BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Superconducting Magnet Program at BNL

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Overview

- **Projects and Facilities**
- **Selected Superconducting Magnet Activities at BNL**
  - **HTS Magnets (react & wind only)**
  - **Nb_3Sn Magnets (both wind & react and react & wind)**
  - **NbTi Magnets**
- **Summary**

(high field hybrid magnet to be discussed in a separate presentation)

Projects and Facilities: HTS

High Temperature Superconductors (HTS) aka High Field Superconductors (HFS)

- **Primarily ReBCO (now), but also Bi2212, Bi2223 and MgB_2**
- **Universal Winder for flat coils – pancake, racetrack**
- **HTS Quadrupole for FRIB (Facility for Rare Isotope Beams)**
- **Low field solenoids for Energy Recovery Linac**
- **High field solenoids for Muon Collider**
- **SMES (Superconducting Magnetic Energy Storage)**
- **Quench detection/protection system for HTS**

Projects and Facilities: NbTi & Nb_3Sn

- **Relativistic Heavy Ion Collider (RHIC)**
  - **General support to RHIC- only operating large circular collider in US**
  - **RHIC helical magnet (for polarized protons)**
  - **Layer Wind NbTi solenoids for RHIC electron lens**
  - **Direct Wind IR multipole magnets for eRHIC electron-ion collider**
- **US-LHC and APUL (present machine)**
- **HL-LHC aka LARP (High Luminosity Upgrade)**
- **Direct Wind machine for work for others**
  - **CERN anti-hydrogen, DESY, BEPC (China), JPARC, SuperKEKB**

Supporting Facilities

- **Superconductor development and test**
  - ➢ **HTS for new project initiatives**
  - ➢ **Nb3Sn for LARP**
- **Cryogenic facilities for testing**

HTS Magnet Program

HTS Magnet Program at BNL

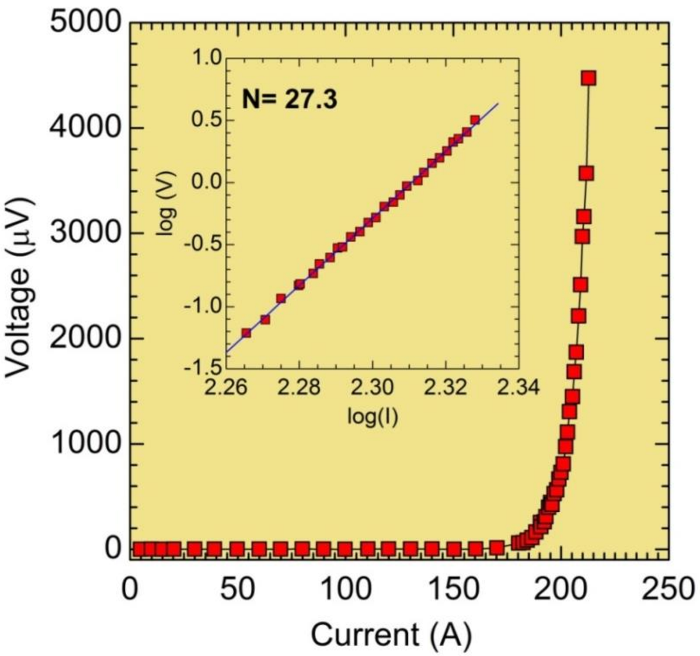
- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – racetrack, cosine theta, solenoid
- Number of HTS coils/magnets designed built & tested:
  - Over 150 HTS coils and over 15 HTS magnets
- Type of HTS used:
  - ReBCO, Bi2212, Bi2223, MgB_2 – wire, cable, tape
- Amount of HTS acquired:
  - Over 50 km (4 mm tape equivalent)
- Our recent activities have been largely on magnets with ReBCO
  - (yet just tested Bi2223 and one MgB_2 magnets)

Selected HTS ReBCO Tape Magnet Programs at BNL

ReBCO Tape Cosine θ R&D for Hadron Collider

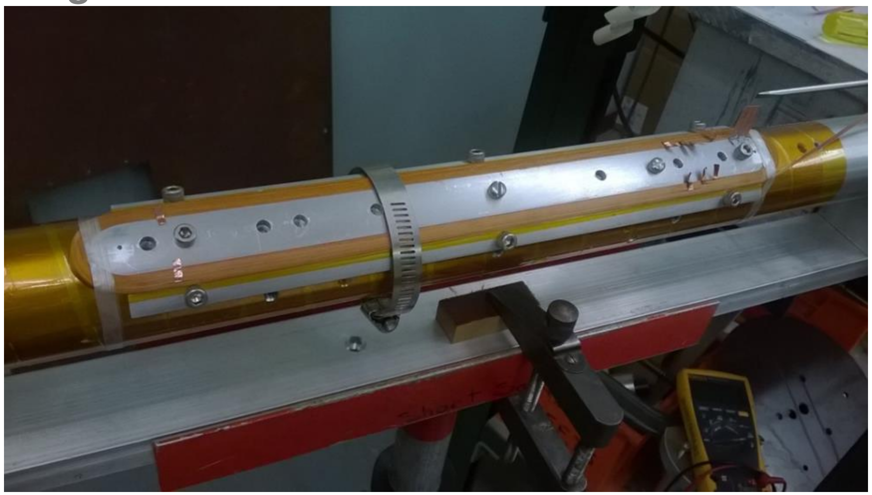
Cos (θ) Coil - PBL/BNL STTR#1 (12 mm, one block, 77 K)

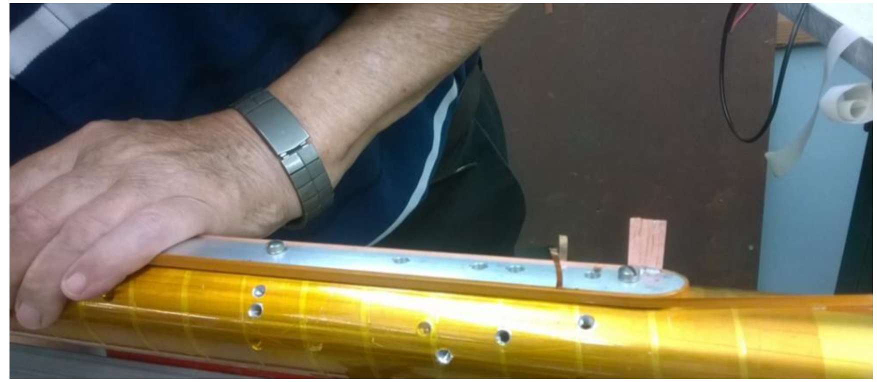
No measurable degradation@77 K



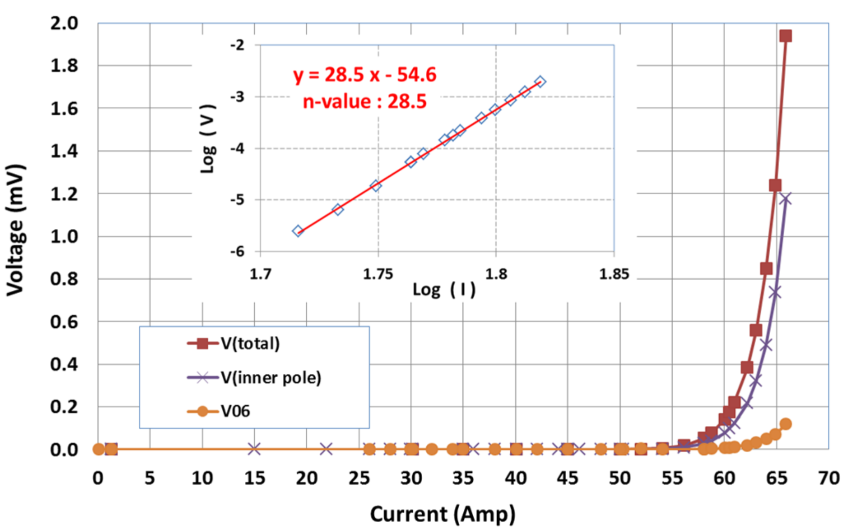
- Kapton Ci Insulation
- Possibility of bonded tapes (mutli-tapes)

