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A collaboration framework to advance high-temperature superconducting magnets for accelerator facilities

US-Japan Hawaii Symposium of the US-Japan Science and Technology Cooperation Program
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1. Kyoto University, 2. KEK, 3. Lawrence Berkeley National Laboratory,

4. Brookhaven National Laboratory & UC Berkeley

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Outline

- Background
- Introduction of our team
- Tasks in the program
  1. HTS magnet technologies for high-radiation environment
  2. Stability, quench protection, and magnet safety
  3. Measuring and modeling AC loss and field quality of HTS accelerator magnets
  4. HTS/LTS high field hybrid accelerator dipole technology
- Conclusion

Why high-temperature superconducting (HTS) accelerator magnets required?

- High field generation
  (e.g.) ~ 20 T magnets for high-energy upgrade of the LHC
  -> Maximal central-mass collision energy of 35 TeV

- Improvement of power efficiency
  Replacement of conventional resistive magnets or raising the working temperature of superconducting magnets from 4.2 K to 20-50 K

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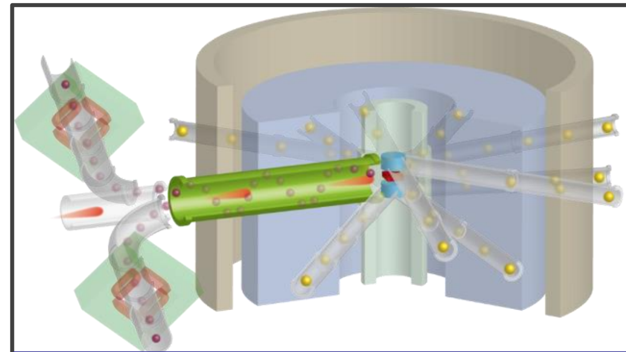
What is difficult for HTS accelerator magnets?

- High-radiation environment
  - ✓ Especially for capture magnets
  - ✓ Sustainable materials to high radiation



Muon Capture Solenoid for J-PARC MLF Second Target

- Magnet stability
  - ✓ Quench protection (quench: unexpected normal transition of magnets)

- AC loss and field quality
  - ✓ AC loss: energy dissipation caused by time-varying current and/or magnetic field
  - ✓ Persistent eddy currents in HTS cables/wires deteriorate field quality

Tasks

1. HTS magnet technologies for high-radiation environment
2. Stability, quench protection, and magnet safety
3. Measuring and modeling AC loss and field quality of HTS accelerator magnets
4. HTS/LTS high field hybrid accelerator dipole technology

The team: bringing together teams at KEK, Kyoto University, and LBNL, BNL to develop HTS magnet technology

Japanese Collaboration Members			
No.	Name	Institution	Position
1	Toru Ogitsu	KEK	Professor (PI)
2	Tatsushi Nakamoto	KEK	Professor
3	Michinaka Sugano	KEK	Associate Professor
4	Msami Iio	KEK	Lecturer
5	Naoyuki Amemiya	Kyoto University	Professor (co-PI)
6	Yusuke Sogabe	Kyoto University	Assistant Professor
7	Xijie Luo	Kyoto University	Graduate Student

U.S. Collaboration Members			
No.	Name	Institution	Position
1	Tengming Shen	LBNL	Staff Scientist (PI)
2	Xiaorong Wang	LBNL	Staff Scientist (co-PI)
3	Ramesh Gupta	BNL	Senior Scientist (co-PI)
4	Laura Garcia Fajardo	LBNL	Research Engineer
5	Cory Myers	LBNL	Postdoctoral Researcher
6	Christopher Reis	LBNL/UC Berkeley	Graduate Student Affiliate
7	Piyush Joshi	BNL	Electrical Engineer
8	Jesse Schmalzle	BNL	Mechanical Enginner
9	Glenn Jochen	BNL	Mechanical Technician
10	Shresht Joshi	BNL	Scientific Associate

Advanced HTS Magnet Technologies for Future Accelerator Sciences

Kyoto Univ.
Graduate School of Engineering Department of Electrical Engineering
Advanced Technologies on AC-Loss and Field Quality Analysis on HTS magnets

UC Berkeley
Dept of Nuclear Engineering
Experimental material science for nuclear applications

BNL
Member of US-MDP
Developing Various HTS Magnets
Advanced Technologies for HTS Magnet

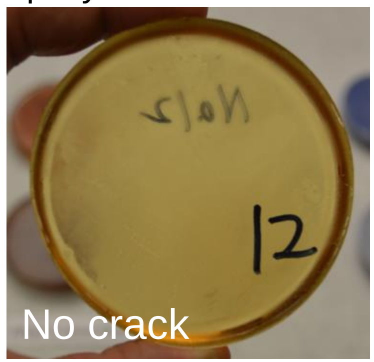
LBNL
Member of US-MDP
Developing 20 T HTS Accelerator Magnets
Advanced Technologies for High Field Accelerator Magnet

KEK
Developing HTS Magnets for High Radiation Environments
Advanced Technologies for HTS Magnet with Radiation Hardness

