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Development of HTS Accelerator Magnets for Next Generation Colliders

Soren Prestemon, Xiaorong Wang

Superconducting Magnet Program

Lawrence Berkeley National Laboratory

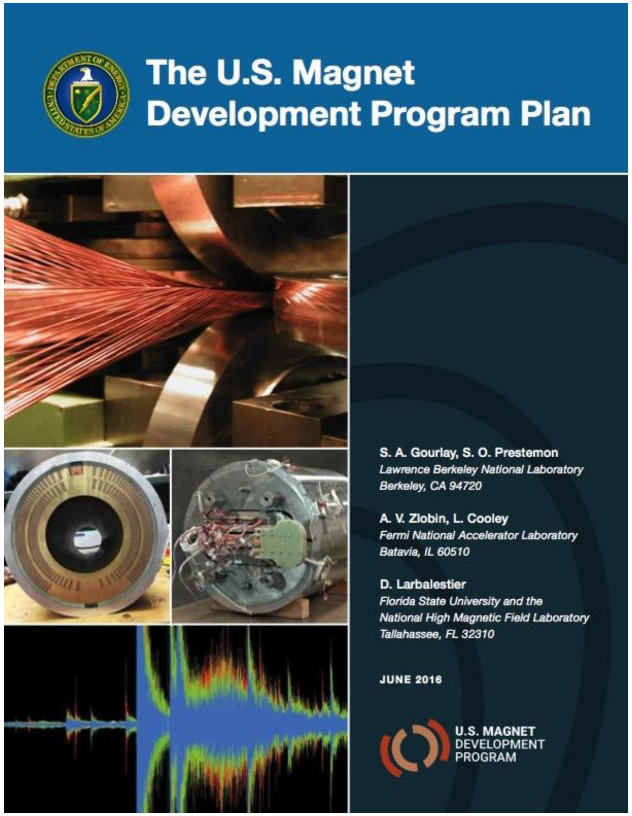
IAS High-temperature Magnet Workshop

January 19th – 20th, HKUST

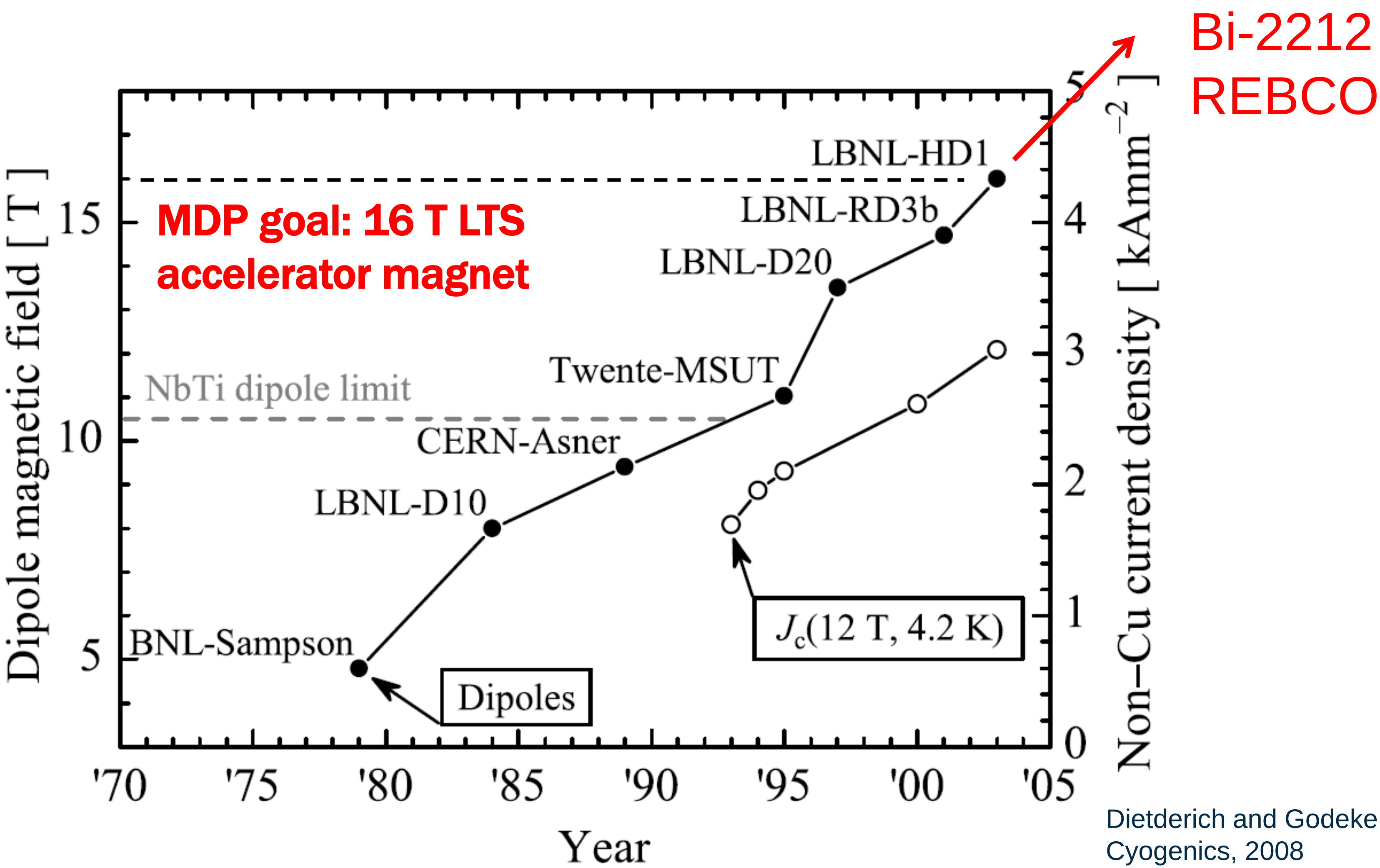
Renewed strong interest for high-field accelerator magnet R&D

