Development of Radiation-Tolerant SC Magnets - COMET and a Future Muon Source

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Muon Collider Demonstrator Workshop
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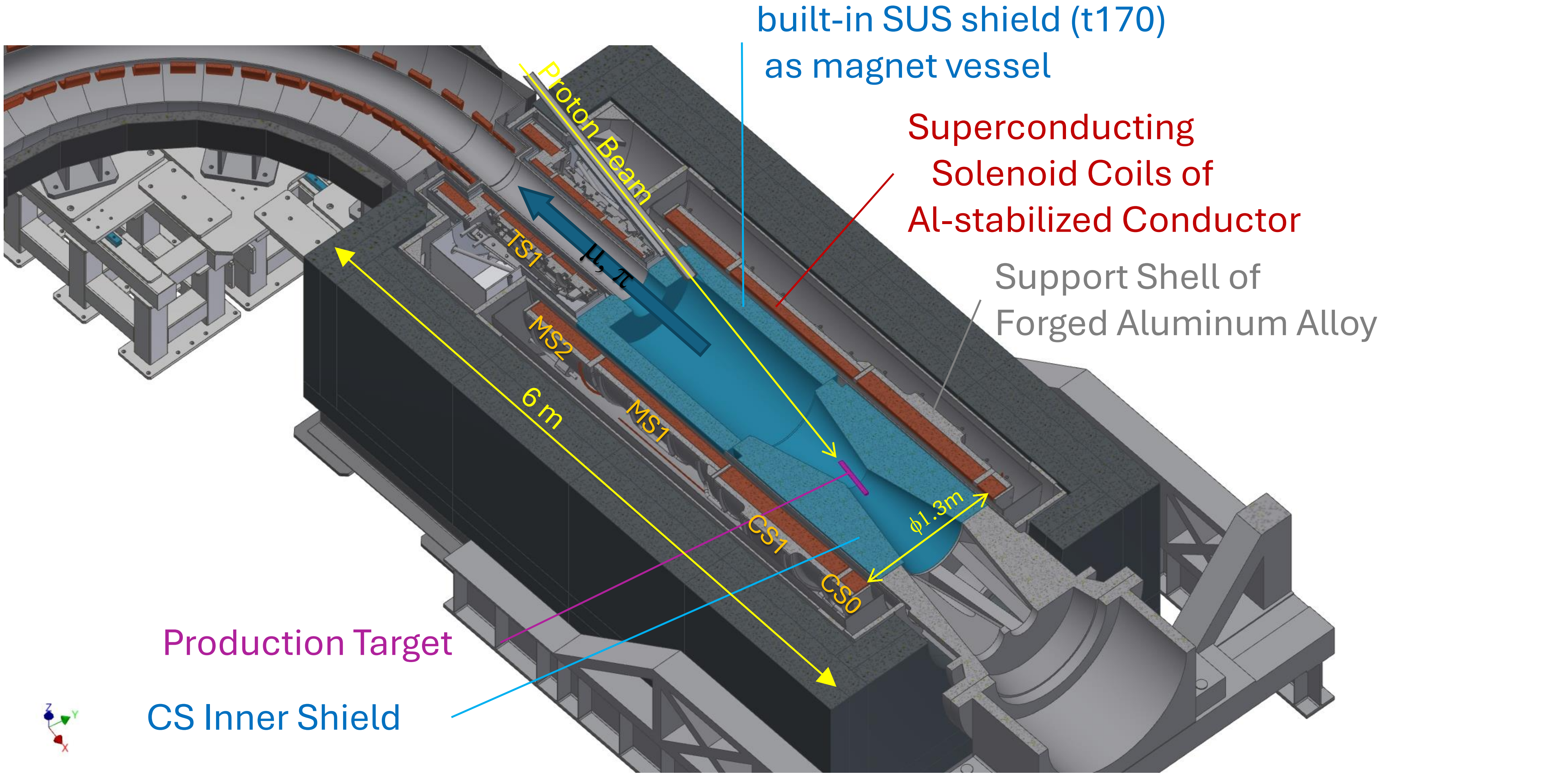
Contents

- COMET Pion Capture Solenoid
- Irradiation tests on magnet materials
- R&D on HTS magnet for the next generation muon sources

COMET Pion Capture Solenoid has just been delivered at J-PARC yesterday!

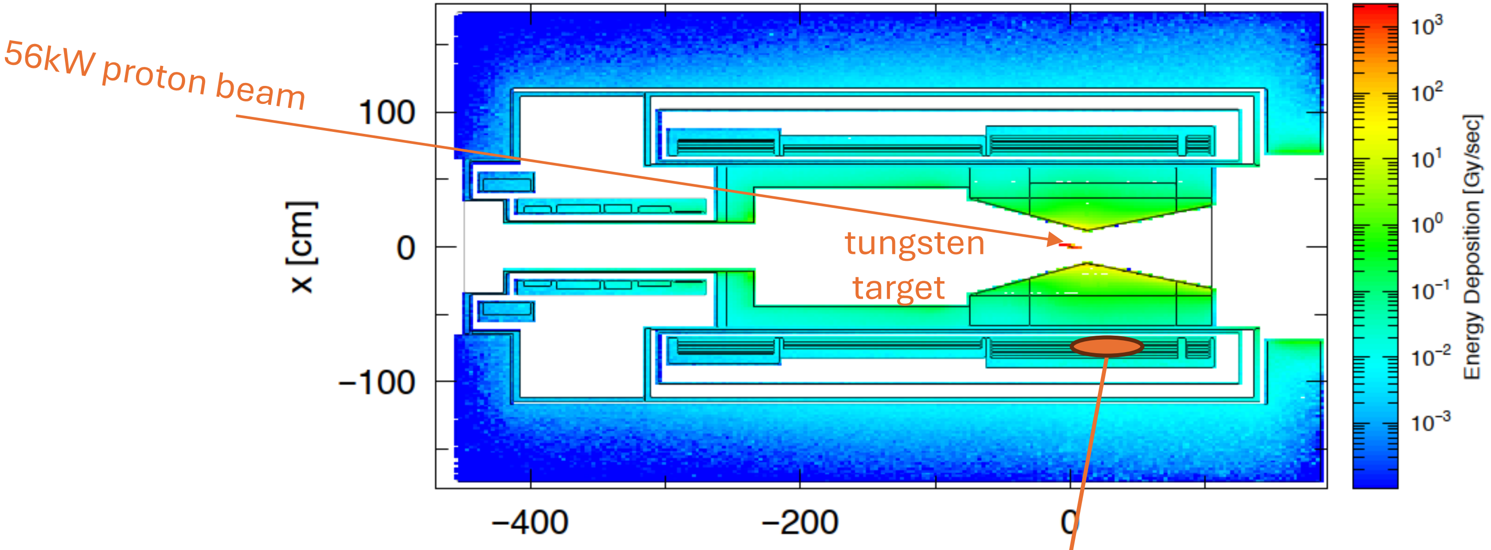
COMET Pion Capture Solenoid

Goal: $10^{11}\ \mu^{-}$/sec
with 56kW 8GeV proton beam

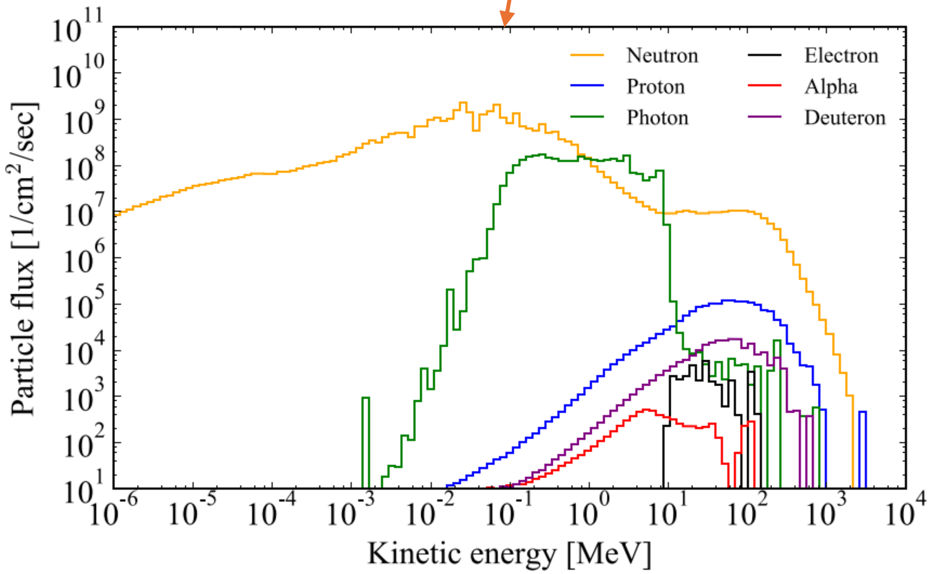


Radiation Environment
COMET Pion Capture Solenoid

- COMET Phase-2
  - 56kW 8GeV proton beam
  - Tungsten target
  - Tungsten shield



- Peak heat deposit
  - ~40 mW/kg
    → 1MGy for 300day operation
- Peak neutron flux
  - ~4x10^{14} n/m2/s
    → 10^{21} n/m2 for 30day operation