Cos (θ) Coil - PBL/BNL STTR #2





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



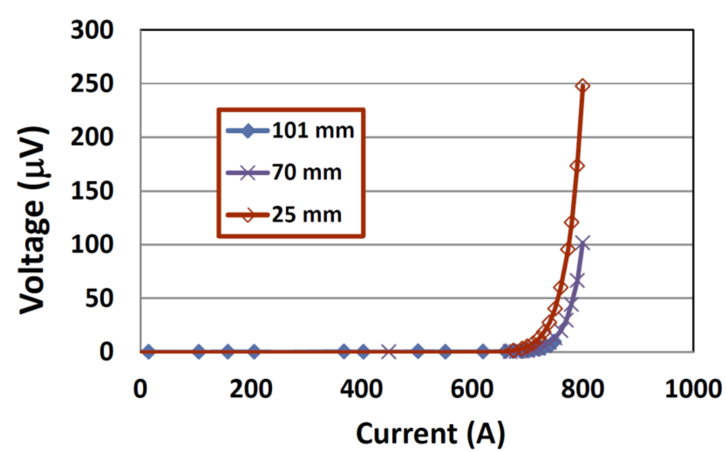


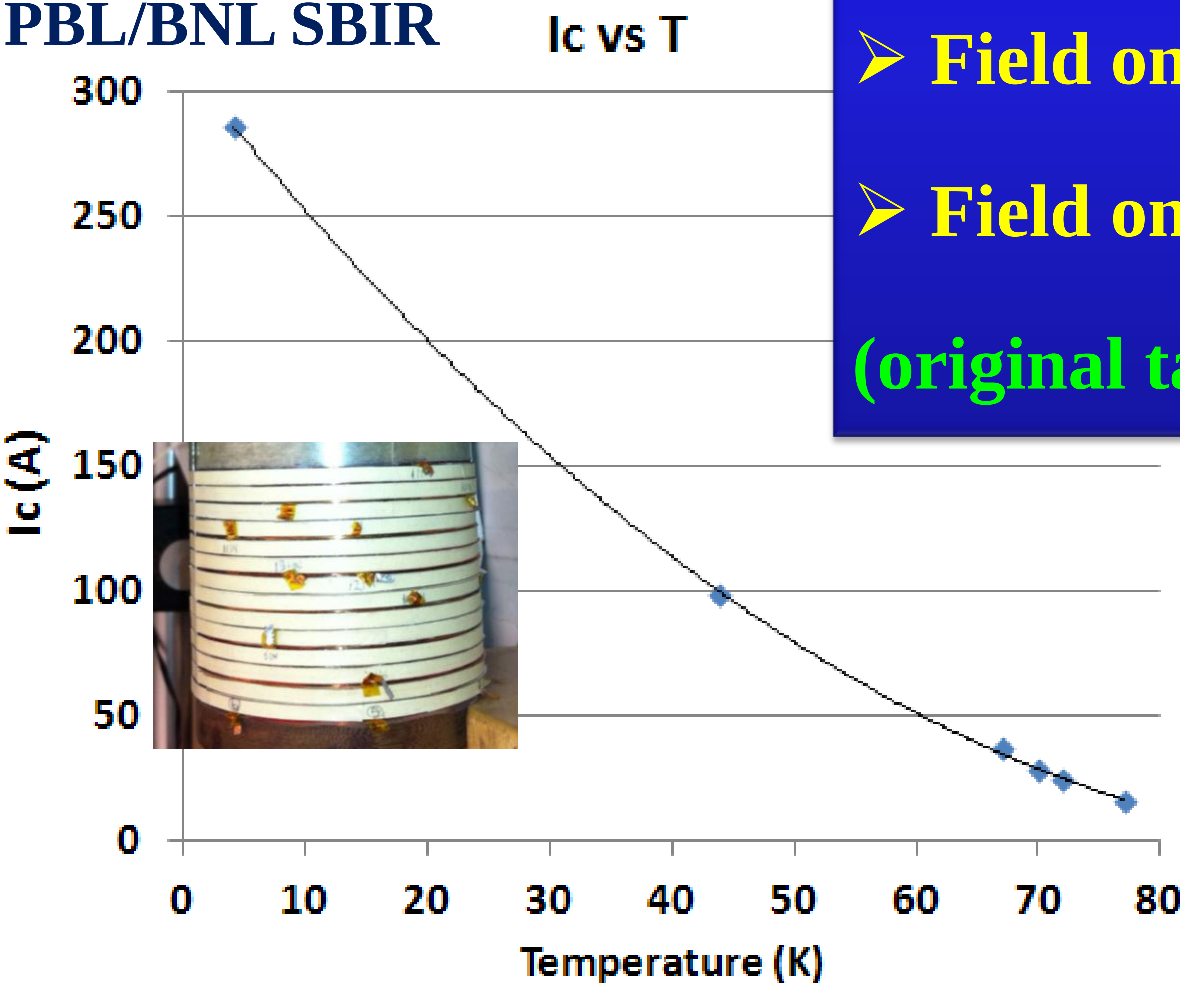
Fig. 17. Bend test results for bonded tape with the YBCO layer oriented toward the central Cu strip. Degradation in I_c begins between a bending diameter of 75 mm and 25 mm.

No measurable degradation@77 K

High Field HTS Solenoid with ReBCO Tape

High Field (16T) Demo of HTS Magnet

PBL/BNL SBIR



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

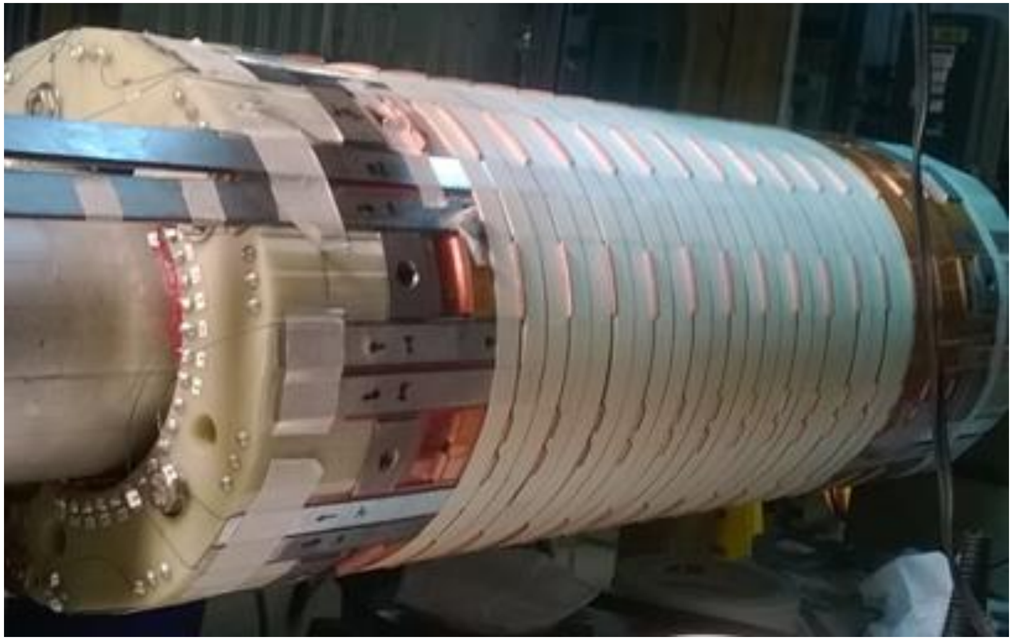
(original target: 10-12T)

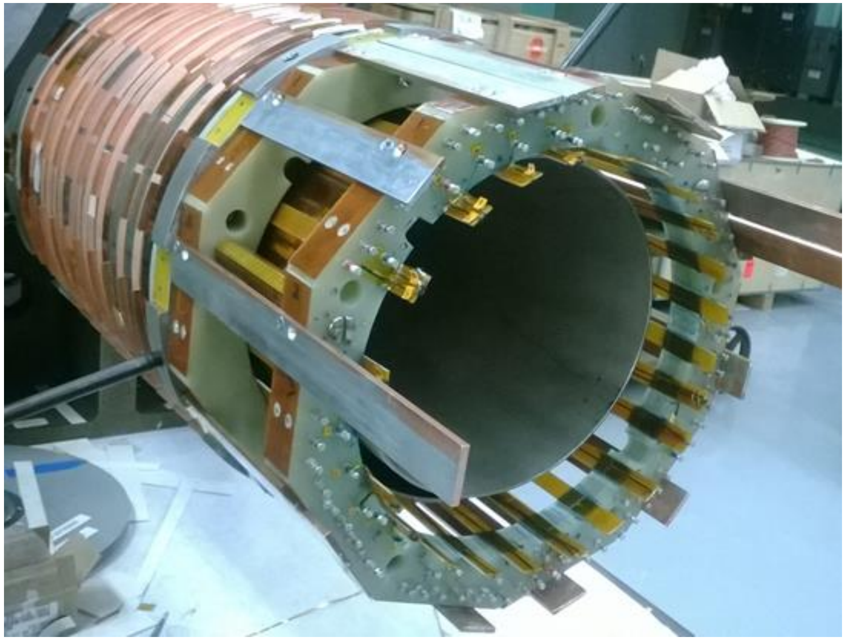
Overall J_o in coil:
>500 A/mm^2 @16 T

Insert solenoid: 14 pancakes, 25 mm aperture

SMES Magnet

Superconducting Magnetic Energy Storage (SMES)





