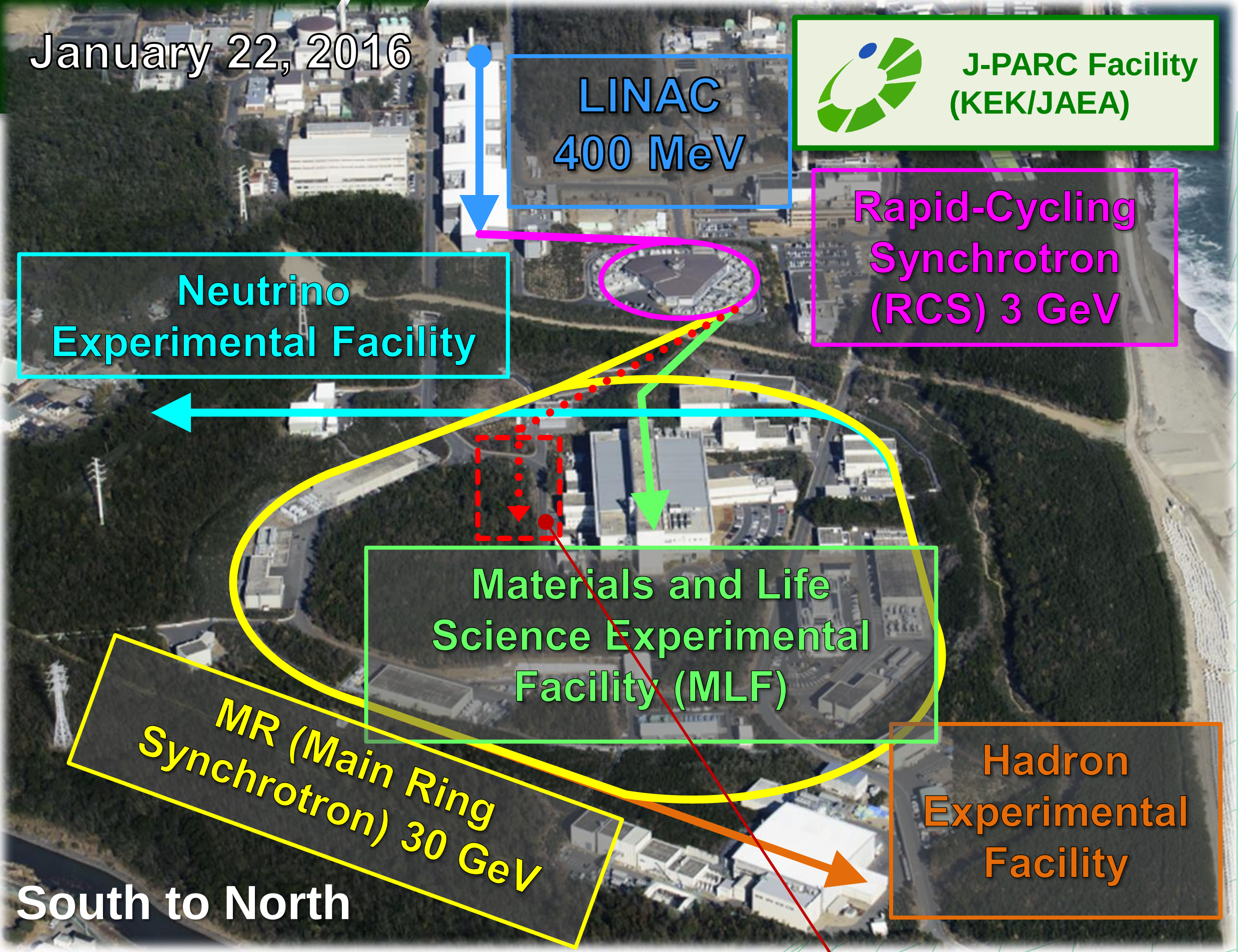
R&D towards radiation-hard HTS magnets

Masami IIO

Cryogenics Section, J-PARC

Cryogenics Science Center, KEK

Contents



Purpose of J-PARC:

Research for the creation and structure of our universe by investigating matters at all levels, from quarks to atoms.

