Effect of Radiation on Stabilizer

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Muon Collider Collaboration Meeting
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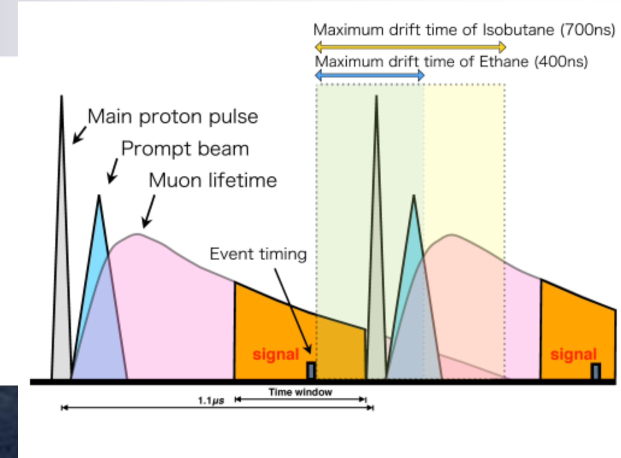
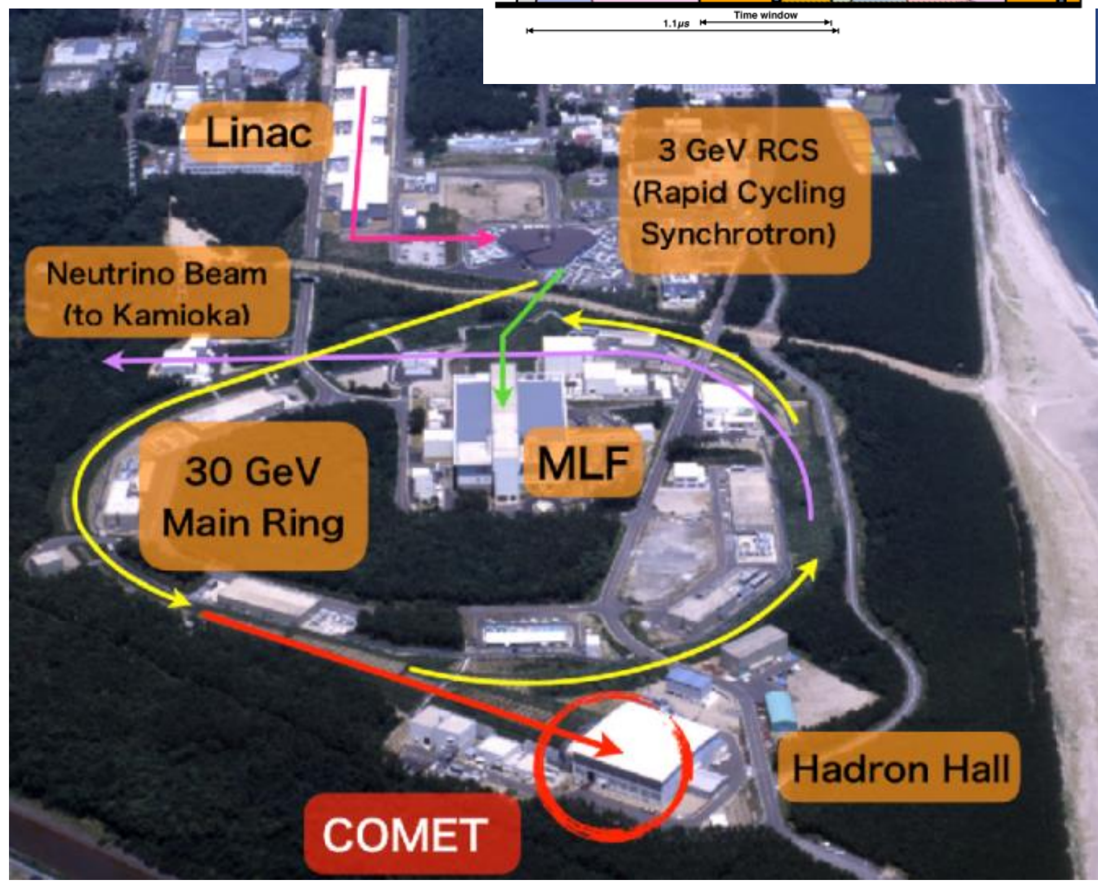
- Superconducting Magnet for COMET
- Radiation effects
- Irradiation Tests

COMET at J-PARC



- J-PARC E21
- search for mu-e conversion
- Pulsed proton beam at 8GeV from Main Ring
  - 56kW in Phase2
  - 3.2kW in Phase1
- New muon beamline is under construction at Hadron Experimental Facility



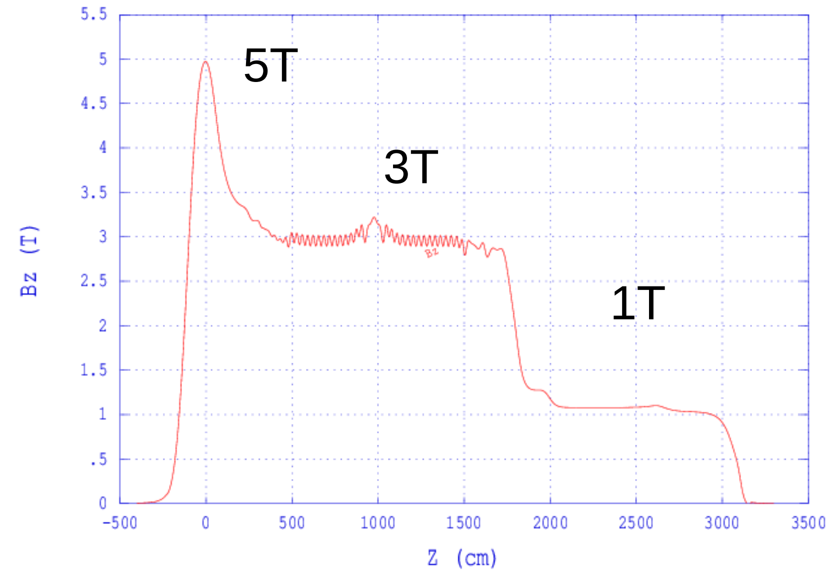
Physics Reach: $Br<10^{-16}$ (Phase2)
$<10^{-14}$ (Phase1)