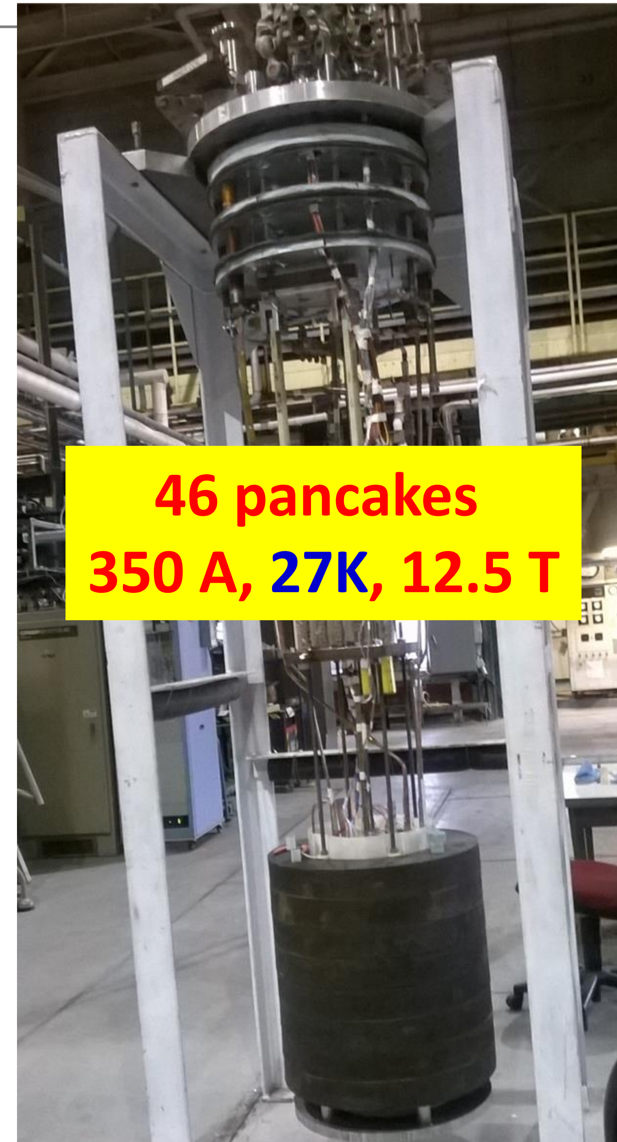
Inner Coil
(28 pancakes)

Outer Coil
(16 pancakes)

HTS SMES Magnet Test Results
100 mm bore ReBCO SMES Coil

2 pancakes
1140 A, 4K

12 pancakes
760 A, 4K, 11.4 T



46 pancakes
350 A, 27K, 12.5 T

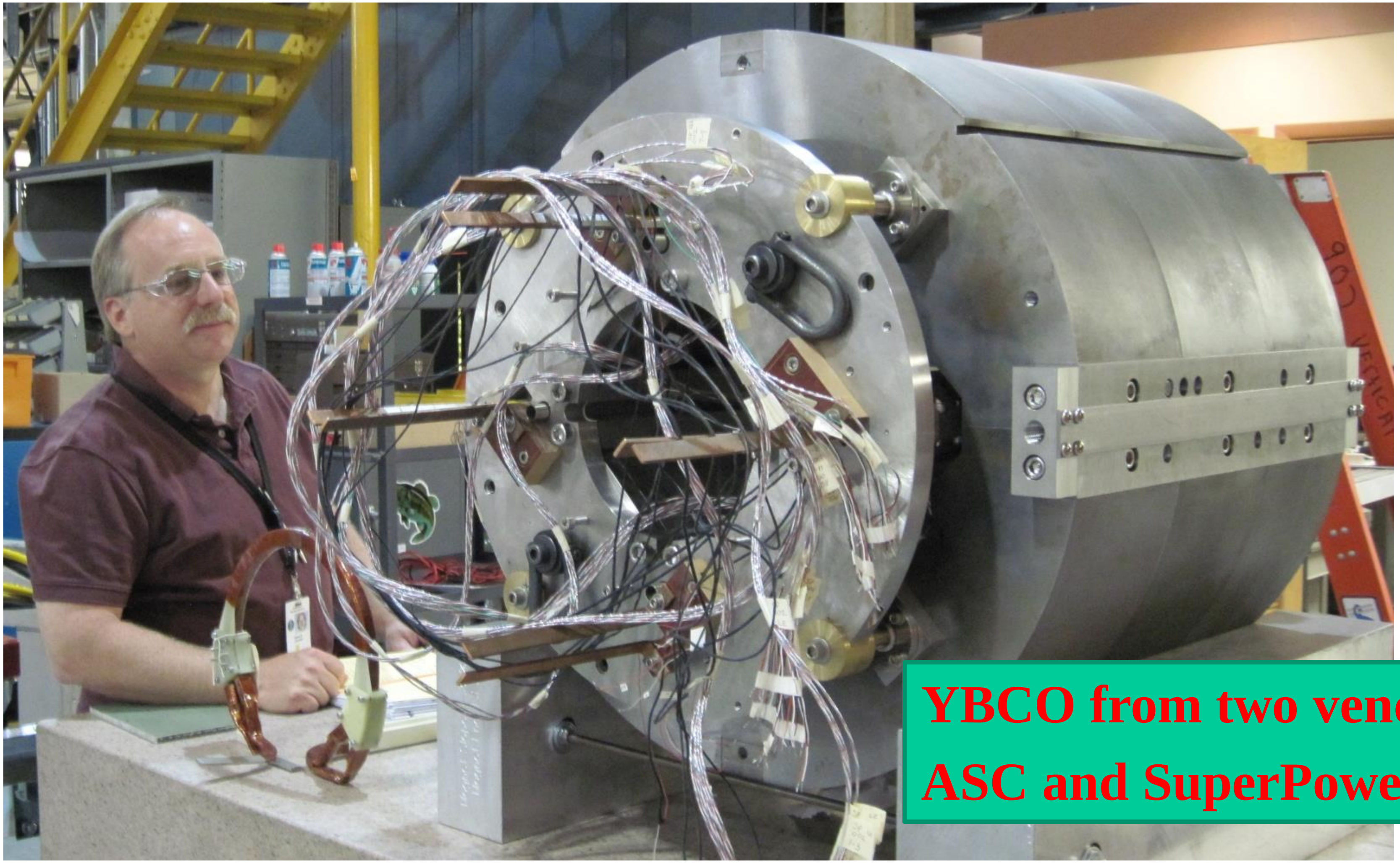
Peak fields higher

HTS Medium Field Quadrupole for FRIB

FRIB: Facility for Rare Isotope Beams, now under construction at MSU, USA.

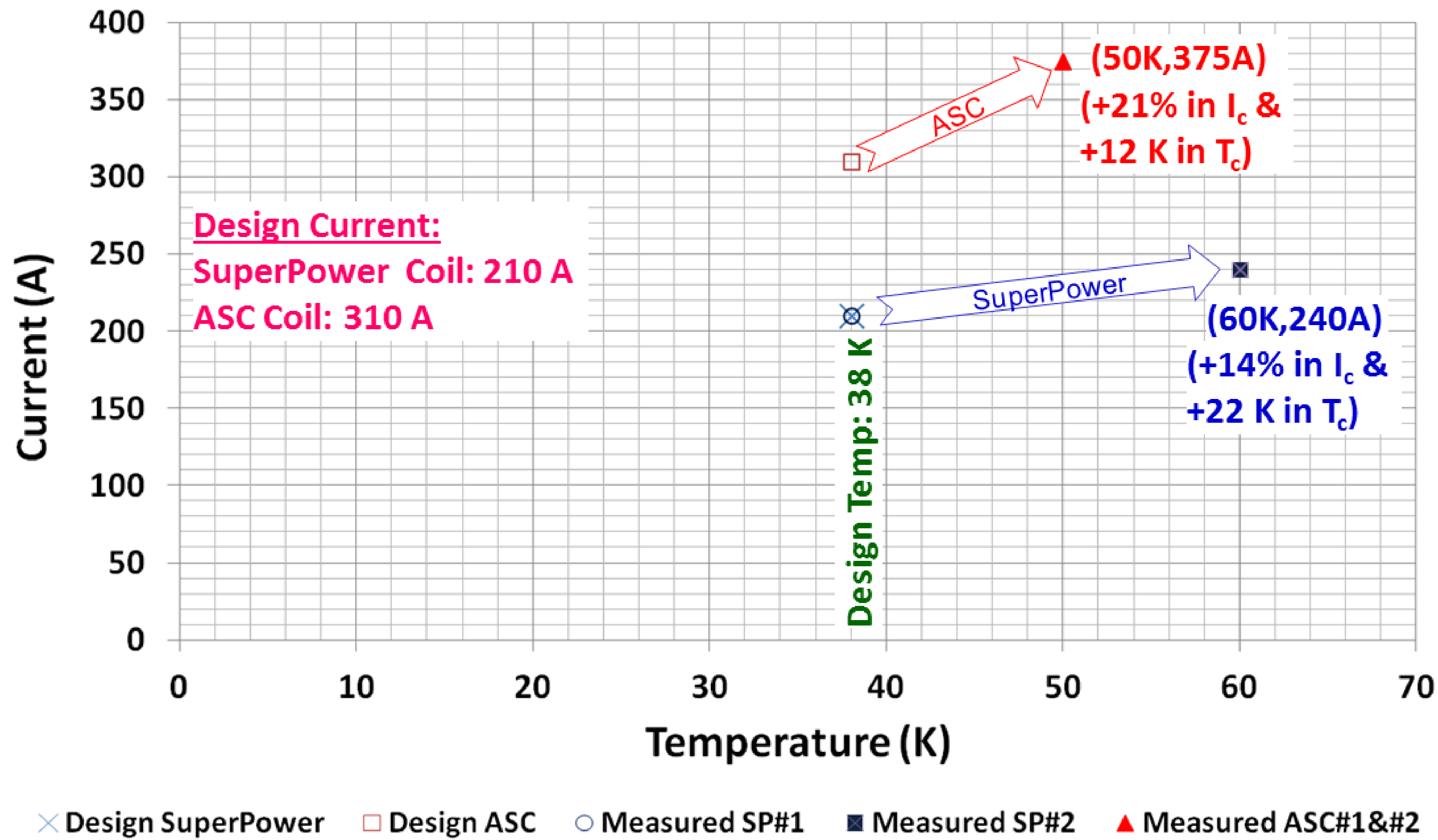
ReBCO HTS Quad for FRIB

2nd Generation Design



YBCO from two vendors
ASC and SuperPower

Large Temperature Margins (only possible with HTS)



