Design of superconducting magnets and shieldings for high-radiation environments:

Research and development of ceramic-insulated HTS magnets for high-radiation environments

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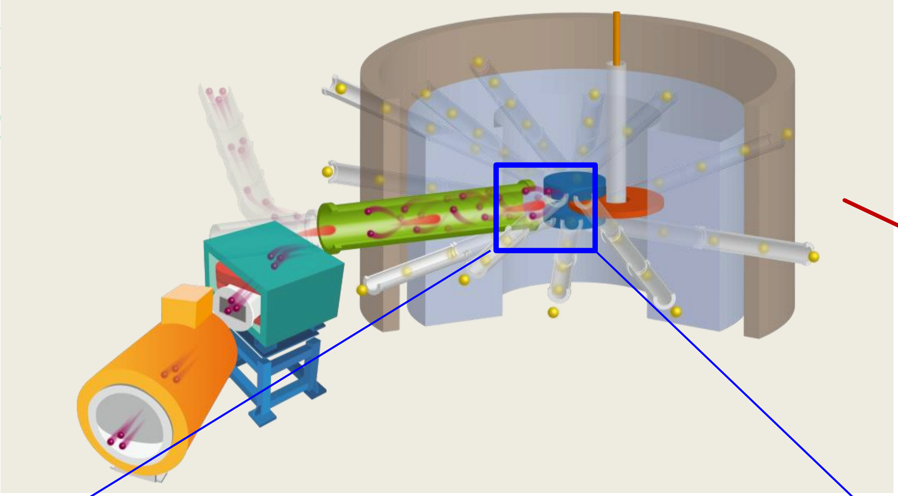
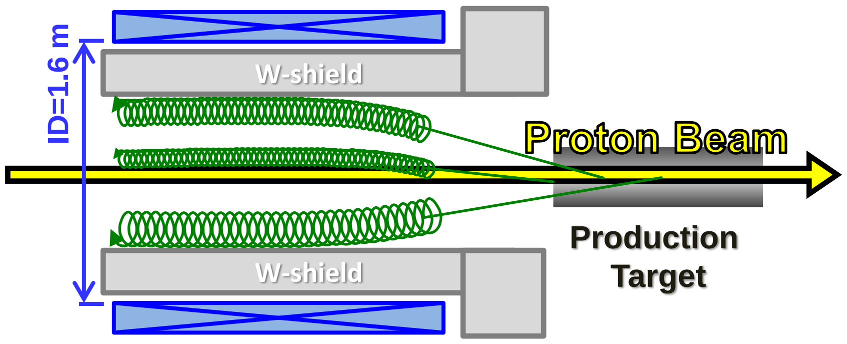
1. Introduction

J-PARC MLF 2nd target station

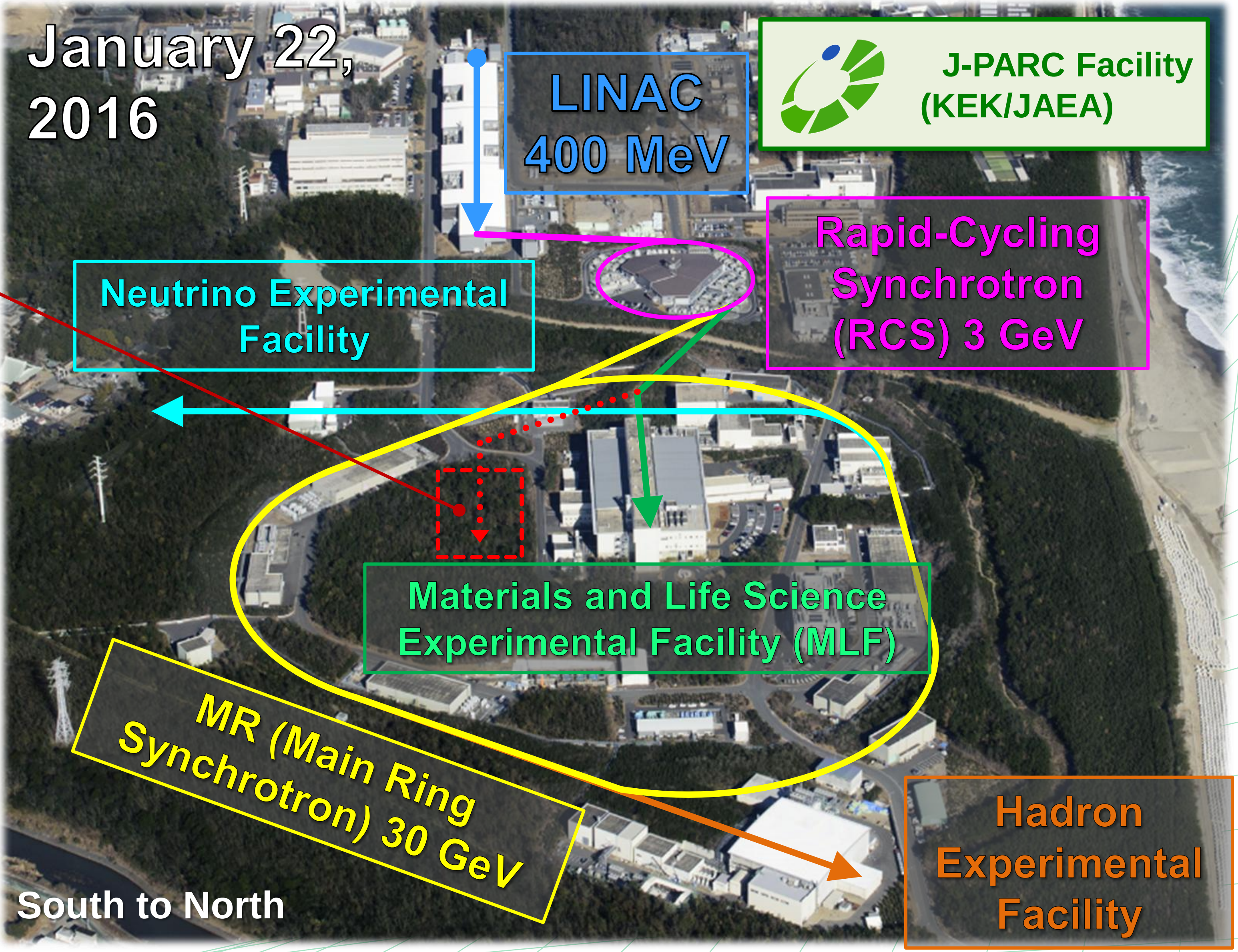
Construction plan for MLF-TS2





TS2-PCS: 1 T, 100 MGy?

- Power of the primary proton beam : 1 MW

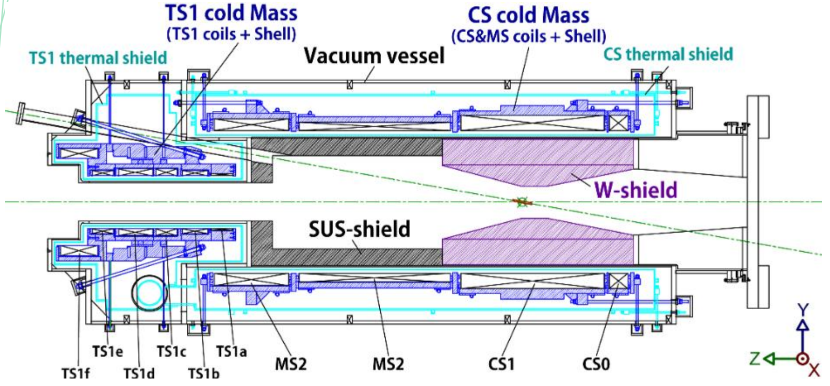


Conduction-cooled HTS based solenoid

□ Beam power: 56 kW(COMET) → 1 MW (TS2)

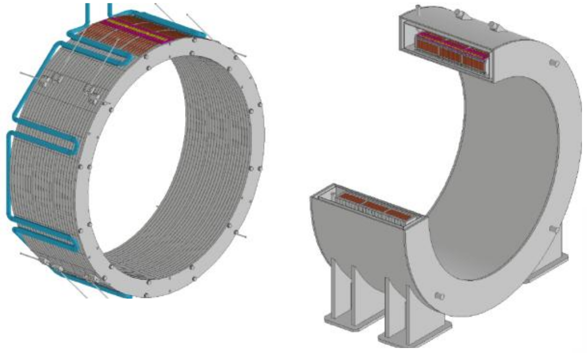
[COMET-PCS]

NbTi based radiation-resistant magnet technology

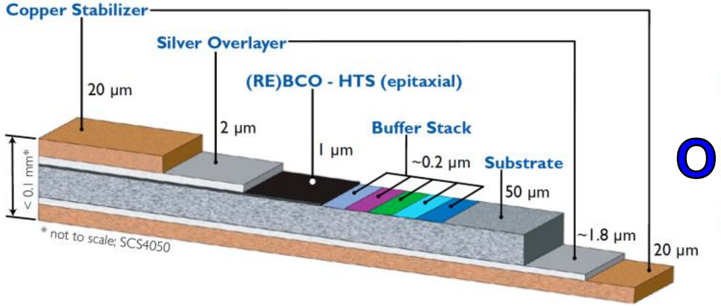


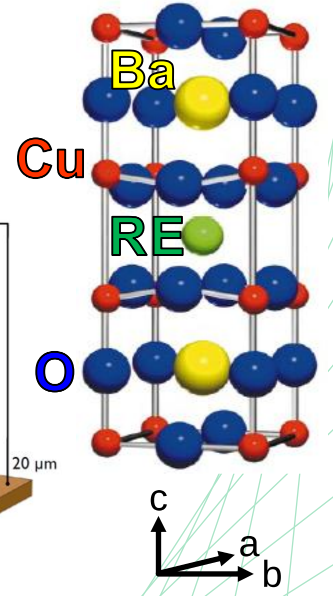
[TS2-PCS]

REBCO based conduction-cooled magnet



REBCO



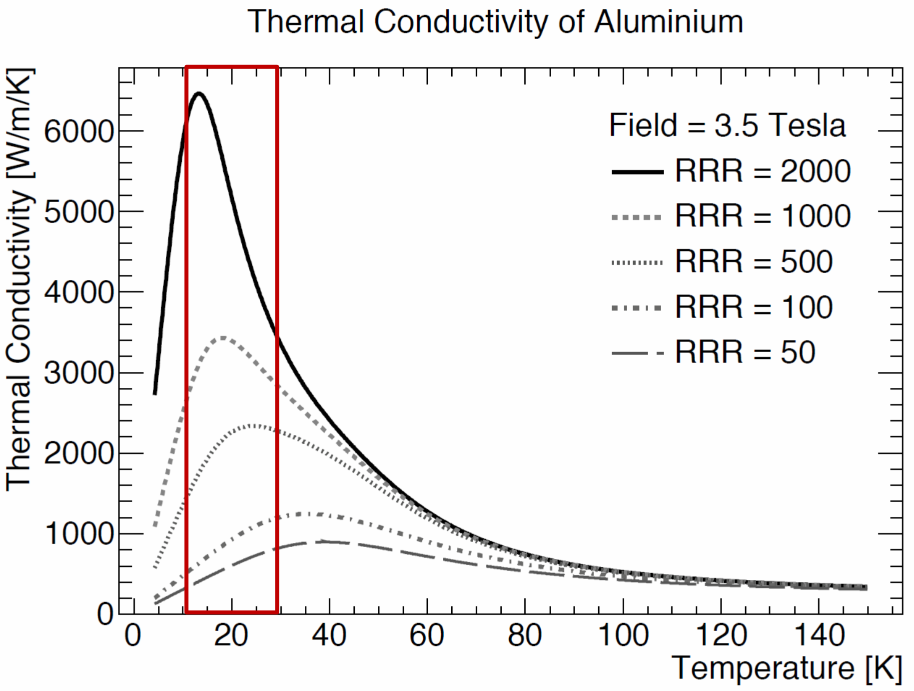


➤ <u>High temperature margin</u> (T_C=~90 K)

