The Japanese High Field Magnet programs for accelerators

T. Ogitsu, M. Sugano, T. Nakamoto, K. Suzuki, M. Iio, M. Dhakarwal; KEK,
S. Awaji; Tohoku Univ., H. Oguro; Tokai Univ., N. Banno; NIMS
A. Ballarino, A. Devred, T. Bothboul, S. Hopkins; CERN,
S. Kawashima, T. Kawarada, Y. Murakami, K. Saito; Kobe Steel and JASTEC
D. Asami, H. Ii, H. Sakamoto, T. Kato; Furukawa Electric
N. Amemiya, Y. Sogabe, X. Luo; Kyoto U.
T. Shen, X. Wang, L.G. Fajardo, C. Myers; LBNL, C. Reis; UC Berkeley,
R. Gupta, P. Joshi, J. Schmalzle, G. Jochen, S. Joshi; BNL

R&D programs of High Field Magnet for Accelerator in Japan

- On going (based on international collaborations)
  - HTS: US-Japan collaboration framework
    - KEK, Kyoto U., LBNL, BNL, UC Berkeley
  - Nb3Sn: CERN-KEK collaboration
    - KEK, Tohoku U., Tokai U., NIMS, JASTEC, Furukawa, CERN
- Submitted Proposal
  - R&D program of High Field Magnet for Accelerator
    - To Science Council of Japan (Future Science Promotion 2023)

R&D programs of High Field Magnet for Accelerator in Japan

- On going (based on international collaborations)
  - **HTS: US-Japan collaboration framework**
    - **KEK, Kyoto U., LBNL, BNL, UC Berkeley**
  - Nb3Sn: CERN-KEK collaboration
    - KEK, Tohoku U., Tokai U., NIMS, JASTEC, Furukawa, CERN
- Submitted Proposal
  - R&D program of High Field Magnet for Accelerator
    - To Science Council of Japan (Future Science Promotion 2023)

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

Advanced HTS Magnet Technologies for Future Accelerator Sciences

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

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

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

Tasks

Task1: HTS magnet technologies for high-radiation environment

Irradiation tests of organic resins

KEK, LBNL; Mechanical tests of irradiated samples

Irradiation tests of superconductors:

- KEK, LBNL and UC Berkeley; Neutron irradiation at the IMR Oarai and preform Ic test.
- LBNL and UC Berkeley; Microscopic analysis of irradiation damage.

Task 2: Stability, quench protection, and magnet safety

- LBNL and Kyoto U.: Quench experiments of various spiral conductors: current sharing among coated conductors, impact of conductor length etc.).

Task 3: Measuring and modeling AC loss and field quality of HTS accelerator magnets

- Kyoto U.: Advanced analyses of magnets wound with CORC wires. Fundamental study on applications of multifilament coated conductors.
- KEK: Prepare field measurement of CT1.
- LBNL: Field measurement of C3. Develop FEM model of C1 and C2.
- BNL: Participate in the discussion.

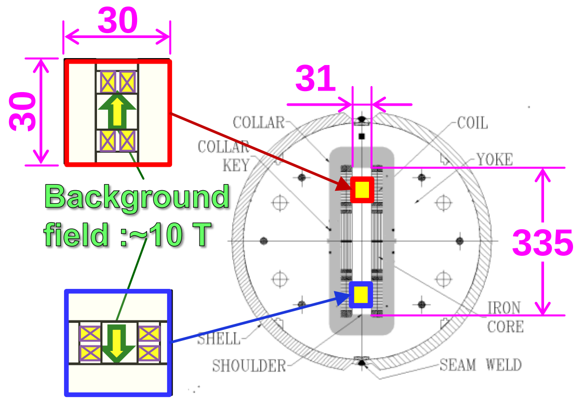
Task 4: HTS/LTS high field hybrid accelerator dipole technology

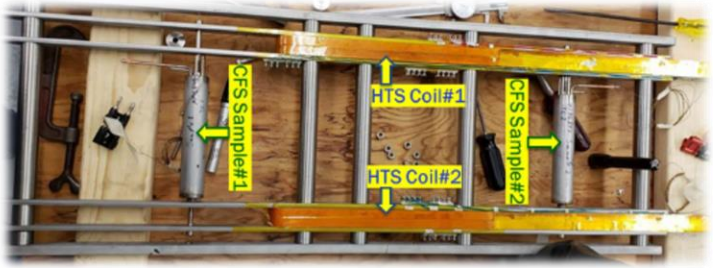
- KEK and LBNL: Non-organic insulation technology R&D for HTS and Nb_3Sn conductor.
- KEK and BNL: Develop rad-hard racetrack coils that can be tested at BNL 10T test stand.
- BNL: Prepare test stand, debag quench protection system. Device a detailed test program including magnetization measurement.

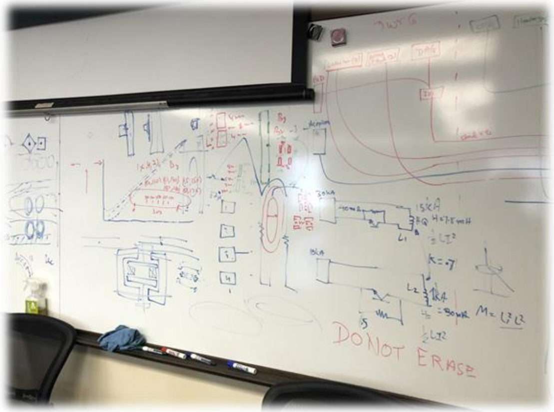
Task 4. High Field Test with Common Coil Configuration @BNL

Preparations for the test are in progress

KEK and BNL members discussed the details of the test plan and preparation items on site

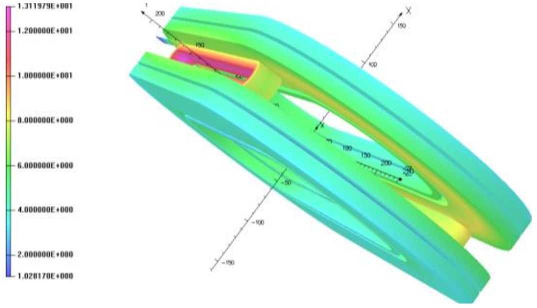






Test plan on common coil test stand

- TC measurement during cooling
- Excitation test (B_{Backup}=0, 1, 5, 10 [T])
- Coil magnetization measurement
- Quench test (B_{Backup}=10, 7, 5, 3, 1 [T])

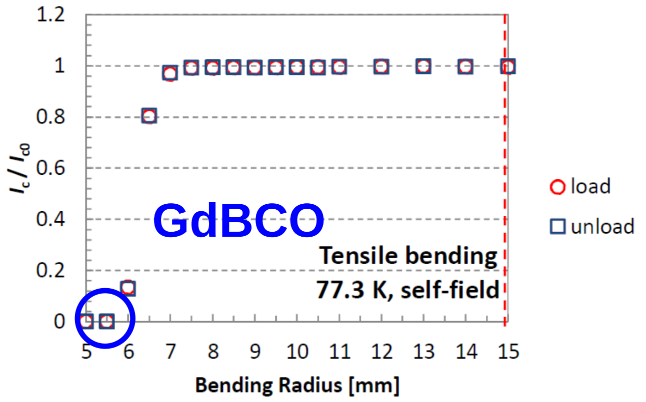


BROOKHAVEN NATIONAL LABORATORY

Task 1 Inorganic Insulation HTS coil

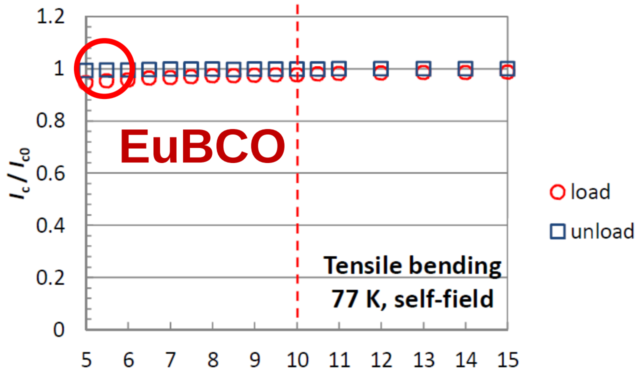
Insert coil design for the test equipment at BNL

- Concerns about I_C degradation due to small bend radius
  →EuBCO tapes (Fujikura FESC-SCH) has good bending radius tolerance