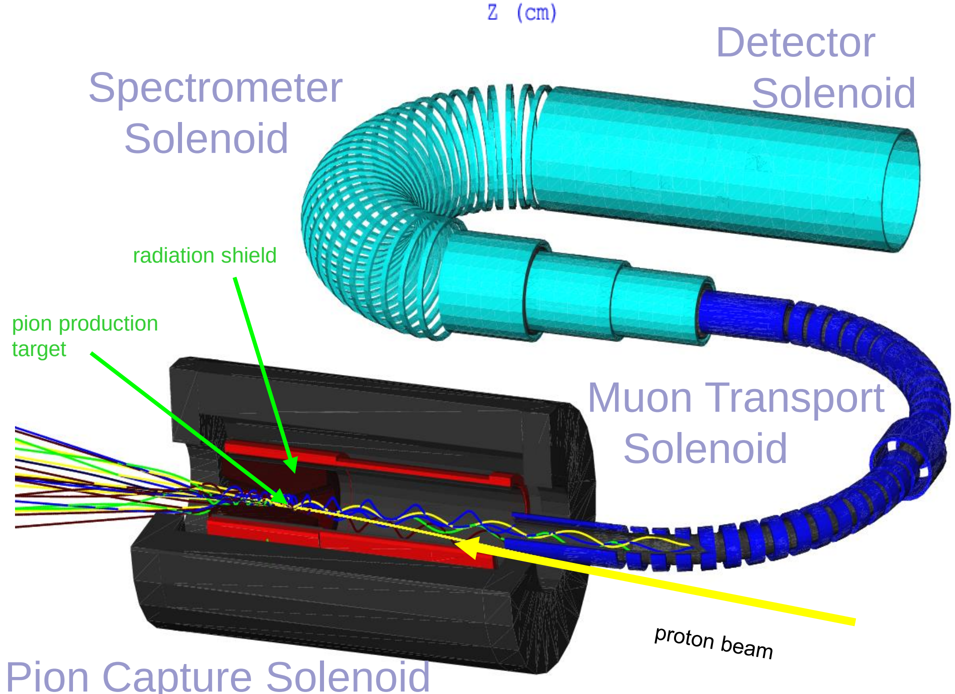
→ 2×10^{18} muon stops

→ 10^{11} μ^{-}/sec

COMET Magnet (Phase2)

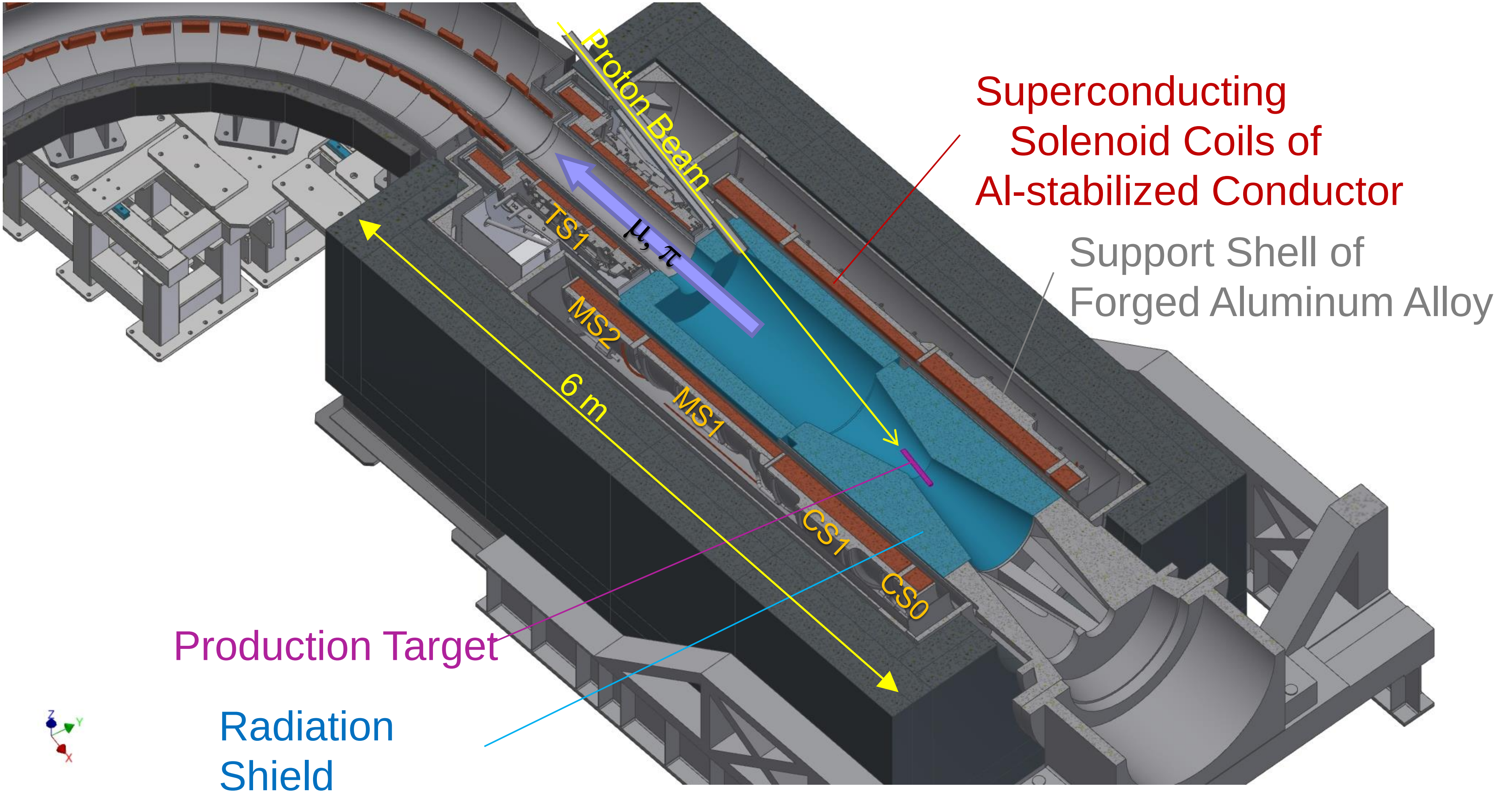
- Pion Capture Solenoid
  - *5T High field on Target*
  - *Tungsten shield inside*
- Muon Transport Solenoid
  - *3T curved solenoid*
  - *Correction dipole 0.03T~0.06T*
- Stopping Target Solenoid
  - *3T→1T graded field*
- Spectrometer Solenoid
  - *1T curved solenoid*
- Detector Solenoid
  - *1T curved solenoid*





