HTS Coils for High Field Hybrid FCC Dipoles

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CERN | FCC hh ee he — U.S. DEPARTMENT OF ENERGY | Office of Science

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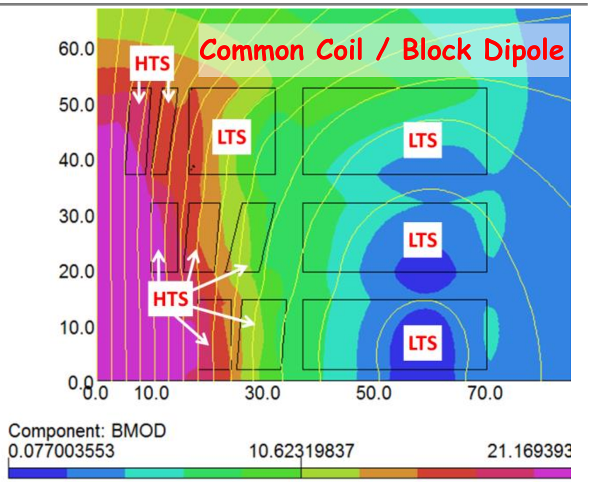
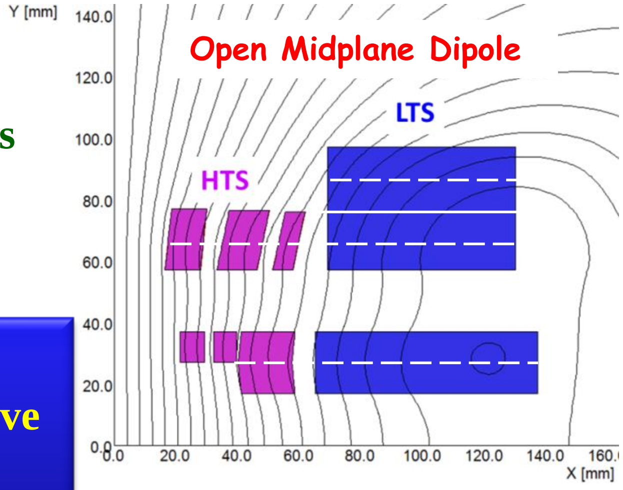
Overview

- HTS Coils in a Hybrid Design for a ~20 T Dipole
- Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes
  - This could be a game changer for ReBCO
- HTS Coil R&D at BNL and Future Possibilities
- Summary

HTS/LTS High Field (~20 T) Hybrid Dipole (Racetrack Coil Designs)



Cross-section
(¼ of one aperture)



Hybrid design to minimize cost:

- HTS in high field region for ~4 T
- LTS in low field region for ~16 T

HTS options

– Bi2212
  - Advantages: Round wire, high current Rutherford cable
  - Challenges: Limited production & long term economic viability
    Degradation in performance under large stresses

– ReBCO
  - Advantages: Larger production from multiple vendors
    Can tolerate large stresses as in high field magnets
  - Challenges: Tape form could cause large magnetization
    Lower current without new or complex cable

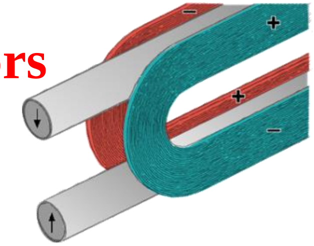
Focus of this presentation:

Possibility of making ReBCO based hybrid magnets more attractive

➢ Both in performance, and in cost …

Magnetization in ReBCO Magnets

- **Issue:**
  - **ReBCO is primarily available in tape form**
  - **Magnetization is large in cosine theta or common coil designs**
    - ➢ **related to tape width: 12 mm for high current conductors**



- **Solution #1 : conductor design**
  - **Round wire**
  - **Striated tape**
- **Solution #2 : coil design**
  - **See what we can do to use and enhance the strengths of the conductor**

Next few slides on the technique

Design Technique to Reduce Magnetization

- Conductor magnetization and hence the persistent-current induced harmonics are related to the width of the conductor (or rather filament) subtended

  "***perpendicular to the field***"

- In most Nb-Ti magnets, the filament size is ~ 6 μm
  - higher in Nb_3Sn, but usually <100 μm
- In ReBCO it is considered to be ~12 mm for high current tapes

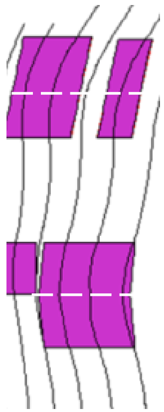
Design Technique to Reduce Magnetization Effects:

- Align the tape conductor (thickness few μm) such that primarily the

  "***narrow side sees the perpendicular field***"

- It's possible to align HTS tape to a good extent in **hybrid magnets**

  "by carefully designing the coil"



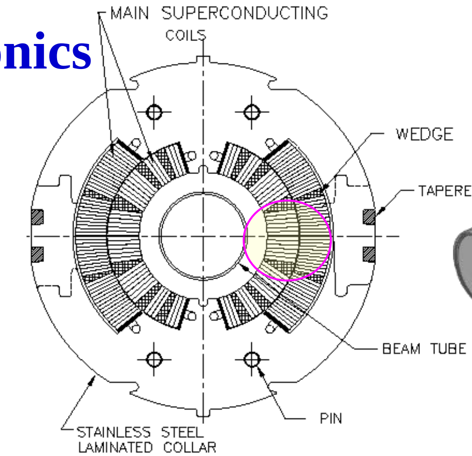
Effective filament size 12 mm ⇨ a few μm in an ideal design

➢ **small in a real design, depending on the optimization**

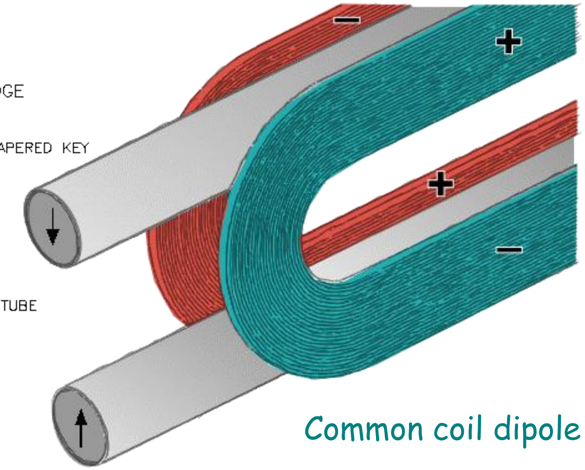
Comparing Designs for Magnetization

If persistent current induced harmonics is only the figure of merit

- **Bad designs for HTS tape**
  large area covered by the perpendicular component of the field



SSC 50 mm dipole


Common coil dipole

- **Good designs for tape (small area curved by the perpendicular component of the field)**

Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes

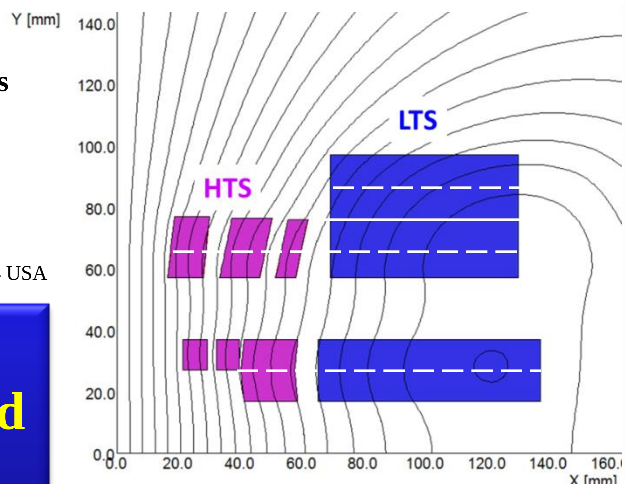
R. Gupta[1], A. Ghosh[1], R. Scanlan[2] and R. Weggel[2]

BNL Magnet Division Note: MDN-676-41

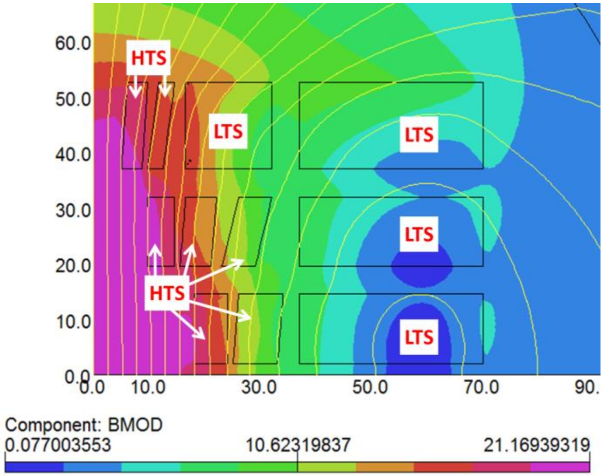
[1]Brookhaven National Laboratory, Upton, NY 11973 USA

[2]Particle Beam Lasers, Inc., 18925 Dearborn Street, Northridge, CA 91324 USA

Persistent current induced harmonics should come down dramatically



Open midplane dipole



FCC dipole

Goal : Magnetization

- **Reduce magnetization to a reasonable amount.**
- **Try to determine variation in persistent current induced harmonics between coil to coil to determine the "systematic" and "RMS" variations.**
- **We don't have to be perfect in making it zero. As long as it is manageable with correctors, etc., it may be good enough.**

Other Benefits of Aligned Tape Design (conductor efficiency)

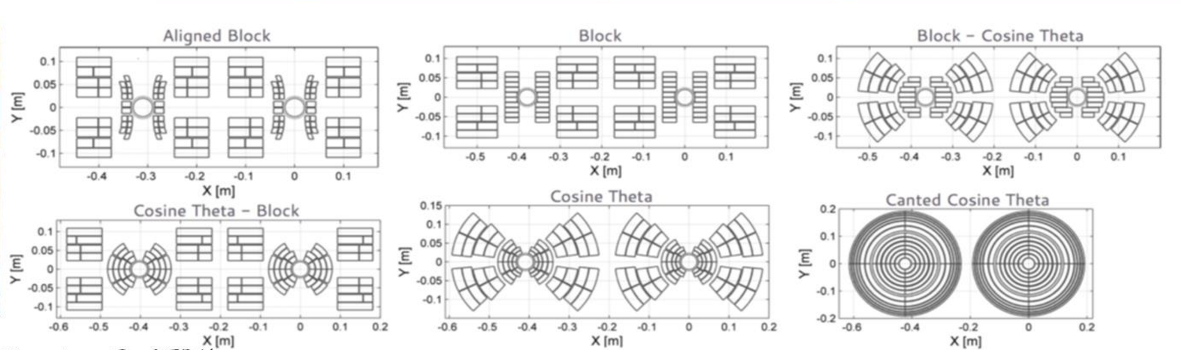
5

Survey of 20 T Magnet design possibilities

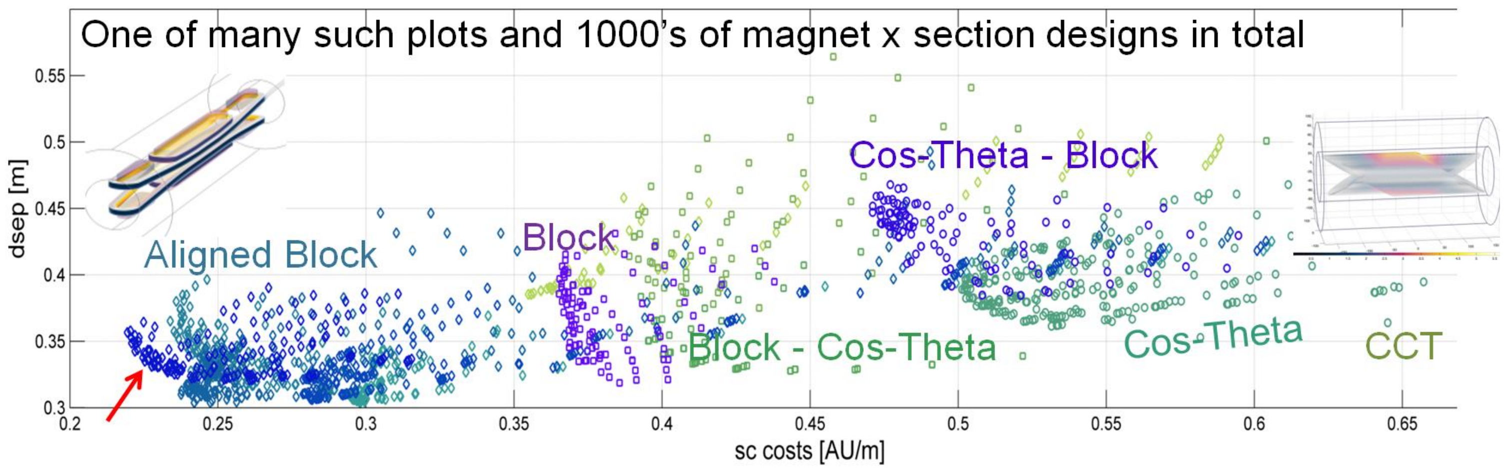
Courtesy:

