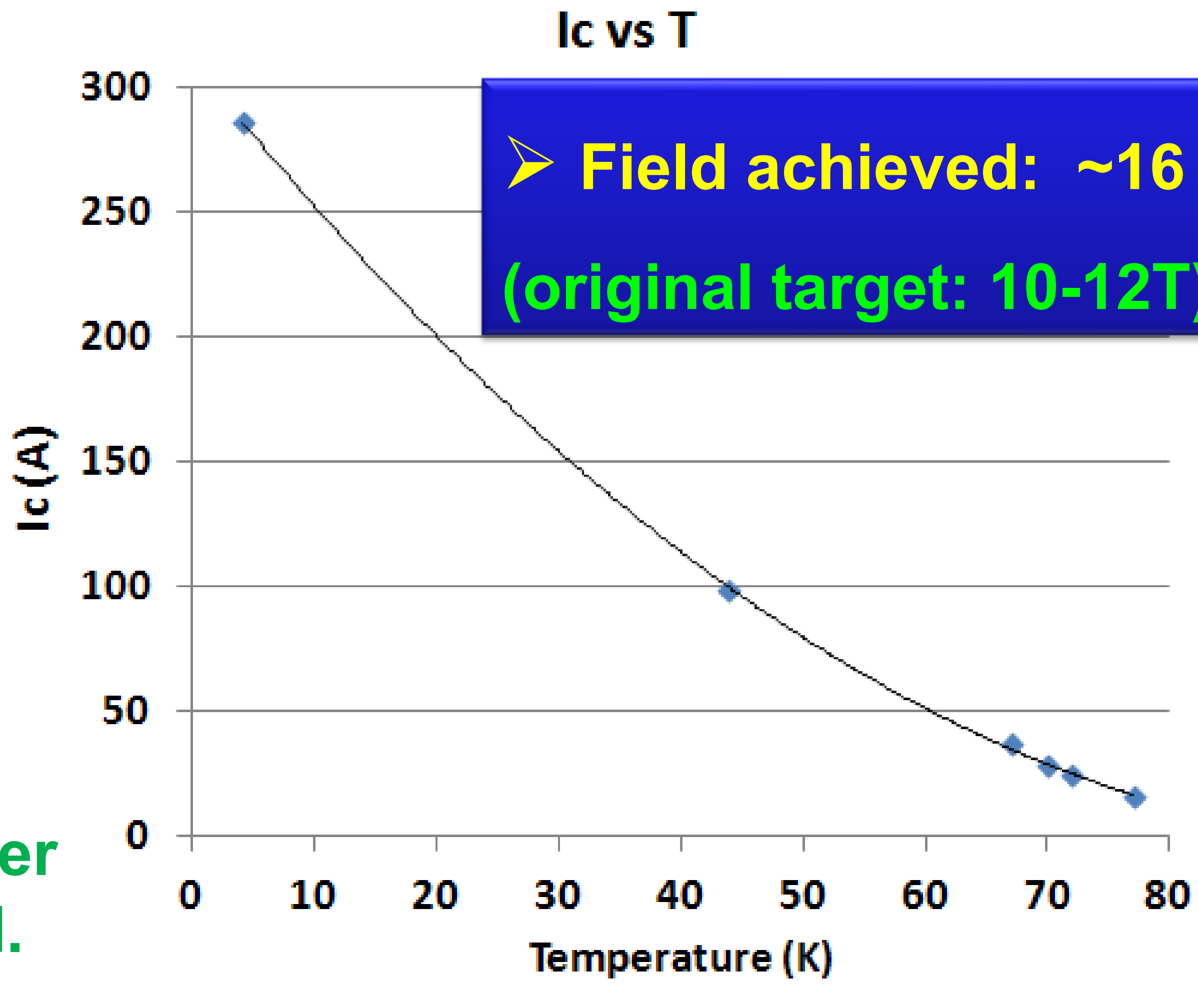
Insert solenoid



Outsert solenoid

- 1st known use of metal insulation in HTS

Task of testing insert & outsert together for trying ~25 T couldn't be completed. Coils are still at hand for further R&D.

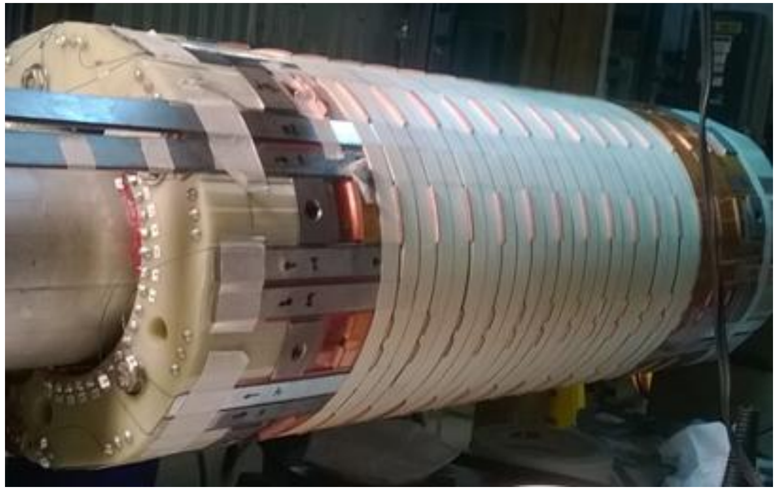


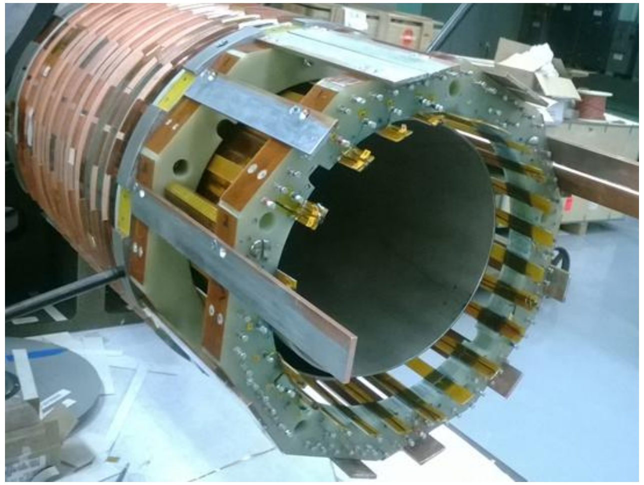
- **Field achieved: ~16 T**

(original target: 10-12T)

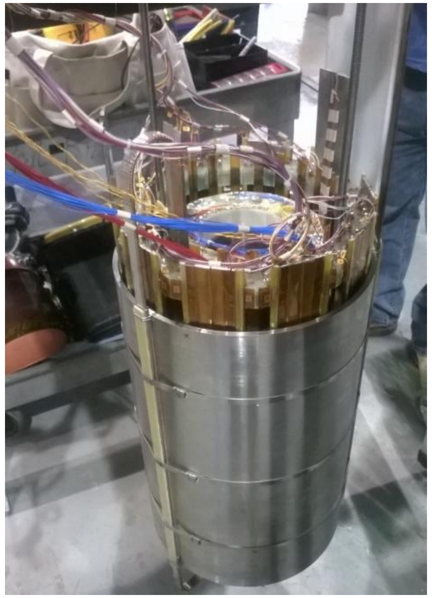
Overall Current Density (J_o) in the coil: >500 A/mm^2 @16 T

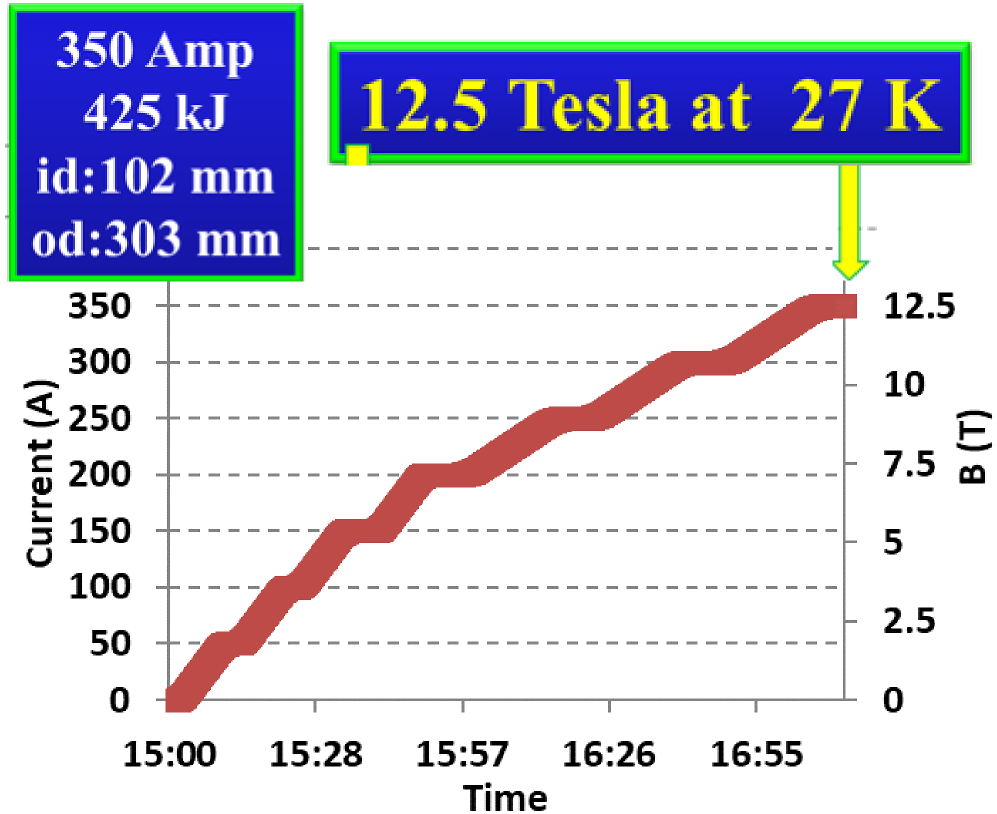
High Field 100 mm HTS Solenoid for SMES (funded by ARPA-E)





Record field/energy at 10 K or higher
(referenced in early fusion proposals)





*4 K test couldn't be carried out because of the issues with the leads placed at the coil od

Coils should still be available to try 25 T.