- US HEP Magnet Development Program (HEP/MDP) is proposed as a premier national effort to develop high-field accelerator magnets
    - Address the P5 recommendations and regain global leadership in magnet technology
    - Significantly increase magnet performance/cost ratio

- A key focus of HEP/MDP is to investigate the feasibility of HTS magnet technology
    - Bi-2212 round wire and REBCO tapes
    - We focus on the REBCO magnets here



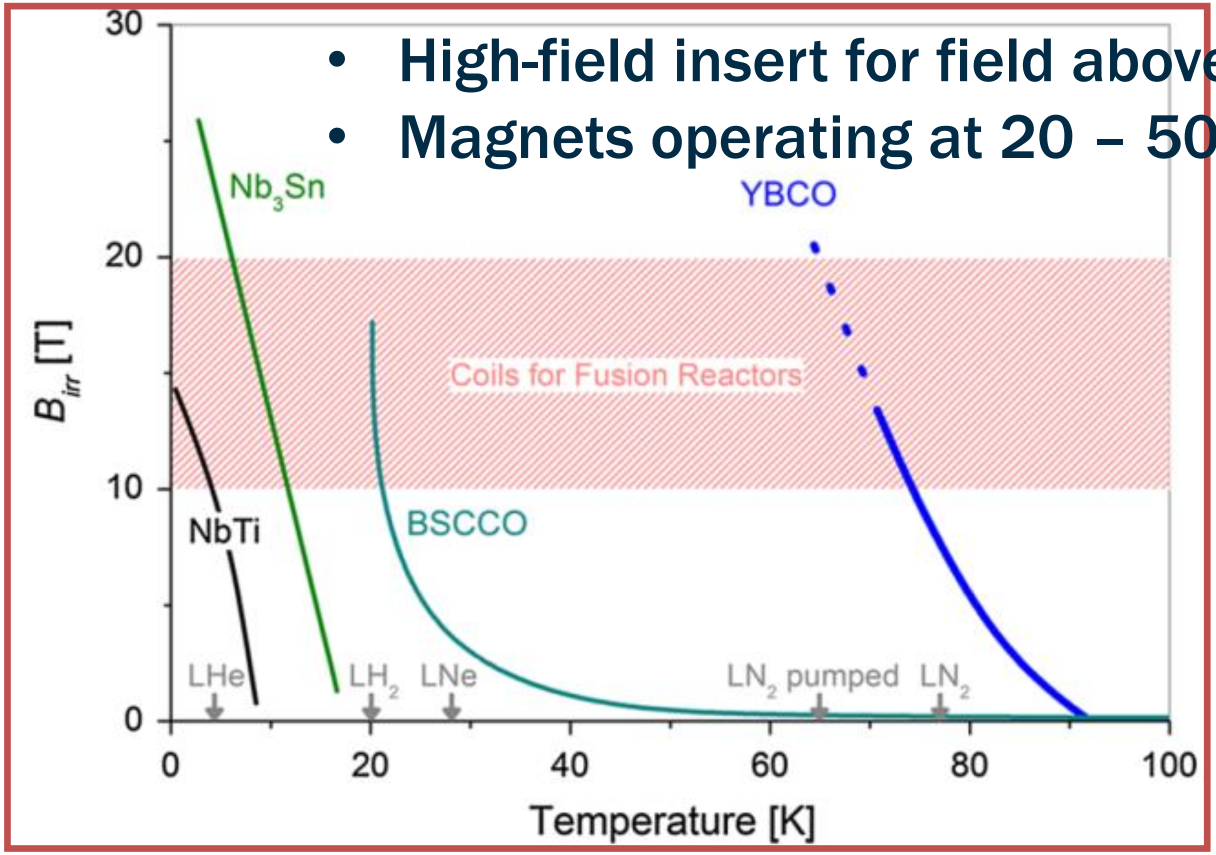
HTS conductors enable dipole fields beyond 16 T