- Conduction cooling operation in the temperature range of 20 K

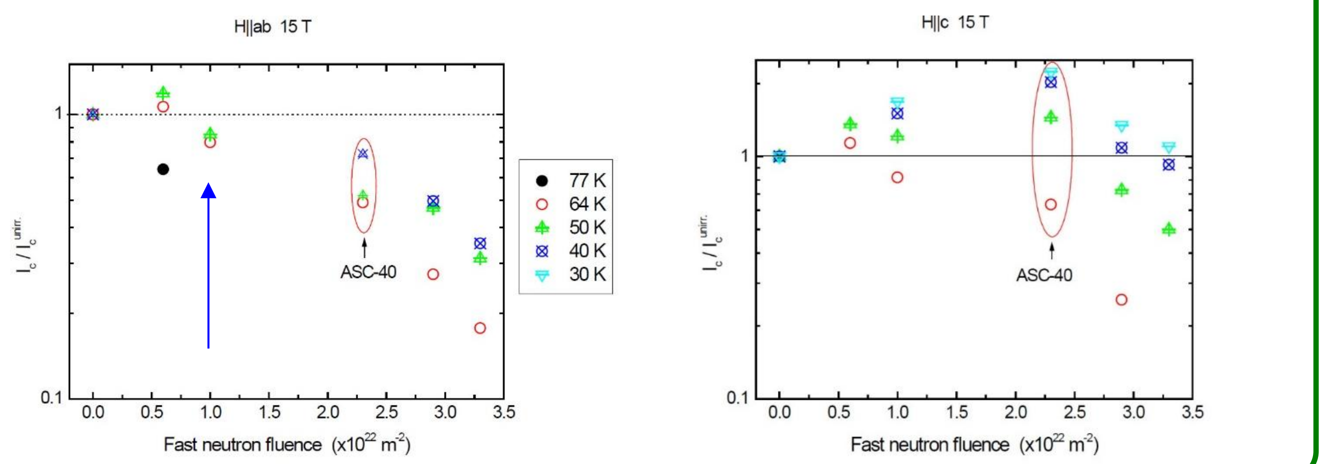
➤ <u>High magnetic field tolerance of Ic</u>

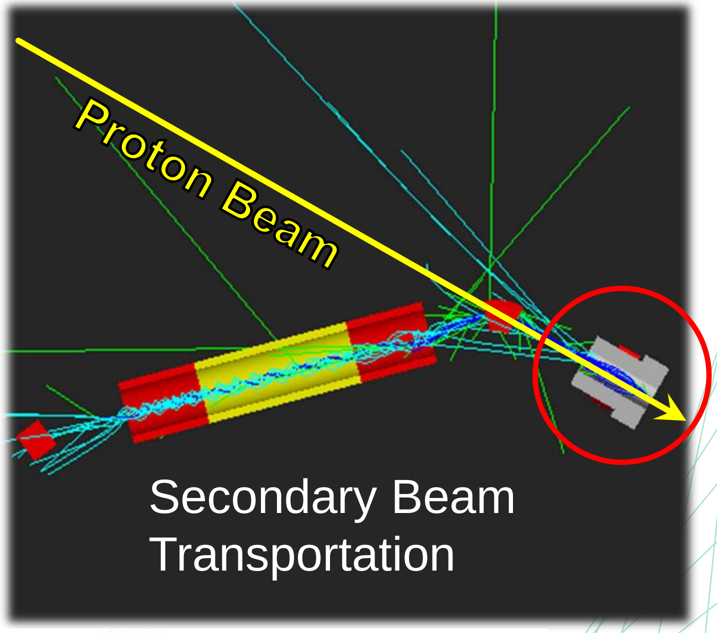
- Potential for 20T class high field magnet



TS2-PSC conceptual design

R. Fuger et al., Physica C 468 (2008) 1647., M. Eisterer, RESUMM2015.



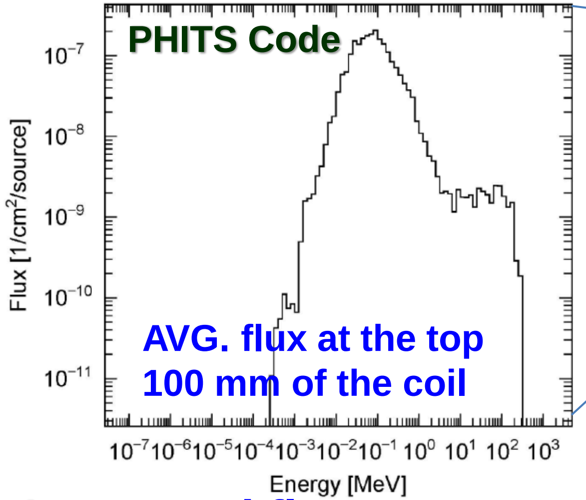


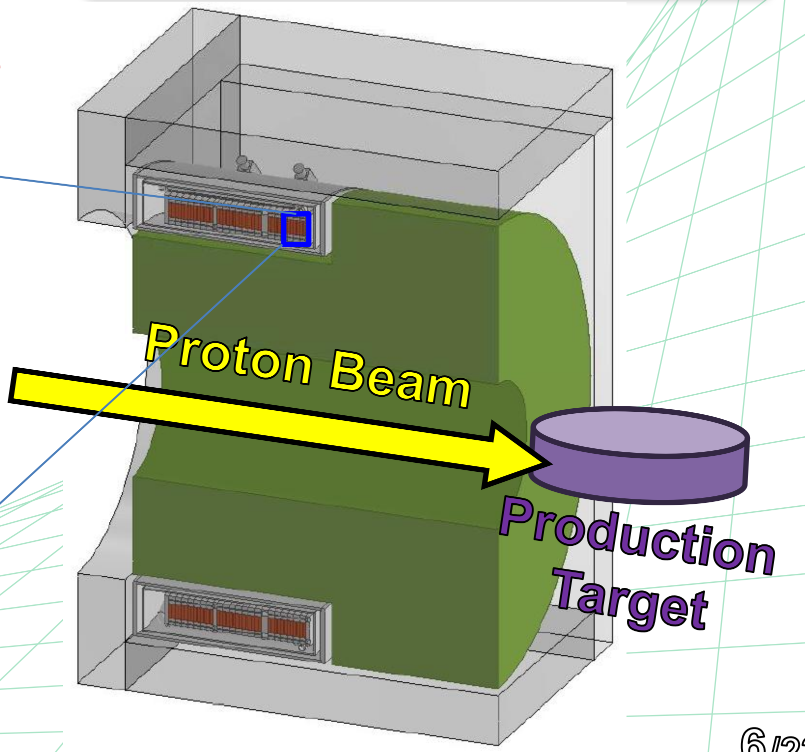
I_C of REBCO degrades from 1 x 10^{22} n/m^2 ⇐ **Target limit fluence**

Magnet designed to reach
8×10^{21} n/m^2 fluence in 10 years
(~100 MGy, 450 W)

⇓

Massive tungsten alloy radiation shield is required



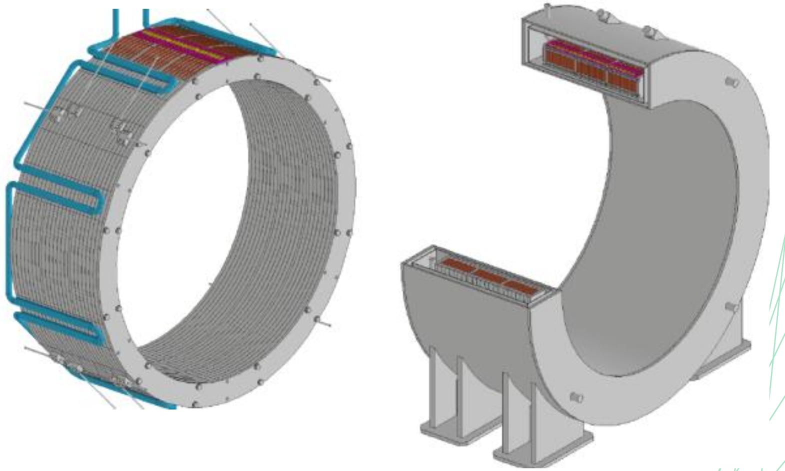


Integrated flux:
7.74×10^{20} n/m^2/y(@1 MW)