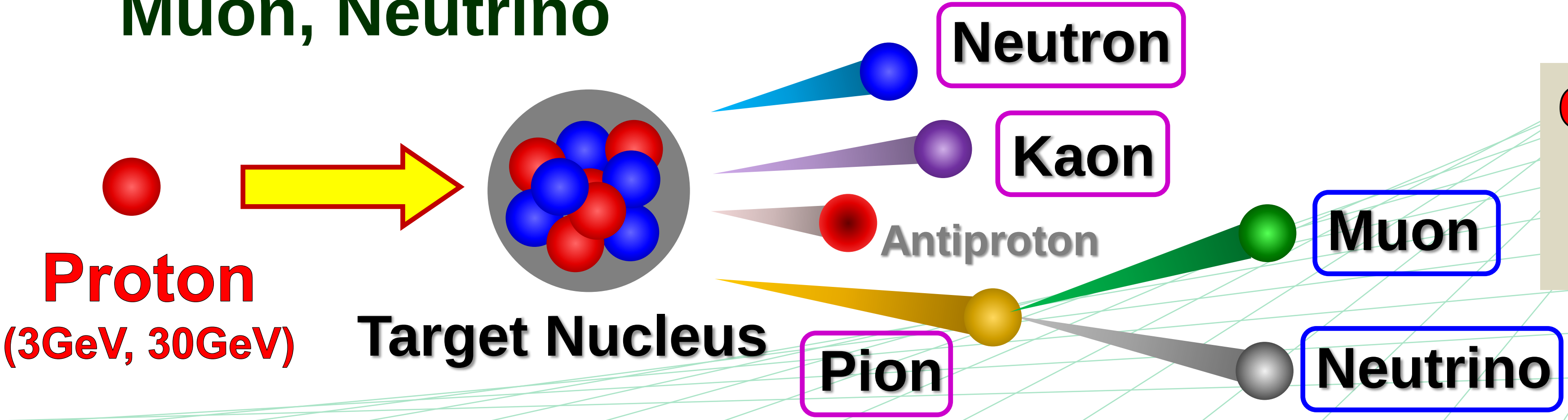
MW-class High Power Proton Driver

→ **Hadrons:**

Neutron, Pion, Kaon

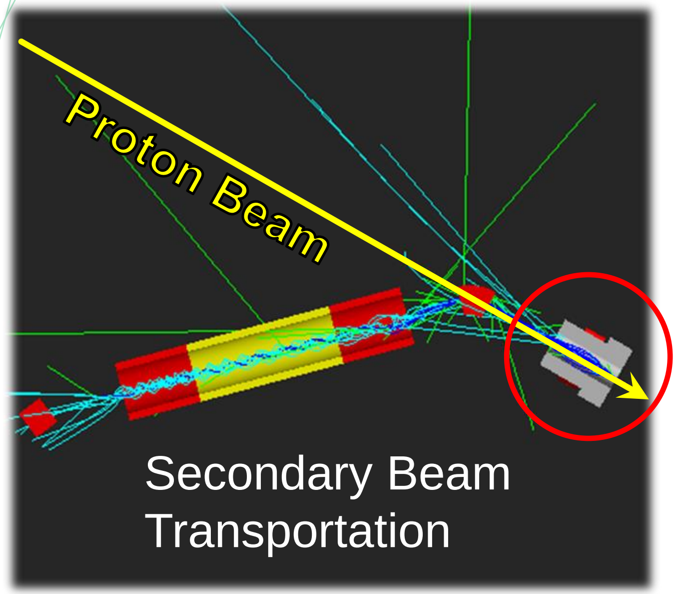
→ **Leptons:**

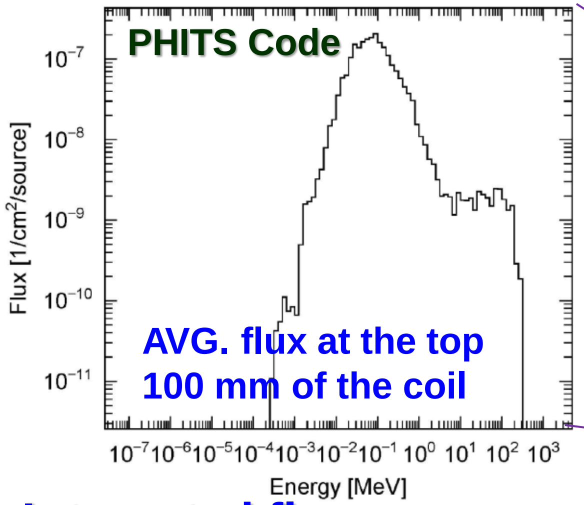
Muon, Neutrino



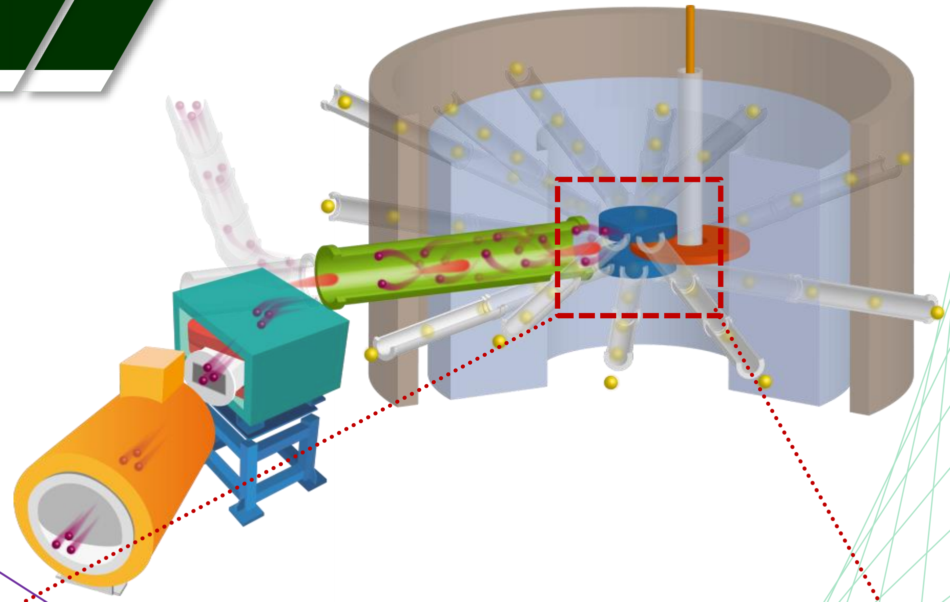
Construction plan for MLF 2nd Target Station

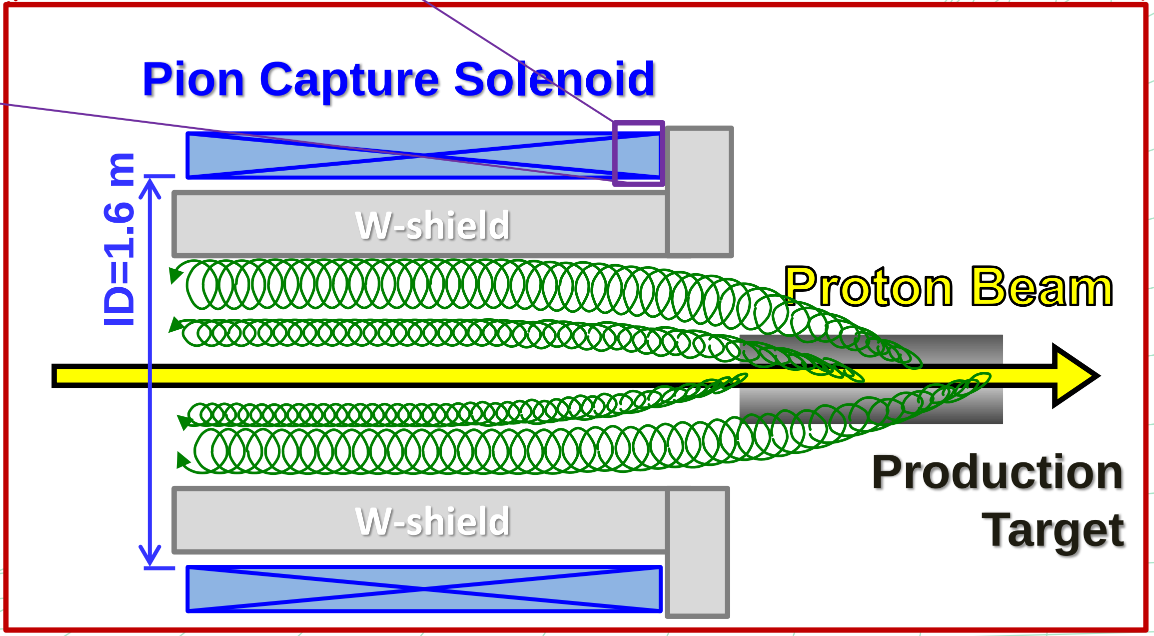
□ Pion Capture Solenoid for muon beamline at the MLF 2nd Target Station (TS2-PCS)





Integrated flux：
7.74×10^{20} n/m^2/y(@1 MW)

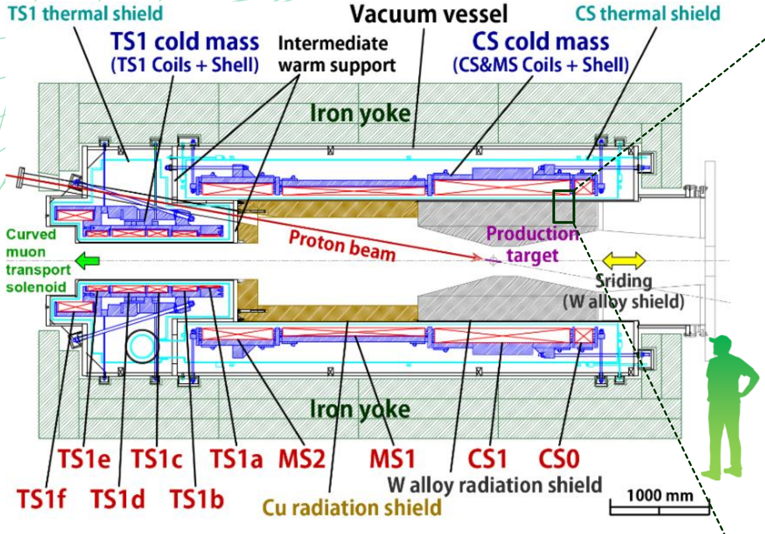




Radiation Conditions **(10 years operation)**

- **Heat Deposit: ~ 650 W**
- **Neutron flux: 7.8 x 10^{21} n/m^2**
- **Absorbed Dose: > 130 MGy**

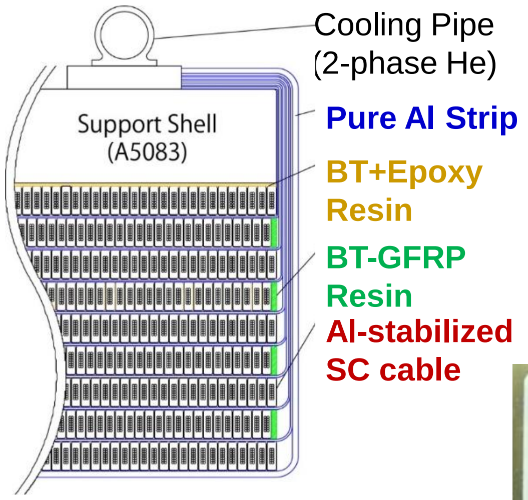
Cooling method of radiation resistant coils

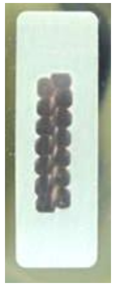


COMET-PCS (under construction)

- Proton beam: 8 GeV, **56 kW**
- Magnetic field: **5 T**
- Radiation resistance: **2~3 MGy**

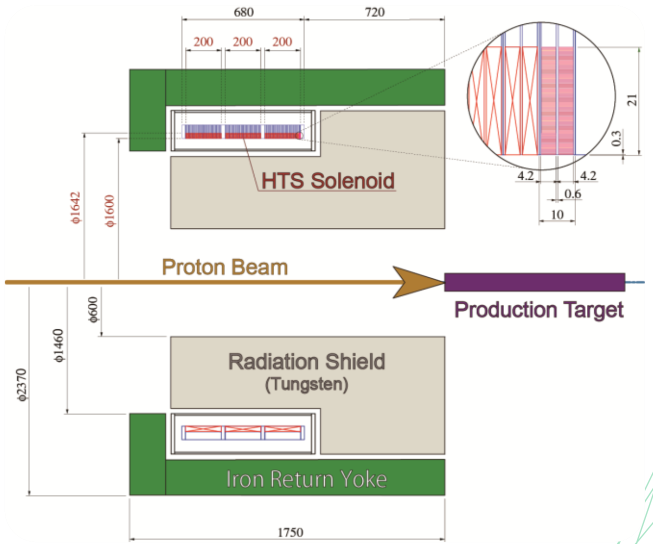
Light coil structure with conduction cooling





[Al-stabilized Superconductor]