COMET Superconducting Magnet System

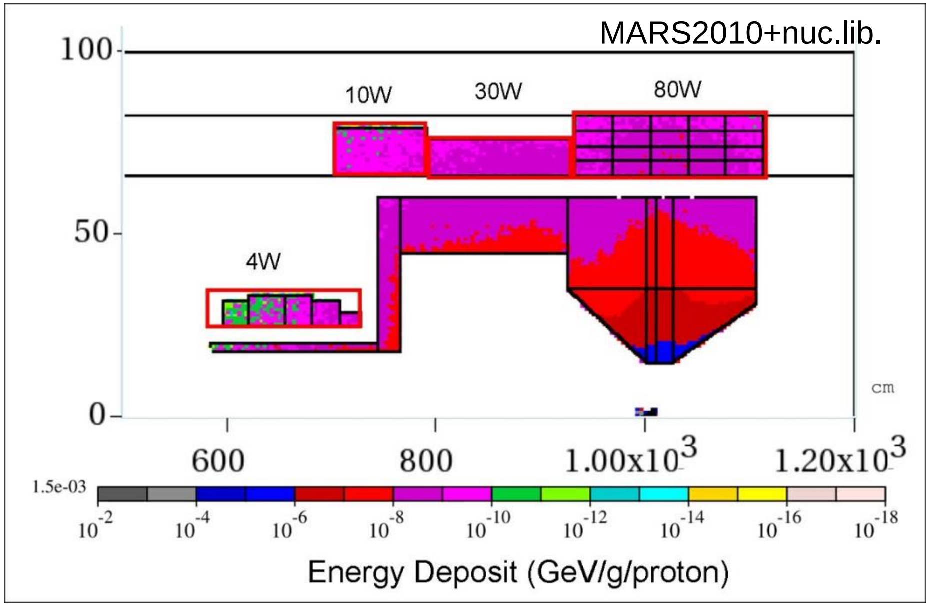
COMET Pion Capture Solenoid

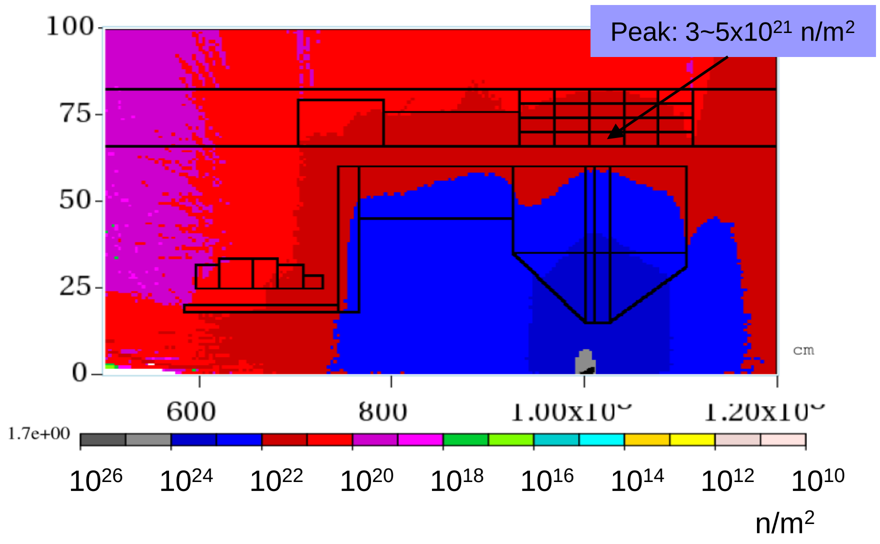


Key Issues on PCS

Nuclear Heating : >100W
Peak dose rate in Al : ~1MGy
Neutron fluence : $>10^{21}$ n/m^2

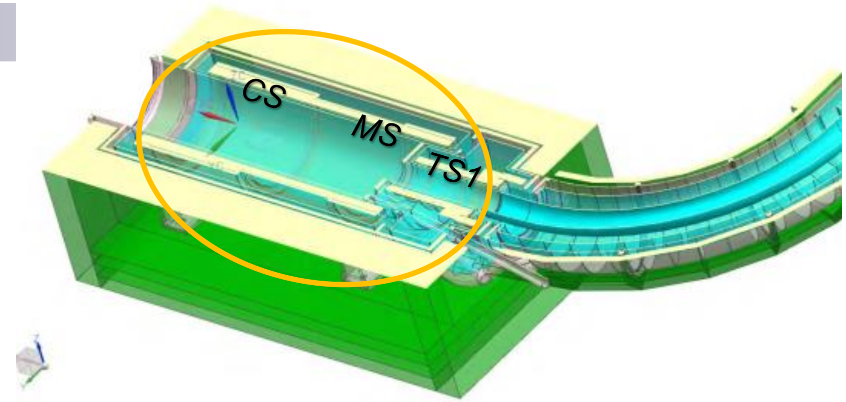
- Radiation tolerance of magnet materials is important
- Organic material
  - Insulation, structure
  - Strength
  - Out gas
- Metal
  - Cooling path, stabilizer
  - Electrical conduction
  - Thermal conduction
- Radioactivation of He





Coil Structure (Pion Capture Solenoid)

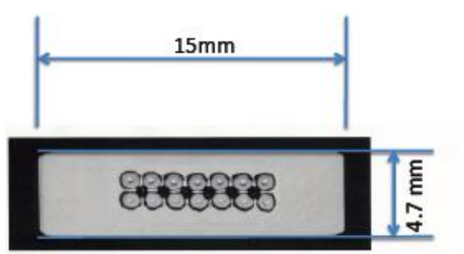
- Aluminum stabilized SC cable
  - for less nuclear heating (max. 35mW/kg)
- Radiation resistant insulator, resin
- Pure aluminum strips in between layers
  - to cool down a coil inside



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 mm^2 (without insulation) 15.3×5.0 mm^2 (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)
Coil length	~1.6 m (CS0+CS1) ~1.4 m (MS1), ~0.7m(MS2), ~1.6 m (TS1a~TS1f overall)
Coil layers	9 (CS0+CS1) 5 (MS1), 7 (MS2) 1~6 (TS1a~TS1f)
Quench protection	active quench back heater

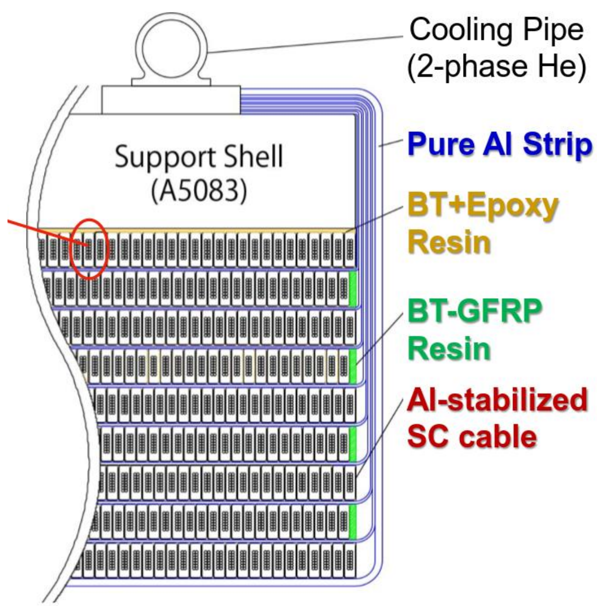
[a] T_{cs} is critical temperature at the maximum temperature.



Al stabilized SC cable

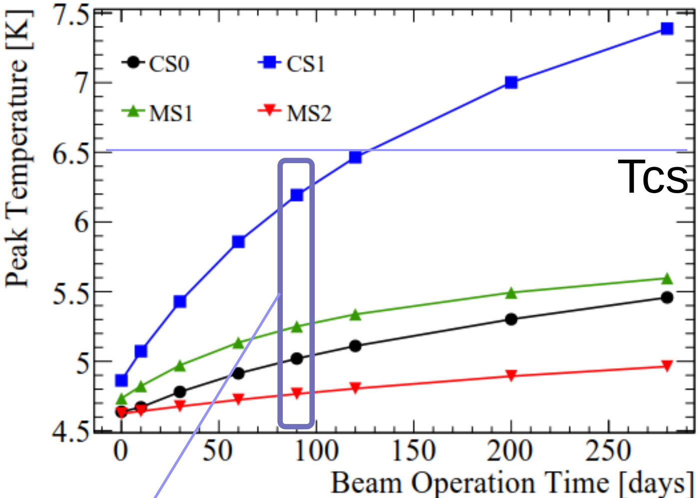
- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

