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

Tengming Shen (US PI), Lawrence Berkeley National Laboratory
Mukesh Dhakarwal (KEK) for Toru Ogitsu (Japan PI), KEK

With Xiaorong Wang (US CO-PI), Lawrence Berkeley National Laboratory, Ramesh Gupta, (US CO-PI), Brookhaven National Laboratory, and Naoyuki Amemiya (Japan CO-PI, Kyoto University).

Who we are?

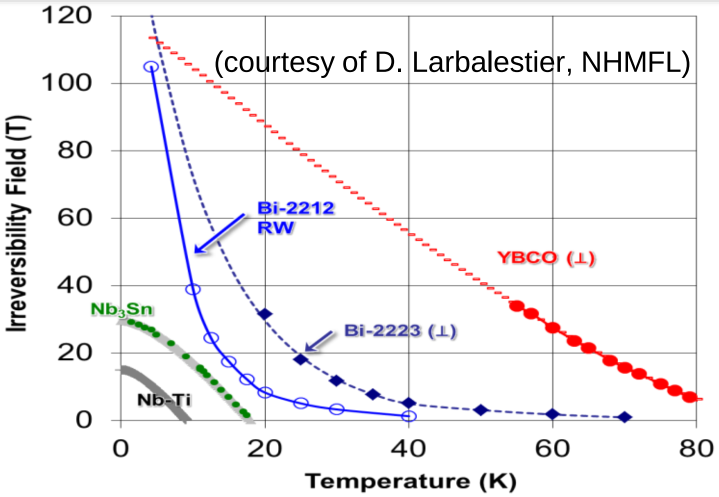
Members of the US Magnet Development Program

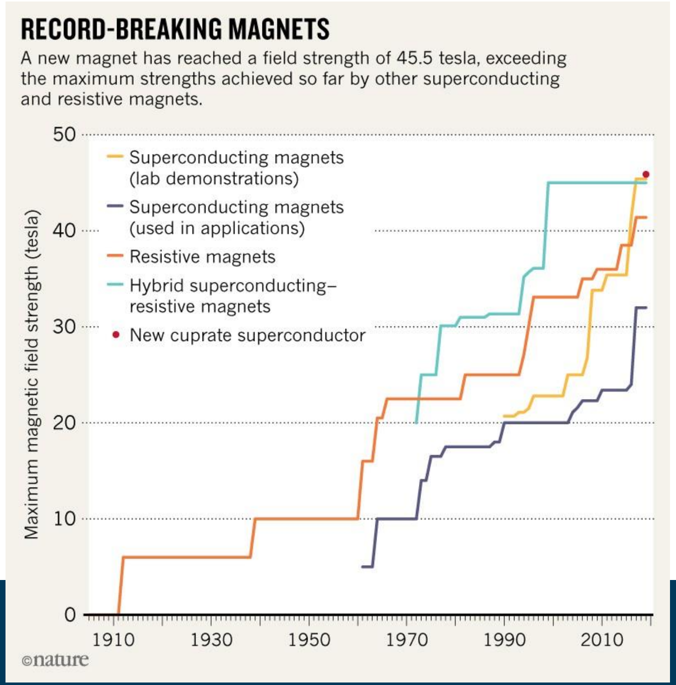
Peter Hosemann

- Kyoto Uni: Naoyuki Amemiya, **Yusuke Sogabe**, Guangwei Xu, Mao Shigemasa
- KEK: Toru Ogitsu, Tatsushi Nakamoto, Michinaka Sugano, Masami Iio, **Kento Suzuki**, **Mukesh Dhakarwal**
- BNL: Ramesh Gupta, Piyush Joshi, **Mithlesh Kumar**
- LBNL: Chris Reis, **Laura Garcia Fajardo**, Tengming Shen, Xiaorong Wang

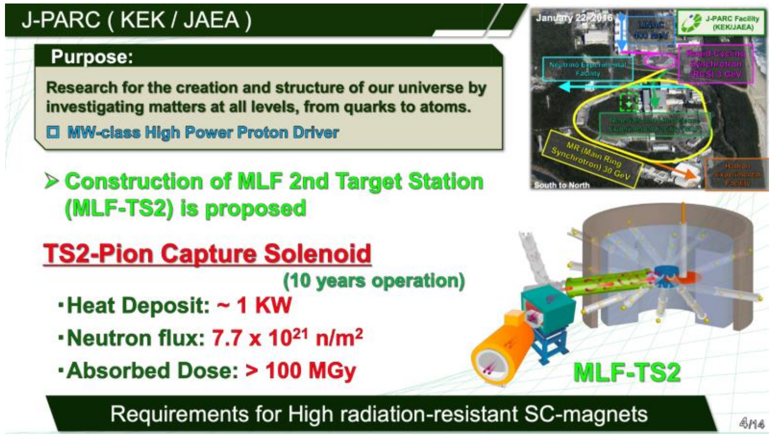
Early Career Scientists Graduate students

Why study HTS magnets?





- **High field frontier – enable frontier accelerator, fusion, and scientific facilities.**
- **High temperature frontier – reduce the reliance on liquid He supply**



Instruments **2020**, *4*(4), 30; https://doi.org/10.3390/instruments4040030

Our tasks

- Task 1: HTS magnet technologies for high-radiation environment
  - KEK, LBNL - Ceramic insulation, gamma-ray radiated epoxy resin composites, and neutron irradiation of REBCO tapes

- Task 2: Stability, quench protection, and magnet safety
  - Kyoto Uni., LBNL, BNL – quench modeling, experiments with single tapes and REBCO wires/cables.

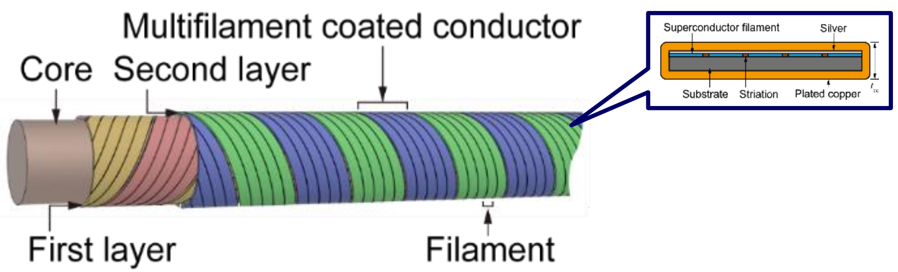
- Task 3: Measuring and modeling AC loss and field quality of HTS accelerator magnets
  - Kyoto Uni., LBNL, KEK, BNL – magnets from C0 to C2, from modeling to experiments

- Task 4: HTS/LTS high field hybrid accelerator dipole technology
  - KEK – racetrack coils fab; BNL – test of KEK racetrack coils in 10 T background fields.

The current funding: 07/01/2021 - 06/30/2024; Will submit a renewal proposal in Dec 2023.

Exchanges

Prof. Amemiya, Sept 2022, learned how to fabricate a terminal/joint with LBNL's flute design with Hugh Higley, applied to his SCSC cable design, And provided improvement.