J. Van Nugteren

CERN



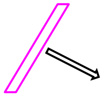
Jeroen Van Nugteren PhD student @ CERN



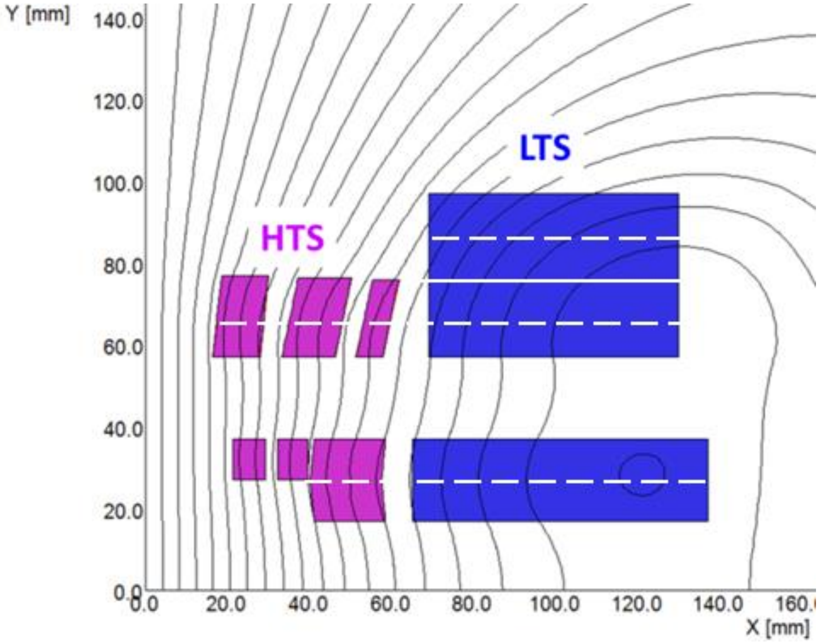
Other Benefits of Such Designs (2)

- **Lorentz forces are primarily on the wide face of the conductor**

I × B



  - ReBCO can tolerate large stresses on the wide side



- **Blocks are easy to segment**
  - Between HTS and LTS
  - For stress management

PBL/BNL/E2P DoE Phase II STTR (just funded)

STTR:

Small Business Technology Transfer

A unique opportunity to investigate the idea and to develop the basic technology

Project Summary/Abstract

Company Name & Address:	Particle Beam Lasers, Inc. 18925 Dearborn Street Northridge, CA 91324-2807
Principal Investigator:	Ramesh C. Gupta
Project Title:	A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets
Topic No: 33	Superconductor Technologies for Particle Accelerators
Subtopic: (b)	Superconducting Magnet Technology

Abstract:

Proposed designs for a Future Circular Collider (FCC) to collide protons with a center-of-mass energy of 100 TeV call for dipoles with fields up to 20 Tesla (T). This is significantly beyond the present technology and requires using High Temperature Superconductors (HTS). The recent Particle Physics Project Prioritization Panel (P5), organized by the U.S. Department of Energy (DOE), strongly supports the U.S. maintaining its leadership in superconducting magnet technology. This STTR proposes to design, build and test a proof-of-principle hybrid dipole that uses HTS in its highest-field regions and less-expensive low-temperature superconductors, Nb_3Sn and NbTi, where they suffice. During Phase I, a coil block with ReBCO tape with Kapton insulation was fabricated and tested, confirming that winding had no measurable degradation. A major concern in the magnets built with ReBCO is the large field errors associated with the conductor magnetization in the tape geometry. The major discovery during Phase I was finding a solution to reduce those errors considerably. Based on this and work performed under previous SBIR/STTRs and other programs, HTS coils will be designed and built in Phase II and then integrated with the existing Nb_3Sn common coil dipole. This provides a unique opportunity to test the concept in a proof-of-principle hybrid magnet with field approaching 15 T. A 20 T hybrid dipole design will also be developed with the goal of satisfying the requirements of accelerator magnets and reducing cost.

Objectives of PBL/BNL/E2P STTR

Technique to Reduce Field Errors Due to Magnetization in HTS Tape ...

Proof-of-Principle Demonstration Magnet ....

Optimization of the High Field Accelerator Magnet Design...................

Coil Ends (practice windings)..

Cost Reduction ....

Commercialization and Technology Transfer to E2P ....

<u>Previous noteworthy PBL/BNL SBIR/STTR:</u>

Development of high field HTS solenoid and HTS cosine theta coils

- **Resulted in significant development in HTS magnet technology**

(Thank you SBIR/STTR office)

Test of Principle in A Real Magnet

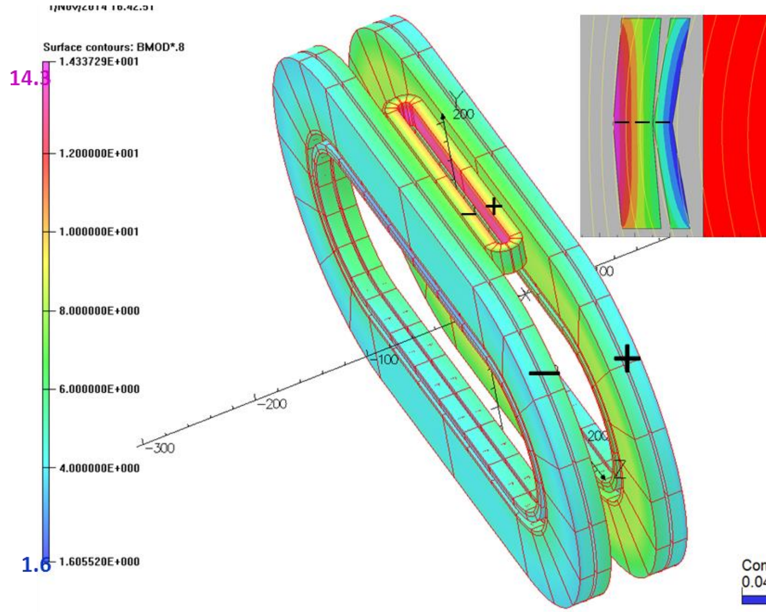
(measure and compare magnetization in two configurations)

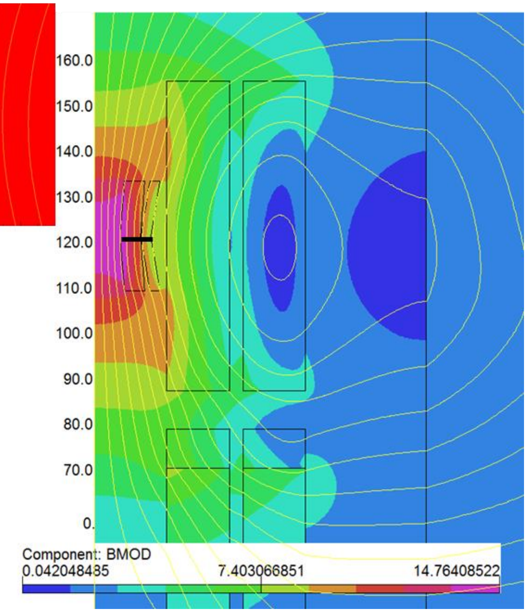
Common Coil Dipole with a large open space