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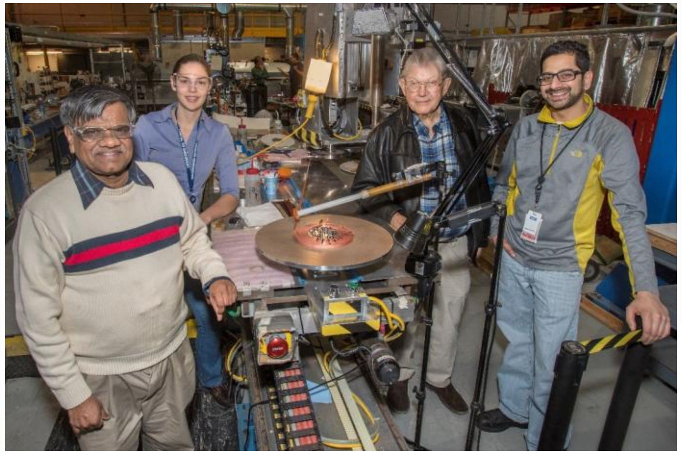
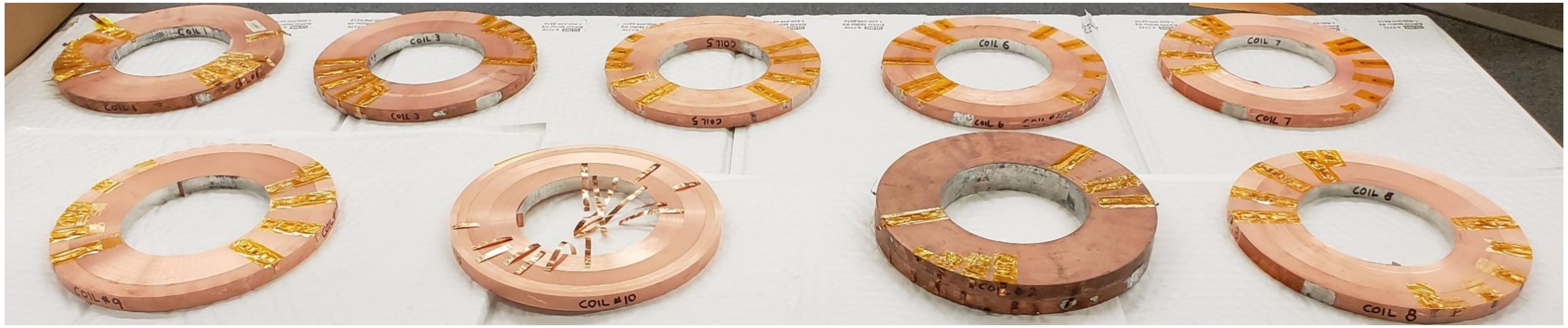
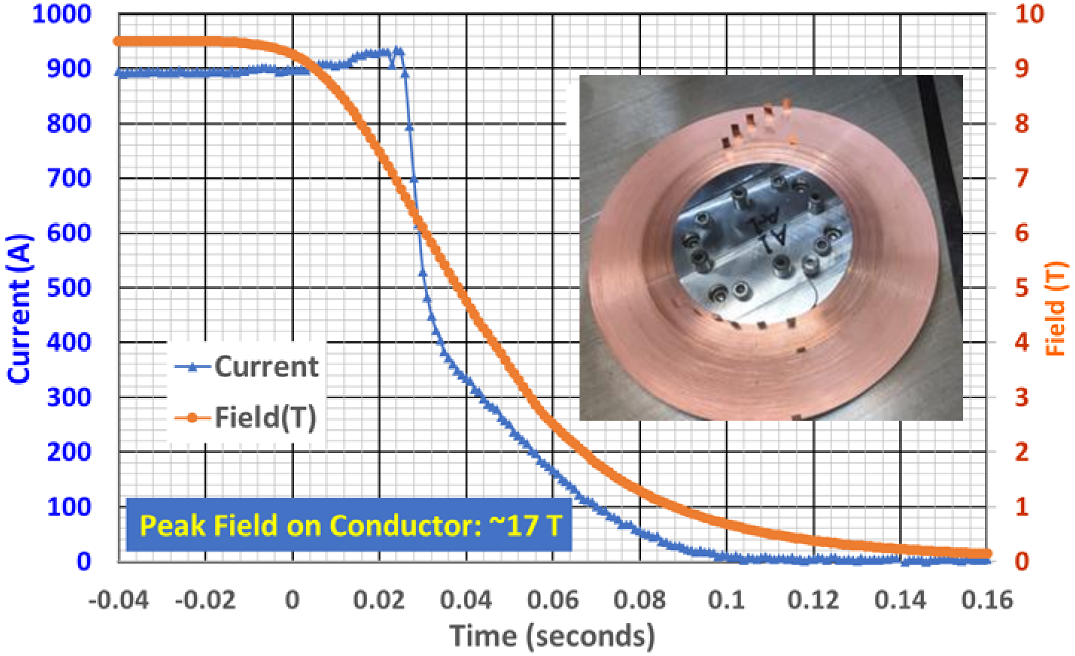
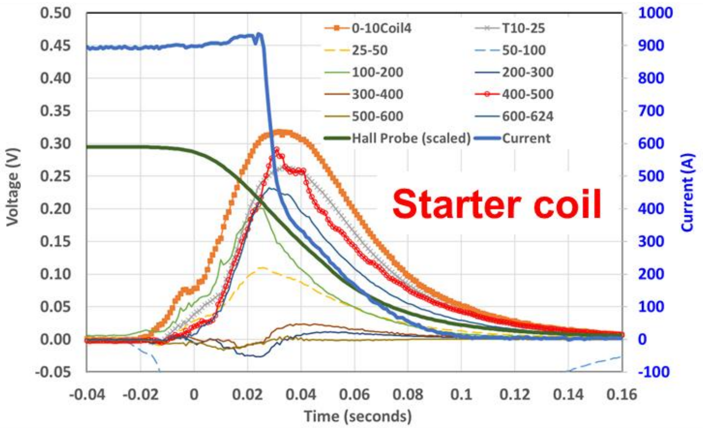
No-Insulation HTS Solenoid for Axion Search (IBS, Korea)

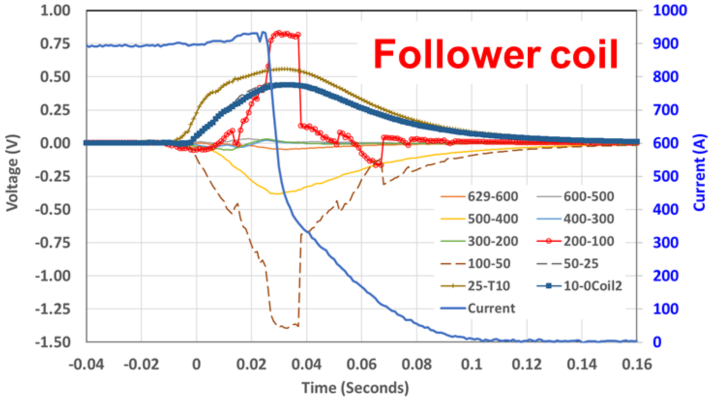
No-insulation coil winding for IBS (id 105 mm, od=200 mm)





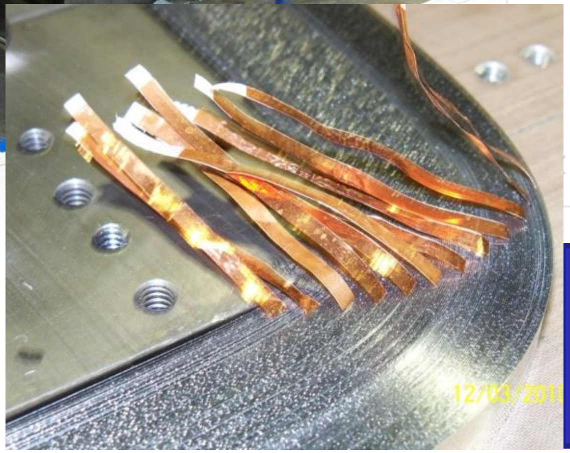


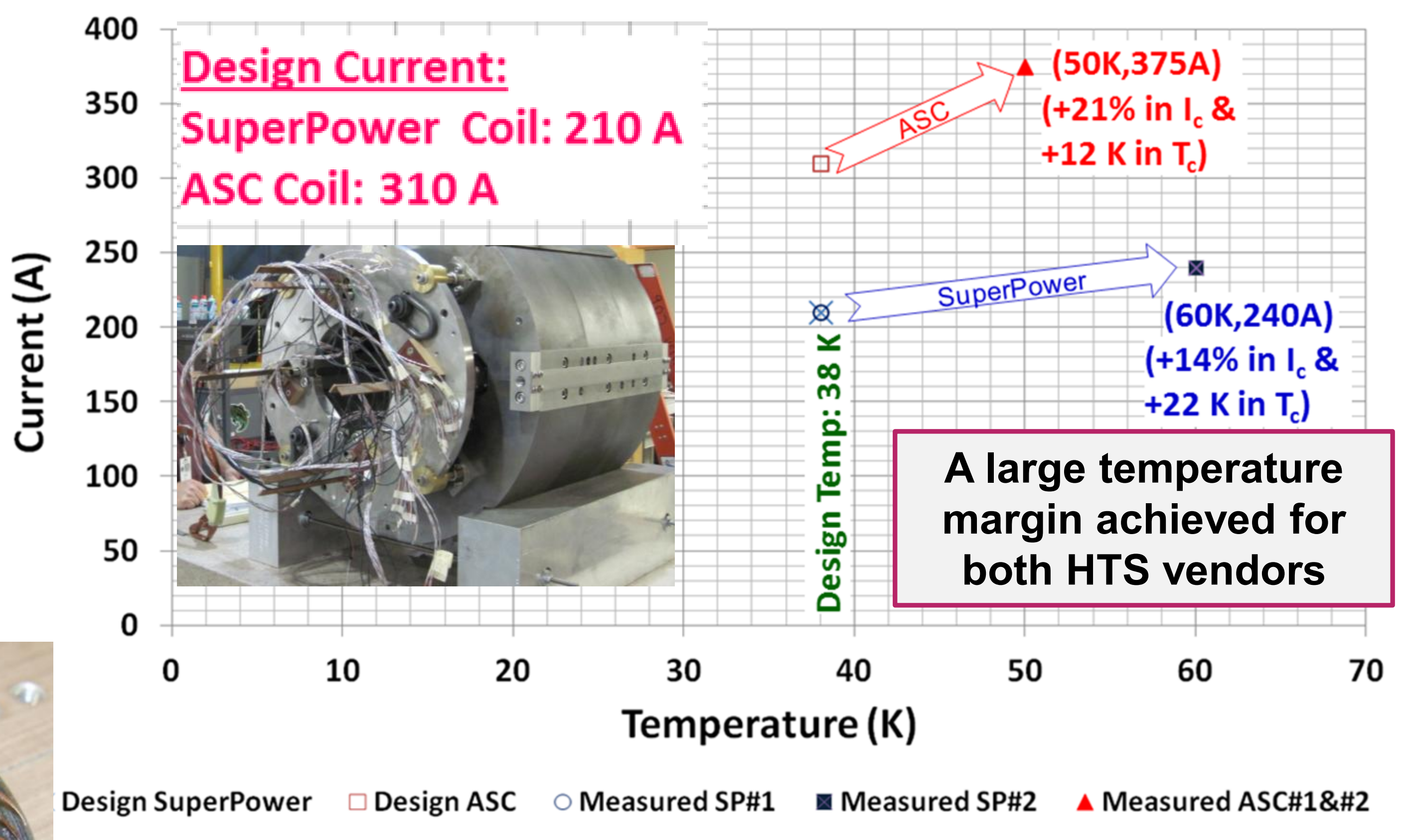




Initial drop in current assigned to copper discs between the HTS coils

Racetrack HTS Coils for FRIB Quads (large heat & radiation loads)
(High temperature operation relevant to muon collider)