- Thickness：4.70±0.05 mm
- Width：15.0±0.05 mm
- RRR：>400

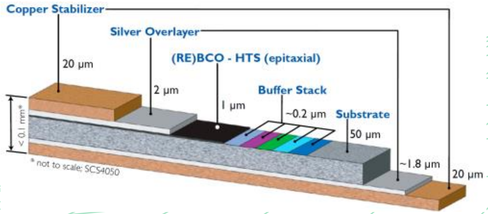


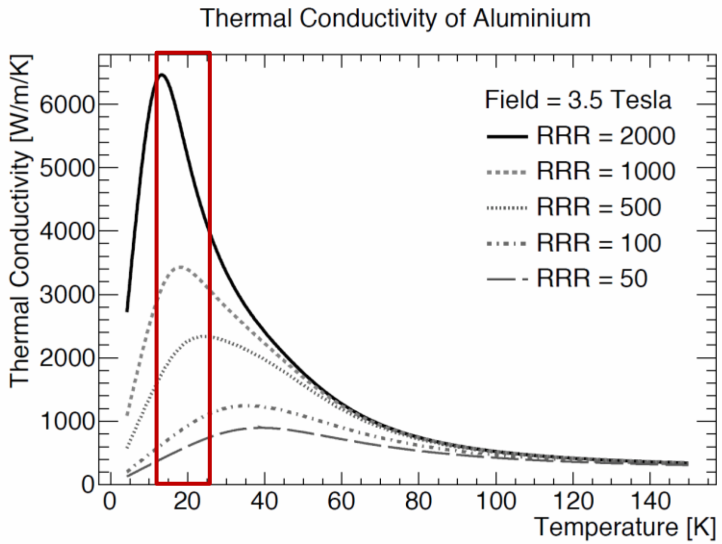
TS2-PCS

- Proton beam: 3 GeV, **1 MW**
- Magnetic field: 1 T
- Radiation resistance: **130 MGy?**

Rare-Earth Barium Copper Oxide (Re: Y, Gd, Eu, etc.)

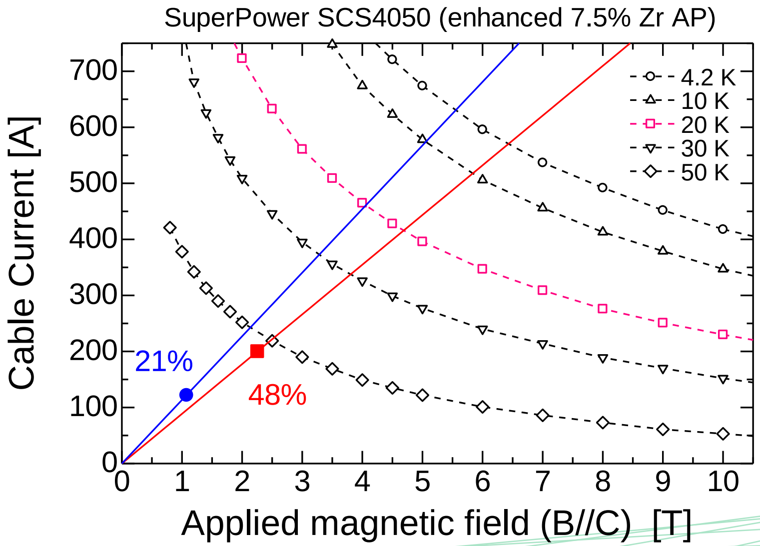
- **High temperature margin**
  - **- Conduction cooling at around 20 K**
- **High magnetic field tolerance of Ic**
  - **- Potential for 20 T class high field magnet**



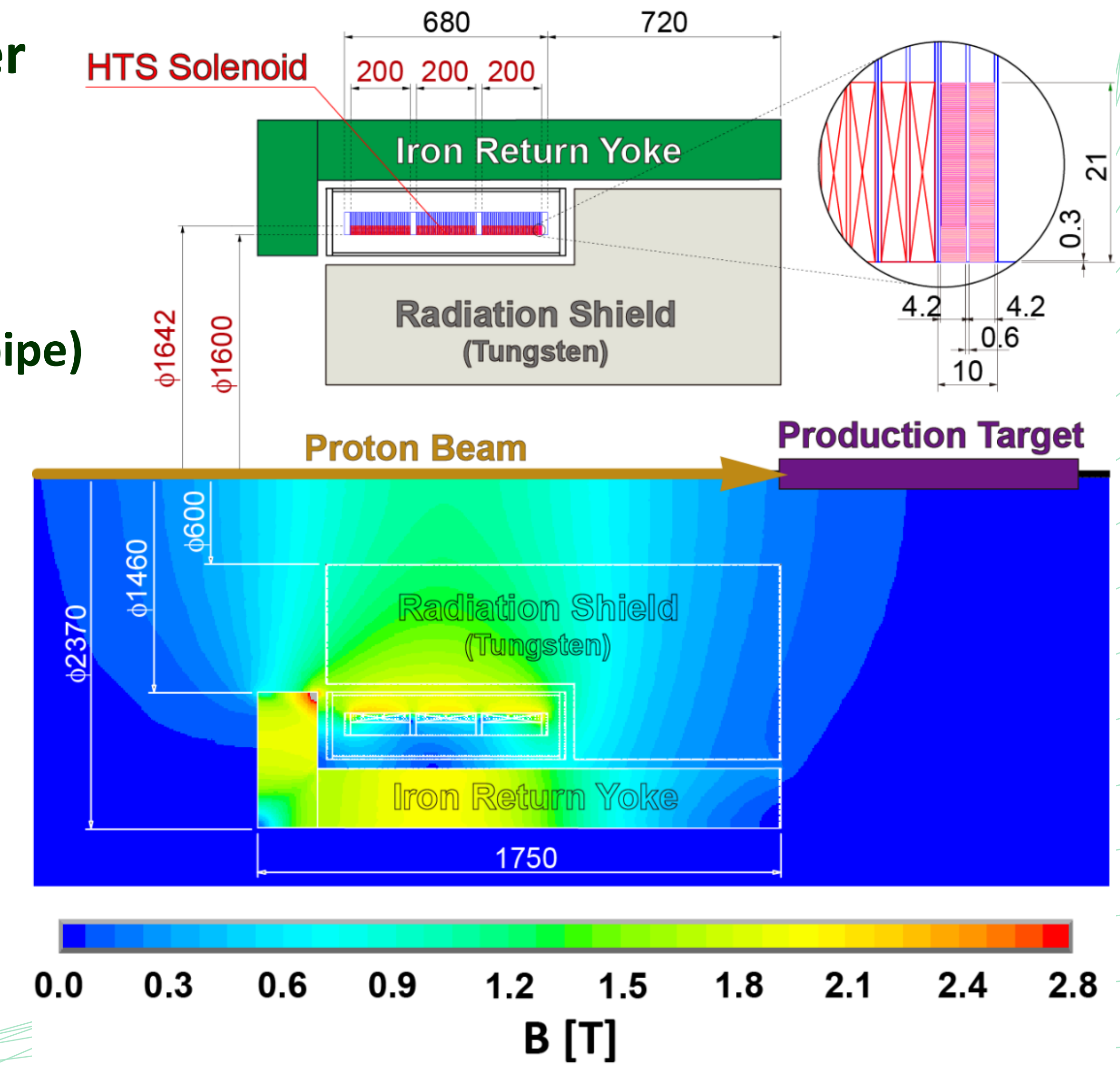


Stack of double pancake coil

- **ID=1600 mm, T=21 mm, L=10 mm, 70 turns/layer**
- Number of double pancake coils: **60** (20 x3)
- Conductor : **REBCO,** W=4 mm, T=0.1 mm
- Insulation: Mineral, t=0.1 mm
- **Operation Temperature: 20 K (He gas cooling with pipe)**
- Transport current: **200 A** (Load line ratio: 0.48)
- Peak Field: **1.11 T** at center,
  2.25 T (B//c) at coil (200 A)



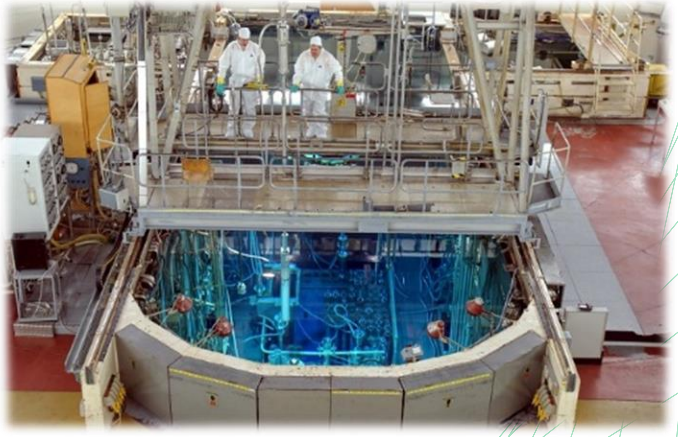
Current density: 128 A/mm^2
Load line ratio: 48%



□ Studies on radiation resistance

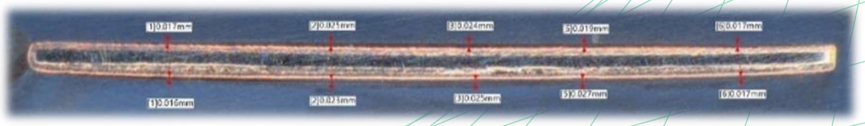
- ➢ **Neutron irradiation**
  - REBCO tapes, Ceramic coating samples, BT-GFRP
- ➢ **Gamma-ray irradiation**
  - REBCO tapes, Ceramic coating samples