Coil design parameters

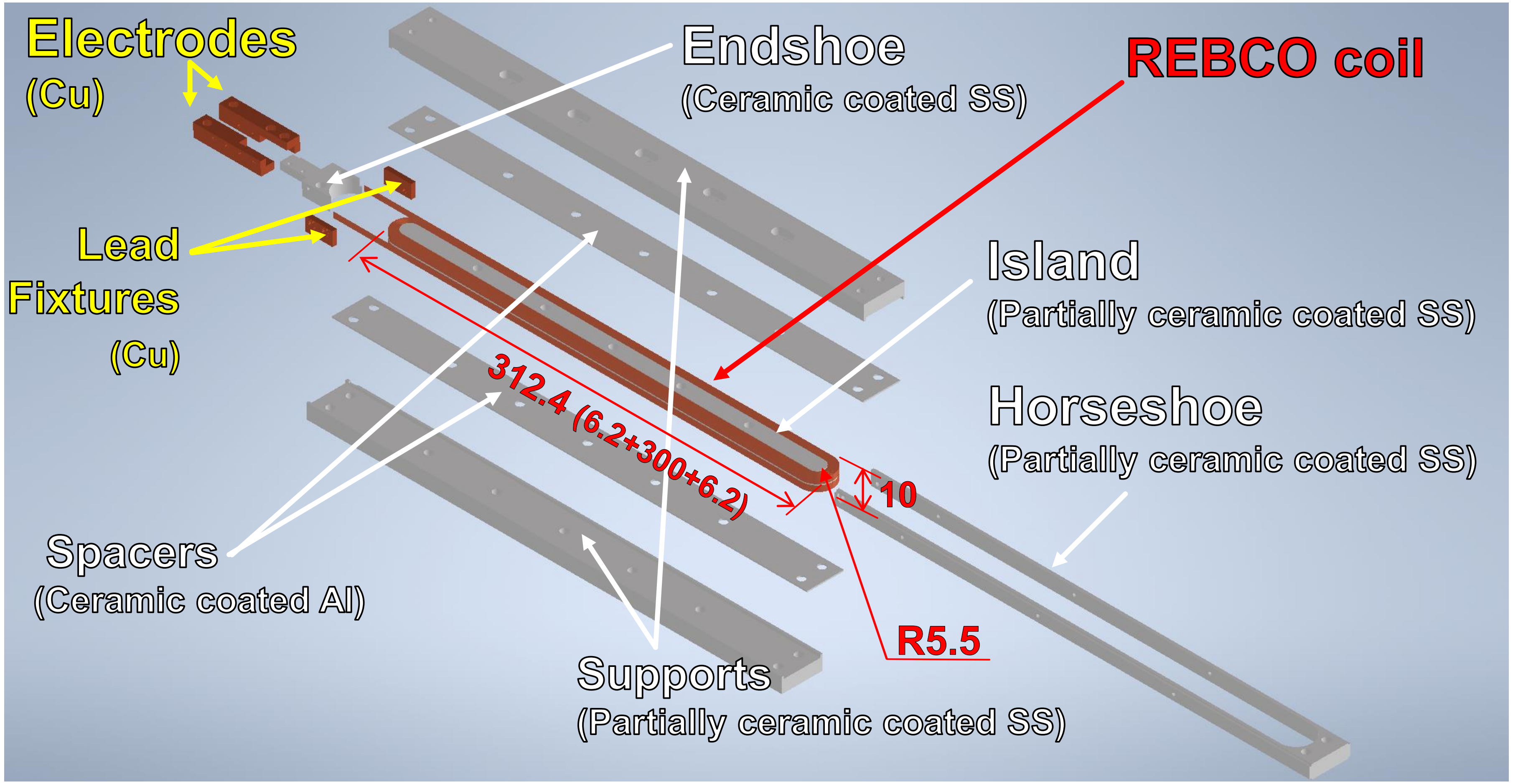
- Type: **EuBCO**, I_C (77K, S.F.): **201 A**
- Thick. of Hastelloy: 50 μm,
- Thick. of Cu: 40 μm (one side)
- Coil width (Avg. of meas.): 4.08 mm
- Coil Thick. (Avg. of meas.): **0.16 mm**
- Thick. of coating: **0.026 mm (one side)**
- Thick. per turn: **0.31 mm (Tape+Coating+Adhesive)**
- Number of turns per layer: **20 turns**



BNL Insert Coil

Task 1 Inorganic Insulation HTS coil

Insert coil design for the test equipment at BNL



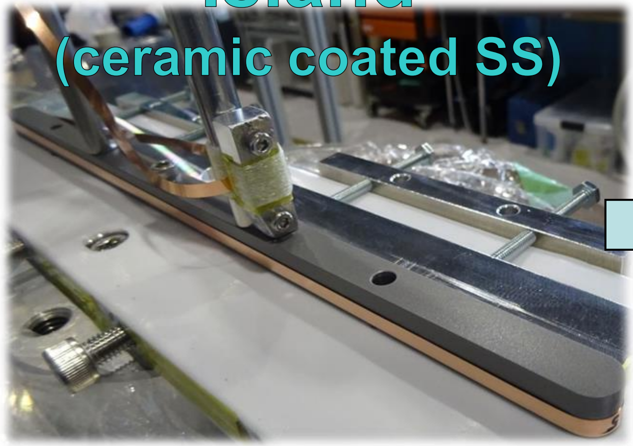
Task 1 Inorganic Insulation HTS coil

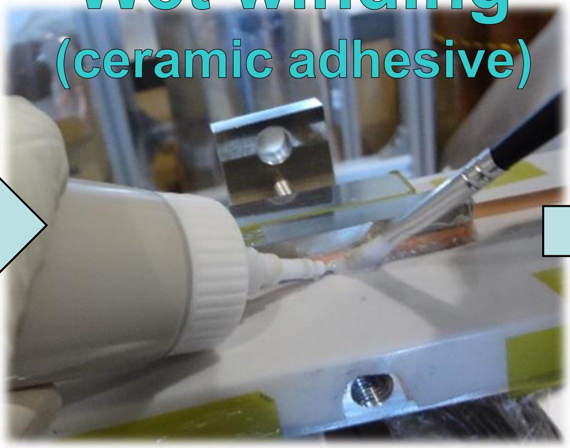
Trial winding of the insert coils with Cu tapes

Purpose

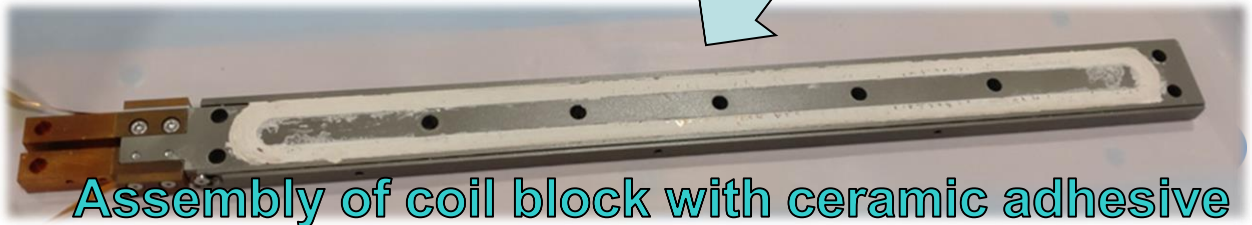
- Establishment of winding technology
- Improvement of coil parts and winding jigs
- Feedback to the actual coil design

Aron Ceramic Type C (Toagosei Co., Ltd)	
Main Ingredients	Silica (SiO_2)
Viscosity	70,000 mPa·s
CTE	13×10^{-6} (0-600℃)
Heat Treatment	16h at R.T. →1h at 90 ℃ →1h at 150 ℃





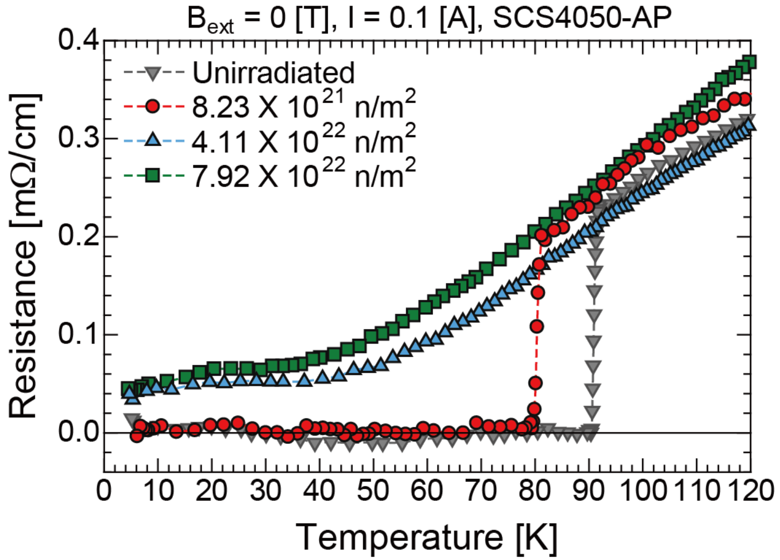
Winding of actual coils winding will be performed soon.

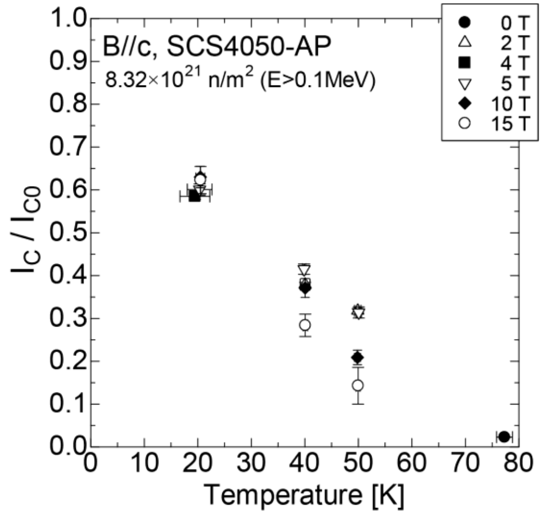


Task 1 Neutron irradiation to HTS conductors

Publication of a paper on neutron irradiation of ReBCO

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

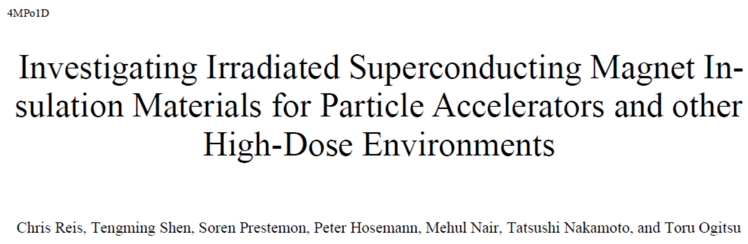




Activity in LBNL and UC Berkeley

- **Irradiated sample shipment to Berkeley: under preparation**
- **FIB-SEM procedures for TEM lamella preparation developed**
- **TEM access approved**
- **NERSC Supercomputing resource access proposal underway**

➢ **GdBCO conductors degrade at neutron fluences higher than 8.23 x 10^{21} [n/m^2]**


4MPo1D

Investigating Irradiated Superconducting Magnet Insulation Materials for Particle Accelerators and other High-Dose Environments

Chris Reis, Tengming Shen, Soren Prestemon, Peter Hosemann, Mehul Nair, Tatsushi Nakamoto, and Toru Ogitsu

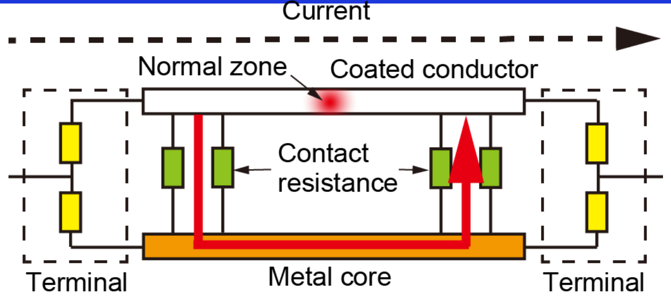
Irradiation of new samples is now underway at JRR3