~3 km of 12 mm wide HTS tape

8 Large HTS coils are available for R&D

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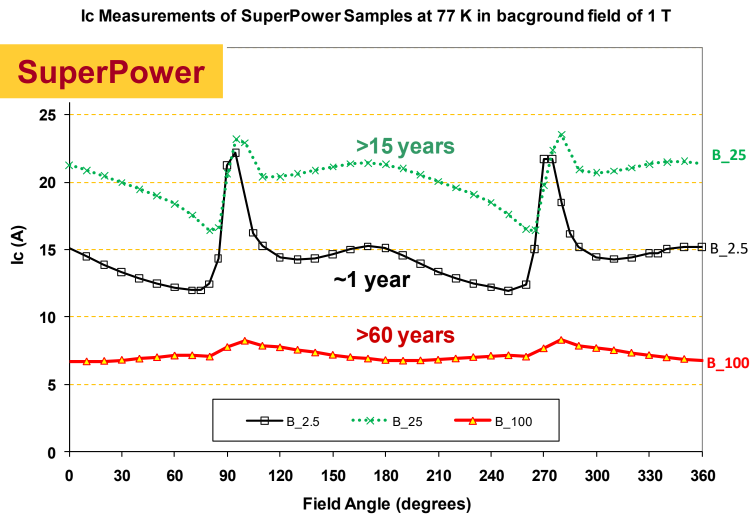
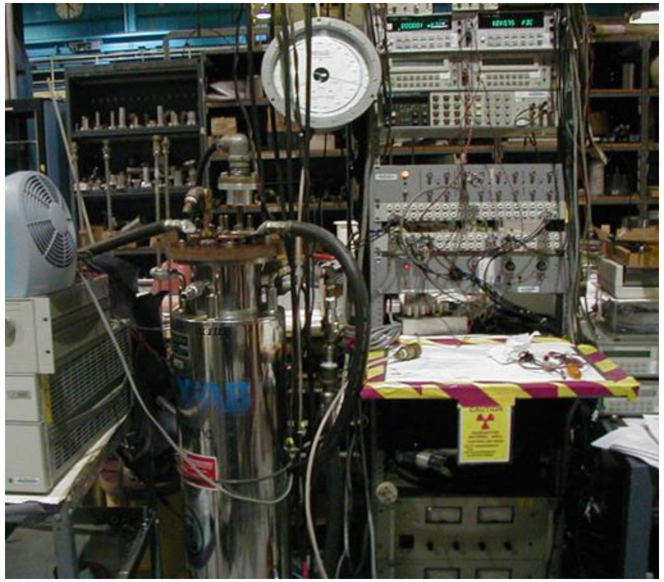
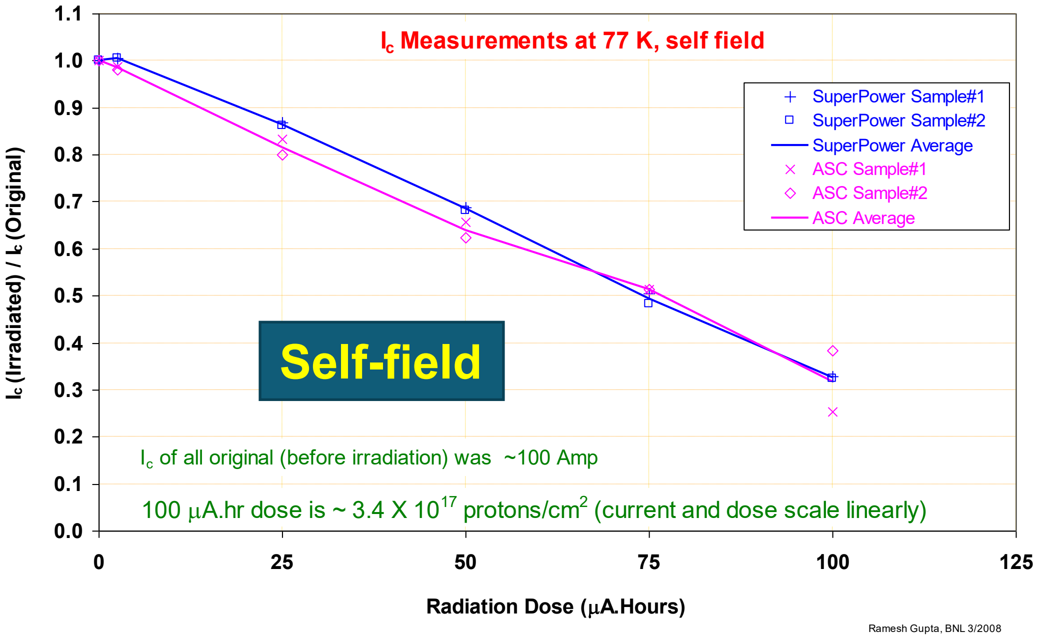
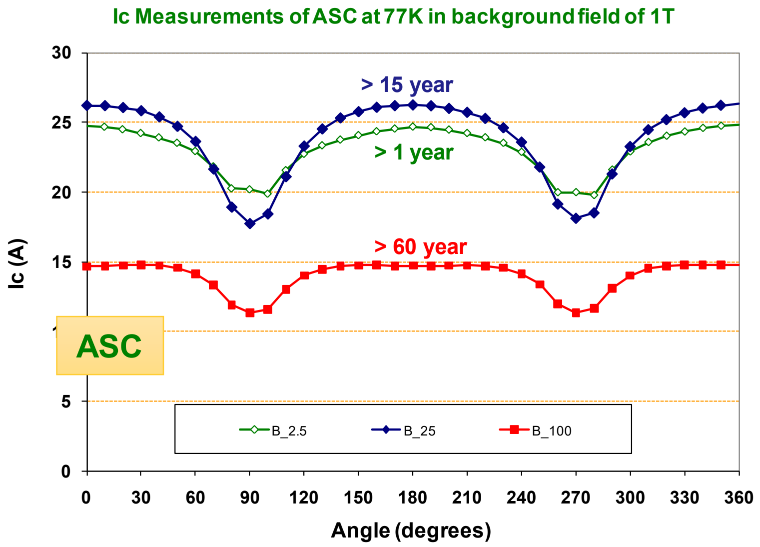
Radiation Damage Studies @BNL in HTS: Relevant to Muon Collider
(measurements @77K in self-field and in 1 T Applied Field)

1 T applied field

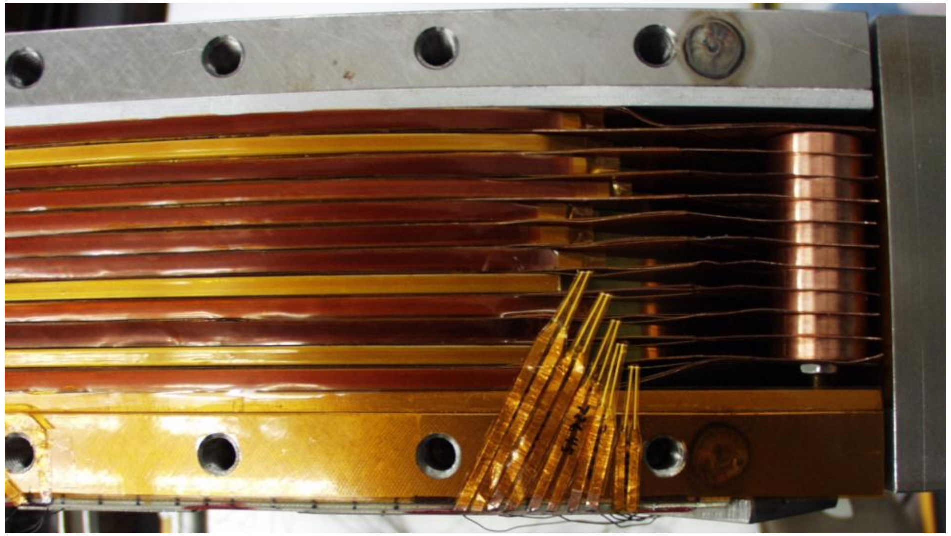






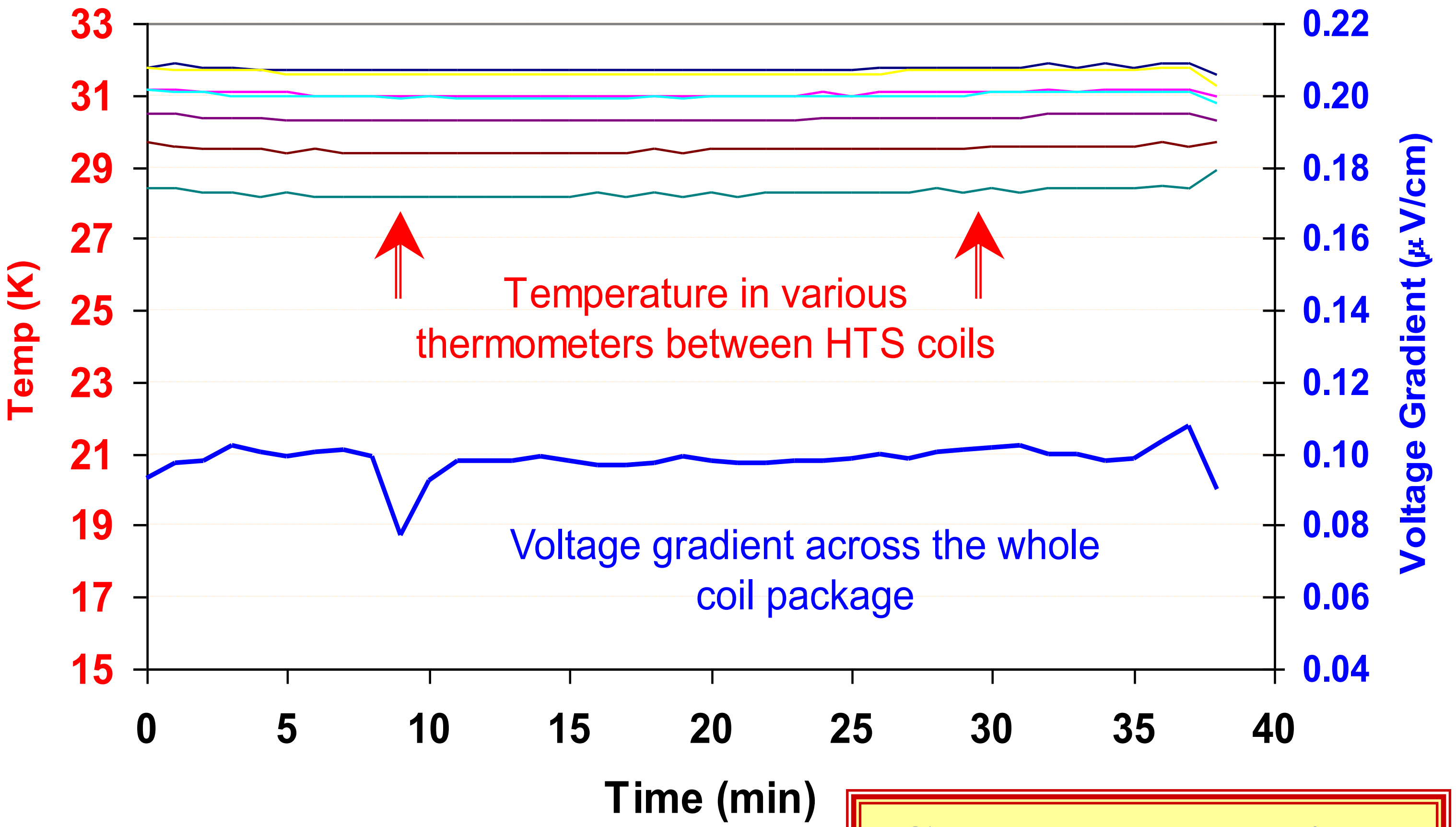


Energy Deposition studies: Relevant to Muon Collider



Stainless steel tape heaters for energy deposition experiments

Magnet operated at ~30 K in a stable fashion with large heat loads (25 W, 5kW/m³) at 140 A



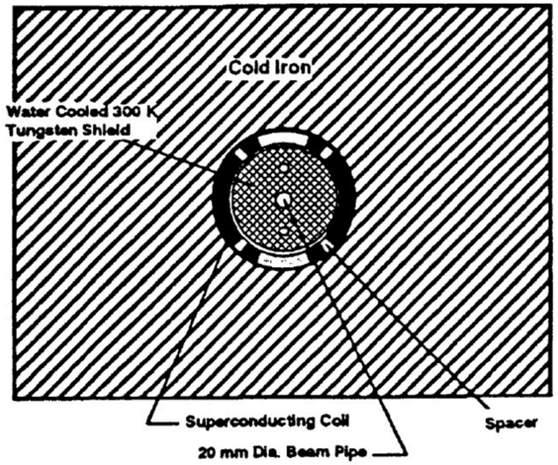
Voltage spikes are related to the noise

Stable operation for ~40 minutes

New Magnet Designs

- Open Midplane Dipole
- OverPass/UnderPass or Cloverleaf

Motivation for the Open Midplane Design (and a true open midplane)

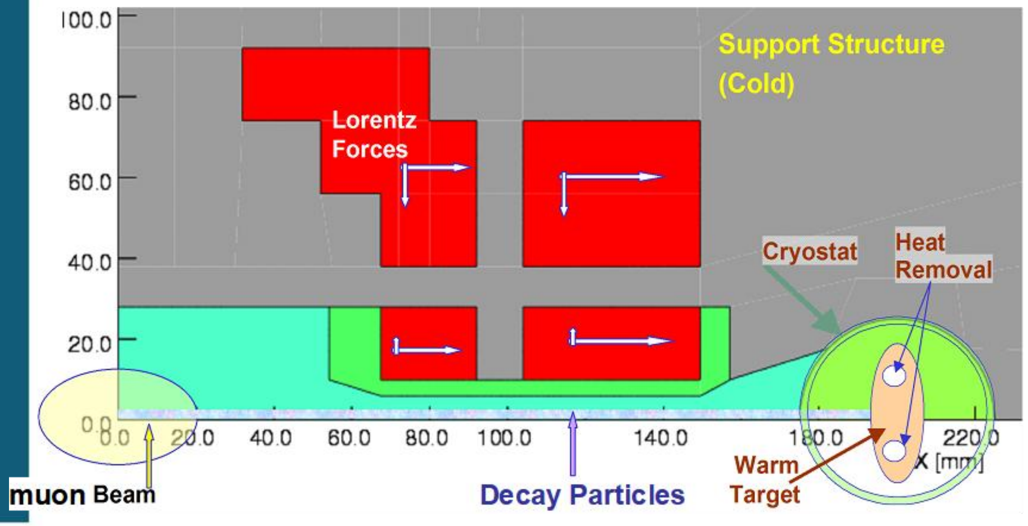


Conventional design with thick Tungsten Liner

•Superconducting coils in a muon collider dipoles will be subjected to a large amount of decay particles (a few kW/m) from short lived muons.

