COMET Superconducting Magnet

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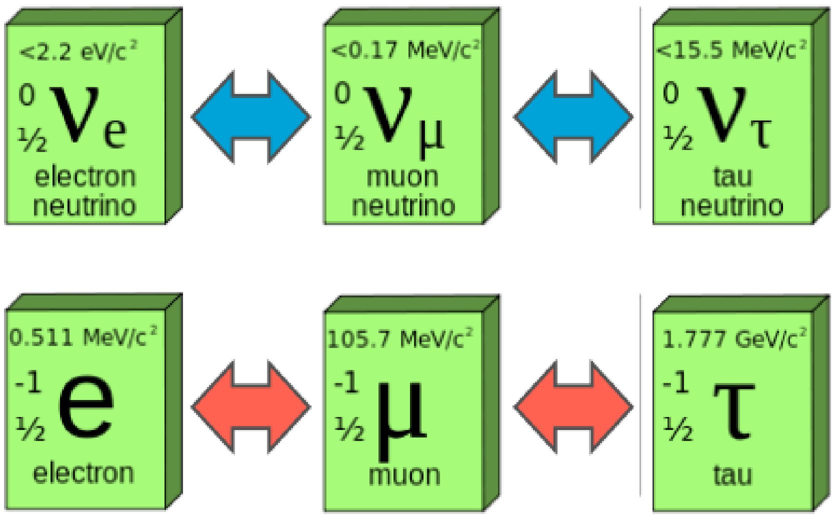
Contents

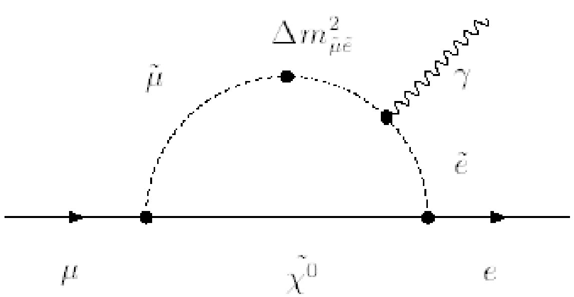
- COMET experiment
- Superconducting Magnet for COMET
- Radiation effects in Magnet Materials

Lepton Flavor Mixing

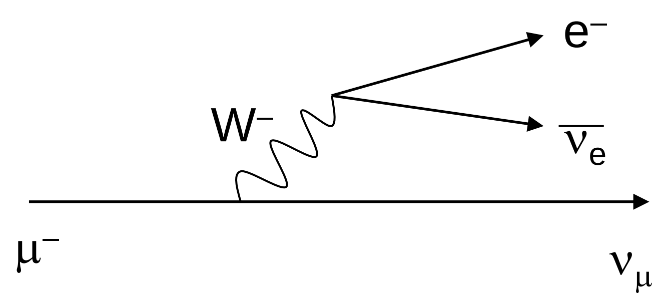


Neutrino Oscillation

Charged Lepton Mixing (No evidence so far)



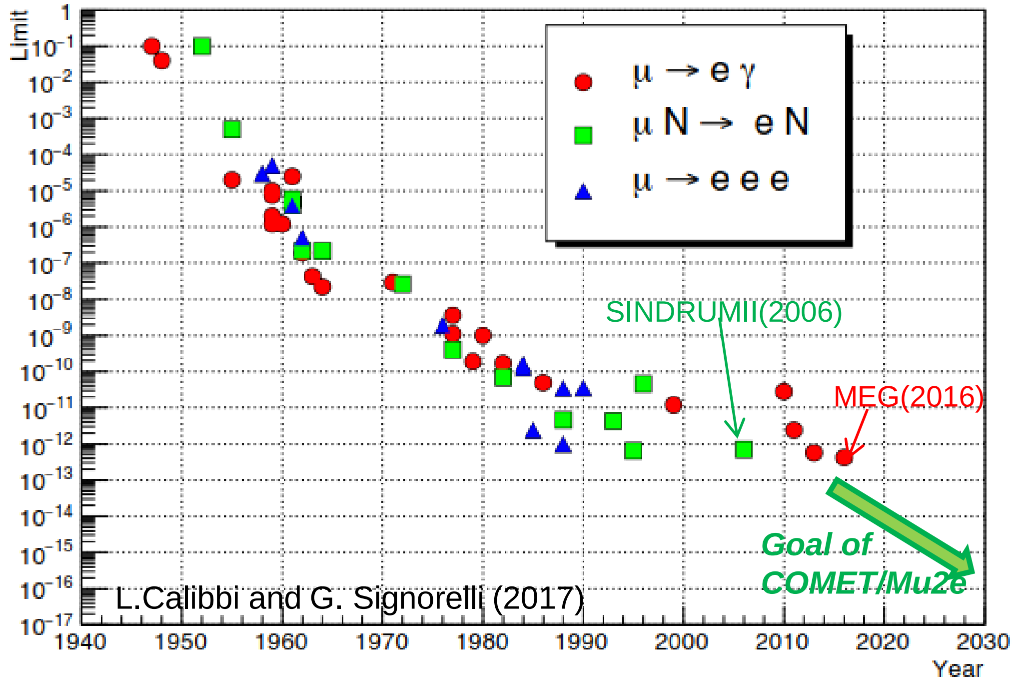
Muon decay in Beyond SM



Muon decay in SM

Searches for Charged Lepton Mixing

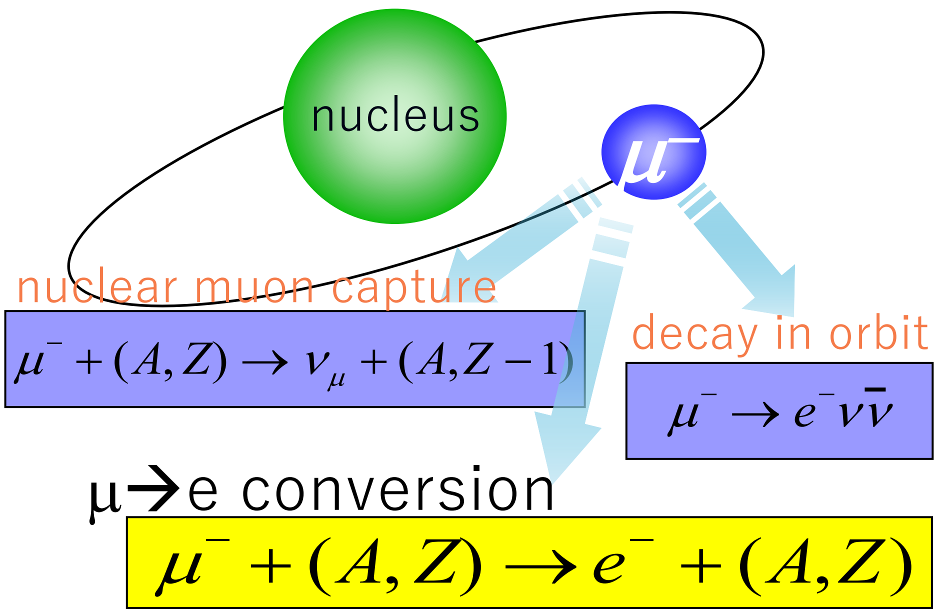
- Lepton flavor violation
  → Beyond standard model
- Muon plays important role in the searches
  - Low mass → High statistics
  - Long life → easy to handle



- $\mu \rightarrow e\gamma$
  $<4.2\times10^{-13}$(MEG2016)
- $\mu N \rightarrow e N$
  1/400 (Al) of $\mu \rightarrow e\gamma$
  Awaiting searches for $Br<10^{-16}$

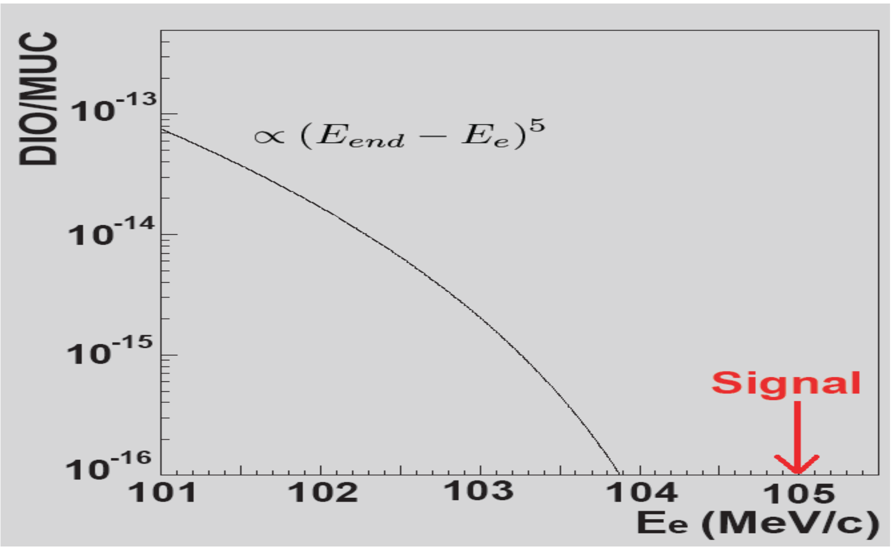
The COMET Experiment

- stopping μ^- → Muonic atom



$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu N \rightarrow e N)}{\Gamma(\mu N \rightarrow \nu N')}$$

Detect monoenergetic electrons from μ-e conversion



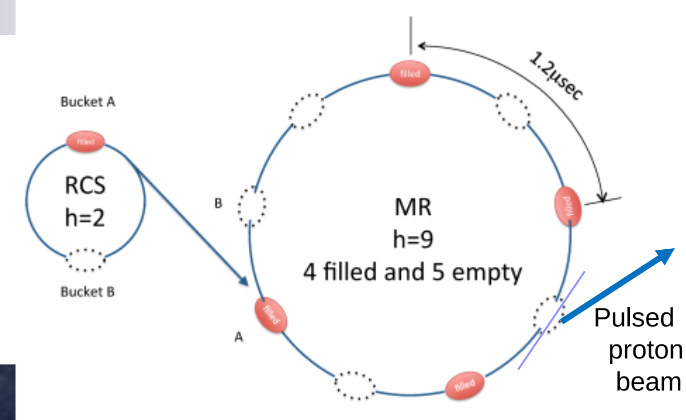
Physics Reach: Br<10^{-16} (PhaseII)
<10^{-14} (PhaseI)

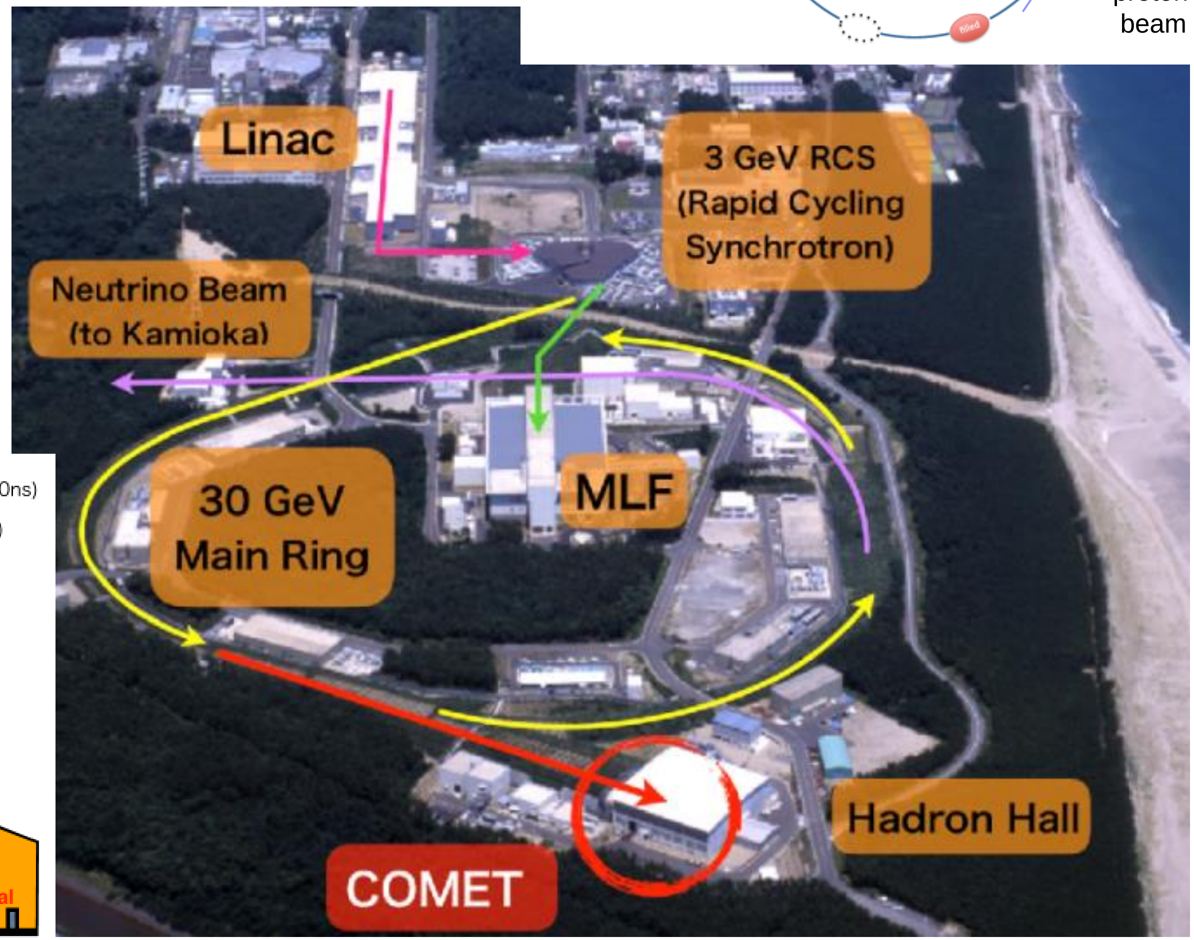
→ 2×10^{18} muon stops

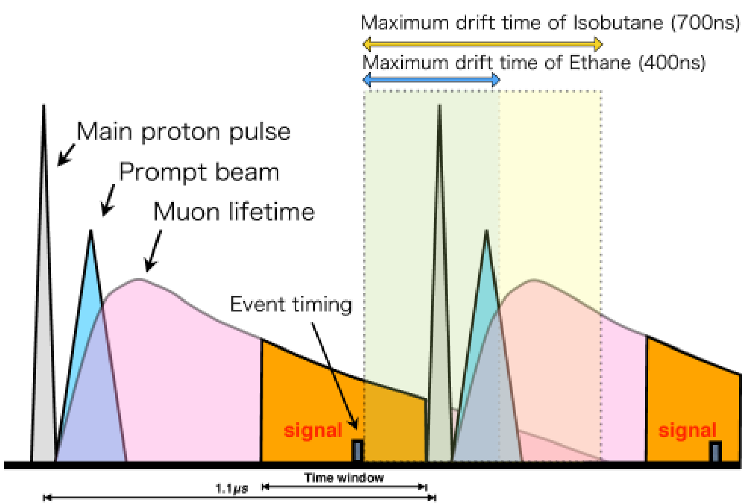
→ 10^{11} μ^-/sec

COMET at J-PARC

- J-PARC E21
- Pulsed proton beam at 8GeV from Main Ring
- New muon beamline is under construction at Hadron Experimental Facility