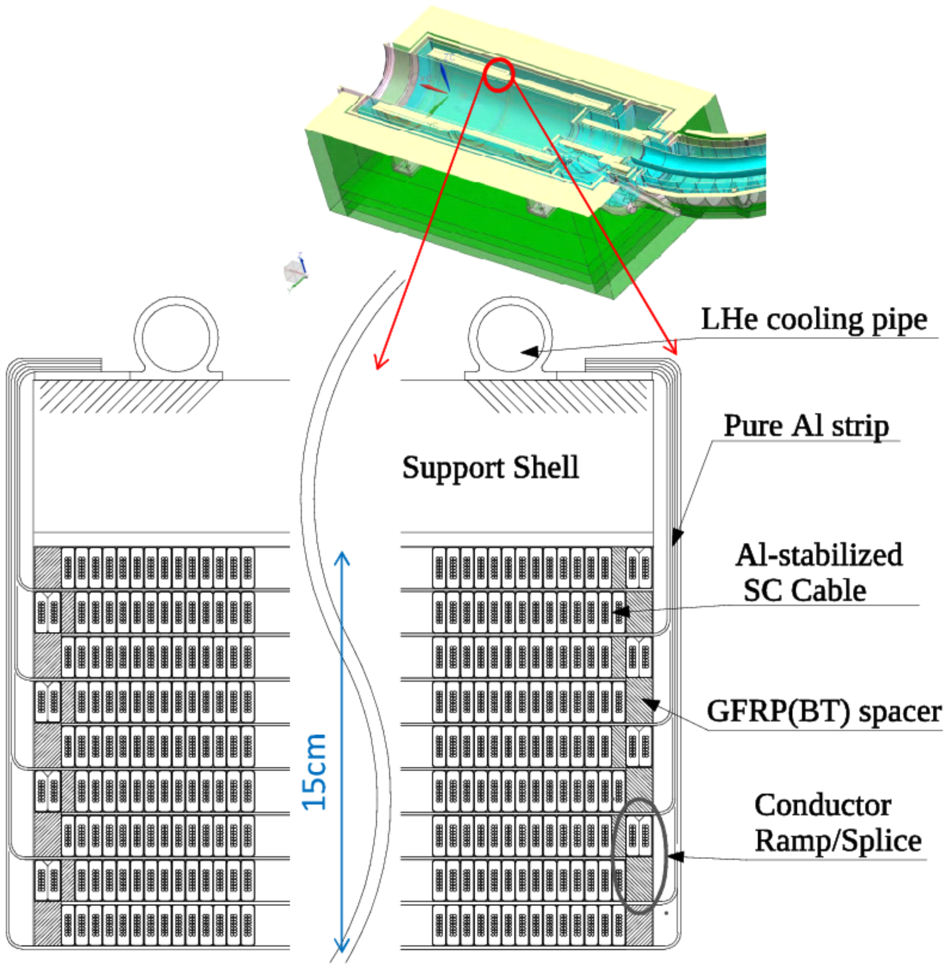
Radiation-tolerant magnet is mandatory

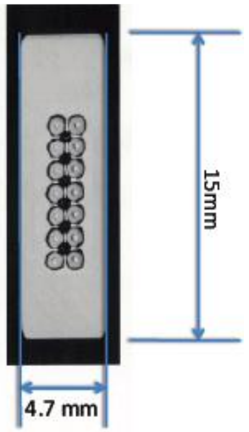
Coil Structure

- Aluminum stabilized SC cable
  - for less nuclear heating
- Radiation resistant insulator, resin
  - Polyimide film, Bismaleimide-Triazine resin
  - Boron-free glass in GFRP
- Pure aluminum strips in between layers
  - to cool down a coil inside

DESIGN PARAMETERS OF CAPTURE SOLENOID MAGNET

Item	Value
Conductor	Aluminum stabilized SC cable Al/Cu/NbTi = 7.3/0.9/1
Cable dimensions	15.0 × 4.7 mm² (without insulation) 15.3 × 5.0 mm² (with insulation)
Cable insulation	Polyimide film/Boron-free glass cloth/BT-Epoxy prepreg.
Magnet length	~6 meters
Num. of coils	10
Operation current	2700 A
Max. field on conductor	5.5 T (T_{cs} = 6.5 K) [a]
Stored energy	47 MJ
Coil inner diameter	1324 mm (CS0~MS2) 500 mm (TS1a~TS1e) 800 mm (TS1f)





Al stabilized SC cable
- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

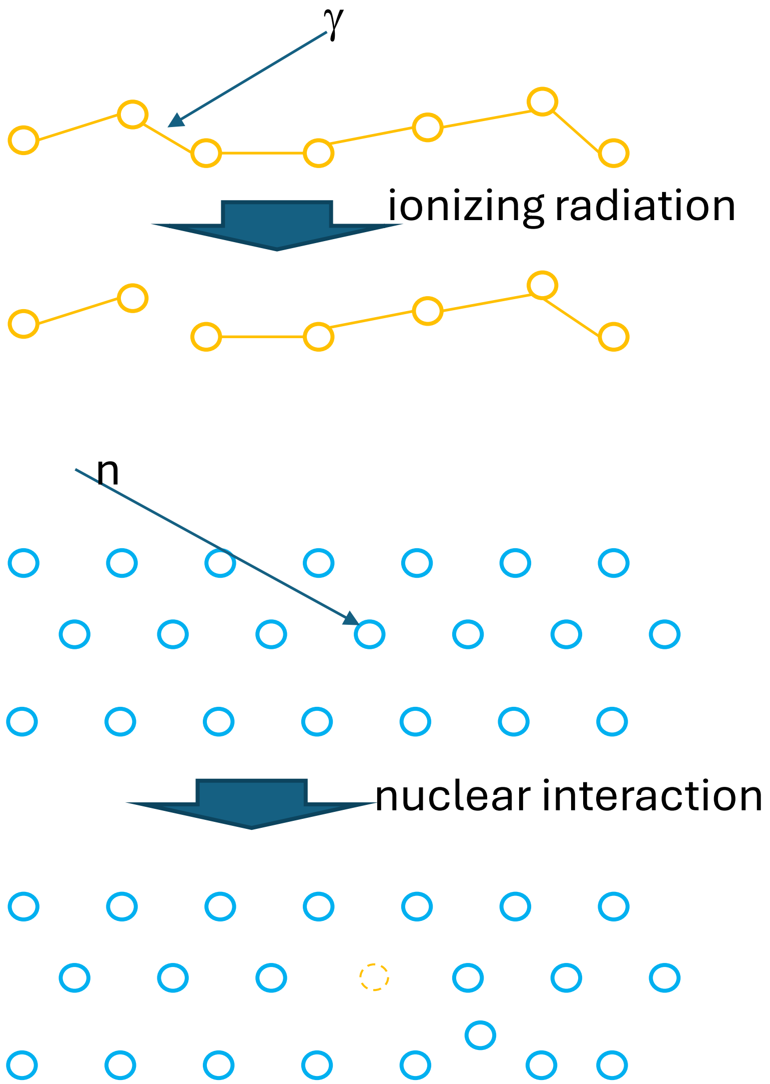
Irradiation Effects in Magnet Materials

- Organic polymer
  - Insulator
  - GFRP
  - Adhesive
  - Impregnation resin

Degradation of mechanical strength, electrical insulation

- Pure metal
  - Stabilizer
  - Thermal conductor

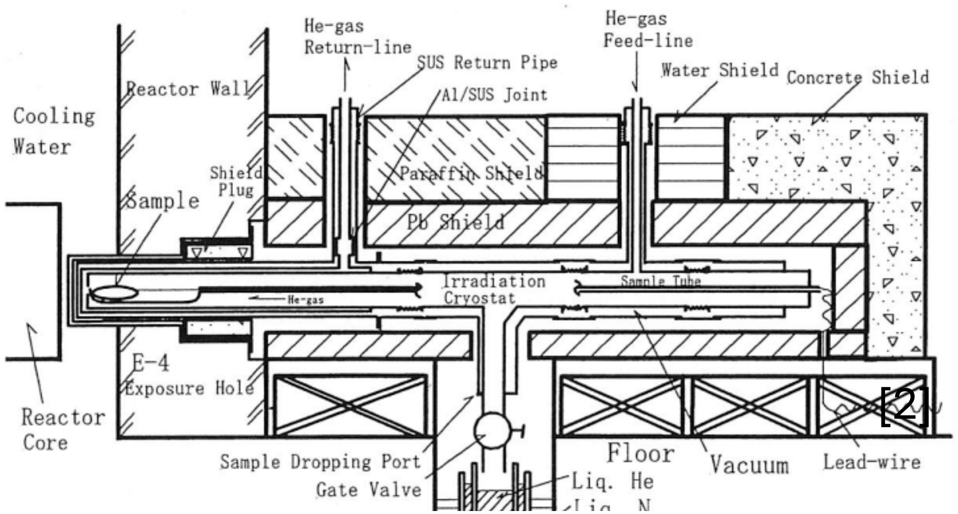
Degradation of conductivity



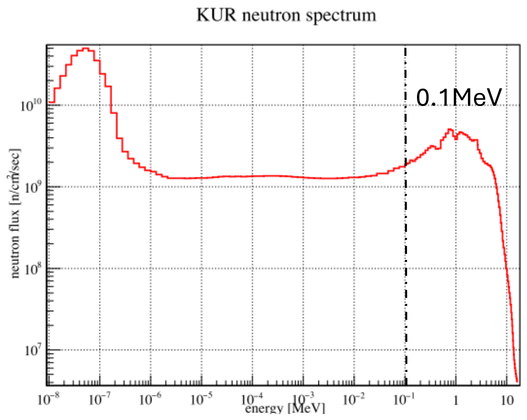
Displacement per Atom (DPA) = fraction of interacted atoms