• Conventional proposal to protect the coils has been to use a Tungsten liner. That liner, however, substantially increases the size of the high field magnet.

•Angular distribution of the decay particles is highly anisotropic with a large horizontal peak. The motivation for the open midplane design was to replace superconductor by other material near the x-axis to minimize the direct hit.



A true open midplane dipole

•That avoided a direct hit from primary showers on coils.

•However, the other material created secondary showers, which deposited a substantial amount of energy on the coils. Therefore, those designs didn't work very well.

•In the proposed "true open midplane design", there will be no material at the midplane. Most decay particles will get transported unhindered to a warm absorber (~80 K) sufficiently away from the superconducting coils.

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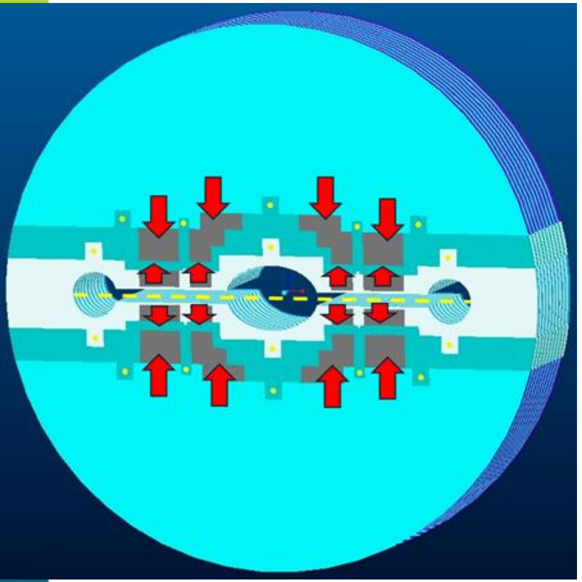
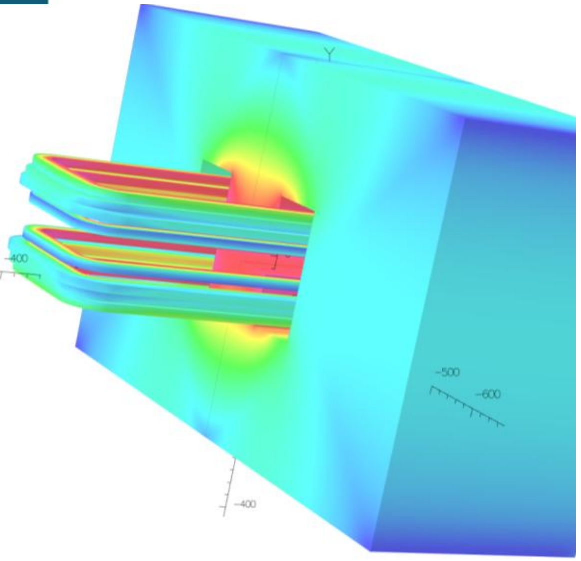
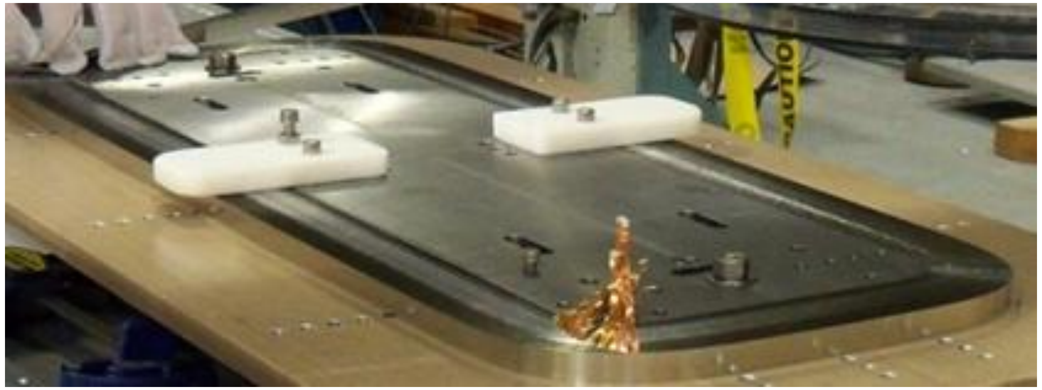
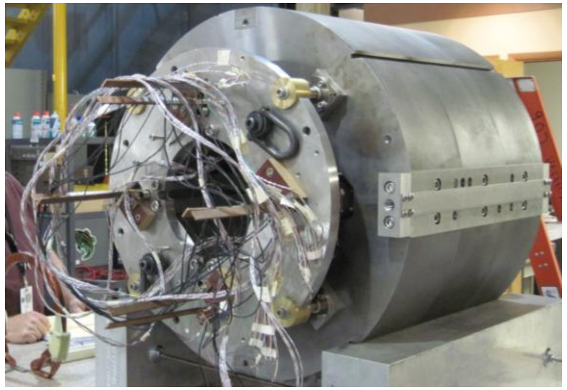
A Possible Demonstration of HTS Open Midplane Dipole





- In a typical dipole design, the accumulated Lorentz forces on coils near midplane are typically, towards the midplane. Since the coils can't hang in the air, this is a major challenge for a magnet design.
- Special open midplane designs were developed during the earlier muon collider program and for LHC "dipole first" optics, where the coils near midplane were made to have forces away from midplane.
- Preliminary mechanical and magnetic analysis for a good field quality were developed with a preliminary engineering design.
- Since the basic design is so different and it must be demonstrated.
- This can be done at a modest cost at 8-10 T field level using the eight large HTS coils, leftover from the FRIB R&D quad program.





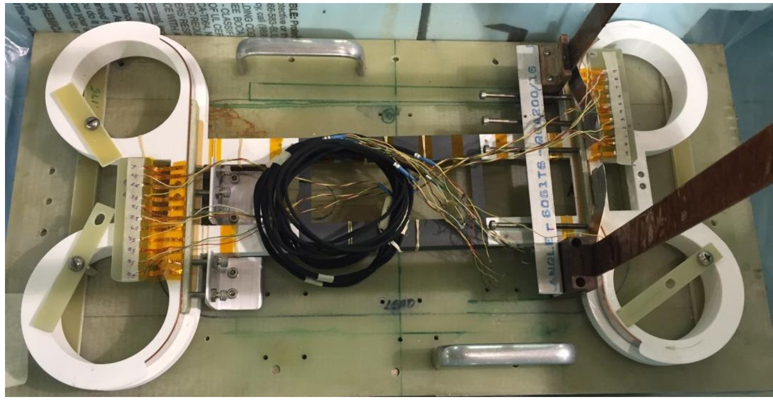
Low-cost PoP test possible at 77 K

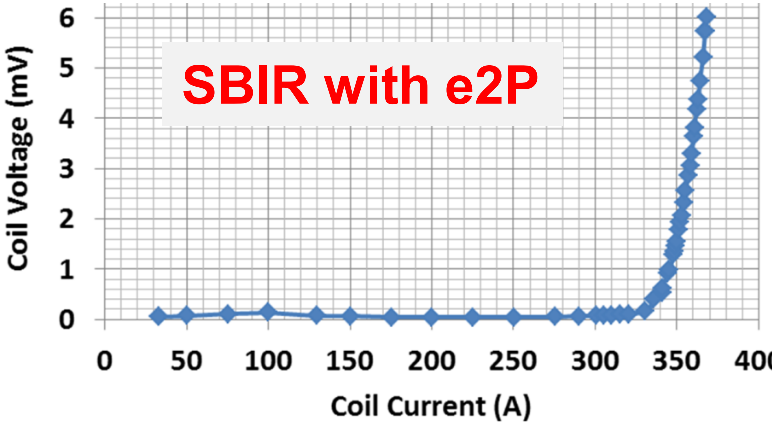
Alternate End Design for HTS or Block Coil Magnets

Conventional (lifted ends)

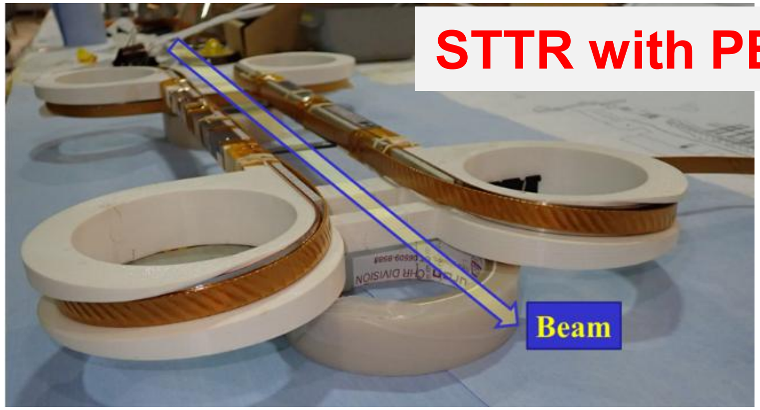
OverPass/UnderPass or cloverleaf

- Most block coil designs or HTS tape/cable designs require long lifted ends to minimize the hardway strain
- Overpass/underpass (aka cloverleaf) overcomes that
- Coils based on that have been built and tested at BNL and at CERN
- Applicable to muon colliders





STTR with PBL



ASC2018

CERN

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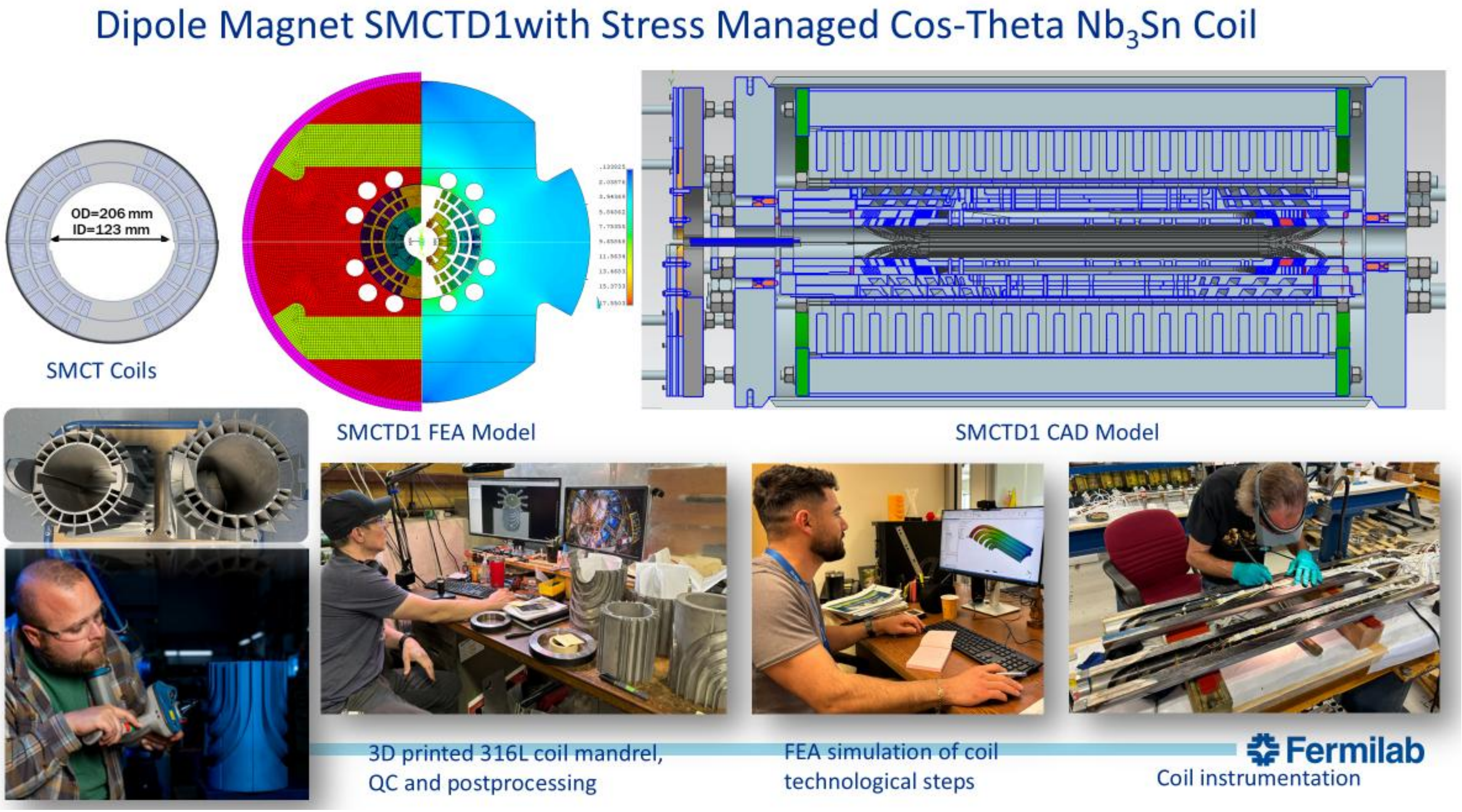
Muon Collider Magnet R&D at Fermilab

R&D at Fermilab on stress- managed high field dipoles

High field, large aperture magnets must deal with large stresses due to Lorentz forces.