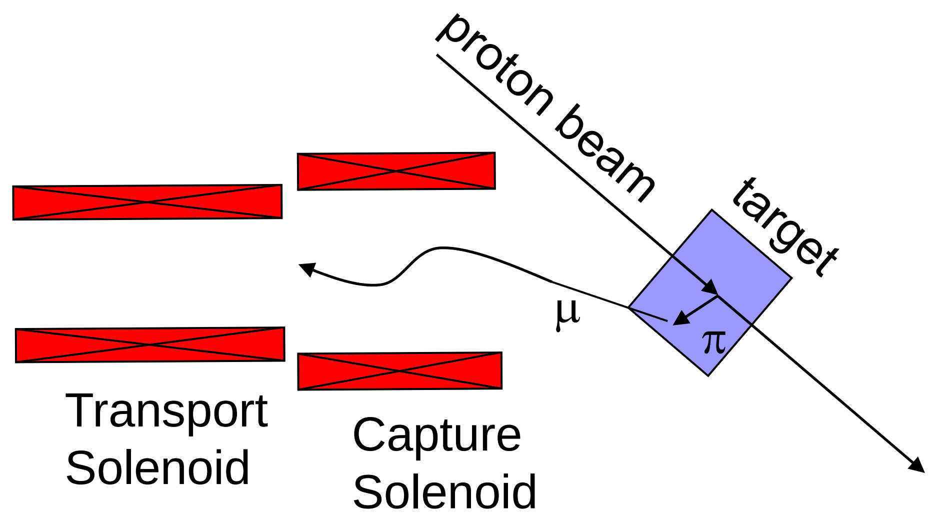






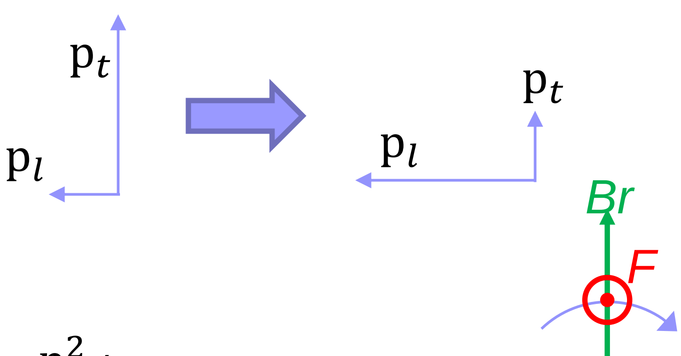
Muon Source

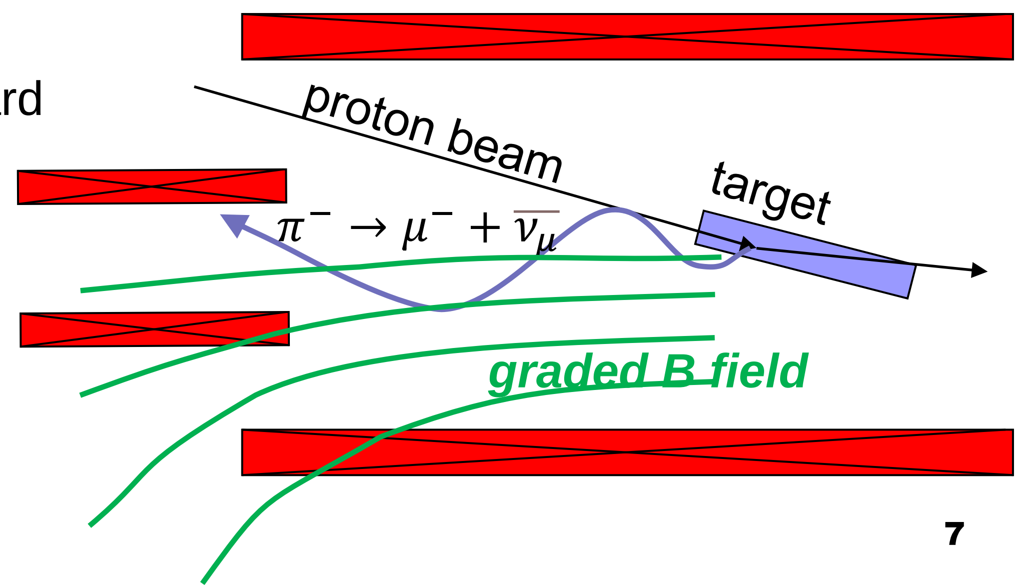
- Inject protons on target
- Trap secondary particles by magnetic field
- Transport pions, muons in long solenoid



Solenoid Focus

- charged particles in graded solenoid field are focused forward

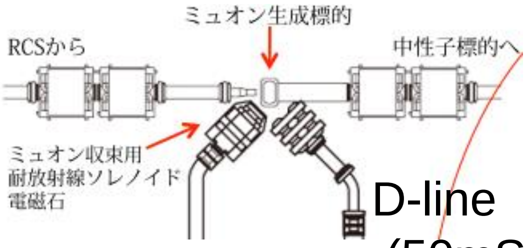




$$p_t^2/_B \propto p_t \times R = \text{const.}$$

High Intensity Muon Source

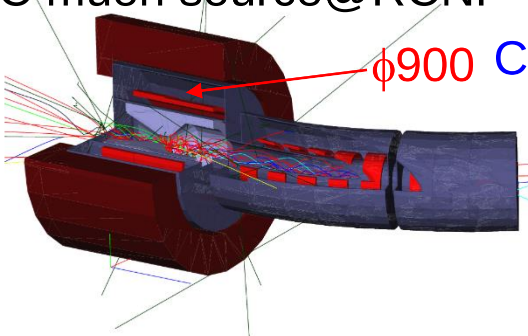
- Large aperture and strong magnetic field to capture π,μ
  - Radiation from production target
- Long solenoid to decay π, transport μ



D-line (50mSr)

MuSIC

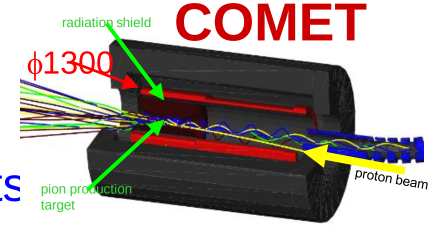
DC muon source@RCNP

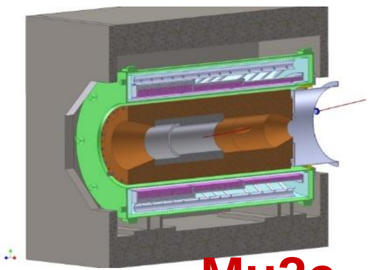


ϕ900 Cryogen-free magnets

- 400W proton beam (100W on target)
- pion capture system
- ~3x10^8 μ$^+$/s, ~10^8 μ–/s

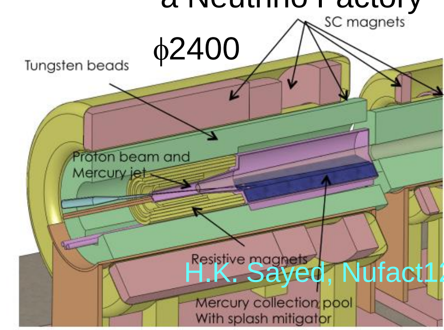
COMET



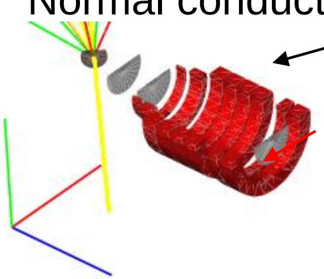


Mu2e
~ϕ1600

a Neutrino Factory



Normal conducting solenoid



SuperOmega

U-line@J-PARC MLF

- 1MW pulsed beam (50kW(5%) on target)
- 400mSr
- ~4x10^8 μ$^+$/s, ~10^7 μ$^-$/s

ϕ380

Superconducting Curved Solenoid

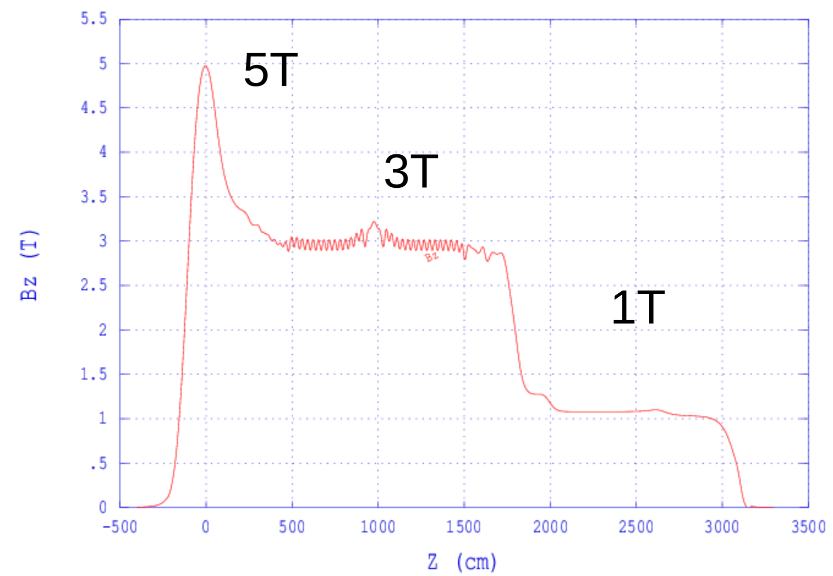
Goal: 10^{11} μ^-/sec

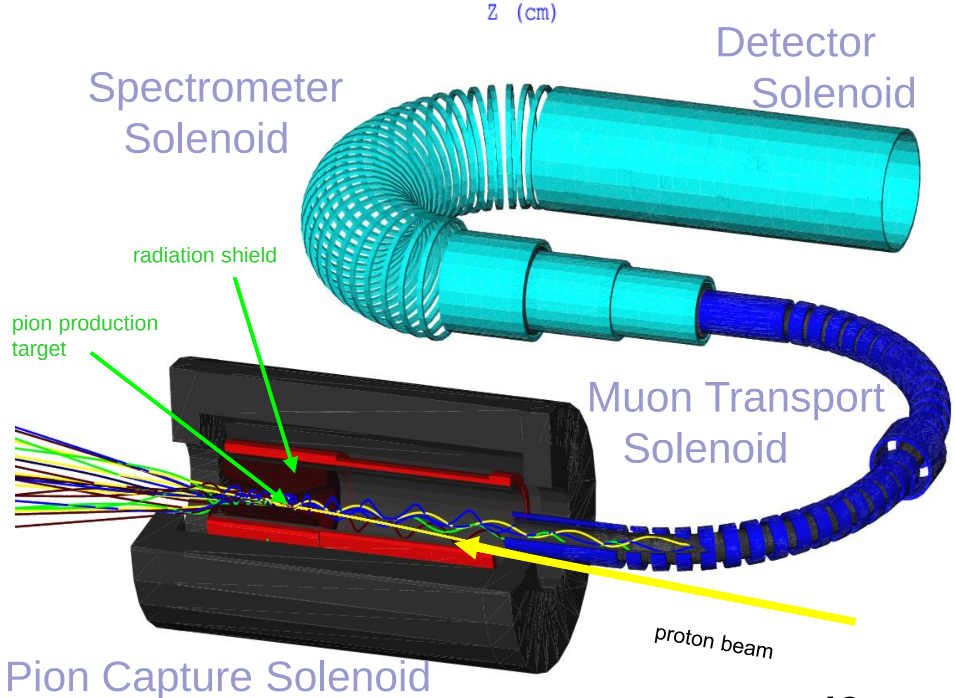
Requirements on COMET muon beamline

1. Large acceptance to collect pions from production target
   - High field on pion production target
   - Graded field to focus pions forward
2. Reduce pion contamination / high energy muons
   - Long solenoids from production to muon stopping target
   - Curved solenoid to select momentum / charge
3. Large signal acceptance. Reduce decay-in-orbit BG
   - Graded field on muon stopping target
   - Curved solenoid to select 105MeV/c electrons

COMET Magnet (Phase2)

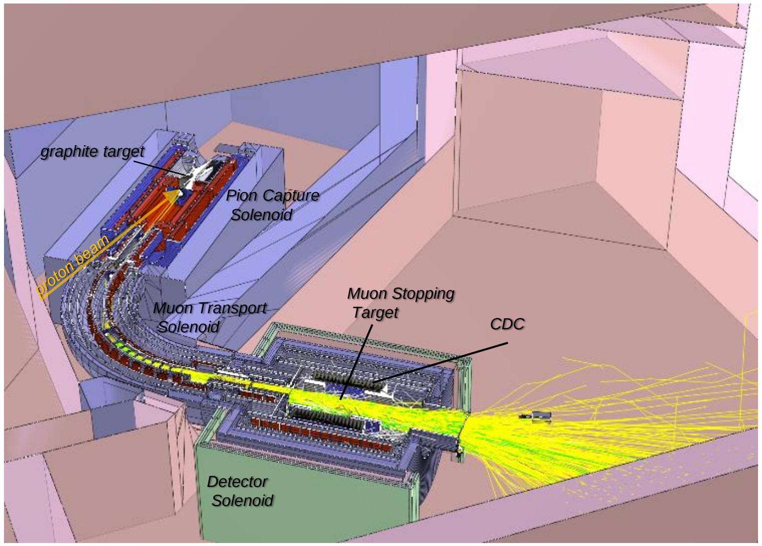
- Pion Capture Solenoid
  - *5T High field on Target*
  - *Tungsten shield inside*
- Muon Transport Solenoid
  - *3T curved solenoid*
  - *Correction dipole 0.03T~0.06T*
- Stopping Target Solenoid
  - *3T→1T graded field*
- Spectrometer Solenoid
  - *1T curved solenoid*
- Detector Solenoid
  - *1T curved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