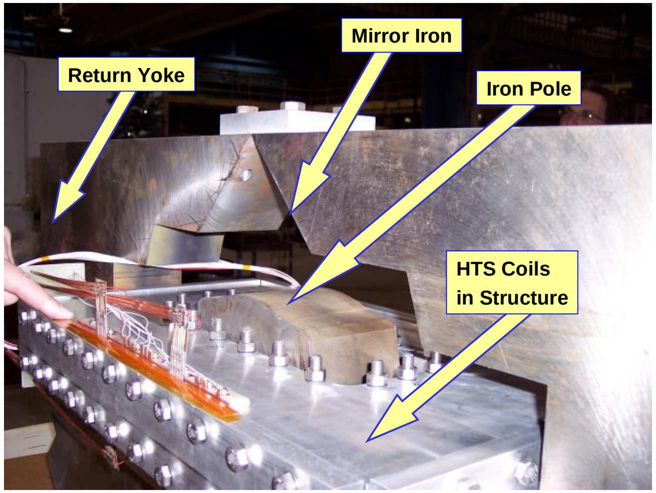
HTS provides robust operation against local and global heat loads

Selected HTS Bi2223 Tape Magnet Programs at BNL

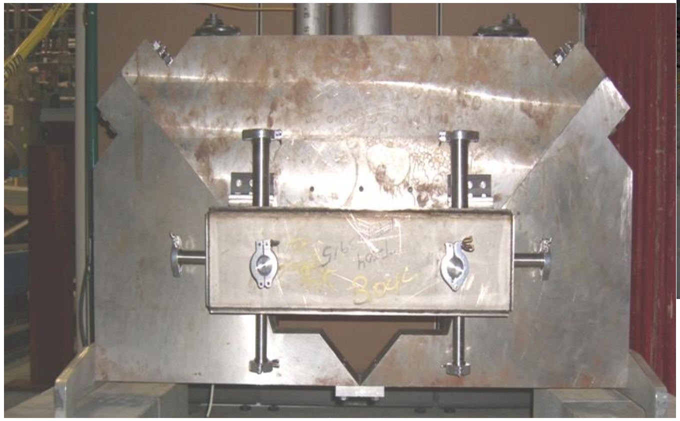
HTS Medium Field Quadrupole for FRIB

FRIB: Facility for Rare Isotope Beams, now under construction at MSU, USA.

