Progress of COMET Superconducting Solenoid System

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RESMM15@FRIB
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- COMET Superconducting Magnet Overview and Status
- Updates on Irradiation Tests
- Estimation of Irradiation Effects in SC Coil

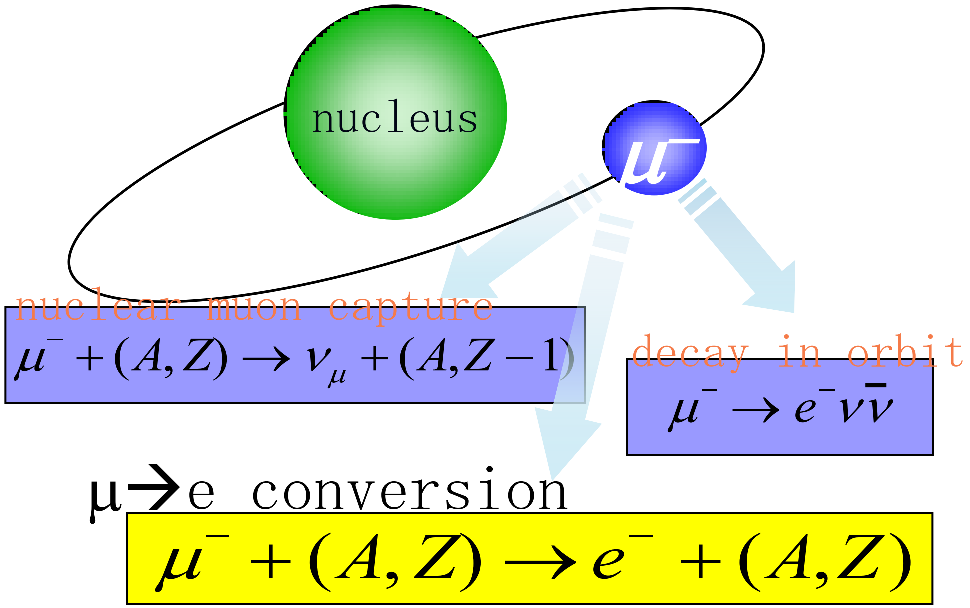
The COMET Experiment

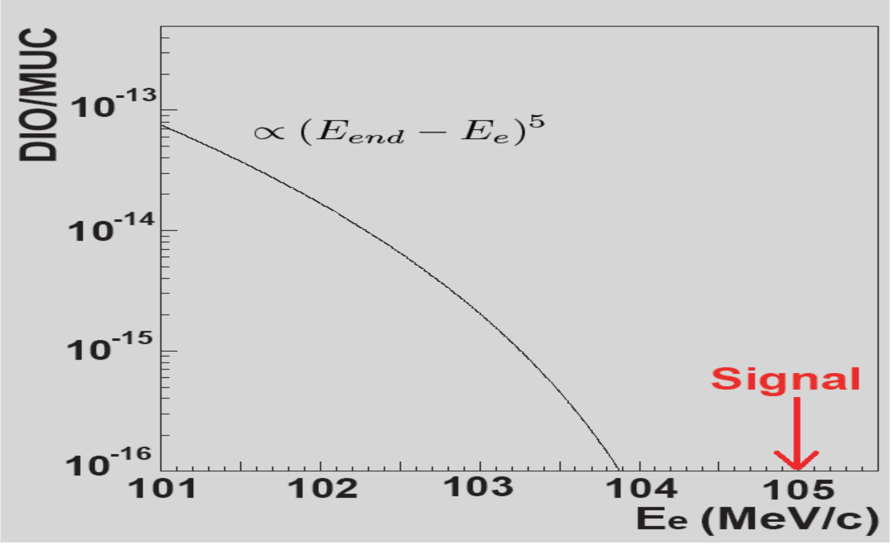
- J-PARC E21
- 8GeVx7μA
- stopping μ⁻ → Muonic atom

$$B\left(\mu^- N \to e^- N\right) = \frac{\Gamma\left(\mu N \to eN\right)}{\Gamma\left(\mu N \to \nu N'\right)}$$

Detect monoenergetic electrons from μ-e conversion

Physics Reach: Br<10^{-16}
→ 2×10^{18} muon stops
→ 10^{11} μ^-/sec





Requirements

Goal: 10^{11} μ^{-}/sec

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

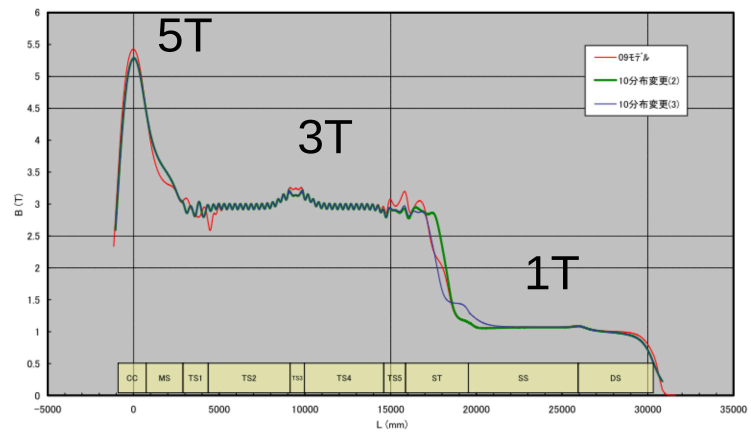
- Long solenoids from production to muon stopping target
- Curved solenoid to select momentum / charge