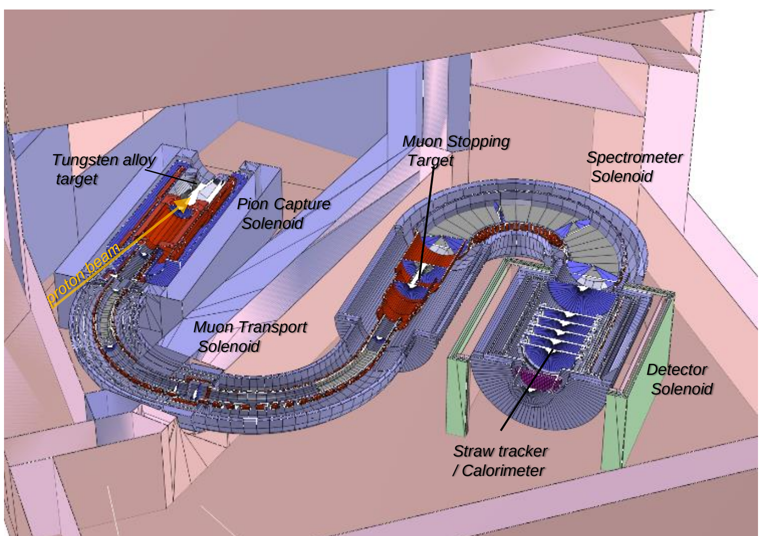




COMET Superconducting Magnet System

Staging Approach





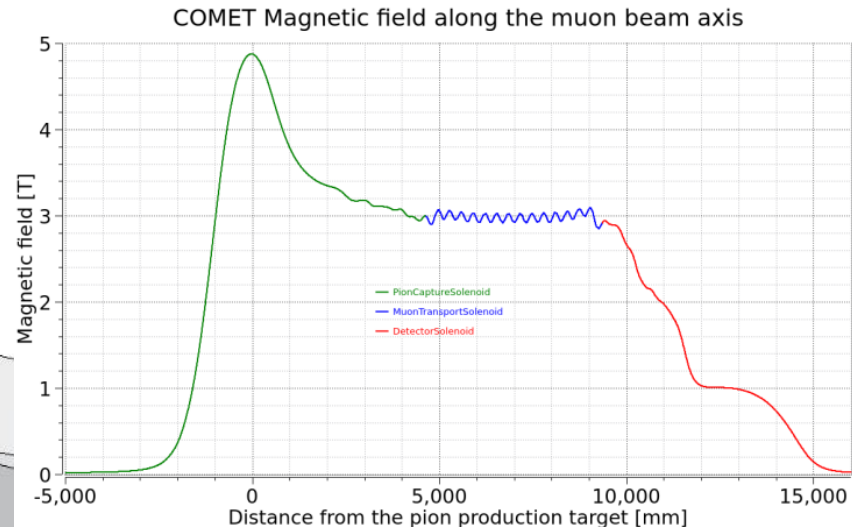
Phase-I

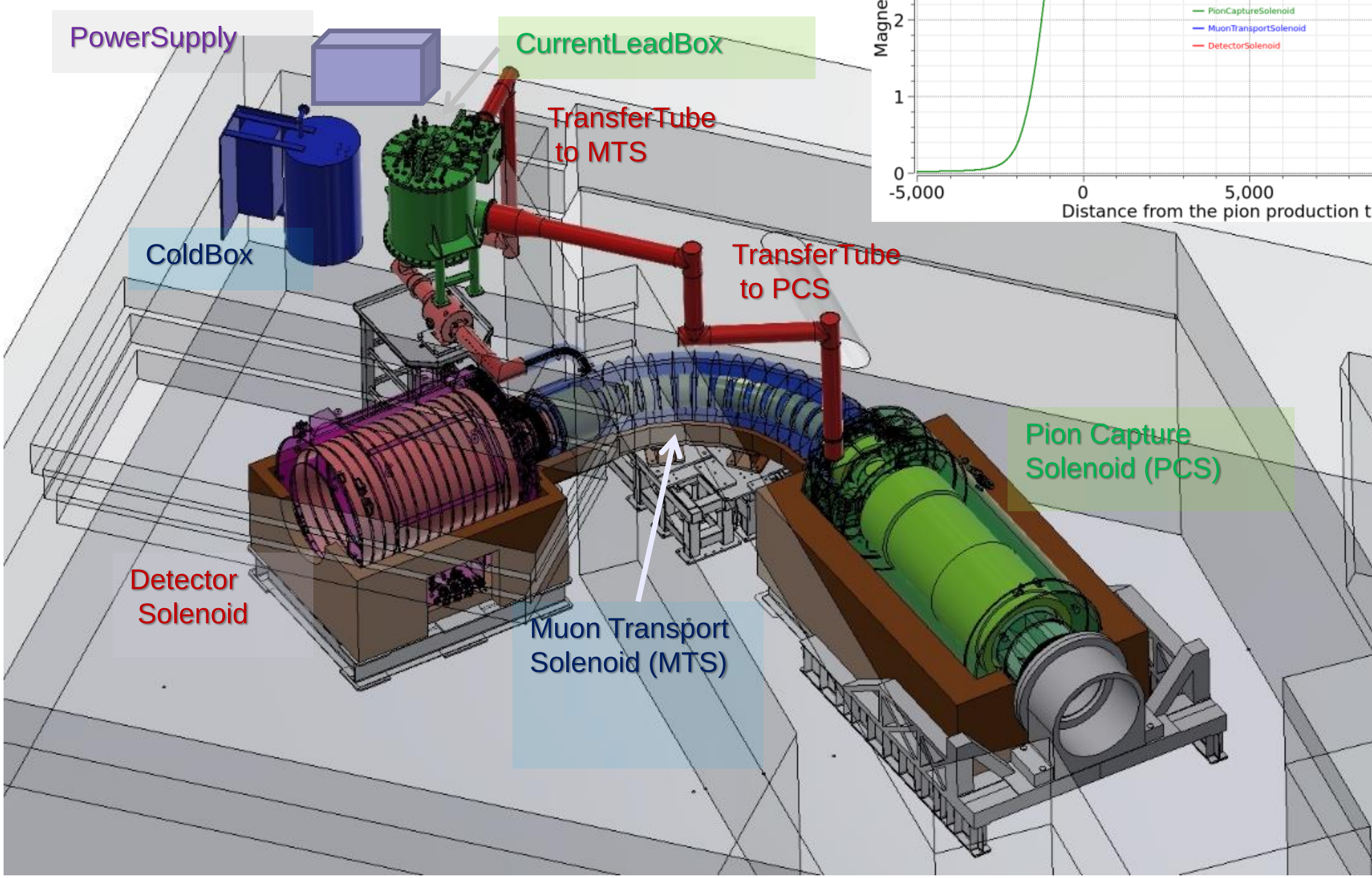
- 3.2kW proton beam (8GeVx0.4μA)
- Sensitivity Br<10^{-14}
- Graphite target
- Pion Capture Solenoid + 90deg curved solenoid
- Cylindrical drift chamber + trigger hodoscope
- Physics run will be in FY2024

Phase-II

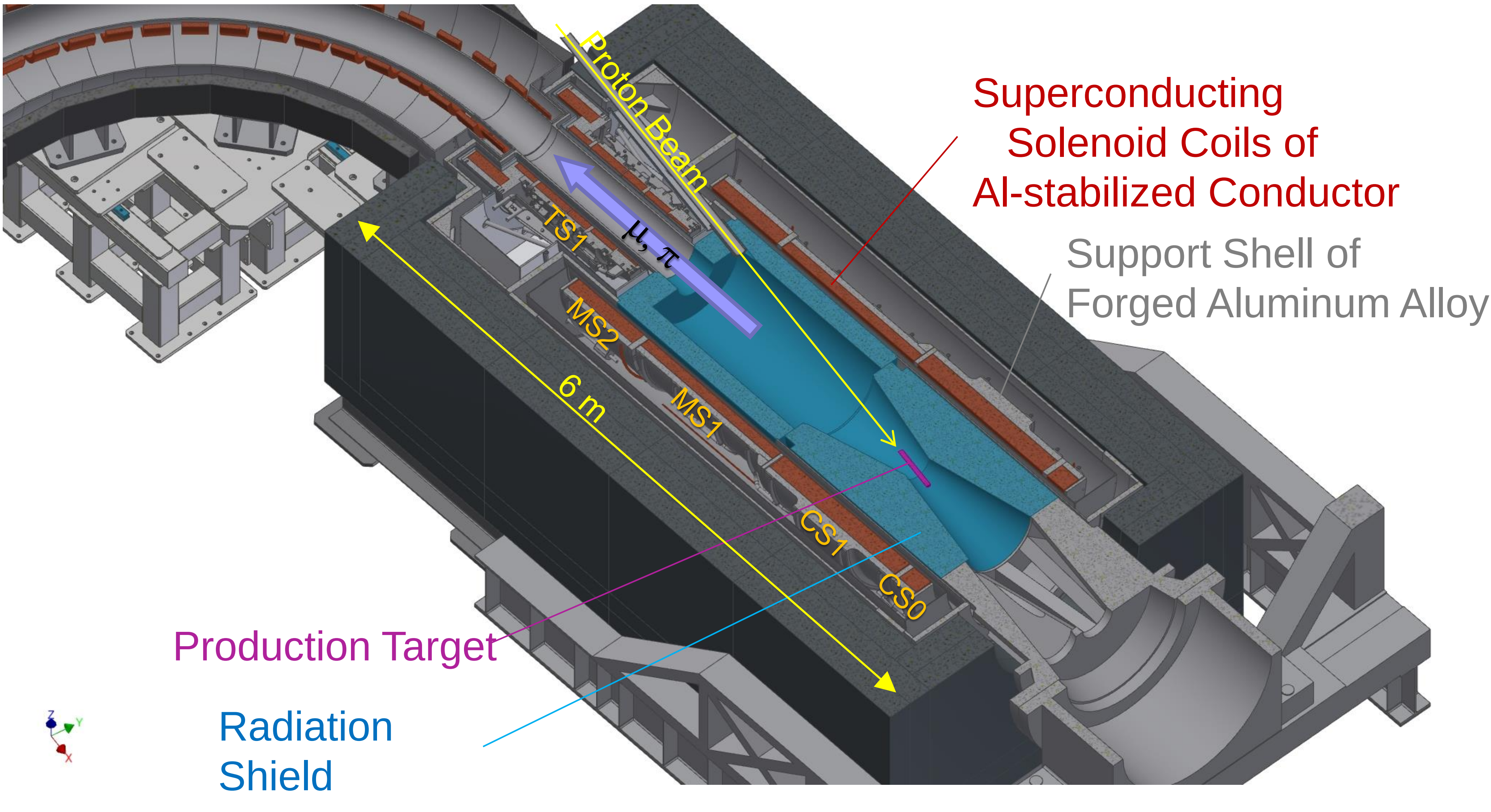
- 56kW proton beam (8GeVx7μA)
- Sensitivity Br<10^{-16}
- Tungsten alloy target
- Pion Capture Solenoid + 180deg curved solenoid + Spectrometer Solenoid
- Straw tracker + calorimeter

COMET Magnet System (Phase-I)





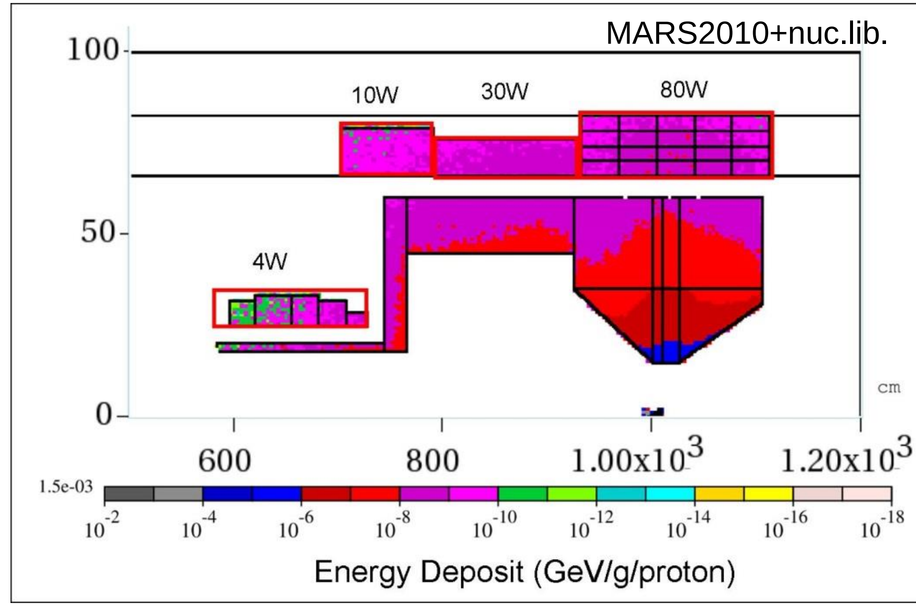
COMET Pion Capture Solenoid

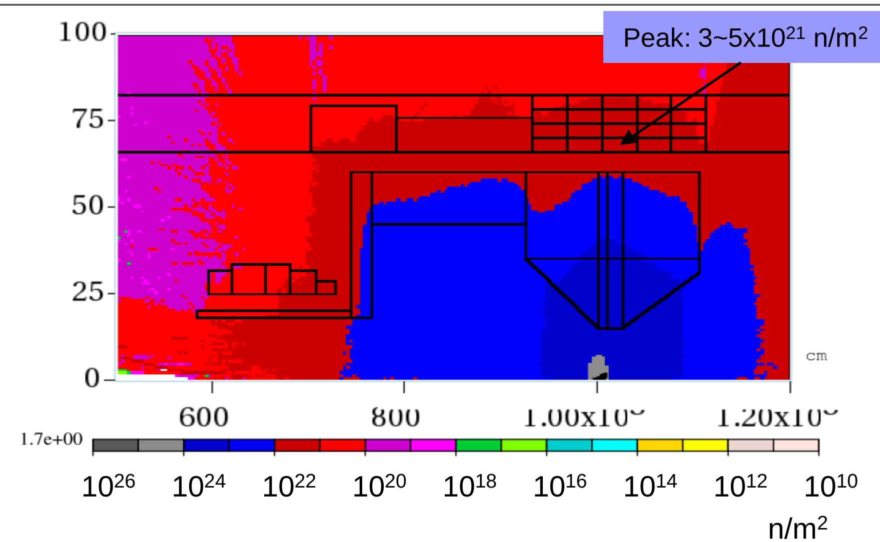


Key Issues on PCS

- 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

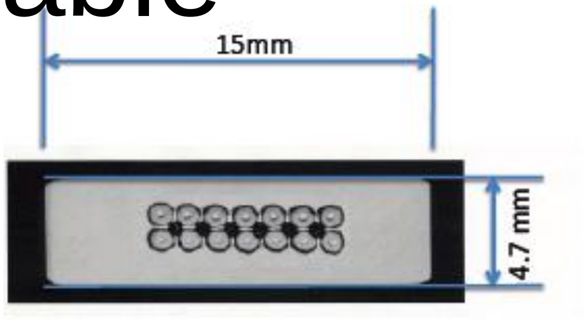
Nuclear Heating : >100W
Peak dose rate in Al : ~1MGy
Neutron fluence : $>10^{21}$ n/m^2