Ogitsu and Shen in front of BELLE-II
April 16, 2023

Lecture (T. Shen) to Kyoto Uni. Students, April 21, 2023

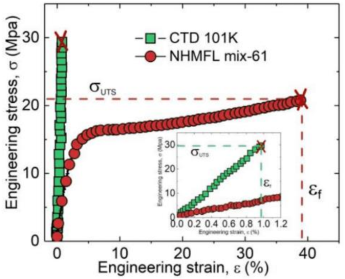
Task 1. Gamma ray radiation of epoxy resin composites and test

- **Epoxy resins are widely used in superconducting magnets.**

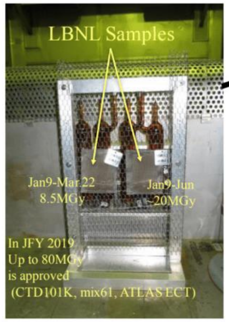
CTD-101K, used by US LARP, after one thermal cycle to 77 K

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

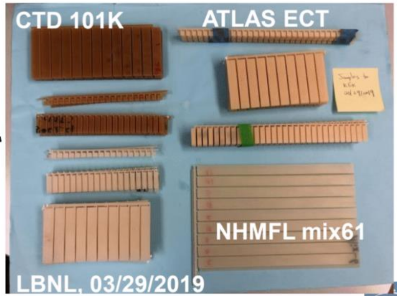
Shijian Yin, Tengming Shen, LBNL



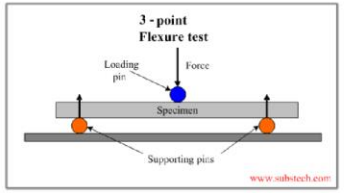
Yin, Shen et al., IEEE Trans. Appl. Supercond., 2019

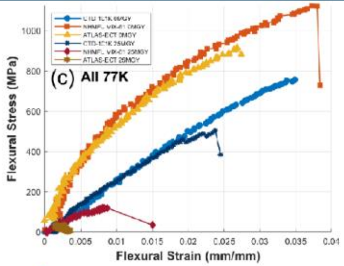


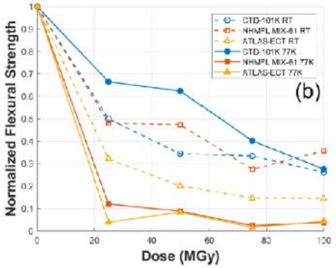
- **10 MGy and 20 MGy samples at QST.**
- **100 MGy experimental time secured for 2019/2020, and samples prepared.**

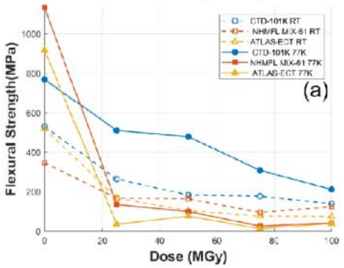


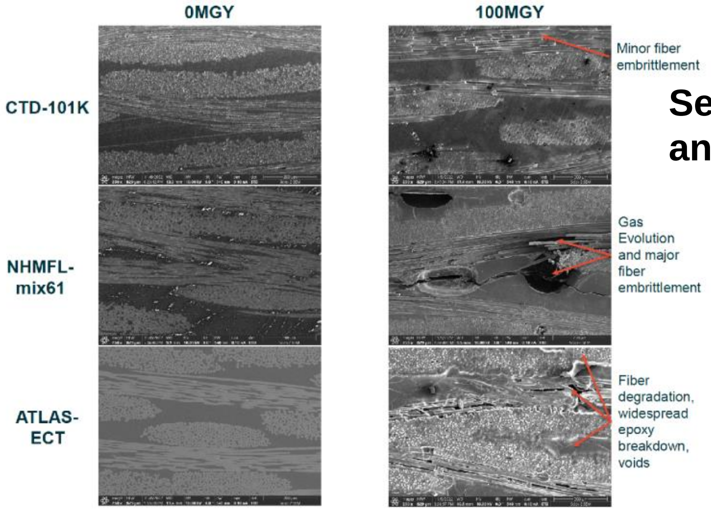
10.1109/TASC.2019.2898124









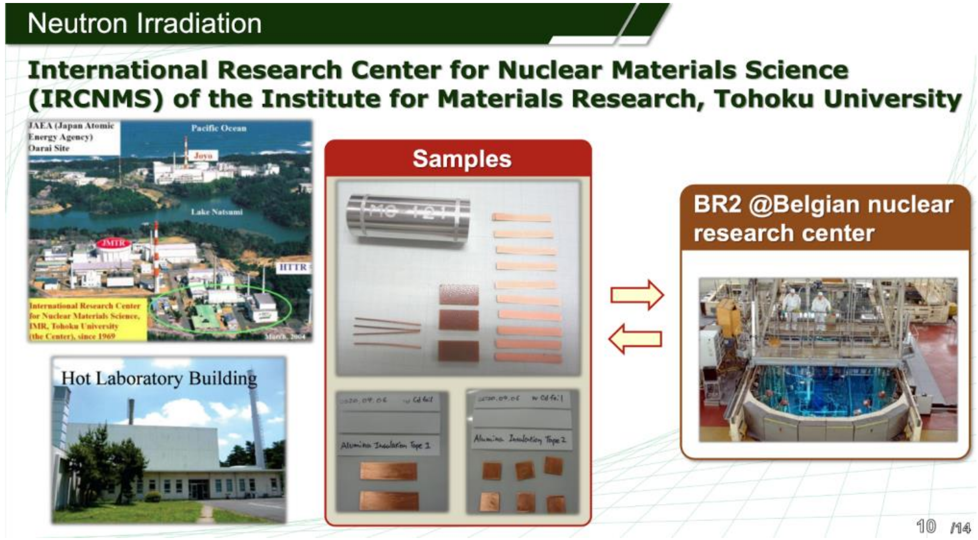


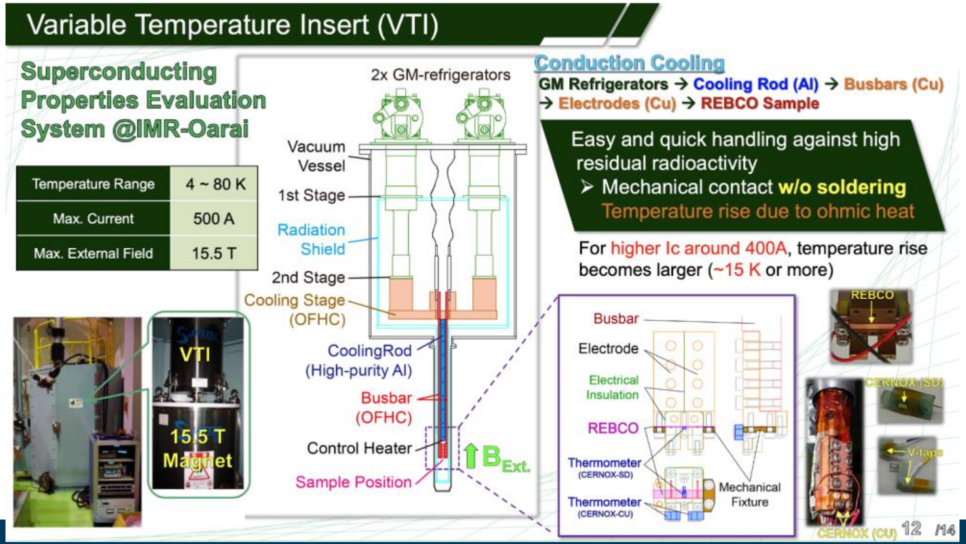
Selected for high-Lumi LHC and AUP Nb_3Sn Quads

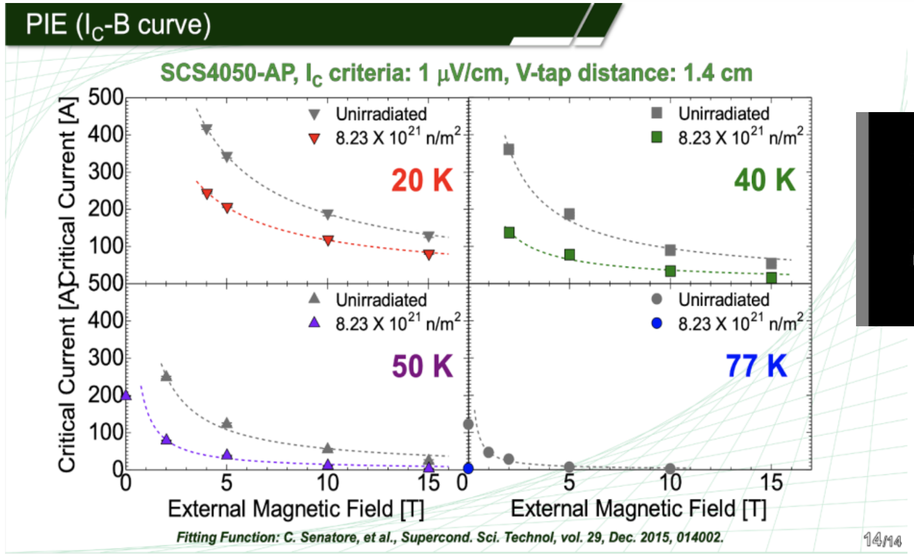
By Chris Reis, LBNL, UCB, published with IEEE Trans. Appl. Supercond.