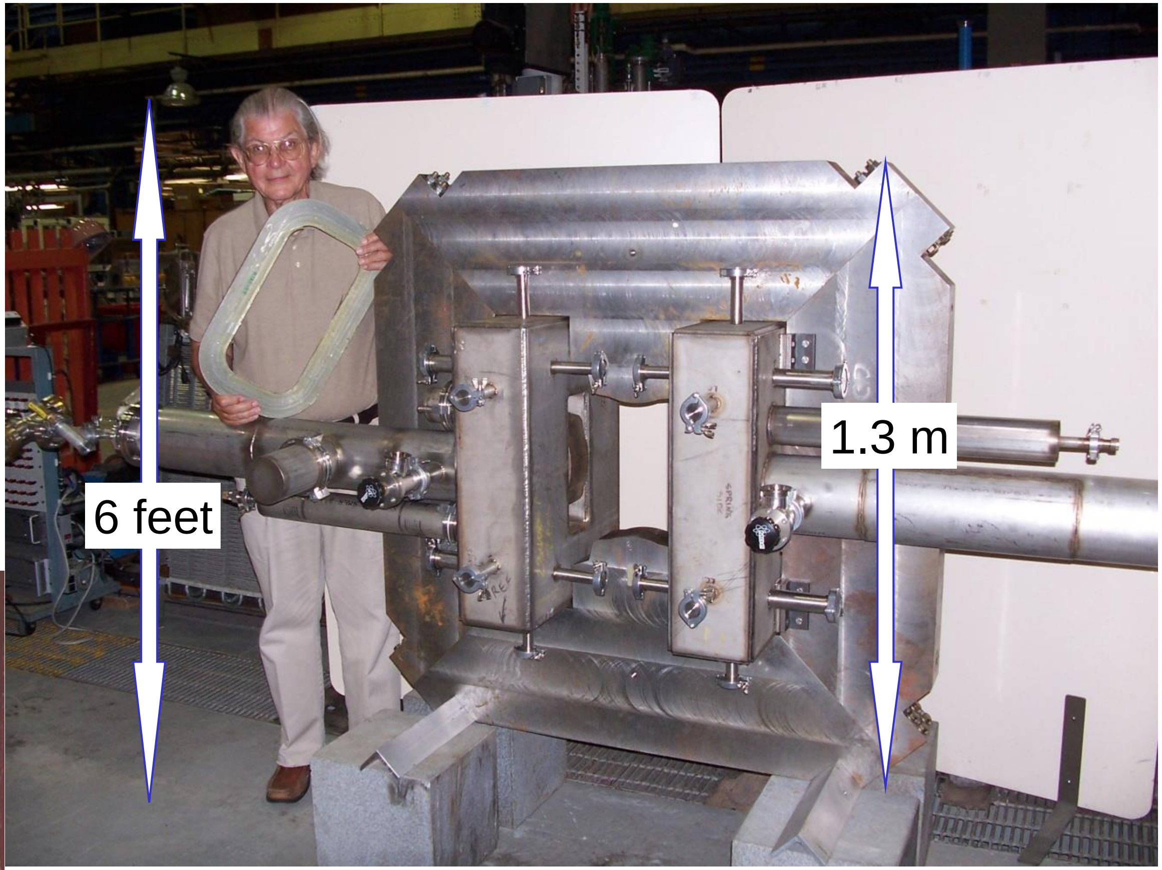
Bi223 HTS Quad for FRIB



Mirror cold iron

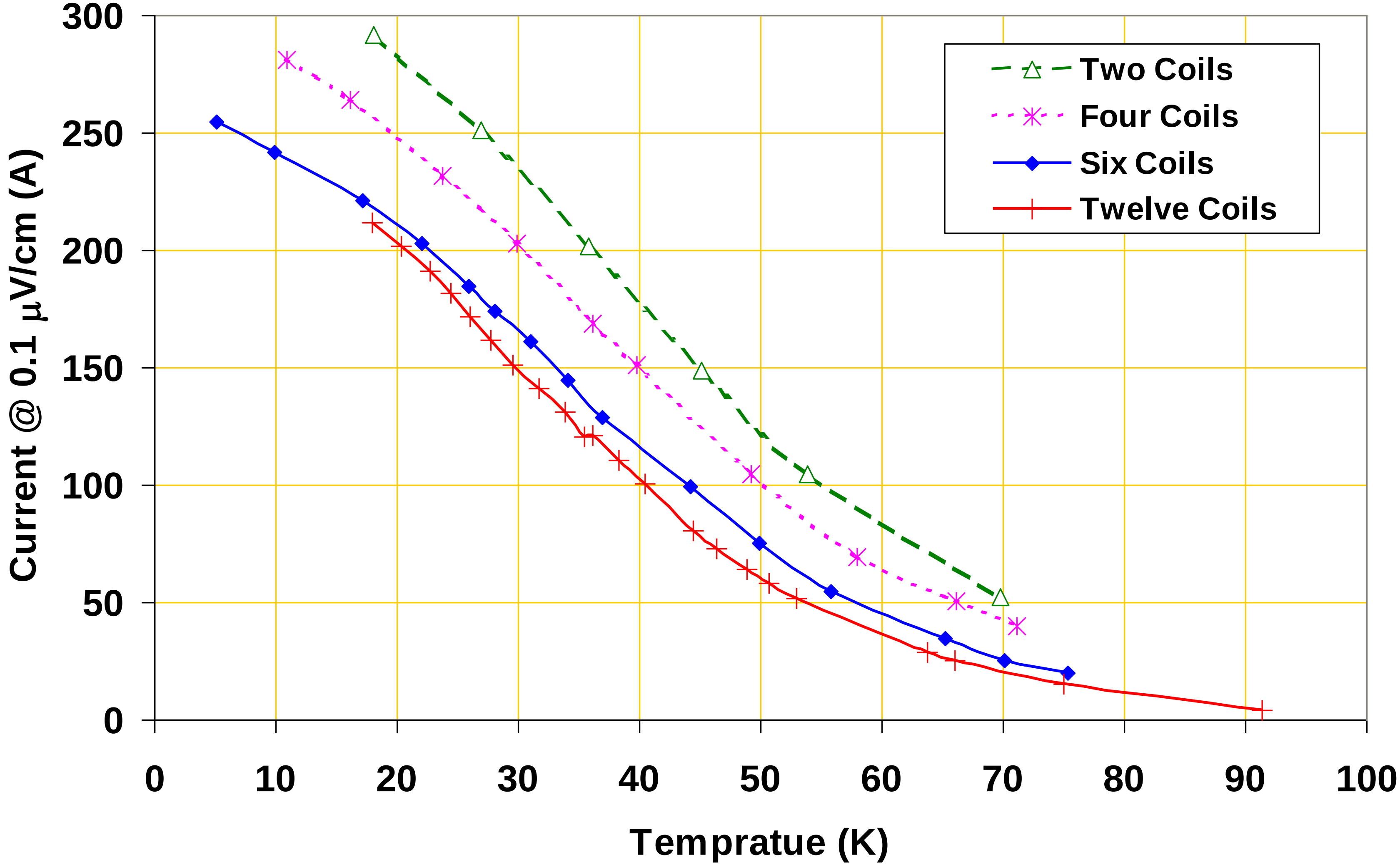


Mirror warm iron

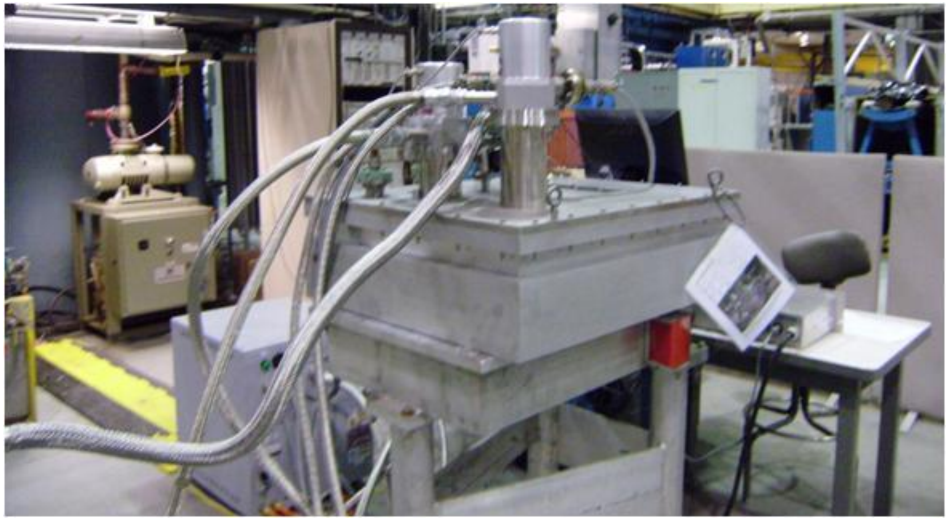


Warm Iron Design with Bi2223 HTS
(1st Generation Design)

First Generation HTS Quad Test (operation over a large temperature range)



A Warm bore Cryo-cooled Magnet with 6 HTS coils



Evening: Switch ON; Morning: COLD

Suitable for various studies

- ❑ **Quench studies**
- ❑ **Measure magnetization induced harmonics**
  - ➢ **as a function of time**
  - ➢ **as a function of temperature**
  - ➢ **as a function of field**

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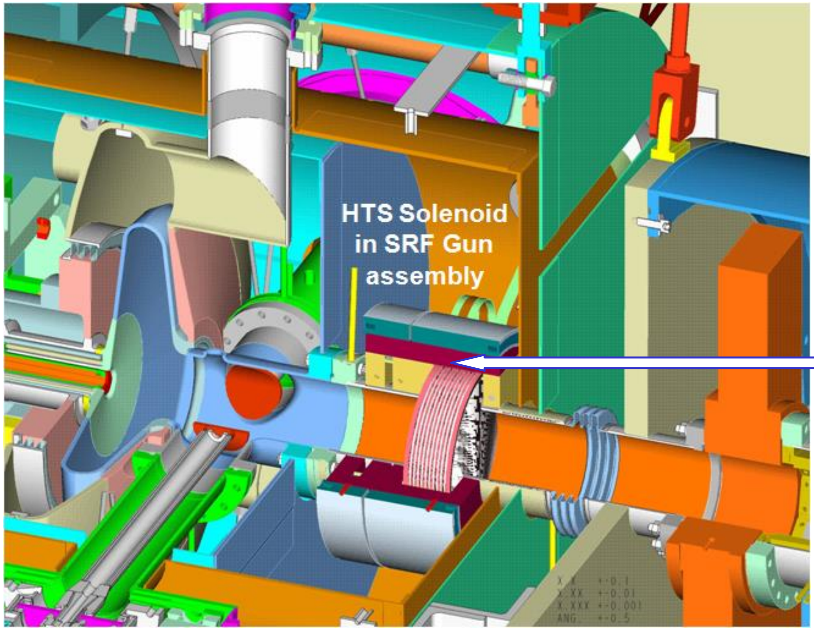
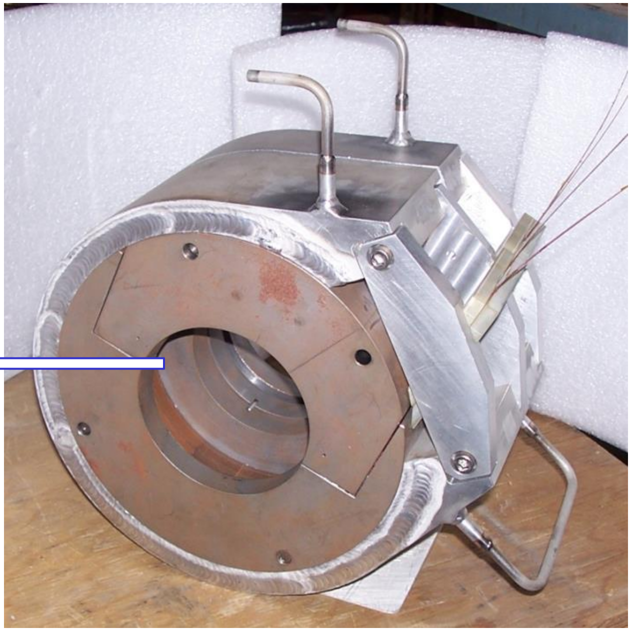
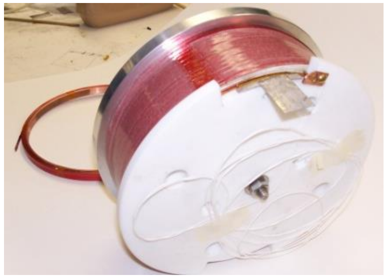
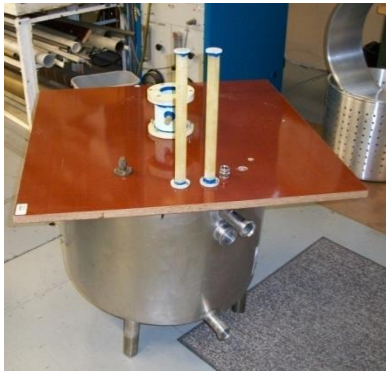
Superconducting Magnet Division

Low Magnetic Field Application
HTS Solenoid with Superconducting Cavity for the Energy Recovery Linac (ERL) at BNL





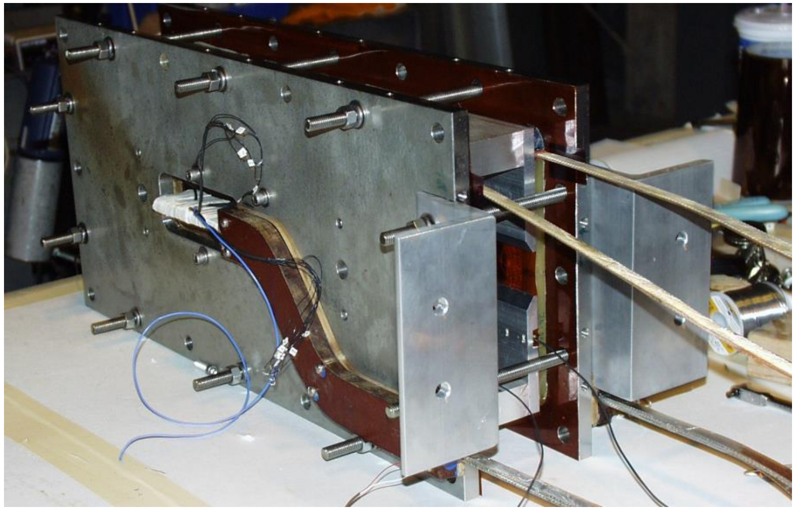


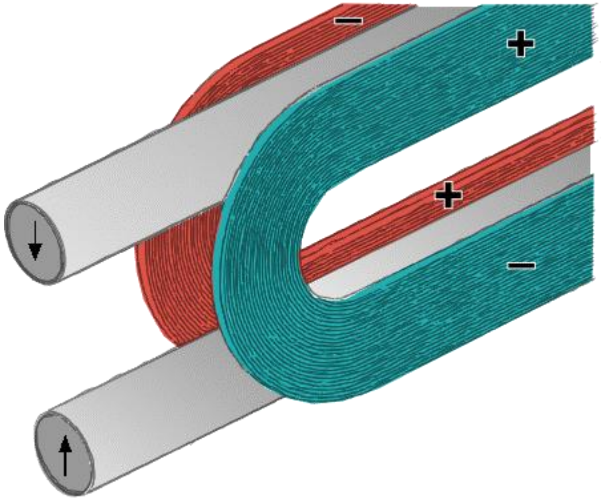


HTS solenoid is placed in cold to warm transition region after the superconducting cavity where neither LTS or copper solenoid would work