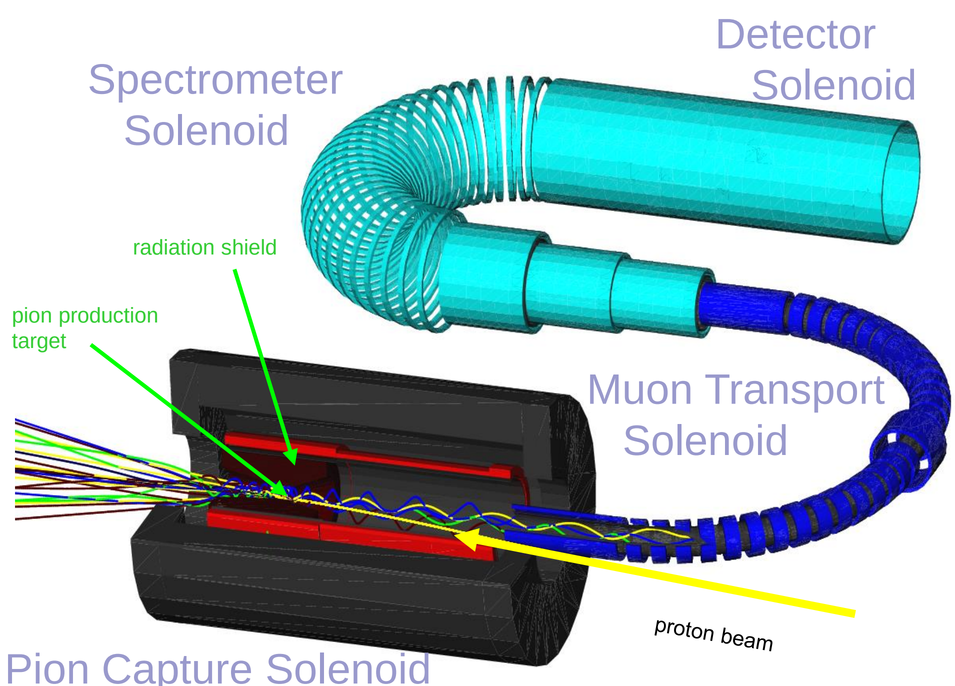
3. Large signal acceptance. Reduce decay-in-orbit BG

- Graded field on muon stopping target
- Curved solenoid to select 105MeV/c electrons

COMET Magnet System

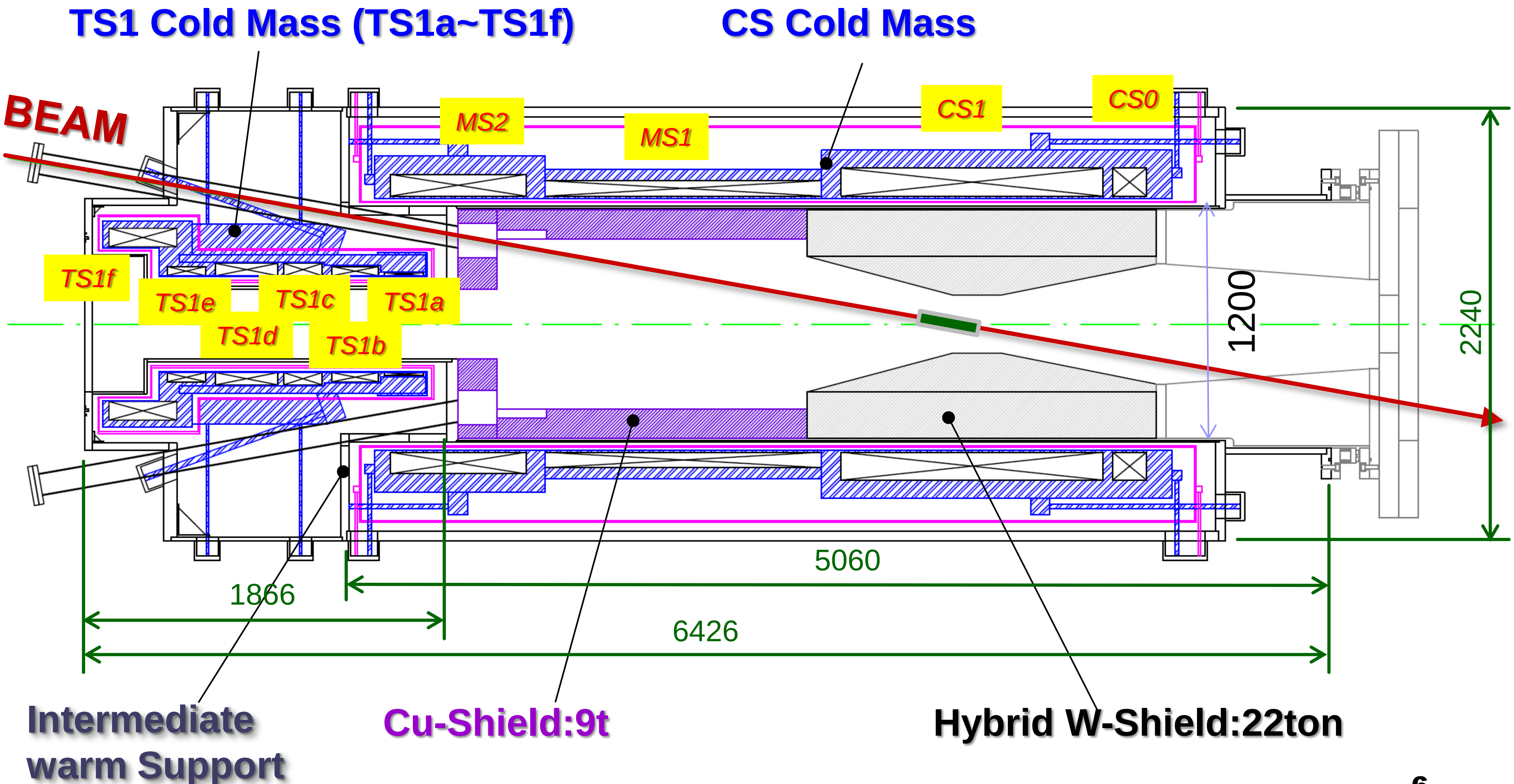
- Pion Capture Solenoid
  - *5T High field on Target*
  - *Tungsten shield inside*
- Muon Transport Solenoid
  - *3T curved solenoid*
  - *Correction dipole 0.03T~0.06T*
- Stopping Target Solenoid
  - *3T→1T graded field*
- Spectrometer Solenoid
  - *1T curved solenoid*
- Detector Solenoid
  - *1T curved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