KEK BERKELEY LAB Lawrence Berkeley National Laboratory

Task 2. Neutron irradiation of REBCO tapes made possible by unique facilities @ BR2 and Tohoku Uni.





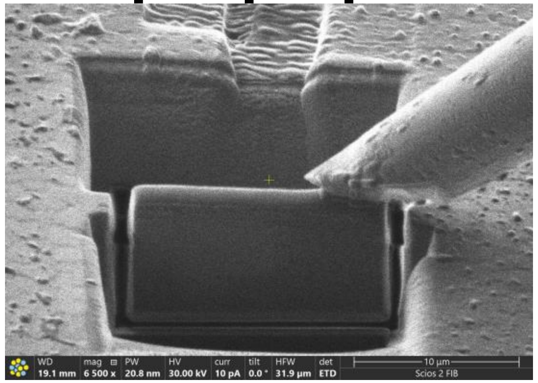


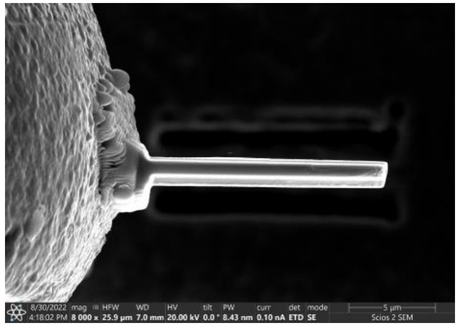
Procedure for handling hot REBCO for FIB-SEM

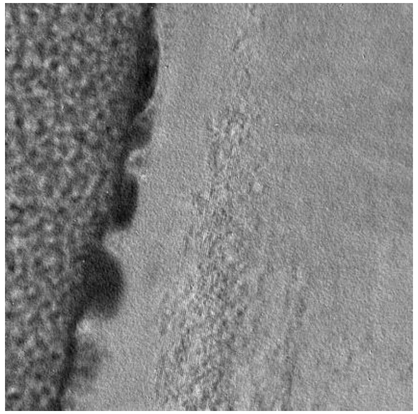
Fourth Draft: October 4th 2022

HR-TEM of REBCO at NCEM, LBNL

Sample prep + FIB-SEM @ UCB







- **Helium ion implantation at LBNL/UC Berkeley**

Masami IIO, KEK

KEK

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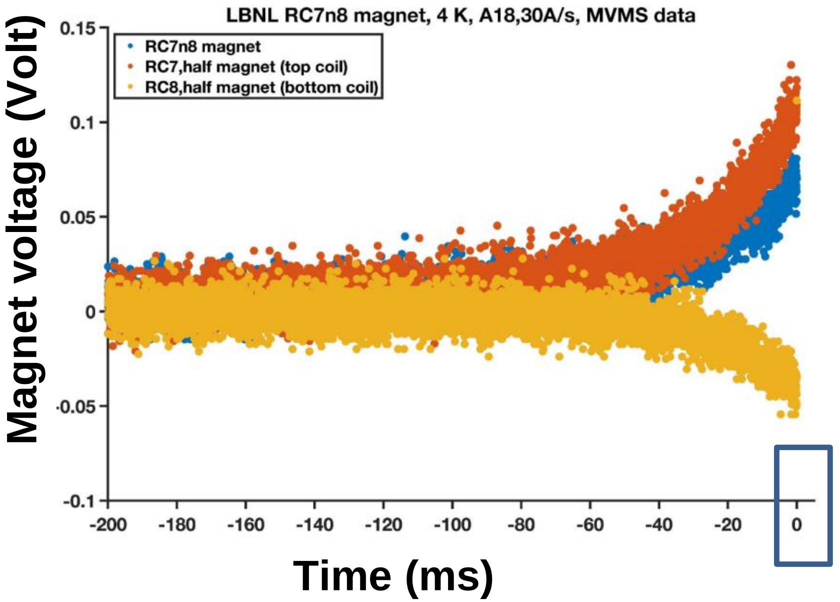
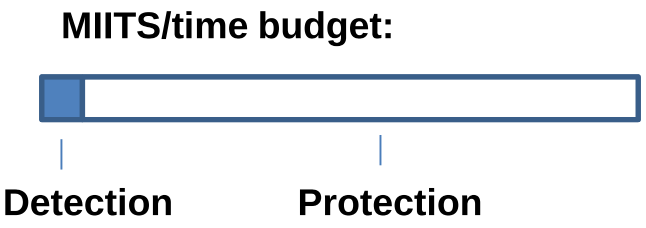
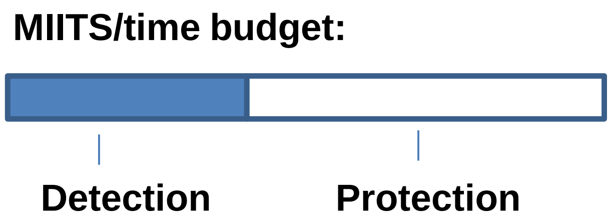
Task 2. Improving quench detection for HTS magnets

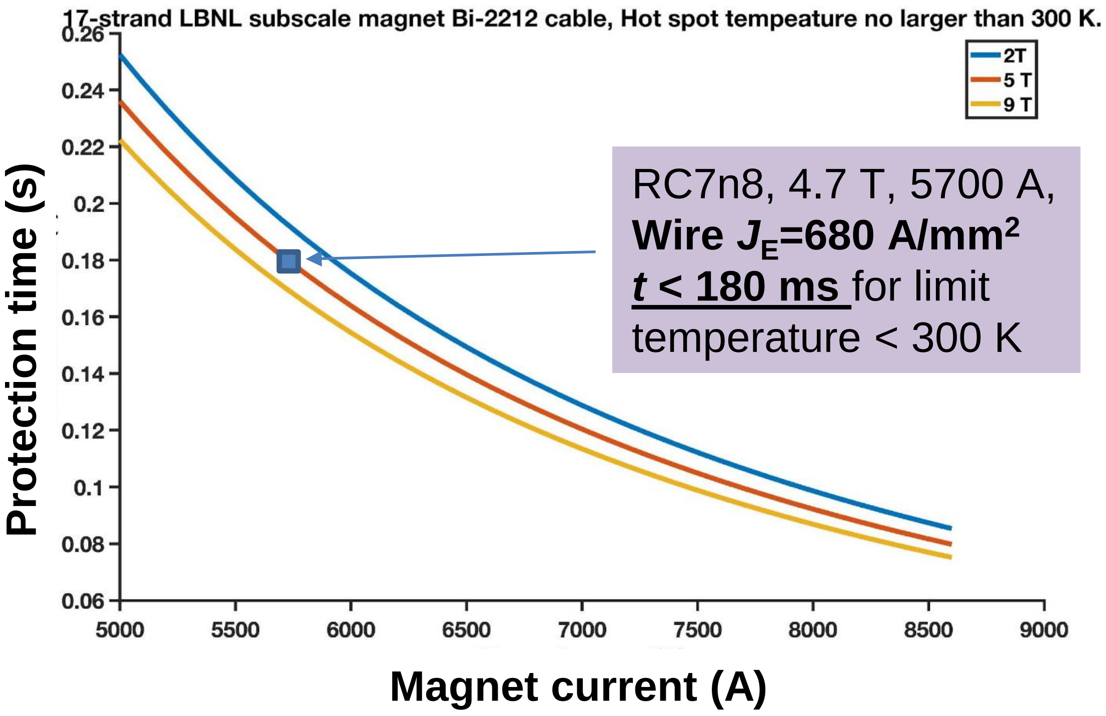
- Known and existing: cRIO + FPGA/PXI, LBNL MTF developed for LTS magnets