CS coil structure

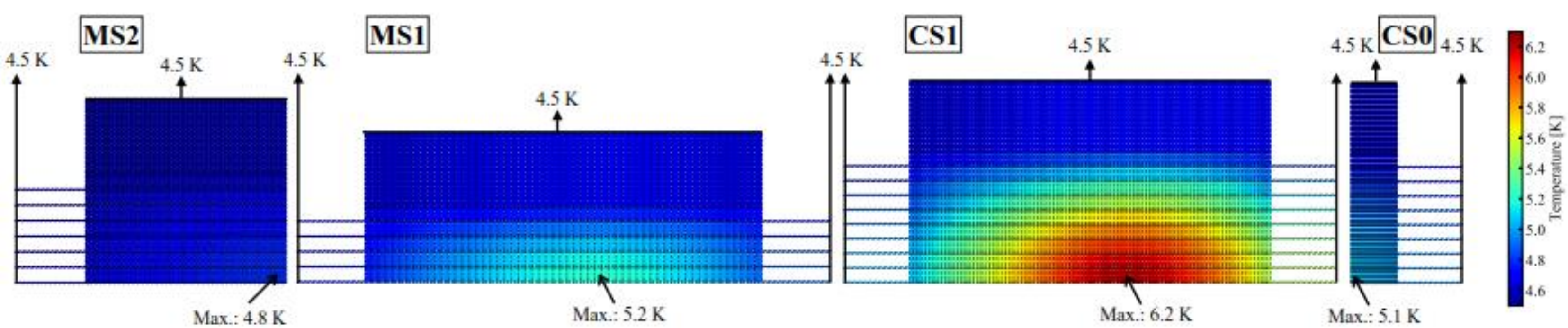


Effects of thermal conduction degradation
- Coil Temperature during Beam Operation

- Peak temperature in coils is estimated assuming irradiation by 56kW beam operation
- Coils in Pion Capture Solenoid will be heat up by irradiation (max. 35mW/kg)
- Temperature will rise as thermal conductivity degrades by irradiation
- Irradiation damage in aluminum can be recovered perfectly by thermal cycling to room temperature.



peak dose ~10^{21} n/m^2



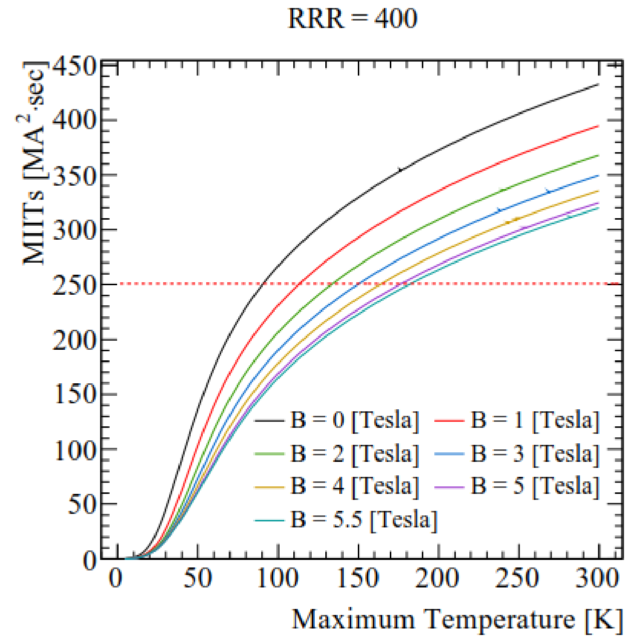
Y. Yang et al., IEEE Trans. App. Supercond., 28(3), 4001405 (2018).

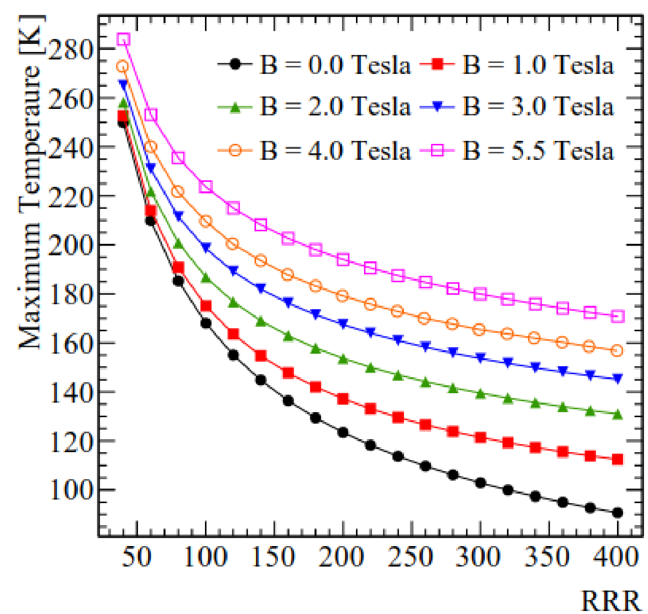
Effects of Stabilizer Degradation

- RRR of Al stabilizer will decrease by irradiation.
  - induced resistivity in Al
    ~ 0.3 nΩm @10^{21} n/m^2 → RRR<100
- Peak temperature at quench is estimated with MIITs
  - I=2700A, L=12.69H, Rdump=0.185Ω
    → MIITs=250 MA^2s

$$MIITs = \int_0^{\infty} I(t)^2 dt = \int_{4.2\,K}^{T_{max}} \frac{C(T)}{R(T)} dT$$

$$I(t) = I_0 exp\left(-\frac{R_{dump}}{L} t\right)$$





Simulation of Temperature Rise at Quench

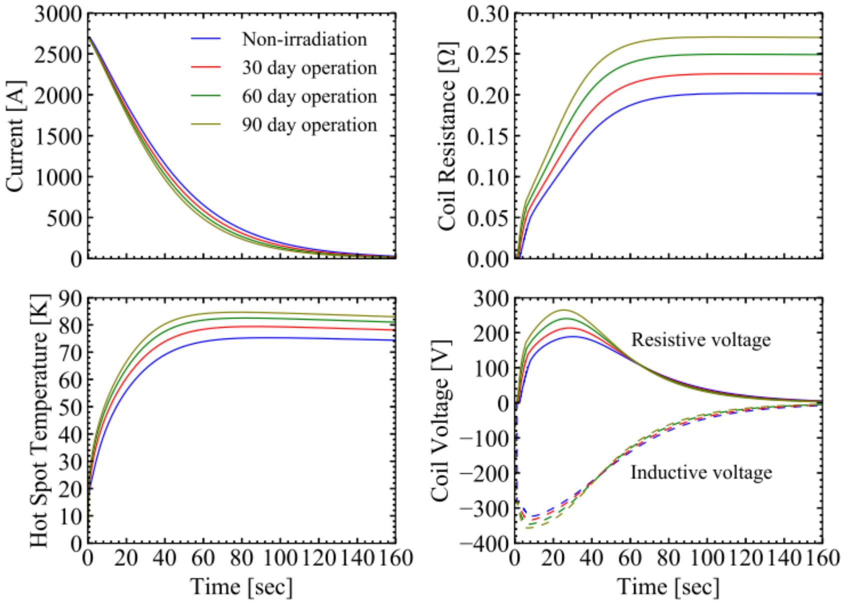


Fig. 5. Predicted current, coil resistance, temperature at hot spot and coil voltage after a accidental quench is occurred at varied beam operation time. The dashed line indicates the inductive voltage.