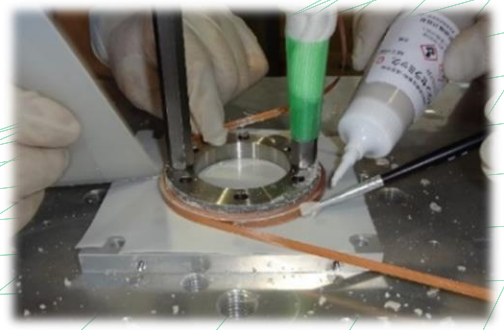
BR2 @Belgian nuclear research center

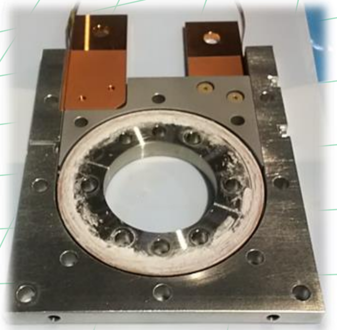


□ Ceramic coating and bonding technology

- ➢ **Ceramic coating on REBCO and magnet materials**
- ➢ **Demonstration of coil assembly with ceramic adhesive**
- ➢ **Cooling and excitation test**



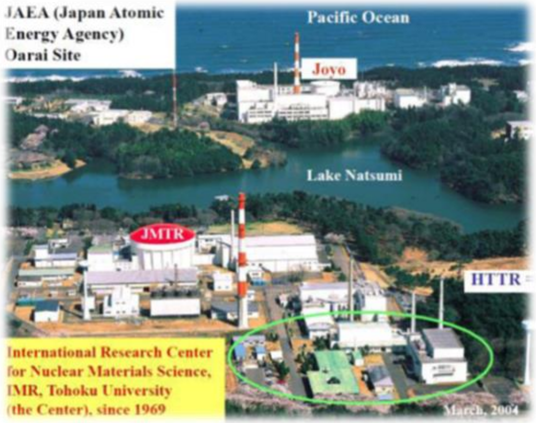




2. Studies on radiation resistance

Neutron Irradiation

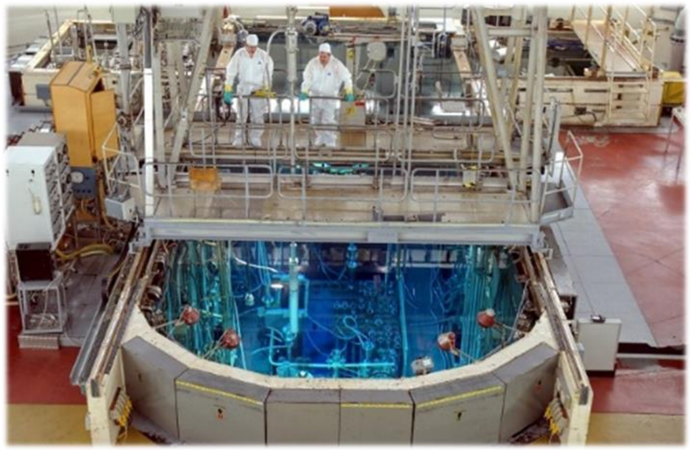
International Research Center for Nuclear Materials Science of the Institute for Materials Research (IMR-Oarai center), Tohoku University



Superconducting Properties Evaluation System @IMR-Oarai

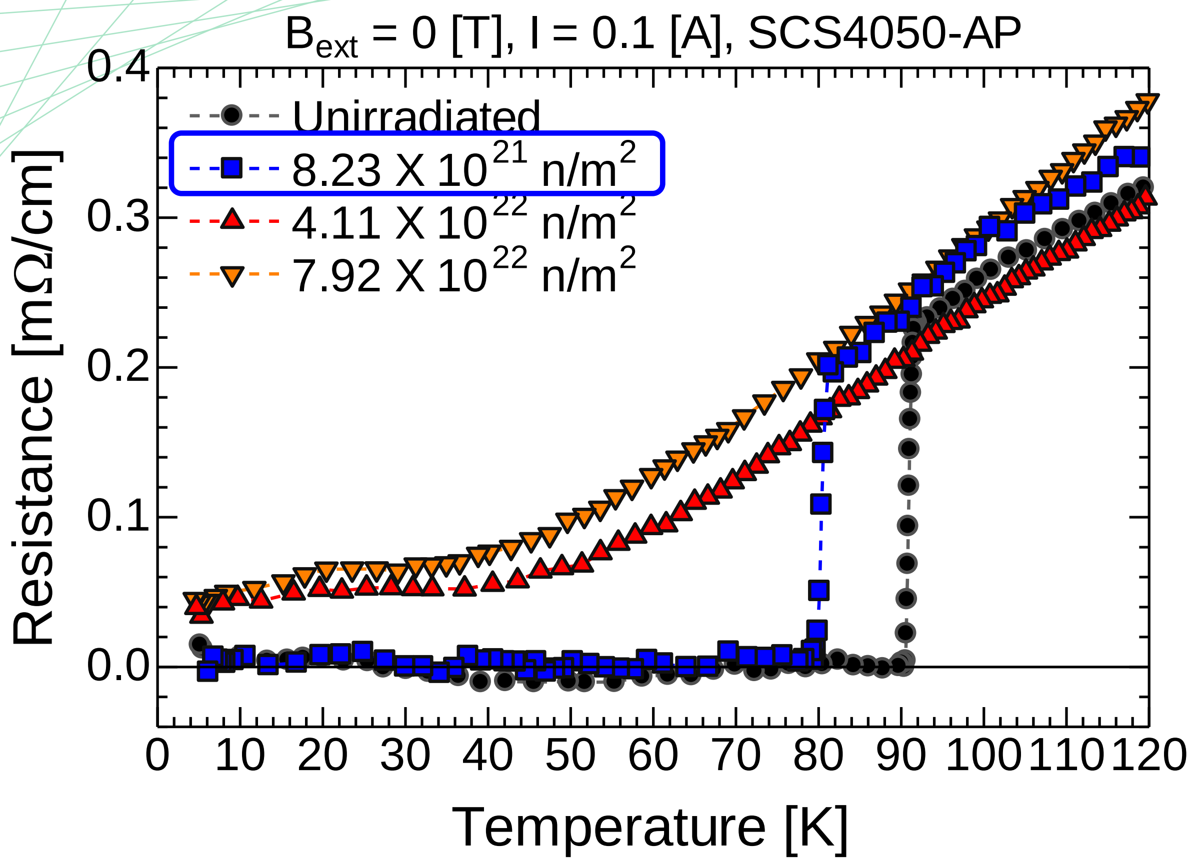
Samples

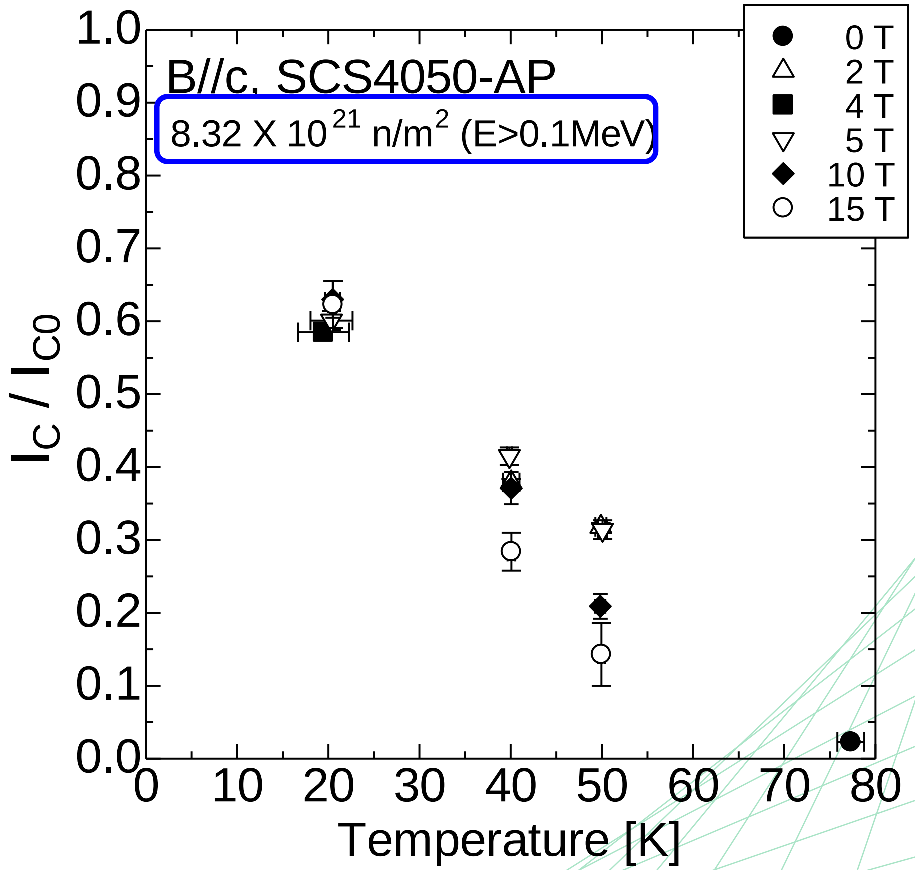
BR2 @Belgian nuclear research center



Temperature Range	4 ~ 80 K
Max. Current	500 A
Max. External Field	15.5 T

Present results of neutron irradiation effect





- Vanishment of superconductivity in GdYBCO tapes even at 4.11 x 10^{22} n/m^2.
- **T_C reduction of 10 K at 8.32 x 10^{22} n/m^2**
- **I_C degradation depending on the measurement temperature at 8.32 x 10^{22} n/m^2**
- Our results are similar to the data published by TU Wien group (D. X. Fischer, et al., Supercond. Sci. Technol. 31 (2018) 044006)