Stress Managed Cosine Theta (SMCT)



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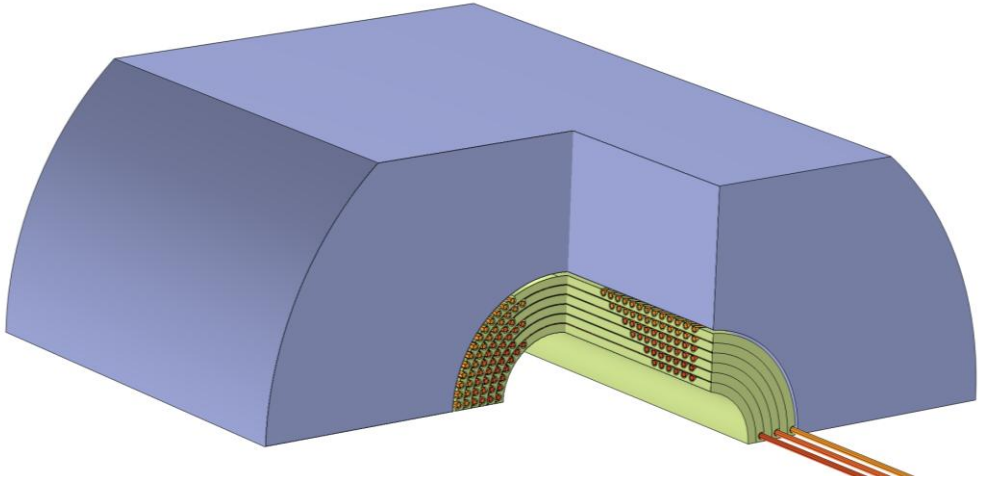
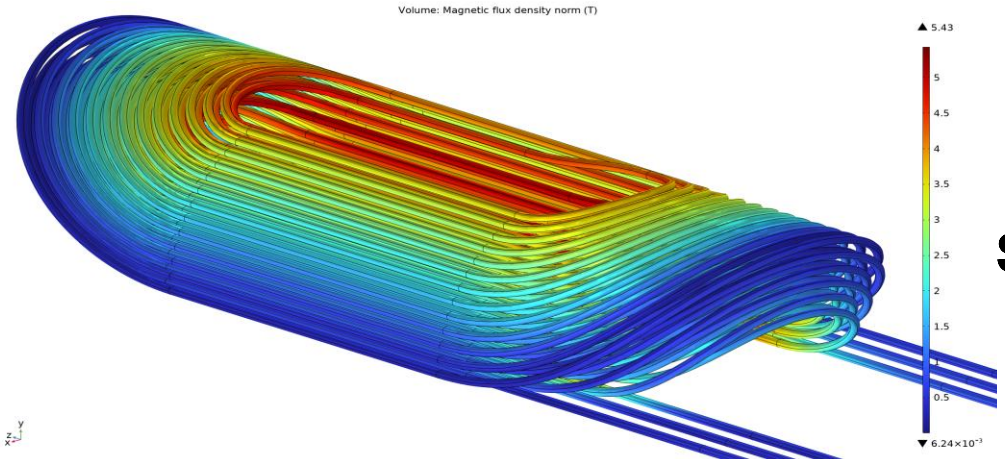
Muon Collider Benefits from HTS Cables (STAR®/CORC®)

R&D at Fermilab on HTS ReBCO round cable in magnets



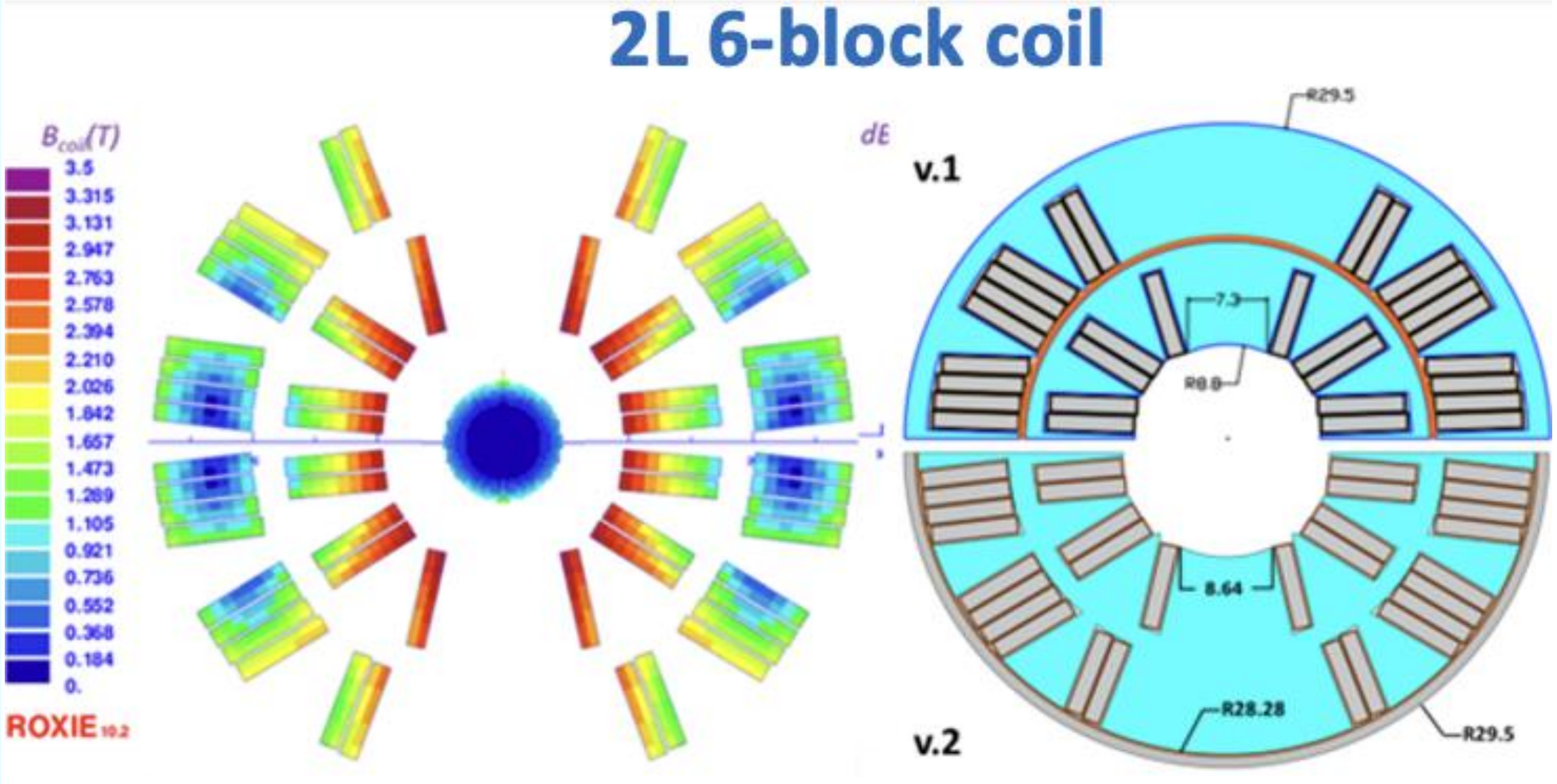


FNAL STTR with Ampeers

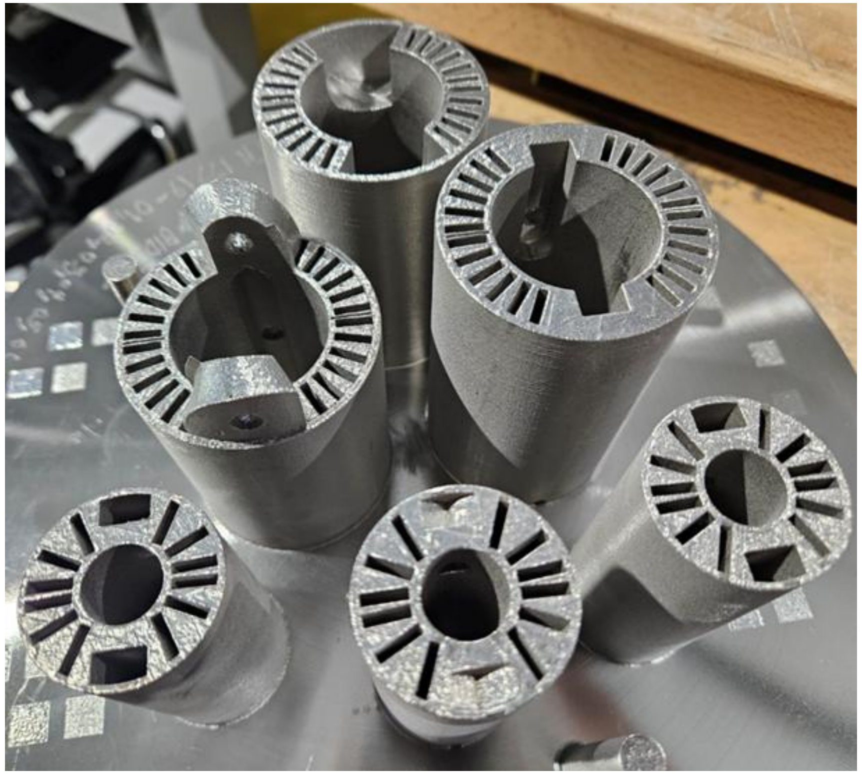
- 60-mm clear bore, 6-layer coil
  - 100 m of REBCO (STAR®) wire
  - 5 T target field at 4.2 K
- 3D coil design and magnetic analysis are complete, structural analysis is in progress
- 50% of the conductor is to be delivered in May and the remainder in July
  - The largest STAR® wire production to date by the vendor
- Standalone magnet test in October-November
  - Possible hybrid test as an insert into a Nb_3Sn coil in 2026

R&D at Fermilab on Bi2212 Coils and Magnets

- Another stress-managed structure



SMCT Bi-2212 Magnet Modes



3d-Printed Inconel 718

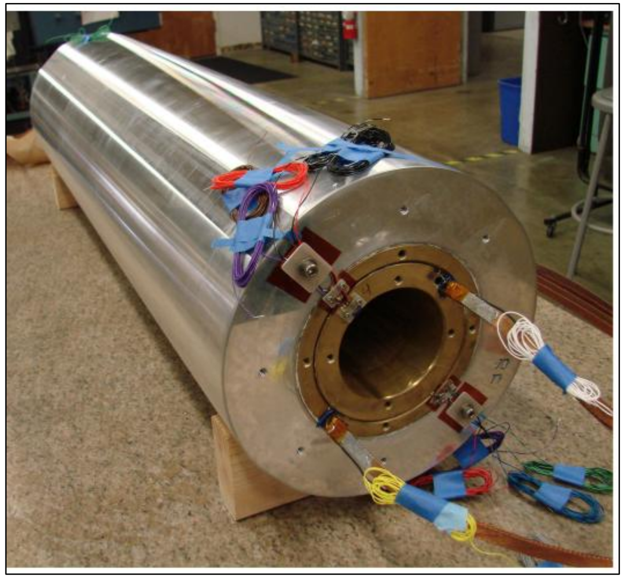
Muon Collider Magnet R&D at LBNL

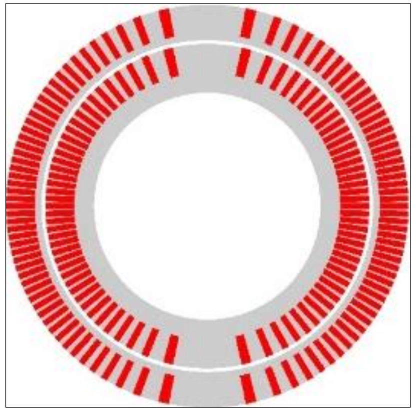
Muon Collider Related Magnet R&D at LBNL