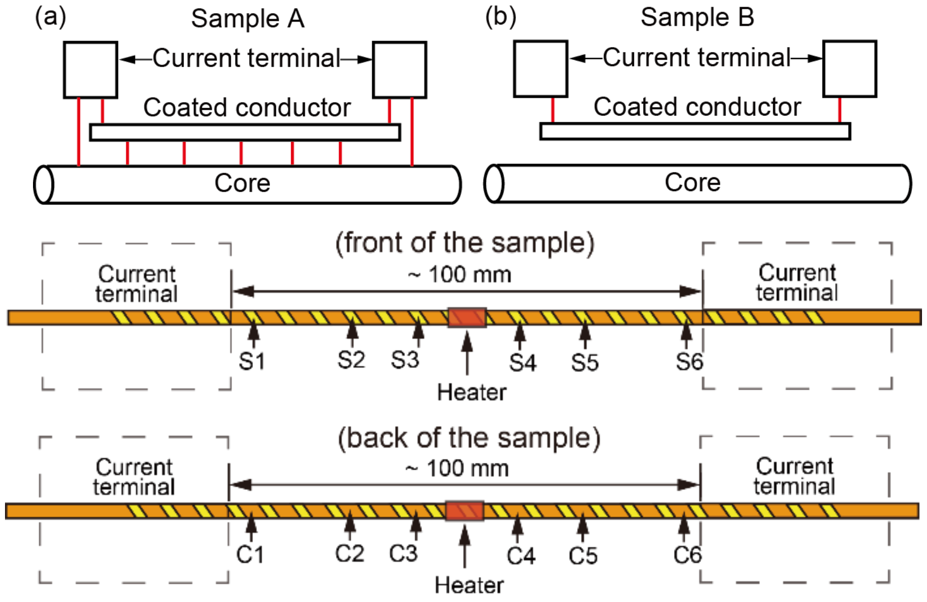
- ☐ **Target fluences: 1.0 x 10^{21} [n/m^2]**
- ☐ **Conductor type: GdBCO, YBCO, EuBCO**
- ☐ **Artificial pining: With or Without**
- ☐ **Low-energy neutron suppression shield: With or Without**

BERKELEY LAB

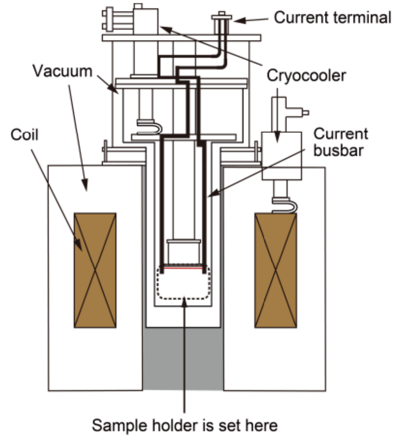
Task 2 (2022FY): Effect of metal core on quench protection of spiral coated conductors

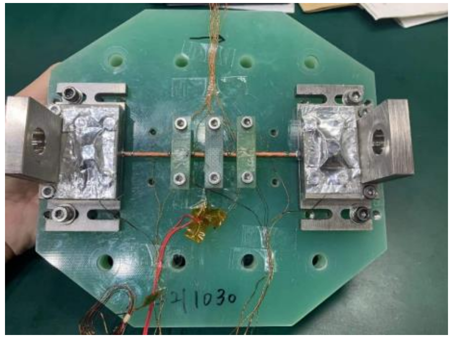
When quench occurs in a spiral coated conductor, the current sharing by the metal core is expected to reduce Joule heating to prevent the coated conductor from burning out.





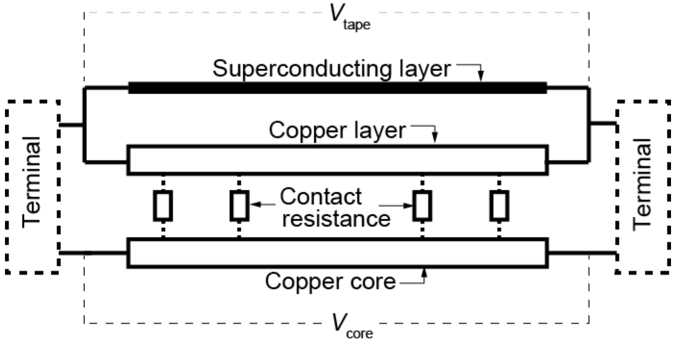
A normal zone was generated by a small heater, and, then, the coated-conductor and core voltages were measured when the sample current was 160 A at 55 K / 0.5 T (I_c ~ 170 A).





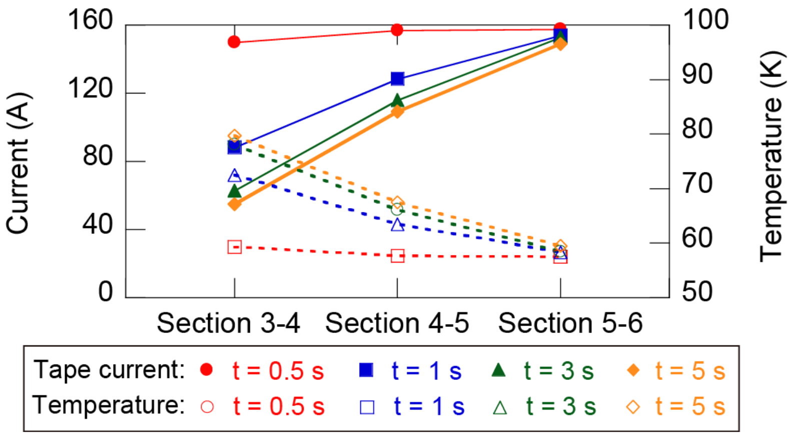
Task 2 (2022FY): Effect of metal core on quench protection of spiral coated conductors

The hot spot temperature and the currents in the coated conductor and the core were calculated by using experimental voltage data.

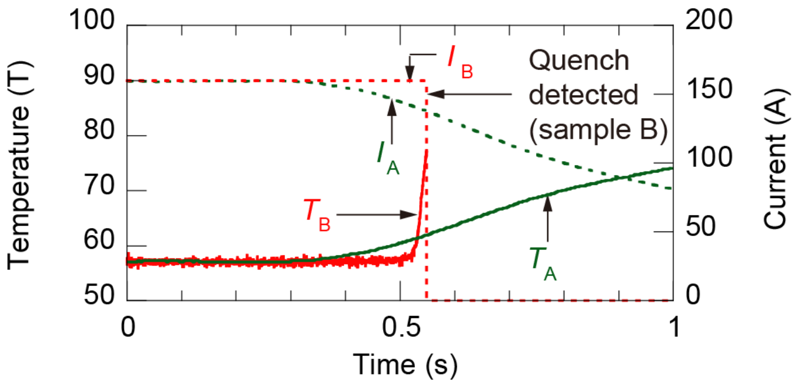


$$I_{tape} = I_c(T) + \frac{V_{tape}}{R_{cu}(T)}$$
$$I_{core} = \frac{V_{core}}{R_{core}(T)}$$
$$I_{tape} + I_{core} = I_{op}$$
$$\alpha = \frac{T_{core} - T_{op}}{T_{tape} - T_{op}}$$

Comparison of current sharing and temperature in each sections



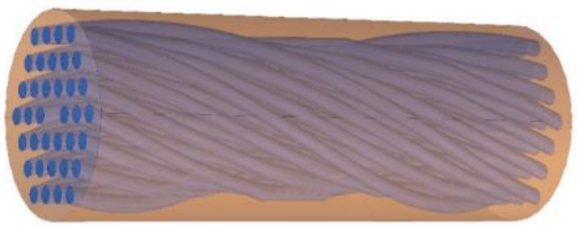
Comparison of hot-spot temperature and tape current between sample A and sample B



Current sharing between the tape and the core through the contact resistance was experimentally examined.

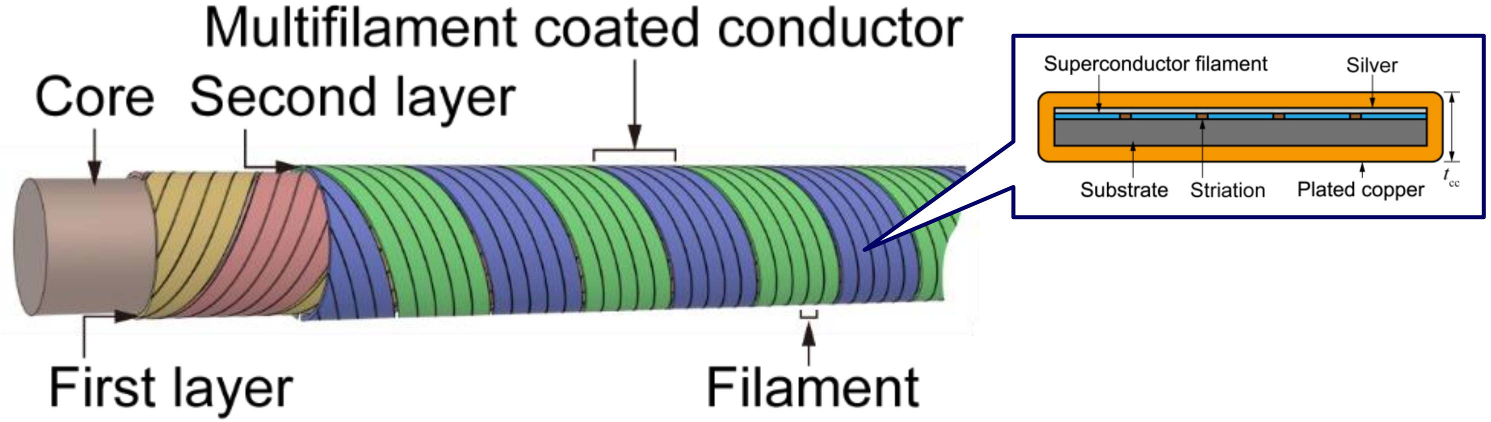
Current sharing was suppressing the hot-spot temperature.