Irradiation test by reactor neutrons

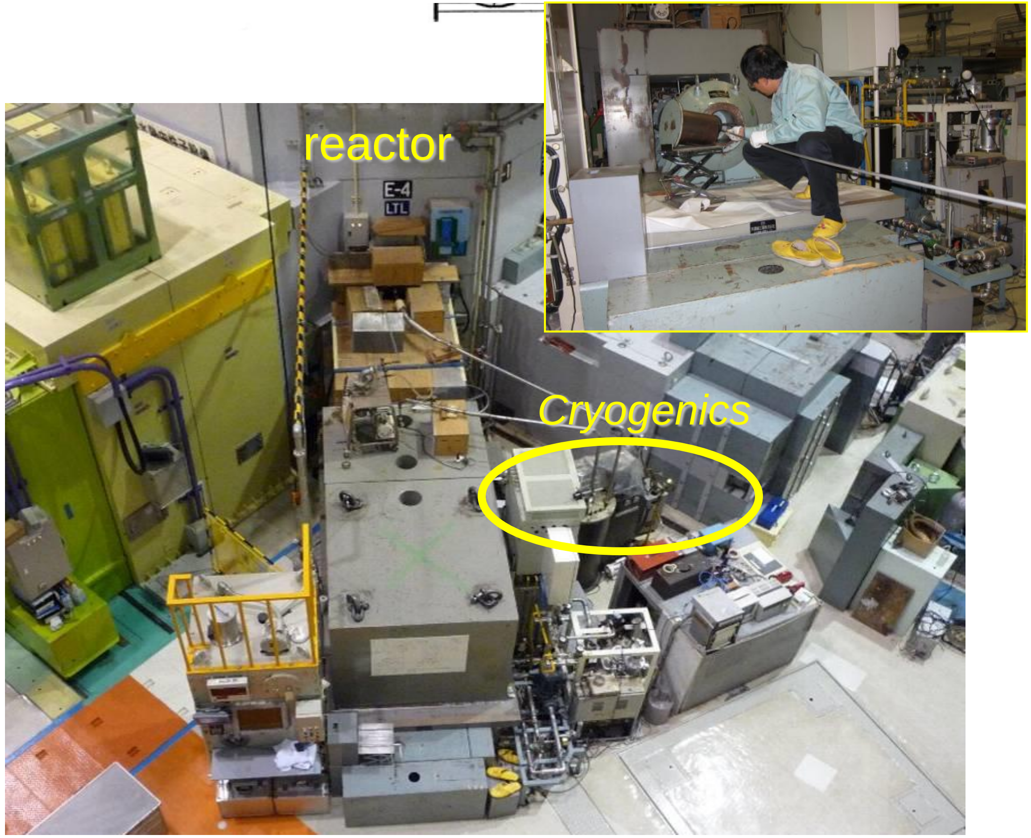
- Kyoto Univ. Research Reactor Institute
- 5MW max. thermal power
- Cryostat close to reactor core
- Sample cool down by He gas loop
  - 10K – 20K
- Fast neutron flux(>0.1MeV)
  - 1.4×10^{15} n/m^2/s@1MW thermal power



[2] M. Okada et al., NIM A463 (2001) pp213-219

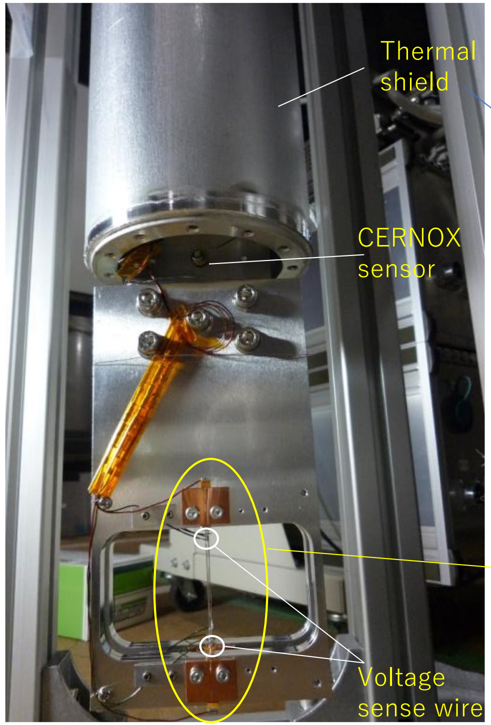


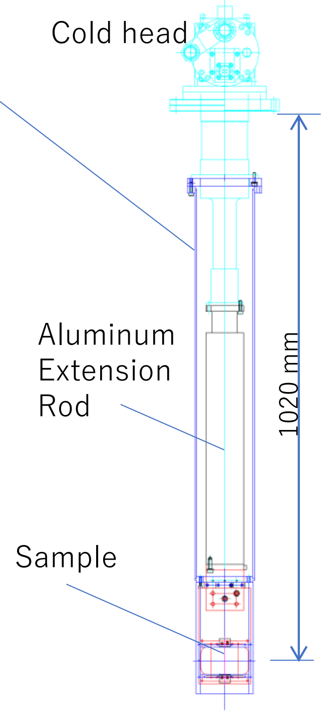
KUR-TR287 (1987)

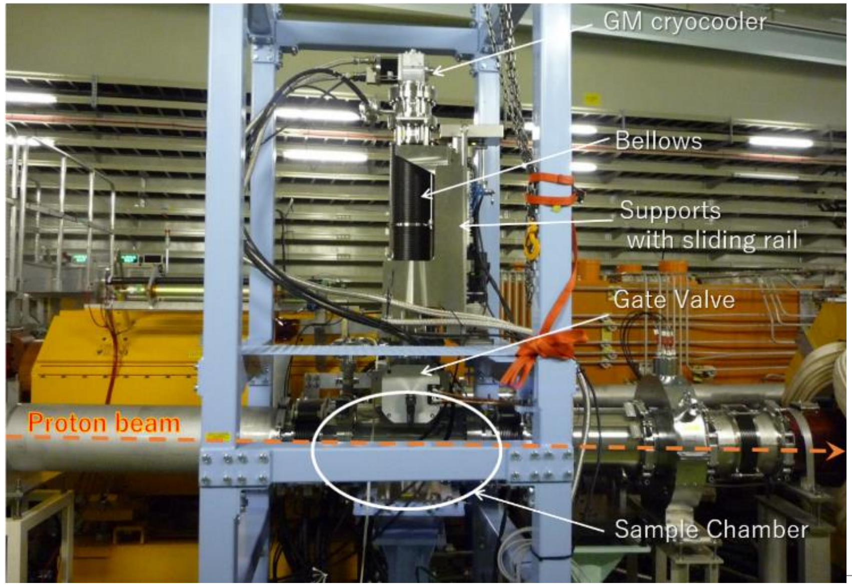


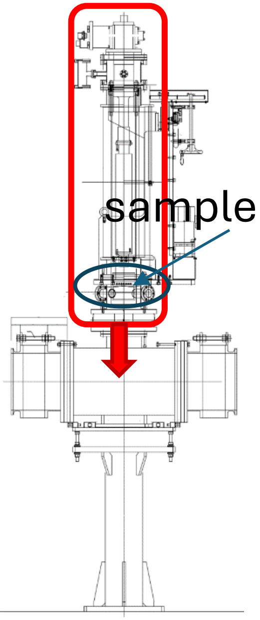
Proton irradiation test at J-PARC

- 3GeV-30GeV proton beam from MR
- Installed in 2019









	purity	RRR	shape
Al	>99.99%	580	wire ϕ 0.25mm
Cu	99.995%	306	wire ϕ 0.25mm
W	99.95%	28	wire ϕ 0.25mm

- Pure metal wire cooled by GM cryocooler
- Sample can be inserted to the beam line on demand.
  - remote handling

Repetitive Irradiation

- Pure aluminum and copper was irradiated by 8GeV and 30GeV protons
- Damage rate is reproduced by simulation with extensive Molecular Dynamics (arc-dpa model)
- **Recovery was observed**
  - Could be perfect even in Cu in this high energy range

TABLE V
DAMAGE RATE BY PROTON IRRADIATION

Material	30 GeV protons	8 GeV protons
Aluminum	1.03±0.12 (~100%)	1.05±0.15
Copper	3.55±0.23 (~100%)	3.88±0.27
Tungsten	95.8±5.6 (26%)	95.3±5.6

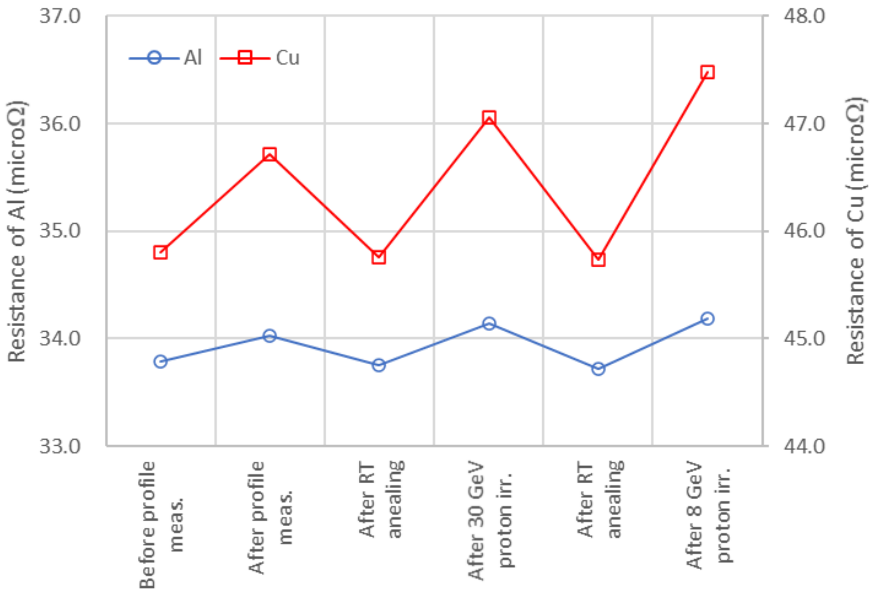
Values are in the unit: $10^{-31}\Omega m^3$ with errors indicating statistical fluctuation only. Recovery rate by thermal cycle after 30 GeV proton irradiation is indicated in parentheses.