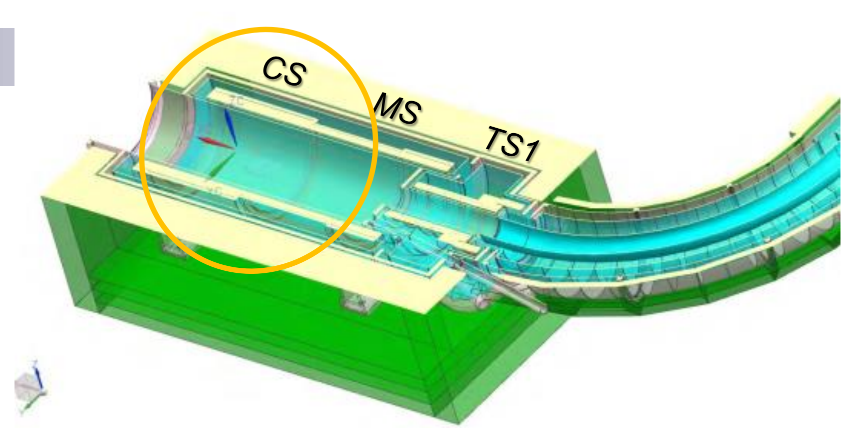


COMET Superconducting Magnet System

Pion Capture Solenoid Magnet System



Coil Structure

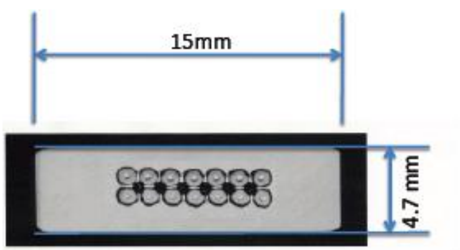


- Aluminum stabilized SC cable
  - to reduce nuclear heating (max. 35mW/kg)
- Radiation resistant insulator, resin
- Pure aluminum strips in between layers
  - to cool down a coil inside

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

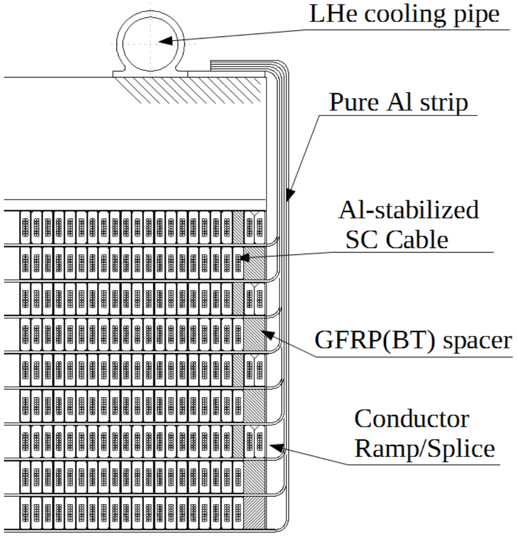
[a] T_{cs} is critical temperature at the maximum temperature.