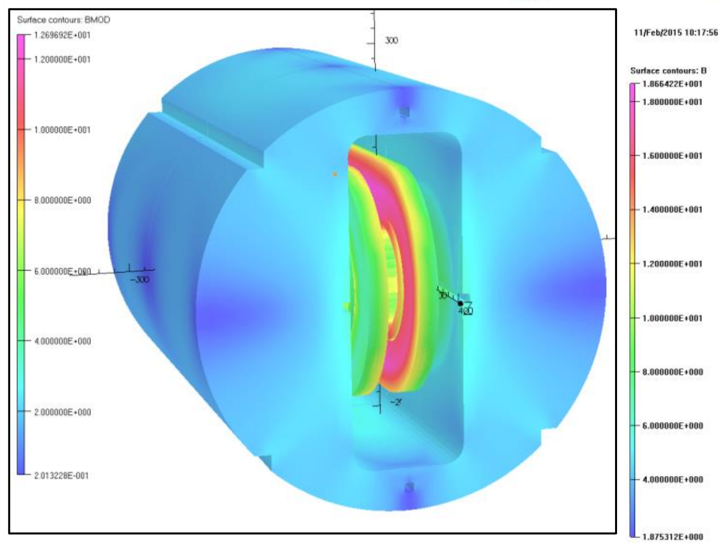
- **Coils can be inserted without opening the magnet**

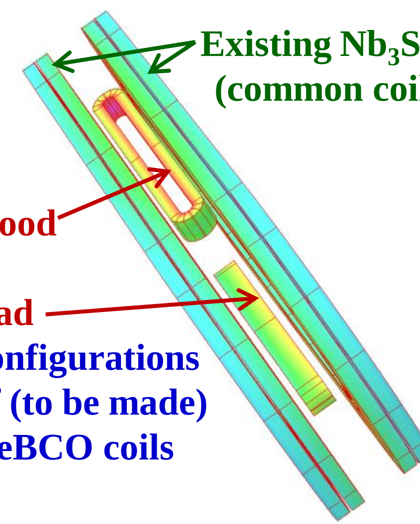
A Hybrid HTS/LTS …High-Field Accelerator Magnets

➢ STTR Phase II   PBL/BNL/E2P (funded)







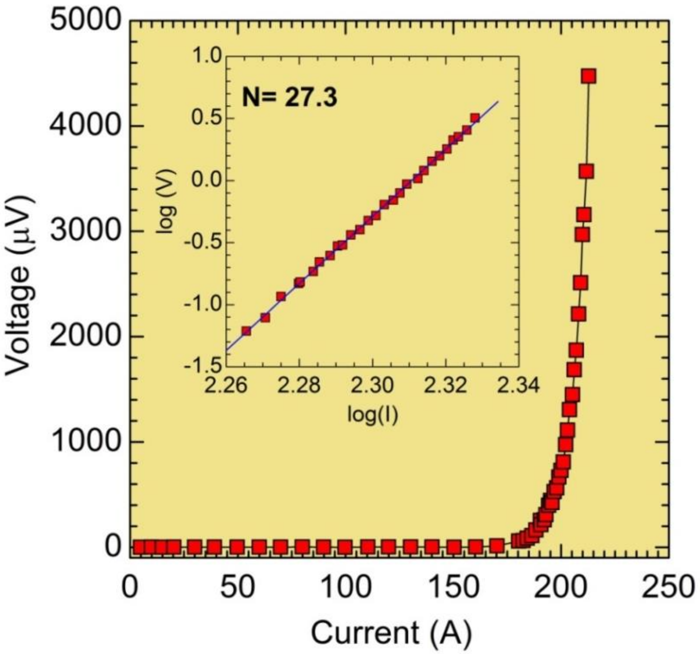


Existing Nb_3Sn (common coil)

Good & Bad configurations of (to be made) ReBCO coils

Cos (θ) Coil - PBL/BNL STTR (Willen) (12 mm, one block, 77 K)

The coil block made here is similar to what would be needed for testing reduction in magnetization



No measurable degradation@77 K

Cos (θ) Coil - PBL/BNL STTR (Scanlan)

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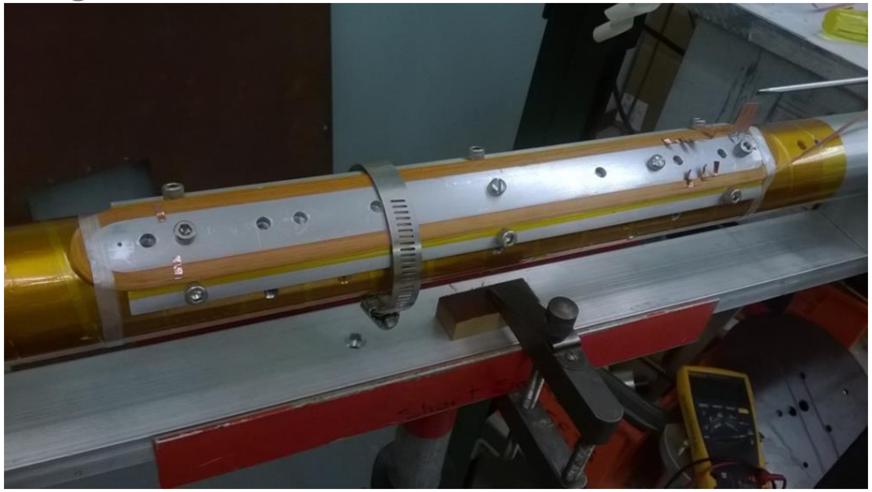
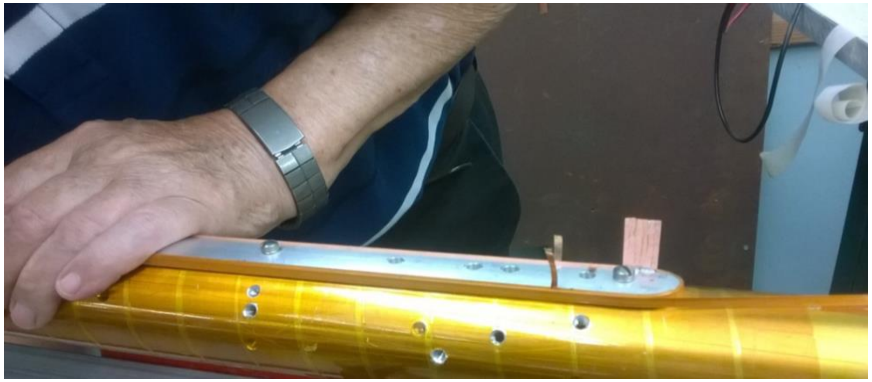
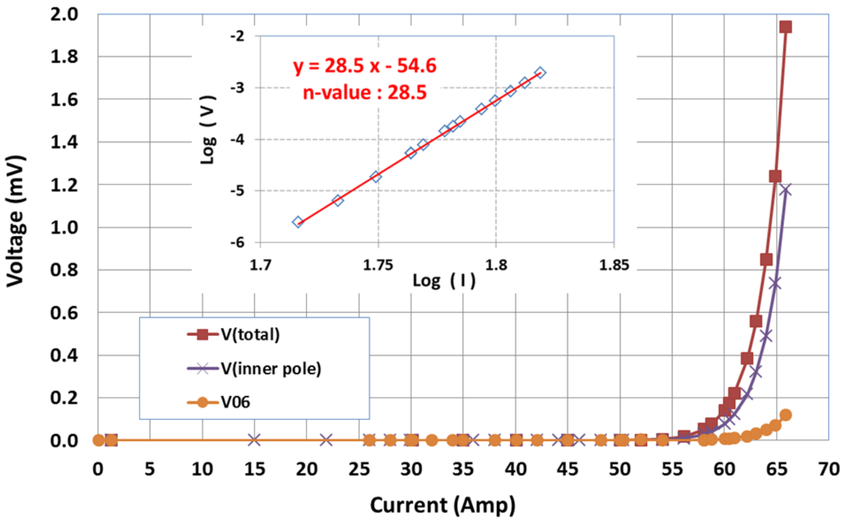
Superconducting Magnet Division