Canted Cosine Theta (CCT for stress-managed structure)

CCT3

Subscale CCT using CORC
Step toward **5 T** goal with
6-Layer magnet

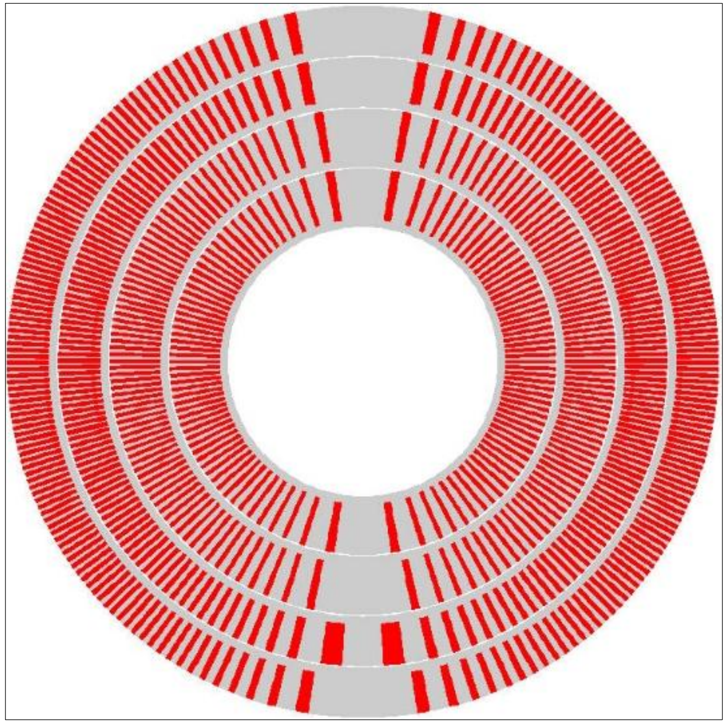




CCT5

ID: 90 mm; OD: 152 mm

8.5 T



CCT6

Mandrel under fabrication

LD1 and MQXF cable

Target: 12-13 T in 120 mm aperture

Muon Collider Related Magnet R&D at LBNL

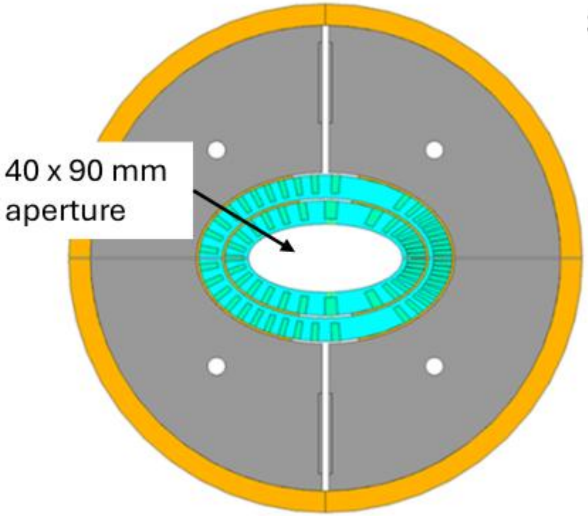
Combined Function
Elliptical Aperture
CCT at LBNL

LBNL is developing combined function magnets with superconducting Canted-Cosine-Theta (CCT) coils

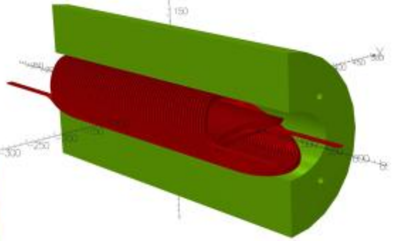
BERKELEY LAB
Bringing Science Solutions to the World

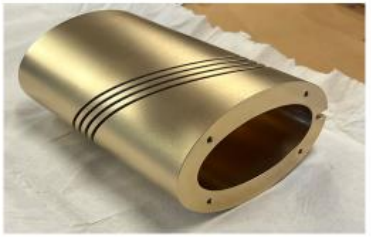
Program goals: demonstrate SC magnet technology with (1) combined function fields and (2) non-circular aperture
Relevance for muons: fixed-field accelerators, non-circular radiation shielding, combined function arc magnets

We are building a NbTi magnet demonstrator (5 T)



3.8 T dipole + 27 T/m gradient



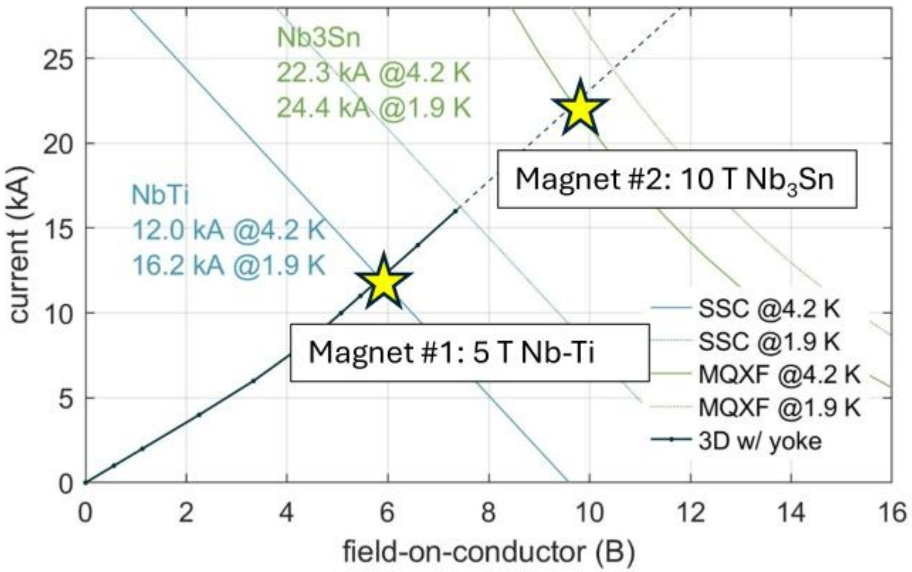


See Y. Yan presentation at the poster session

fabrication in progress
(1st test expected 2026)

Next step: scaling to high field with Nb_3Sn (10 T +)

~2 years from the test of the NbTi demonstrator



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Muon Collider Related Magnet R&D at LBL

BERKELEY LAB

ReBCO CORC®
SBIR with ACT

- LBNL is working with conductor vendor on a feasibility study of low-inductance high-field solenoid using REBCO cables, with the goal of identifying the critical issues and searching for potential solutions
  - CORC® based designs: SBIR phase I collaboration with Advanced Conductor Technologies

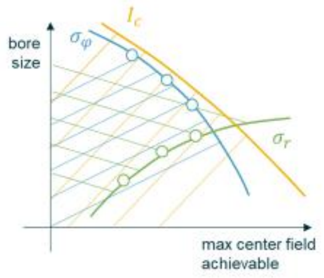
state-of-art cable technology

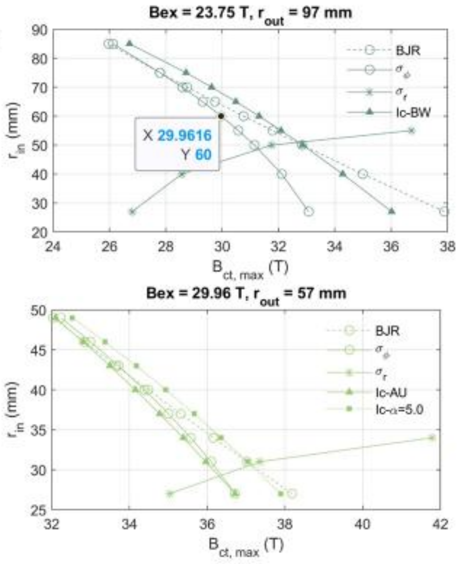
small bending radius & high tensile limit

D C van der Laan *et al* Supercond. Sci. Technol. **37** (2024) 115007

probing performance limit and critical issues

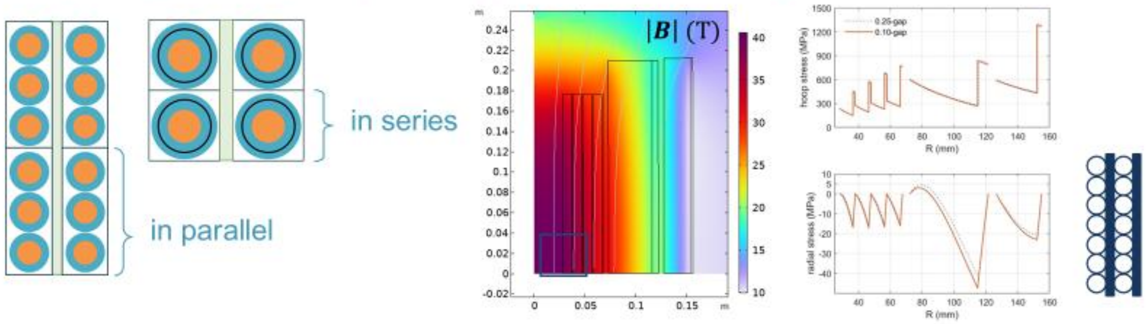
stress limited vs I_c limited





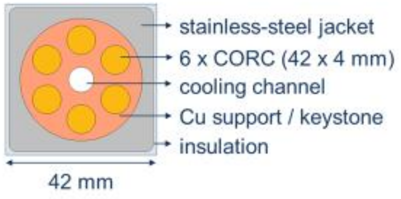
case study: 40-T 50-mm bore for final cooling

preliminary design driven by min power supplies and stress management

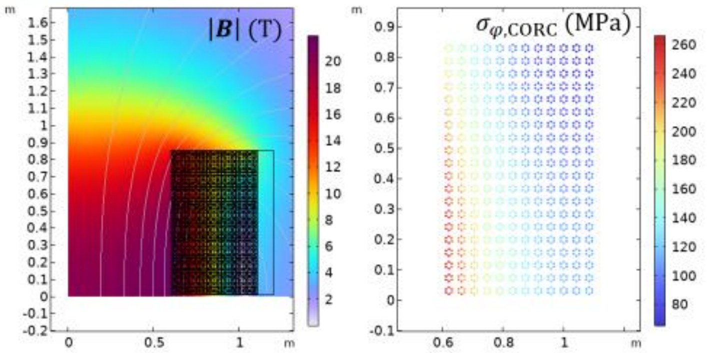


case study: 20-T 1.2-m bore for the target and capture channel

jacketed cable for higher current and lower inductance



J D Weiss *et al* Supercond. Sci. Technol. **36** (2023) 085002



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Muon Collider Magnet R&D at Magnet Lab

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Muon Collider Related Magnet R&D at the Magnet Lab

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Selected Challenges in Stepping from 32T to 40T

Muon Collider Related Magnet R&D at the Magnet Lab

Background

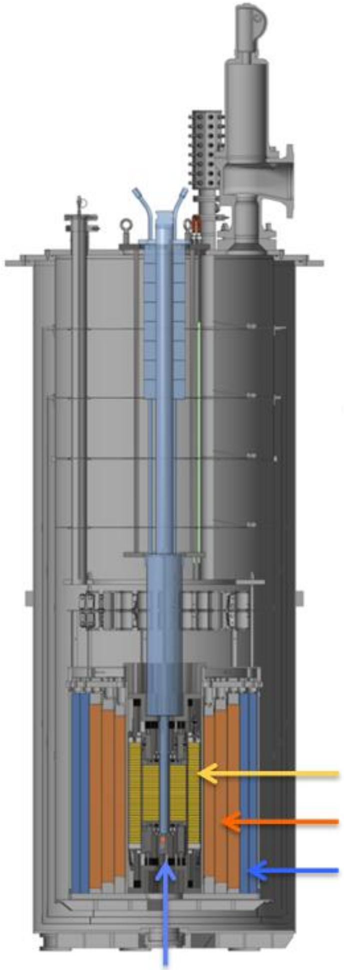
Demonstration of the 32 T superconducting solenoid and plan to design and build 40 T solenoid will be a major benefit to muon collider