- Used to protect all MDP-LBNL Bi-2212 magnets.
- **RMS noises in 10^{-2} V.**
- **Quench detection at 50 – 100 mV.**







BERKELEY LAB
Lawrence Berkeley National Laboratory

KEK

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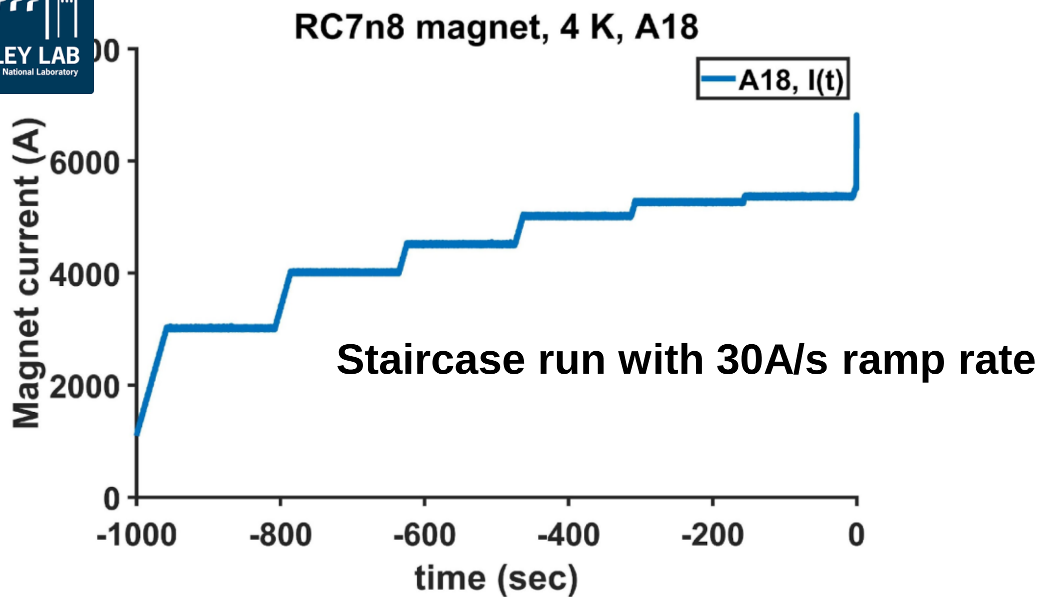
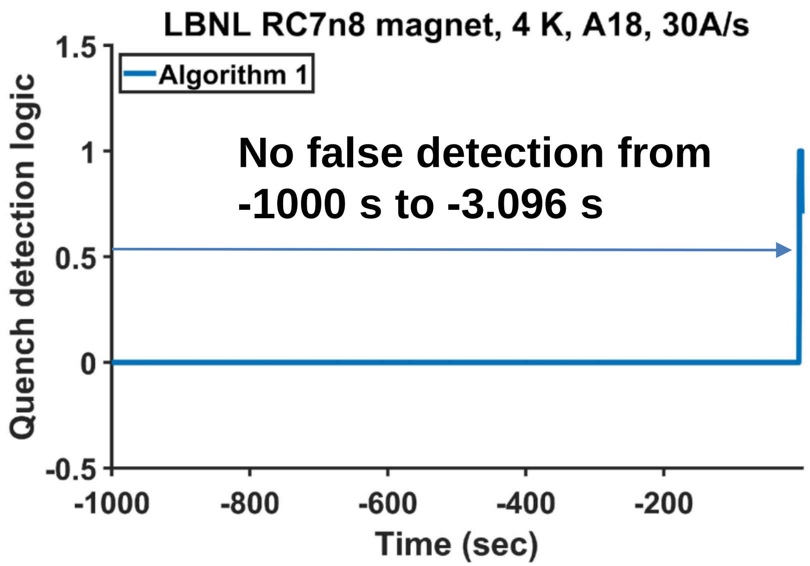
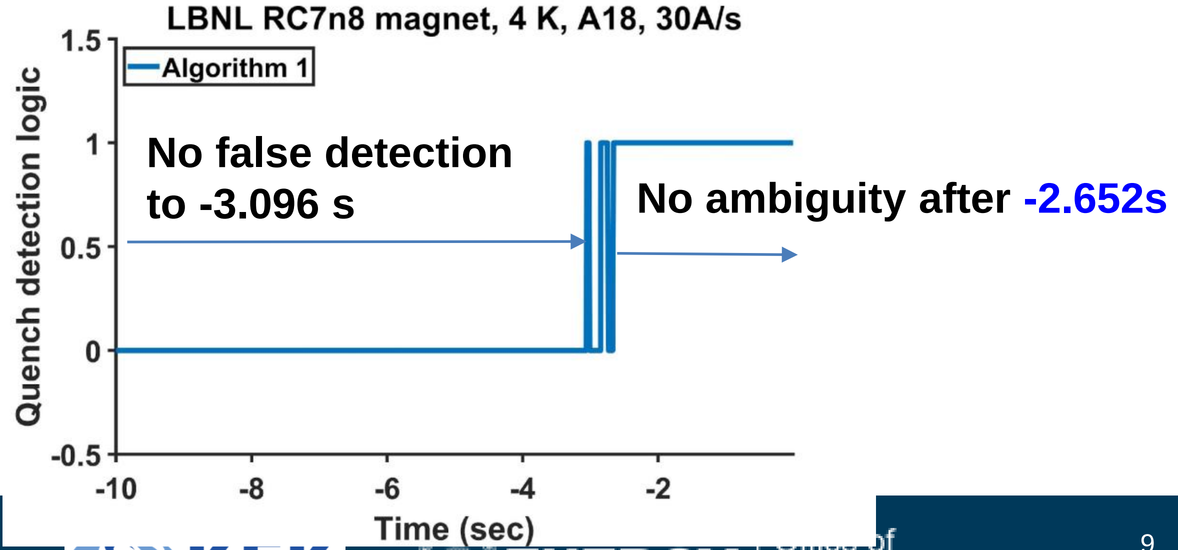
Task 2. Improving quench detection for HTS magnets – quench detection made 2.6 s ahead of the state of the art method – hugely important for safety of HTS magnets



Time = 0 s
SCR opened





Able to have quench detection 2.5 seconds ahead, why it is exciting, and why this collaboration is interested and qualified to perform this work.

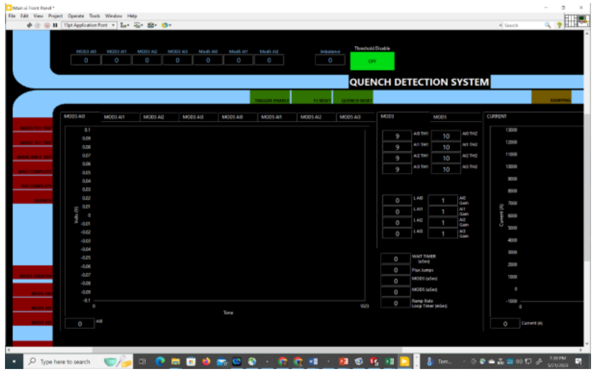
NEW LBNL QDS algorithm

- **Fast** (discrimination at every **1 ms)**
- **Work with all magnet operating scenarios**
- **Implementable with FPGA.**

- **To be applied, tested, and enhanced by US-Japan HTS magnets**
  - Test of KEK magnets at BNL
  - KEK (CT0)
- **Current also investigate machine learning for autonomous learning and anomaly detection (with Dan Wang, LBNL)**