No measurable degradation@77 K

Also investigated "bonded" or "clad" 12 mm tape from SuperPower

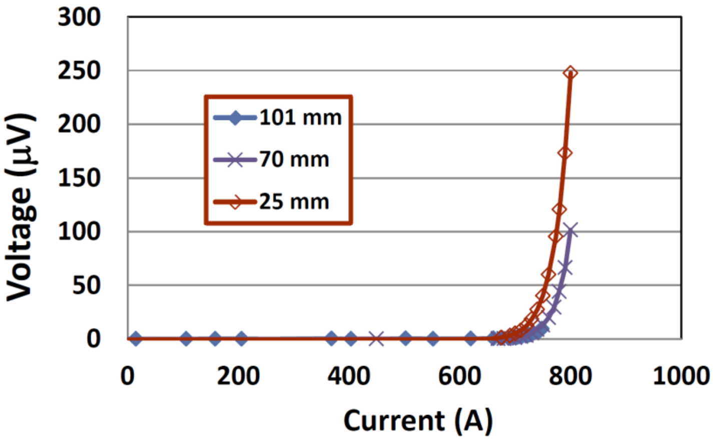


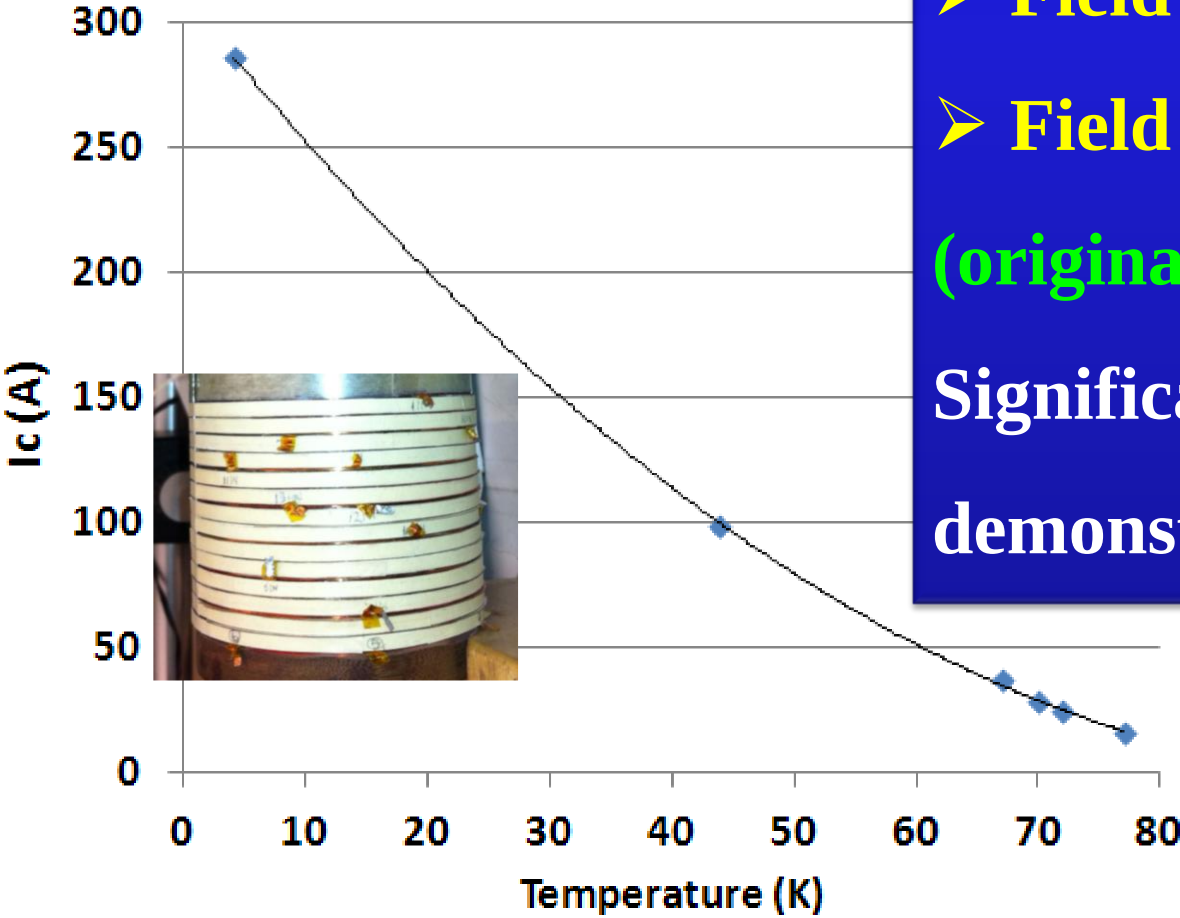
Fig. 17. Bend test results for bonded tape with the YBCO layer oriented toward the central Cu strip. Degradation in I_c begins between a bending diameter of 75 mm and 25 mm.