Dietderich and Godeke, Cyogenics, 2008

REBCO has a strong potential for high-field magnets

- **High-field insert for field above 16 T**
- **Magnets operating at 20 – 50 K**



Whyte et al., J. Fusion Energy, 2016

- **Room for significant cost reduction**
  - **Low cost of raw materials and fabrication process**

REBCO tapes are not easy to use, …

- Brittle REBCO layer in a tape
  - Can be degraded by stress/strain during cabling, coil winding, and impregnation
  - We have to learn how to work with tapes for complicated magnet geometries

- Anisotropic I_c => complicated to predict the device performance

- Large filament => large magnetization and hysteresis losses

- Piece length and joints

..., but there is significant room for optimization

A few examples

- How much more current can the conductor carry?
- What is the optimal conductor architecture for cabling? What is the best cable configuration for accelerator magnets?
- Can we engineer the conductor/cable to make it self protected in case a quench?

- We need to build magnets to guide the optimization on
  - Conductors, cables
  - Auxiliary components (epoxy, structure and etc.)

Issues – conductor and cable

Issues	Remarks
Conductor performance	Critical current, quench behavior and AC loss as a function of strain, temperature and background fields.
Cable architecture	Differ between applications (e.g., fusion vs. HEP)
Mechanical tolerance	Mechanical load on conductor/cable during winding, cooldown, energization.
Fatigue tolerance	Impact of cycling on conductor performance.
Quench tolerance	Quench induced conductor degradation.
Radiation tolerance	Impact on superconductor, impregnation and insulation materials.
AC loss	Sources of AC loss and dependence on the conductor and cable design.
Joints	Low loss and demountable for fusion applications.

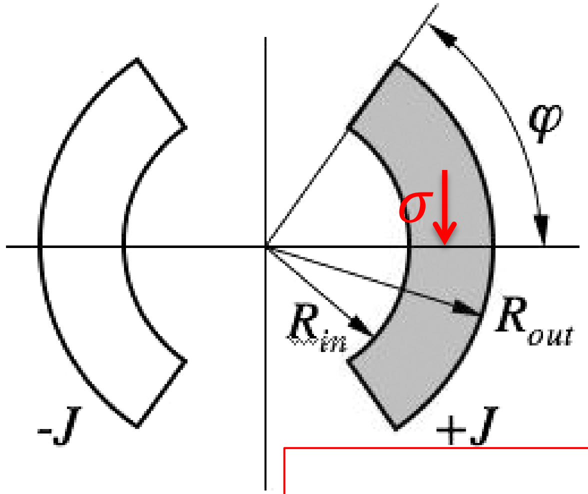
Issues – Magnet

Issues	Remarks
Design and analysis for high-field magnets	Integrated magnetic, mechanical, thermal design and analysis.
Structure materials and fabrication	Mechanical, electrical and thermal properties. Compatibility with HTS conductors. Fabrication method.
Coil fabrication technology	Winding of HTS cables, strain induced degradation. Insulation. Impregnation.
Cooling mode	Thermal budget and optimal cooling mode
Quench detection and protection	Advanced diagnostics for early detection and scheme for effective energy extraction.
Cost analysis	Analysis of cost-driving elements.