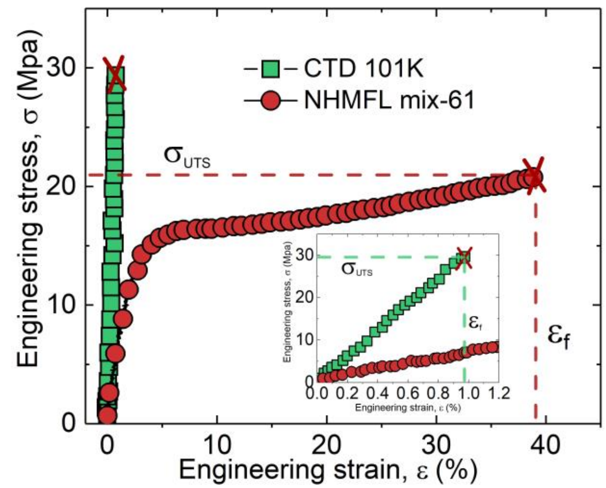
Task 1: Irradiation of a novel epoxy developed at QST gamma-ray facility (KEK + LBNL)

CTD-101 k, used by US LARP, after one thermal cycle to 77 K

NHMFL-mix61, an amine-based epoxy after one thermal cycle to 77 K

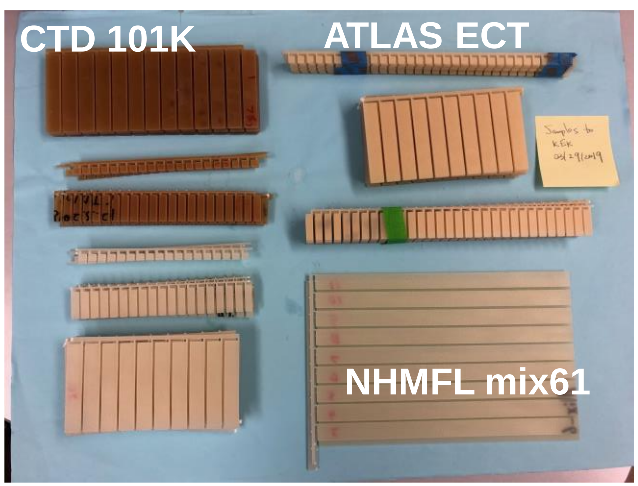


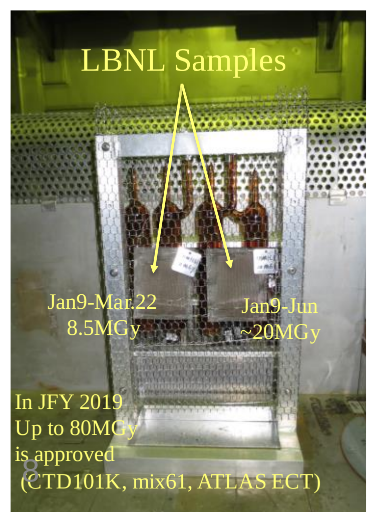
RT tensile test



Yin, Shen et al., IEEE Trans. Appl. Supercond., 2019

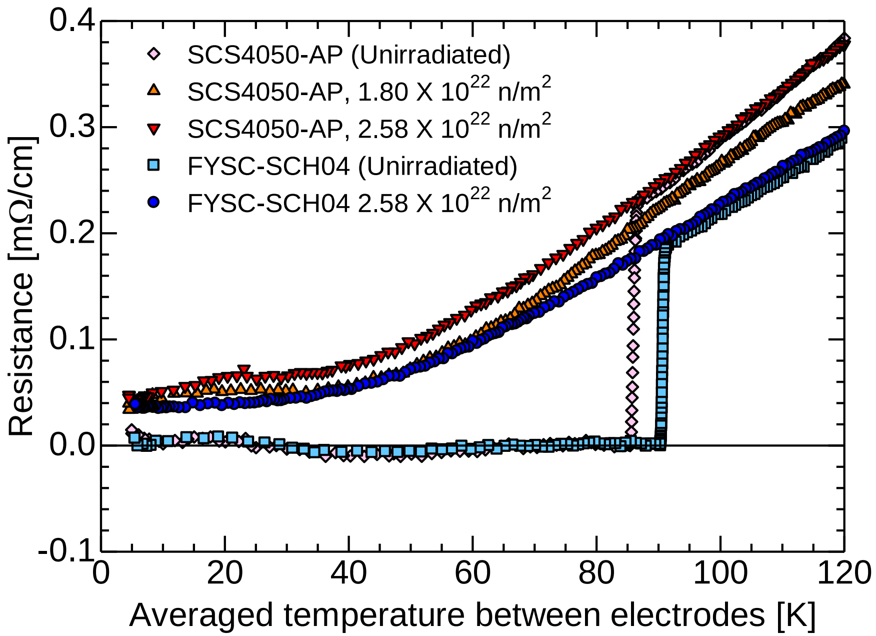
- **25 MGy, 50 MGy, 100 MGy irradiated**
  - **Samples shipped to LBNL.**
  - **Mechanical tests pending.**





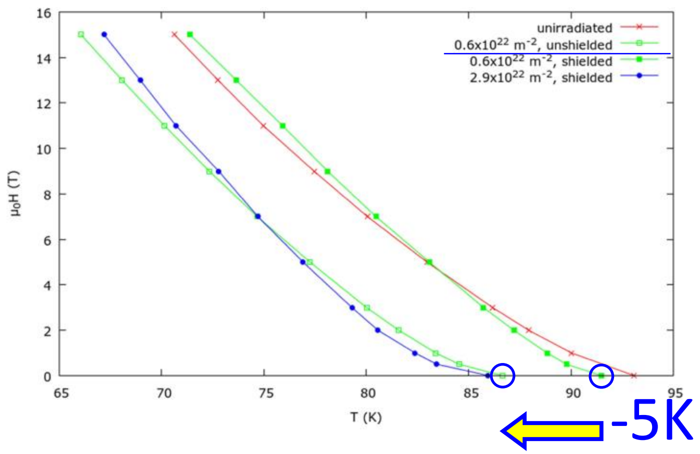
Task 1: Neutron irradiation to HTS conductors