Task 3 (2022FY): SCSC cables: spiral coated conductor cable using multifilament coated conductors



Twisting round LTS wire

Twisting flat HTS tape



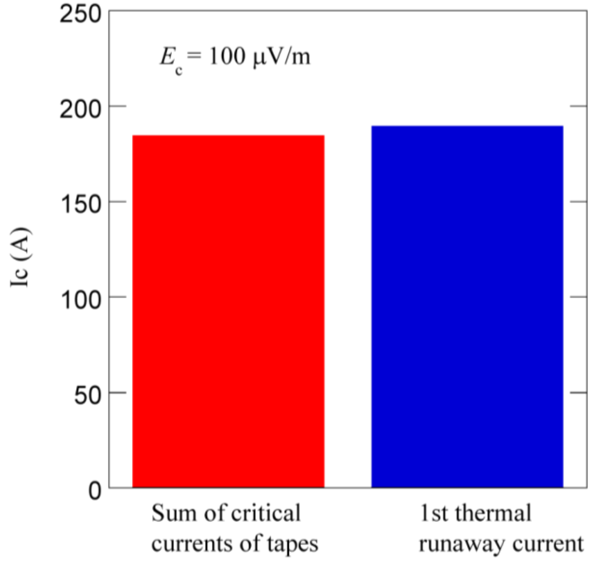
Winding copper-plated multifilament coated conductors spirally on a round core

SCSC cable (double "SC" cable, standing for <u>S</u>piral <u>C</u>opper-plated <u>S</u>triated <u>C</u>oated-conductor cable), with which shielding-current induced field can be reduced effectively

Task 3 (2022FY): Technology of fabricating terminals was transferred from LBL to KU through this Japan-US cooperation program


Hugh Higley of LBL


Naoyuki Amemiya of KU

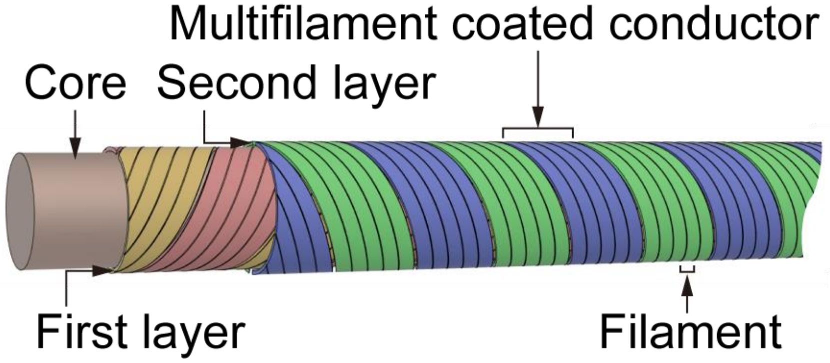


The sample cable successfully transported current.

A sample cables with terminals, which were fabricated by Naoyuki Amemiya of KU at LBL.

Task 3 (2022FY): Electromagnetic field analysis of spiral coated conductor cables in magnet environment

Analyses of Spiral Copper-plated Striated Coated-conductor (SCSC) cables carrying transport current I_t under external magnetic field B_{ext} is necessary for magnet application.

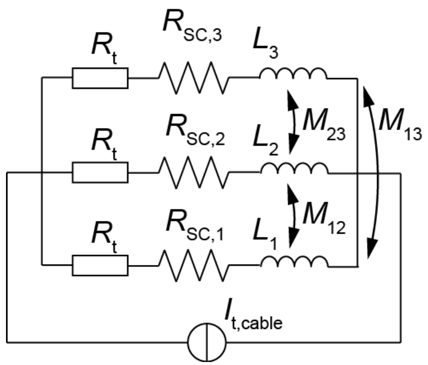


SCSC cable

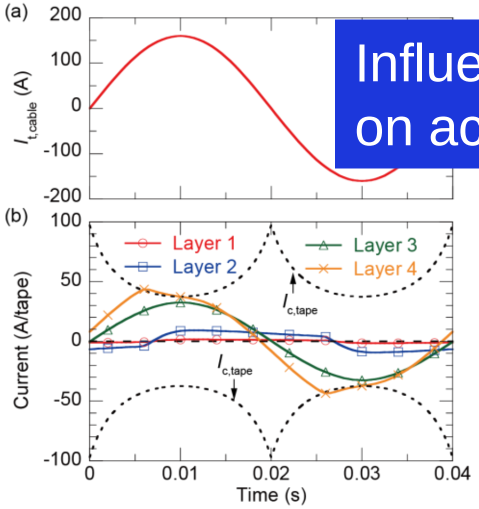
Considering non-uniform current distribution among layers

The impedance imbalance of each layer results in different time variation of the current in each layer (non-uniform current distribution)

Combination of circuit model for current distribution calculation and electromagnetic field analysis model

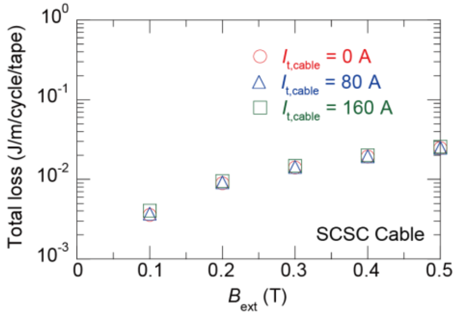


Circuit model



(a) cable current
(b) current in each layer

Influence of transport current on ac loss is negligible.



Calculated ac loss

Future Plan under discussion

Task1: HTS magnet technologies for high-radiation environment

- Continue Irradiation tests of superconductors:

Task 2: Stability, quench protection, and magnet safety

- Advanced Quench Detection?

Task 3: Measuring and modeling AC loss and field quality of HTS accelerator magnets

- Continue including SCSC Cable?

Task 4: HTS/LTS high field hybrid accelerator dipole technology

- Test coil based on SCSC and/or CORC Cable?

R&D programs of High Field Magnet for Accelerator in Japan

On going (based on international collaborations)

- HTS: US-Japan collaboration framework
  - KEK, Kyoto U., LBNL, BNL, UC Berkeley
- **Nb3Sn: CERN-KEK collaboration**
  - **KEK, Tohoku U., Tokai U., NIMS, JASTEC, Furukawa, CERN**

Submitted Proposal

– R&D program of High Field Magnet for Accelerator
  – To Science Council of Japan (Future Science Promotion 2023)

Nb_3Sn conductor development program

- The first phase of Nb_3Sn conductor development program for FCC within the CERN-KEK collaboration was conducted in 2016–2022.
- Two Japanese wire manufacturers (JASTEC, Furukawa) participated in this program.
- J_c improvement was the first priority.

KEK

- Evaluation of J_c, B_{c2}
- Mechanical property

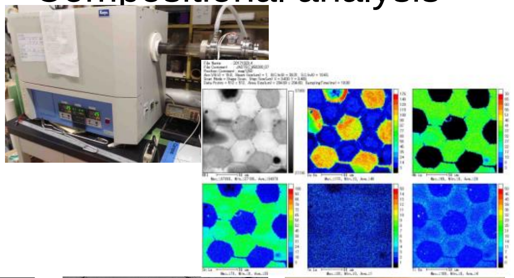
CERN

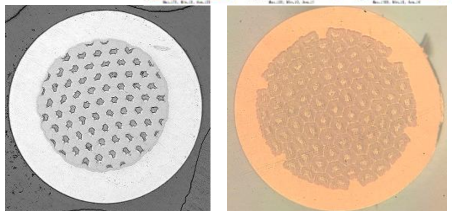
- In-depth characterization HT, J_c, composition, d_{eff} ...

Program coordination
Defining specification
Conceptual design

Tokai University

- Optimization of HT condition
- Microstructure observation
- Compositional analysis