TABLE III
THE DAMAGE RATE BY NEUTRON IRRADIATION IN EACH IRRADIATION PERIOD.

KUR neutrons ~MeV

Sample name	2010 Nov	2011 Sep	2011 Nov	2012 Nov	2013 July	2014 Apr
Al-CuMg	2.4					
Al-5N		2.5				
Al-Y1			2.8	2.9		
Al-Y2			2.6	2.7	2.3	2.2
Al-Ni					2.3	2.3
Cu			0.94 (82%)	1.0 (92%)	0.77 (95%)	0.73 (96%)

Values are in the unit: $10^{-31}\Omega m^3$. Recovery rate by thermal cycle after irradiation is indicated by the values in parentheses for the Cu sample.



“Repetitive Irradiation Tests at Cryogenic Temperature by Neutrons and Protons on Stabilizer Materials of Superconductor,“ M. Yoshida et al., *IEEE Trans. Appl. Supercond,* 32(6), 7100405 (2022); doi:10.1109/TASC.2022.3178944

120GeV proton irradiation

- Irradiated by 120 GeV protons at FNAL
- DPA cross sections above GeV agree with arc-dpa model

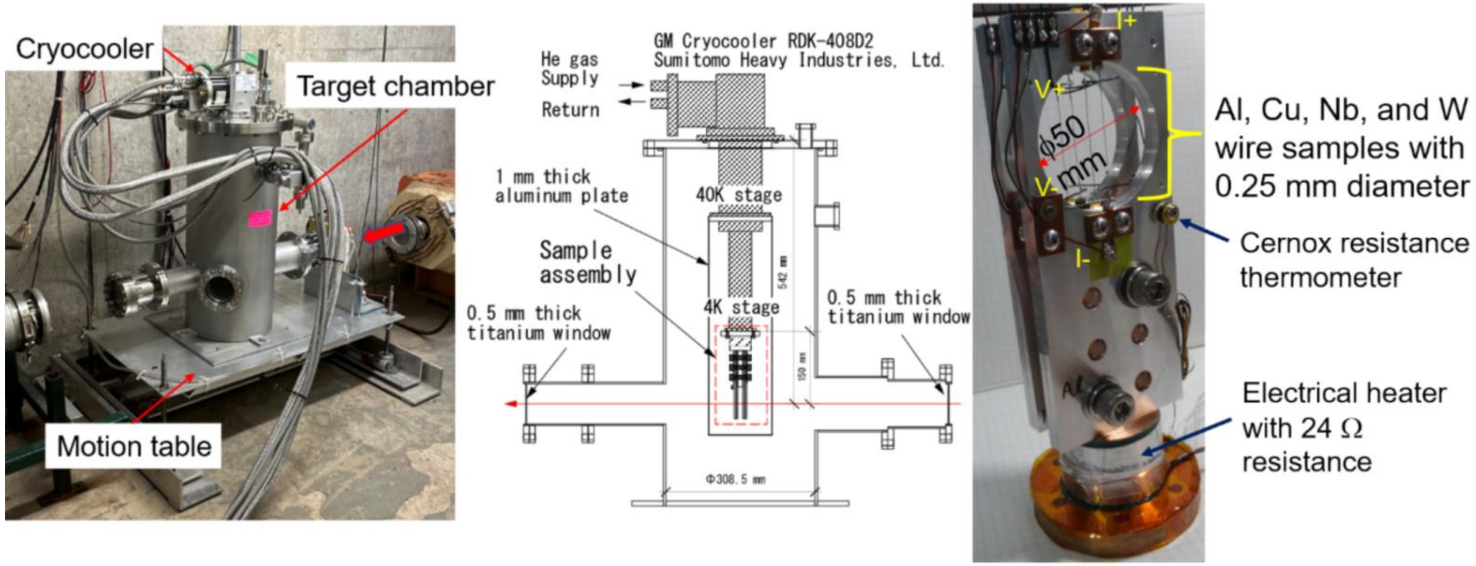


Fig. 2. Target chamber with GM cryocooler (left and center sides) and the sample assembly (right side).

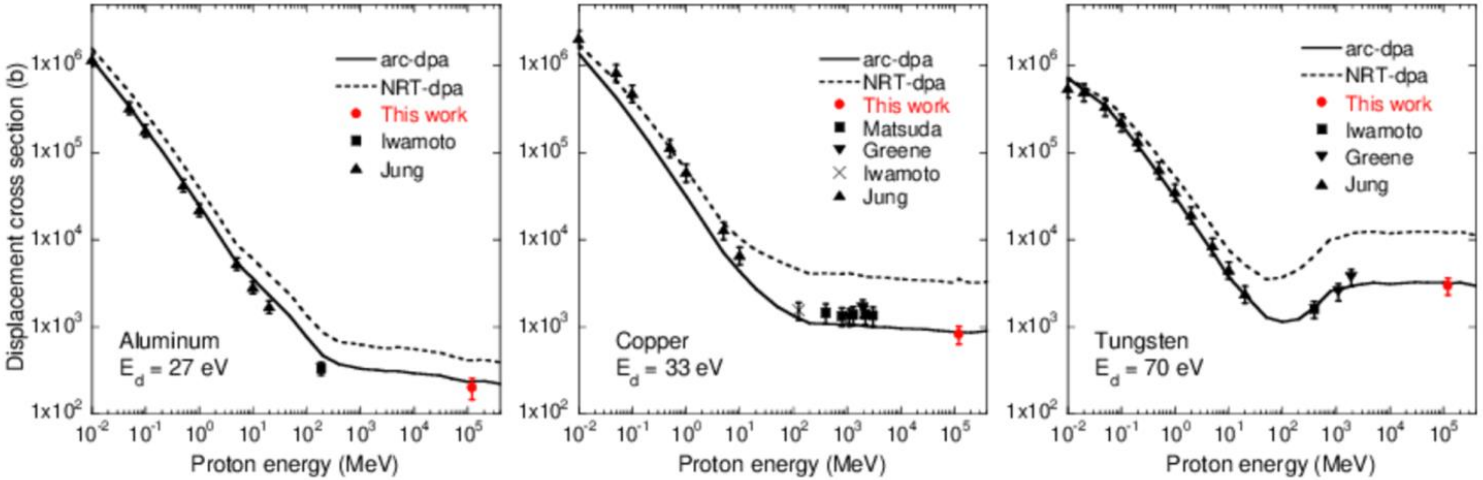
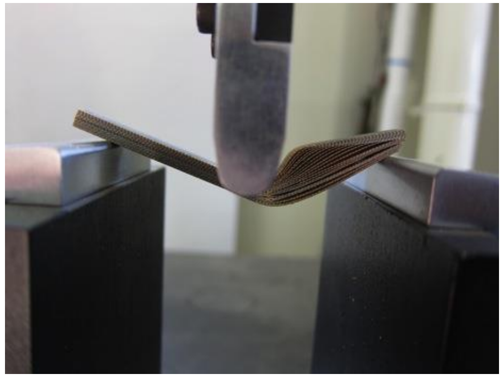


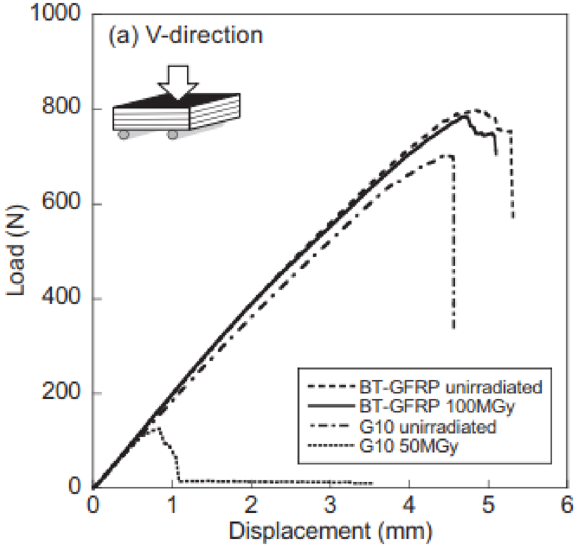
Fig. 7. Displacement cross sections of aluminum, copper and tungsten with proton. The dots indicate experimental data measured at the FTBF for 120 GeV proton (red points) and other facilities for low-energy protons of all targets [23], 185-MeV protons of aluminum and copper [7], 0.4–3 GeV protons of copper [9], 1.1 and 1.94-GeV protons of copper and tungsten [24], and 196-MeV protons of tungsten [8], respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Y.Iwamoto et. al., *Nucl.Instrum.Meth.B* 557 (2024) 165543; DOI: 10.1016/j.nimb.2024.165543

Rad-hard GFRP

- BT(bismaleimide triazine)-Epoxy GFRP has excellent performance.