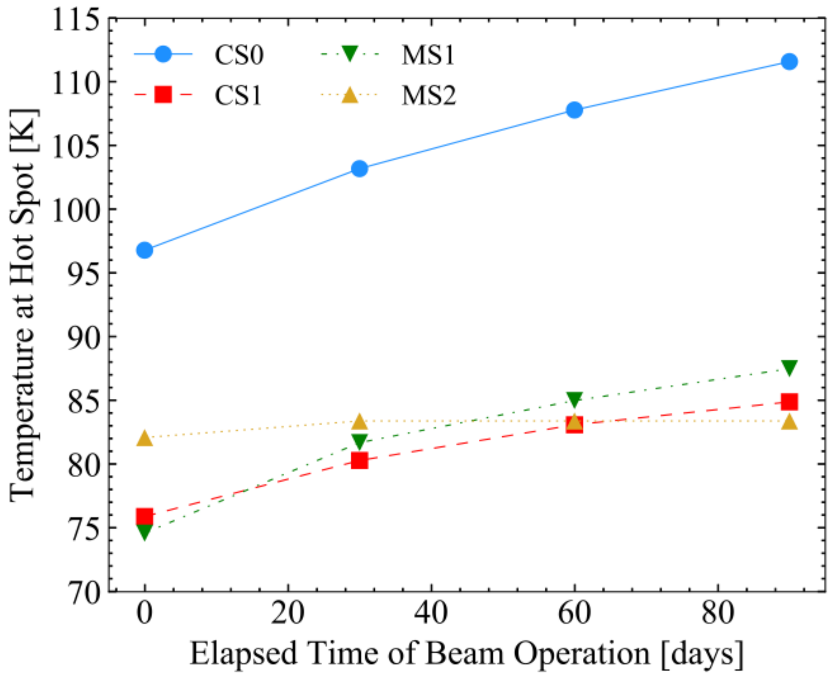


Fig. 6. Maximum temperature at hot spot for CS0 (blue line), CS1 (red line), MS1 (green line) and MS2 (golden line) coil as a function of beam operation time.

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

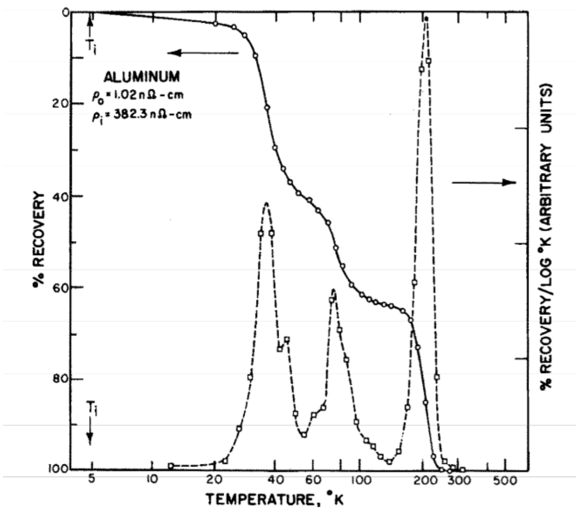
Irradiation Tests of Stabilizer

- Reactor Neutron at KUR
- Protons at J-PARC

Pure Metal Degradation by Reactor Neutrons

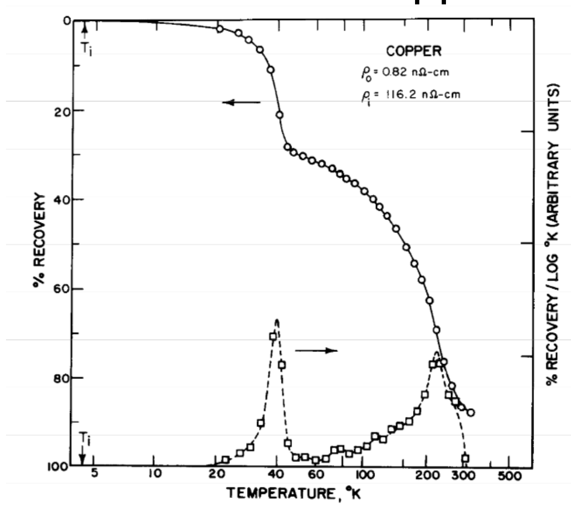
Recovery after irradiation
$2x10^{22}$ n/m^2 (E>0.1MeV)

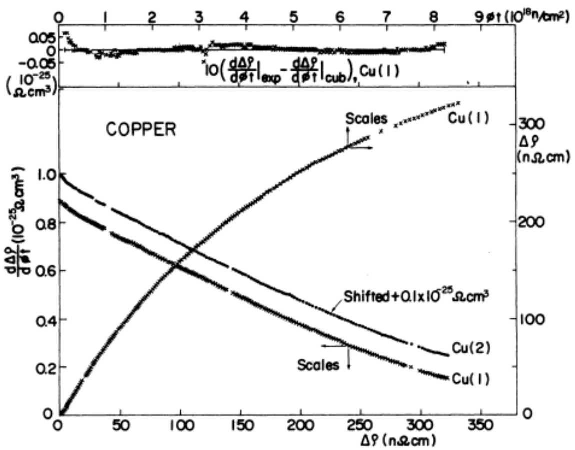
Aluminum

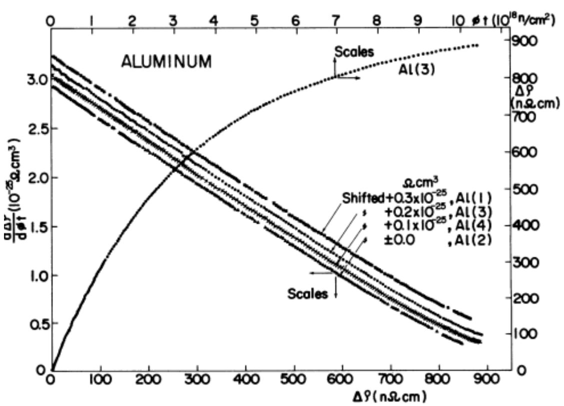


- Electrical resistivity increase with reactor neutrons
  - fast neutrons >~0.1MeV
- Irradiation damage can be recovered by annealing.
  - perfect recovery in Al
- Effect of impurity and strain?