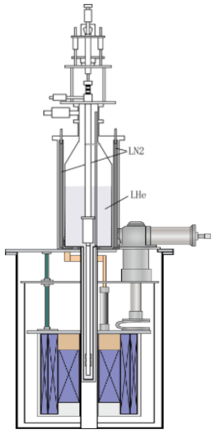




Tohoku University

- High field magnet facility
- Evaluation of d_{eff}

28 T HM



Spec, design

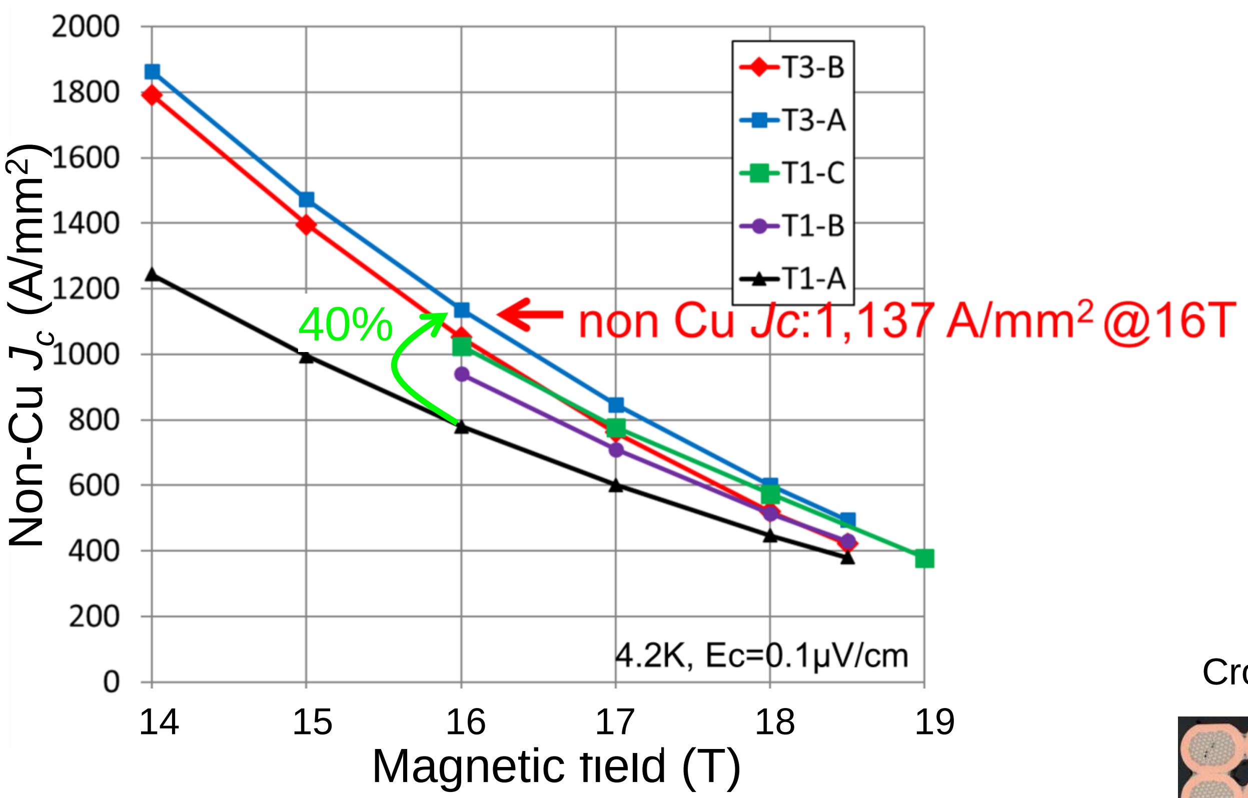
R&D billets

Fabrication

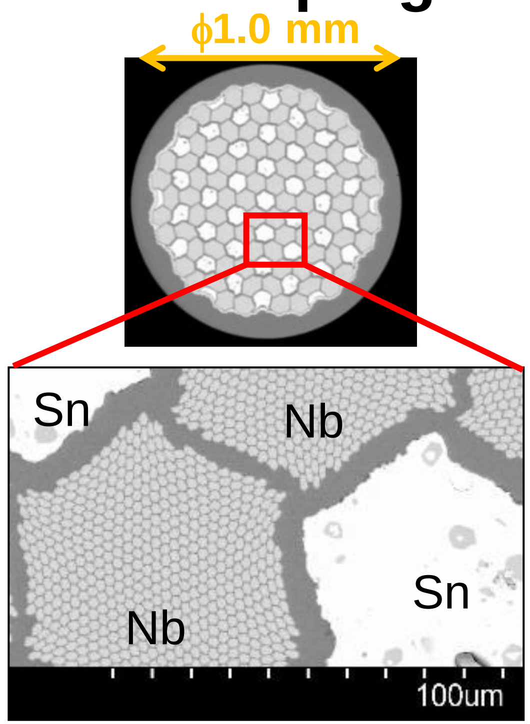
Kobe Steel / JASTEC

Furukawa Electric

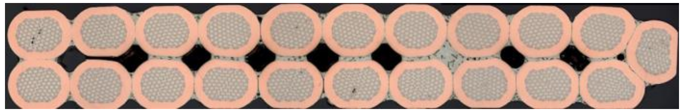
Achievement in the first phase of conductor R&D program



J_c-B curve of the JASTEC trial wires



Cross-section of DT wire by JASTEC



Cross-section of Rutherford cable made up of ϕ1.1 mm JASTEC wires

- Non-Cu J_c of distributed-Sn wires fabricated by JASTEC was improved by 40% by the reduction in Sn diffusion distance and controlling Ti ratio. The J_c of 1100 A/mm^2 at 16 T and 4.2 K was achieved.
- Around 3 km of DT wires with a diameter of 1.1 mm and 1.2 mm were delivered to CERN for the cabling test.
- Drawability should be improved for longer-length production. The extracted wires from the cable showed a stability issue.

Next step for further improvement of JASTEC DT wires

Targets

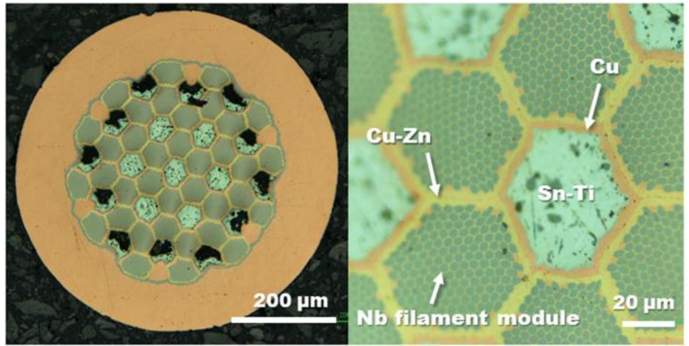
1. The industrialization of the process by focusing on improved workability to achieve longer piece length while maintaining non-Cu J_c~1000 A/mm^2 at 16 T and 4.2 K and stability at 0.85 mm in diameter.
2. Continue R&D to further enhance performance (J_c and mechanical property) towards requirements for HFM

Strategies

• Improvement of drawability
– Optimization of annealing condition of Nb

• Improvement of non-Cu J_c in collaboration with NIMS
– Zn addition to Cu matrix to promote Sn diffusion
– Doping of Ti to Nb instead of using Sn-Ti
– Basic R&D to understand the effectiveness of Hf doping to Nb on higher J_c

• Enhancement of tolerance of transverse compression stress
– Zn addition to Cu matrix



Banno et al, IEEE Trans. Appl. Supercond., 30 (2020) 6000705.

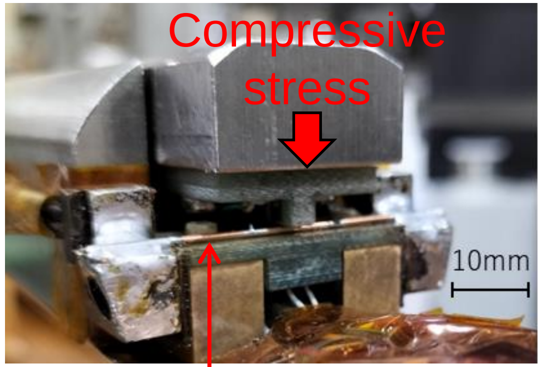
Characterization of mechanical properties of Nb_3Sn wires by KEK

- KEK is addressing improvement in the tolerance of transverse compression stress of Nb_3Sn conductors. As a first step, we started the characterization of I_c-transverse compressive stress and internal strain measurement by using neutron diffraction.

– Fracture behavior of DT wires from JASTEC under transverse compression

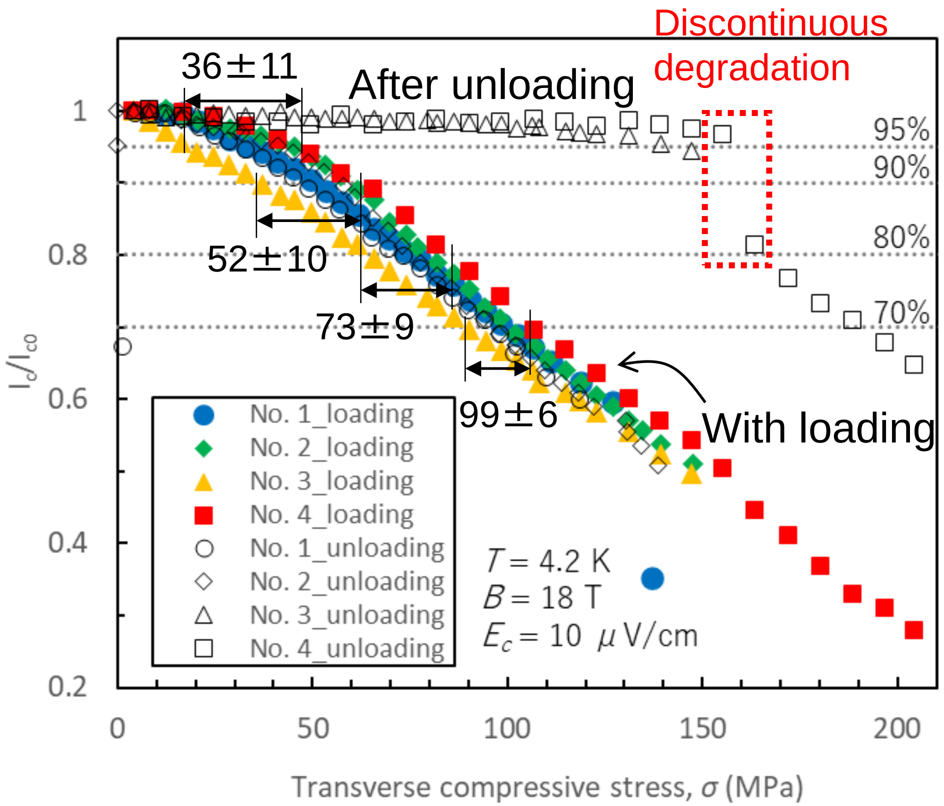
– Verification of the strengthening effect of Cu-Nb reinforcement against transverse compression in bronze wires from Furukawa

I_c-transverse compressive stress in JASTEC DT wire



Tolerance of transverse compressive stress was evaluated for JASTEC DT wires with J_c of 1100 A/mm^2 at 16 T, 4.2 K .

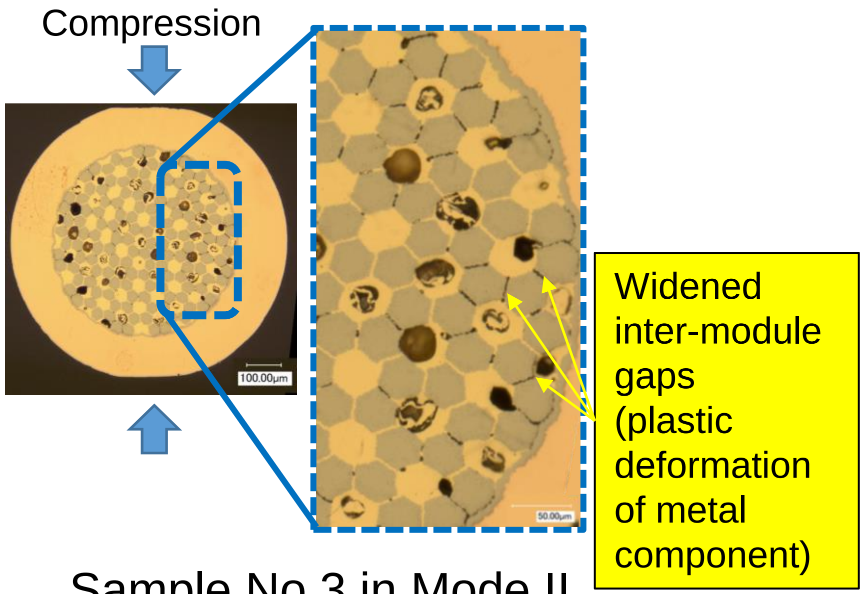
- Lever-cam type probe in Tohoku University
- A transverse load was applied with a 3 mm-wide G10 anvil.
- Reversibility of I_c change was checked by loading/unloading.
- I_c was evaluated on the 10 μV/cm criterion at 18 T and 4.2 K.