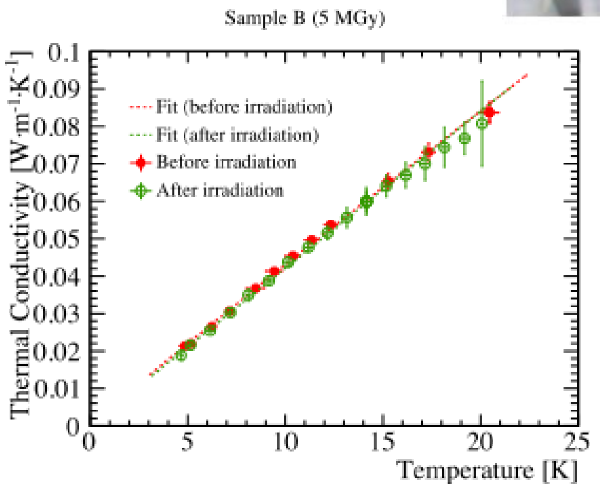


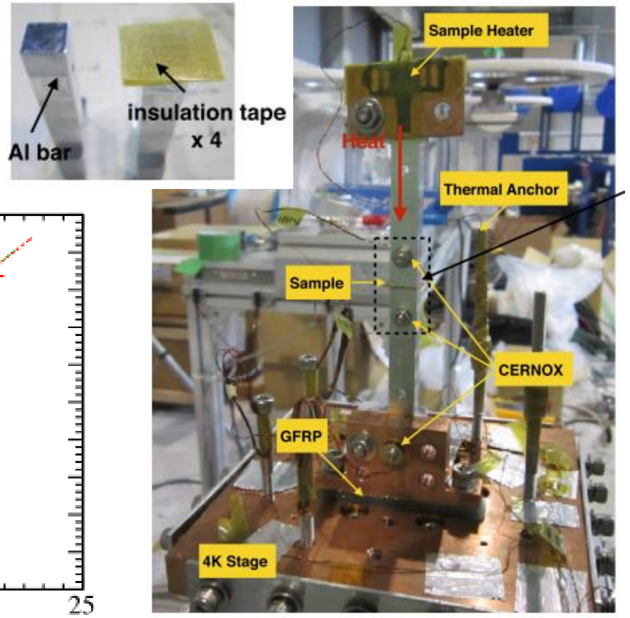
Flexural strength test w/ G10 sample irradiated at 30 MGy. Delamination of glass sheets is observed.

A. Idesaki et al., *Fusion Engineering and Design* 112 (2016) 418–424

Rad-hard Insulation tape

- BT-Epoxy prepreg insulation tape was irradiated at 5MGy
- No degradation of thermal conductivity was found

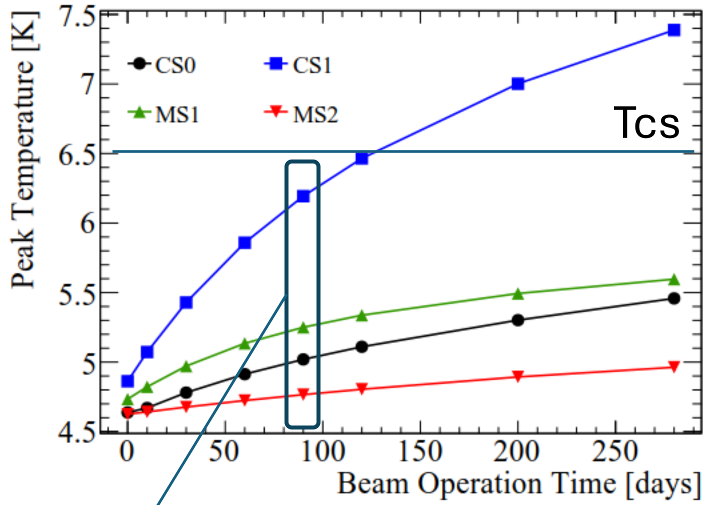


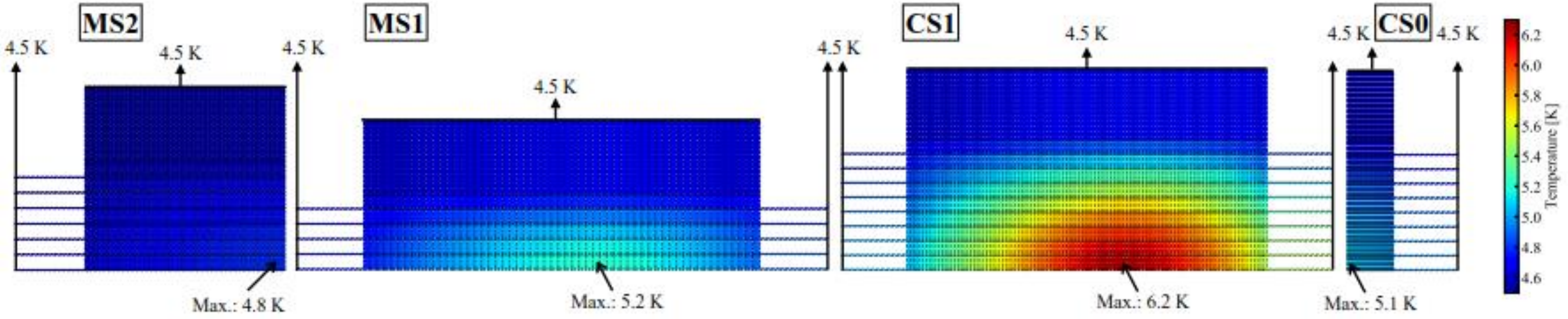


Y. Yang et al., *Cryogenics*, 89, 107-112 (2018).

Coil Temperature during Beam Operation (phase-2)

- Peak temperature in coil is estimated assuming irradiation by 56kW beam operation
- Assume damage rate at 0.03 nΩm for 10^{20} n/m^2
- Temperature will rise as thermal conductivity degrades by irradiation
- Irradiation damage in aluminum can be recovered perfectly by thermal cycling to room temperature.





Y. Yang et al., *IEEE Trans. App. Supercond.*, 28(3), 4001405 (2018).

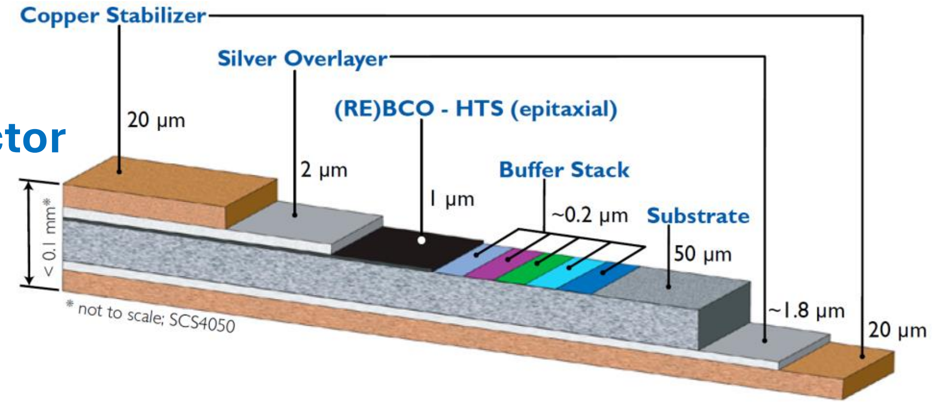
- Radiation effects in magnet materials are considered in the COMET magnet design.
- Influence of conductivity degradation is serious for LTS coils, while COMET magnet is expected to survive.