PIE of GdBCO samples with neutron flux of 1.80, 2.58x10^{22} n/m^2



☐ Vanishment of superconductivity is confirmed

Neutron irradiation effect on Tc
***influence of Cd foil for SuperPower SCS4050**
D. X. Fischer, et al., Supercond. Sci. Technol. 31 (2018) 044006



- **No significant degradation in shielded HTS tape at 0.6 x 10^{22} n/m^2.**
- **But, reduction of Tc by 5 K in unshielded sample.**

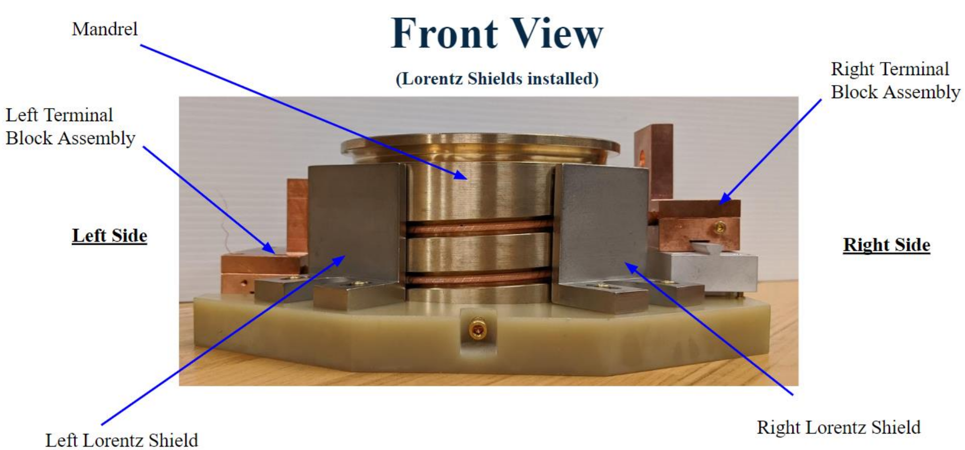
Further study

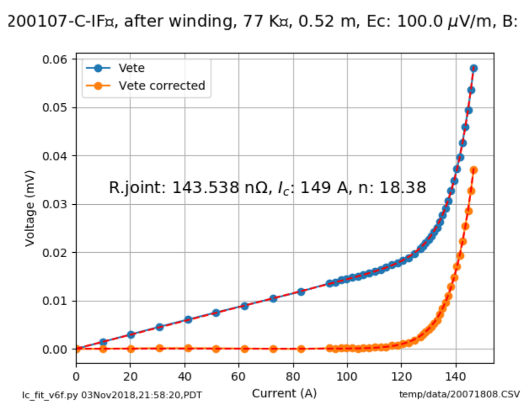
- **PIE of GdBCO samples of target fluence 1x10^{21}, 5x10^{21} n/m^2**
- **Fast neutron irradiation by shielding of samples with Cd foil**
- **Irradiation of EuBCO samples to confirm the contribution of Gd**
- **Materials analysis of irradiated samples by X-ray diffraction**

Task 2: Stability and quench protection of HTS magnets – LBNL delivered samples and sample holder for quench experiment at Kyoto Uni.

Samples provided by Advanced Conductor Technologies

- The multi-REBCO-tape CORC® wire is promising for HEP magnet applications
- The collaboration under US-Japan will enable us to fully understand the stability and quench behavior of CORC® wires in conditions relevant for applications





- I_c 149 A at 1 μV/cm criterion, 91% of expected I_c
- After multiple times of winding and unwinding during the development of sample holder
- Reproducible VI transition

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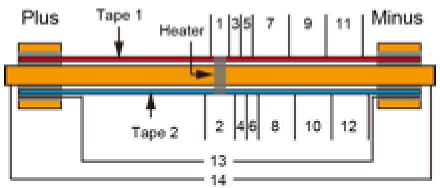
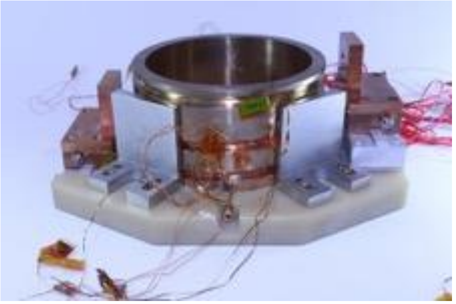
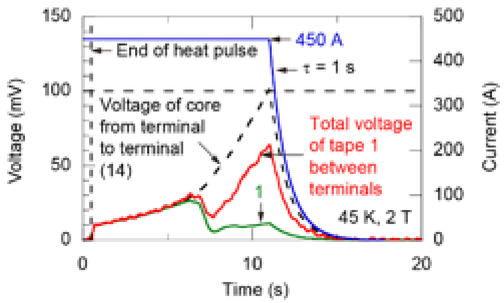
Task 2: Quench experiments of CORC and other spiral conductors

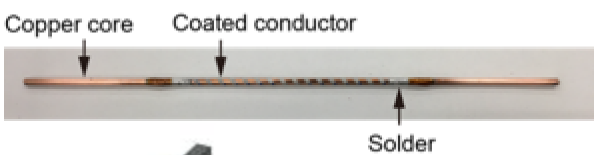
Quench experiments using CORC samples provided by LBL