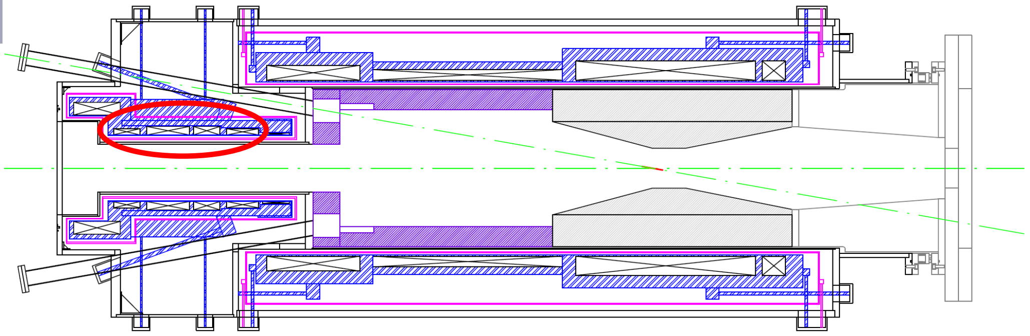
Al stabilized SC cable

- 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

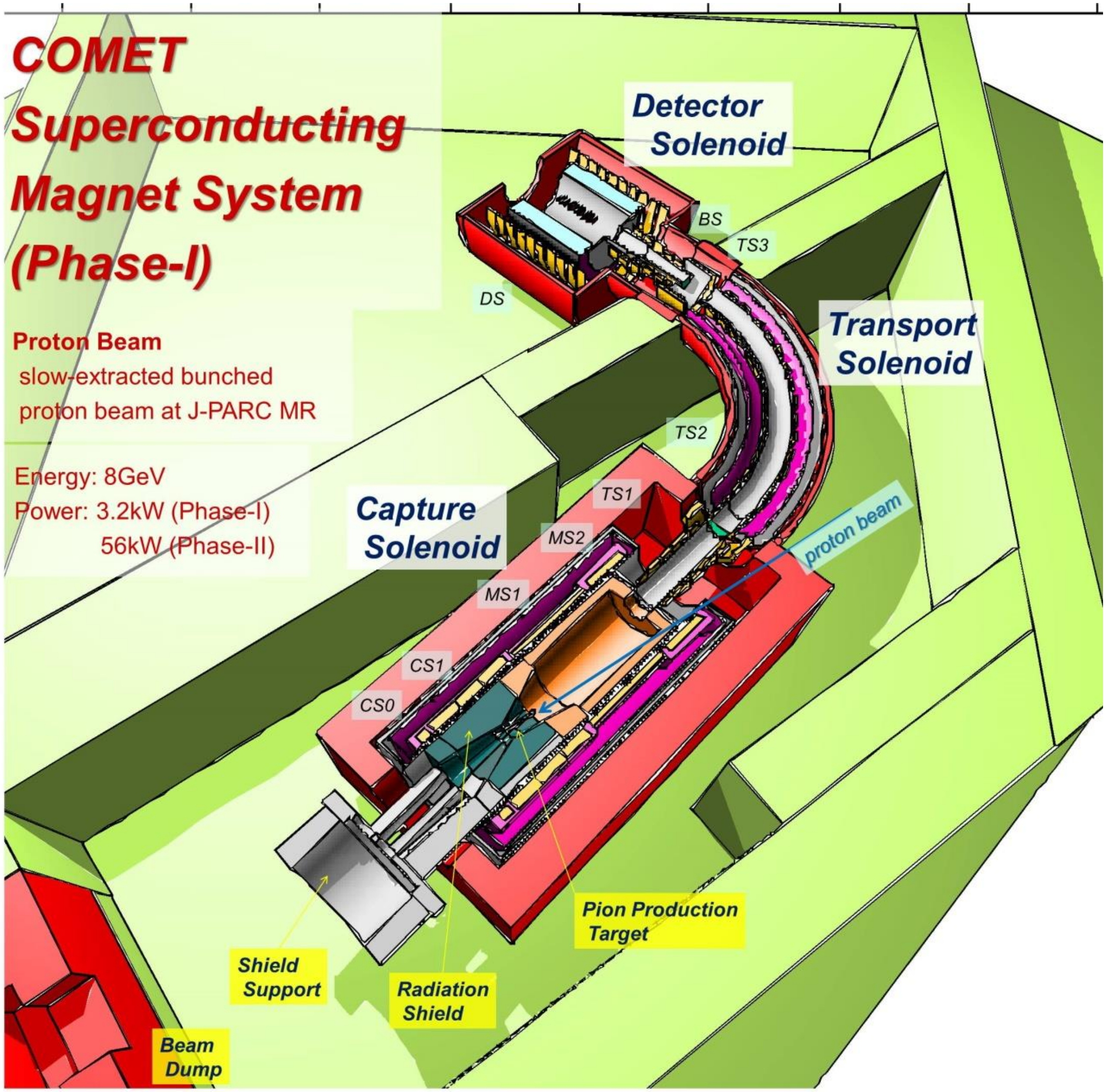


Coil Winding



- Completed coil winding of TS1b,c,d,e in FY2014.
  - cured with BT+Epoxy resin

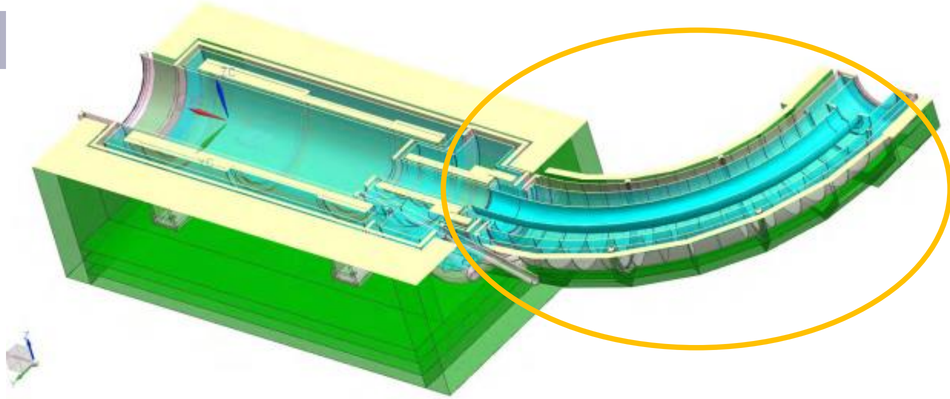
COMET at J-PARC



Civil Construction at J-PARC

- Building construction was completed in FY2014

Muon Transport Solenoid



- Curved solenoid with correction dipole

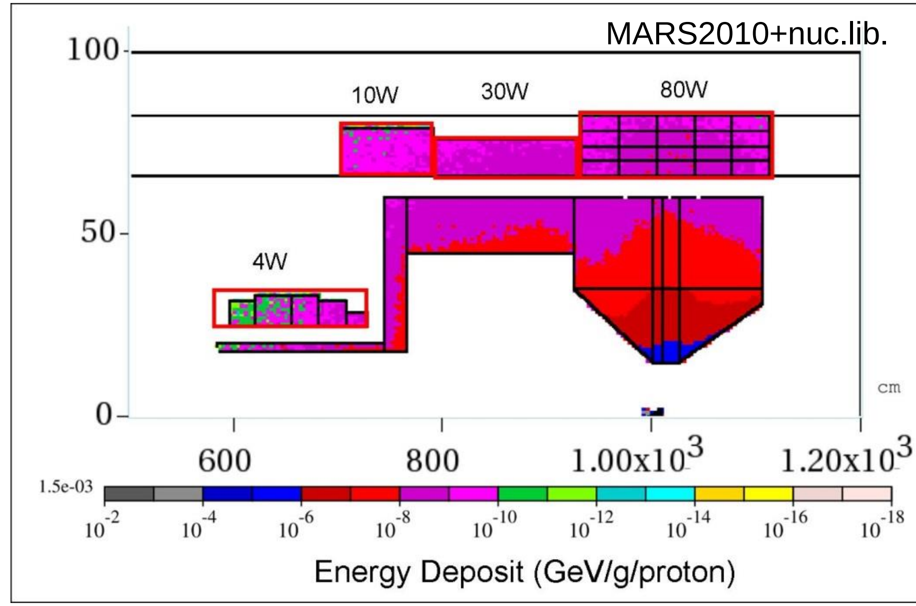
DESIGN PARAMETERS OF TRANSPORT SOLENOID MAGNET

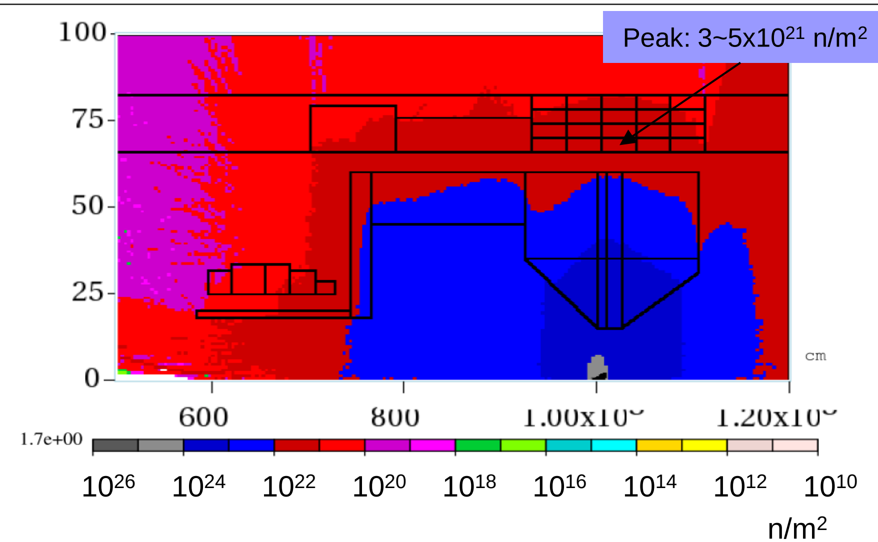
Item	Value
Conductor	NbTi/Cu monolith wire Cu/NbTi = 6
Cable dimensions (Solenoids)	ϕ1.5 mm (without insulation) ϕ1.56 mm (with insulation)
Cable dimensions (Dipole coils)	ϕ1.2 mm (without insulation) ϕ1.3 mm (with insulation)
Cable insulation	Polyamide-imide enamel (AIW), PVF (TS2-15,16, TS3)
Magnet 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