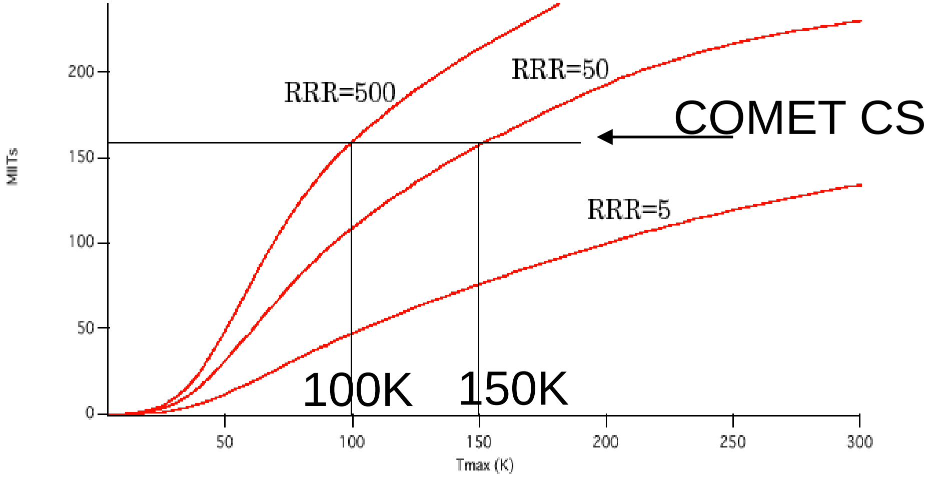


Aluminum-stabilized Superconducting Cable

- Developed for detector solenoids
  - needs transparency for particles
- Small nuclear interaction cross section
  → Small internal heating
- Low residual resistivity
  - stabilizing
  - quench protection
- High-strength
  - Doping additives
  - Hardened by cold work

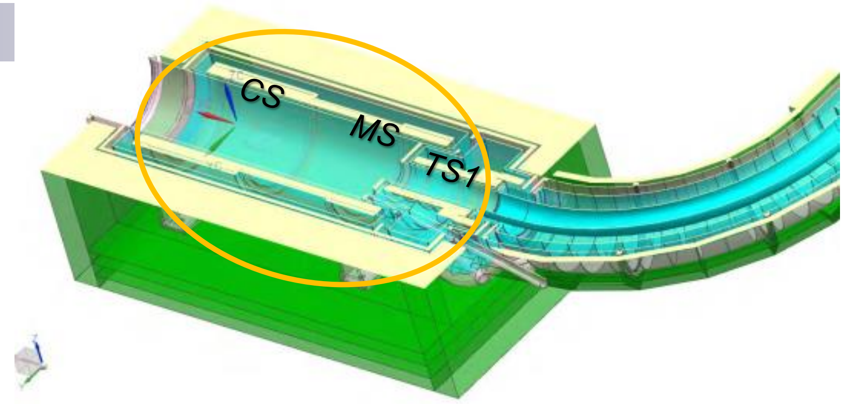


- Size: 4.7x15mm
- Yield strength@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1



Coil Structure (Pion Capture Solenoid)

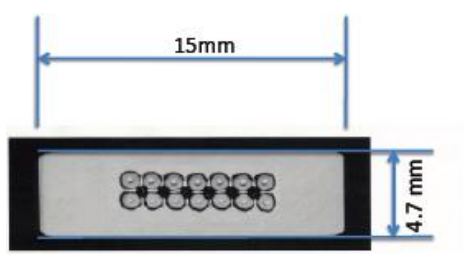
- Aluminum stabilized SC cable
  - for less nuclear heating (max. 35mW/kg)
- Radiation resistant insulator, resin
- Pure aluminum strips in between layers
  - to cool down a coil inside



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

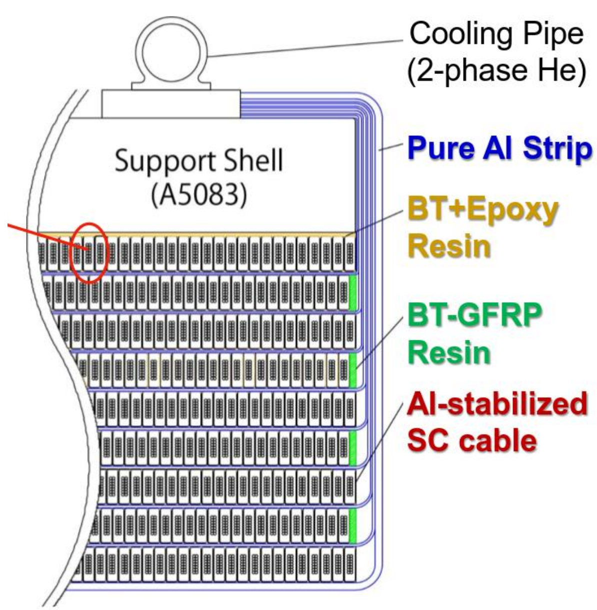
[a] T_{cs} is critical temperature at the maximum temperature.



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



Coldmass Fabrication

Support shell of forged A5083

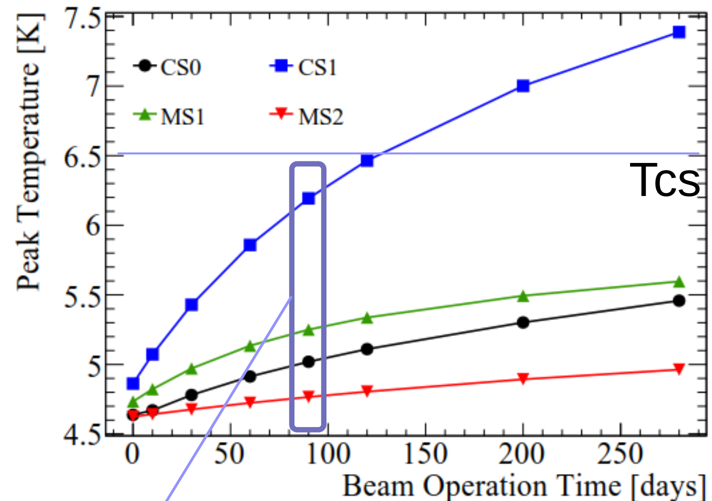
heat curing

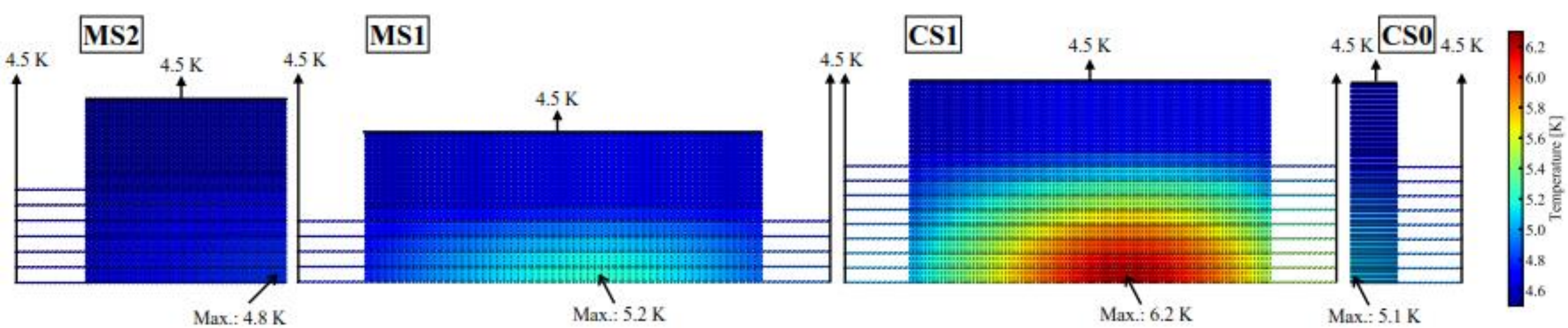
Wet winding with BT+Epoxy resin

Impregnation with BT+Expoxy

Coil Temperature during Beam Operation

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





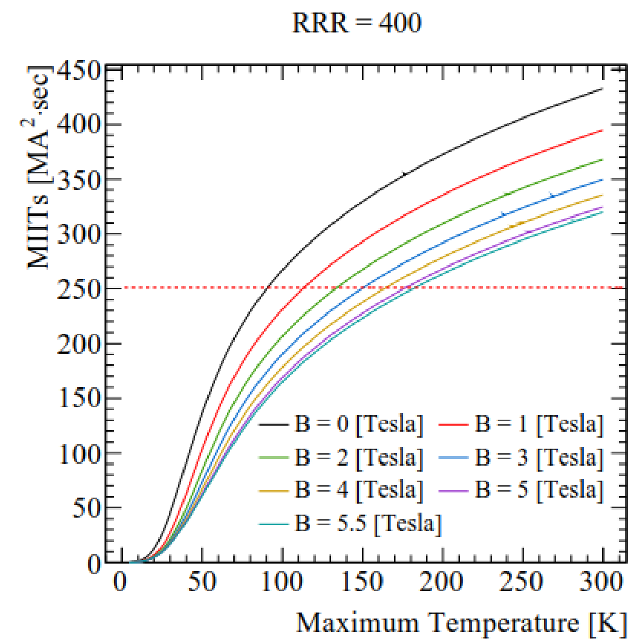
Y. Yang et al., IEEE Trans. App. Supercond., 28(3), 4001405 (2018).

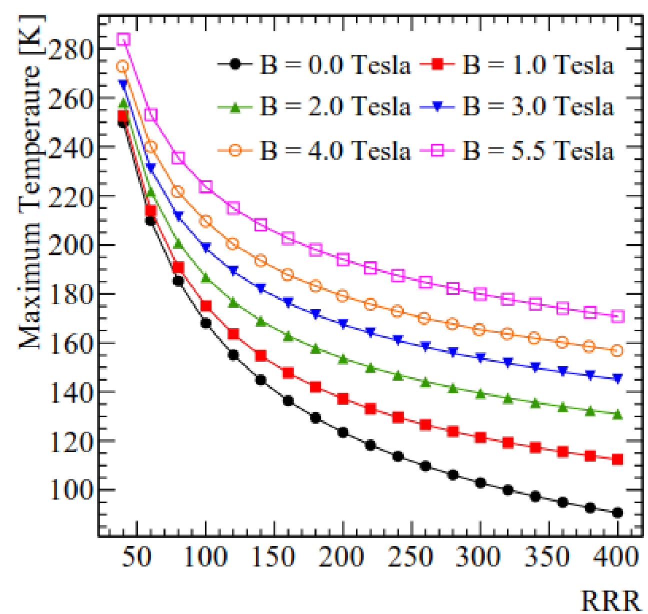
Effects of Stabilizer Degradation

- RRR of stabilizer will decrease by irradiation.
- Temperature at quench is estimated with MIITs
  - adiabatic condition

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

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





Simulation of Temperature Rise at Quench

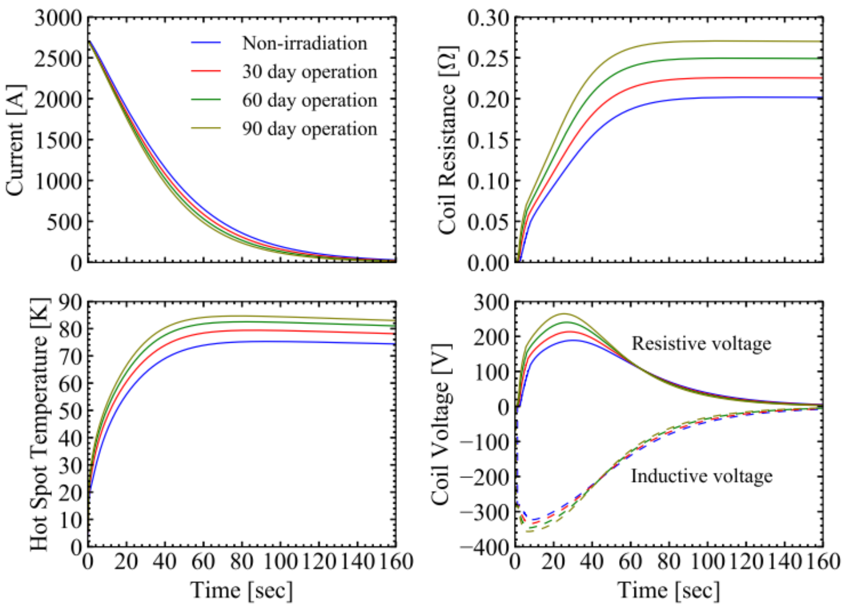


Fig. 5. Predicted current, coil resistance, temperature at hot spot and coil voltage after a accidental quench is occurred at varied beam operation time. The dashed line indicates the inductive voltage.

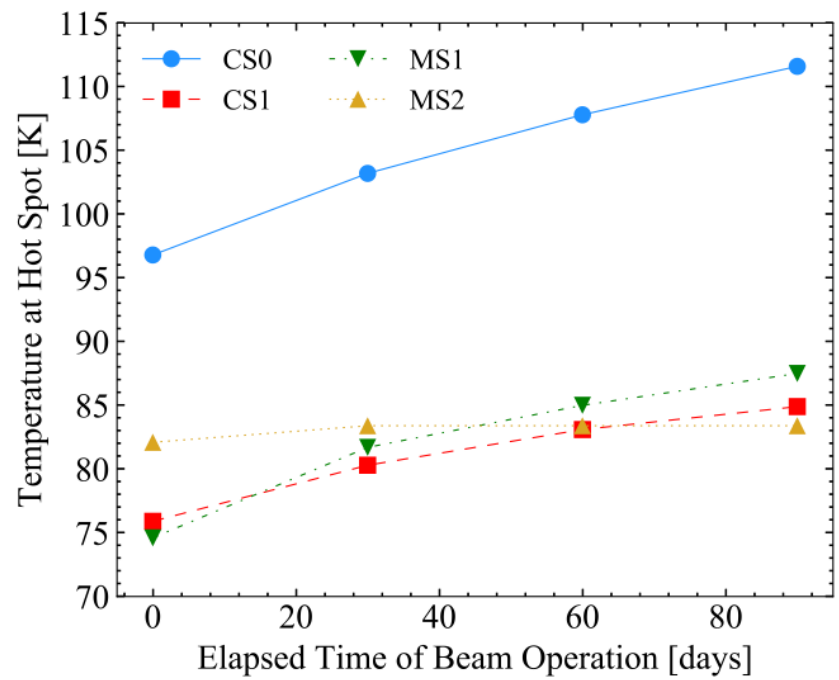
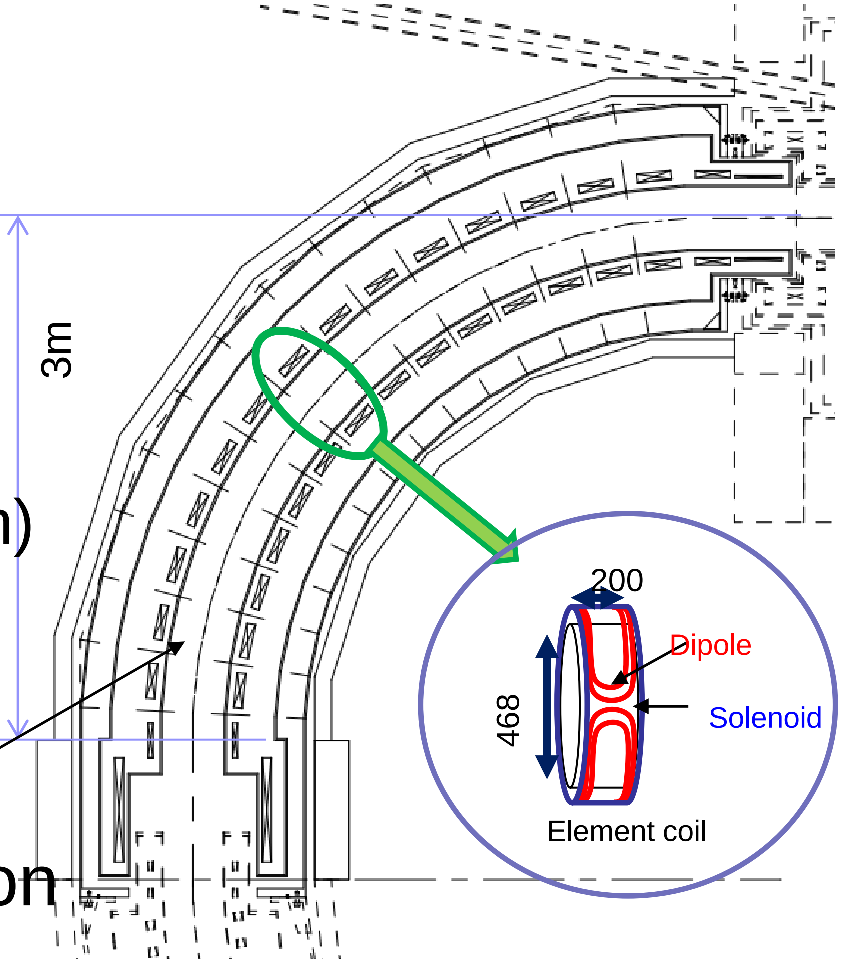


Fig. 6. Maximum temperature at hot spot for CS0 (blue line), CS1 (red line), MS1 (green line) and MS2 (golden line) coil as a function of beam operation time.