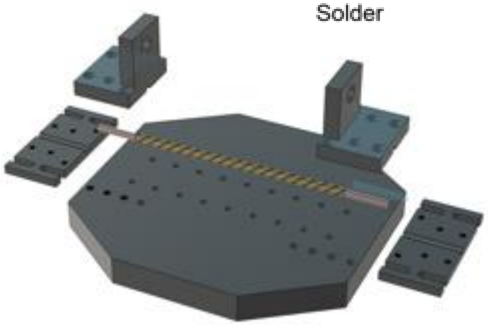




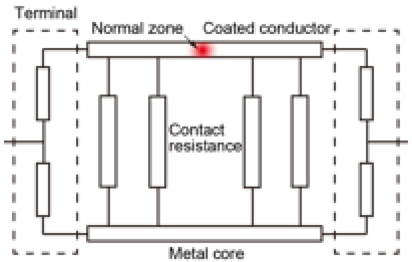


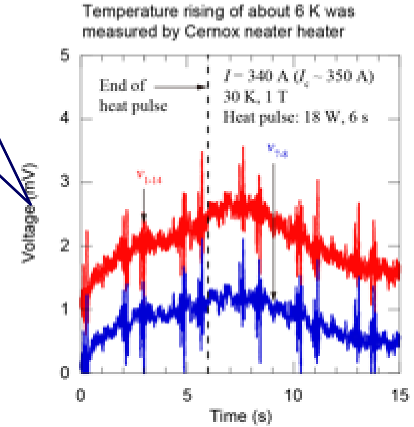
Quench experiments using short "home-made" spiral samples





Normal voltage appeared but not quenched





Copper core looks helping protection.

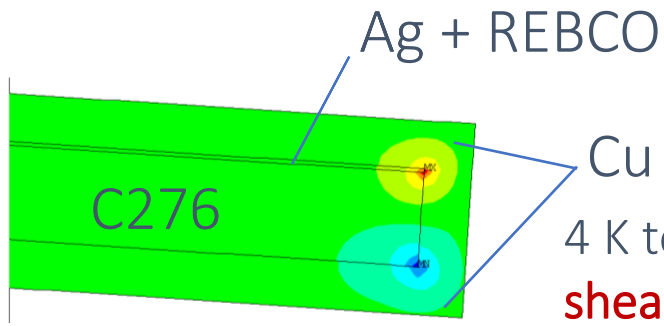
Task 2: Stability and quench protection of HTS magnets: LBNL developed a method to minimize damages during a quench of REBCO tapes


Journal of Applied Physics

Degradation of REBCO coated conductors due to a combination of epoxy impregnation, thermal cycles, and quench: Characteristics and a method of alleviation

Cite as: J. Appl. Phys. 128, 173903 (2020); https://doi.org/10.1063/5.0026000
Submitted: 21 August 2020 . Accepted: 20 October 2020 . Published Online: 05 November 2020

Shijian Yin, Mattia Duranti, Charles A. Swenson, Pei Li, Liyang Ye, Xinguo Zhang, and Tengming Shen



4 K to 300 K,
shear stress >23 MPa

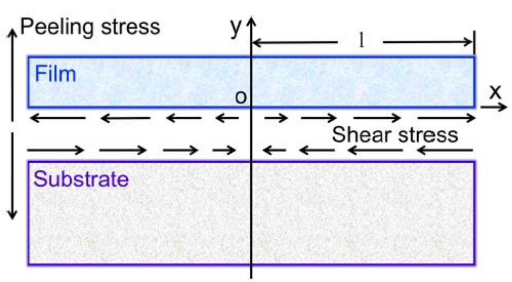
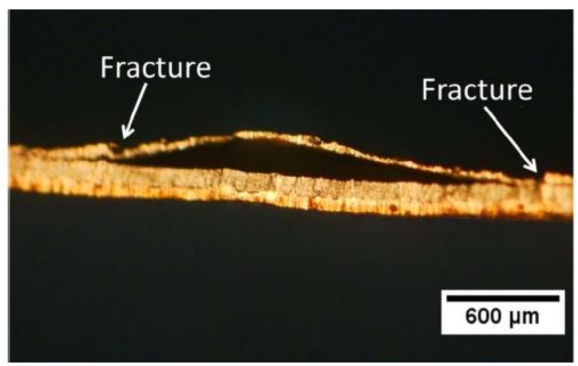
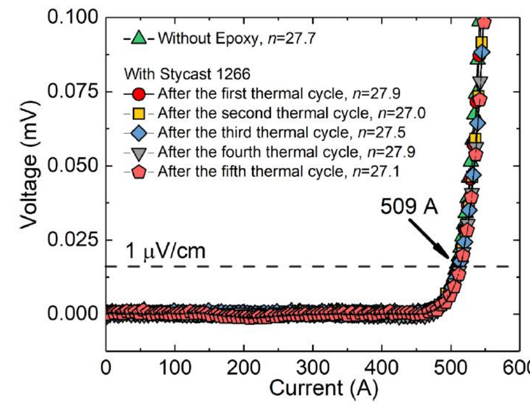


FIG. 9. A two-layer thin film with a width of 2l experiencing both peeling stress and shear stress during a temperature change.

Delamination by thermal stress.



Removal of damages using a simple and scalable method.



- Methods to determine peeling and shear stress during a quench established. Simple analytical model also cross-checked with FEM models.