Copper



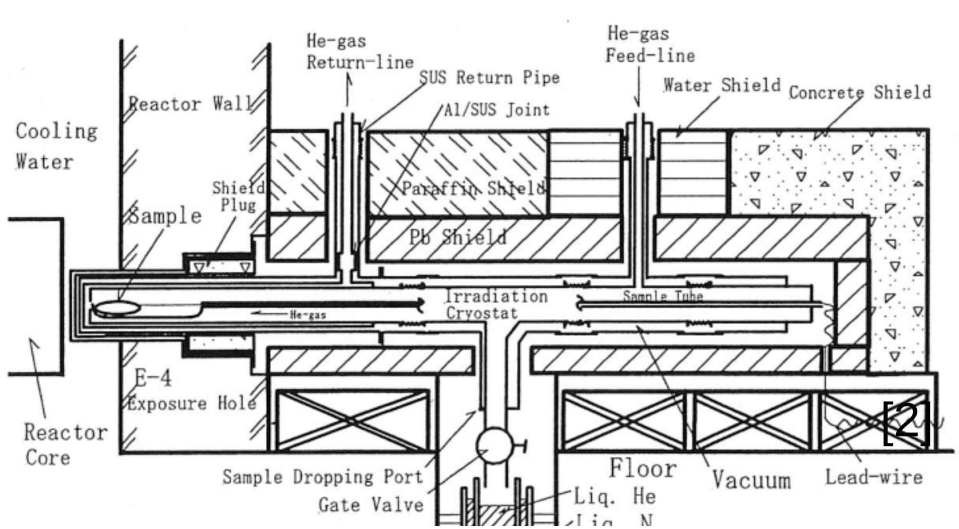




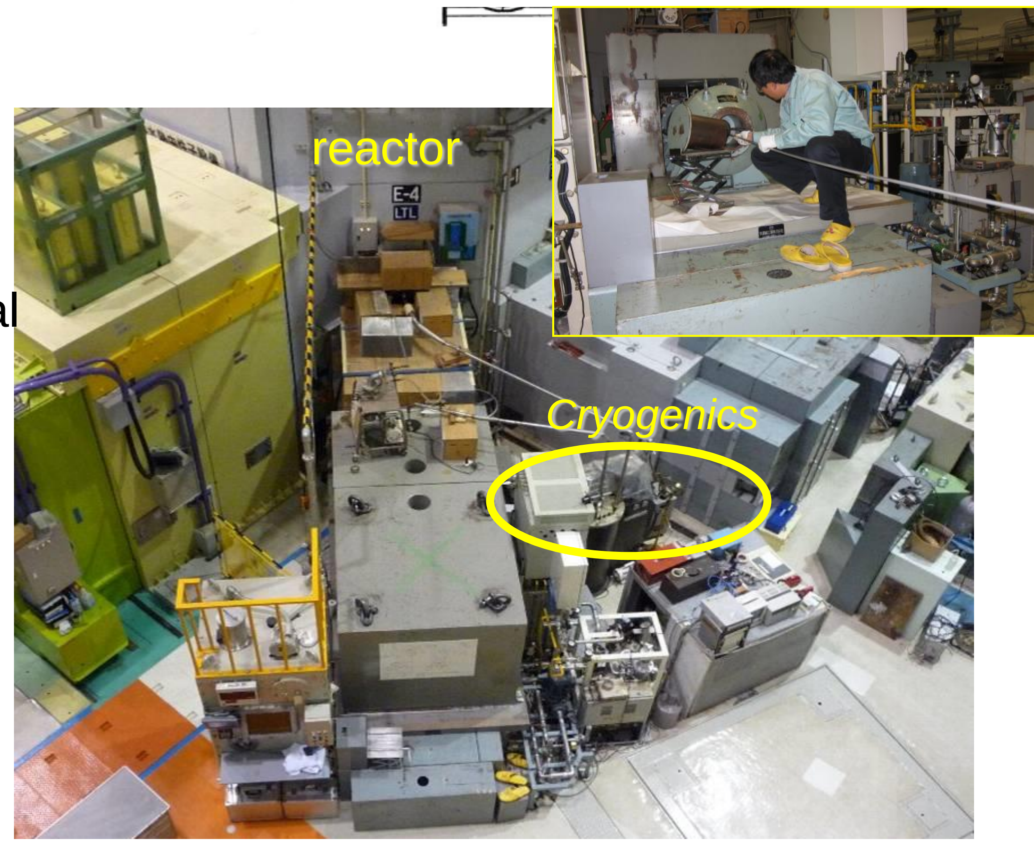
M. Nakagawa, K. Boning, P. Rosner, and G. Vogl, *Phys. Rev. B* **16**, pp. 5285-5302 (1977)

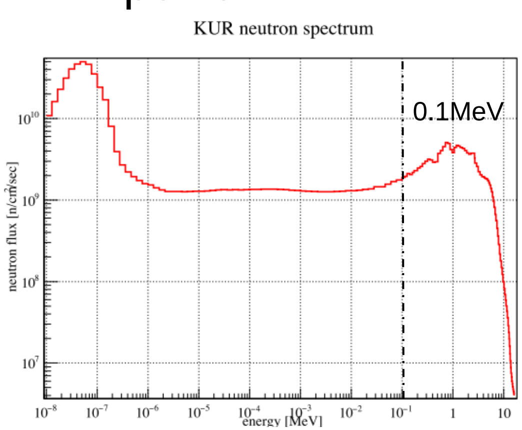
Low Temperature Irradiation Facility

- 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



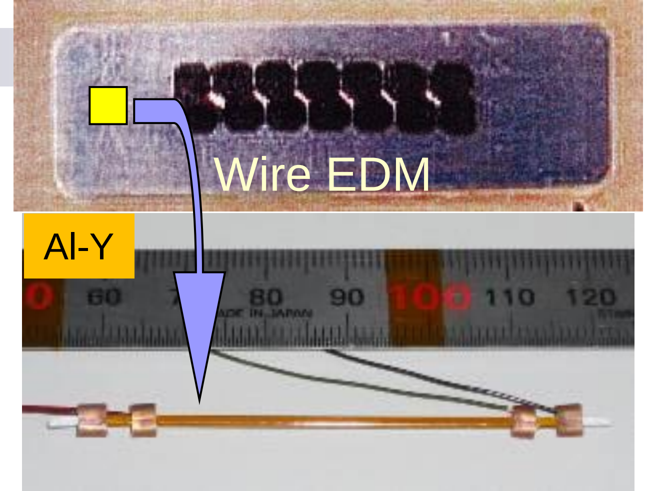
[2] M. Okada et al., NIM A463 (2001) pp213-219



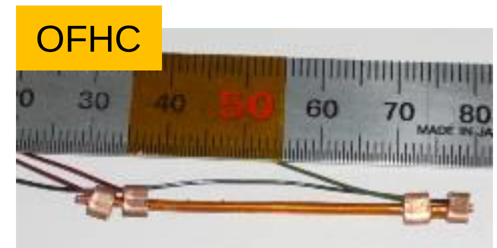


KUR-TR287 (1987)