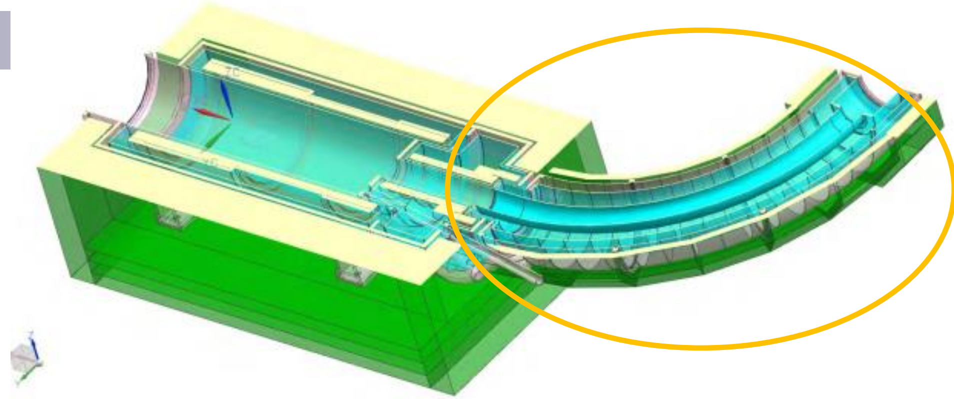
Y. Yang et al., IEEE Trans. App. Supercond., 28(3), 4001405 (2018).

Muon Transport Solenoid

- 3T toroidal field
- Solenoid + correction dipole
- Cu-stabilized SC wire
  - 1.5mm dia. (w/o insulation)
  - Cu/NbTi=6
- Indirect cooling with 2-phase LHe pipe
- Muon beam duct / radiation shield at 60K
  - t10mm of SUS



Muon Transport Solenoid

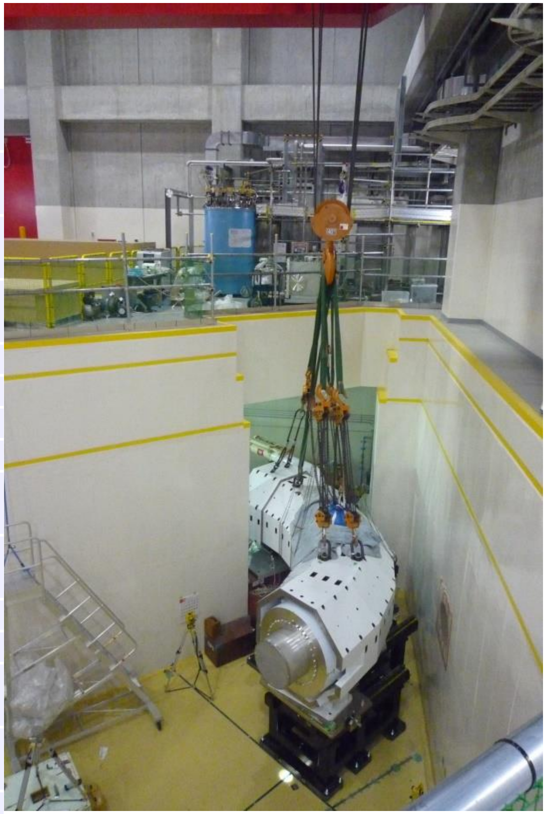


- Curved solenoid with correction dipole

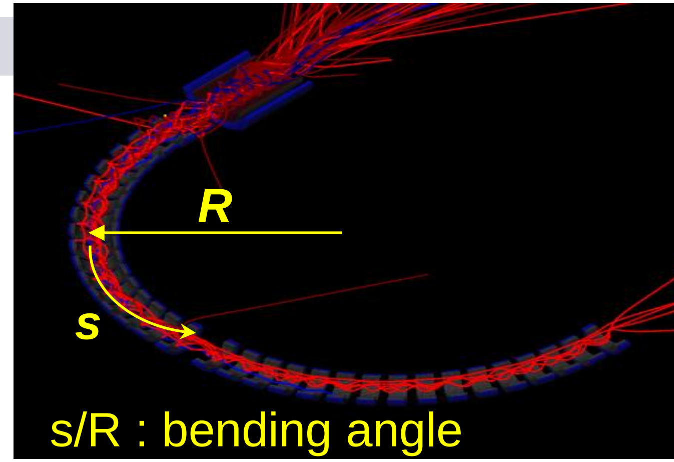
Magnet already delivered at J-PARC.

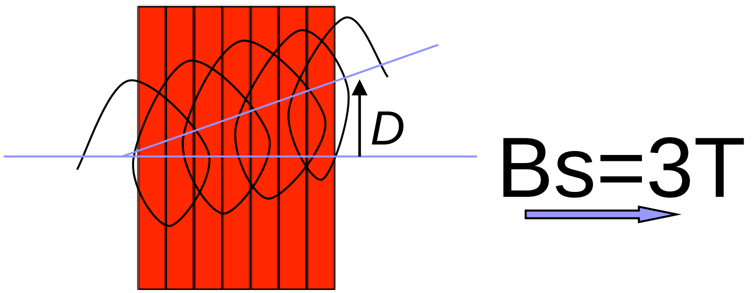
Design Parameters of Transport Solenoid

Conductor	NbTi/Cu monolith wire Cu/NbTi = 6
Cable dimensions (Solenoids)	ϕ1.5 mm (without insulation) ϕ1.56 mm (with insulation)
Cable dimensions (Dipole coils)	ϕ1.2 mm (without insulation) ϕ1.3 mm (with insulation)
Cable insulation	Polyamide-imide enamel (AIW), PVF (TS2-15,16, TS3)
Magnet length	~6 meters
Curvature Radius	3 meters
Num. of solenoid coils	18
Num. of dipole coils	16 pairs
Operation current	210 A (solenoids) 175 A (dipole coils)
Field on axis	~3 T (solenoid) ~0.056 T (dipole)
Stored energy	5.6 MJ
Total inductance	254 H
Coil inner diameter	468 mm (TS2a~TS2-16) 600 mm (TS3)
Refrigeration	conduction from forced flow 2-phase LHe piping (7~10 g/s)
Quench protection	semi-active quench back heater

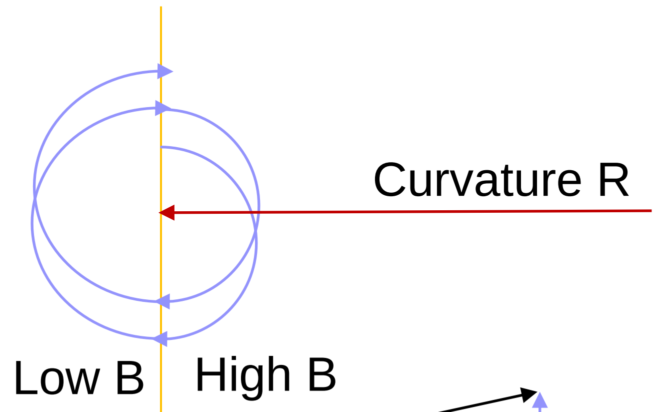


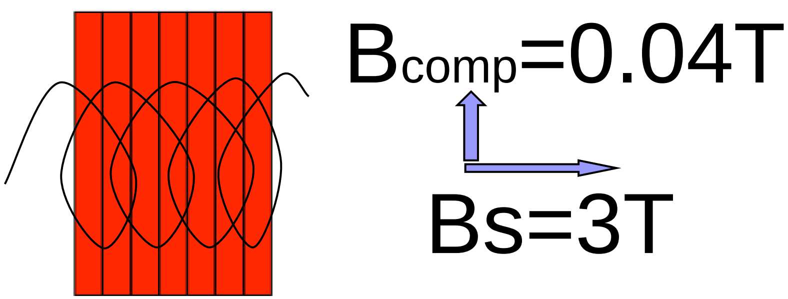
Trajectory in Curved Solenoid



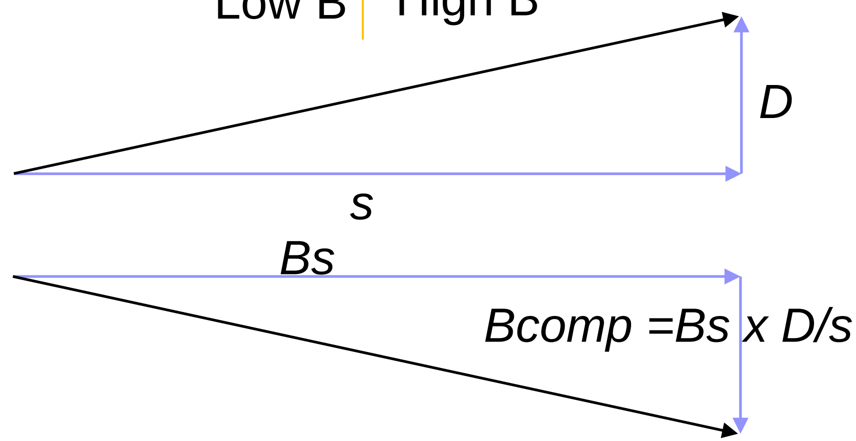


$$D = \frac{1}{qB}\left(\frac{s}{R}\right)\left(\frac{p}{2}\right)\left(\cos\theta + \frac{1}{\cos\theta}\right)$$



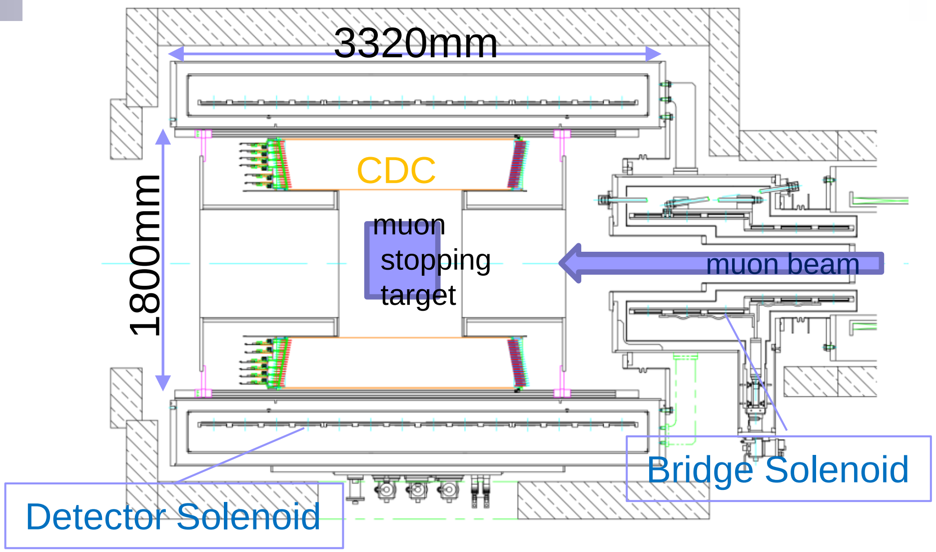


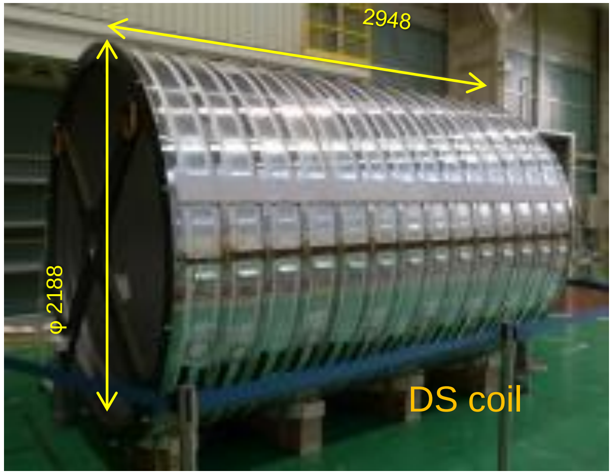
$$B_{comp} = \frac{1}{qR}\left(\frac{p}{2}\right)\left(\cos\theta + \frac{1}{\cos\theta}\right)$$



Detector Solenoid for phase1

- 1 Tesla on the muon stopping target
- Large aperture for CDC and trigger hodoscope
- Cyogen-free magnet
  - Cooled by 3 cryocoolers