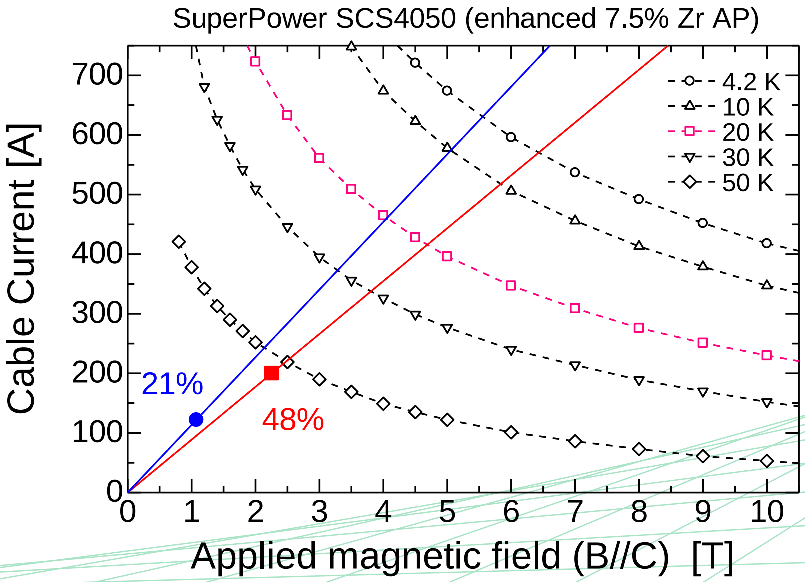
Basic design of TS2-PSC

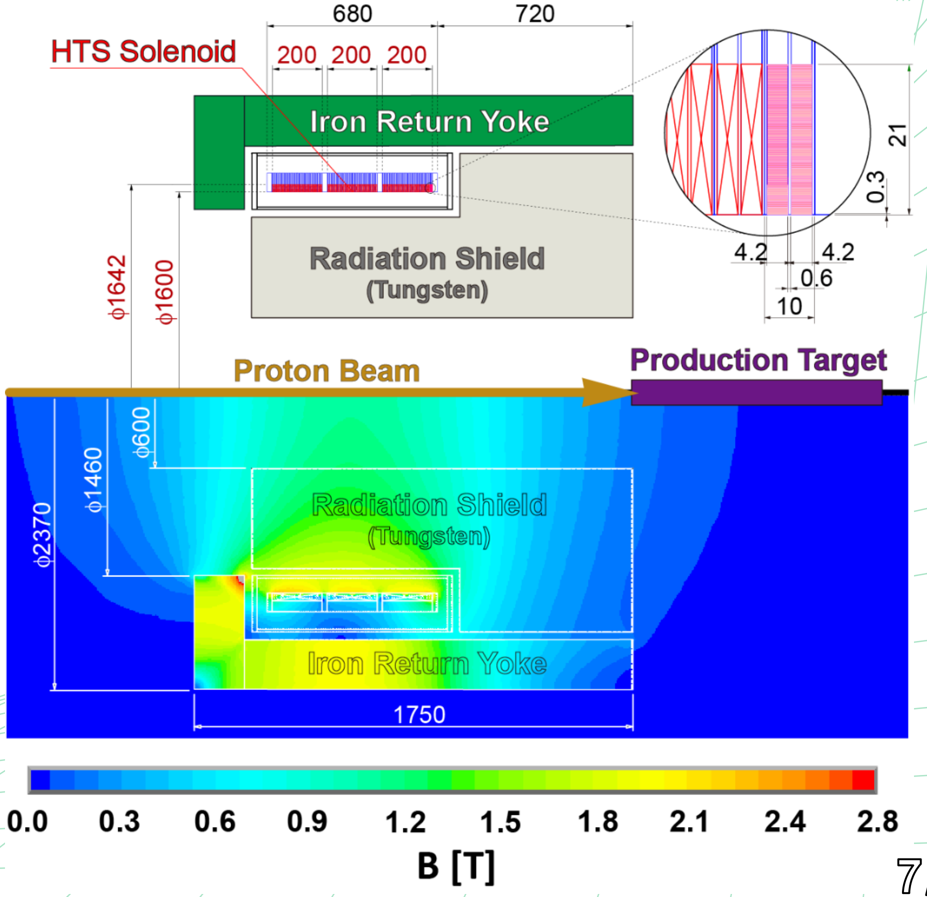
Stack of double pancake coil

- Conductor : REBCO, W=4 mm, T=0.1 mm
- ID=1600 mm, T=21 mm, L=10 mm, 70 turns/layer
- Number of double pancake coils: 60 (20 x3)
- Length of solenoid: 680 mm
- Operation Temperature: 20 K (He gas cooling with pipe)
- Transport current: 200 A (Load line ratio: 0.48)
- Peak Field: 1.1 T at center, 2.3 T (B//c) at coil (200 A)



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

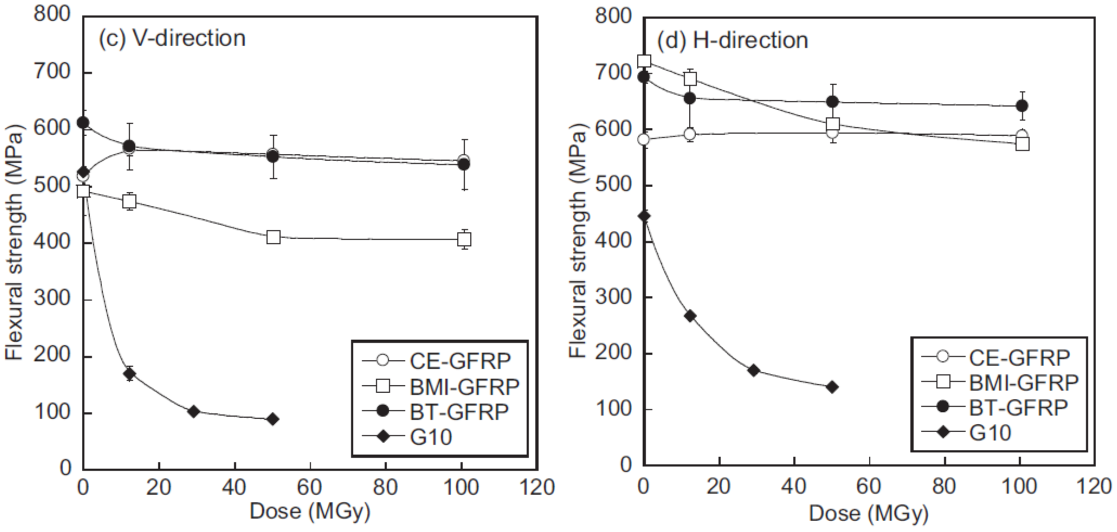




Challenging issue (Insulation materials)

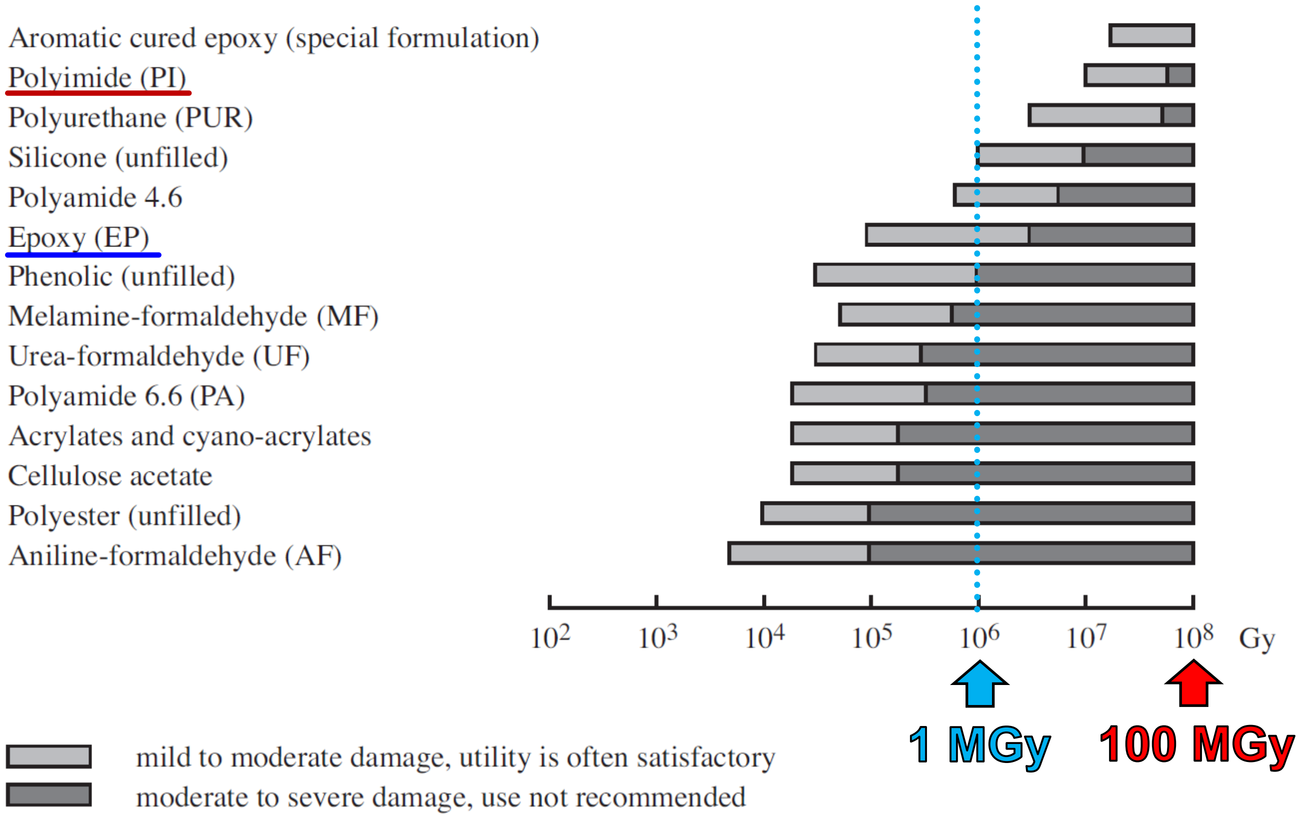
□ Radiation reduces the strength of polymer materials due to molecular chain scission

- ➢ **Epoxy deteriorates at doses higher than a few MGy**
- ➢ **Polyimide may be acceptable below 80 MGy**
- ➢ **Cyanate and BT based materials will withstand up to 100 MGy.**



Ref.: CERN Yellow Reports 2001-006

Table 2: Classification of adhesives according to their radiation resistance



The end-point criterion is chosen at **50%** of the initial value (prior to irradiation) for the **strength** or for the **deformation at break**.

Ceramic-insulated accelerator magnet

- **Inorganic materials are likely to be usable even at dose over 100 MGy.**

Accelerator magnets based on magnesium oxide insulated copper conductors (MIC) are already in practical use around the world.

Application researches of ceramic insulation to superconducting magnets have been performing