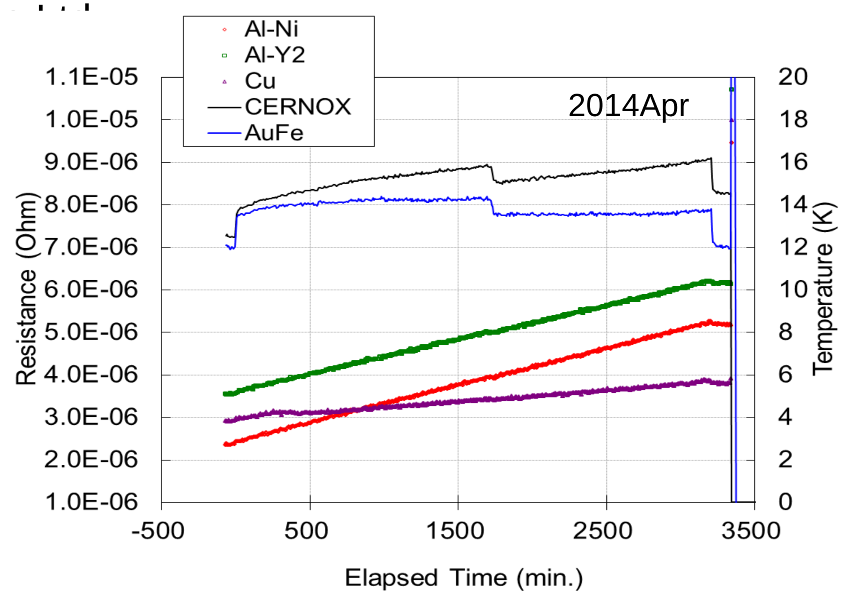
Irradiation Sample



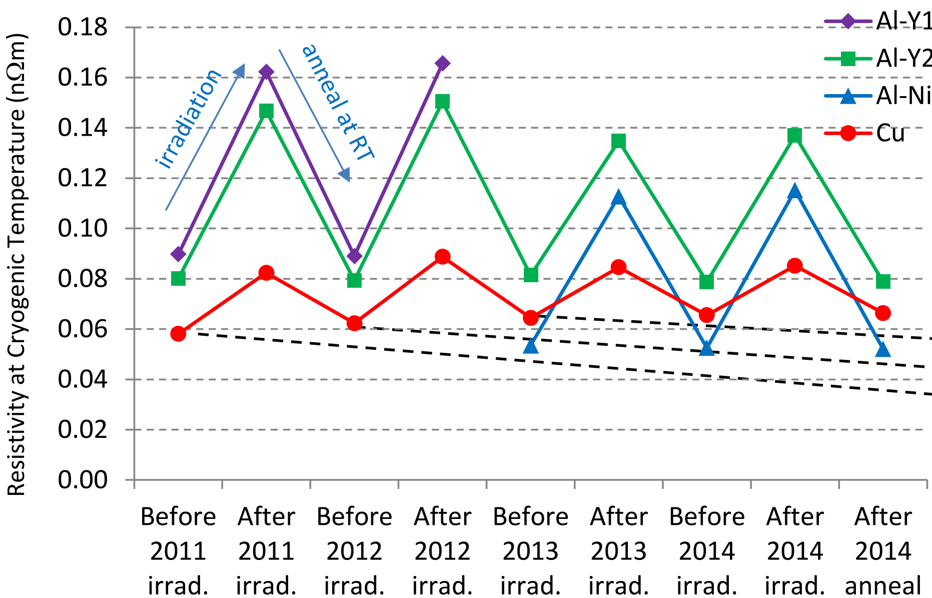
- Aluminum alloy
  - EDM cut from aluminum-stabilized SC cable
  - 1mmx1mmx70mm (45mm Vtap)
  - Al-CuMg
    - 5N Al + Cu(20ppm) + Mg(40ppm) with 10% cold work (RRR~450)
  - Al-Y
    - 5N Al + 0.2%Y with 10% cold work (RRR~330-360)
  - Al-Ni
    - 5N Al + 0.1%Ni with 10% cold work (RRR~560)

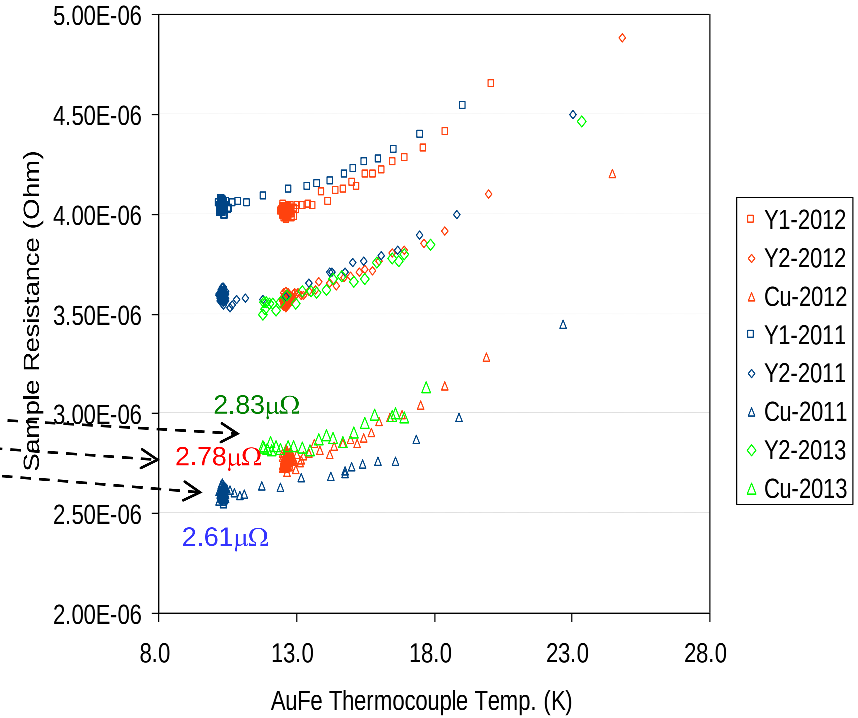


- Copper
  - OFHC for SC wire, provided by Hitachi Cabl
  - ϕ1mm x 50mm (35mm Vtap)
  - RRR~300
- 5N aluminum
  - provided by Sumitomo Chemical
  - ϕ1mm x 50mm (32mm Vtap)
  - RRR~3000
- Thermometer
  - CERNOX CX-1050-SD, CX-1070-SD
  - Thermocouple (AuFe+Chromel)



Irradiation / Annealing Effect in Electrical Resistance



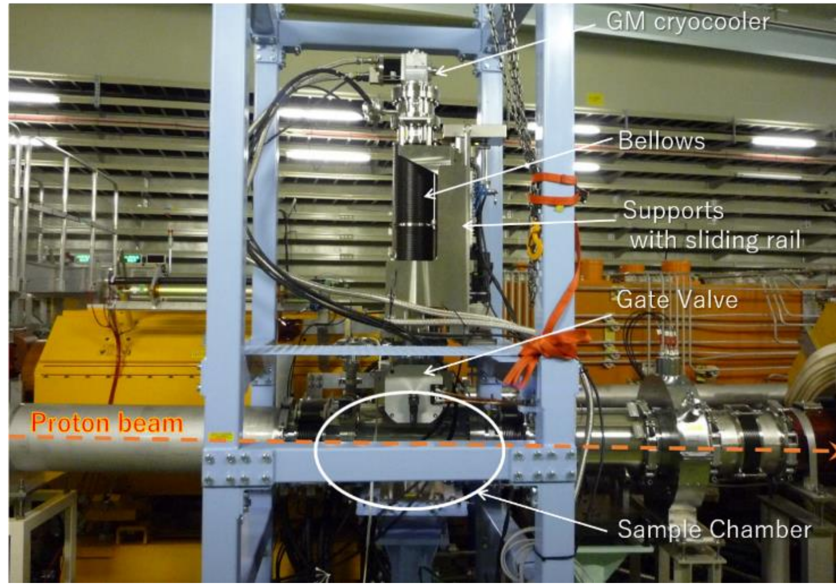


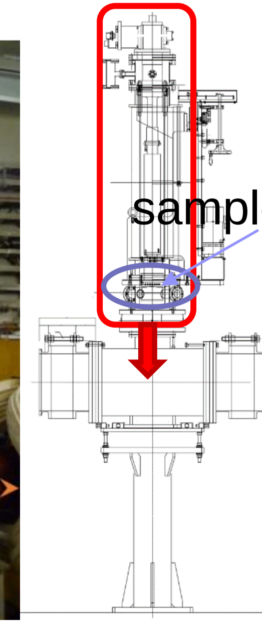
- Al: 0.03 nOhm.m for 10^{20} n/m^2
- Cu: 0.01 nOhm.m for 10^{20} n/m^2
- All Al samples show "full" recovery of electrical resistivity after thermal cycle to RT.