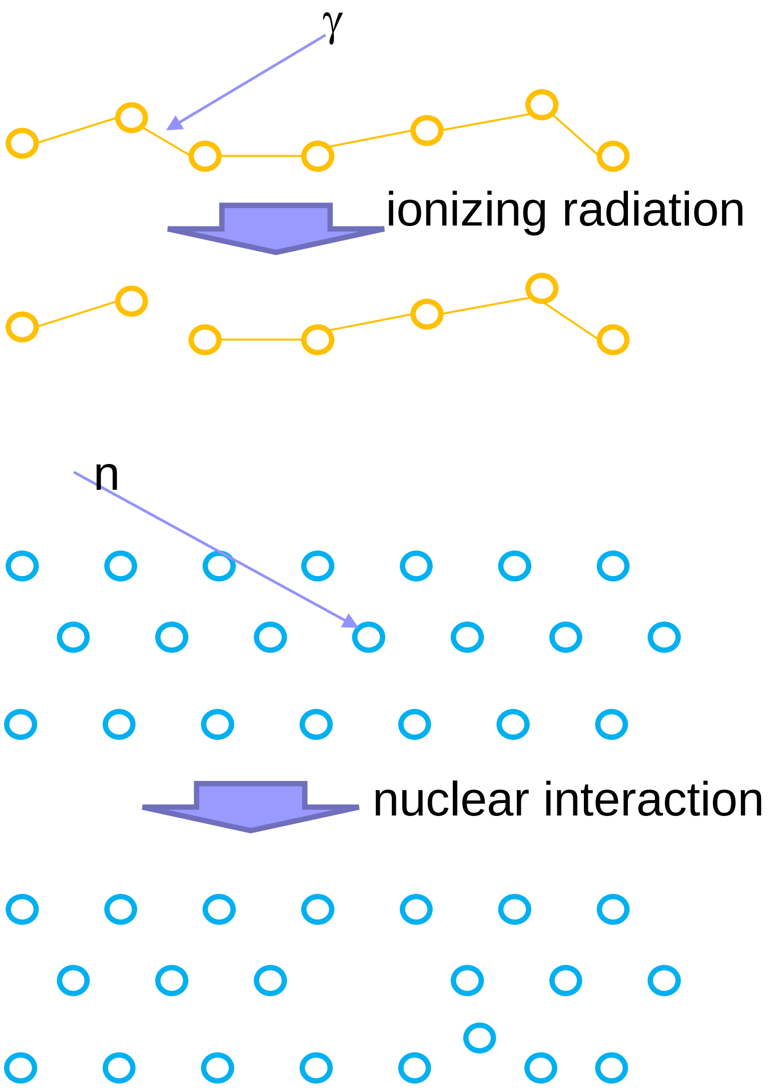




Item	Value
Conductor	NbTi/Cu monolith wire Cu/NbTi = 4
Strand dimensions	ϕ1.2 mm (without insulation) ϕ1.3 mm (with insulation)
Cable insulation	PVF
Magnet length	~1 m (BS), ~2.5 m (DS)
Operation current	210 A
Field on axis	3~1 T (BS), ~1 T (DS)
Stored energy	~14 MJ
Coil inner diameter	460~620 mm (BS), 2140 mm (DS)
Refrigeration	conduction cooling by GM refrigerators
Quench protection	active or semi-active quench back heater

Irradiation Effects in Magnet Materials

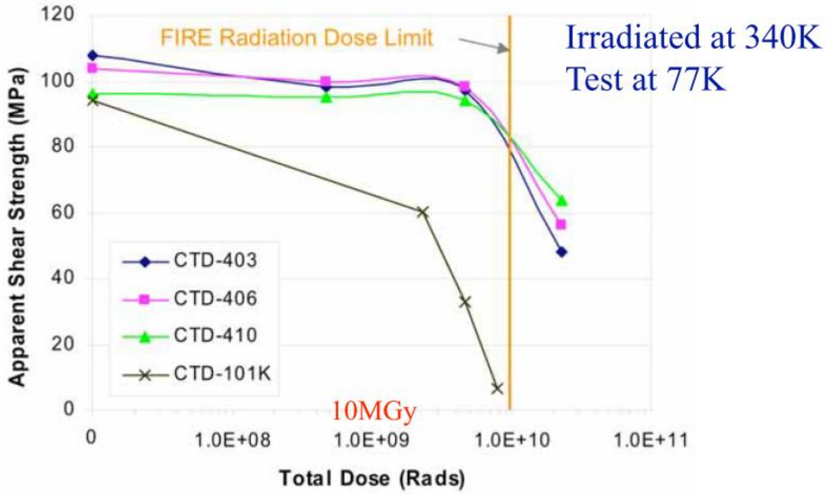
- Organic polymer
  - Insulator
  - GFRP
  - Adhesive
  - Impregnation
- Pure metal
  - Stabilizer
  - Thermal conductor



Insulator, Resin

- Need radiation hardness above 10 MGy
  - epoxy degradation ~1MGy

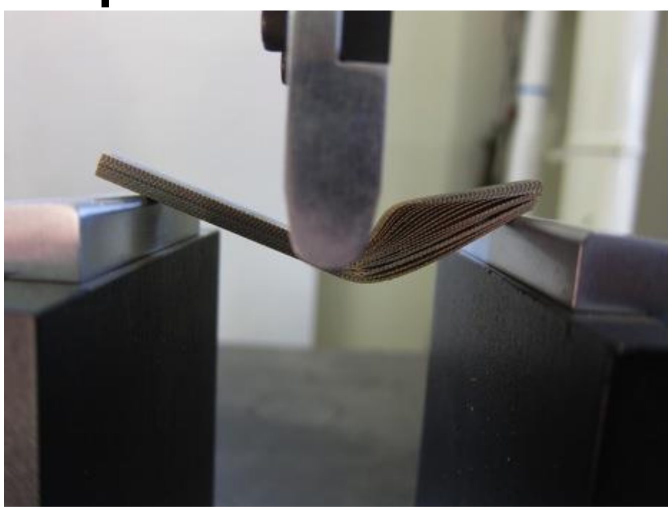
- Polyimide
- Bismaleimide-Triazine
  - MGC BT3309T, BT2160, …
  - Applied in J-PARC accelerator magnet, Super-Omega, etc.
- Cyanate ester
  - Applied in ETER



Fabian and Hooker et. al., presented at “HHH-AMT, Topical Meeting on Insulation and Impregnation Technologies for Magnets”

Irradiation Tests of GFRPs

- BT-based GFRP has excellent performance.



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

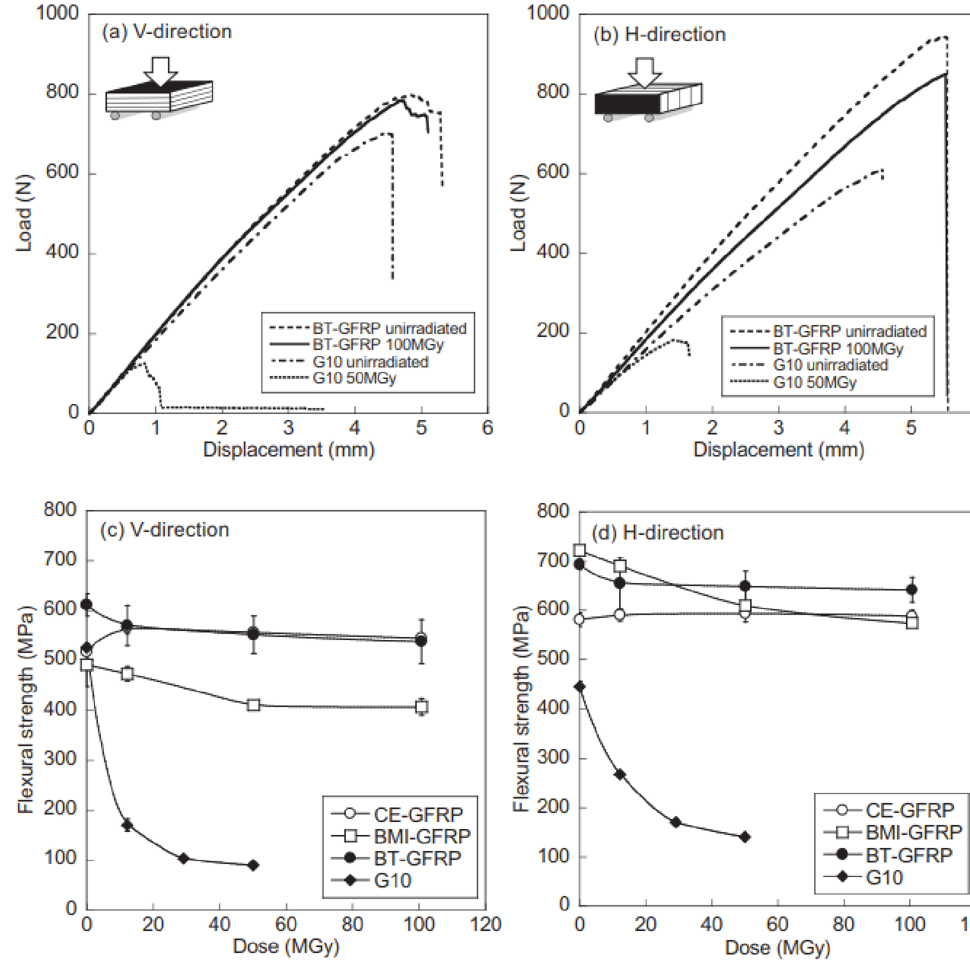
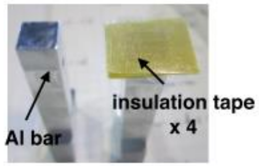
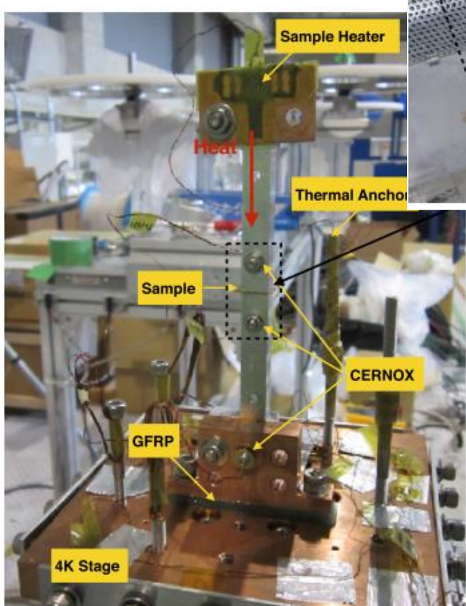


Fig. 3. Change in flexural property of GFRPs after gamma-ray irradiation: displacement-load curves ((a) V-direction and (b) H-direction) and flexu and (d) H-direction).

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

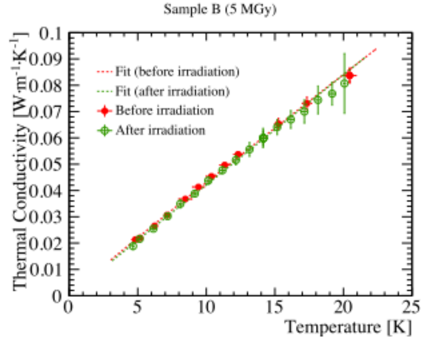
Irradiation Test on Thermal Conductivity of Insulation

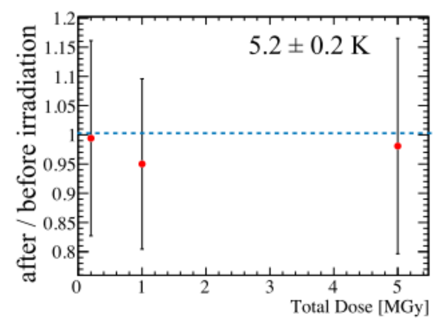




Thermal Conductivity of Insulation and Its Radiation Resistance

- Thermal conductivity of insulation tape is measured from 4.5K to 20K and tested by gamma-ray irradiation up to 5MGy.
- k_{ins} ~ 0.02W/m/K at 4.5K
  - Assuming as polyimide (k_{ins} ~ 0.01W/m/K at 4.5K) conservatively in thermal and quench analysis
- No significant degradation is observed by gamma ray irradiation with total dose up to 5 MGy.





18

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

Superconductor

- NbTi
  - No degradation up to 10^{22}n/m^2
- ReBCO
  - Discussed in the next talk

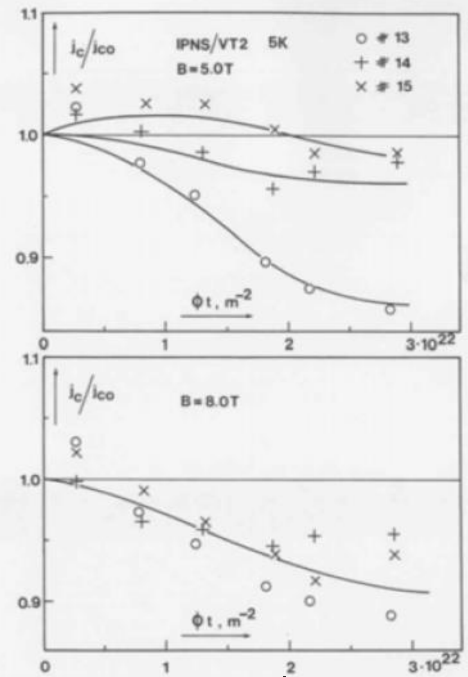
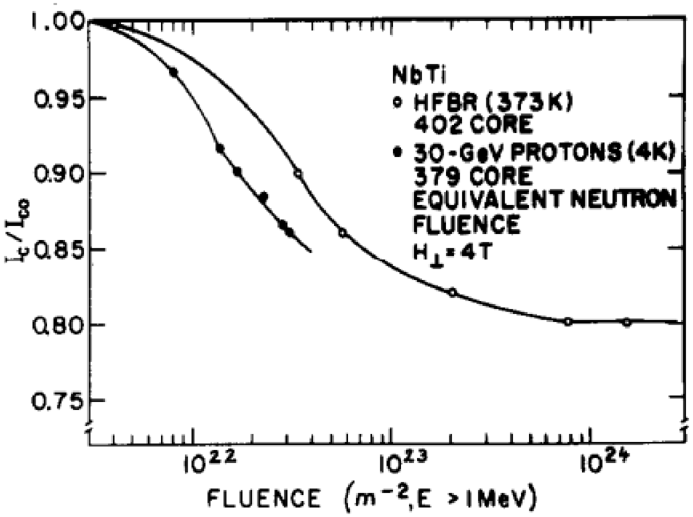


Fig. 2. Change of critical current densities with fast neutron fluence (E >0.1MeV) at 5 and 8 T. #13,14,15: 42,49,54 wt%Ti; annealing temperature: 350°C; final cold work: 71%.

5K

Adv. Cryo. Eng., 32, p853 (1986)



J. Nucl. Materials, 108&109, p572 (1982)

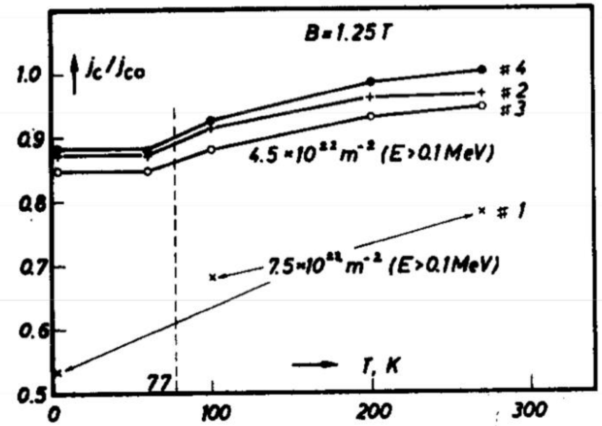


Fig. 9. Recovery of j_c/j_{c0} up to room temperature for 4 different samples of Nb–50 wt% Ti (measured at 4.2 K and 1.25 T), after [44]. The measurements were made on one filament (Nos. 1–3: 11 μm filament diameter, No. 4: 21 μm) of multifilamentary wires.