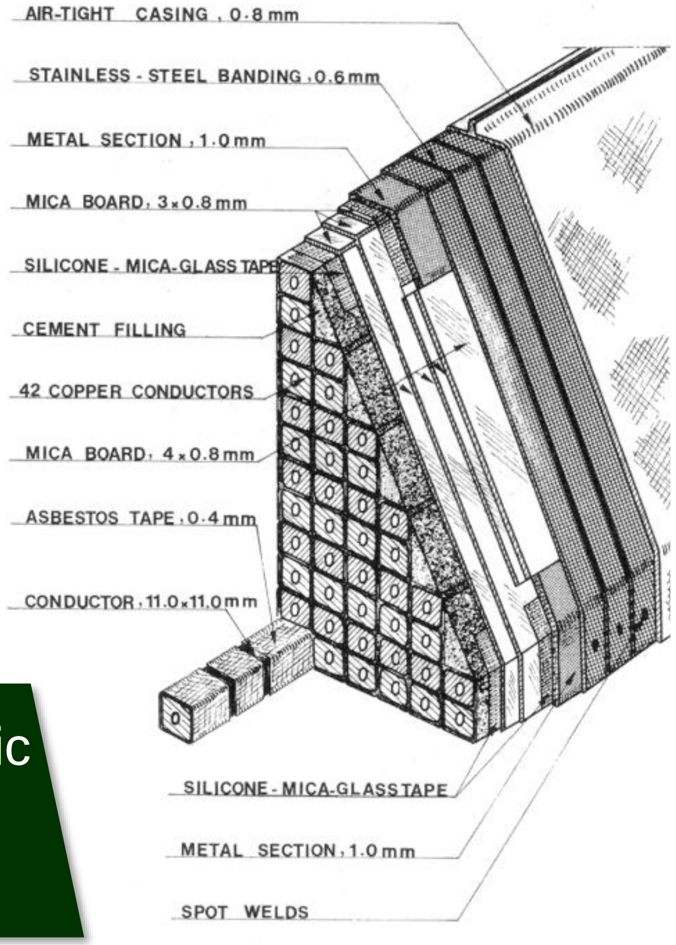


Fig. 20 QNL-B coil construction

Ref.: CERN Yellow Reports 1982-005

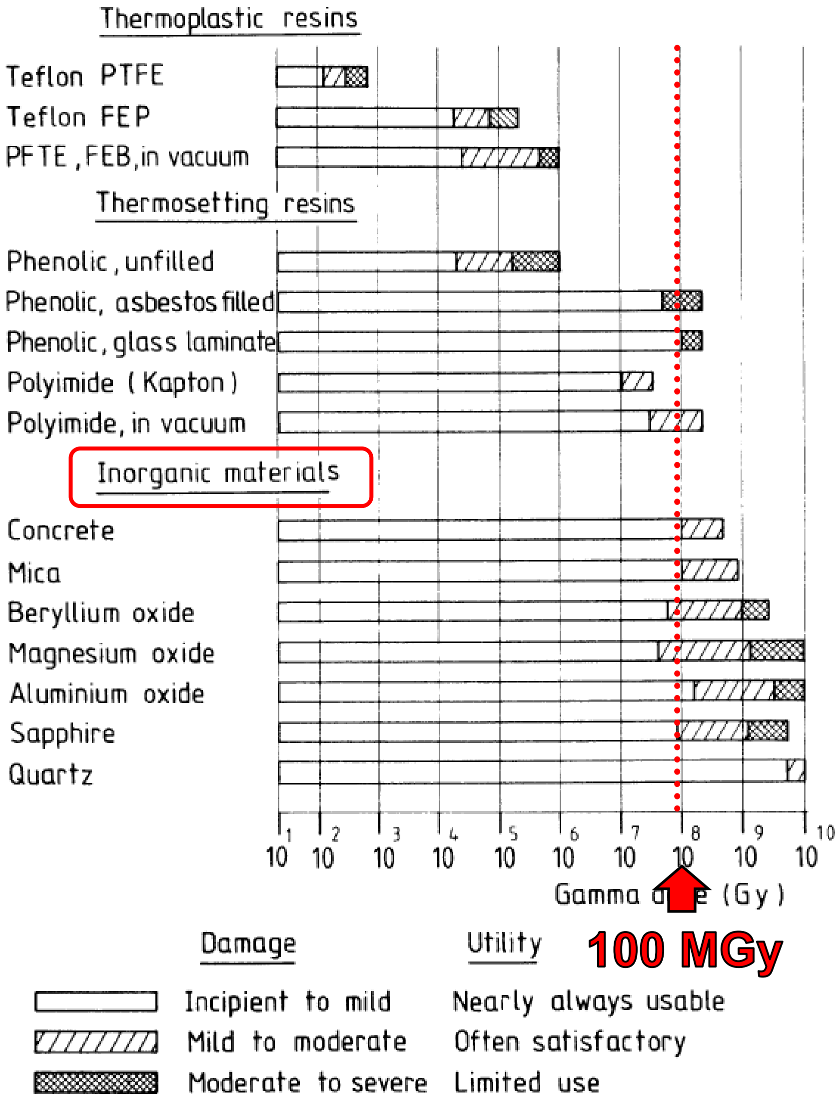


Fig. 2 Radiation resistance of several electrically insulating materials

3. R&D of ceramic-insulated HTS coils

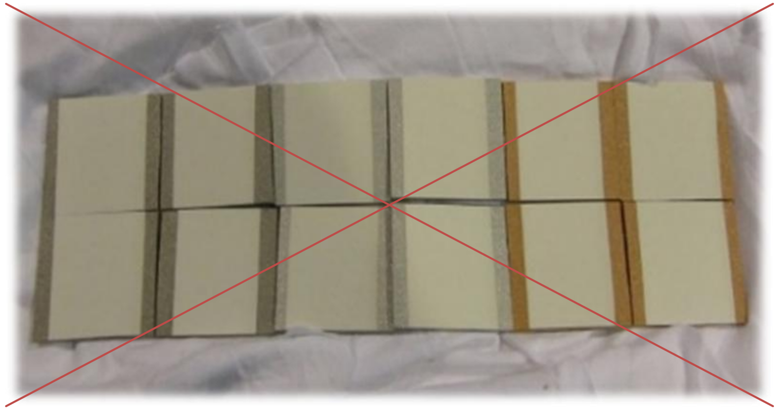
Ceramic molding

Advantages ceramic insulation

- Higher radiation tolerance of mechanical strength than resin materials
- 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

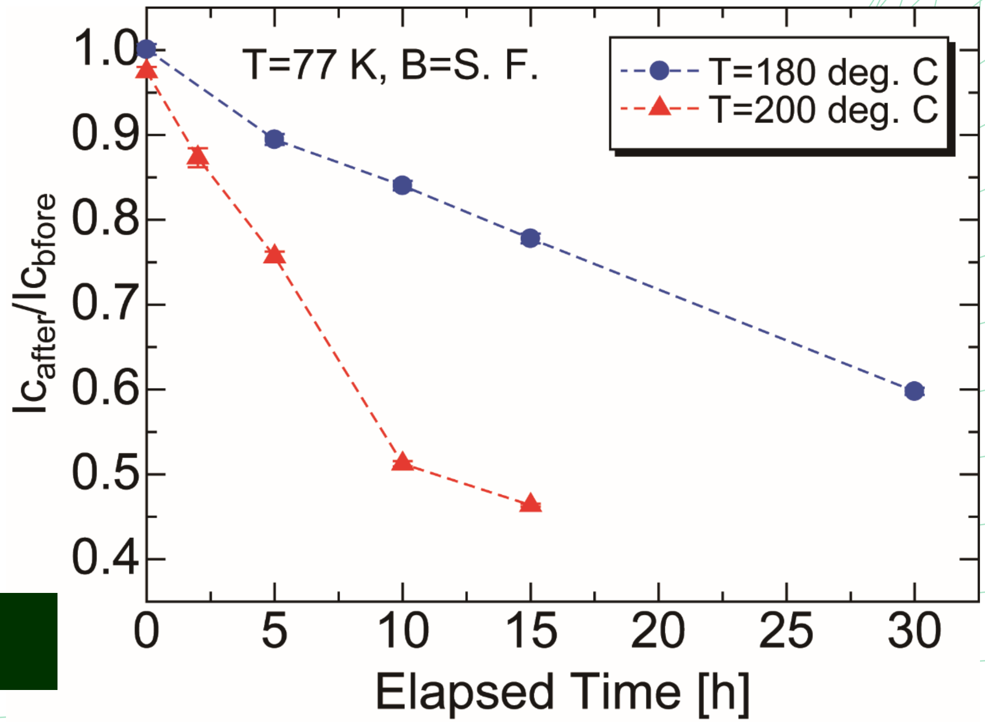
Ceramic firing temperature >1000℃

➢ **Superconductivity of REBCO disappears**



□ **Heat treatment temperature of less than 200℃ and for a short period of time**

Decrease in Ic due to heat load

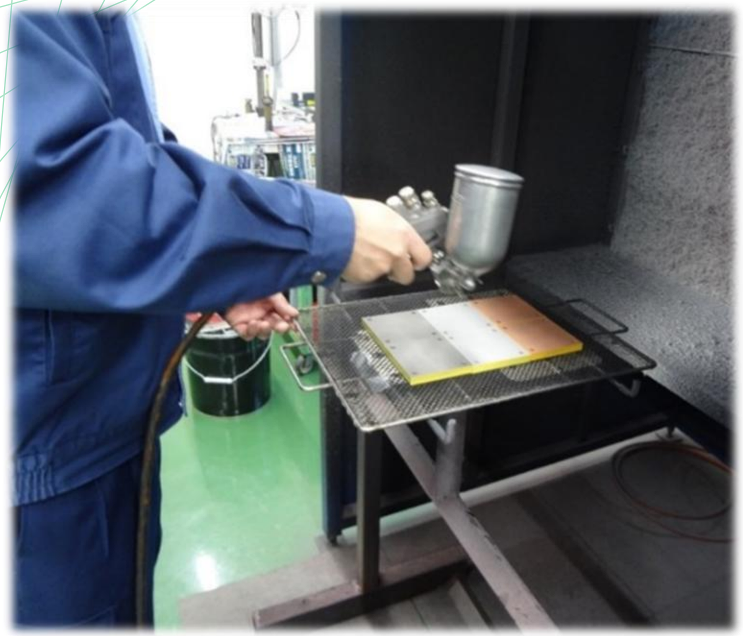


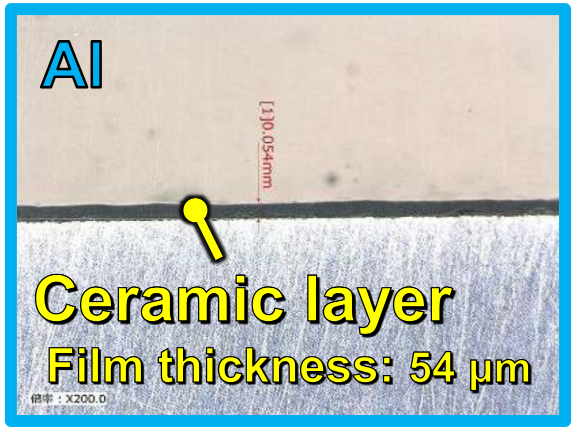
Application of ceramic coatings by sol-gel process

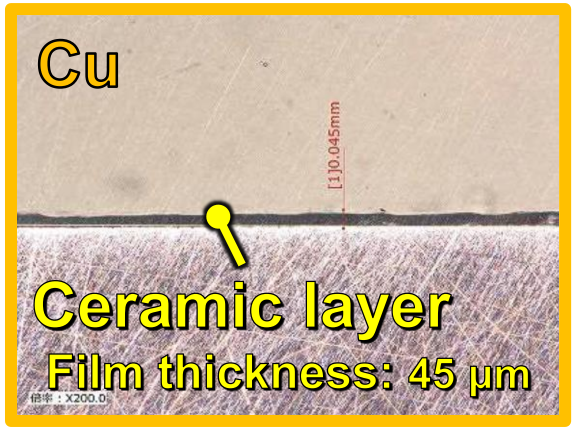
➢ Heat treatment: Evaporation of water and alcohol

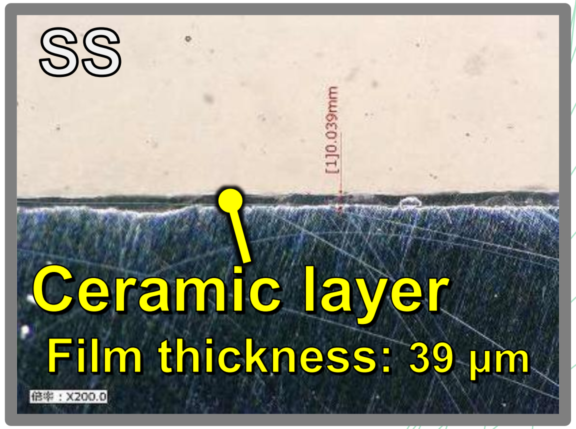
Application of ceramic coating technology