Early focusing provides a unique and better technical solution

Bi2212 Rutherford Cable Racetrack Coil Magnets for Hadron Collider





React & Wind Bi2212 Racetrack Coils for High Field Hybrid Magnets

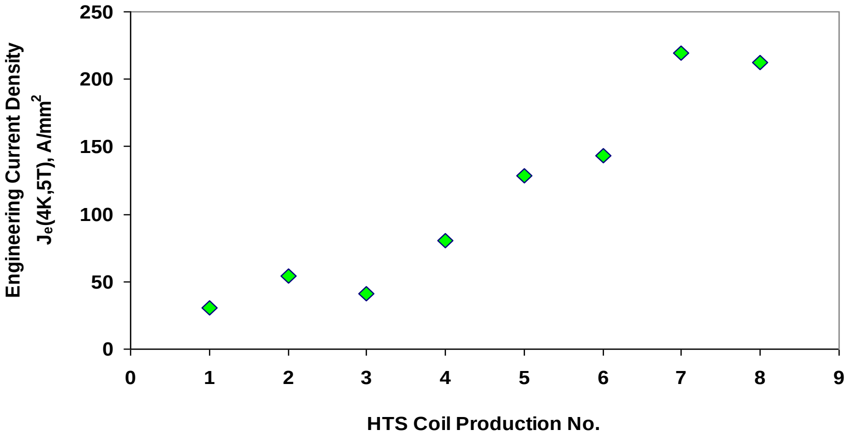
COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

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

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

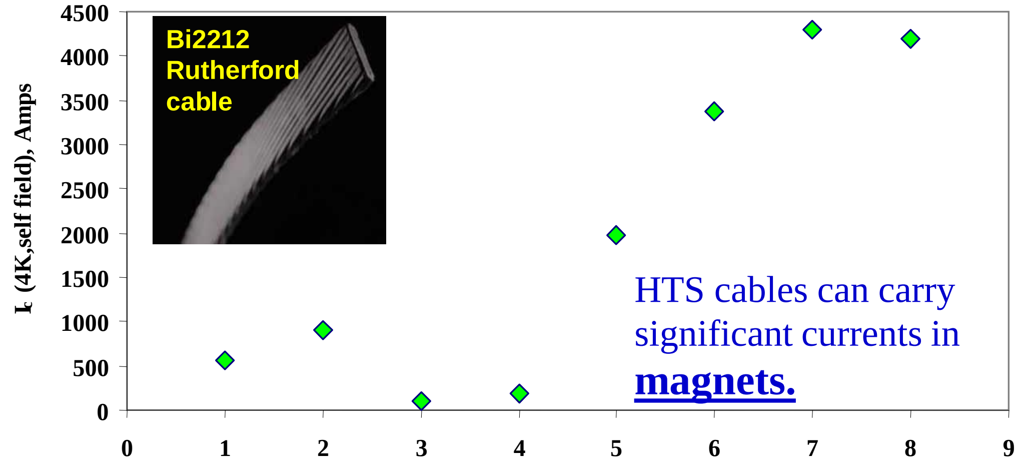
HTS Common Coil Dipole with React & Wind Bi2212 Rutherford Cable

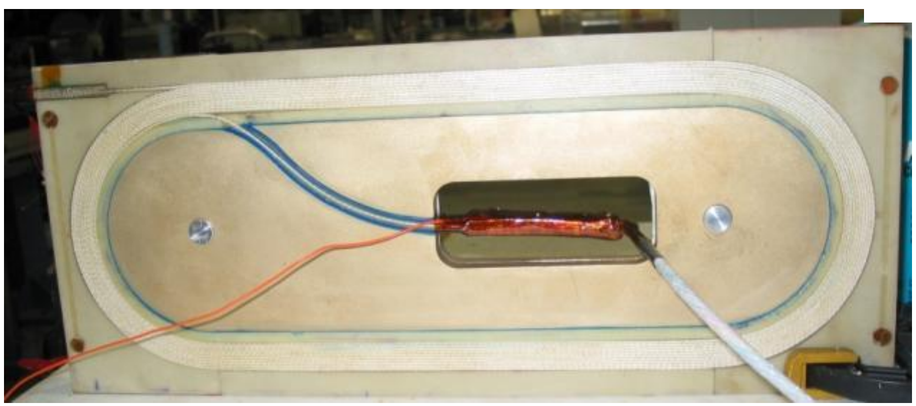
8 Coils and 5 Magnets built with Rutherford Bi2212 Cable



Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)





Racetrack HTS coil with Bi2212

2T

Still a record

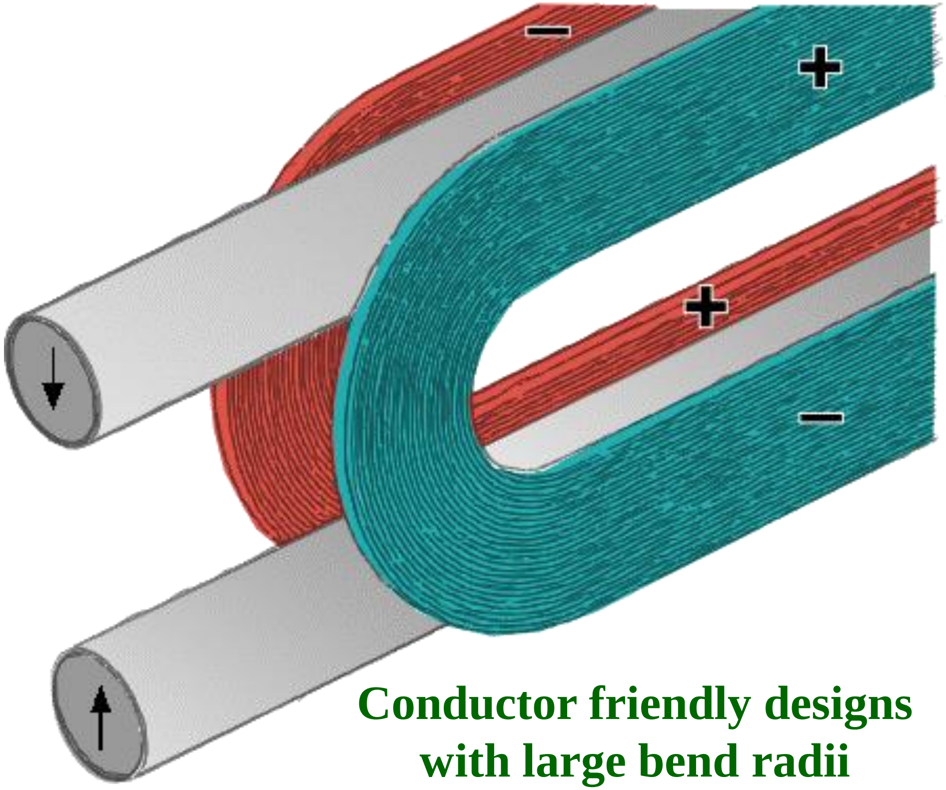
A Select Few Nb_3Sn Magnet Programs at BNL

LHC High Luminosity Upgrade

- LARP – Development of higher performance IR quadrupoles for LHC (ATLAS and CMS) – Nb_3Sn replacing NbTi
- New US (DOE + NSF) – CERN agreement signed May 7, 2015
- "LARP the Project" planned to begin FY18
  - CD-0 planned for FY16
  - TPC $181 M
- Magnets: BNL, Fermilab, Berkeley. SLAC also involved
- BNL tasks: conductor development and test, make coils, test magnets in vertical dewar