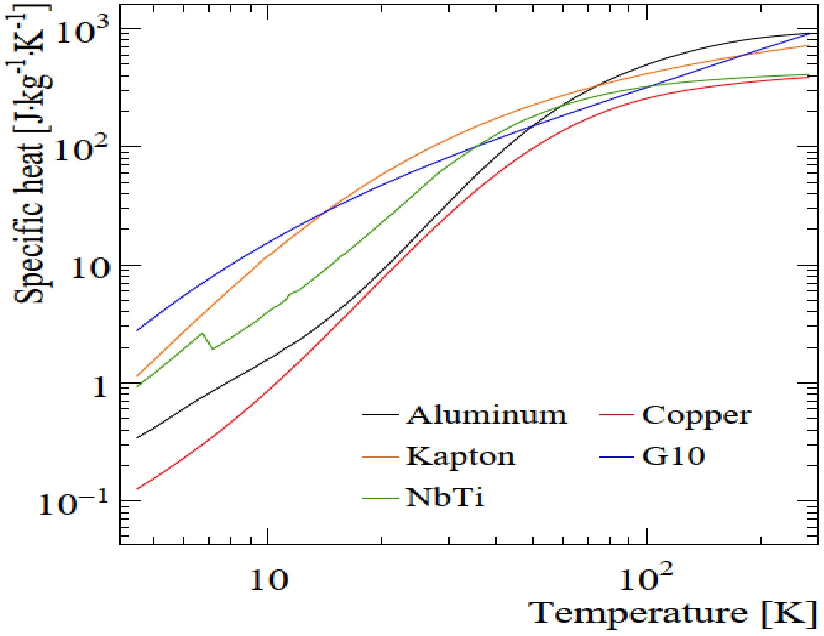
- Need R&D for next generation magnet

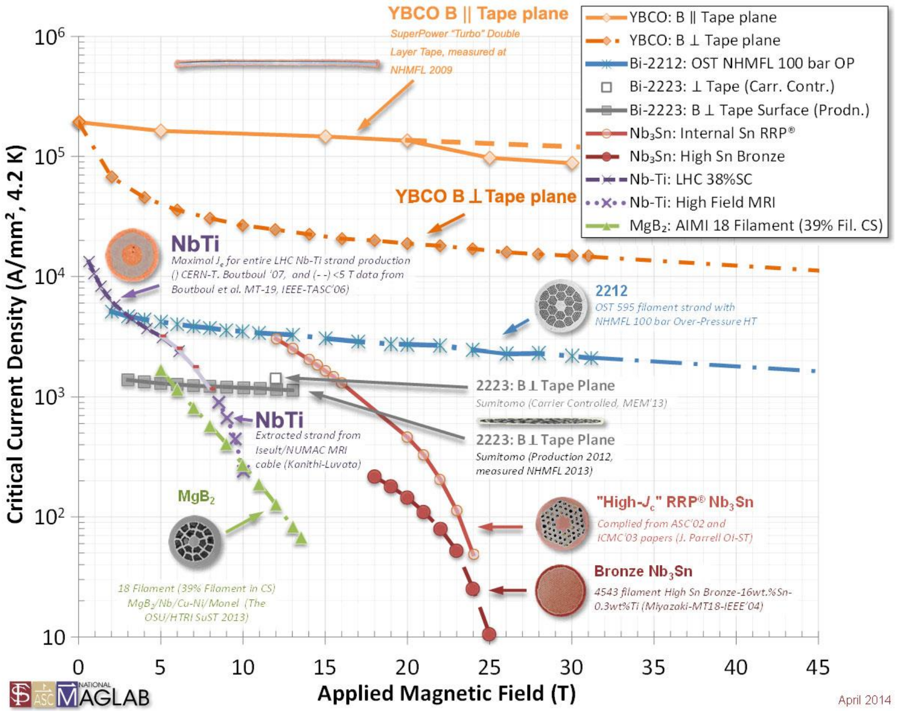
Superconductor for the Next Generation Magnet

- Cooling of deposit heat by radiation particles is an issue in LTS coils
- High Temperature Superconductor (HTS) is better candidate for the next generation magnets
  - Larger heat capacity at higher temperature
    - High tolerance for deposit heat
  - Less refrigerator power at higher temperature
  - Capability for higher field

REBCO tape conductor
Re=Gd,Y,Eu,...





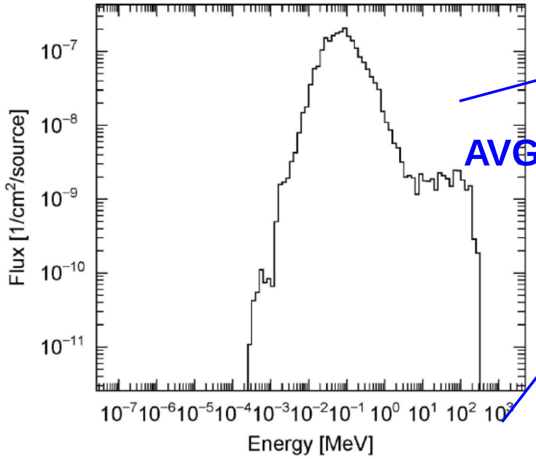


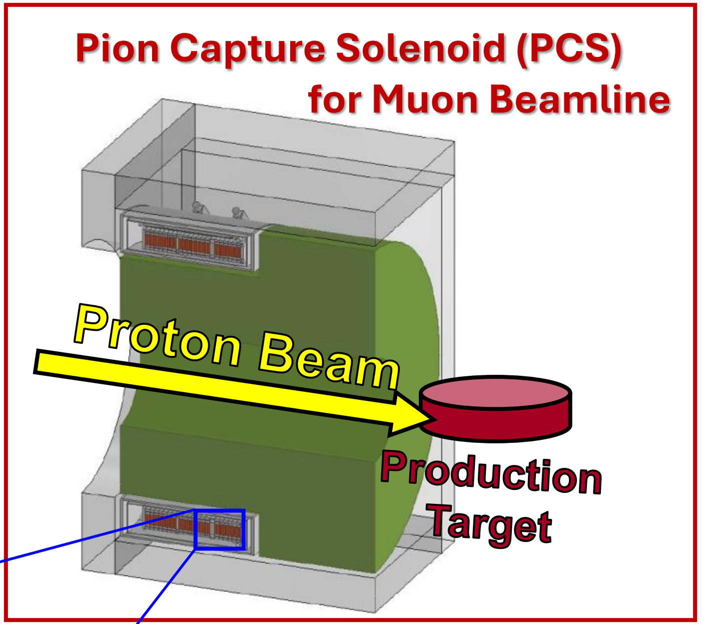
Conceptual Design of Capture Solenoid for J-PARC MLF 2nd Target Station (TS2)

(10 years operation)

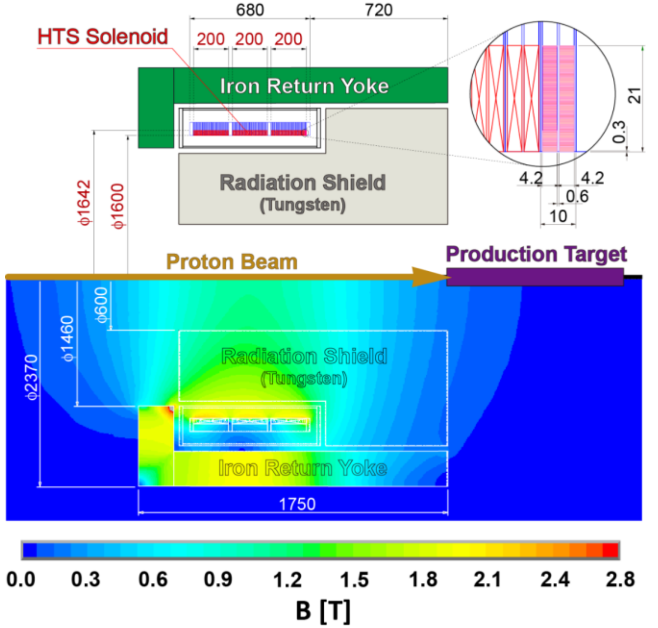
- **Heat Deposit: ~450 W**
- **Neutron fluence: ~ 10^{22} n/m^2**
- **Absorbed Dose: > 100 MGy**

PHITS Code





AVG. flux at the top 100 mm of the coil

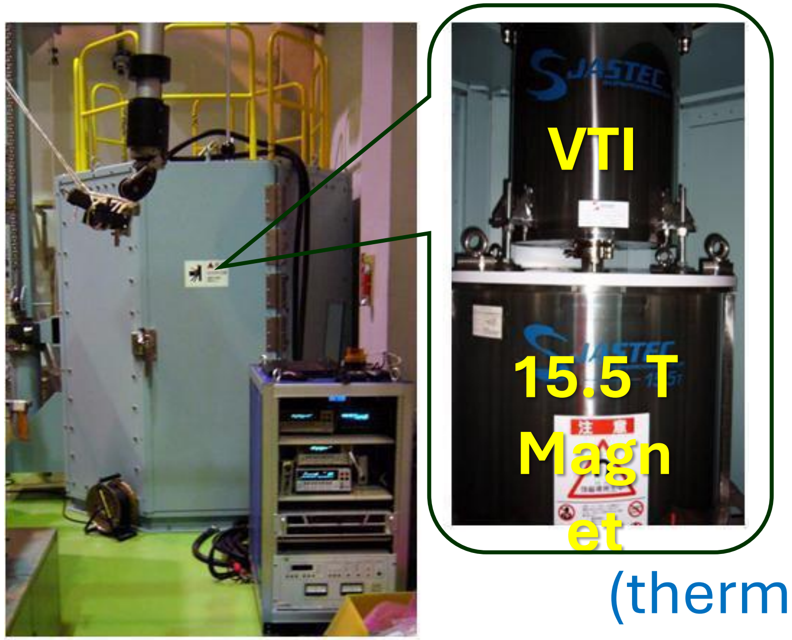


- **Stack of double pancake coil**
- ID=1600 mm
- Conductor : **REBCO**
- Operation Temperature: **20 K** (He gas cooling with pipe)
- Peak Field: **1.11 T** at center, **2.25 T (B//c)** at coil