- The 32 T all-superconducting magnet first reached field in 2017
- Its popularity by the condensed matter physics and NMR science user groups helped start development of a higher field magnet
- Starting in 2018 the NSF funded development towards 40 T, which considered Bi2223, Bi2212, insulated and non-insulated REBCO
- The 40 T is using much of the technology from the 32 T but there are many challenges. A few are discussed here
  - Tolerance to axial pressure
  - Radial coil compliance
  - Quench

Muon Collider Related Magnet R&D at the Magnet Lab

Basic design of the 32 T solenoid

The 32 T magnet



Key parameters:

Center field	32 T
Clear bore	34 mm
Ramp time	1 hour
Uniformity 1 cm DSV	5×10^{-4}
Total Inductance	254 H
Stored energy	8.3 MJ
Expected cycles/20 years	50,000
System weight	2.6 ton

15 T / 250 mm bore LTS magnet
17 T / 34 mm bore REBCO coils
Separately powered, simultaneously ramped

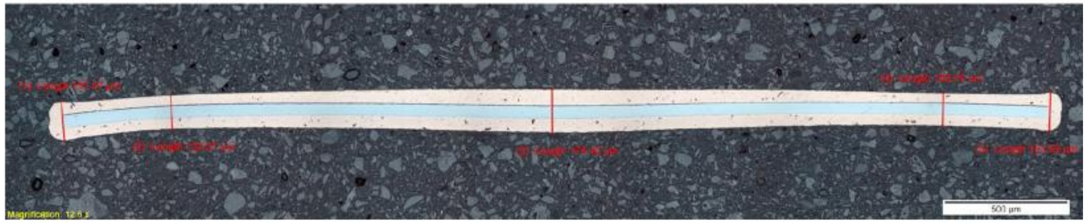
REBCO: 2 double pancake coils
Nb_3Sn coils
NbTi coils

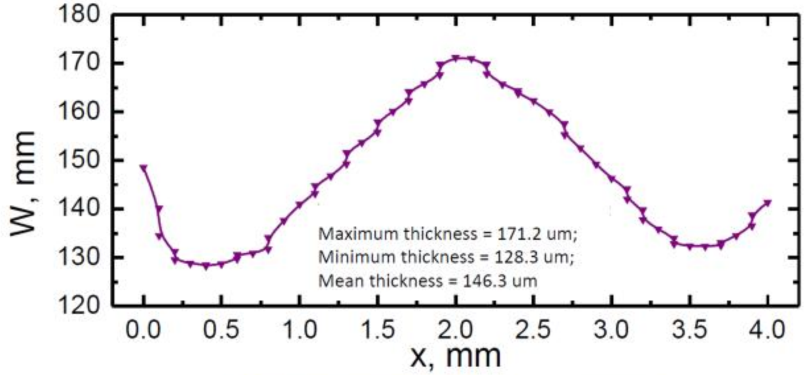
Muon Collider Related Magnet R&D at the Magnet Lab

Key technologies in the construction and protection

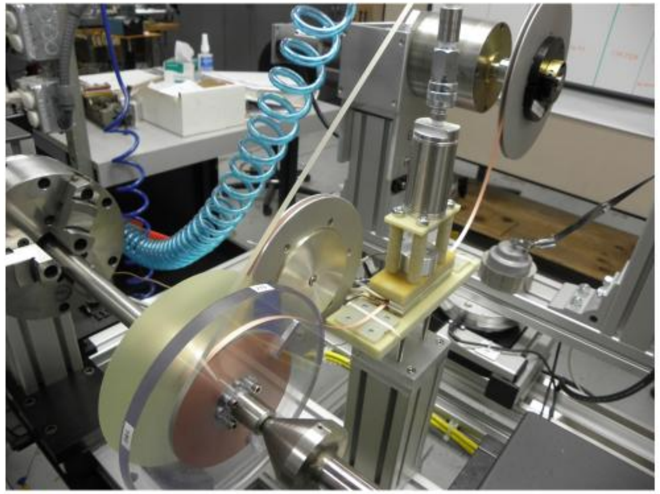
The 32 T magnet

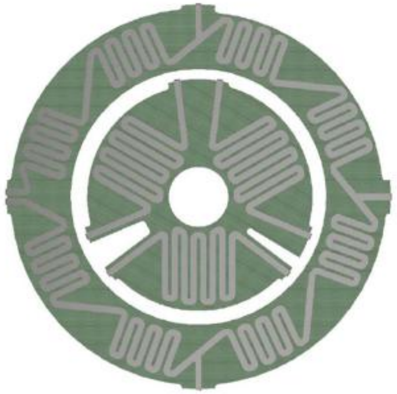
- 32 T Construction
  - Co-wind of REBCO + insulated stainless steel, dry wind
    - REBCO thickness = 0.150 mm with 0.050 mm substrate
    - J_{ave} = 242 A/mm^2
  - Modules consisting of double pancakes
  - Active quench heaters
  - Battery bank for fast, long duration (0.5 s – 1.0 s) energy discharge





Courtesy D. Abraimov





32 T Quench Heater Design

PFN for 40 T, J. Rogers MT29

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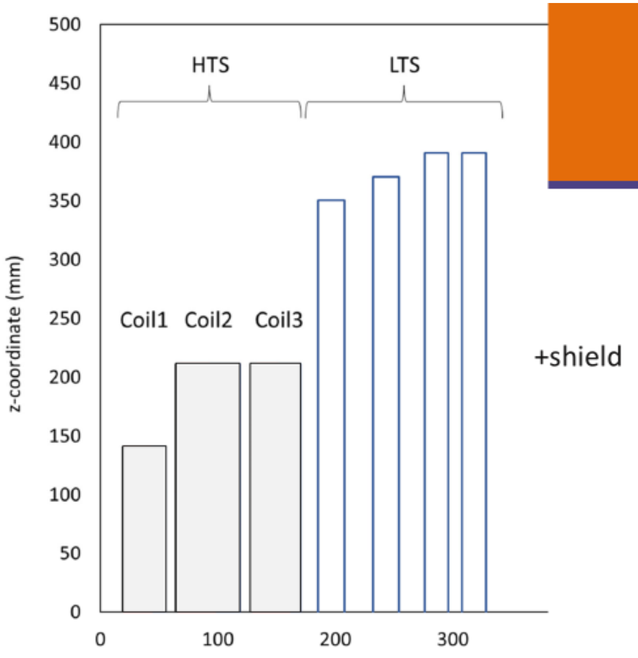
Muon Collider Related Magnet R&D at the Magnet Lab

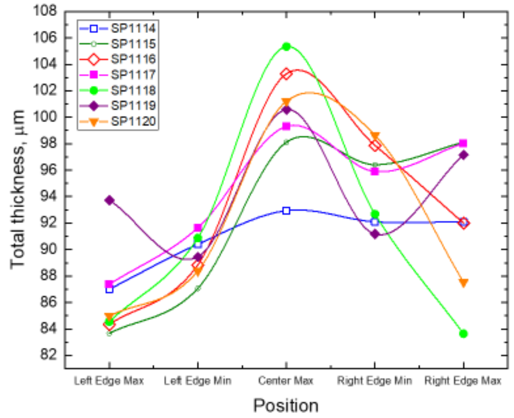
40 T All-Superconducting Magnet

- Simple scaling of the 32 T to 40 T is not feasible
  - Scaling of HTS/LTS combination from 32 T to 40 T is not feasible
- Need to increase current density of HTS coils, J_{eng}, J_{cu}
  - For J_{eng} we need to increase $f_{Ic} = I_{op}/I_c$
  - For J_{cu}
    - 32 T: J_{cu} = 420 A/mm^2
    - 40 T: J_{cu} = 760 A/mm^2
- Two-in-hand REBCO winding with segregated copper co-wind and insulated SS
  - Smaller copper thickness → smaller thickness variation
  - Lower inductance
  - Can wind modules without joints
  - Improves defect tolerance
- Other Challenges
  - Axial pressure tolerance
  - Radial compliance and strain
  - Quench protection

Advancement in design and technologies in going from 32 T to 40 T



40 T Conceptual Layout



Measured REBCO Tape Thickness Variation

Courtesy D. Abraimov

Muon Collider Magnet R&D at Muons, Inc.

Muons, Inc. received many SBIR/STTR awards and contributed to many areas.

Magnet Paper from Muons, Inc., BNL and Univ. of MS

An early paper (PAC 2007) on high field HTS solenoid for muon cooling.

Well cited!

MOPAN118 Proceedings of PAC07, Albuquerque, New Mexico, USA

A HIGH FIELD HTS SOLENOID FOR MUON COOLING*

S.A. Kahn#, M. Alsharo'a, R.P. Johnson, M. Kuchnir, Muons Inc, Batavia IL
R.C. Gupta, R.B. Palmer, E. Willen, Brookhaven National Laboratory, Upton, NY
D.J. Summers, University of Mississippi, Oxford, MS

Abstract

The ability of high temperature superconducting (HTS) conductor to carry high currents at low temperatures makes feasible the development of very high field magnets for uses in accelerators and beam-lines. A specific application of a very high field solenoid is to provide a very small beta region for the final cooling stages for a muon collider. Since ionization cooling in a solenoid acts simultaneously on both transverse planes, any improvement in maximum field has a quadratic consequence in the reduction of the 6-dimensional (6D) beam emittance. This paper describes a conceptual design of a 45 Tesla solenoid based on Bi-2223 HTS tape, where the magnet will be operated at 4.2 K to take advantage of the high current carrying capacity at that temperature. In this design, an outer Nb_3Sn shell surrounds the HTS solenoid. This paper describes the technical issues associated with building this magnet. In particular it addresses how to mitigate the large Lorentz stresses associated with the high field magnet and how to design the magnet to reduce the compressive end forces. Also this paper discusses the important issue of how to protect this magnet if a quench should occur.

MAGNET DESCRIPTION

The choice of the physical dimensions of the magnet is determined by the muon cooling requirements. The magnet is 1 m long, which provides a reasonably uniform field over the 70 cm long vessel, which contains the liquid hydrogen absorber needed for muon cooling. The inner radius of the solenoid is determined by the minimum bending radius of the HTS conductor, but it allows for the radial size of the liquid hydrogen absorber vessel, radiation shielding, and the necessary insulation.

Conductor Choice

HTS conductor was chosen over Nb_3Sn or NbTi superconductor because it can carry significant current in the presence of high fields. Fig 1 shows the critical current as a function of field for NbTi, Nb_3Sn and Bi-2212 cable at 4.2 K [5]. For fields larger than 15 T, only the HTS wire has sufficient current carrying capacity. In this study we have chosen to use the Bi-2223 HTS conductor tape available from American Superconductor (ASC) instead of the Bi-2212 conductor shown in figure 1. The Bi-2223 conductor tape has an effective current density (J_E) of only 2/3 of that of Bi-2212 and is not isotropic with

Muon Collider Magnet R&D from Muons, Inc. & FNAL

Important work on muon cooling with helical cooling channel.

4-coil demo unit reached 85% of short sample (4.4 T)

DESIGN STUDIES OF MAGNET SYSTEMS FOR MUON HELICAL COOLING CHANNELS*

V.V. Kashikhin, V.S. Kashikhin, M. Lamm, M.L. Lopes, A.V. Zlobin#, FNAL, Batavia, IL 60510
M. Alsharo'a, R.P. Johnson, S.A. Kahn, Muons Inc, Batavia, IL 60510, U.S.A.

Abstract

Helical cooling channels with superimposed solenoid and helical dipole and quadrupole coils, and a pressurized gas absorber in the aperture offer high efficiency of 6D muon beam cooling. In this paper, we continue design studies and comparison of two basic concepts of magnet system proposed for a helical cooling channel focusing on the high field sections. The results of magnetic analysis and Lorentz force calculations as well as the superconductor choice are presented and discussed.

service equipment inside the magnet aperture, etc., and providing the required beam cooling.

The main goal of this study was to understand the possibilities and limitations of generating the required field components in high-field sections with given geometrical parameters. To study and compare different magnet designs for multistage HCC, as target parameters we used those reported in [3]. They are summarized in Table 1. Field components in the table are defined in a cylindrical coordinate system (r,τ,z).