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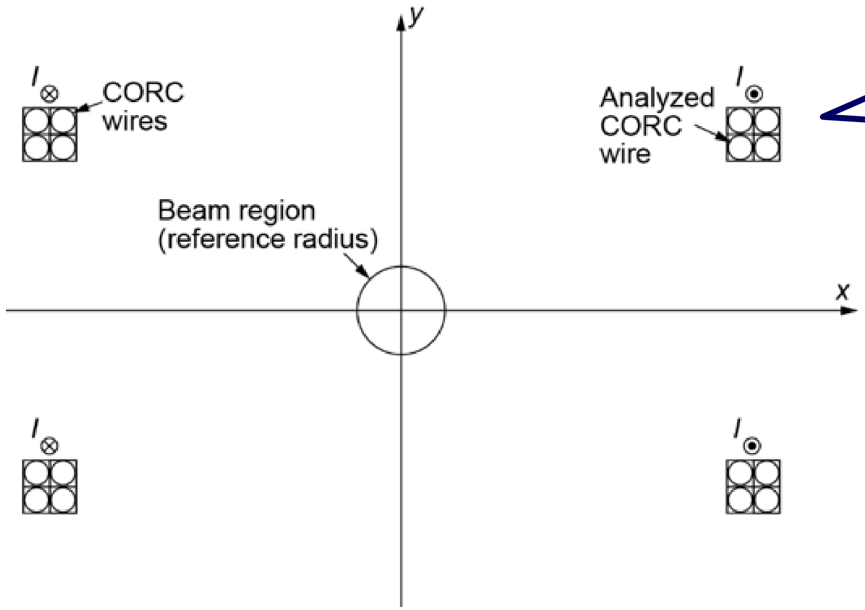
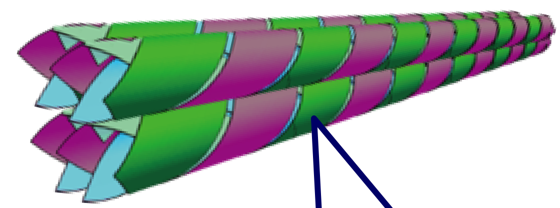
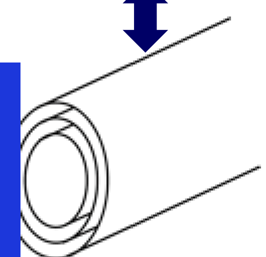
Task 3: Simple calculation and analyses of field quality of CORC magnets

Simple field calculation (quasi-3D model for RTC)





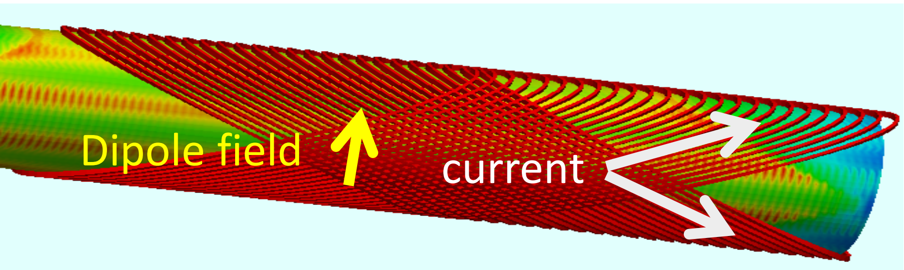
Calculated current distribution

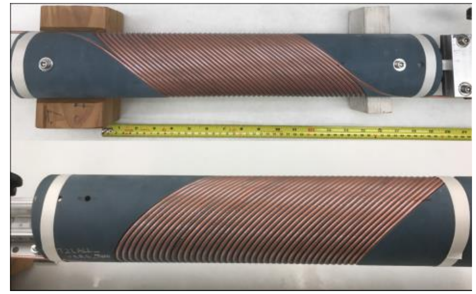


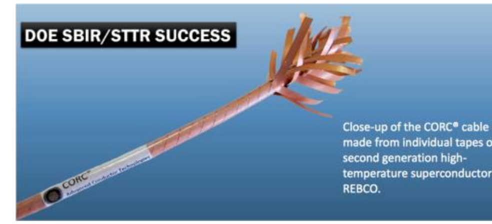
Coaxial three layers with uniform current distribution

A simple calculation method was developed in order to evaluate influence of CORC wires' geometry and shielding currents on field distribution along *z*-axis.

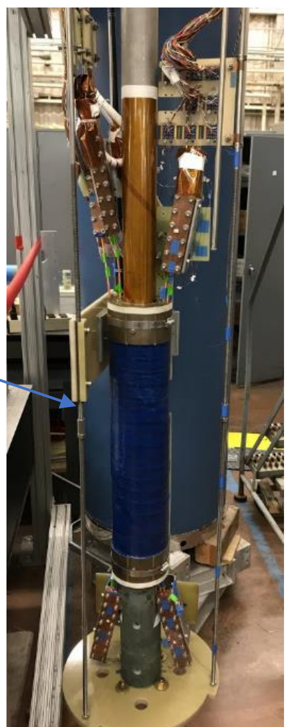
Task 3: Field quality of LBNL C2 magnet based on a new round REBCO CORC wire (65 mm aperture, 2.9 T dipole field at 4 K) accessed at LBNL and provided to Kyoto University for analysis.