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

Key Issue

- Radiation tolerance of magnet materials
- Organic material
  - Strength
  - Out gas
- Metal
  - Electrical conduction
  - Thermal conduction
- Radioactivation of He





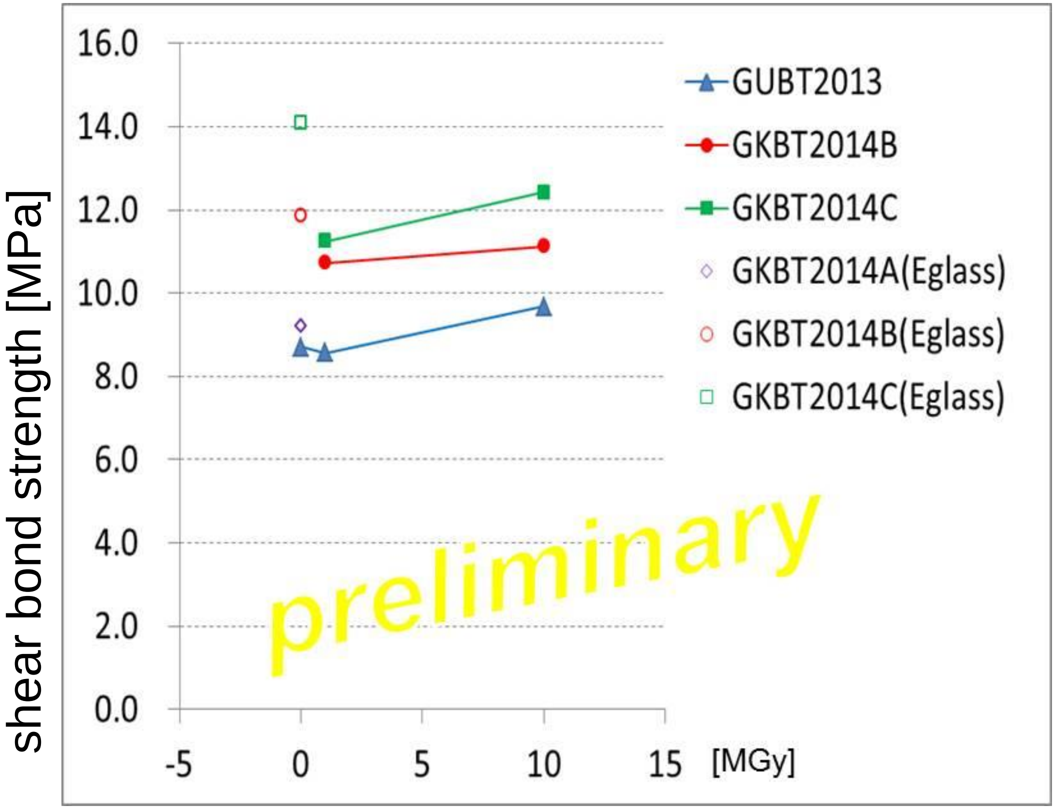
Irradiation Tests

- Insulation tape (BT+epoxy prepreg) by gamma ray at JAEA Takasaki
- Protection Diode for Muon Transport Solenoid by neutrons at Kyushu Univ.
- Stabilizer (Al, Cu) by reactor neutrons at KUR
  - 2010 Nov.:
    - Al+CuMg(#1)
  - 2011 Jan.:
    - Al+CuMg(#2) (check reproducibility)
  - 2011 Fev.: 5MW operation
  - 2011 Sep.:
    - 5N pure Al, Cu(#1)
  - 2011 Nov.:
    - Al+Y(#1), Al+Y(#2), Cu(#2)
  - 2012 Nov.: (check recovery & cyclic irradiation)
    - Al+Y(#1), Al+Y(#2), Cu(#2)
  - 2013 Mar.: No irradiation (check recovery)
    - Al+Y(#2), Cu(#2)
  - 2013 July: (cyclic irradiation)
    - Al+Ni(#1), Al+Y(#2), Cu(#2)
  - 2014 Apr.: (cyclic irradiation)
    - Al+Ni(#1), Al+Y(#2), Cu(#2)
  - 2014 Dec.: No irradiation (check recovery)
    - Al+Ni(#1), Al+Y(#2), Cu(#2)