Other HTS Magnet Program at BNL

- **HTS magnet R&D over a wide range:**
  - **High field, Medium field and low field (high temperature)**
  - **Many geometries – racetrack, cosine theta, solenoid**
- **Number of HTS coils/magnets designed built & tested:**
  - **Well over 100 HTS coils and well over 10 HTS magnets**
- **Type of HTS used:**
  - **Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape**
- **Amount of HTS acquired:**
  - **~50 km (4 mm tape equivalent)**
- **Our recent activities have been largely on magnets with ReBCO**

High Field (16T) Demo of HTS Magnet

PBL/BNL SBIR



- Field on axis: 15.7 T
- Field on coil : 16.2 T

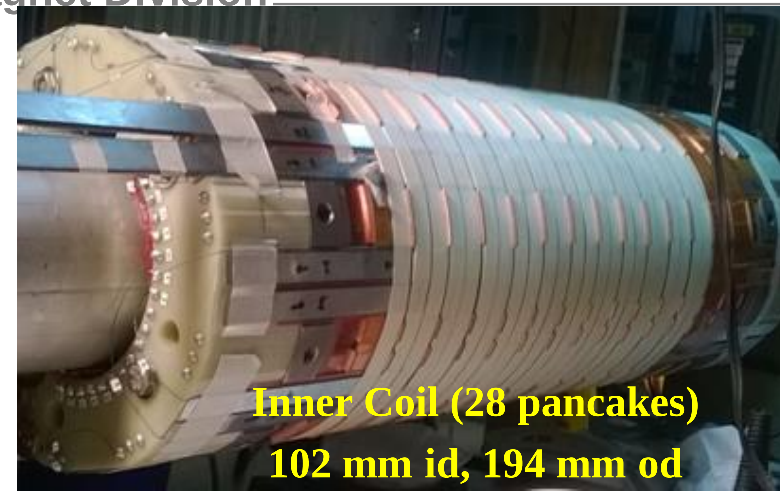
(original target: 10-12T)

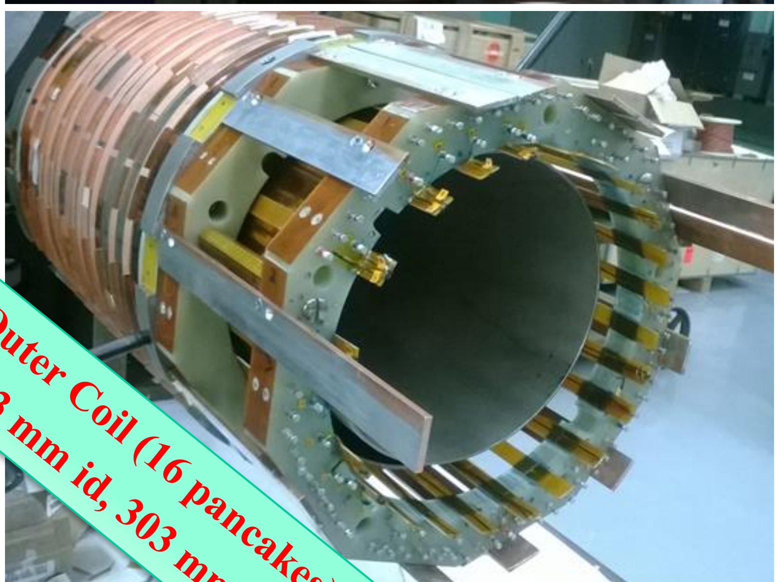
Significant technical demonstration at a low cost

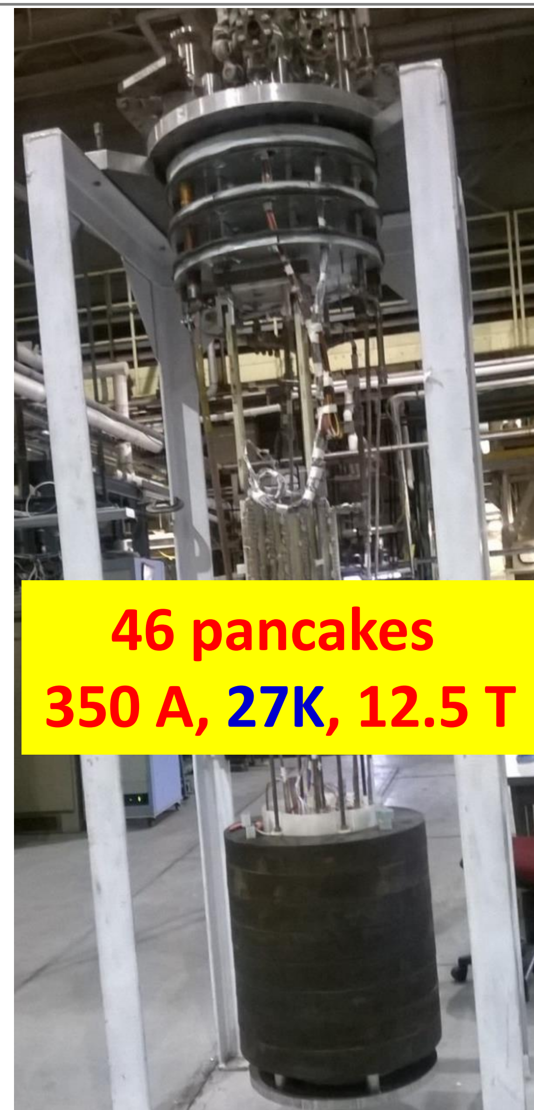
Overall J_o in coil:
> 500 A/mm^2 @16 T

HTS Solenoid: 14 pancakes, 25 mm aperture

High Field HTS Magnet Test Results
100 mm bore, 12 mm ReBCO SMES Coil







Goal:

~25 T at 4 K

Large Stresses:

>400 MPa

Record Field:

12.5 T at >10 K

in the 1st test itself

Significant use of HTS : over >18 km (4 mm equivalent)

Significant ReBCO Programs in 2015

High Field Solenoid for Axion Search

Funded by Korean research institute

SuNAM has partly delivered and partly on the way to delivery about 5 km (~4 mm equivalent) as a part of this research and/or its contribution to HTS R&D at BNL