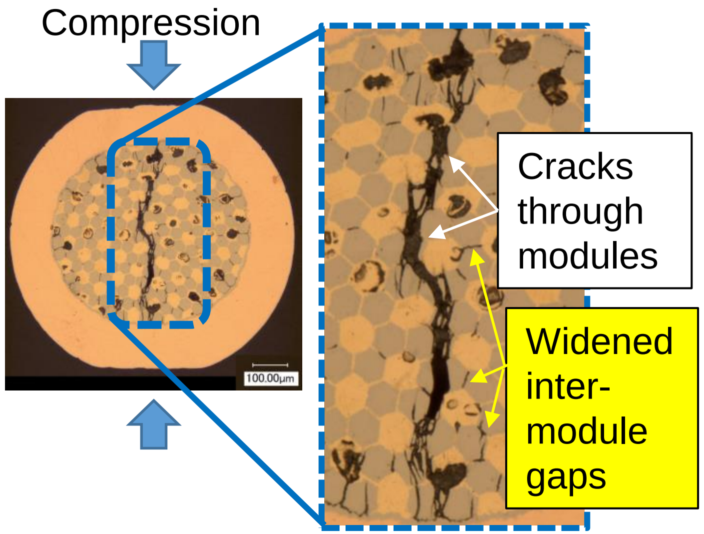
- Good reproducibility among 4 samples

- Change of I_c after unloading
  - At low stress, the I_c recovers to the initial value.
  - At medium stress, the I_c after unloading gradually decreases with $\Delta I_c/I_{c0}$ < 6%.
  - At high stress, discontinuous degradation of I_c occurs.

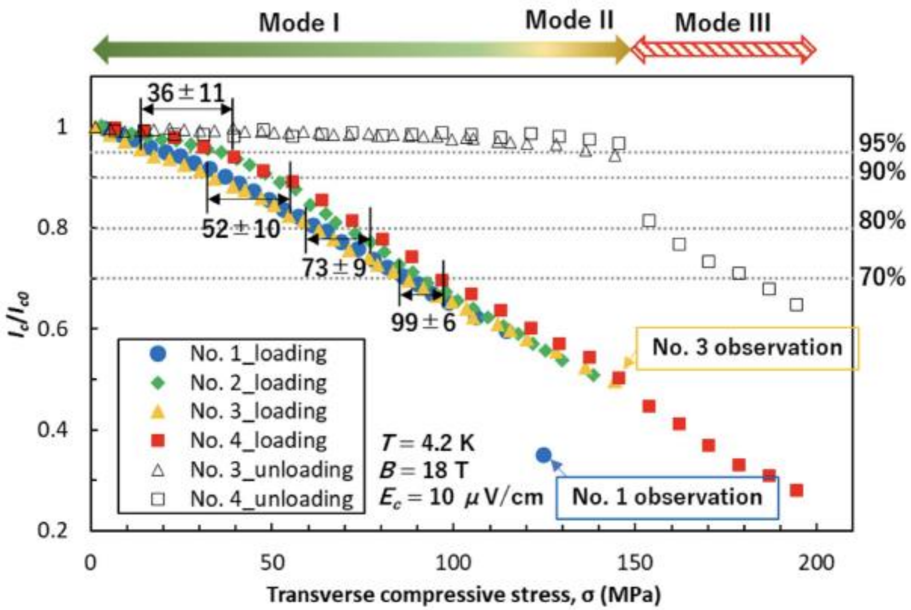
Fracture behavior by transverse compressive stress in JASTEC DT wire



Sample No.3 in Mode II



Sample No.1 in Mode III

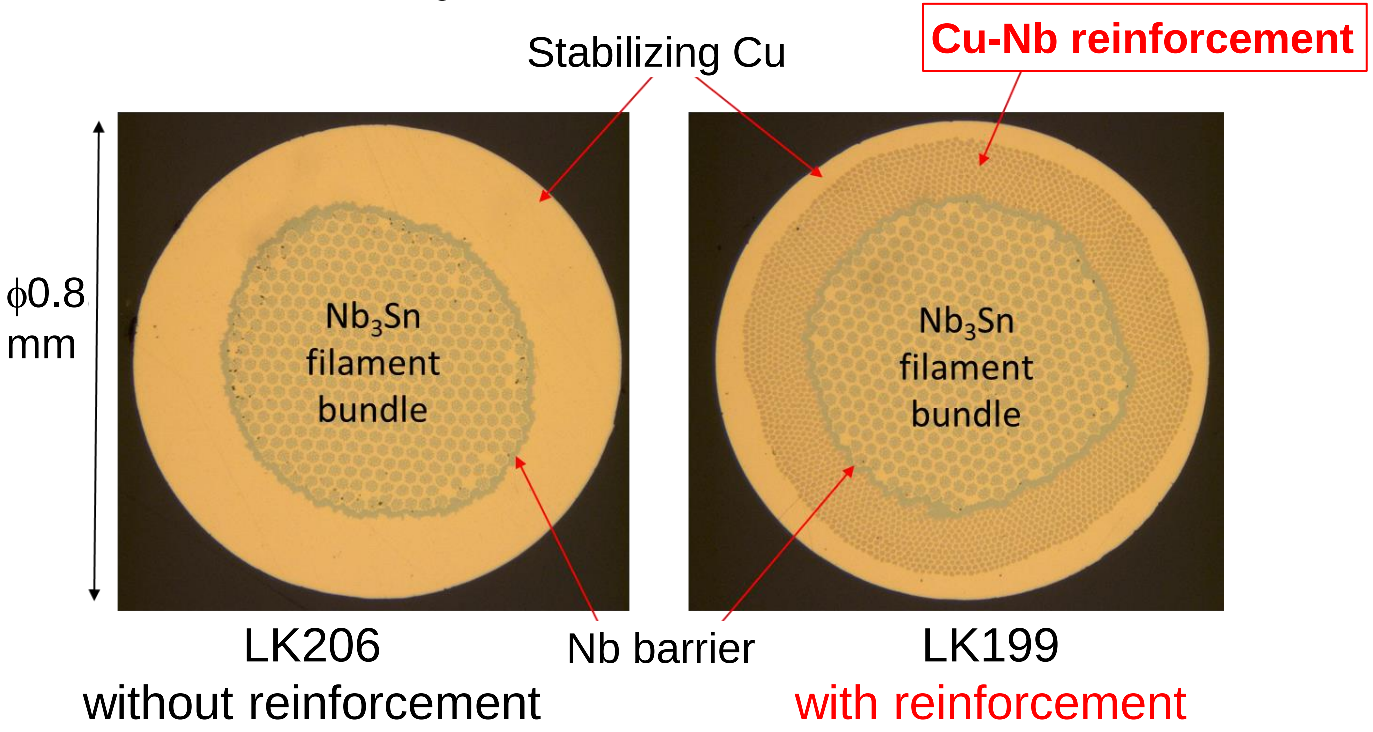


Mode I: Reversible I_c change caused by elastic deformation of Nb_3Sn and metal components

Mode II: Gradual I_c degradation caused by plastic deformation of metal component without cracking of Nb_3Sn modules

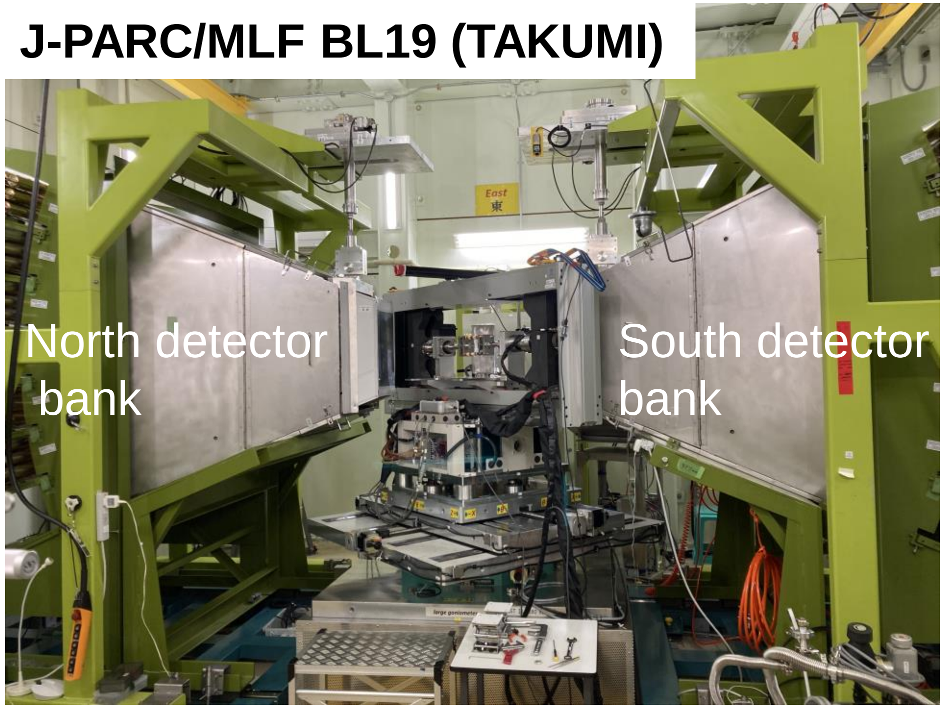
Mode III: Discontinuous I_c degradation caused by fracture of Nb_3Sn modules

Cu-Nb reinforced Nb_3Sn wires



- High strength bronze-routed wires were originally developed for high field solenoid magnets by Tohoku University and Furukawa Electric
- Stabilizing Cu is partially replaced by Nb-fiber-reinforced Cu (Cu-Nb).
- High axial stress tolerance has been validated, while the reinforcement effect against transverse compressive stress has not been fully understood.
- Neutron diffraction measurements were conducted to compare the internal strain state of Nb_3Sn filaments under transverse compression for the wires with or without Cu-Nb reinforcement.