  - LTL is closed in 2015

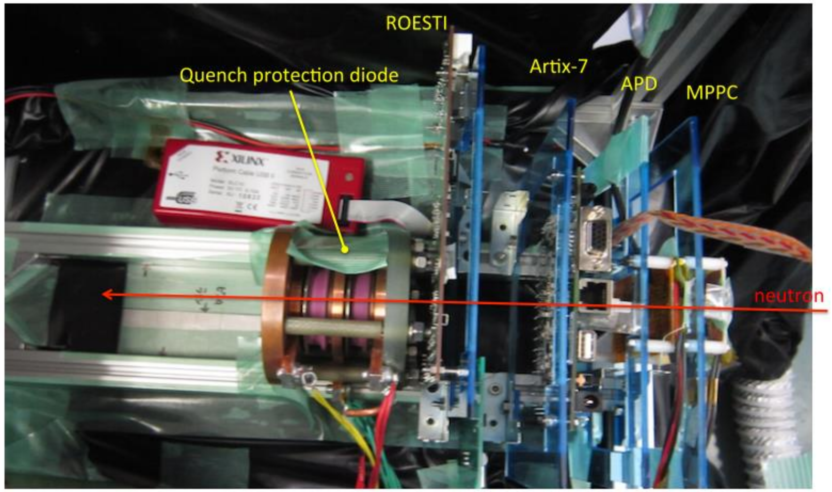
Irradiation Tests on Insulation Tape

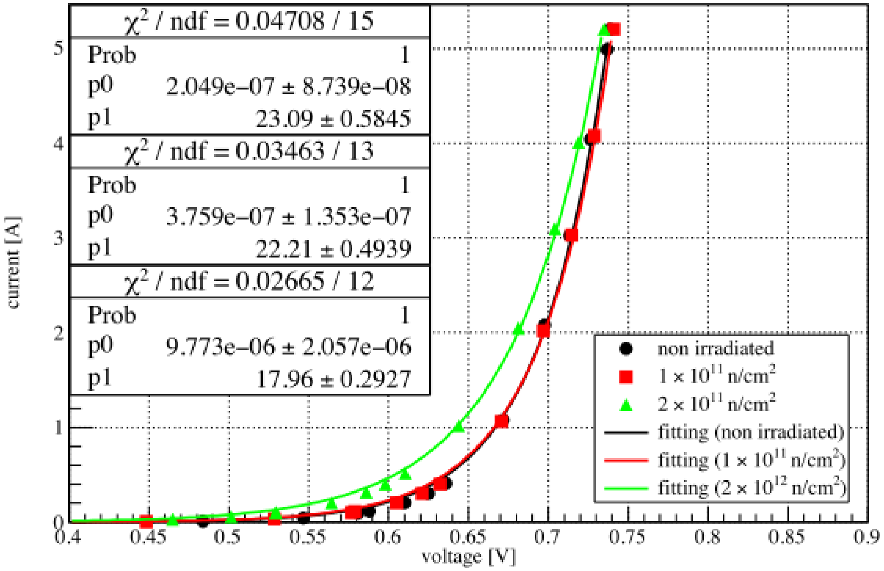
- BT+Epoxy prepreg tape was irradiated by Co gamma at Takasaki
- Shear bond strength is not affected by irradiation at 10MGy



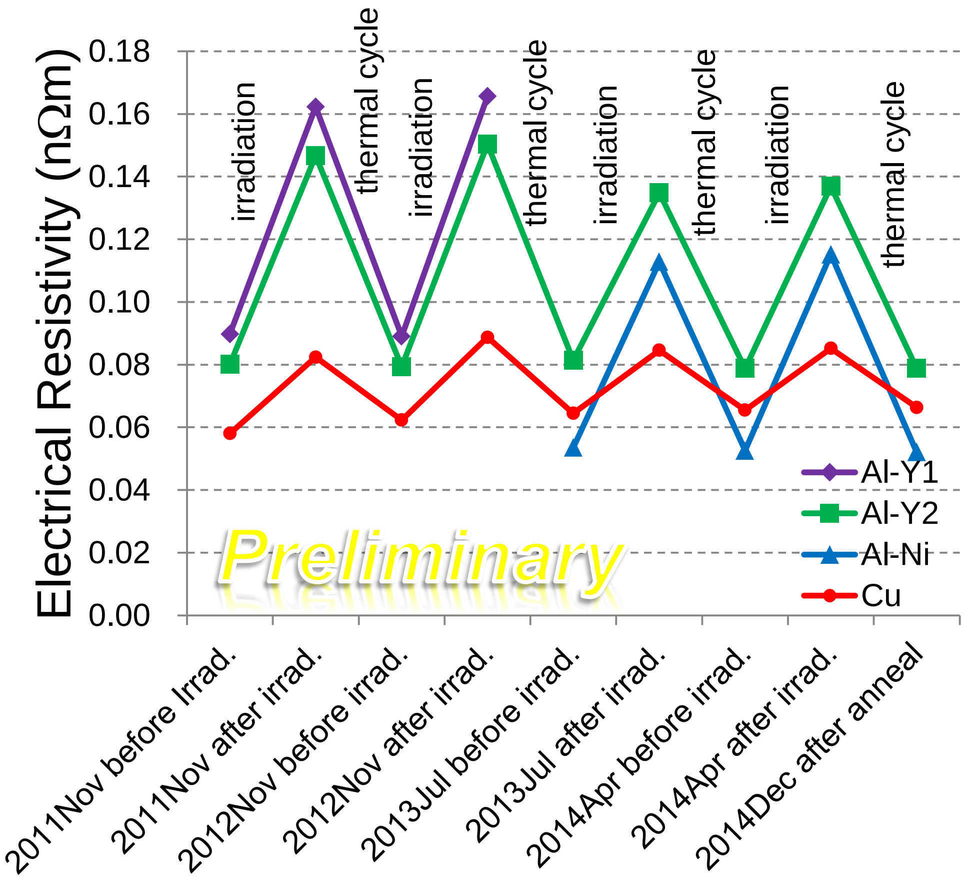
Radiation Effect in Diode

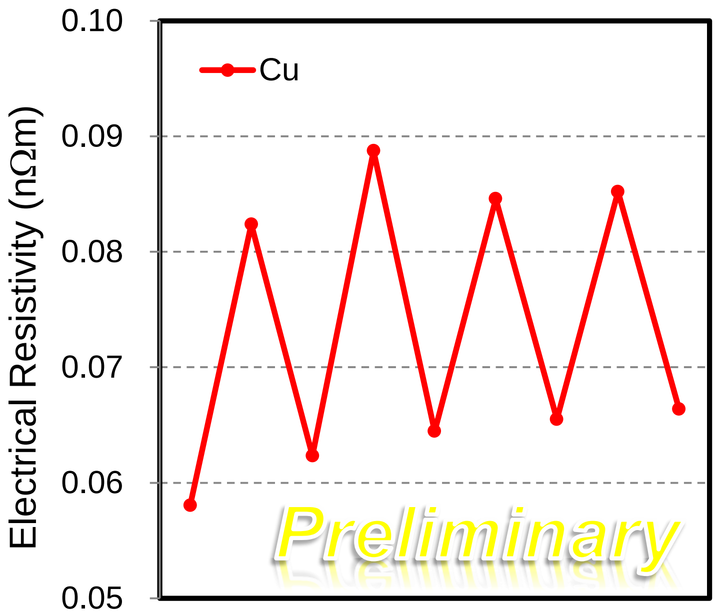
- Estimated irradiation on protection diodes
  - 10^{16} n/m^2 at PhaseII
- Diode was irradiated by neutrons at Kyushu Univ.
- Irradiation effect was observed in the forward voltage
- Influence on magnet operation is under estimation





Recovery by Anneal Effect





- All Al samples show "full" recovery of electrical resistivity after thermal cycle to RT.
- Nevertheless, Cu sample shows "partial" recovery of 82%~96%.