HTS Coils for High Field Hybrid Dipole

PBL/BNL/E2P STTR

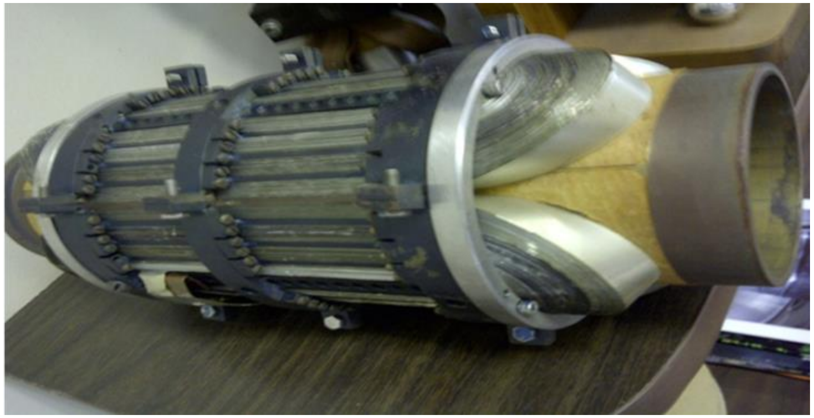
Base Program

Very important for performing R&D – not yet funded

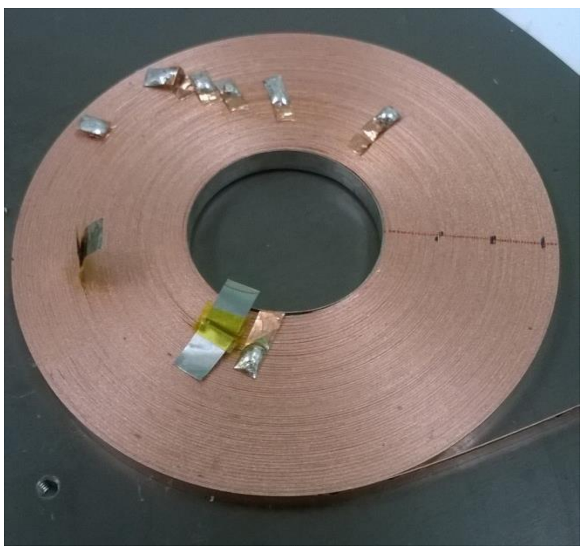
Requested 1st shipment: 2 X 140 m

Delivered: 282 m (without splice)

No Insulation and Other R&D

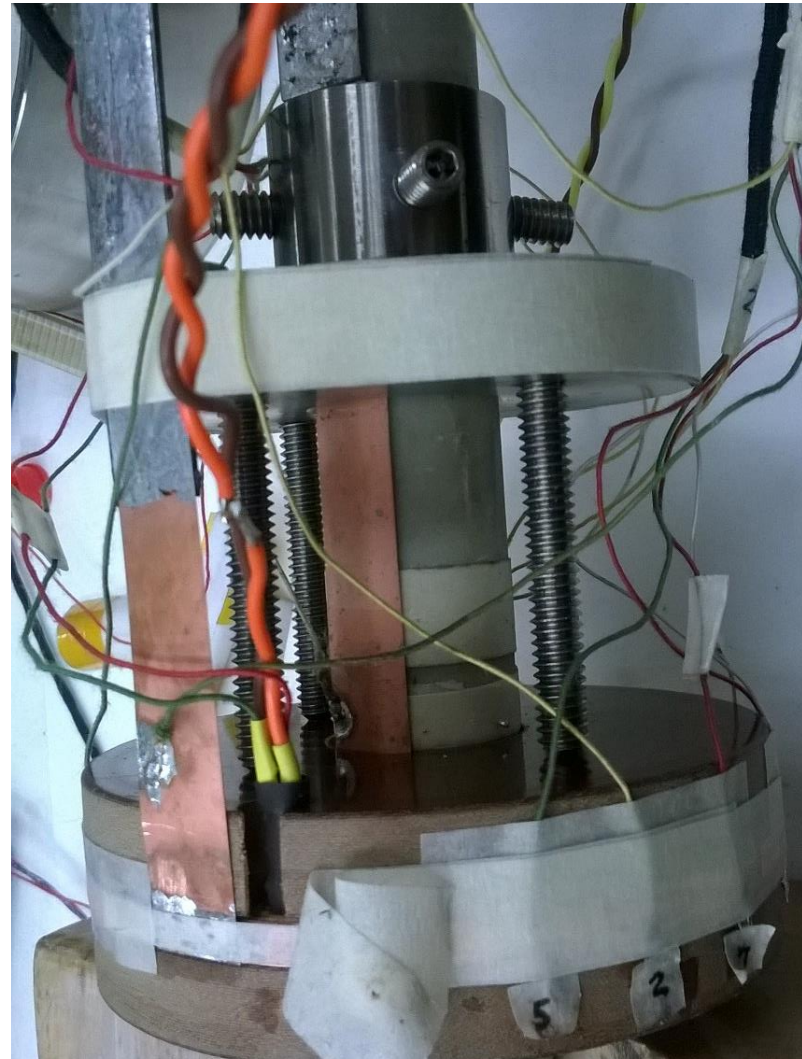


No-insulation Nb_3Sn Tape Coils
Bill Sampson (before my time)



Coil #1

Conductor:
Courtesy: SuNAM



Coil #2

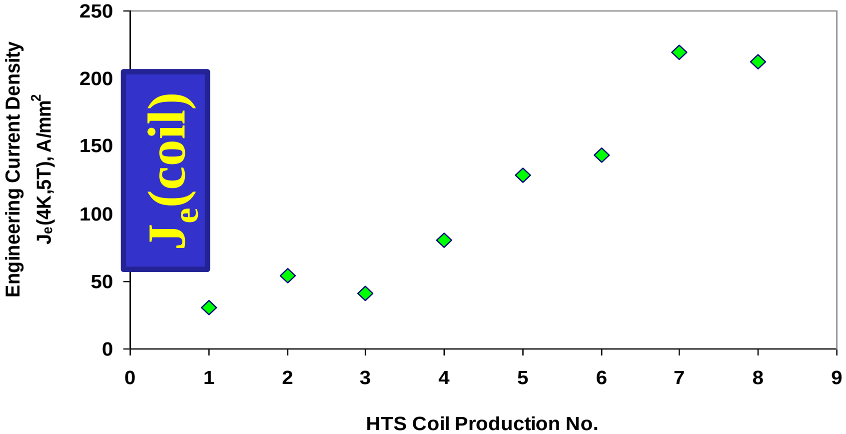
High Current Conductor/Cable

- Present value of field parallel I_c is over 3 kA for single tape
  - Likely to increase as ReBCO thickness becomes several μm
- Develop simple multi-tape (bonded, multi-ply, …) conductor
  - This increases kA value of conductor
  - This should make conductor more robust as current may bypass from one tape to another (as in "no-insulation") in case of local defect or variation
- Explore wide multi-tape robust cable configurations
  - Perform experiments in magnet coils