Front-end electronics

cRIO-FPGA



LabVIEW FPGA User VI

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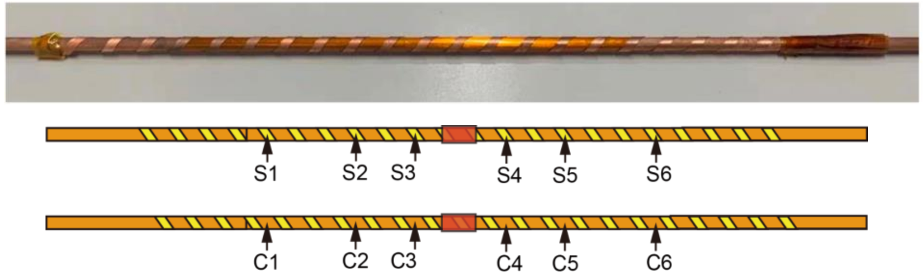
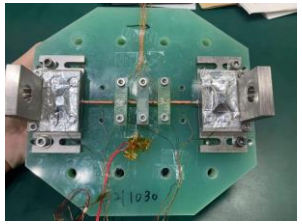
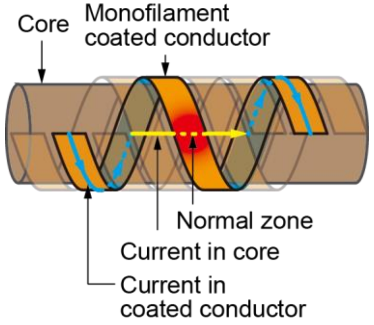
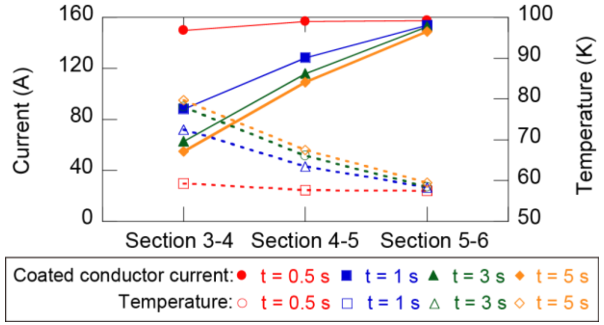
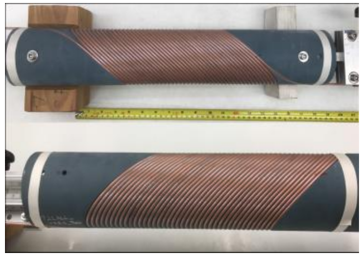
Task 3. Kyoto Uni.: Effect of current-sharing on AC loss of CORC-like conductors and field quality

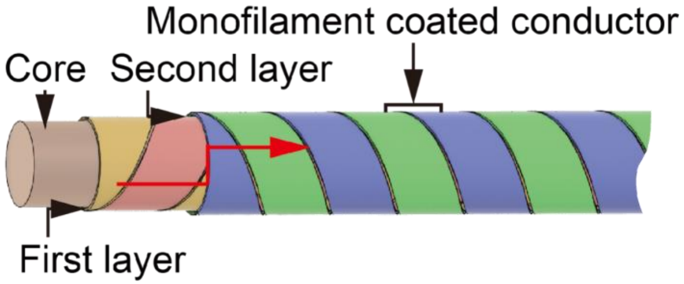


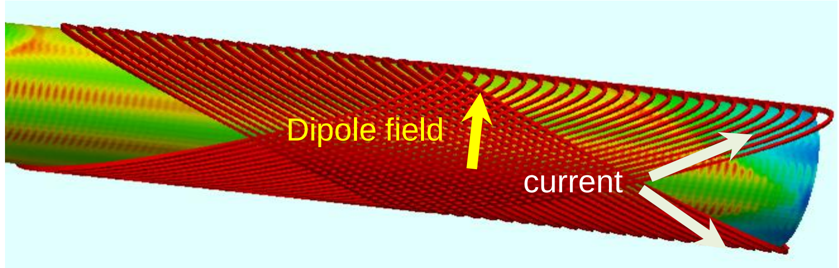




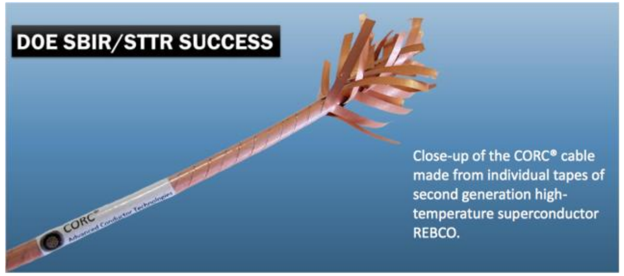








REBCO CORC Canted cosine theta dipole magnet demo

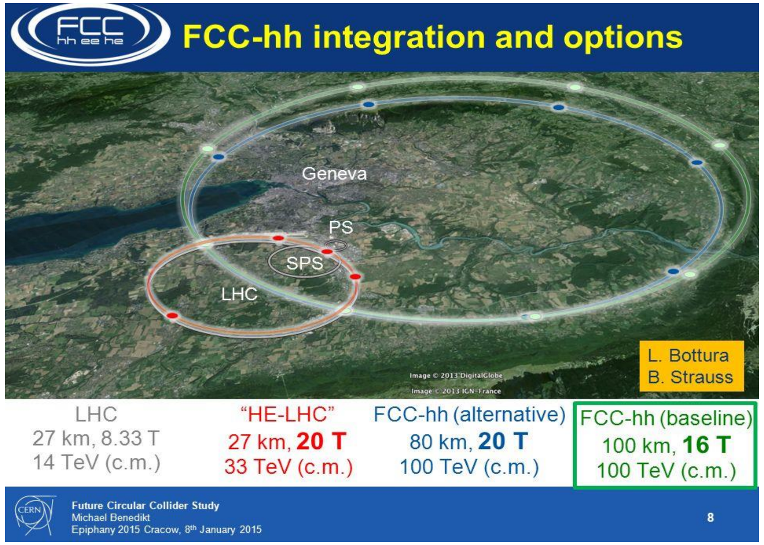


C0, C1, and C2 have been constructed (Wang et al., 10.1088/1361-6668/ab0eba; /10.1088/1361-6668/abc2a5
C3, 6-layer, 5 T CCT dipole magnet is ongoing.

Test by Guangwei Xu, Kyoto Uni.. REBCO CORC CCT by Xiaorong Wang, LBNL, with ACT

Future in the Accelerator Field

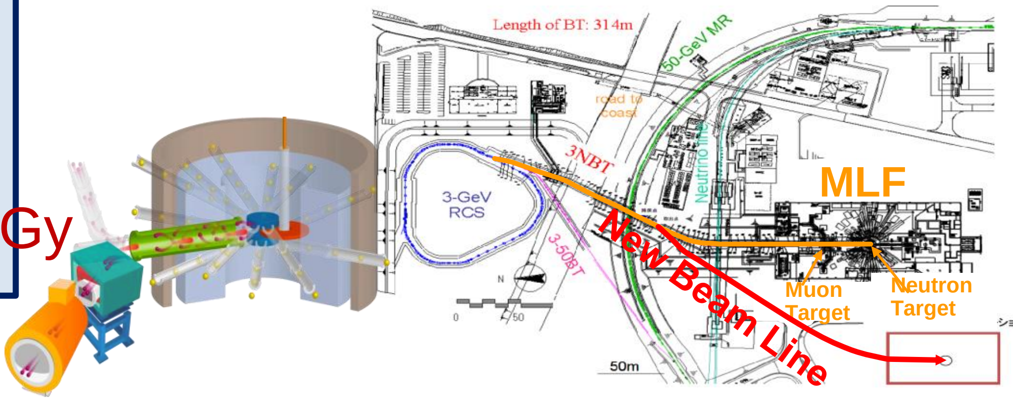
- **FCC@CERN: 100 TeV**
  - **20 T high-field magnet**
- **CERN**
  - **Hilumi-LHC: 40 MGy (W-shield)**
  - **FCC: >100 MGy?**
- **J-PARC**
  - **MLF2 : 130 MGy ?**