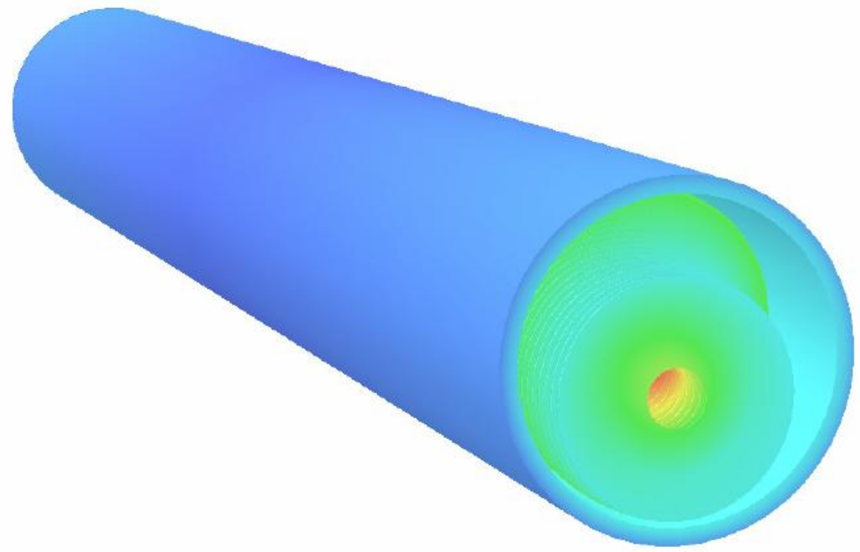


Figure 5: High-field helical solenoid with external correction solenoid.

4-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MANX*

M.J. Lamm#, N. Andreev, V. S. Kashikhin, V. V. Kashikhin, A. Makarov, M. Tartaglia, K. Yonehara, M. Yu, A. Zlobin, Fermilab, Batavia, IL 60510, U.S.A.
R.P. Johnson, S.A. Kahn, Muons Inc., Batavia, IL 60510, U.S.A.

Abstract

Magnets for the proposed muon cooling demonstration experiment MANX (**M**uon collider **A**nd **N**eutrino factory e**X**periment) have to generate longitudinal solenoid and transverse helical dipole and helical quadrupole fields. This paper discusses the 0.4 M diameter 4-coil Helical Solenoid (HS) model design, manufacturing, and testing that has been done to verify the design concept, fabrication technology, and the magnet system performance. The model quench performance in the FNAL Vertical Magnet Test Facility (VMTF) will be discussed.

INTRODUCTION

Effective emittance cooling is a major challenge in

Table 1: Parameters for full scale vs. 4 coil HS.

Parameter	Long HS	4-Coil HS
Peak Field (T)	5.7	4.4
Operating Current (kA)	9.6	13.6
Coil ID (mm)	510	420
Number of turns/section	10	9 (see text)
Fx force/section (kN)	160	119
Fy force/section (kN)	60	21
Fxy force/section (kN)	171	121
Fz force/section (kN)	299	273

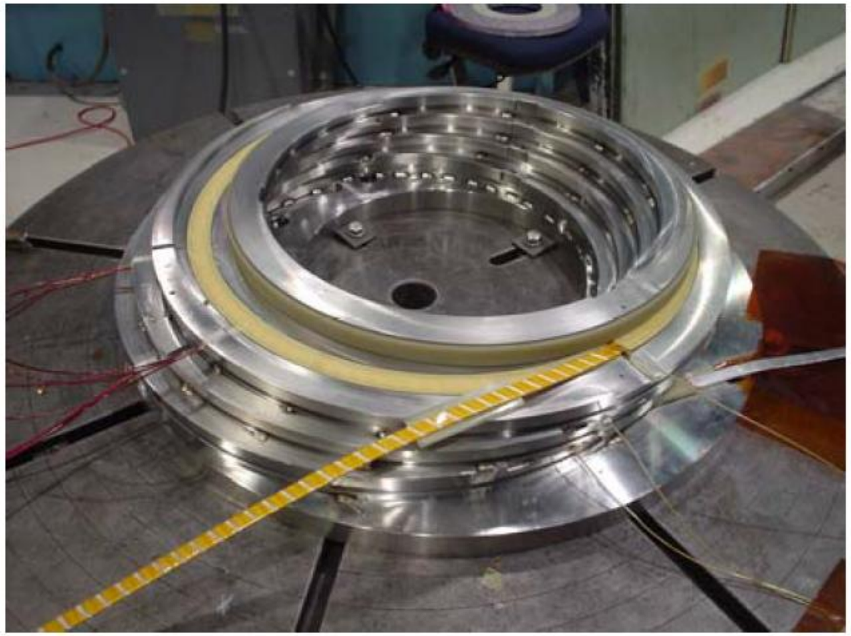


Figure 2: HSM01 During Assembly

Acknowledgements

Slides, papers and discussions with several colleagues from BNL, PBL, FNAL, LBNL, Magnet lab and Muons, inc., contributed to this presentation (in particular, Steve Gourlay from Fermilab, Lucas Brouwer, Yufan Yan, Jose Fernandez, and Paolo Ferracin from LBL, Iain Dixon from magnet lab, and Rolland Johnson and Stephen Kahn from Muons, Inc.).

Summary

- Muon collider needs a variety of magnets - solenoid, dipoles, quadrupoles - most with very challenging requirements.
- In long term, HTS is likely to play a major role in muon colliders, because of its ability to operate at elevated temperatures or its ability to tolerate large energy deposition or its ability to create very high fields or all above.
- Thanks to so many challenges and need for new designs and technologies, this is an ideal field for the next generation scientists and engineers to get involved. You can really make a difference!
- A summary of past work at US institutions was presented. One can build upon them and/or come up with something more creative.

Extra Slides

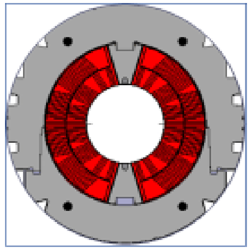
Muon Collider Needs Large Aperture High Field Dipoles

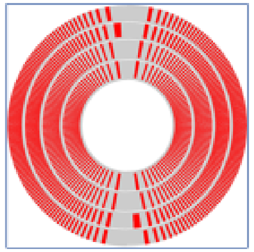
Exploring Stress Managed Coil Designs

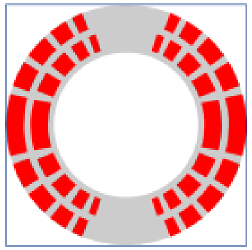
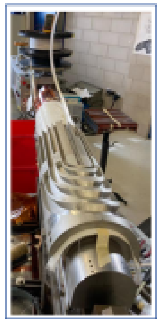
R&D at LBNL and Fermilab

> CCT
> SMCT

- In traditional cos-theta design
  - Accumulation of Lorentz forces, both azimuthally and radially, resulting in high coil stress
- In stress managed cos-theta design
  - Lorentz forces are intercepted by mechanical “stoppers”, both azimuthally and radially
    - Originally proposed by P. McIntyre for block-design in 1997
- Two options consider by MDP
  - Canted Cos-theta design (CCT)
    - Each turn on a groove, separated by spars and ribs, in a tilted solenoid configuration
  - Stress management cos-theta (SMCT)
    - Traditional cos-theta with individual conductors or blocks in a groove





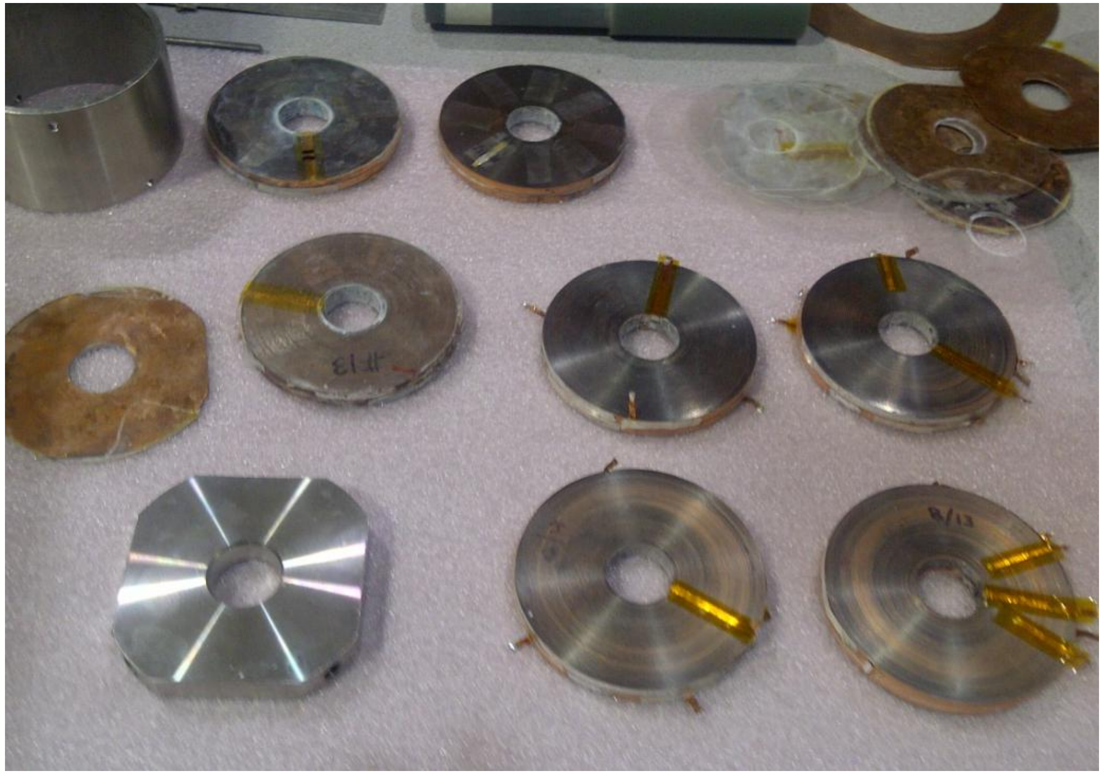
Fermilab

7 8/6/2025

Brookhaven National Laboratory

Quench studies with a large number of expensive HTS coils leftover from the previous R&D programs

(No fear of destroying them for a “burn to learn” approach)




Development of BNL’s Advanced Quench Protection Electronics for protecting HTS and HTS/LTS hybrid magnets. Also, recent R&D on cryo-electronics.

Viability of ReBCO in Accelerator Magnets and in Fusion

ReBCO comes in tape form and that poses several challenges:

- A local defect, not always detectable at 77 K QA test of ReBCO tape, could cause an irrecoverable damage to the accelerator magnet coils, when operated at high fields and/or high stresses. This challenge is faced in fusion magnets as well.
- Tape conductors (rather than round wire) create field errors that may be too large for accelerator magnets. Similarly, tape conductors cause large losses that may be too much for fusion devices.
- Quench protection of the large high stored energy HTS magnets is a major issue for the accelerator magnets. This is also a major issue for the large fusion devices.

High current HTS cables are essential to deal with the above issues.

- Will that and other development in technologies be sufficient? Fusion community has made a massive investment and is counting on developing a reliable solution.
- Can/should accelerator community partially align its program to benefit from above?

Emphasizing the Similarities

- Accelerator magnets and fusion applications both need coupled tapes (wires) either to reduces losses or to reduce field errors.
- Both applications need high current ReBCO cables.
- Both applications need significantly longer length cables with more uniform performance along the length.
- Both need the price of the HTS cable to go down by a large amount to make the devices being developed viable.

Pointing out the Differences and Possible Path Forward

The conventional magnet designs need HTS cables that can be bent in small bend radii; fusion cables typically don't require that.

- Can a relatively small strategic investment leverage the development of the cables that can be bent in small radii with a little to no loss in the full potential of REBCO?

------------ AND/OR ------------

- Can accelerator magnet community become open to developing and demonstrating magnet designs that can use fusion cables despite them having large bend radii?

A Dialogue Between Users and Manufacturers

Challenge for accelerator magnet designers:

- What can be done to develop and demonstrate new magnet designs that can allow the most efficient ReBCO cables as getting developed now? Example: magnet designs that can use large fusion cables.

Challenge for ReBCO wire/cable manufacturers:

- What can be done to modify cable architect (to the extent possible with incremental funding) to allow their use in a wide variety of magnet designs for accelerators? Example: cables that bends with small radii.

Challenge for both to work jointly to improve the end-product:

- What can be done to find integrated solutions to develop cable and magnet designs together? Examples: dealing with large stresses (CICC?), internal cooling (hole in the middle?), etc..