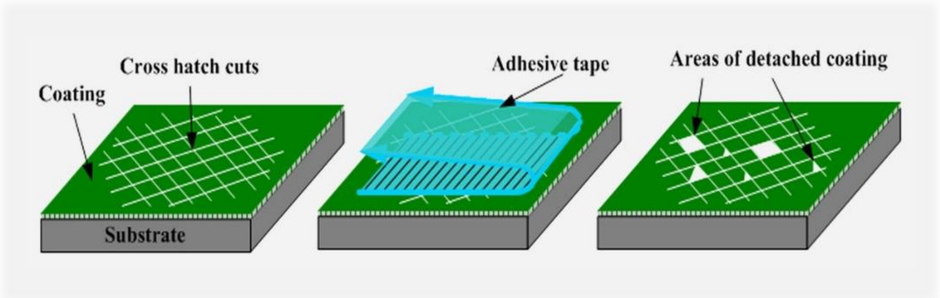
Target film thickness: 50 mm, Withstand voltage: > 2 kV



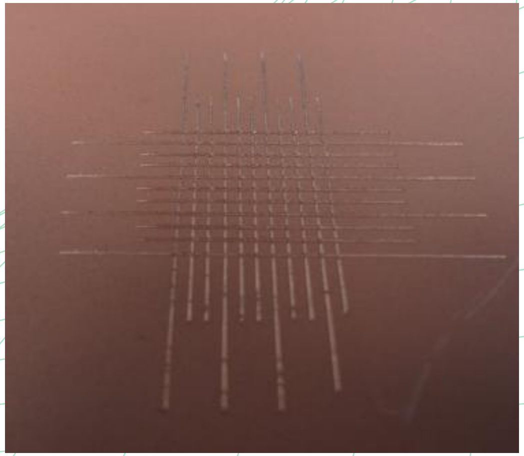








Cross-cut test
(ISO 2409, Paints and Varnishes)



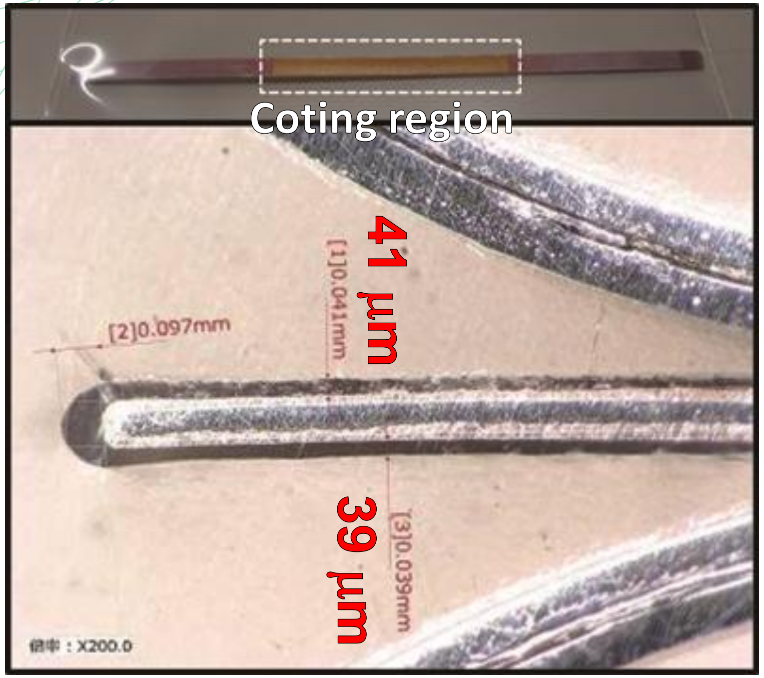
Class 0 (0/100)

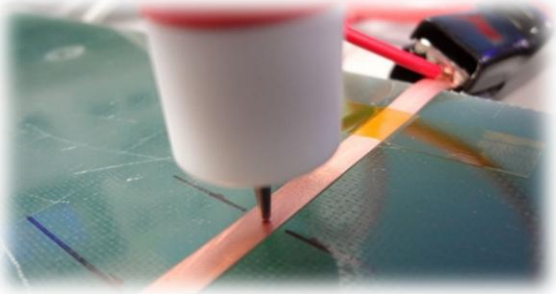
Optimized coating conditions

- 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

Ceramic coating trial of REBCO tapes

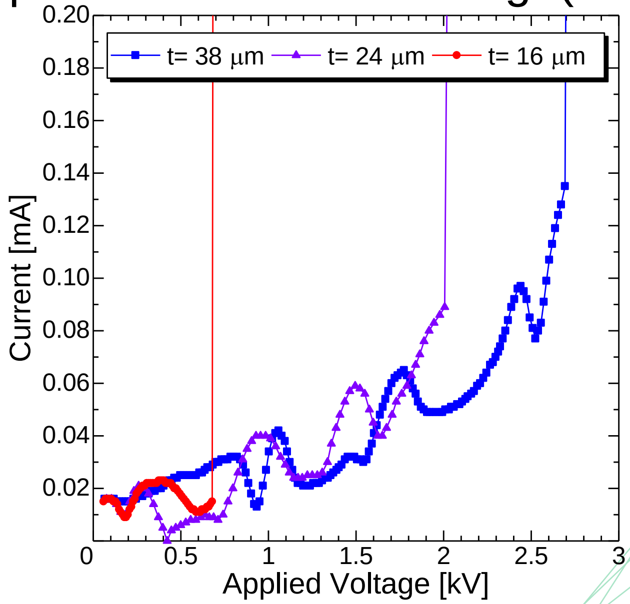
SCS4050-AP (SuperPower)



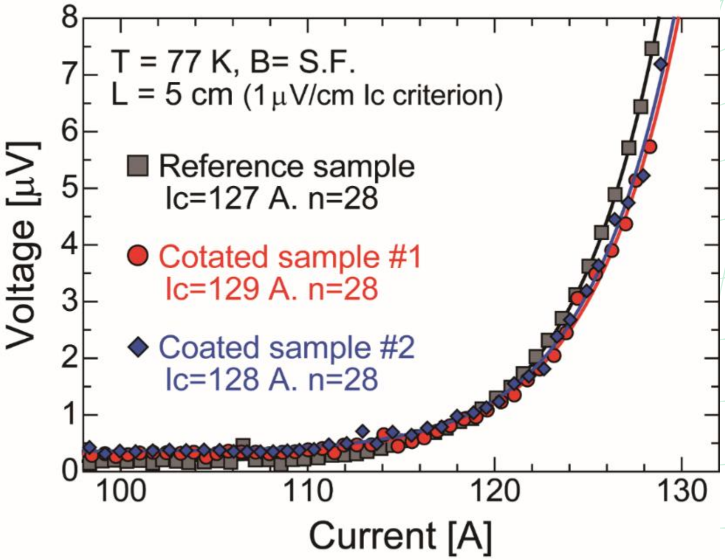


Withstand voltage
- t=16 μm : 0.679 kV
- t=24 μm : 2.006 kV
- t=38 μm : 2.693 kV

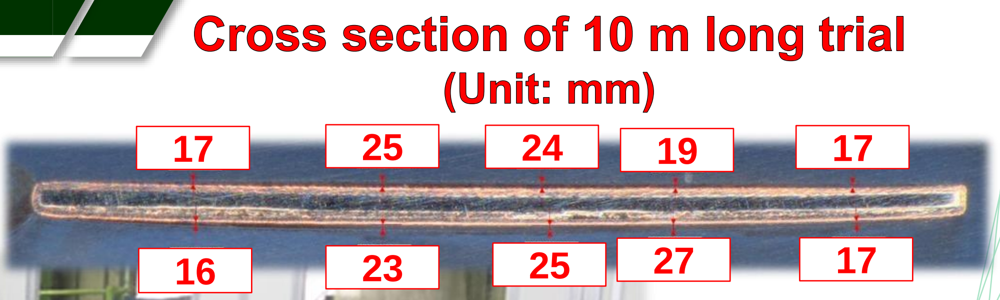
Applied load with AC voltage(50 Hz)