Confirmed items and next irradiation plans

- Superconductivity of GdBCO under neutron irradiation degrades by **10^{21} n/m^2 order**. → **Target fluence: 10^{21} -10^{22} n/m^2 @JRR3**

- The contribution of **low-energy neutrons** seems to be large (TU Wien)
  → **Irradiation with and without shield for low-energy neutron suppression**

Neutron capture reaction with low-energy neutrons

$$^{155}\mathrm{Gd}(n,\gamma)^{156}\mathrm{Gd}\ (\sigma\ \sim 60.5\ \mathrm{kb}(0.025\ \mathrm{eV}),\ Abundance: 14.8\%)$$
$$^{157}\mathrm{Gd}(n,\gamma)^{158}\mathrm{Gd}\ (\sigma \sim 253.6\ \mathrm{kb}(0.025\ \mathrm{eV}),\ Abundance: 15.7\%)$$

Atom displacement due to recoil

- What is the effect of **Gd** (extremely large cross section) ?
  → **Other REBCO samples（EuBCO、YBCO）** **[Gd: 49000 barn, Eu: 4600 barn, Y 8.9 barn]**

- Effects of **artificial pins** ? →**Sample with and without artificial pins**

Irradiation at JRR3 is planned from FY2023

3. R&D of mineral insulated REBCO coil

Application of ceramic coating to SM materials

☐ Degradation of organic materials is a serious problem at dose above 100 MGy

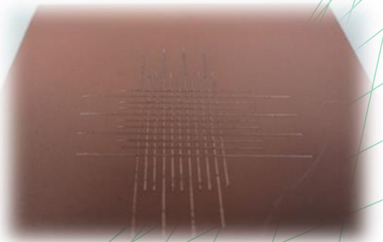
Ceramic insulation

- Higher radiation tolerance of mechanical strength than resin
- Better thermal conductivity (Al_2O_2:32, SiO_2:10 >> EP resin:0.3 [W/m·K @300K])
- Close to the coefficient of thermal expansion of cable

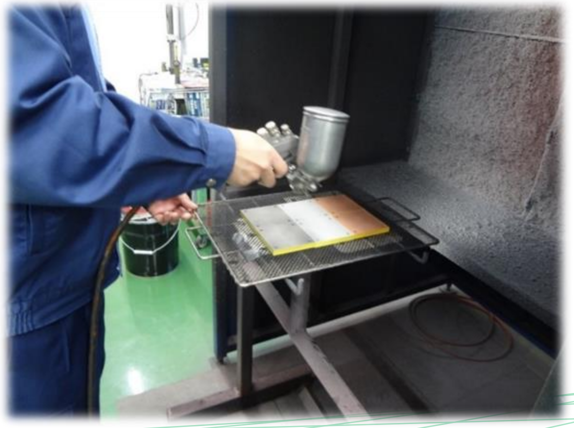
Optimized coating conditions

- Coating material: Al_2O_3 : SiO_2 = 1 : 1 (G-92-5, NIKKEN .Ltd)
- Cycle forming of 10 μm thick by spray method (Drying temp. 80℃)
- Final heat treatment: 100℃, 20 min

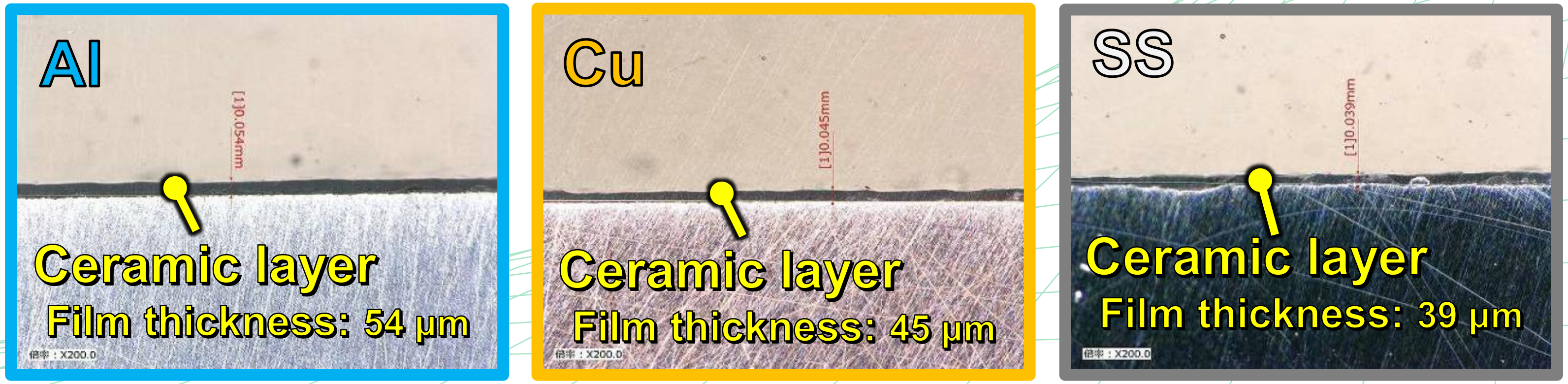
Cross-cut test
(ISO 2409, Paints and Varnishes)



Class 0 (0/100)

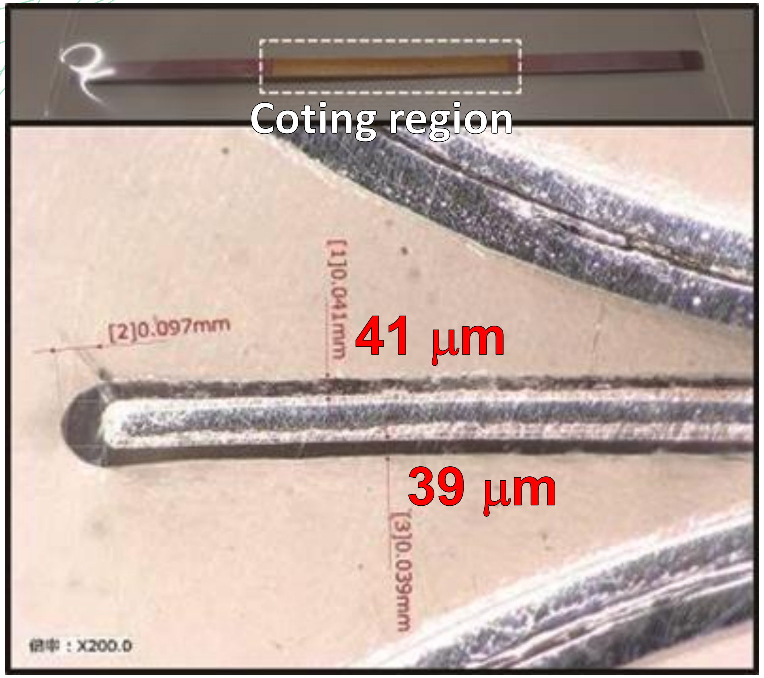


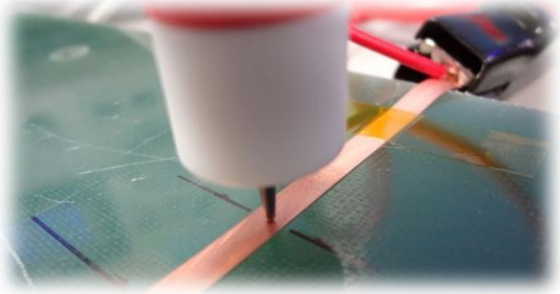
Target thickness: 50 μm, Withstand voltage: > 2000 [V]