- We will discuss a few specific issues in more details

Challenges for REBCO High-Field Accelerator Magnets: Cables with high current density

- High J_e is desired for high-field accelerator magnets to limit coil size and magnet cost ()



Rossi and Bottura, Reviews of Accelerator Science and Technology, vol. 5, 2012, 51–89

- 10 – 20 kA class cable with J_e 200 – 600 A/mm^2
  - Allows current sharing between tapes
  - Reduces inductance to help with magnet protection (critical for LTS accelerator magnets)
  - But with high Lorentz stress transverse to the flat cable

REBCO cable concepts relevant to HEP application

Twisted stacked Tape by MIT

CORC® by ACT

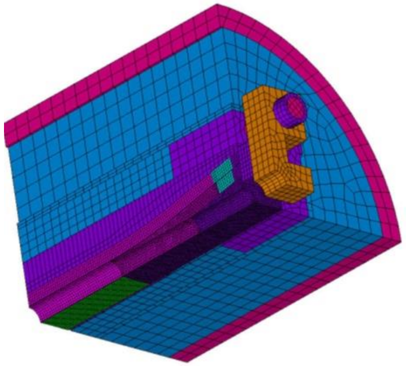
Roebel cable by KIT

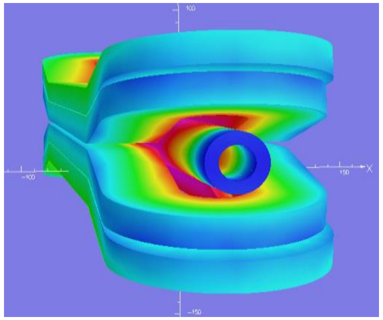
Pros	• Simple • High J_e • Isotropic J(B)	• Flexible round wire • Isotropic J(B)	• Flat cable • High J_e
Cons	• Winding compact coils	• Low cable/conductor length ratio • Relatively lower J_e	• Conductor waste • Anisotropic J(B)

- **The non-uniform contact resistance at terminals is an issue**
- **All three are good enough for magnet test building**
  - **We will show a few example later**

Challenges for REBCO High-Field Accelerator Magnets: Integrated approach for design, analysis and test

- Integrated design and analysis to understand the strain and take advantage/mitigate its impact
  - Magnetics, mechanics, quench dynamics
- Experimental data are critical to validate the analysis
  - Test of conductor, cable and magnet in relevant conditions





Structural and magnetic analysis of HD2 dipole magnet, P. Ferracin and G.L. Sabbi, LBNL

Challenges for REBCO High-Field Accelerator Magnets: Quench Detection, Protection and Magnetization

- Quench detection and magnet protection
  - High tolerance to thermal disturbances, but normal zone propagates slowly if at all => quench detection issue
  - Try different ideas on relevant subscale magnets
    - Fiber-optics, acoustics and etc.

- Strong magnetization with large filament size and high critical current
  - Deteriorate field quality (critical for accelerator magnets)
  - Increases hysteresis loss
  - Filament striation

REBCO accelerator magnet R&D at LBNL

- Develop and demonstrate the feasibility of REBCO accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.
  - Comprehensive development of magnet technology
- Provide rapid feedback between conductor and coil performance through subscale magnet development.
  - Target conductor optimization for specific application and reduce cost

Characterize and understand conductor/cable performance

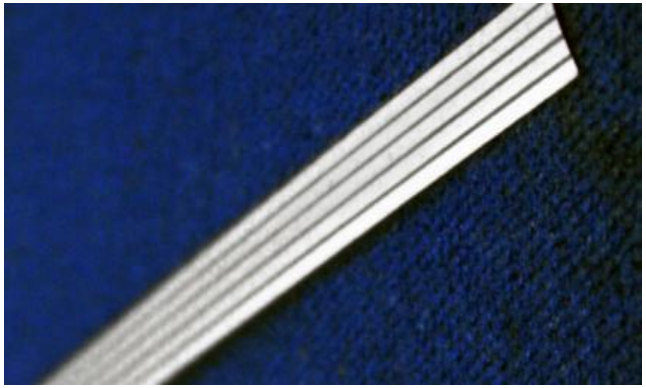
- Critical current, AC loss, quench behavior as a function of field, strain, and temperature
- Understand the impact on magnets
- 15 T solenoid 4.2 K
- Variable-temperature insert
- U springs for strain dependence
- 25 kA SC transformer (now at NHMFL/FSU)
- Tested NbTi, Nb_3Sn, and HTS (Bi-2212 wire, Bi-2223 and REBCO tapes)