Neutron diffraction measurement under transverse stress

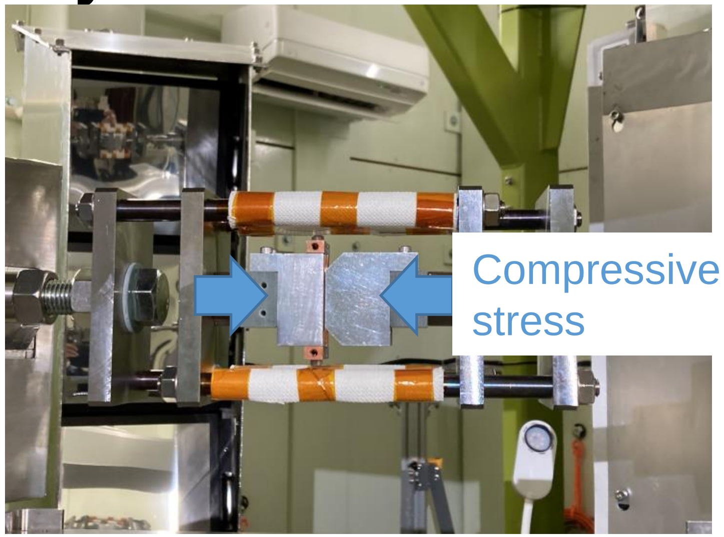


50 kN tensile loading frame

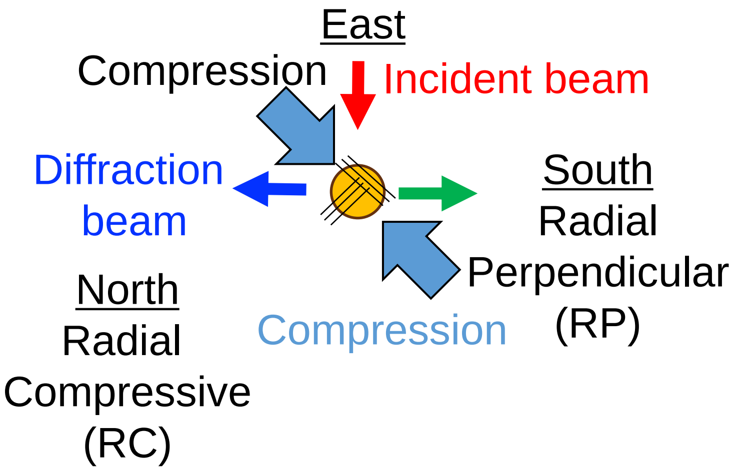
- Neutron diffraction measurement was conducted to evaluate the internal strain of Nb_3Sn in a composite wire under transverse compression.

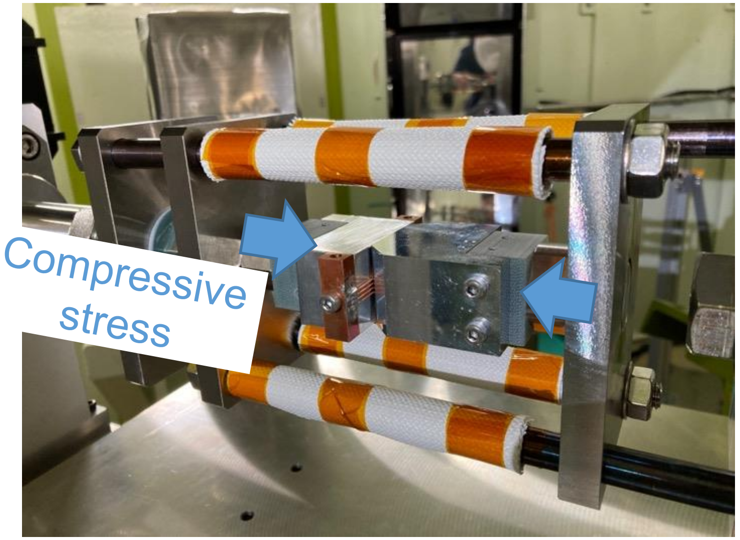
- J-PARC/MLF BL19 (TAKUMI, Engineering materials diffractometer)
  - White neutron beams at 25 Hz
  - 1 MW class-high-intensity neutron beams can shorten the measurement time to obtain sufficient statistics.
  - Time-of-flight (TOF) neutron diffractometer
  - A loading machine with maximum load of 50 kN is installed on the goniometer.
  - Diffraction patterns were taken at room temperature. Measurement at low temperature is also possible by using a cryogenic loading frame.

Geometry of diffraction measurement

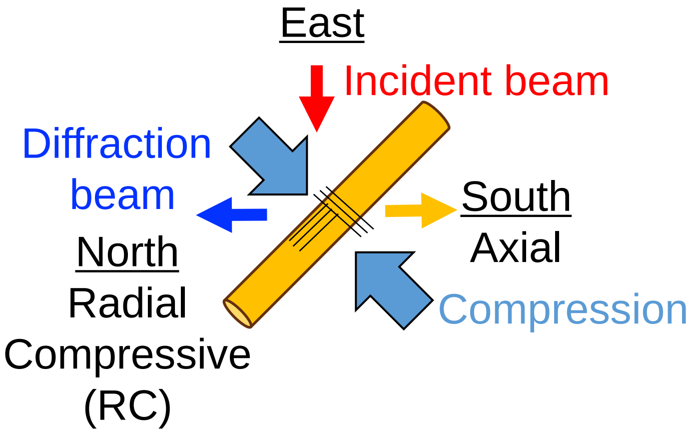


Vertical configuration



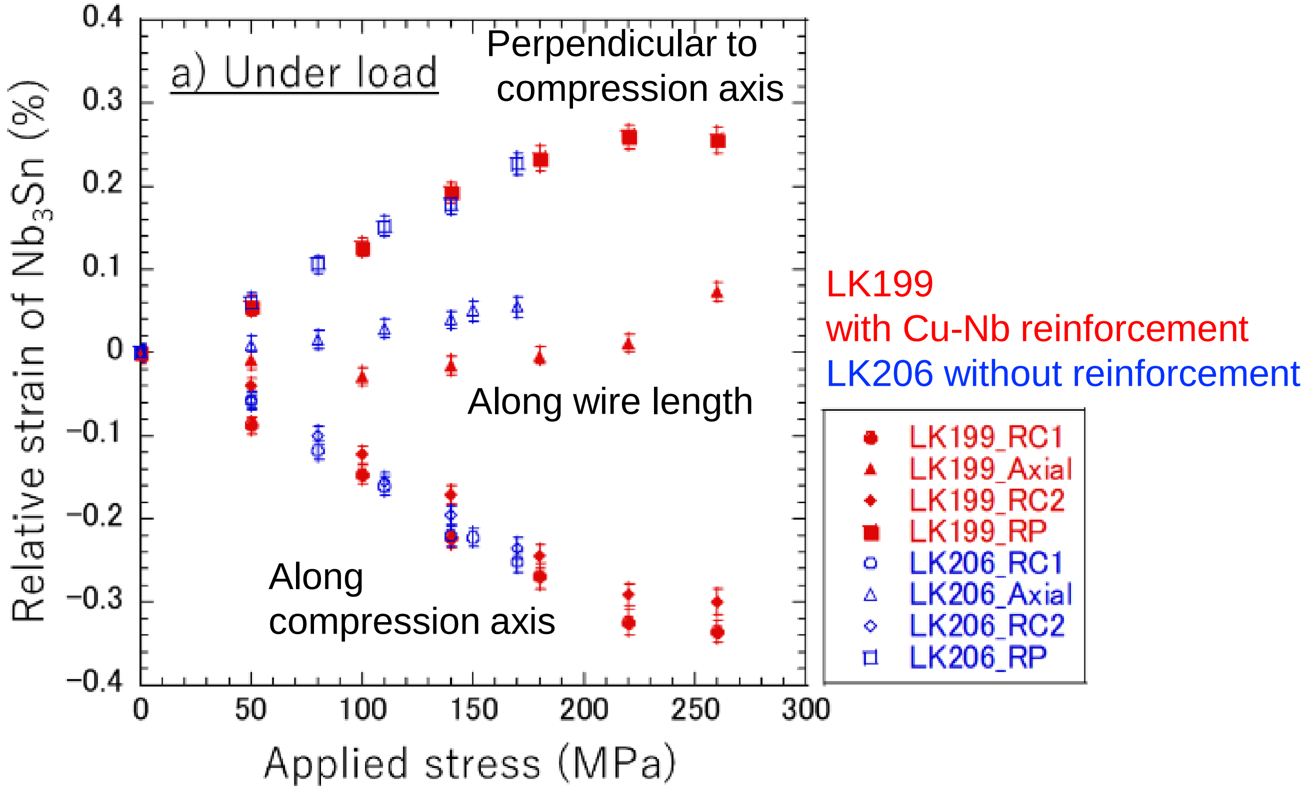


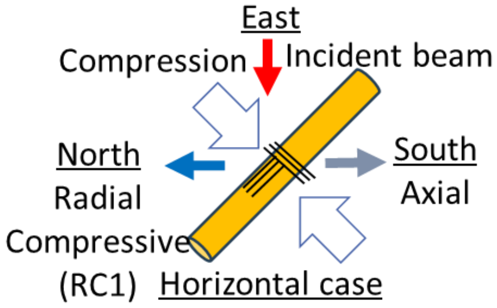
Horizontal configuration

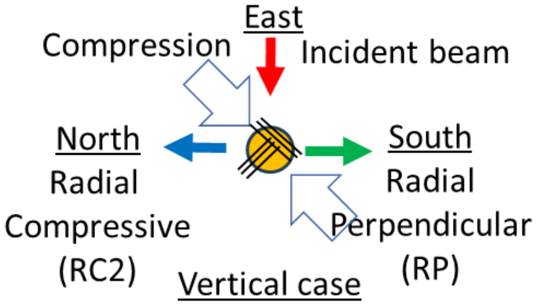


- I_c of Nb_3Sn wires are influenced by 3-dimensional strain states.
- Combining two configurations, strain states along three orthogonal directions of Nb_3Sn was evaluated.