Trial carting on short REBCO samples

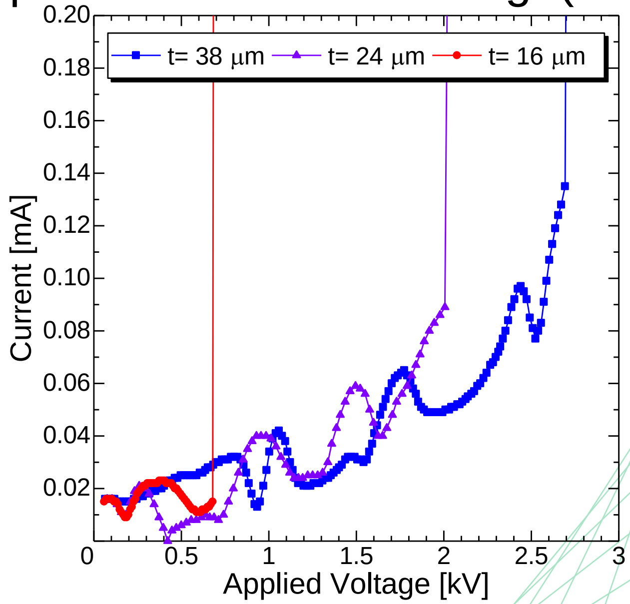
SCS4050-AP (SuperPower)

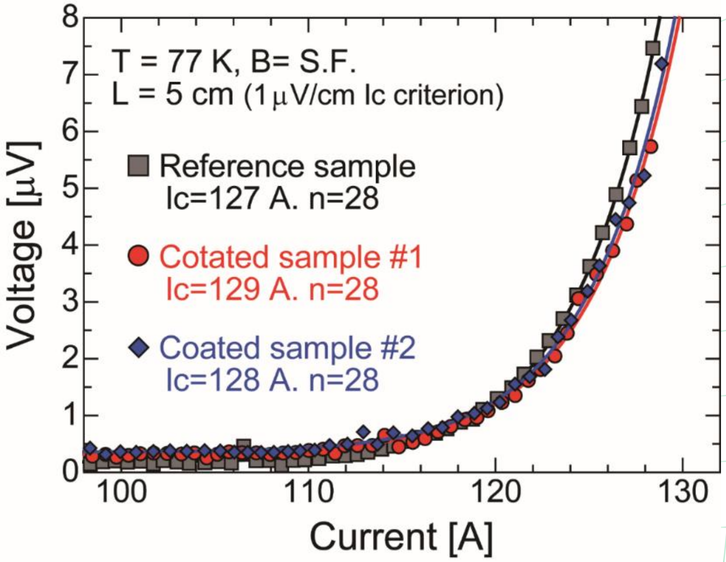




Withstand voltage
- t=16 μm : 0.679 kV
- t=24 μm : 2.006 kV
- t=38 μm : 2.693 kV

Applied load with AC voltage(50 Hz)

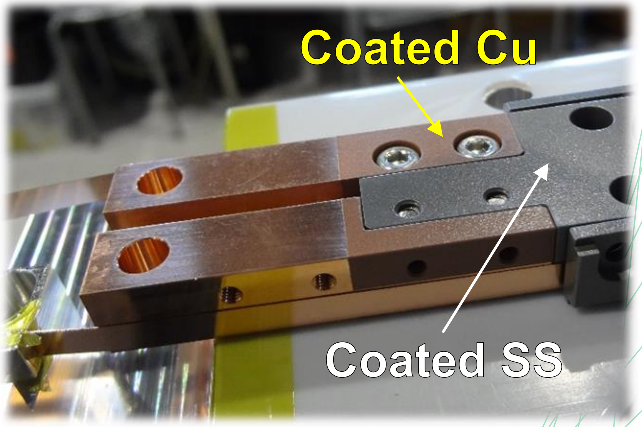


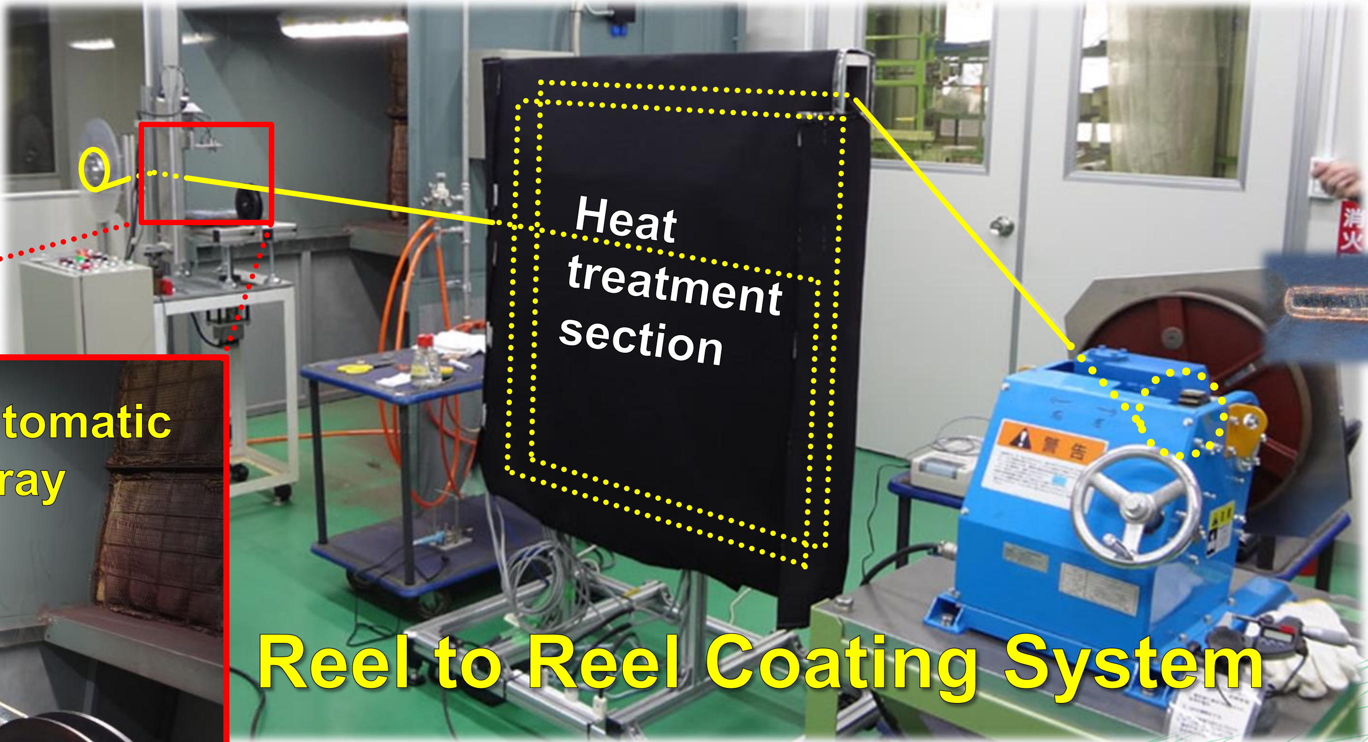


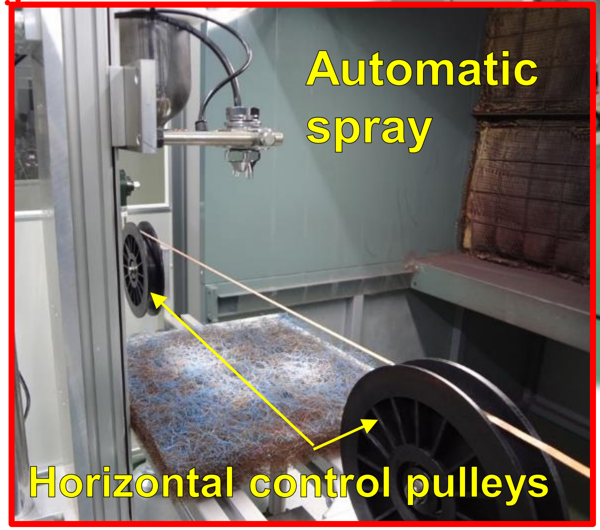
- **Trials of coating succeeded in forming a ceramic film reaching a withstand voltage of 2 kV with a thickness of 30 μm.**
- **No deterioration of the I_C of the REBCO due to the coating process was observed.**

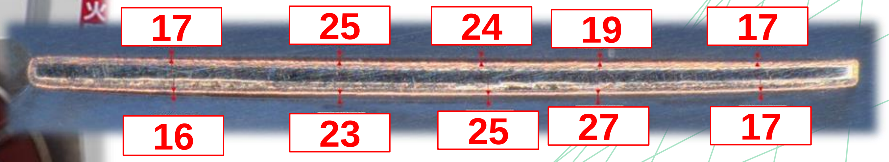
☐ Ceramic coating on magnet materials

- ➢ **Conductor: long REBCO tapes (reel to reel)**
- ➢ **Structural materials: center bobbin, outer supports, spacers, electrodes etc.**