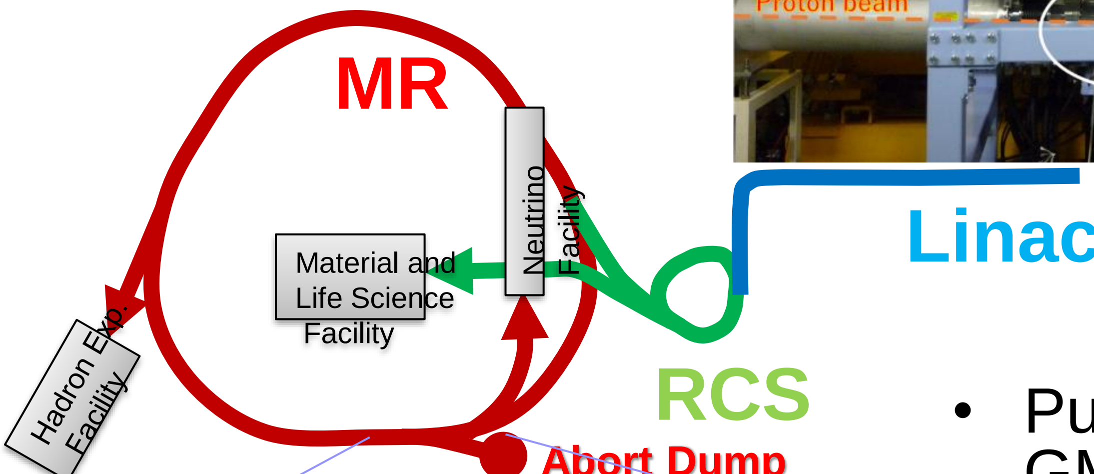
"Repetitive Irradiation Tests at Cryogenic Temperature by Neutrons and Protons on Stabilizer Materials of Superconductor," M. Yoshida et al., *IEEE Trans. Appl. Supercond,* 32(6), 7100405 (2022); doi:10.1109/TASC.2022.3178944

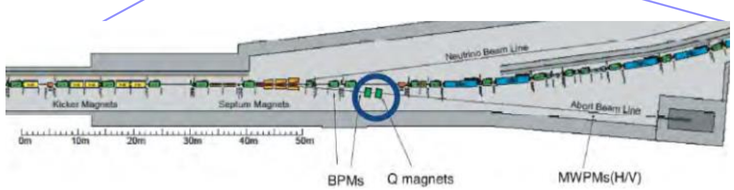
Proton irradiation test at J-PARC

- 3GeV-30GeV proton beam from MR
- Newly installed in 2019



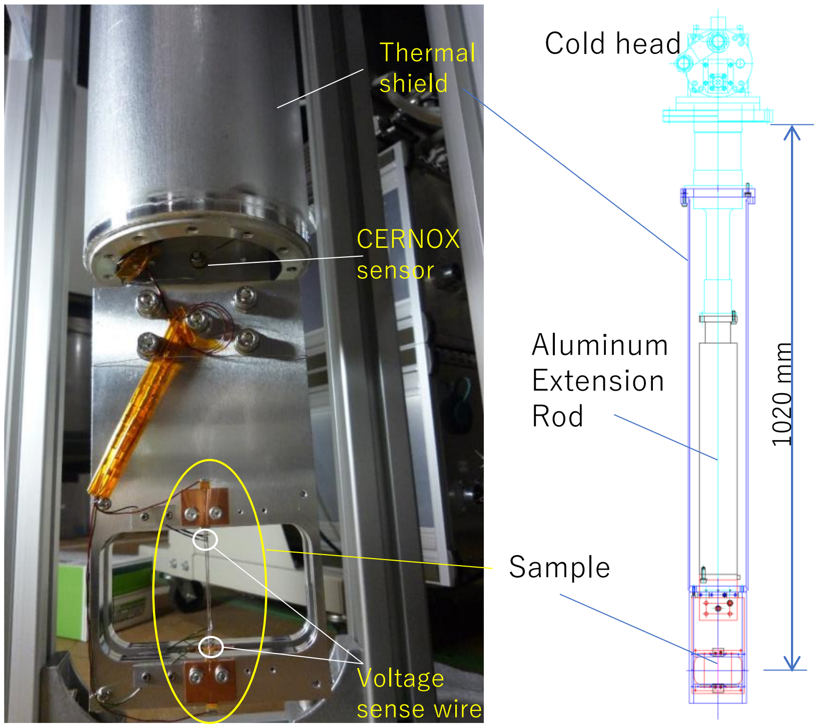


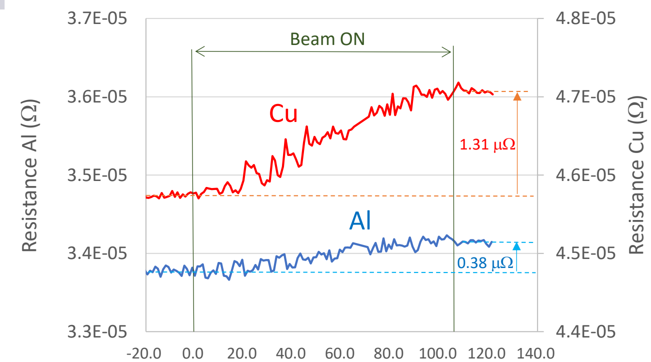


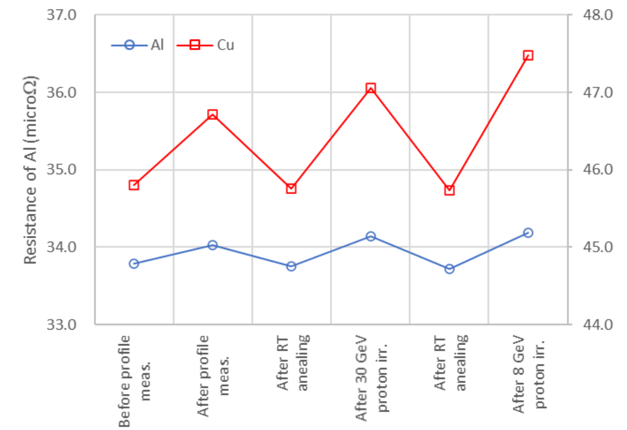


- Pure metal wire cooled by GM cryocooler
- Sample can be inserted to the beam line on demand.
    - remote handling

Proton Irradiation Test at J-PARC







	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 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

"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

Summary

- Radiation-tolerant superconducting magnet, Pion Capture Solenoid, is developed for COMET.
- Effect of irradiation damage in coils is estimated.
  - 10^{21} n/m^2 → RRR_Al<100
- Radiation effects in stabilizer are investigated by neutrons and protons.