Resistance Degradation in COMET Phase-II

KUR measurement

ρi = 0.03 nΩm
for Φ(En>0.1MeV)10^{20} n/m^2

↓ 3×10^{21} n/m^2 in 280 days Phase-II

ρi = 0.9 nΩm

KUR data + PHITS DPA

ρi = 1 $\mu\Omega$m/DPA

↓ 1×10^{-5} DPA in 280 days Phase-II

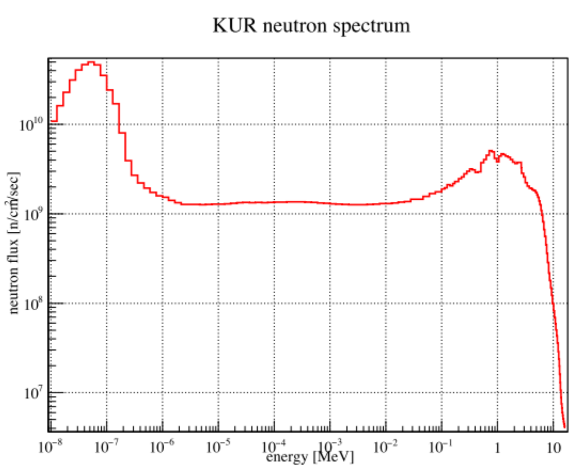
ρi = 0.01 nΩm

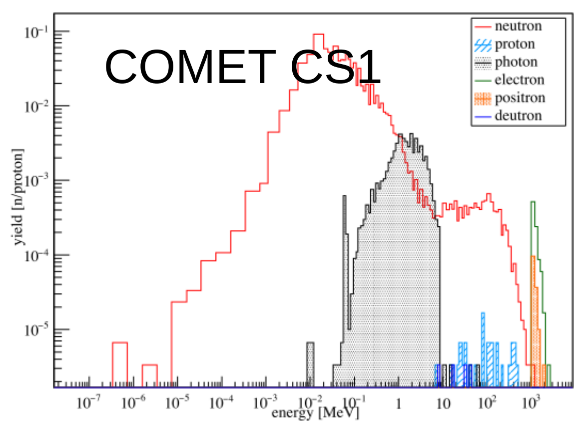
Degradation rate by theoretical calc.