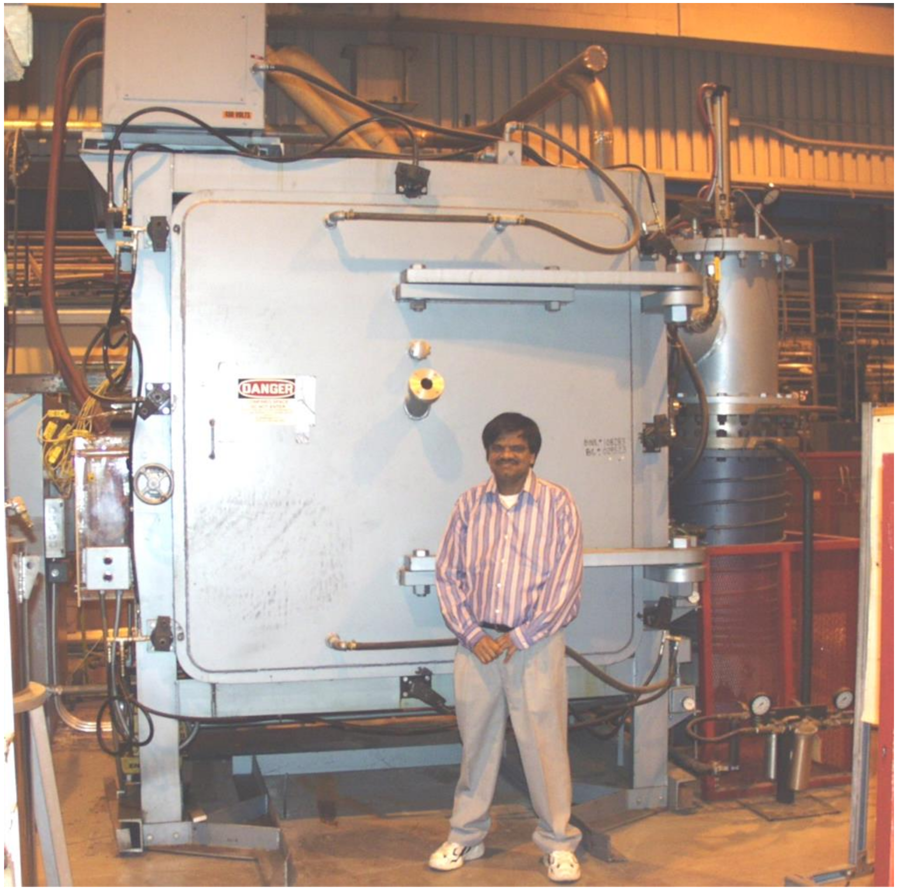
Wind & React Approach for Nb_3Sn Quadrupoles for LHC Luminosity Upgrade

React & Wind Approach for Nb_3Sn Dipole for proton-proton Collider



Conductor friendly designs with large bend radii

Large (1.5 m^3) reaction furnace

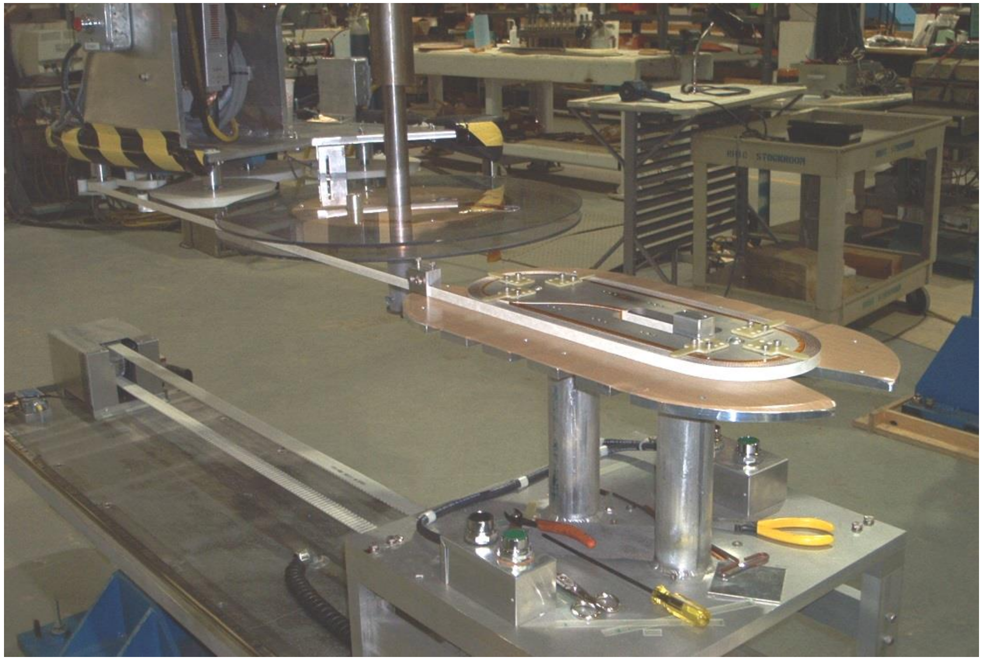


Used for reacting long lengths of Nb_3Sn cable

We use "React & Wind Approach" for HTS and both "React & Wind" and "Wind & React" for Nb_3Sn

Automatic Coil Winder

A Key Component of "React & Wind" Technology



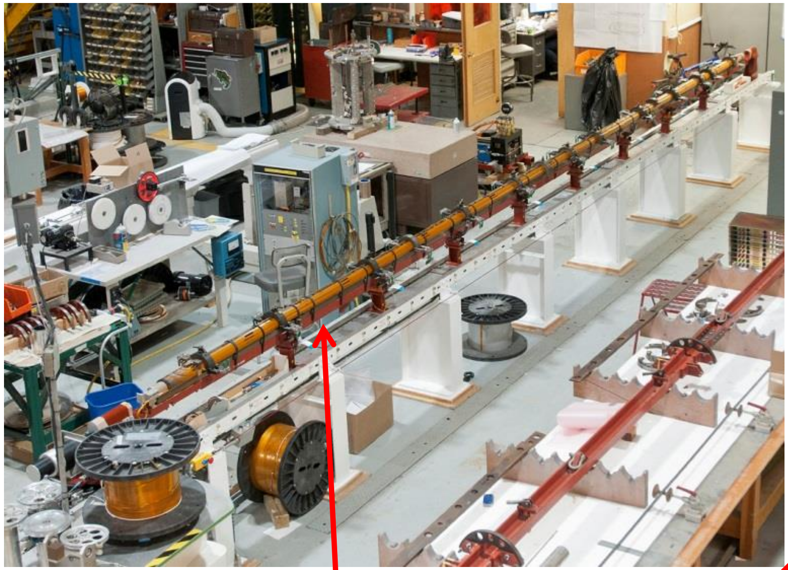
Each part and step in this new automatic coil winder is carefully designed to minimize the potential of bending degradation to brittle superconductors during the winding process. The machine is fully automated and computer controlled to minimize uncontrolled errors (human handling). All steps are recorded to carefully debug the process, as and if required.

A Select Few NbTi Magnet Programs at BNL

NbTi Magnets for RHIC, LHC

- RHIC:
  - Production of 1740 magnets at BNL and in industry
  - RHIC operation for 14 years – only two magnets replaced in that time – no interruption of RHIC operation for replacement
- LHC (present machine; IR ≡ near collision point):
  - Using RHIC tooling for 10 m IR dipoles
  - US-LHC: Produced 22 10 m dipoles for LHC IR's, .
    - No problems in operation
  - APUL: Two additional spare dipoles, completed 4/14
    - DOE Secretary Moniz's Honor Award 5/15

NbTi 10 m Coil Tooling



NbTi 10m coil wind and cure tooling, to be rebuilt for LHC 4.2 m quads

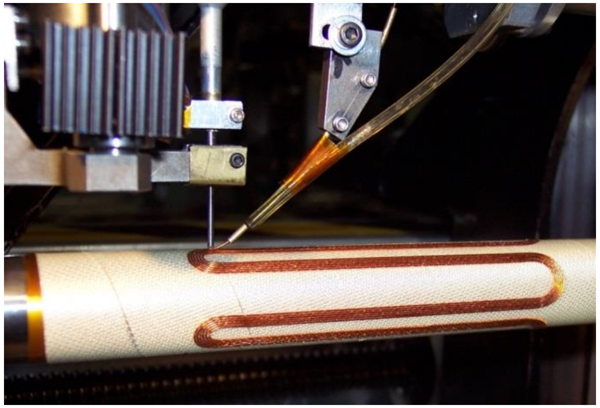
Additional 10 m tooling (collaring press, shell welding, vacuum and leak check, cold mass insertion) available.