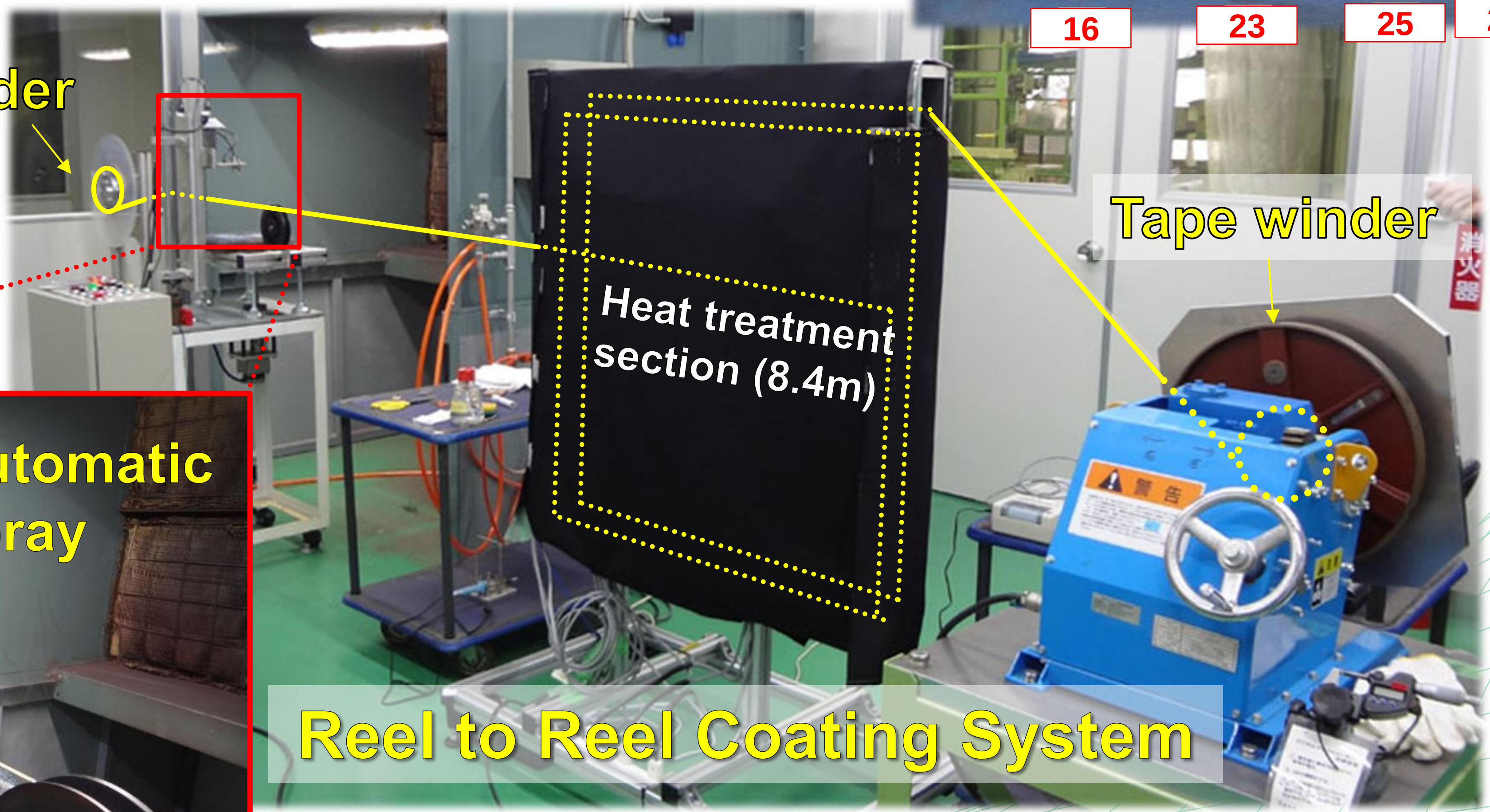


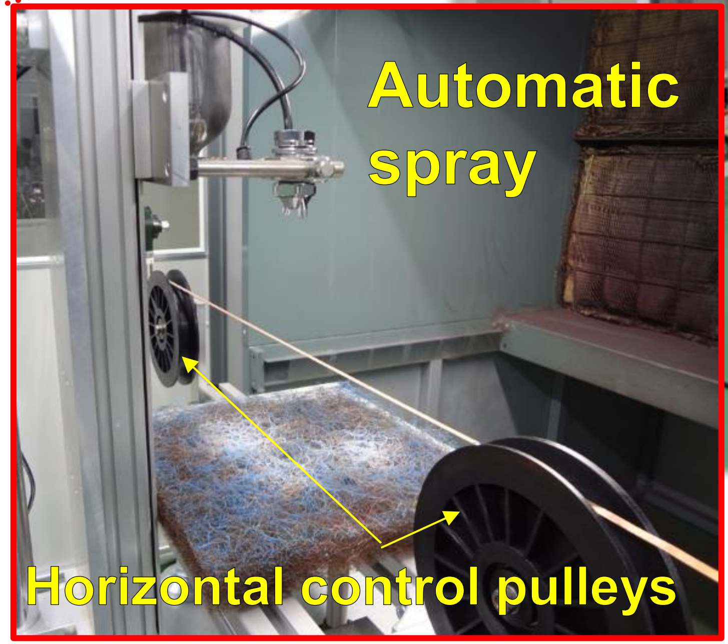
- **The withstand voltage is well above 2 kV with a thickness of 30 μm.**
- **No deterioration of the I_C of the REBCO due to the coating process was observed.**



□ Development of automated reel to reel continuous coating system



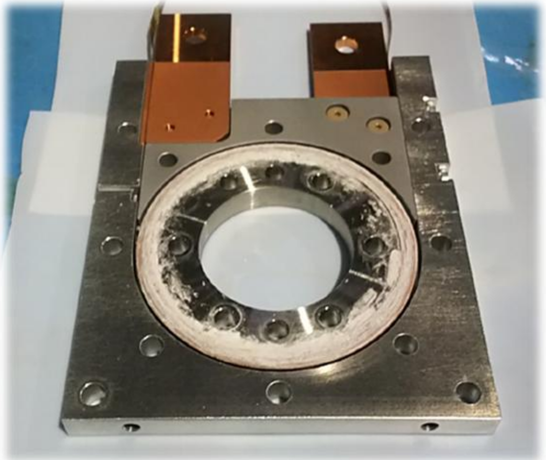


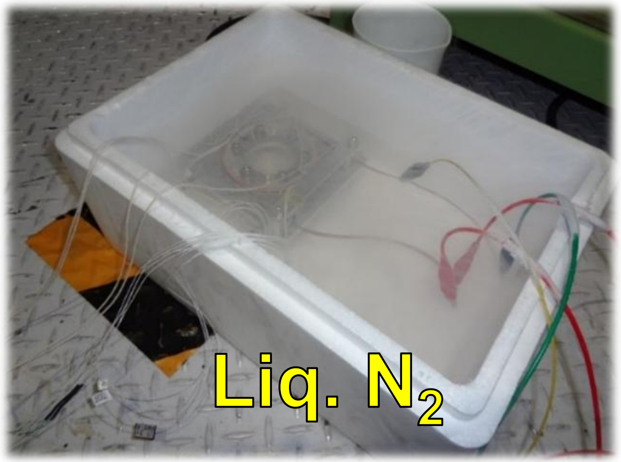


Succeeded in **25 ± 4.7 (σ) μm** thick ceramic coating **40 m length** on both sides of a REBCO tape

Trail winding of ceramic-insulated coil

□ Small demonstration double pancake coil was wound using wet winding technique with ceramic adhesives

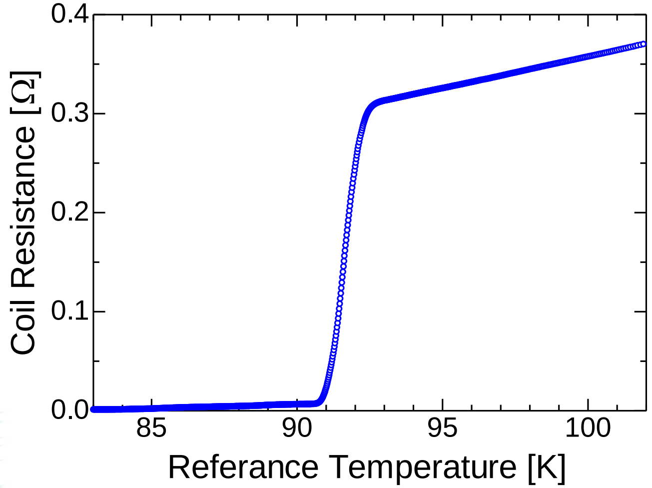


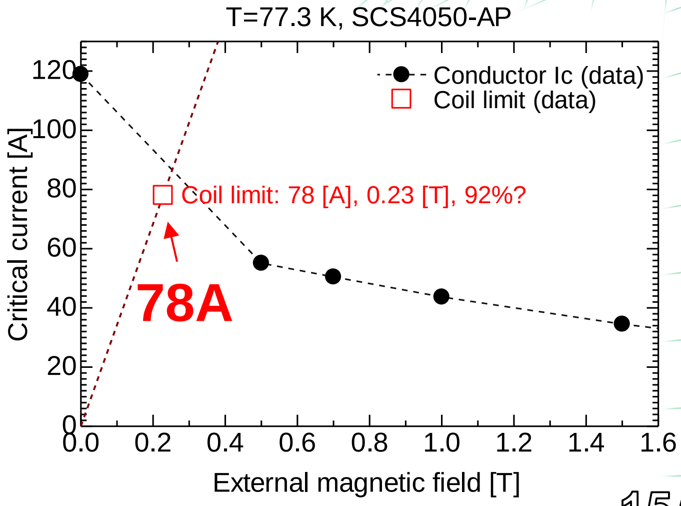


Aron Ceramic Type C (Toagosei Co., Ltd)	
Main Ingredients	Silica (SiO_2)
Viscosity	70,000 mPa·s
CTE	13 X 10^{-6} (0-600℃)
Heat Treatment	16 h at R.T. →1 h at 90 ℃ →1 h at 150 ℃

Tape: L=14 m, W= 4 mm (Ceramic coated)

Coil: ID = 80 mm,
1st: 26 turns, 2nd: 24 turns





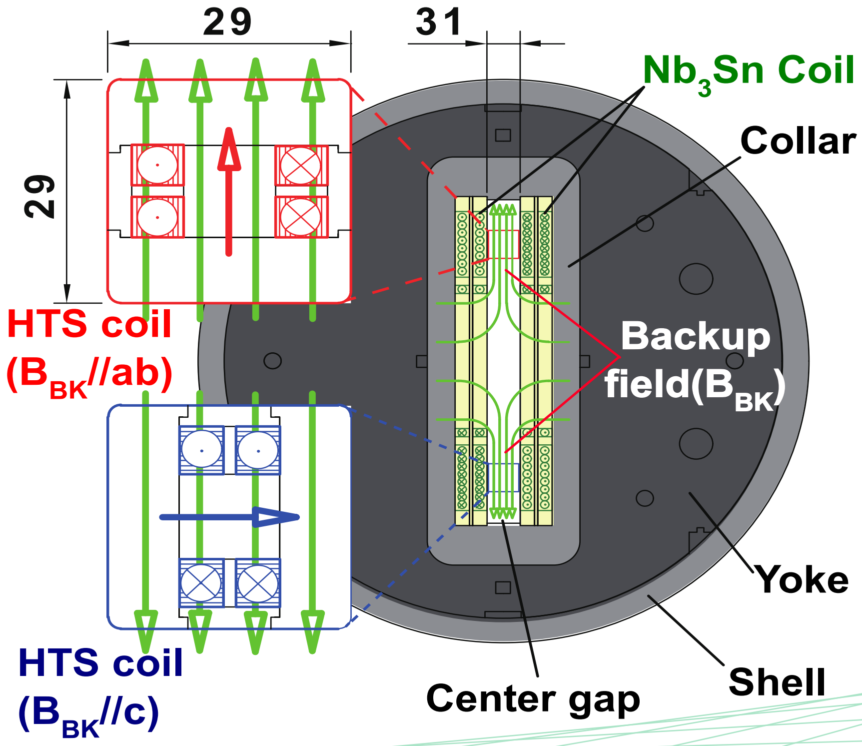
- □ **No significant change in T_C due to coil manufacturing process**
- □ **I_C decrease is less than 10%**

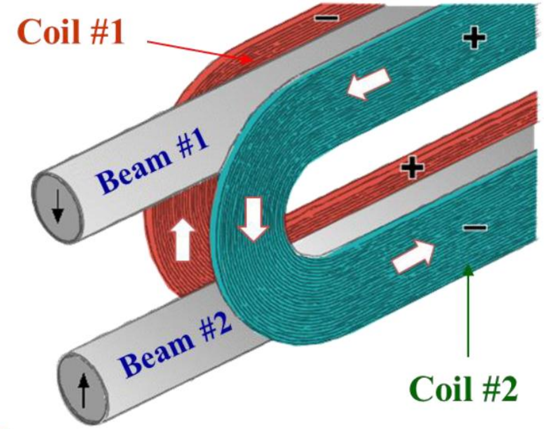
Cooling and excitation test @BNL

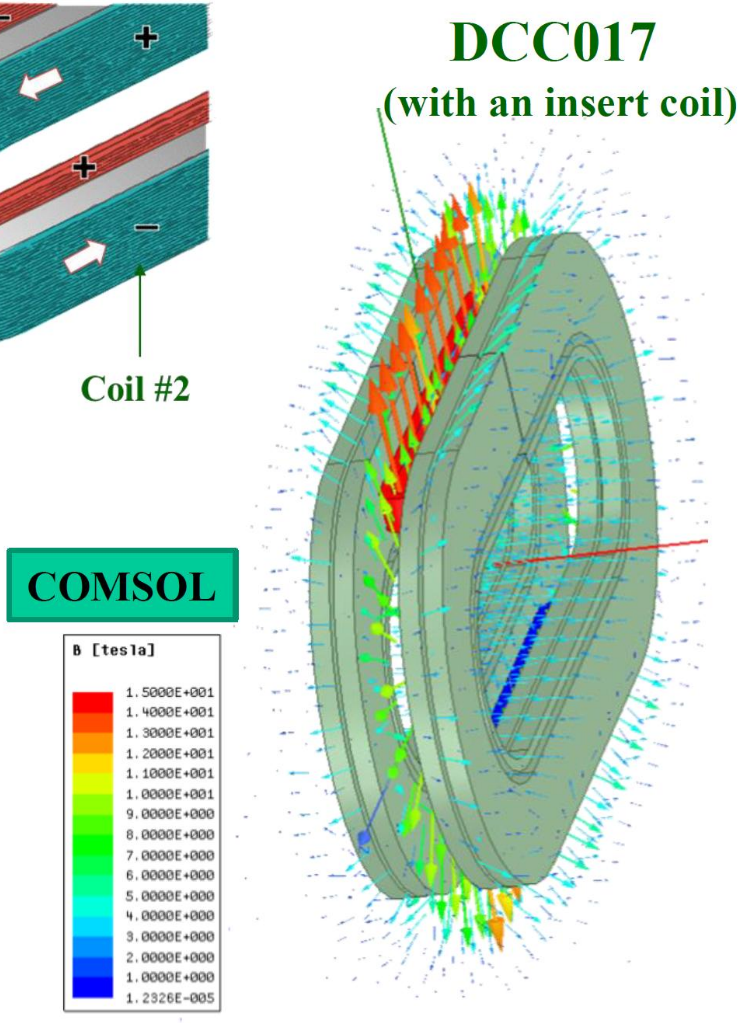
□As a next step, ceramic-insulated coils were tested at BNL under the US-Japan cooperative program.