Irradiation Effects in Pure Metal

- Stabilizer
  - Aluminum alloy
  - Copper
- Thermal conductor
  - Pure aluminum
  - Copper
  - Aluminum alloy
- Thermo sensor
  - drift at high neutron fluence

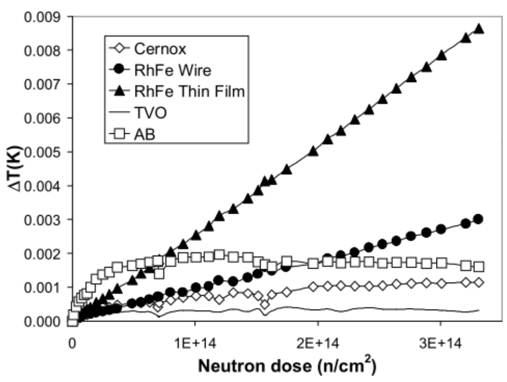
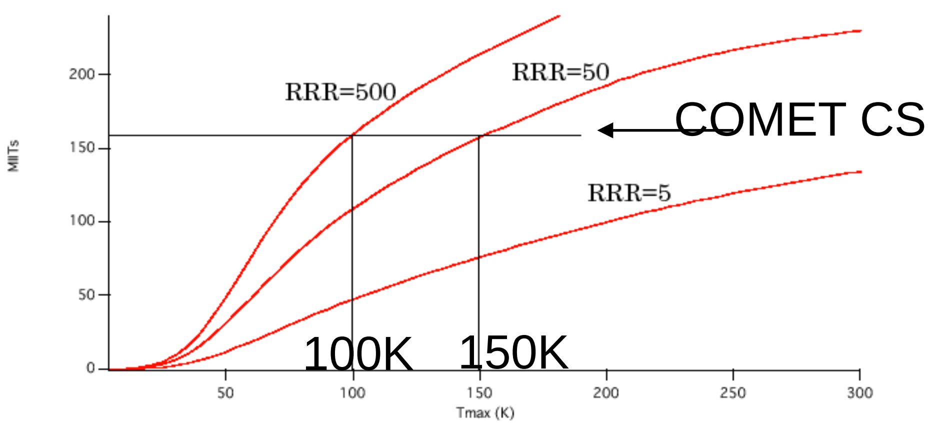


Figure 3 Error on temperature measurement on some sensors during irradiation (Tbath=1.8 K)

LHC Project Report 209

- Fast-neutron irradiation induces defects in metal.
- Defects could be accumulated at Low temperature,
- and causes degradation of electrical/thermal conductivity

- Problems in
  - Quench protection, Stability
  - Cooling

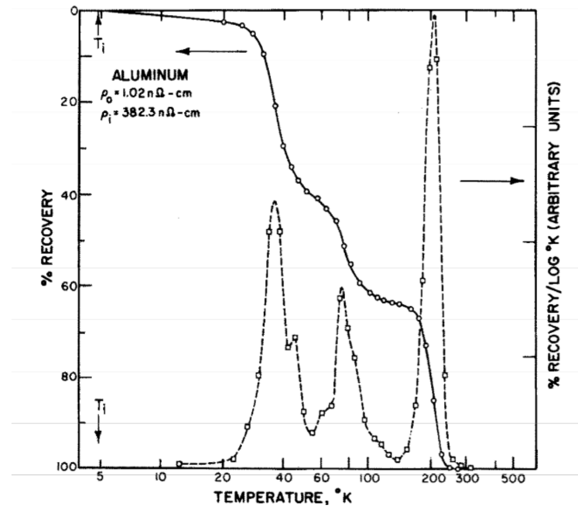


Pure Metal Degradation by Reactor Neutrons

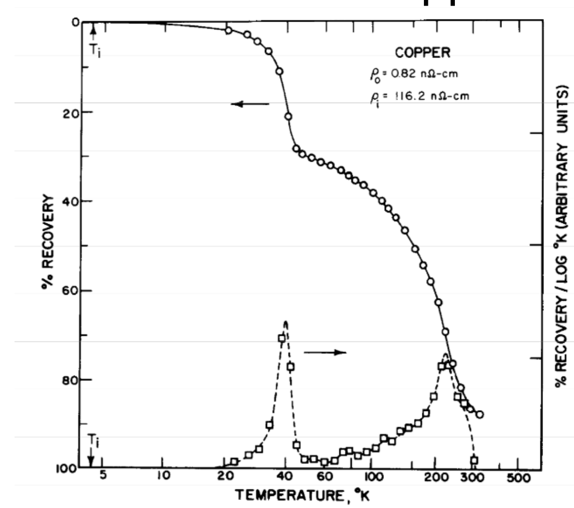
- Electrical resistivity increase with reactor neutrons
  - fast neutrons >~0.1MeV
- Irradiation damage can be recovered by annealing.
  - perfect recovery in Al
- Effect of impurity and strain?

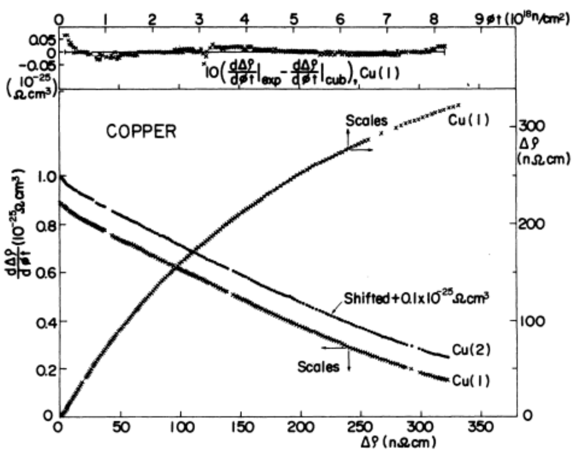
Recovery after irradiation $2\text{x}10^{22}$ n/m^2 (E>0.1MeV)

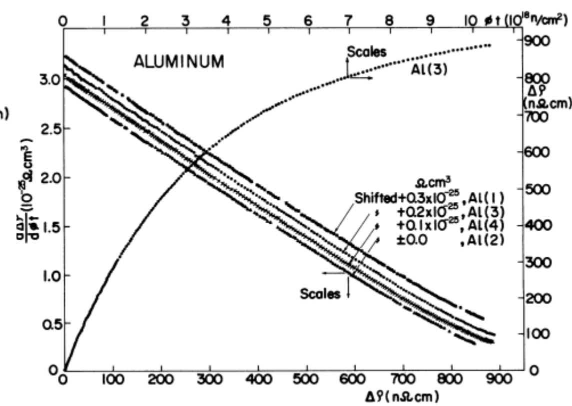
Aluminum



Copper



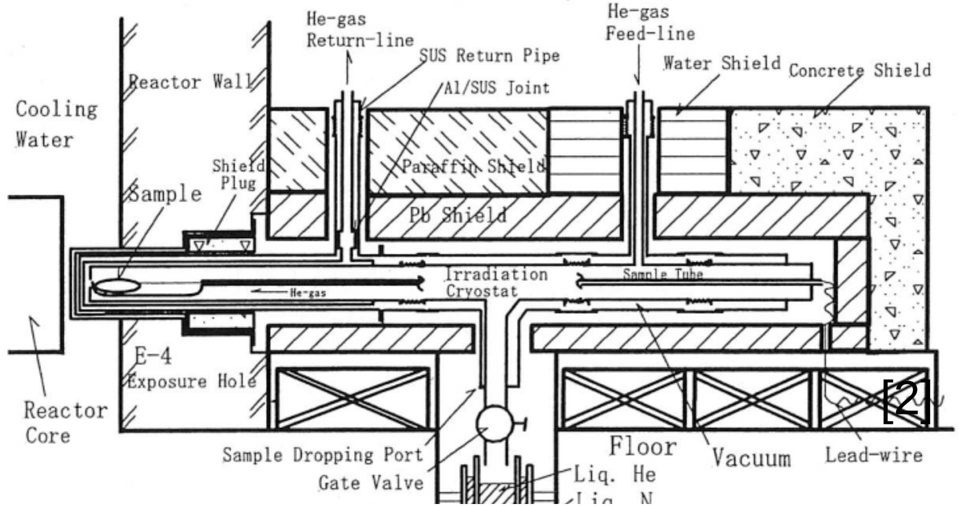




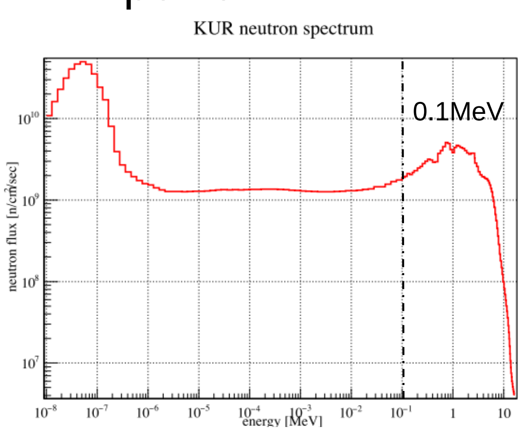
M. Nakagawa, K. Boning, P. Rosner, and G. Vogl, *Phys. Rev. B* **16**, pp. 5285-5302 (1977)

Low Temperature Irradiation Facility

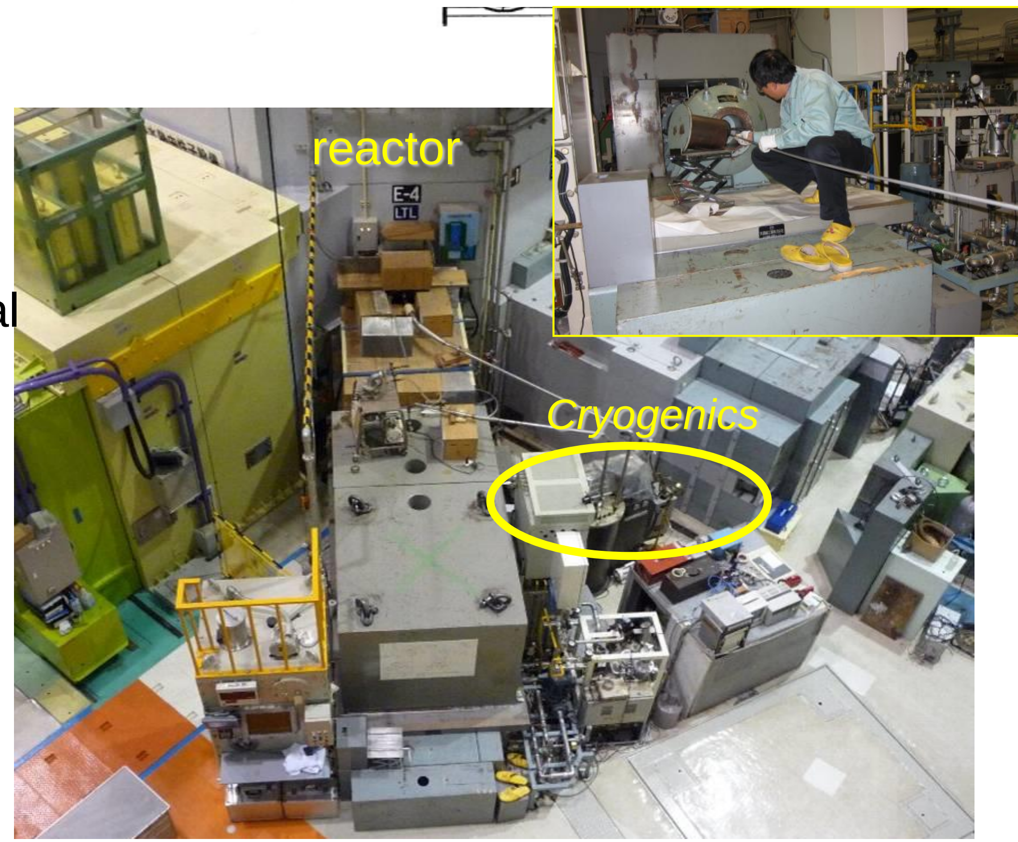
- Kyoto Univ. Research Reactor Institute
- 5MW max. thermal power
- Cryostat close to reactor core
- Sample cool down by He gas loop
  - 10K – 20K
- Fast neutron flux(>0.1MeV)
  - 1.4×10^{15} n/m^2/s@1MW thermal power



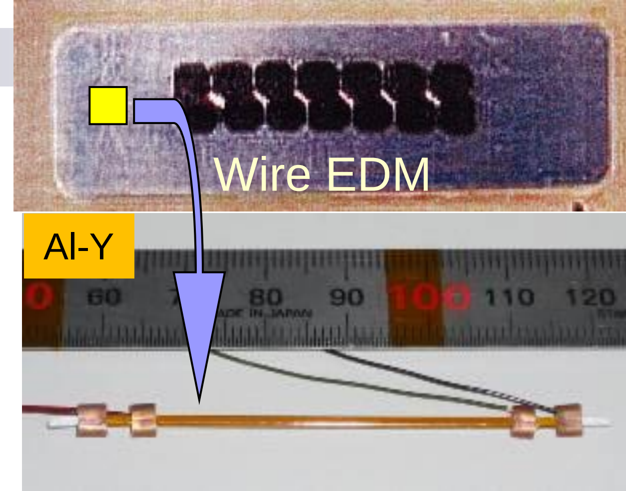
[2] M. Okada et al., NIM A463 (2001) pp213-219



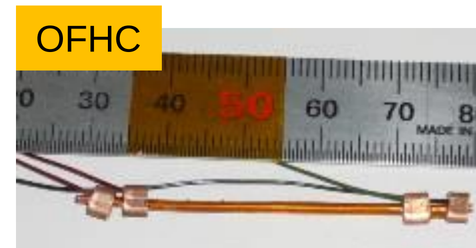
KUR-TR287 (1987)