A dream conductor may be an optimized multi-tape configuration 10-20 kA @ design

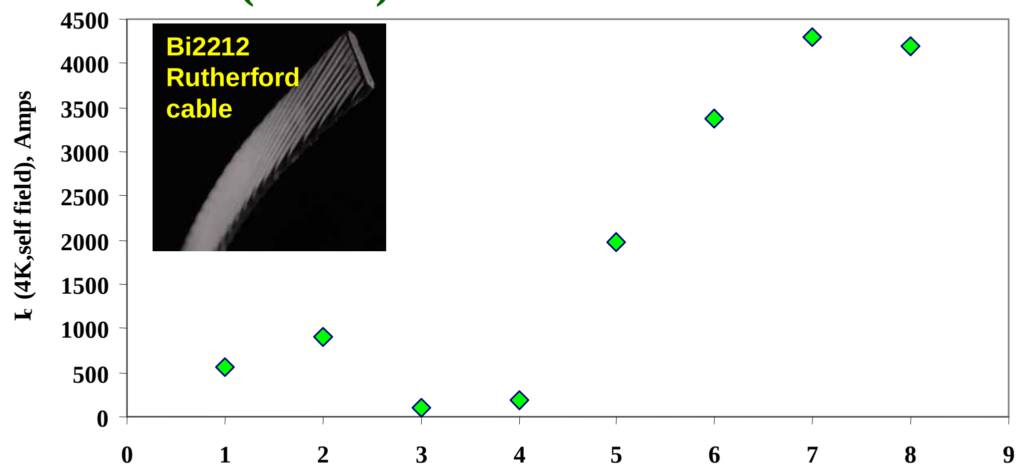
HTS Common Coil Dipole with Bi2212 Rutherford Cable (2001-03)

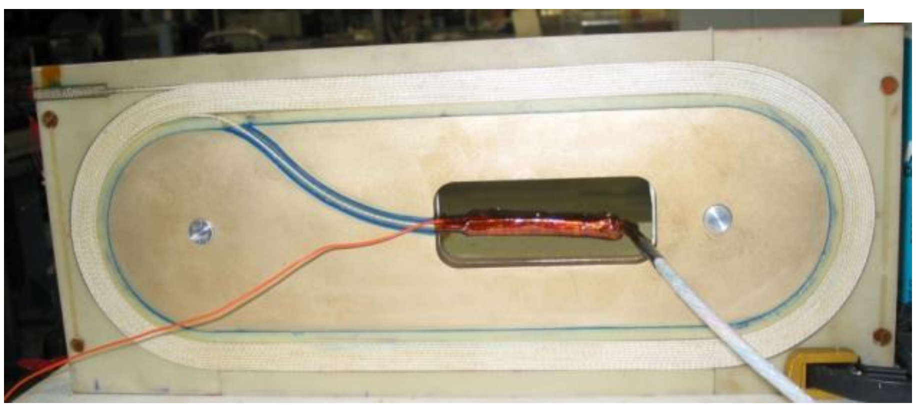
8 Coils and 5 Magnets built with Rutherford Bi2212 Cable



Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)





Still a record ???

Racetrack HTS coil with Bi2212

SUMMARY

- **It may be possible to develop high field hybrid magnet designs in such a way that the conductor magnetization (persistent current induced harmonics) become manageable, overcoming a major technical issue associated with the tape.**

- **Such designs can handle large stresses, as present in high field magnets, as they are against the wider side of the tape.**

- **Requirements of expensive conductor are significantly reduced because of the field orientation (previous design work at CERN).**

- **Degree of above benefits need to be determined by model calculations and demonstration in actual tests. A demonstration is planned under an STTR with a unique background field common coil magnet available for such testing at BNL.**

Bi2212 Coil Experience at BNL

Bi2212 HTS Coils and Magnets @ BNL

TABLE II

COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand)	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag	74 mm spacing Common coil	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	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands	2 HTS, 4 Nb_3Sn coils (total 6 coils)	4200	272 [212]	1.84

BNL pursued "React & Wind" technology for Bi2212

Eight coils and five magnets were built at BNL with Rutherford Bi2212 Cable (Showa/LBNL)

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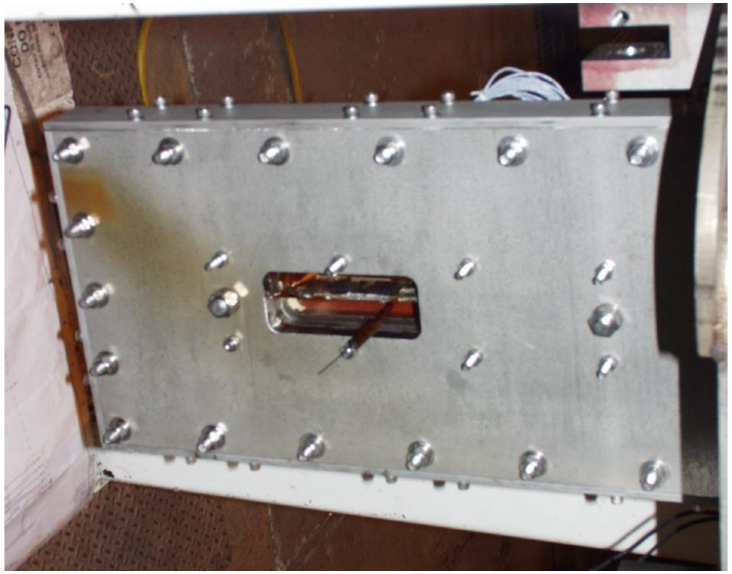
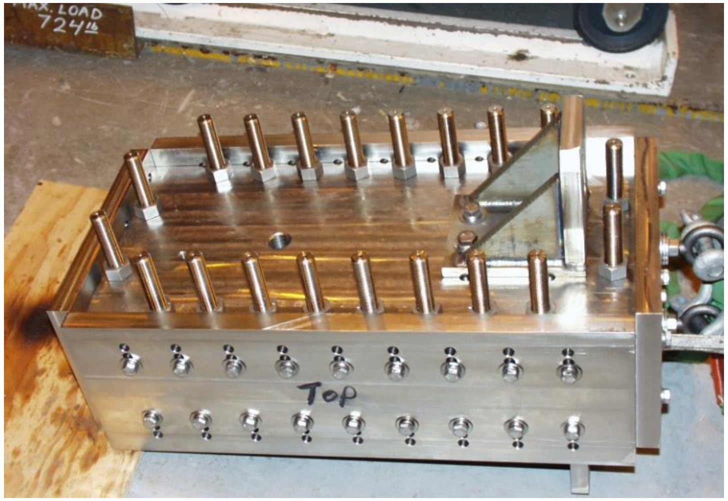
Superconducting Magnet Division

Magnet Structures for Bi-2212





Common Coil Design