60 mm bore, 15 T solenoid magnet

Conductor and cable testing

Engage Vendors to Improve Conductor Performance

- Conductor is an integrated component of the system optimization



Striated tape to reduce magnetization and AC loss

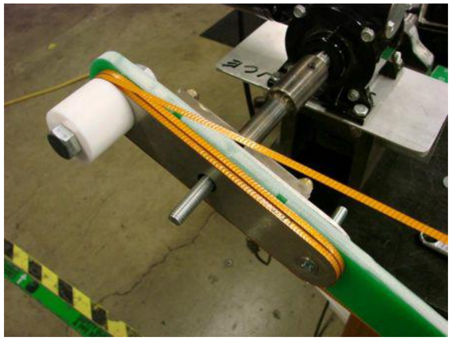
V. Selvamanickam,
University of Houston

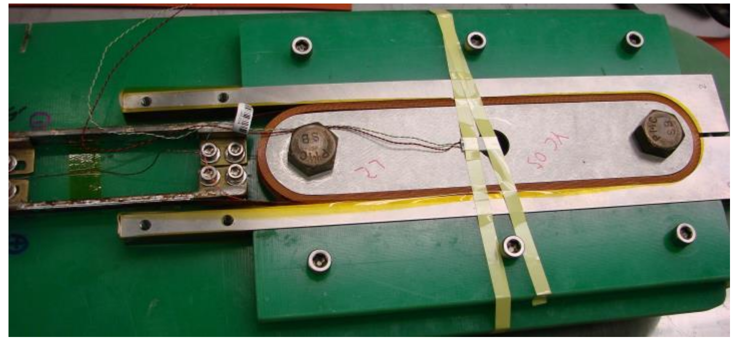
- Feedback to conductor and cable manufacturers on parameters that will improve magnet performance/cost ratio

Develop magnet technologies through subscale coils

- Capture essential magnetic and mechanical features of full scale magnet coils
- Develop advanced tools for integrated design and analysis of magnetics and mechanics
- Develop magnet technology on coil fabrication and test
- Develop and test optimal strategies for quench detection and magnet protection

Subscale racetrack coil with single tapes

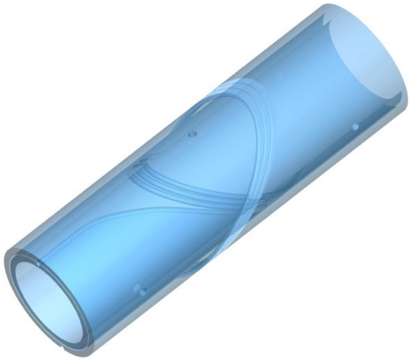


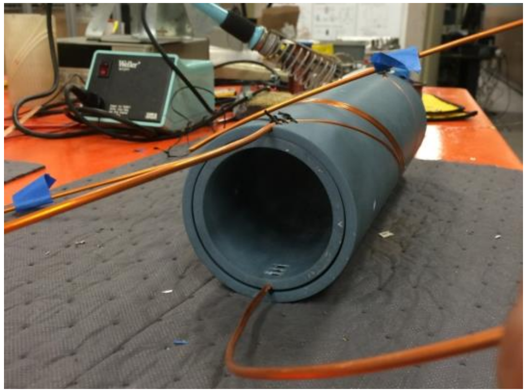


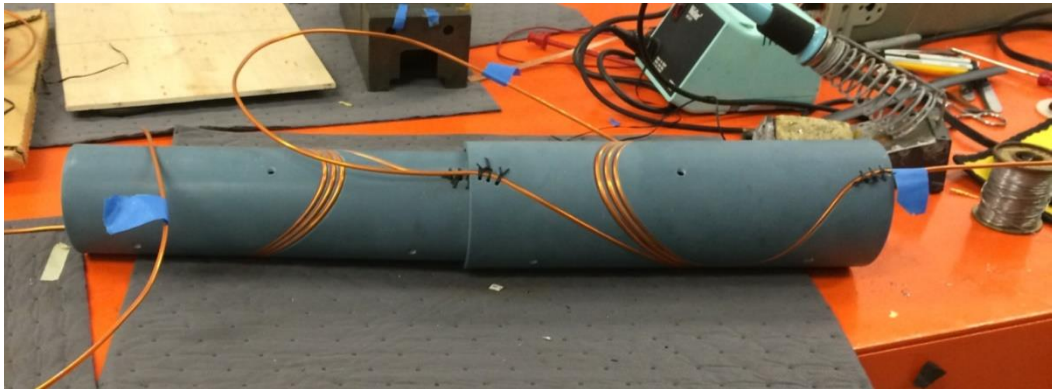
Coil	Turn	Structure	Potted	Meas. /Expected I_c	
				77 K	4.2 K
YC01	2x3	G10 bars	N	95%	-
YC02	2x10	G10 bars	N	91%	-
YC03	2x10	SS horse/end-shoe	Y	21%	-
YC04	2x3	G10 bars	N	92%	85%
YC05	2x10	Split SS horseshoe	N	86%	80%