Radiation effects on REBCO tape is under investigation

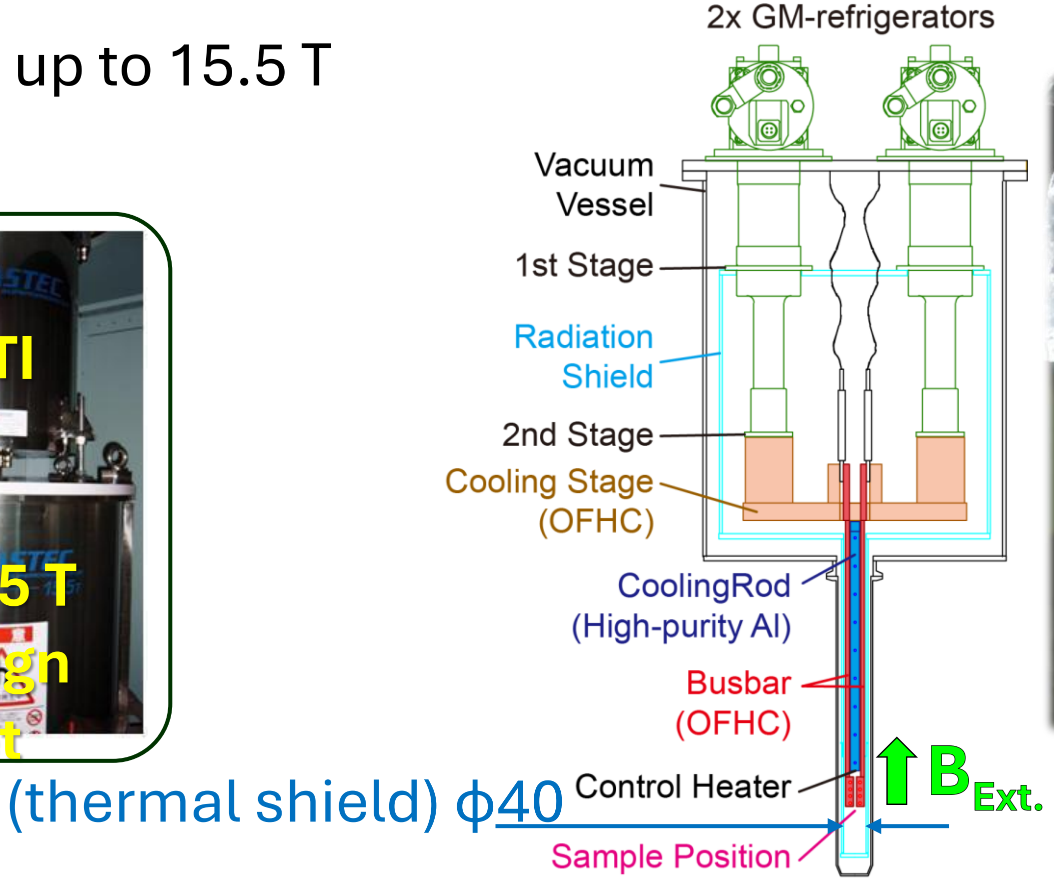
Neutron Irradiation Tests on REBCO conductor

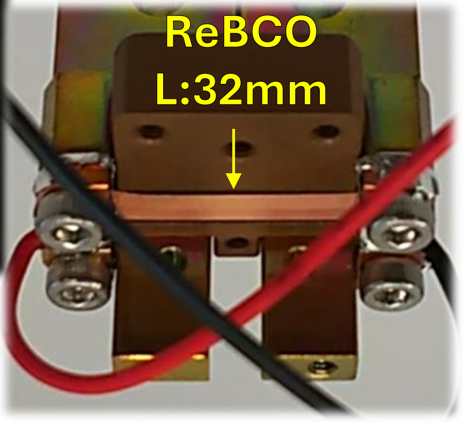
- Neutron irradiation at JRR3 and BR2 reactor is performed under the GIMRT program of the IMR, Tohoku Univ.
- PIE with an external field up to 15.5 T at IMR-Oarai.



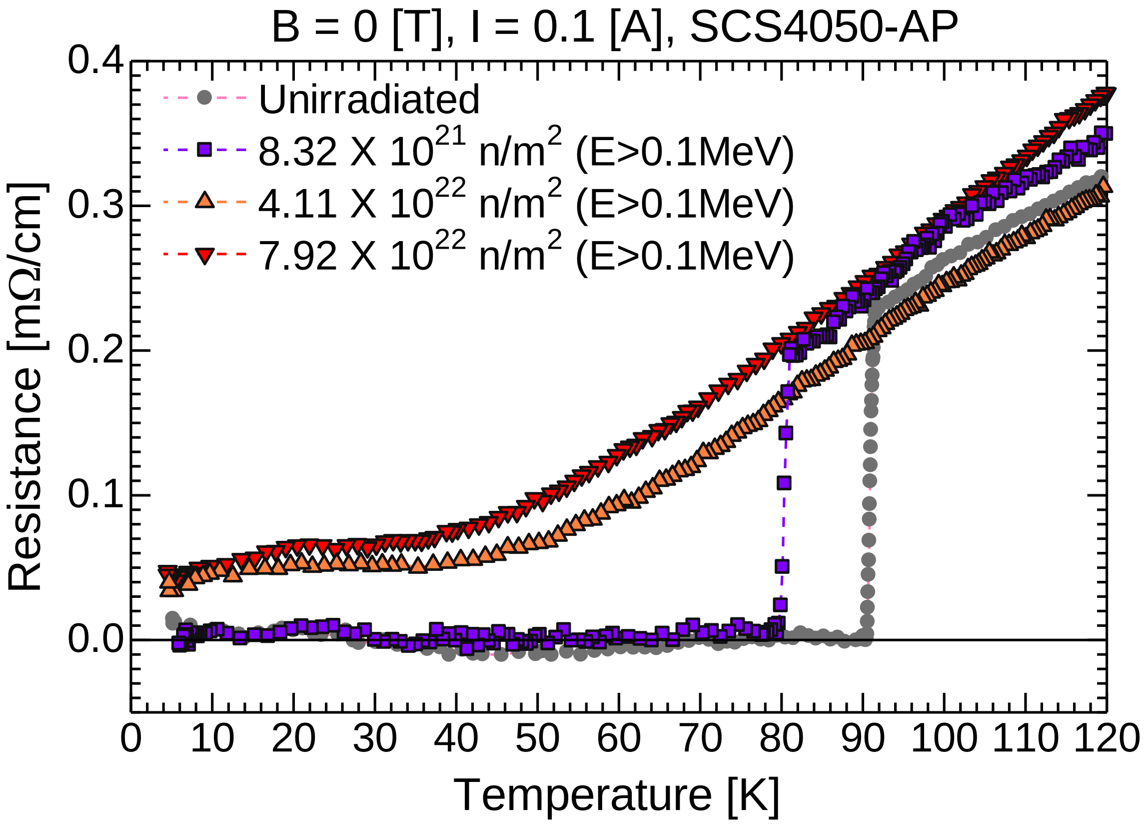
Variable Temperature Insert

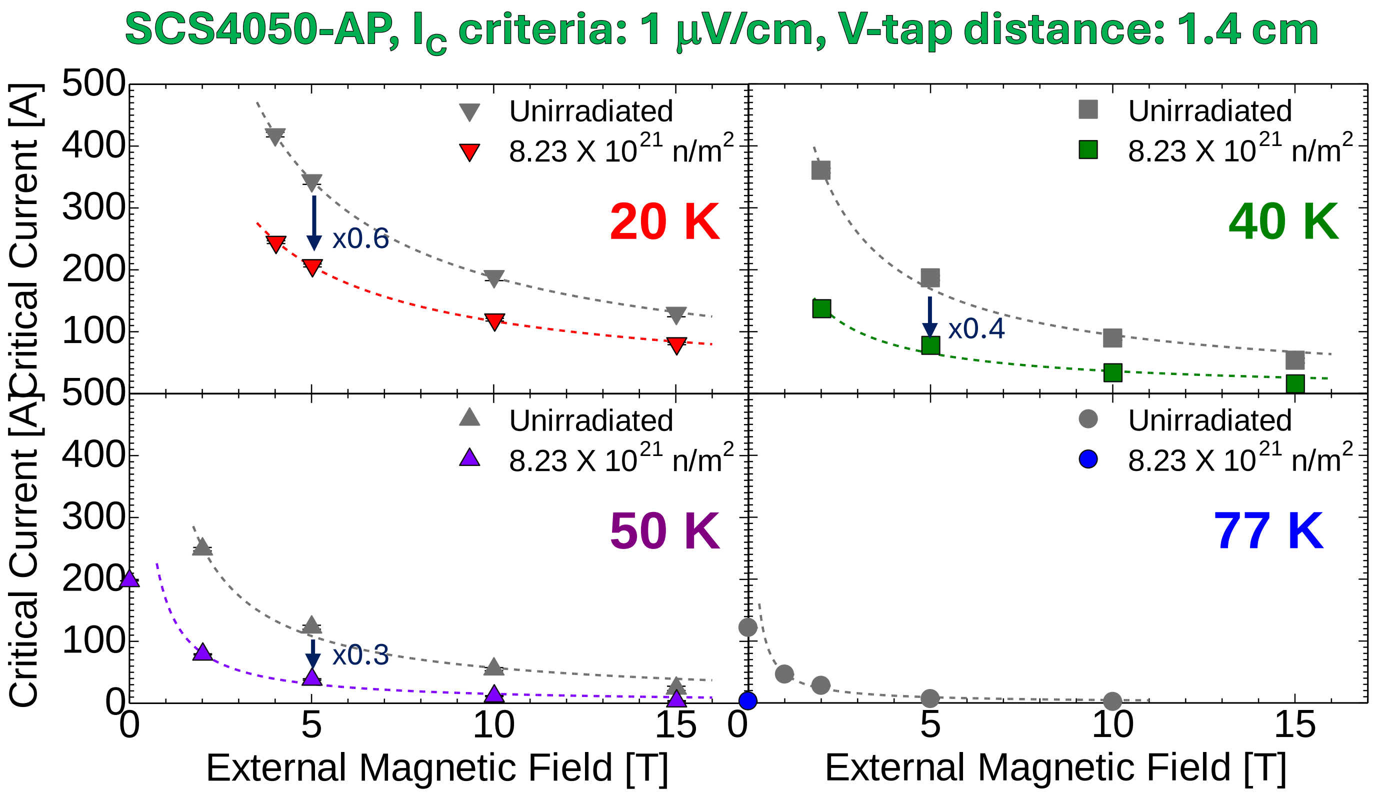
Temperature Range	4 ~ 80 K
Max. Current	500 A
Max. External Field	15.5 T