[Common coil type test stand with Nb_3Sn coils]

- Temperature: 4.2 K（LHe bath cooling）
- Backup magnetic field: ~9 T
- Insert opening: 31 mm x 335 mm



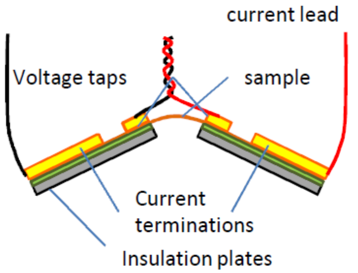


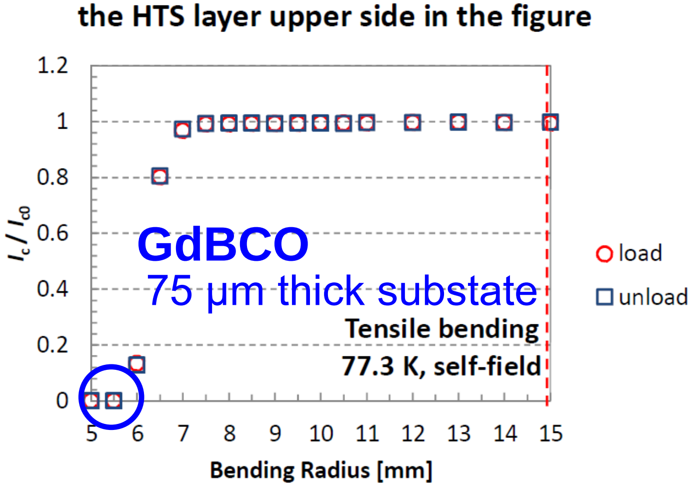


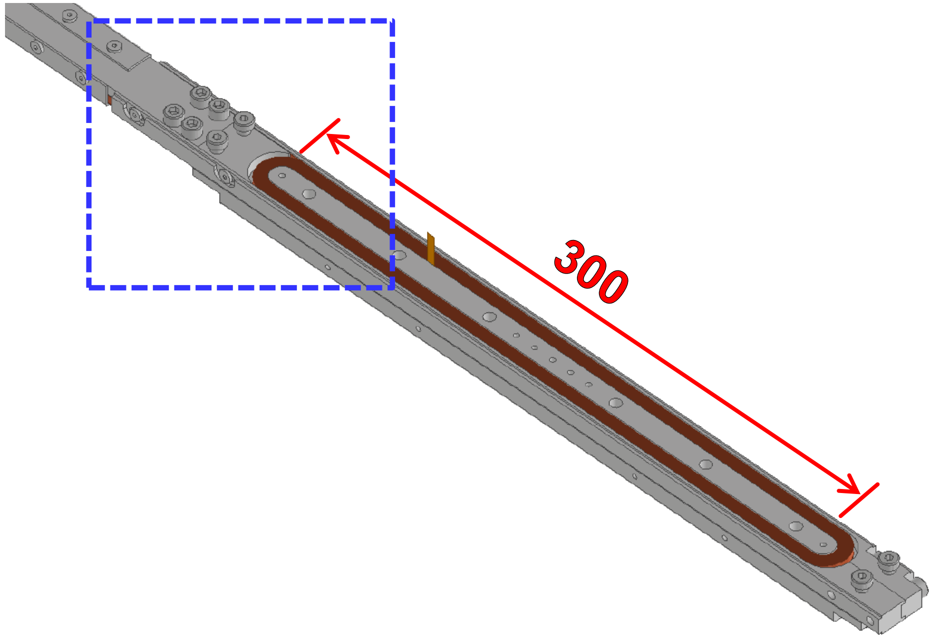
Insert coil design

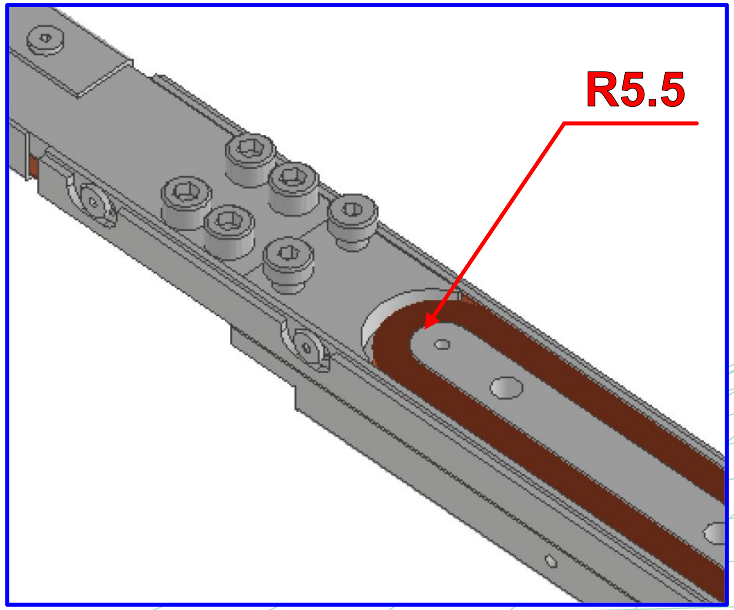
Fujikura FESC-SCH04(40)

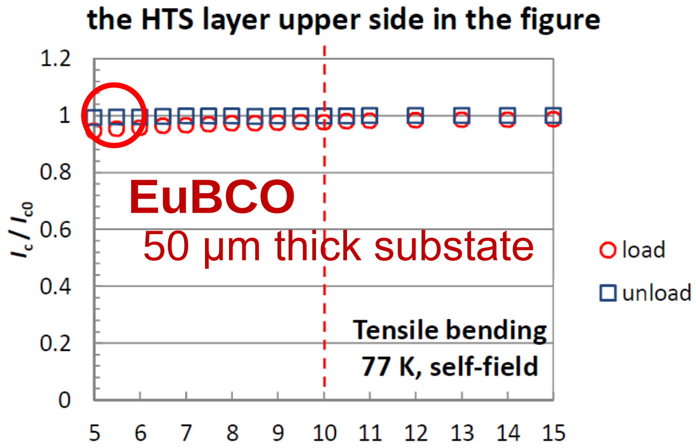
- Type: **EuBCO**, I_C (77K, S.F.): **201 A**
- Thick. of substate: **50 μm**, Thick. of Cu: 40 μm (one side)
- Width (Avg. of meas.): 4.08 mm
- Thickness (Avg. of meas.): **0.16 mm**
- Thickness of coating: **0.025 mm (one side)**
- Thickness per turn: **0.25 mm (Tape + Coating+ Adhesive)**
- Number of turns per layer: **24 turns**







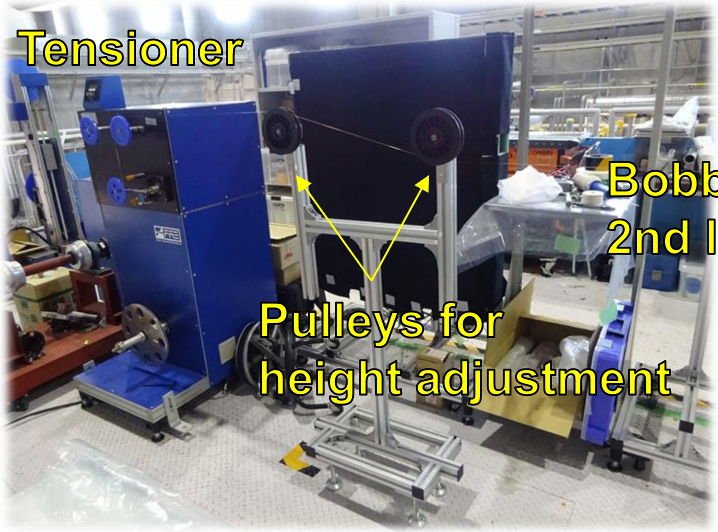


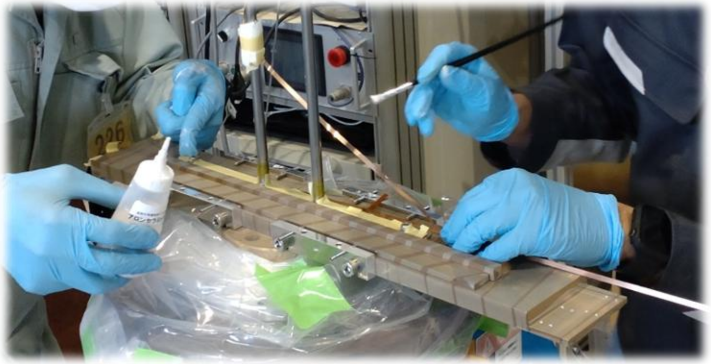


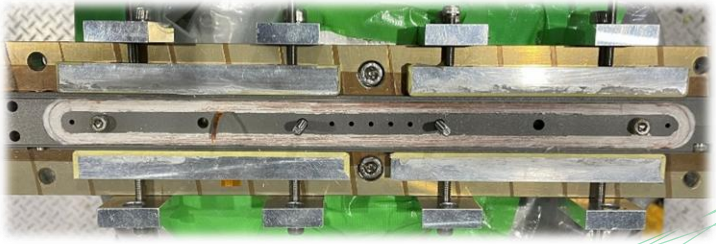
Insert coil production

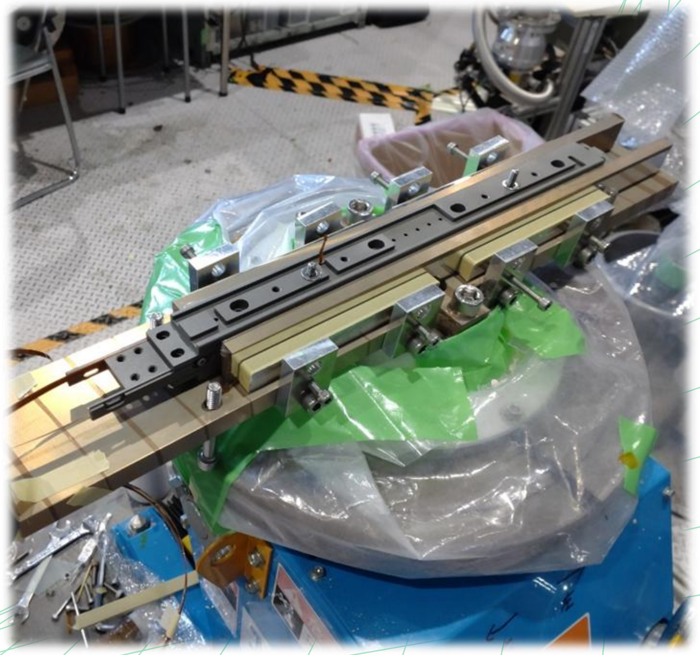
- ☐ **3 double pancake long race track coils were wound using wet winding technique with ceramic adhesives**