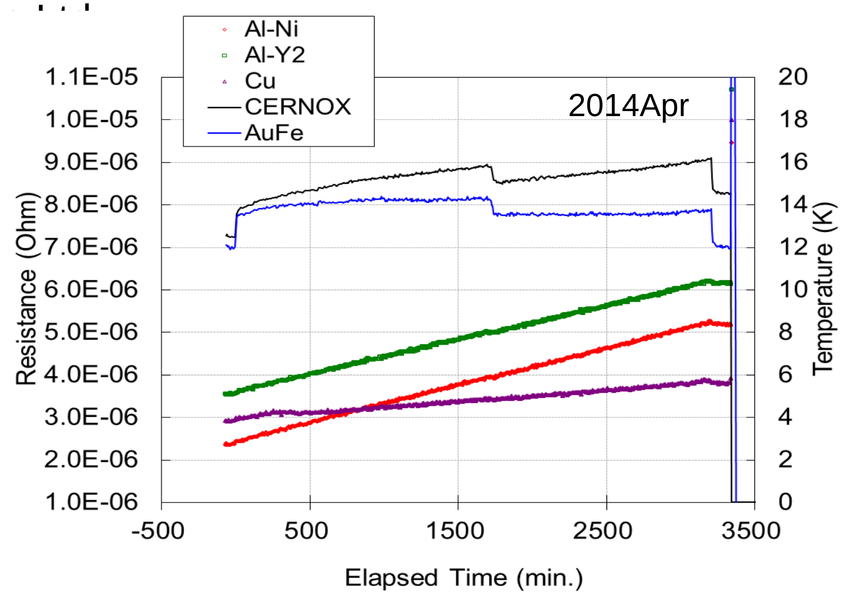
Irradiation Sample



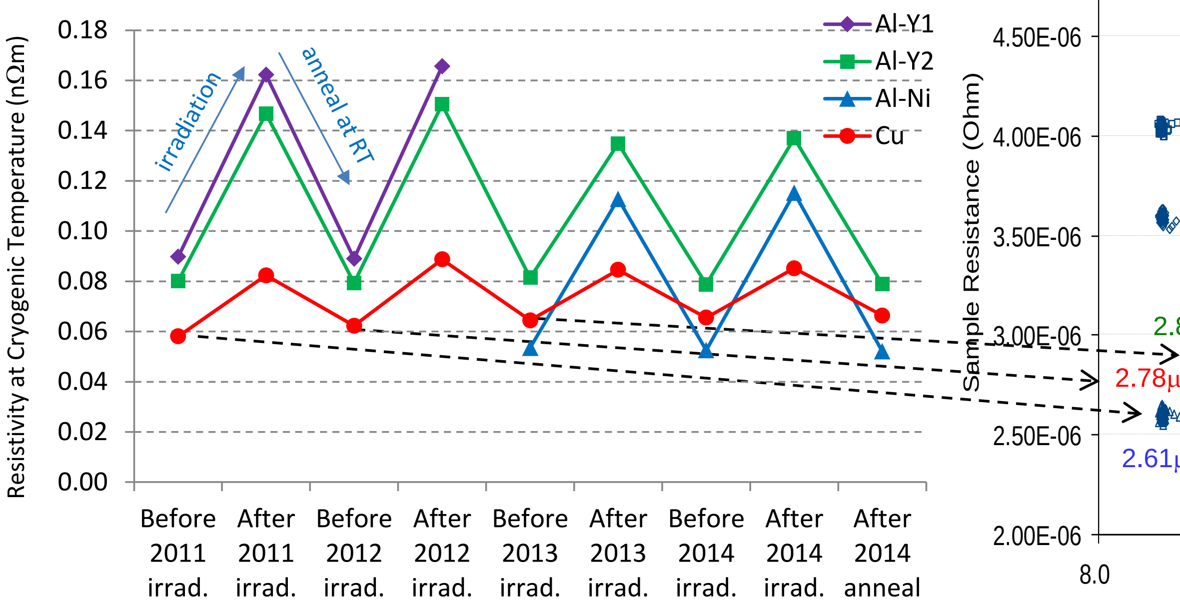
- Aluminum alloy
  - EDM cut from aluminum-stabilized SC cable
  - 1mmx1mmx70mm (45mm Vtap)
  - Al-CuMg
    - 5N Al + Cu(20ppm) + Mg(40ppm) with 10% cold work (RRR~450)
  - Al-Y
    - 5N Al + 0.2%Y with 10% cold work (RRR~330-360)
  - Al-Ni
    - 5N Al + 0.1%Ni with 10% cold work (RRR~560)

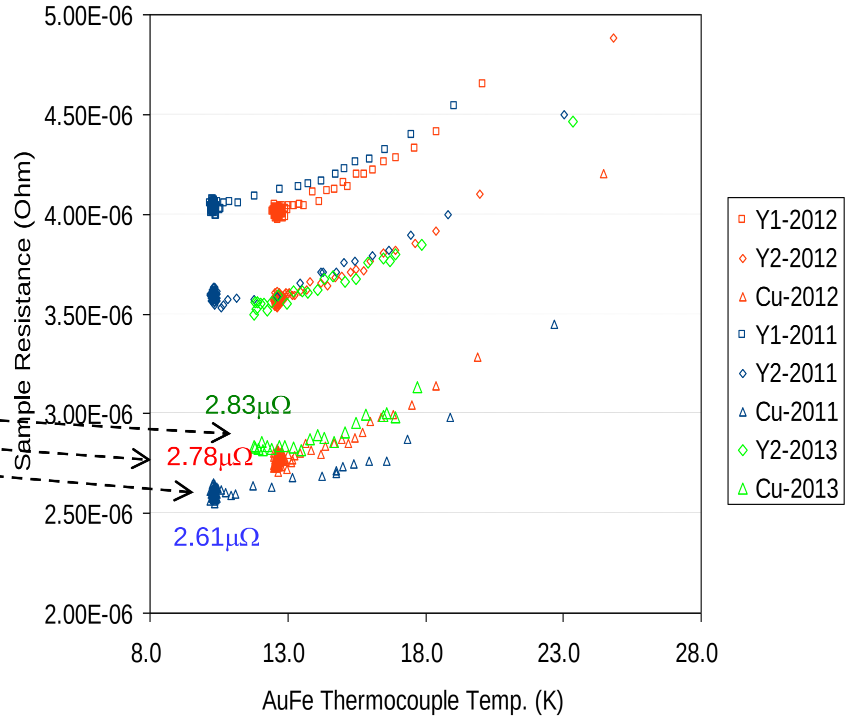


- Copper
  - OFHC for SC wire, provided by Hitachi Cabl
  - ϕ1mm x 50mm (35mm Vtap)
  - RRR~300
- 5N aluminum
  - provided by Sumitomo Chemical
  - ϕ1mm x 50mm (32mm Vtap)
  - RRR~3000
- Thermometer
  - CERNOX CX-1050-SD, CX-1070-SD
  - Thermocouple (AuFe+Chromel)



Irradiation / Annealing Effect in Electrical Resistance



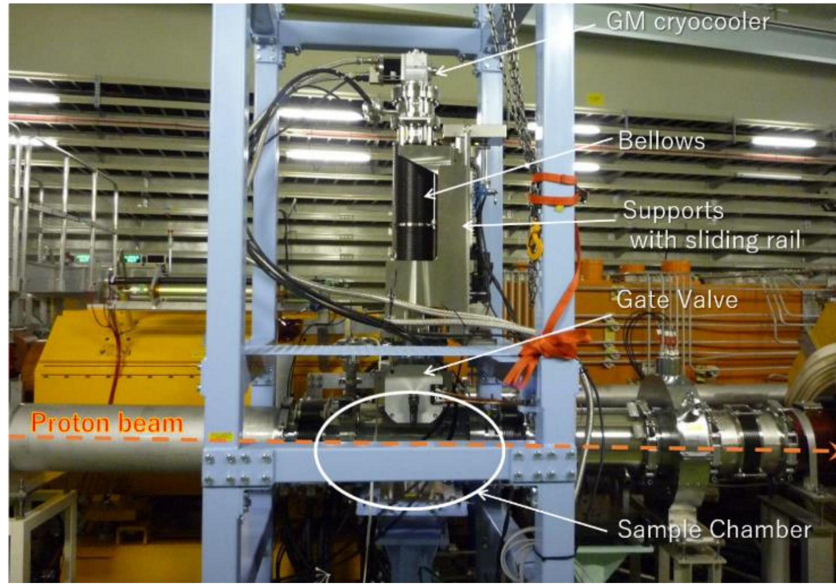


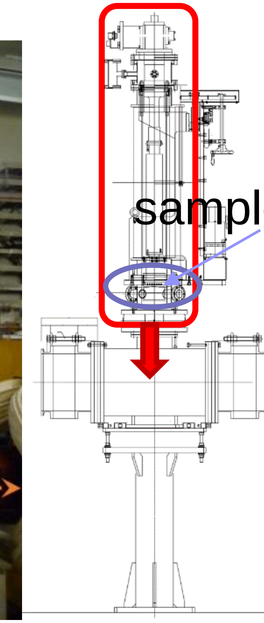
- Al: 0.03 nOhm.m for 10^{20} n/m^2
- Cu: 0.01 nOhm.m for 10^{20} n/m^2
- All Al samples show "full" recovery of electrical resistivity after thermal cycle to RT.

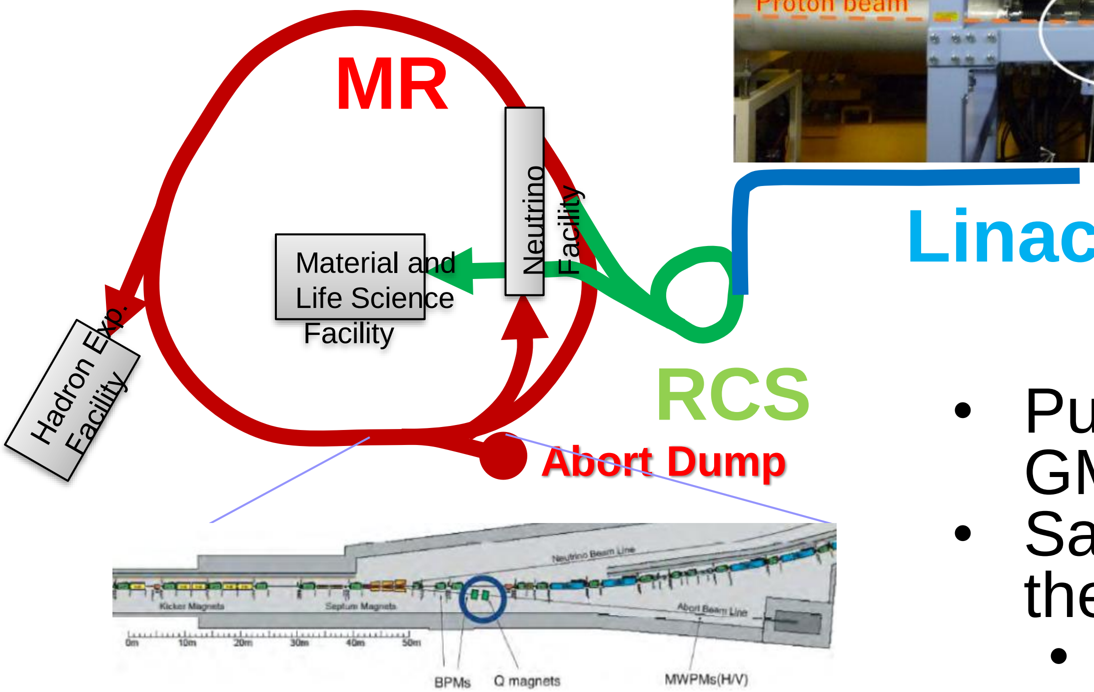
"Repetitive Irradiation Tests at Cryogenic Temperature by Neutrons and Protons on Stabilizer Materials of Superconductor," M. Yoshida et al., *IEEE Trans. Appl. Supercond,* 32(6), 7100405 (2022); doi:10.1109/TASC.2022.3178944

Proton irradiation test at J-PARC

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

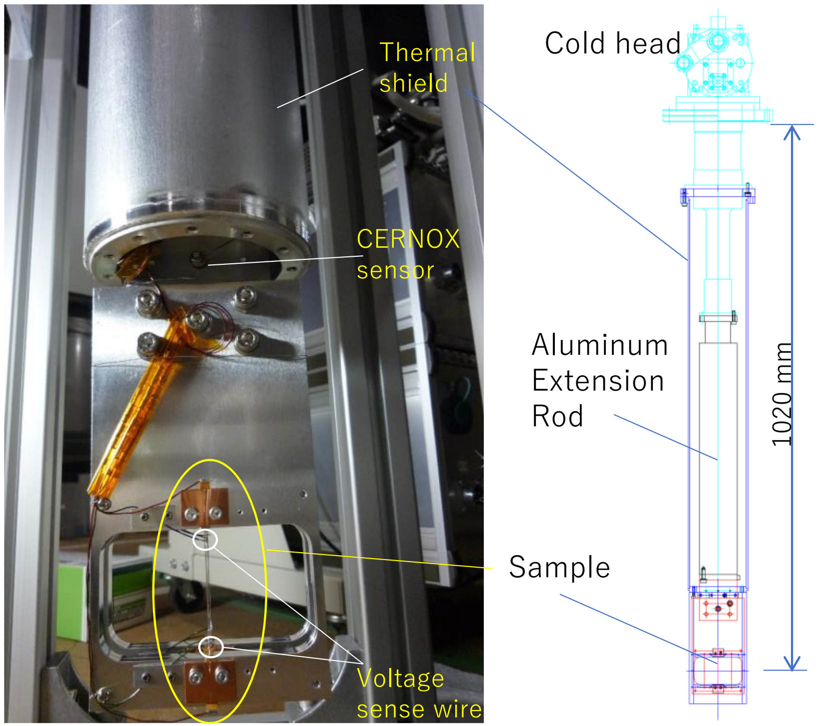


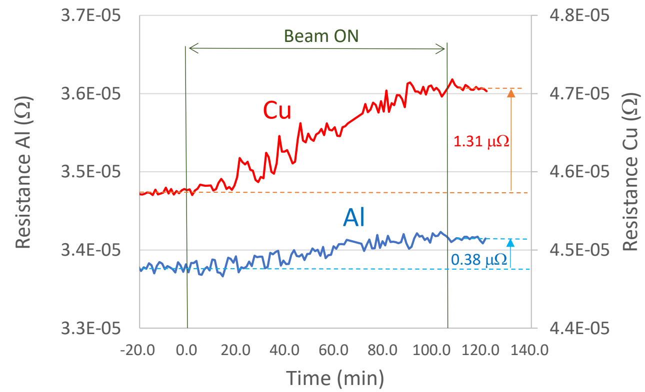


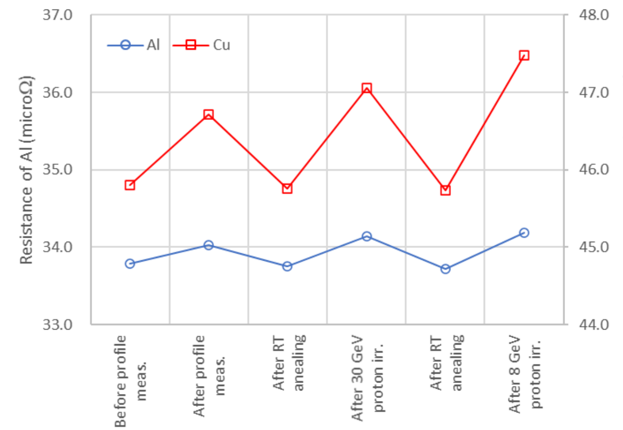


- Pure metal wire cooled by GM cryocooler
- Sample can be inserted to the beam line on demand.
  - remote handling

低温照射実験







	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

- Superconducting muon beamline for COMET phase1 is under construction
- Radiation-tolerant superconducting solenoid, Pion Capture Solenoid, is developed and under fabrication.
- Radiation effects in magnet materials are investigated.