Results on GdBCO irradiated at BR2





M. Iio, M. Yoshida, T. Nakamoto, T. Ogitsu, M. Sugano, K. Suzuki, and A. Idesaki, “Investigation of Irradiation Effect on REBCO Coated Conductors for Future Radiation-Resistant Magnet Applications,”IEEE Trans. Appl. Supercond., vol. 20, no. 6, Sep. 2022, Art. no. 6601905.

Degradation was observed at $8x10^{21}$ n/m^2

Gd has huge cross section (49kb) of thermal neutrons → 9b on Y, 5kb on Eu

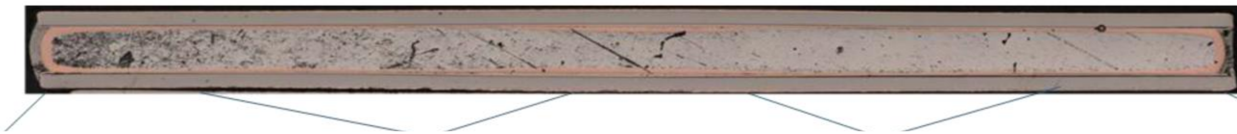
→ PIE on YBCO,EuBCO samples irradiated at JRR3 will be done in this year

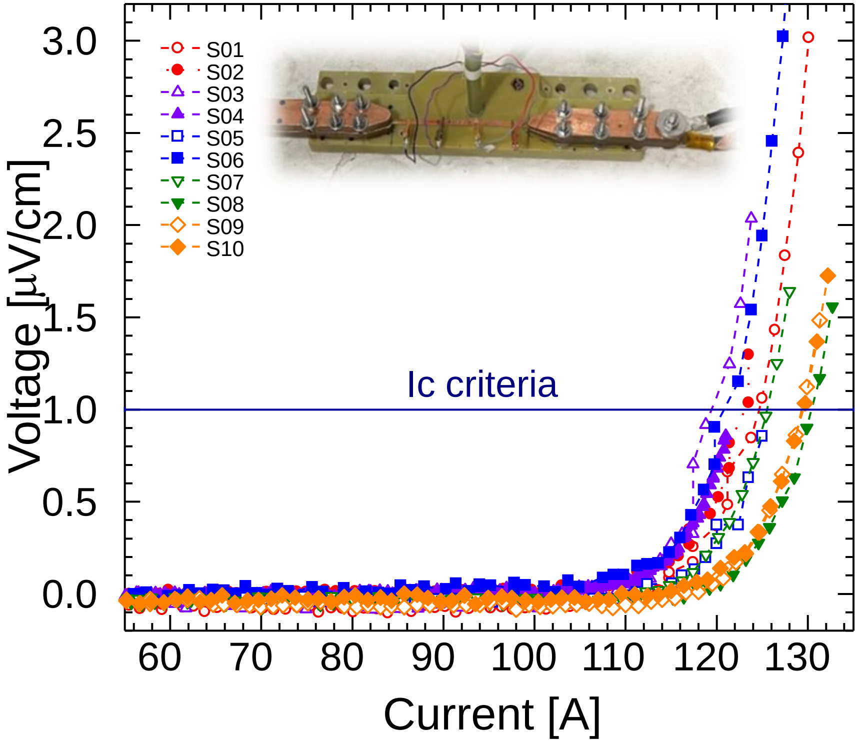
Study of Aluminum-stabilized HTS conductor

- Commercial REBCO tape conductor has less stabilizer, a few 10s micro-meter-thick copper
- More stabilizer is necessary to avoid thermal runaway at quench
- Development of Al-stabilized HTS conductor was initiated

- REBCO tape is soldered on both side of copper-clad aluminum (CCA) flat wire
- No degradation by soldering process was found.
- Trial with thicker aluminum is planed

- CCA: **0.17 mm thick, 4 mm wide** (T_{Cu}=0.015-0.02 mm, Al: 8030 Alloy)
- REBCO: YBCO with AP **x2** (SCS4050HM, W4mm, **Ic= 70A**)
- Joint length: 200 mm
- Temperature conditions: 195℃-2min / 210℃-2.5min / 220℃-4min

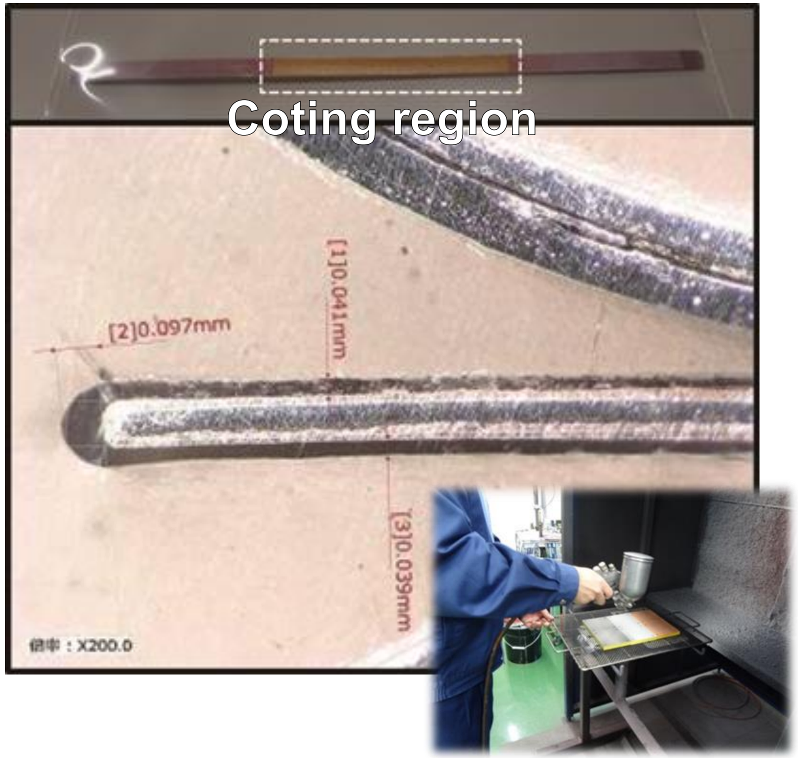


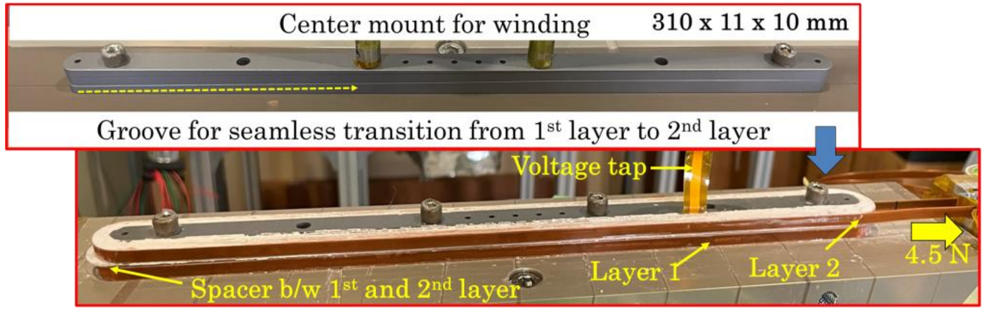


Study of Mineral Insulation

- Insulation is another key issue of radiation tolerance
- Study of mineral insulation is initiated in KEK
- Spray coating of alumina-silica on REBCO tape
  - heat treatment at 100°C
  - No degradation by coating process was observed
- Test coil with mineral insulation is developed and tested at 4K with ext. field of 9T at BNL in US-Japan collaboration
  - Analysis underway

SCS4050-AP (SuperPower)





MI-Seamless Double pancake racetrack coil based on REBCO

Summary

- Radiation-tolerant superconducting magnet is necessary for high-intensity muon source
- COMET Pion Capture Solenoid is designed in consideration with radiation effects on magnet
- R&D for further radiation tolerance is on-going for the next generation magnets
  - Irradiation tests on REBCO tape
  - Studies on mineral-insulated aluminum-stabilized HTS coil