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







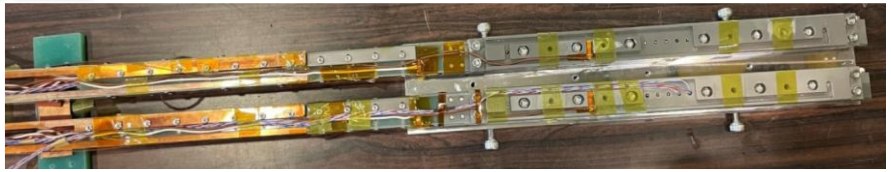


Confirmed Issues

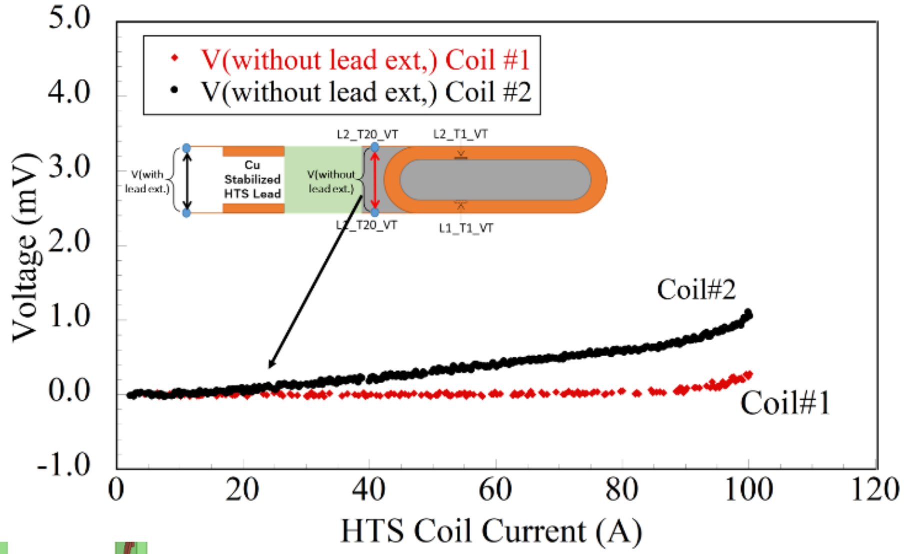
- ☐ The coating on the outside of conductors in the curved section has peeled off → Inside coating OK
- ☐ Short circuit between coil and support parts (ceramic-coated SS) → Insulation between coil block and test stand
- ☐ The conductor was damaged. Normal conductive components were found in the two coils after cooling.

Present status

☐ Three coils were assembled and they were tested at 77 K and a self-magnetic field before shipping



- Transport current limit of two coils is **100 A**, which is **17% lower** than the expected value (120 A, ~0.15 T).
- Two of the three coils appeared to have some conductor damage during the winding and assembly process.
- The coil without problems (#1) and the coil with relatively minor damage (#2) were transported to BNL.

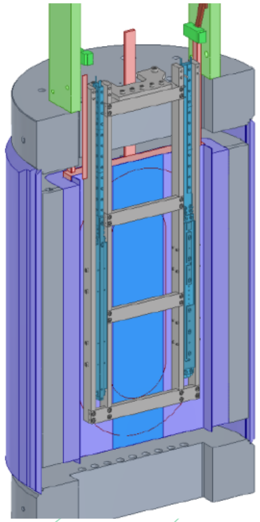


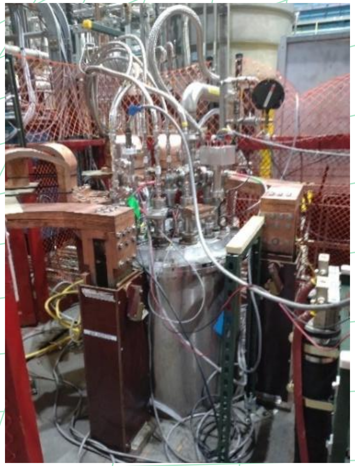
☐ The transported coils were tested at 77 K and a self-magnetic field at BNL

- Results similar to the pre-shipment test at KEK were obtained.

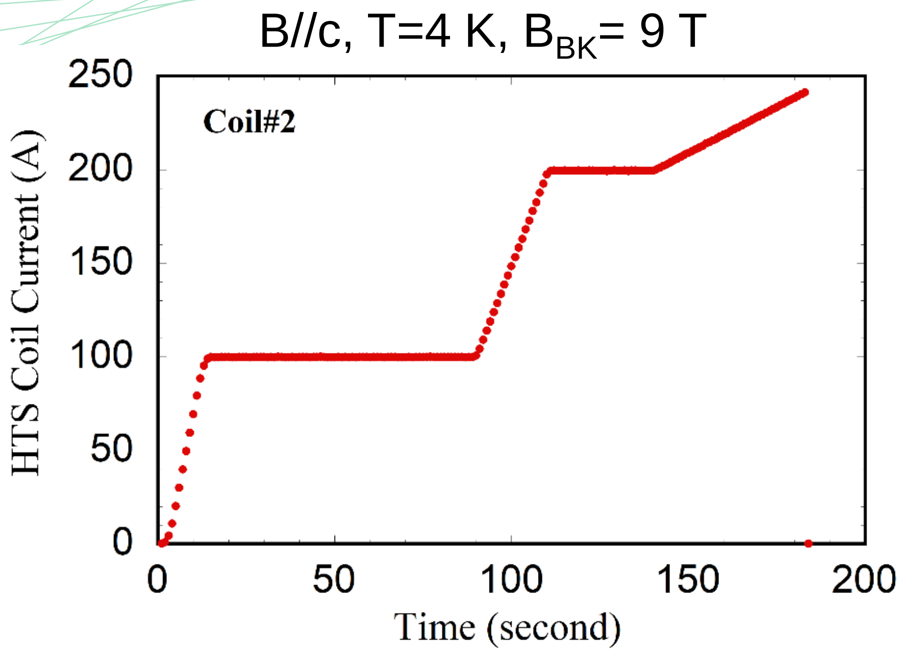
☐ The setup and cooling and excitation test at BNL

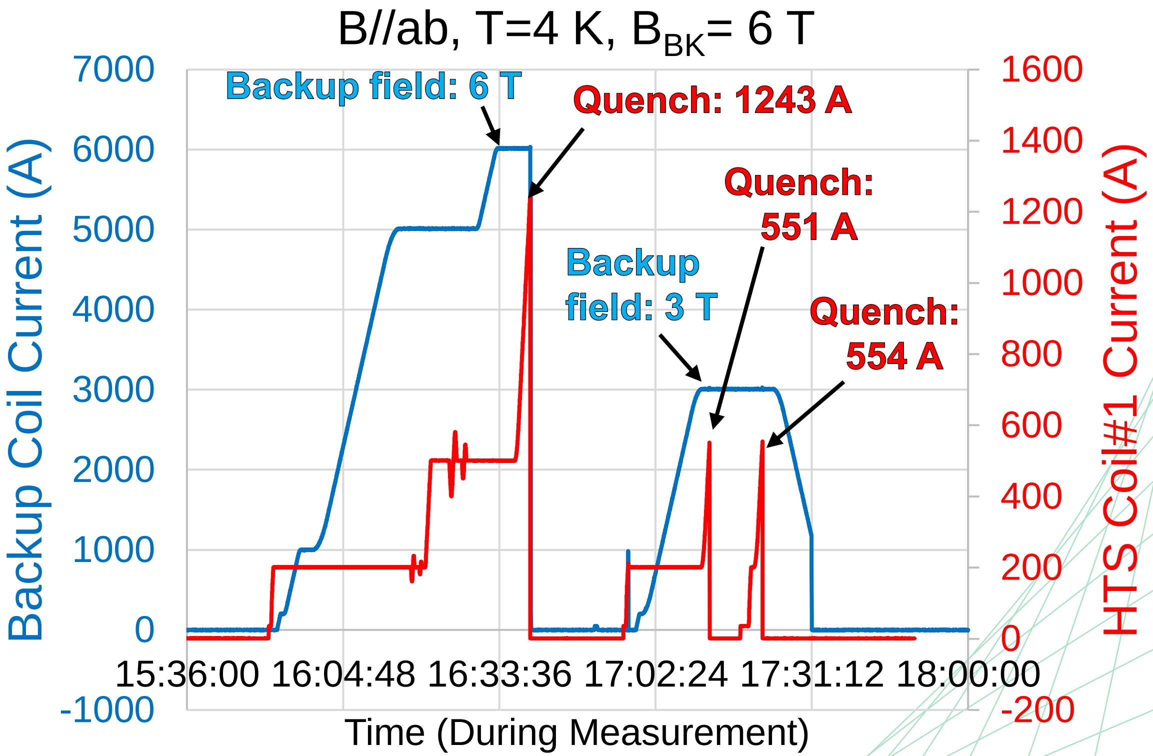
- **Pre-test:** current transfer of ±200 A to coil#1 and coil#2 cooled to 4.5 K was carried out without backup magnetic field
- **Excitation test:** Stepwise current transfer to HTS coils with backup magnetic field





Latest results of the excitation test





Coil # 2 (Damaged, B//c)

- The quench trigger was activated at 241A due to the voltage increase caused by the normal conductive component

Coil # 1 (B//ab)

- 1st quench occurred at **1250A** in an external magnetic field of **6T** (1st layer coil)
  → ~60% of the predicted value [~8.5T (B_{BK}+S.F.), 17% degradation]
- 2nd quench: 541A, B_{Ext}=3T, 3rd quench: 554 A, B_{Ext}=3T (Degraded)

Analysis of experimental data and verification by FEM simulation are currently underway

Summary

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- R&D of ceramic-insulated superconducting magnets based on HTS is underway with the aim of realizing future radiation-resistant superconducting magnets that can operate in high radiation environments exceeding 100 MGy.
- 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.
- The wet winding technique using ceramic bonding was verified by fabricating a small circular coil.
- Long racetrack coils for high-field testing at BNL was fabricated. Two coils were shipped to BNL, one with no problems and one with slight damage to the conductor.
- Cooling and excitation tests have been performed using common coil test facility of BNL.
- A maximum current of 1243 A was transported through the HTS coil in a 6 T backup magnetic field. This corresponds to about 60% of the predicted value, and analysis is ongoing.

Thank you