Conventional Magnet Technology : Challenges

- **NbTi Cable**
  - Ic (< 10 T) cannot achieve the requirement
- **Organic Material for Insulation**
  - Degradation of the machine strength from 10 MGy

JPARC

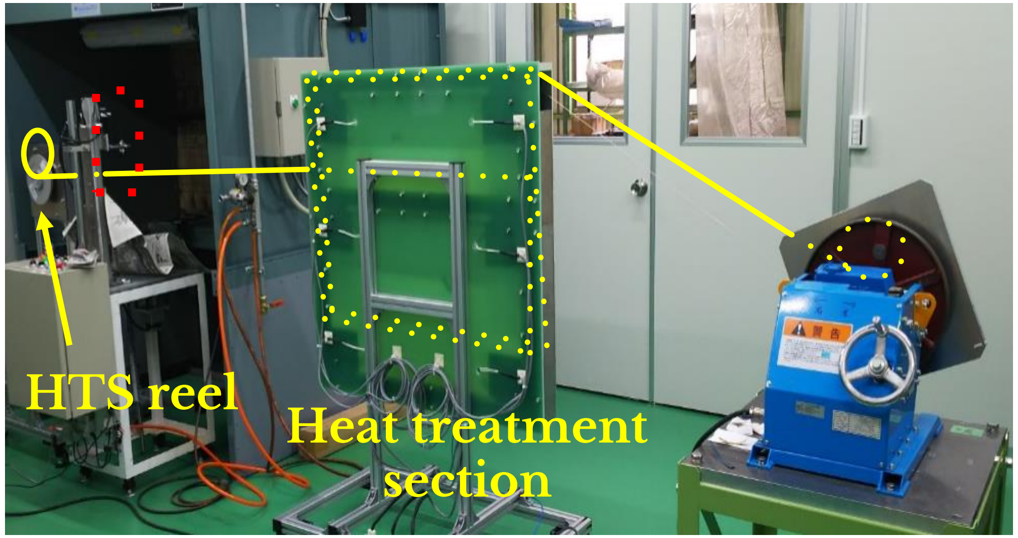


MLF 2nd Target Station

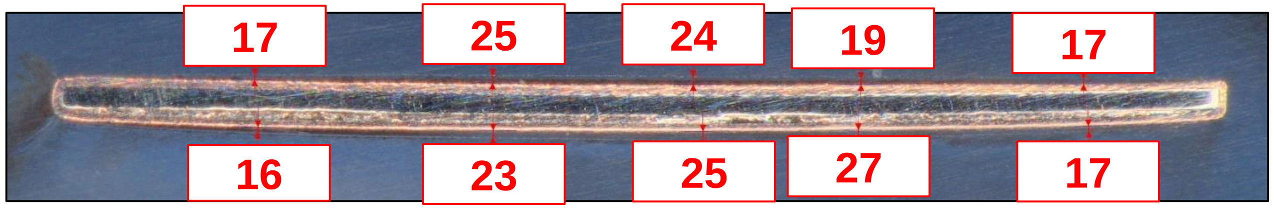
Development of next-generation radiation resistant high field magnet

Task 4. KEK Inorganic Insulation of ReBCO tape

Continuous Coating of long ReBCO tape is performed using reel to reel coating machine



Coating material: $Al_2O_3:SiO_2$ = 1:1
Heat treatment: 100º C, 20 min
Withstand Voltage: 2 kV



Successfully achieved

25 ± 4.7 (σ) µm thick ceramic coating.

Total Length : 40 m (Coated both sides)

➢ **Winding the double pancake racetrack coil for high magnetic field test**

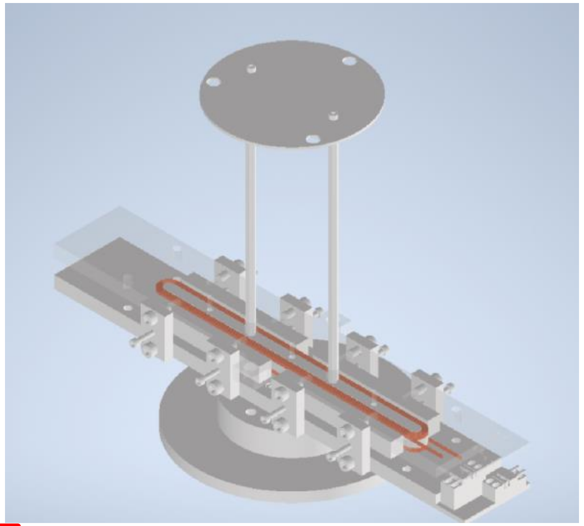
KEK HTS Coil – Winding and Test Status

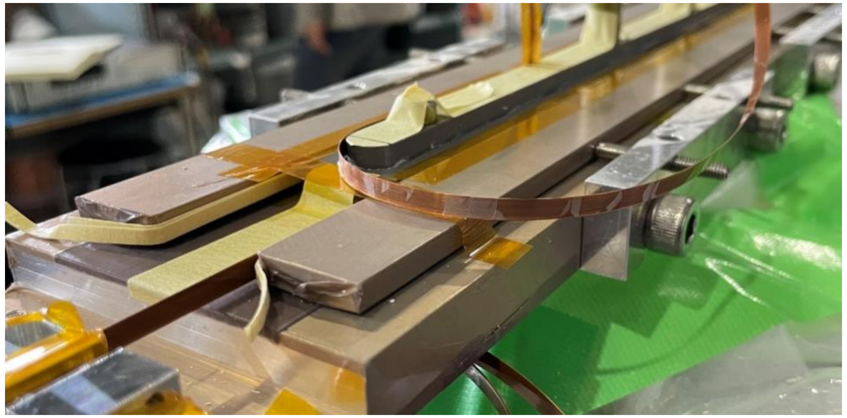
Winding : Three coil with Coated ReBCO tape (wet winding)

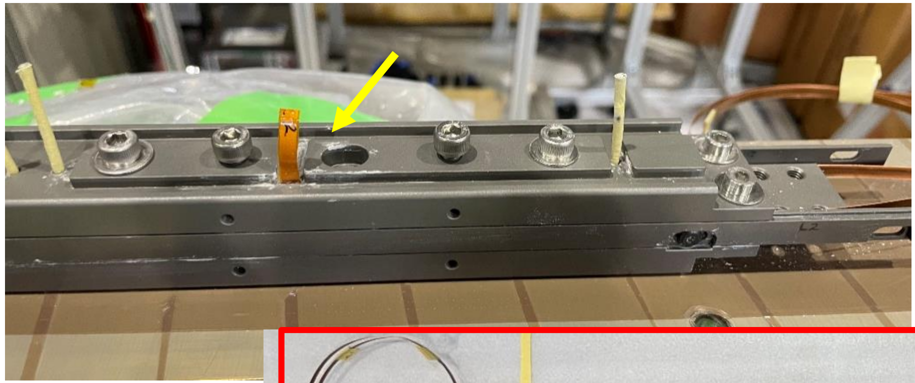
- **The actual conductor thickness: 0.31 mm**

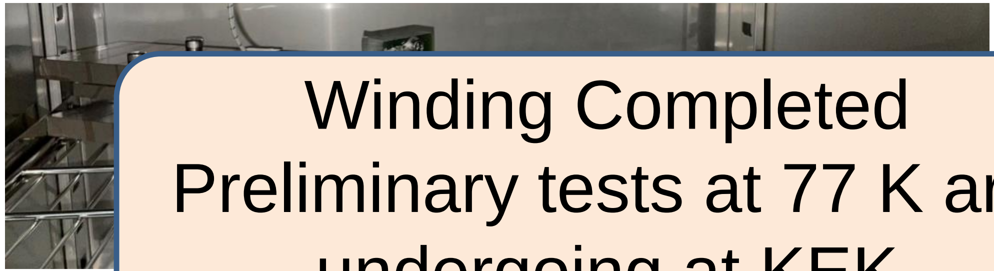
  (EuBCO: 0.16, coating layer: 0.05, adhesive layer: 0.1)
- **The number of turns: 20 turns**