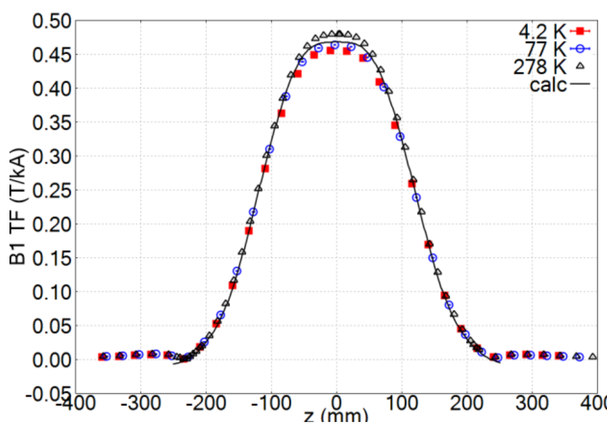


C2 magnet

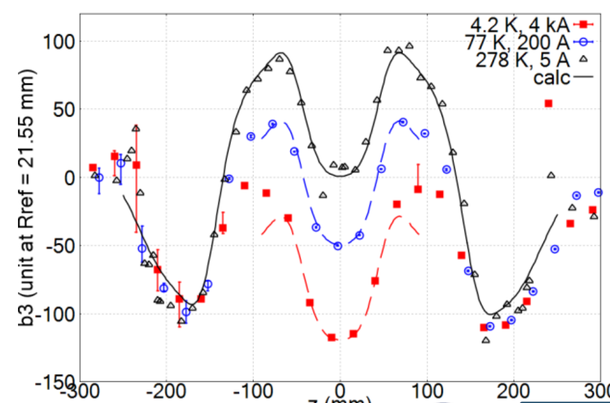


- The 65 mm-aperture C2 magnet generated a dipole field of 2.9 T at 4.2 K, providing the unique opportunity to measure and understand the field quality of a REBCO dipole magnet using CORC® wires

Measurements agree with the calculation for the dipole field

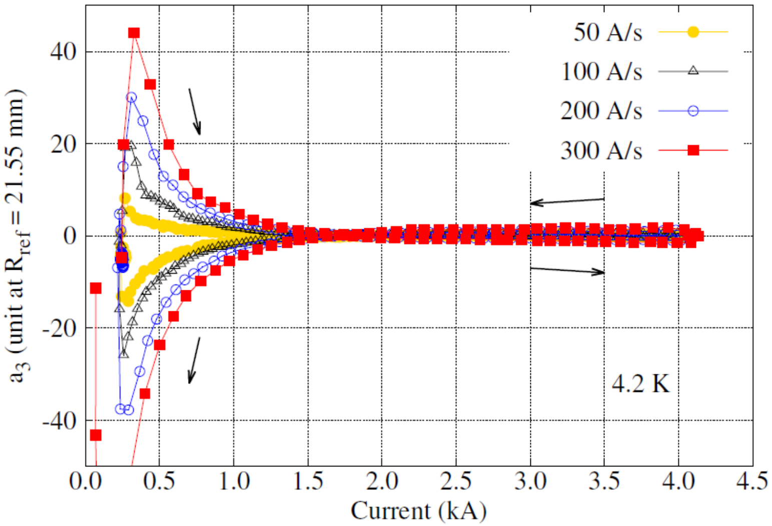


Strong magnetization effects in b_3 – too large due to the high J_c and tape width



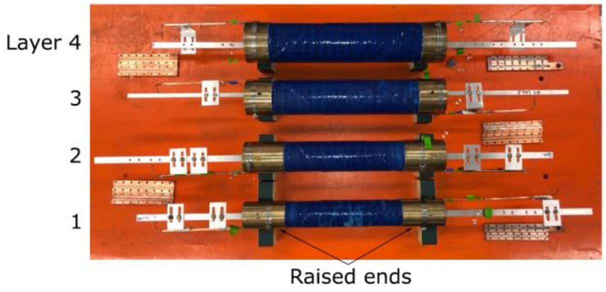
Task 3: Field quality of LBNL C2 magnet. A ramp-rate dependence was observed in non-allowed skew terms. A similar behavior was seen in C1 with the plastic printed mandrel

C2 (aperture 65 mm) on aluminum bronze mandrel



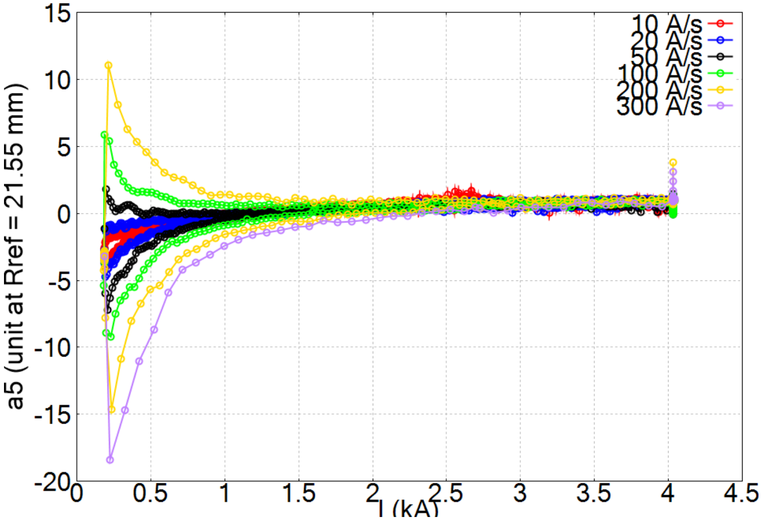
Xiaorong Wang *et al* 2021 *Supercond. Sci. Technol.* **34** 015012