Wang *et al.*, 2016 *Supercond. Sci. Technol.* **29** 065007

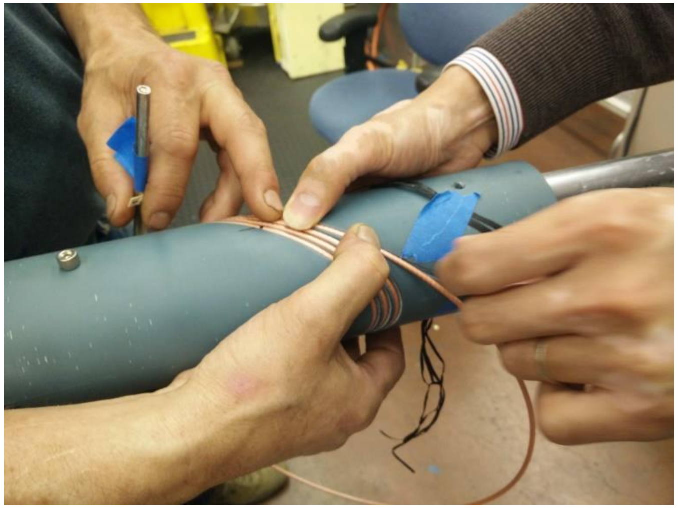
CCT subscale dipole coil with CORC® wires