Winding setup for double pancake racetrack coil



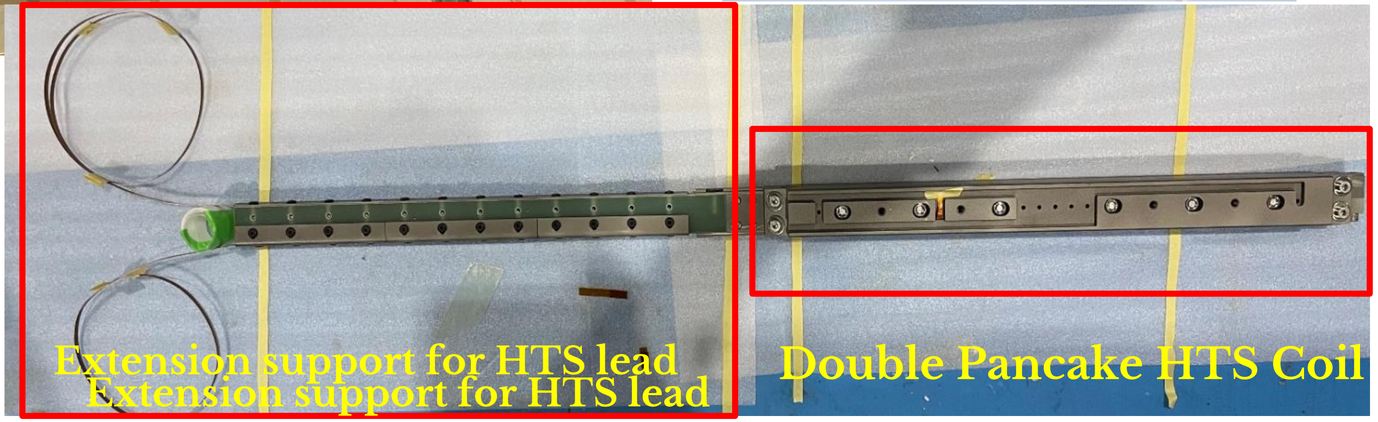






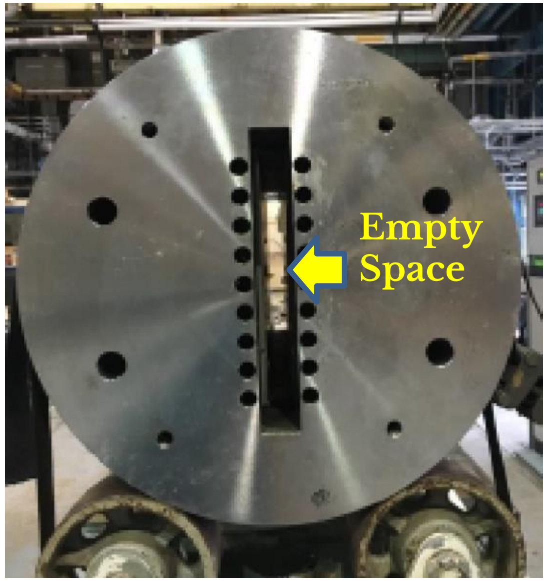
Winding Completed

Preliminary tests at 77 K are undergoing at KEK

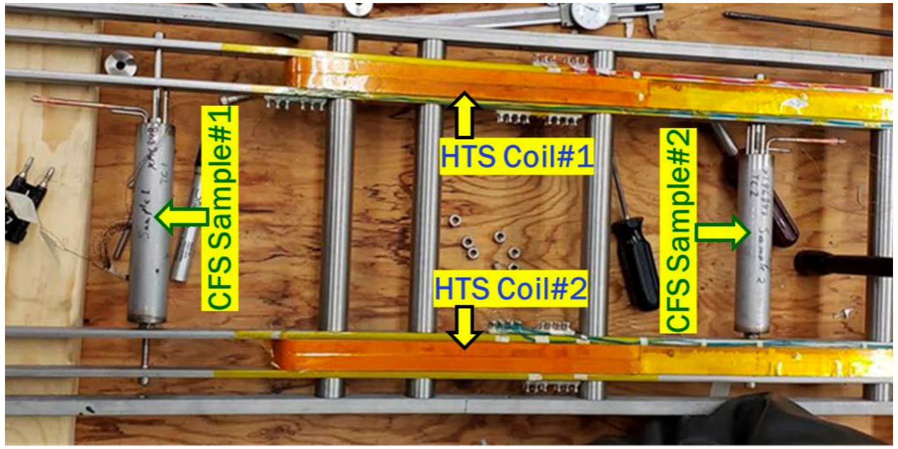


Overview of BNL Nb_3Sn Common Coil Magnet Test Facility

- Nb_3Sn, common coil 2-in-1 dipole that allows two insert coils in two aperture
- Structure is designed to provide a large open space (~30 mm X 335 mm)
- New insert coils can be tested in the background field of up to 10 T (+ self-field)
- Facilitates a rapid-turn around, low-cost R&D approach for high field magnets



BNL Nb3Sn common coil dipole DCC017 without insert coil



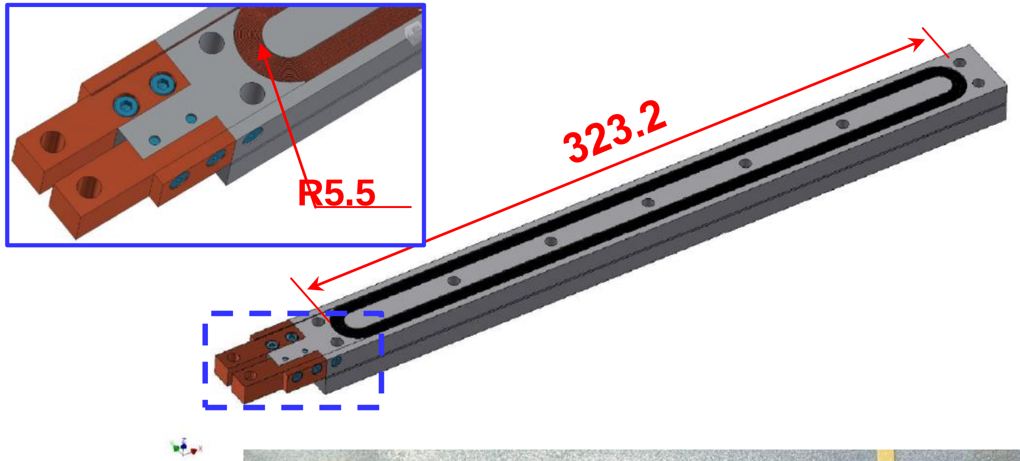
Structure for Test coil insert in Common coil

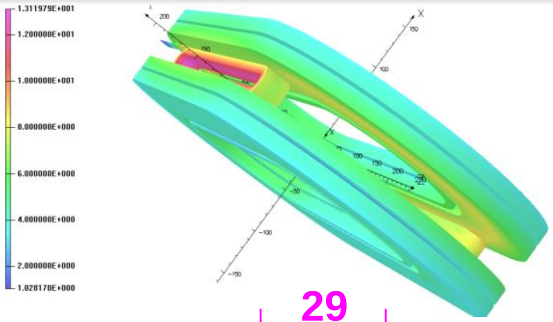
HTS coils inside Nb_3Sn dipole - early experience of HTS/LTS hybrid dipole