- **3.8 mm diameter CORC wire that contains 30 REBCO tapes in 12 layers.**



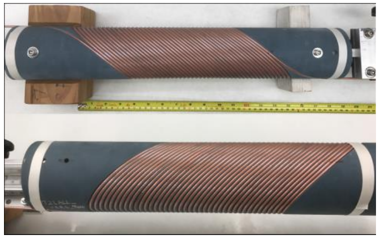
C2 before assembly

C1 (aperture – 70 mm) on bluestone mandrel



Xiaorong Wang *et al* 2019 *Supercond. Sci. Technol.* **32** 075002

- **3.1 mm diameter CORC wire that contains 16 REBCO tapes in 8 layers.**

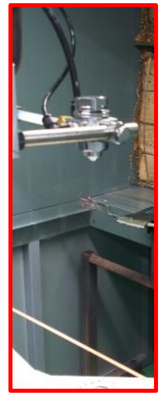


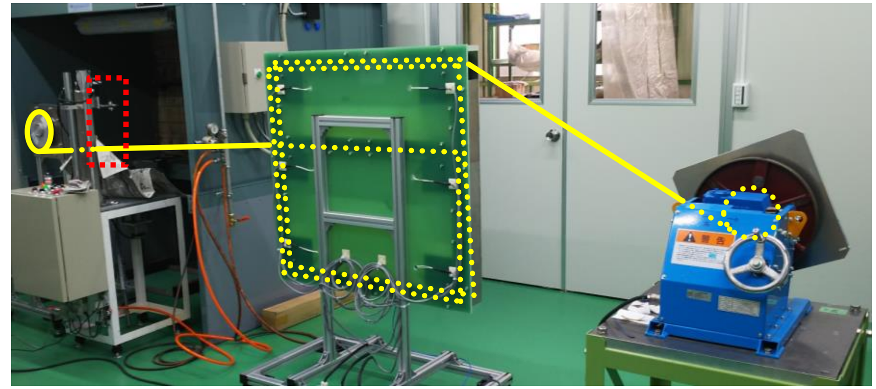
C1 before assembly

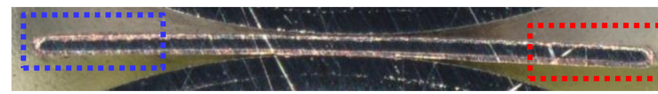
Task 4: Inorganic Insulation HTS coil

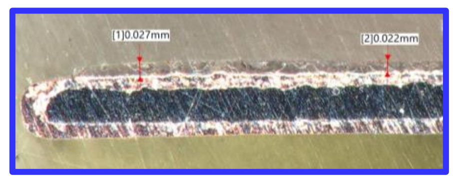
R&D of continuous coating on long tapes by real to real insulation machine is in progress.

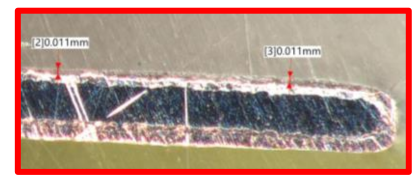
Although continuous coating is successful, difference in thickness of ~16 μm in the width direction is confirmed.



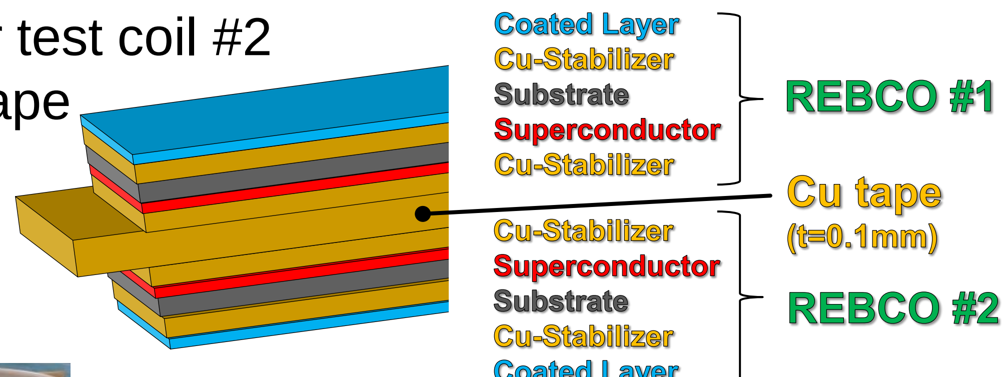


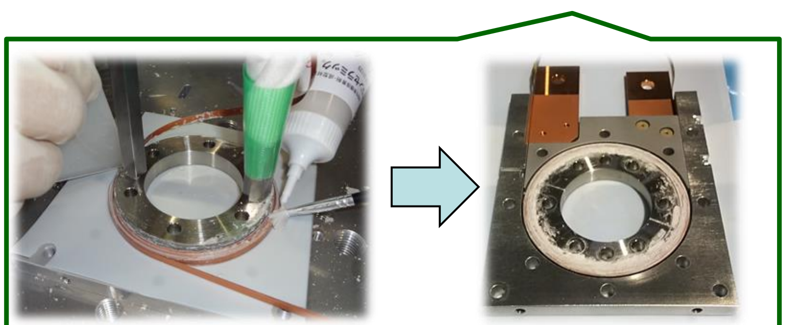






Preparing the winding of the circular test coil #2 with co-winding 2 REBCO and Cu tape (same shape as <u>**Test coil #1**</u>)