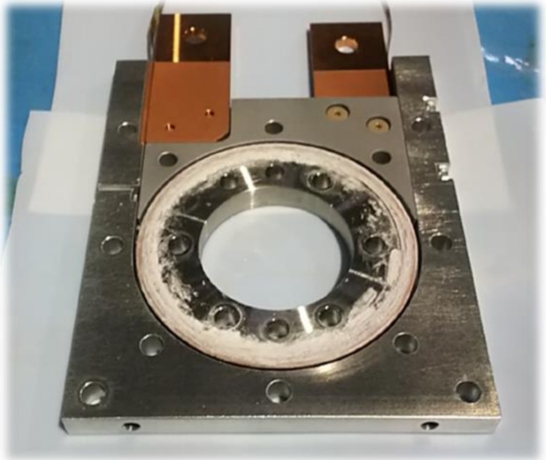


Cross section in 3rd 10 m long trial (Unit: mm)

Succeeded in **25 ± 4.7 (σ) μm** thick ceramic coating
40 m length on both sides of a REBCO tape

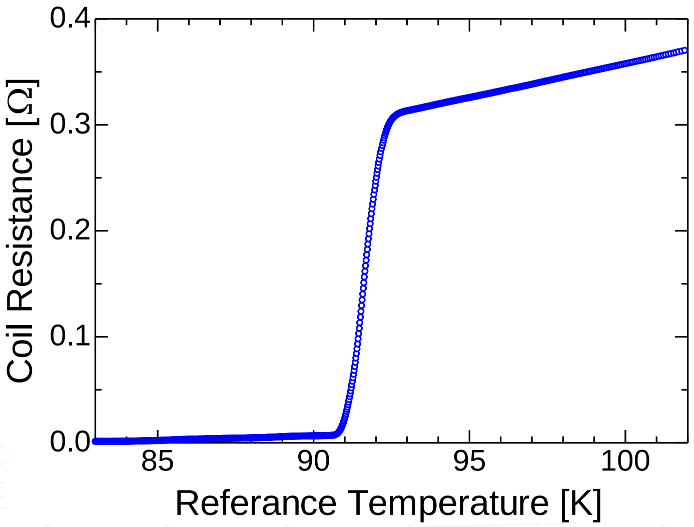
Trail winding of mineral insulated coil

□ Small demonstration coil is wound using wet winding technique with ceramic adhesives



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

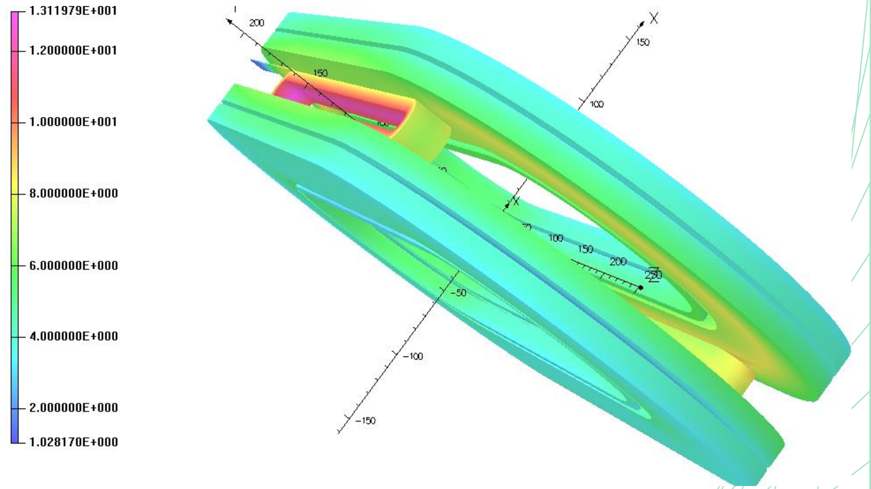
Tape: L=14 m, W= 4 mm (Full surface coating)
ID = 80 mm, 1st: 26 turns, 2nd: 24 turns

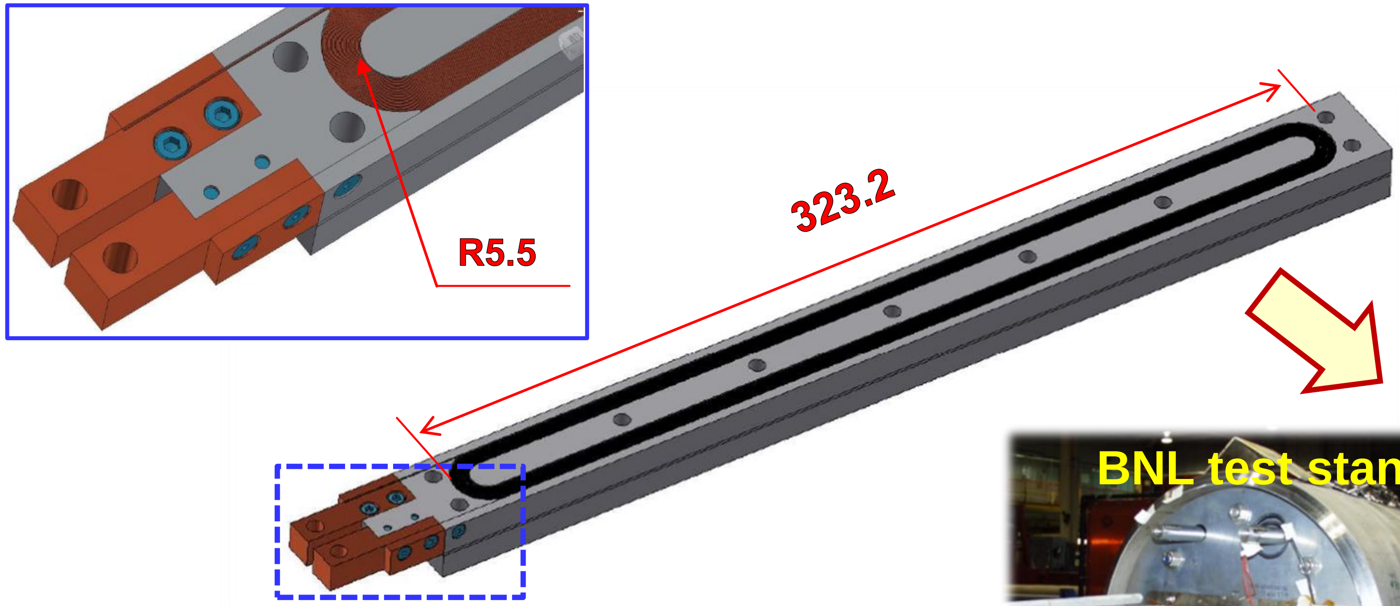


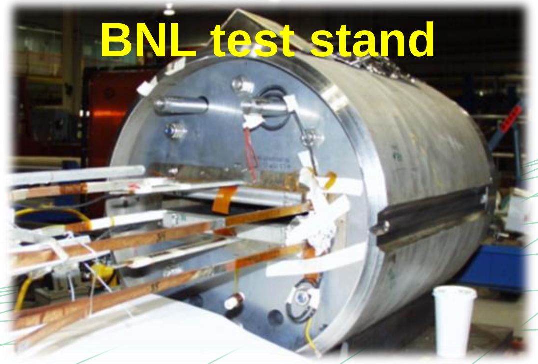
□ No deterioration of superconductivity due to winding process

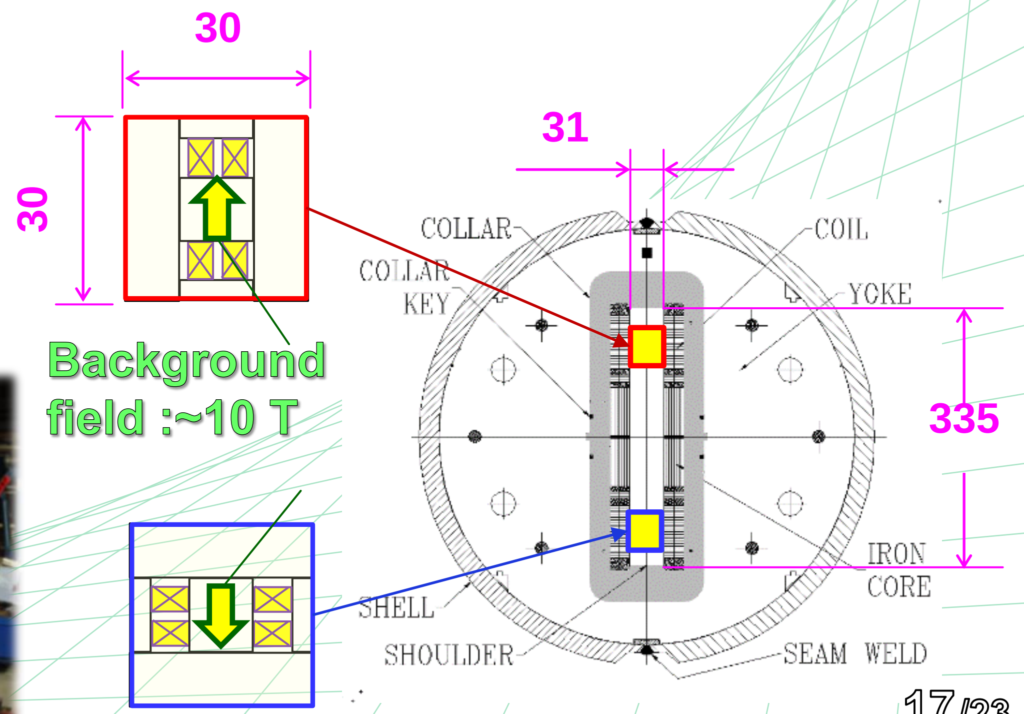
□ Preparing to racetrack coils for cooling and excitation tests at BNL