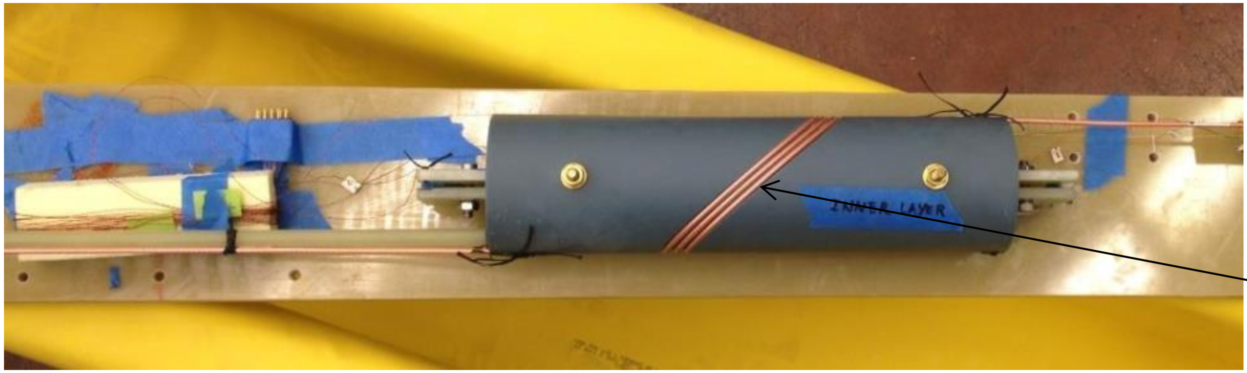




The 3-turn inner layer was wound and tested in LN_2

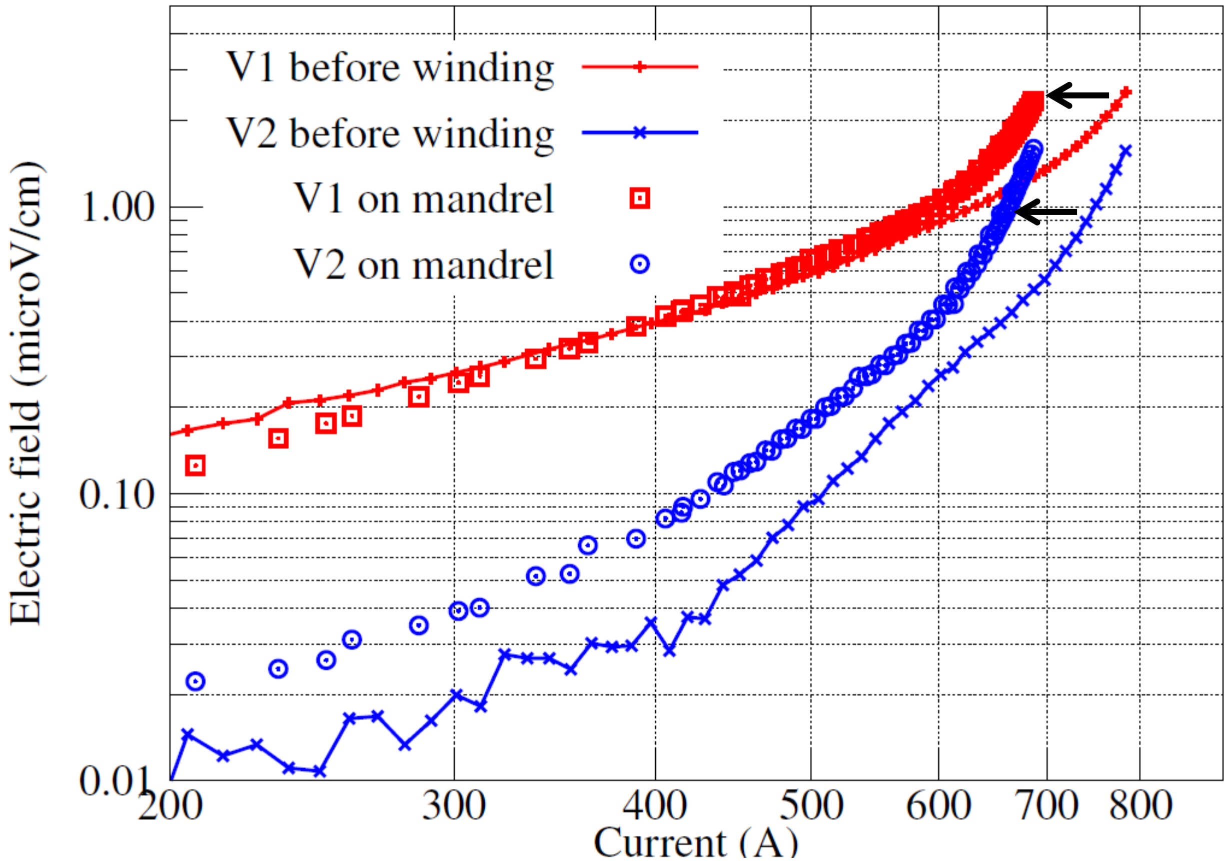


- CORC® wire diameter 3.09 mm
- 8 layer of REBCO tapes (SuperPower Inc.)
- Each tape 2 mm wide with 30 μm thick substrate



Hall sensor in the aperture

I_c degraded 11% after winding, consistent with vendor data



- 754 A to 673 A
- *n* value increased from 9 to 13

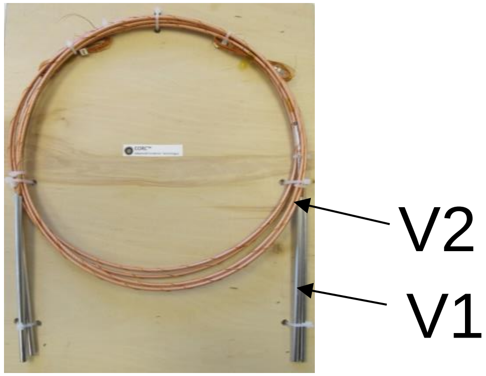


Image courtesy J. Weiss, ACT

Summary

- Renewed interest in high-energy proton-proton colliders to follow the LHC
  - Magnets with higher field/cost ratio will again be critical for the success of next generation machines

- HTS conductors have strong potential for accelerator magnet applications

- LBNL is developing technologies for REBCO accelerator magnet applications
  - Connect conductor developments with magnet needs

Back up slides

The HEP Magnet Development Program:
Overview of the HTS Milestone Plan, Highlighting the Bi-2212 Magnet Development (top) and the REBCO Magnet Development