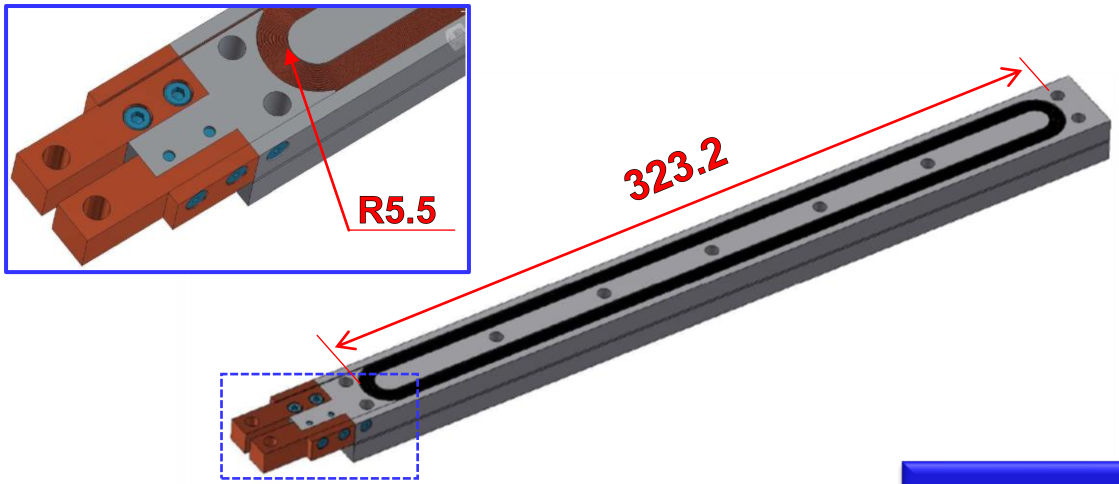


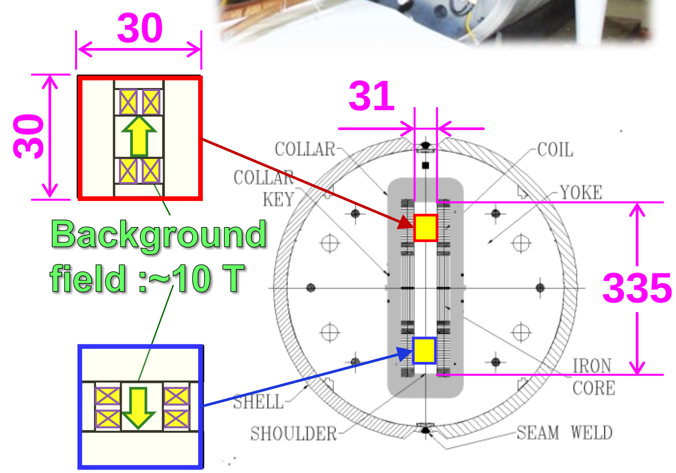


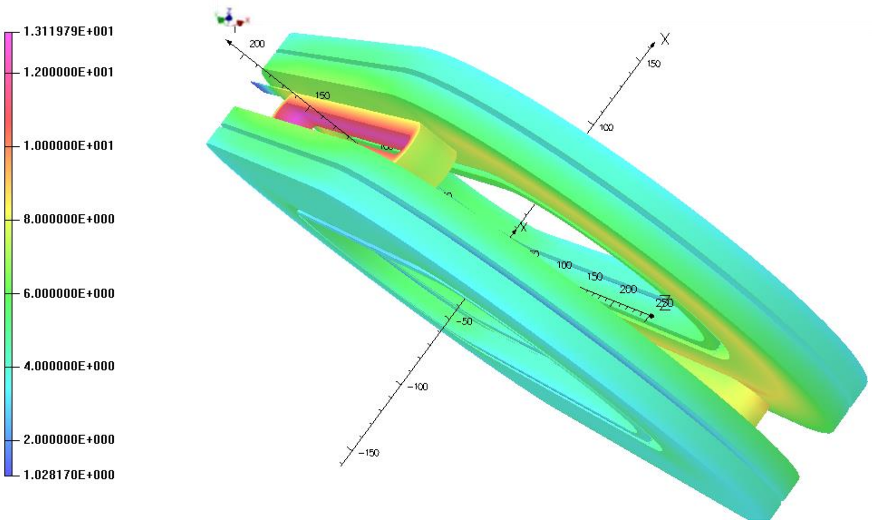
Wires identified and shipped from LBNL to KEK for testing KEK's new ceramic coating insulation on Nb_3Sn and Bi-2212 wires.

R&D on High Field Accelerator Dipole (Highest Field and Field Quality Studies)

Design study in progress







Two tests in one go:
Two HTS insert coils in two apertures of the common coil dipole:

- **Upper Bore: field primarily parallel**
- **Lower bore: field primarily perpendicular**

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Conclusion

- We are working on 4 tasks on advanced HTS magnet technologies for future accelerator sciences
  1. HTS magnet technologies for high-radiation environment
     Irradiation test for materials
  2. Stability, quench protection, and magnet safety
     Experimental and theoretical study on practical HTS cables
  3. Measuring and modeling AC loss and field quality of HTS accelerator magnets
     Measurements and numerical analyses for practical HTS magnets
  4. HTS/LTS high field hybrid accelerator dipole technology
     New technologies for HTS coils systems

We appreciate your continued support!

Related presentations in poster session

- Poster No. 3
  Masami Iio (KEK), “Research and development of next-generation radiation-resistant superconducting magnet based on high temperature superconductor”

- Poster No. 18
  Christopher Reis (LBNL), “Investigating the limits of high-temperature superconductors for high radiation environments with the US-Japan HEP collaboration”