Internal strain of Nb_3Sn under transverse compression







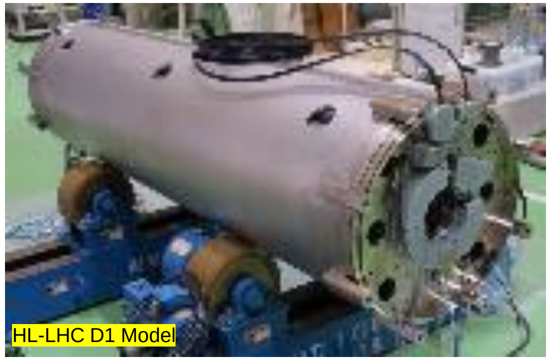
- No significant difference was found between the wire with or without Cu-Nb reinforcement.
- Stress analysis considering anisotropy of mechanical property of uni-directional Nb-fiber-reinforced Cu is necessary.
- The usefulness of neutron diffraction measurement to study reinforcement mechanisms against transverse compressive stress was verified.

R&D programs of High Field Magnet for Accelerator in Japan

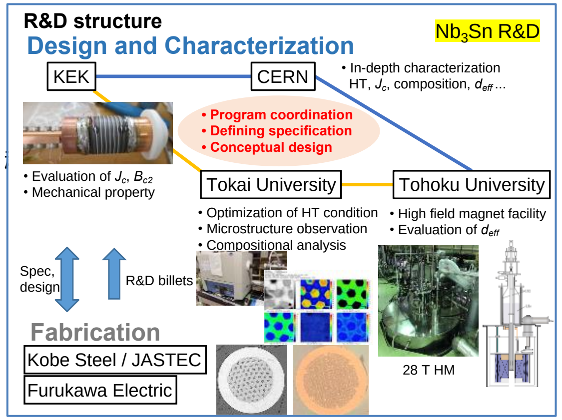
- On going (based on international collaborations)
  - HTS: US-Japan collaboration framework
    - KEK, Kyoto U., LBNL, BNL, UC Berkeley
  - Nb3Sn: CERN-KEK collaboration
    - KEK, Tohoku U., Tokai U., NIMS, JASTEC, Furukawa, CERN
- Submitted Proposal
  - **R&D program of High Field Magnet for Accelerator**
    - **To Science Council of Japan (Future Science Promotion 2023)**

High Field Manget Development Plan

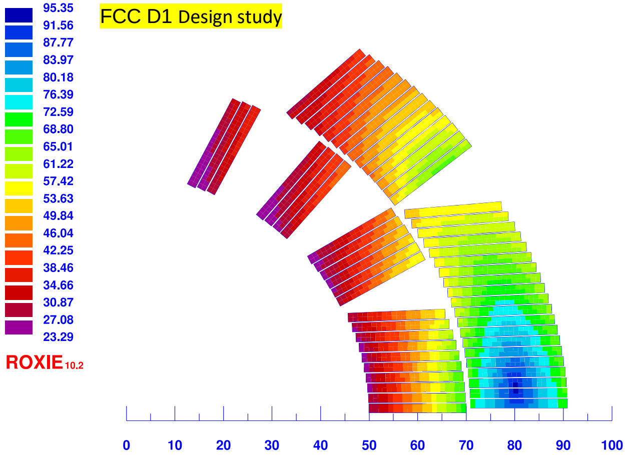
Magnet Manufacturing Technology



Advanced Conductor Development



High Field Magnet Development

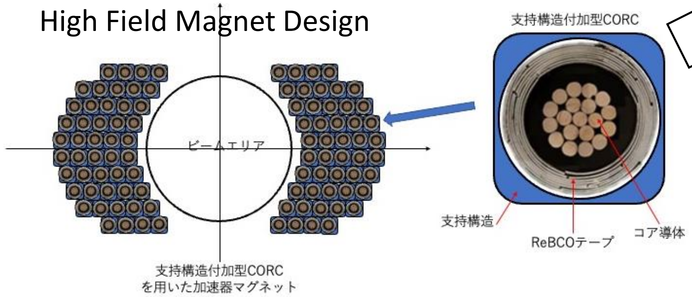


12T Manget

16-20T

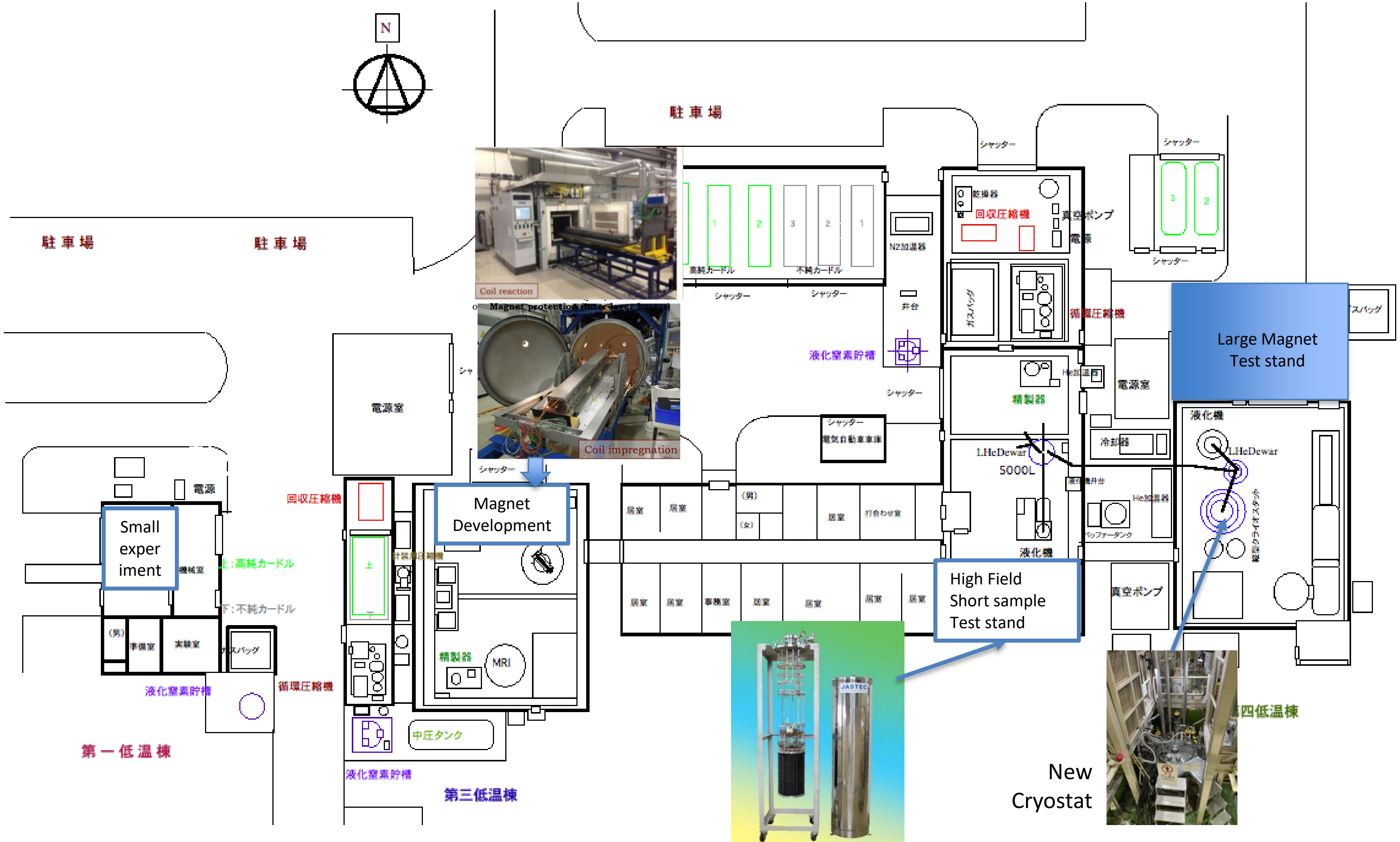
4-8T
Insert Coil

High Field Magnet Design



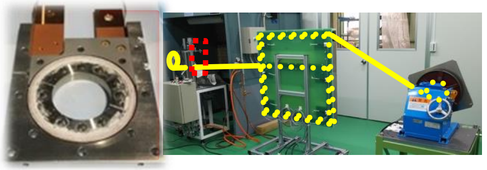
20T High Field Magnet

Renovate KEK Cryogenics Science Center



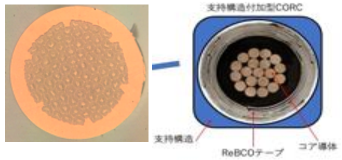
High Field Radiation Hard SC Magnets

←COMET(5T, 10MGy)
LHC(8T, 10MGy)→



HTS Radiation Hard Magnet R&D

Basic R&D

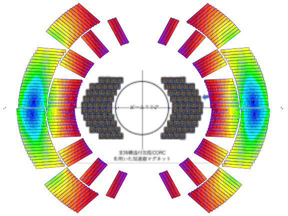


High Field Conductor R&D

Proposal

Magnet R&D assets

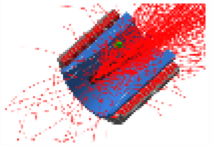
Construct 12T magnet
With R&D insert coil aim for 16-20 T magnet



12T magnet

Output

Compact Muon Source



Muon Industrial application

Science

- Future Collider such as FCC
- Upgrade of J-PARC

Industrial/Medical Applications

Industrial/Medical Accelerator

Summary

- On going (based on international collaborations)
  - HTS: US-Japan collaboration framework
    - High Field Radiation hard HTS magnet
  - Nb3Sn: CERN-KEK collaboration
    - High performance Nb3Sn conductor R&D (DT)
- Submitted Proposal
  - R&D program of High Field Magnet for Accelerator
    - Continue Efforts to get real money