- ➢ The liq. He-cooled test stand with Nb_3Sn coils provides a backup field of ~10 T.
- ➢ We will deliver two double pancake coils to BNL by next summer





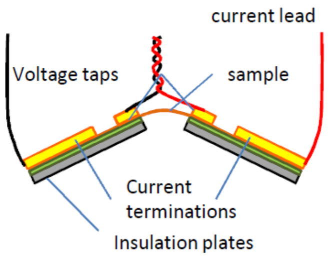


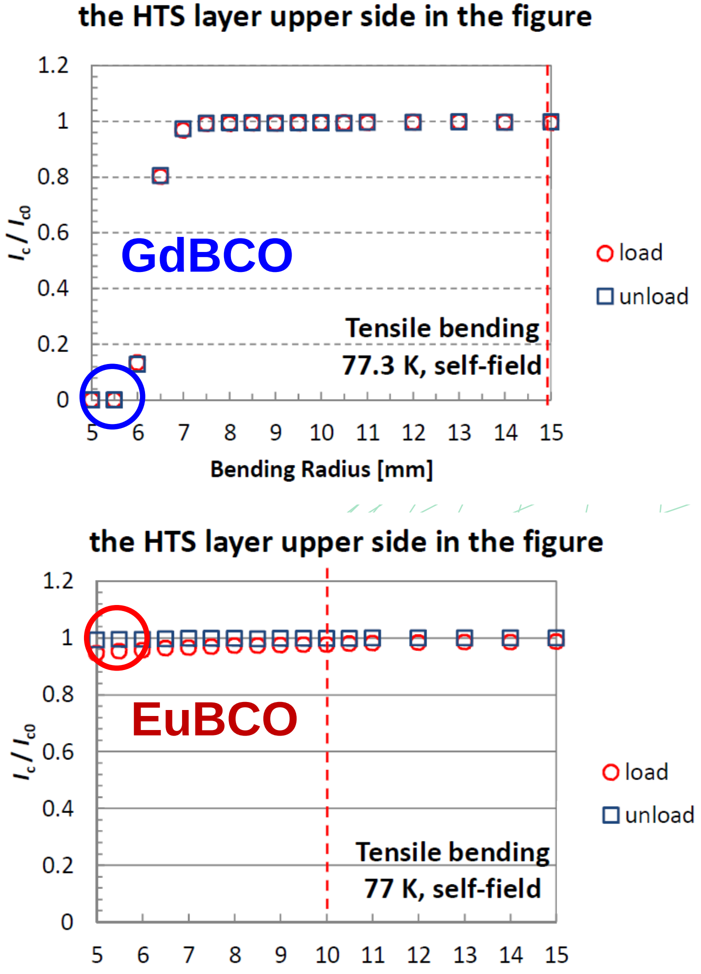


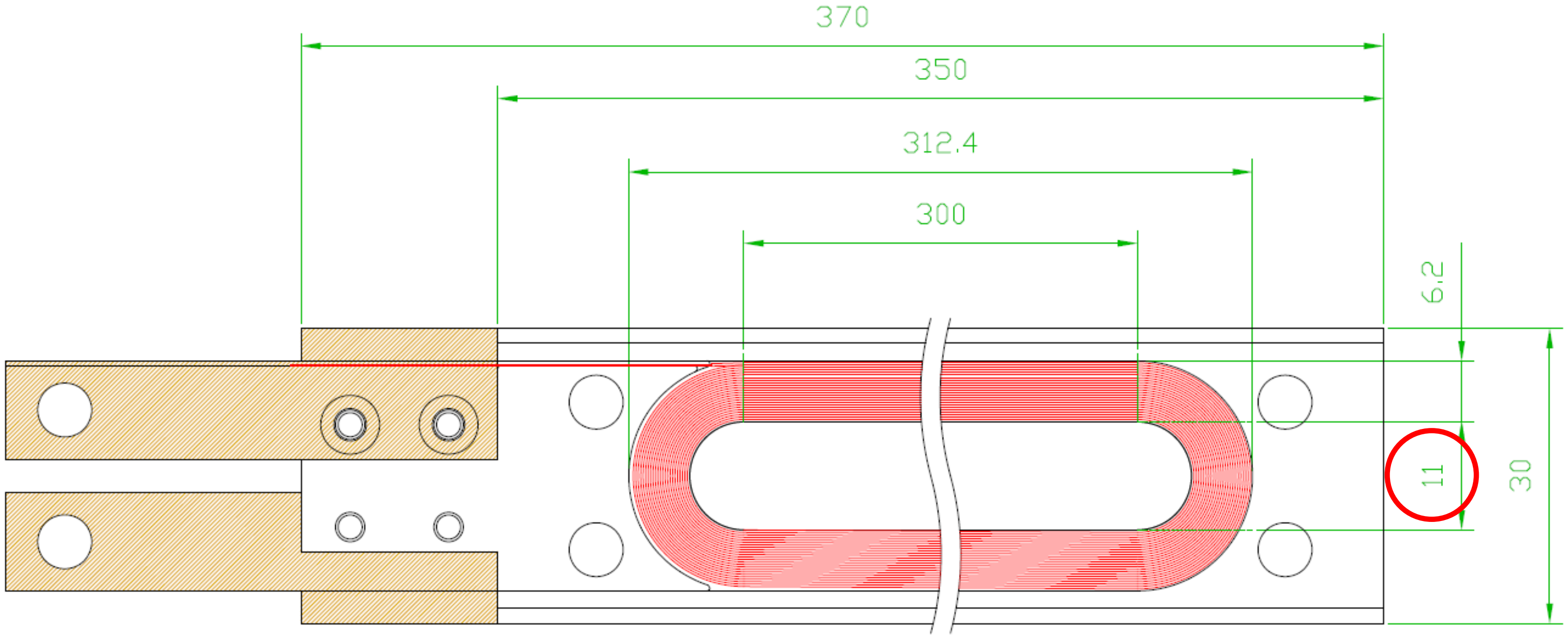
Design of the insert coil

Fujikura FESC-SCH04(40)

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







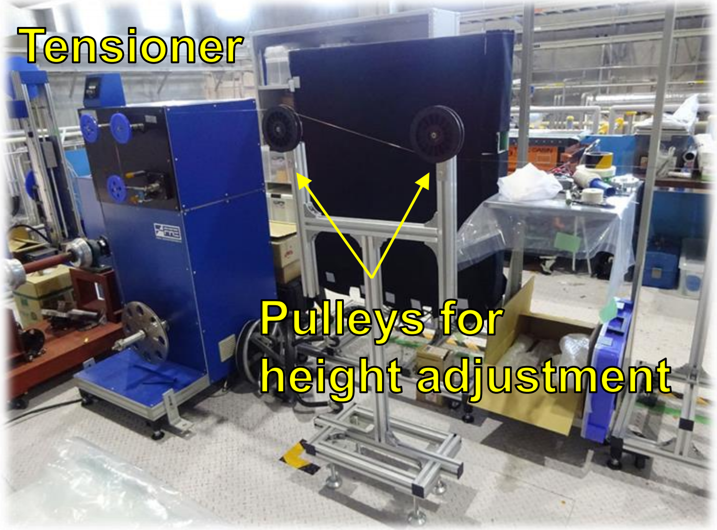
Preparation for winding of the insert coils

☐ **Trial windings with dummy tape has been performed (dry & wet)**

Cu tape: t=0.1 mm, w=4 mm, L=30 m

Purpose

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



☐ **The winding feasibility of the double pancake type long lace track coils with ceramic adhesive was confirmed.**

4. Summary

Summary

- R&D of radiation-hard HTS magnet is in progress to realize the pion capture solenoid for the J-PARC MLF 2nd target station.
- The effects of neutron irradiation on REBCO coated conductors have been studied at IMR-Oarai center, Tohoku Univ.
- Superconductivity of GdBCO tape disappeared even at 4.11 x 10^{22} n/m^2 and T_C reduction and Ic degradation are confirmed at 8.32 x 10^{21} n/m^2.
- Trials of ceramic coating succeeded in forming an insulating film on the surface of REBCO tapes reaching a withstand voltage of 2 kV with a thickness of 30 μm.
- Mineral insulated demonstration coils fabricated by the wet-winding method transitioned to superconductivity without degradation.
- Preparations are underway for the racetrack coils for the cooling and excitation test using the BNL test facility scheduled for next summer.

Collaborators

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Thank you