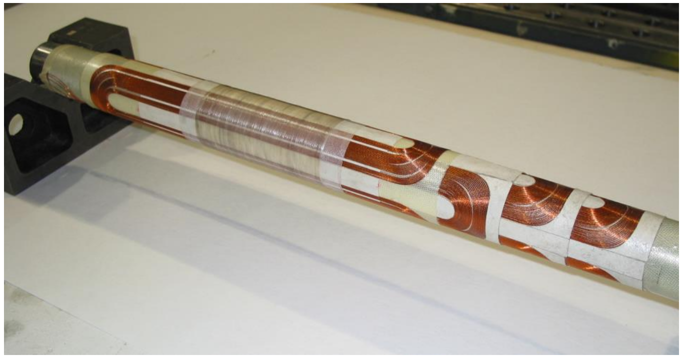
10 m APUL Dipole for LHC

Direct Wind CAD CAM Facility

- NbTi wires and small cables bonded to cylindrical support tubes using ultrasound with heat-activated adhesive.
- Generate multipole or solenoidal fields
- Special software translates physics design into conductor locations with 11 wiring machine parameters (e.g., strength of ultrasound signal)

Direct Wind machine

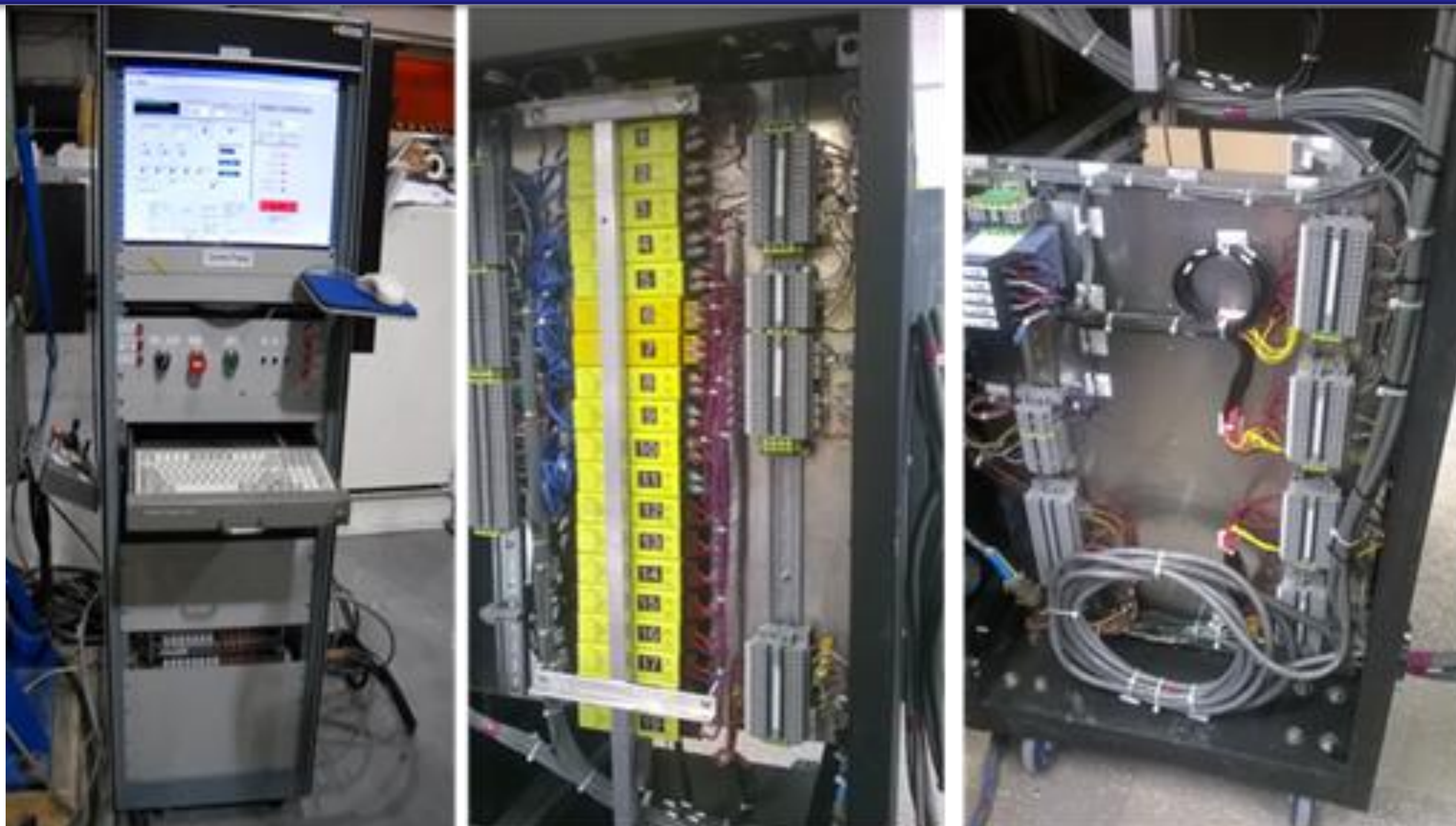




Magnet R&D Support

Advanced Quench Protection Electronics

A Significant Development in Support of HTS Magnets



Detects onset of pre-quench voltage at < 1mV and with isolation voltage > 1kV allows fast energy extraction

Supporting Facilities

- Superconductor characterization and optimization
- Vertical dewar tests of LARP 4.2 m quads (20 kA, 1.9K).
- Horizontal testing of magnets in cryostats (10kA, 4.5K)

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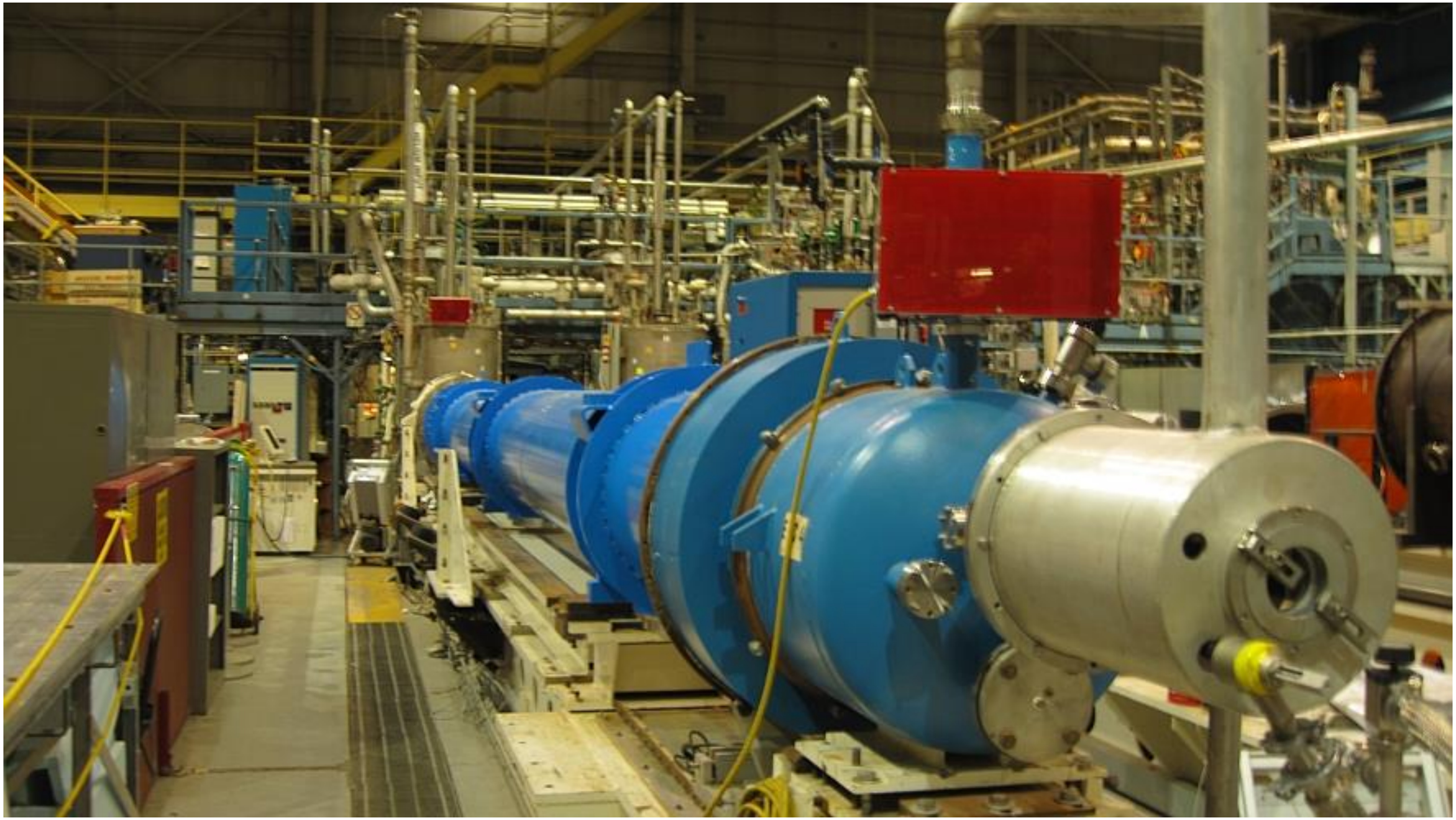
Vertical Test Facility (4.5 m, 1.9 K)

Horizontal Test Facility (10 m, 4.5 K)



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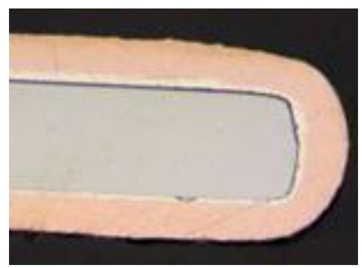
Conductor Testing

LARP conductor development

LARP conductor

HTS ReBCO



Strand test solenoids:

- 16T, 4.5K
- 12T, 1.9K
- 7T, 4.5K, I_c vs. theta (for ReBCO)

Summary

- BNL has built many types of superconducting accelerator magnets and installed them in-house and around the world.
- BNL has built magnets with a variety of superconductors in a wide range of field applications using a variety of technologies.
- BNL has a wide ranging facilities for testing superconductors, making coils and for building and testing magnets.
- BNL Magnet Division is ready to participate in the R&D needed for high energy proton-proton collider.