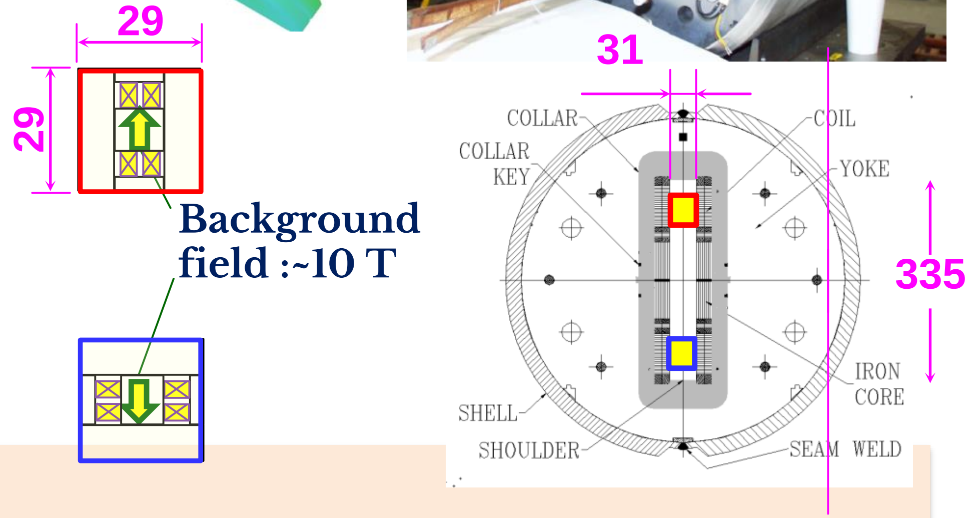
Upcoming Test Plan @ BNL, Upton

Design study in undergoing in parallel

Field Quality studies will be undertaken at BNL







Test Plan in July 2023 @BNL

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

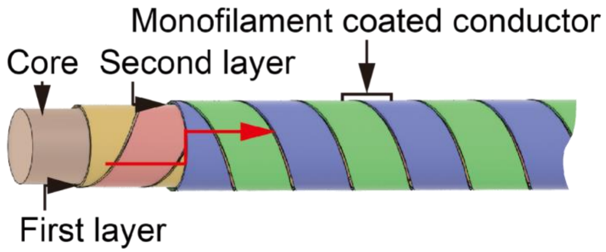
- Upper Bore: field primarily parallel
- Lower bore: field primarily perpendicular
- 7 hall probes will be installed along the length to measure the magnetic field

Summary

- **Enable four institutions (LBNL, BNL, KEK, and Kyoto University) to team up to address critical issues facing high-temperature superconducting magnet technology for accelerator facilities.**

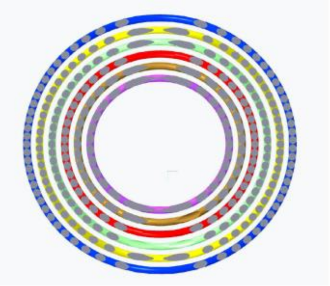
- **Make possible progress and studies at both fundamental and technological fronts impossible with a single institution alone.**
  - **Neutron radiation of REBCO tapes assisted with TEM studies.**
  - **Quench protection of HTS magnets with new concepts, uncertain analysis with Monte-Carlo analysis, and quench protection with FPGA at much improved resolutions and margin of safety.**
  - **LTS/HTS hybrid magnets.**

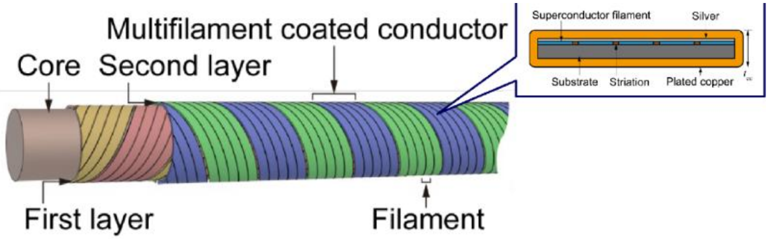
CCT magnet at LBNL and SCSC cable at Kyoto Uni.



6-layer design, minimum bend radius is 30 mm

LBNL C3 magnet



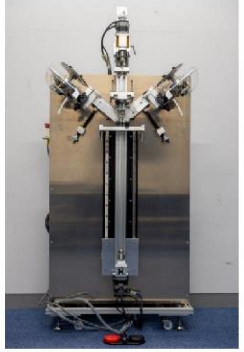


Winding copper-plated multifilament coated conductors spirally on a round core

SCSC cable (double "SC" cable), standing for Spiral Copper-plated Striated Coated-conductor cable)

2022, ASC 2022

Homemade-machine made



- Wound on 3 mm flexible metal core (4 layers)
- Up to 8 layers on GFRP core
- Up to ~ 500 mm long

October 2022 ~

Machine made, 5 m mock-up

- Reel-to-reel cabling machine
- Wound on flexible metal core

Status of Neutron Irradiation

M. Iio et al., IEEE Trans. Appl. Supercond., vol. 30, no. 4, (2020) 4600505.

ID	Sample Type	N	Cd Shield	Fluence $[n/m^2]$	Loading for Irradiation	Irradiation Period	Radioactivity [Bq/sample] (2021.05.12)	Dose Equivalent Rate [mSv/h/sample]	PIE	Remarks
MC121	SCS4050-AP (GdBCO)	10	No	8.37E+22 (E>1MeV) 1.71E+23 (E>0.1MeV)	Nov. 14, 2016	2017.03.14-04.11 (28.2d)	5.204E+08	**1.370** (D15cm, 2021.05.12)	To be done	
MC122	SCS4050-AP (GdBCO)	10	No	1.80E+22 (E>1MeV) 4.11E+22 (E>0.1MeV)			1.119E+08	**0.295** (D15cm, 2021.05.12)	**Yes**	Vanishment of superconductivity
MC131	SCS4050-AP (GdBCO)	5	No	7.06E+22 (E>1MeV) 1.97E+23 (E>0.1MeV)	Feb. 09, 2018	2018.04.24-05.25 (28.2d)	5.682E+08	**1.495** (D15cm, 2021.05.12)	To be done	
	FYSC-SCH04 (GdBCO)	5					7.525E+08	**1.980** (D15cm, 2021.05.12)	To be done	
MC132	SCS4050-AP (GdBCO)	5	No	2.53E+22 (E>1MeV) 7.92E+22 (E>0.1MeV)			2.039E+08	**0.466** (D15cm, 2021.05.12)	**Yes**	Vanishment of superconductivity
	FYSC-SCH04 (GdBCO)	5					2.699E+08	**0.612** (D15cm, 2021.05.12)	**Yes**	Vanishment of superconductivity
MC137	SCS4050-AP (GdBCO)	5	No	1.85E+22 (E>1MeV) 4.12E+22 (E>0.1MeV)	Jan. 10, 2019	2019.07.03-08.06 (34.1d)		**1.3** (D50cm, 2021.01.27)	To be done	
	FYSC-SCH04 (GdBCO)	5								
LIBERTY 12	SCS4050-AP (GdBCO)	5	No	3.40E+21 (E>1MeV) 8.23E+21 (E>0.1MeV)	Nov. 26, 2018	2019.11.06-11.06 (10.83h)		**0.35** (D20cm, 2021.01.12)	Done! (June. 2021)	Degraded
	FYSC-SCH04 (GdBCO)	5								
-	SCS4050-AP (GdBCO)	3	Yes	low flux BAMI, Target: 2-8×10^{22}	Apr. 09, 2020					not irradiated (Shield irradiation not allowed)
	FYSC-SCH04 (GdBCO)	3								
	FESC-SCH04 (EuBCO)	3								
-	SCS4050-AP (GdBCO)	3	No	low flux BAMI, Target: 2-8×10^{22}						not irradiated (Shield irradiation not allowed)
	FYSC-SCH04 (GdBCO)	3								
	FESC-SCH04 (EuBCO)	3								

Irradiation study of Gd and other rare earth sample is undergoing