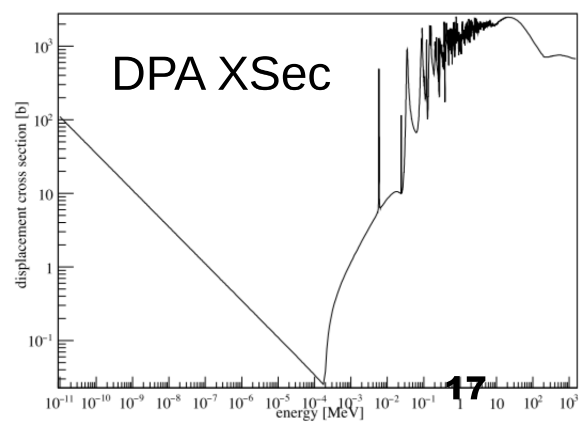
ρi = 7 $\mu\Omega$m/DPA

↓ 1×10^{-5} DPA in 280 days Phase-II

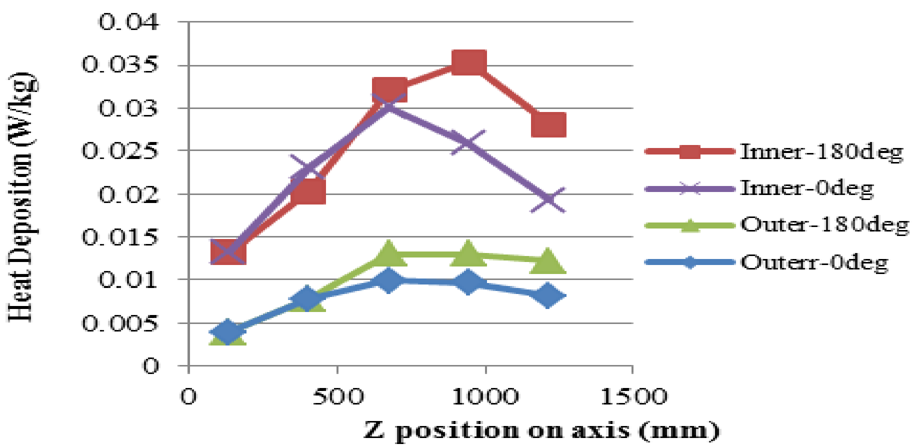
ρi = 0.07 nΩm

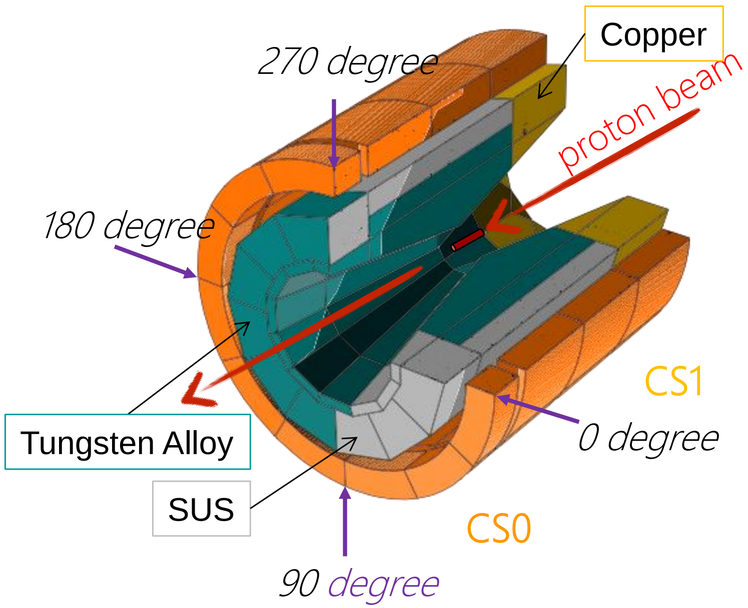


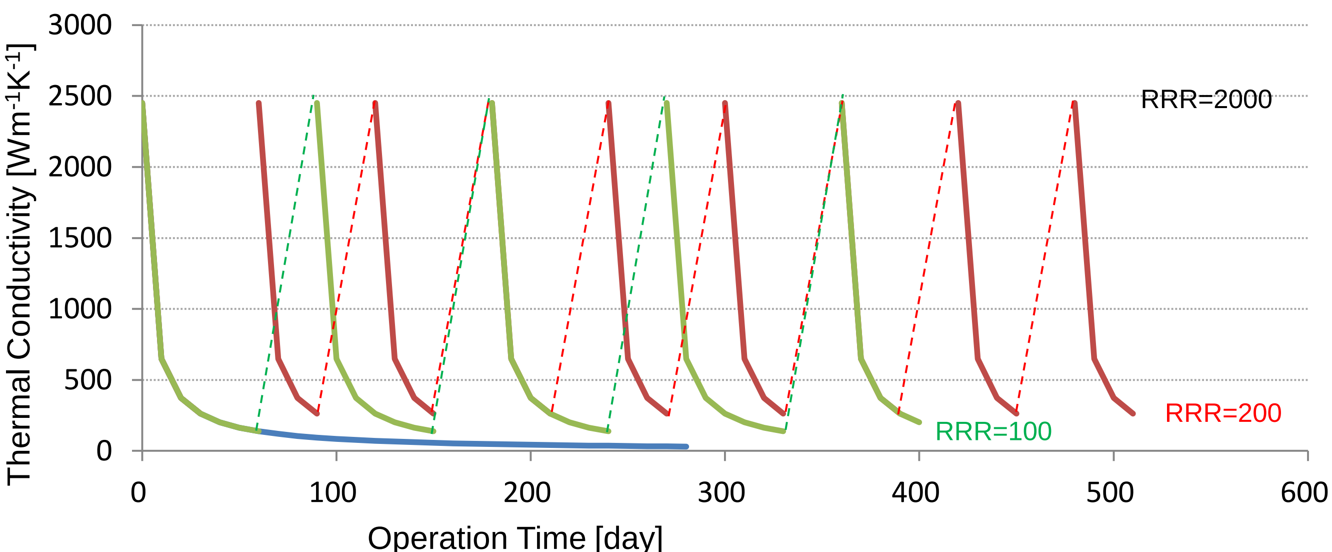




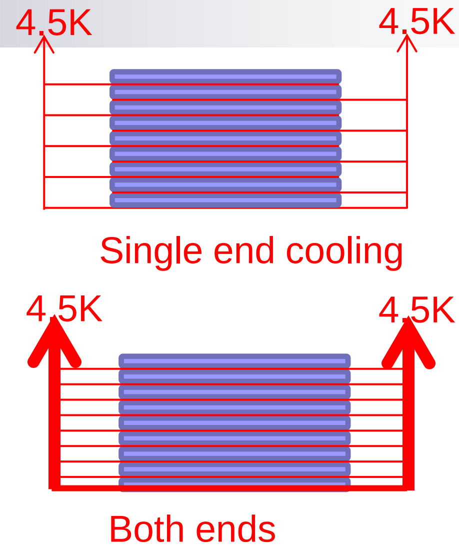
Heat Input and Degradation by Neutron Irradiation

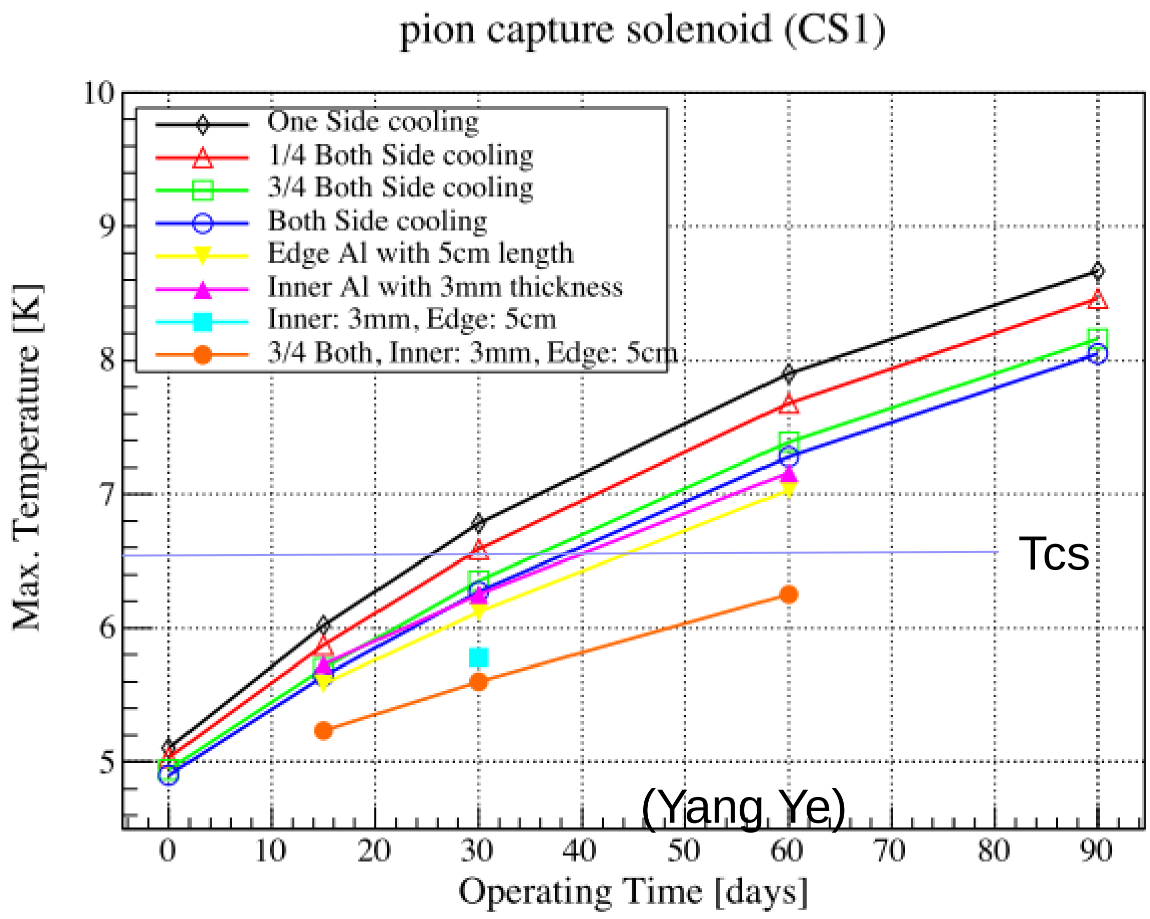






Peak Temperature in CS1 coil during Phase-II beam operation





For more temperature margin

- Cooling path at both ends
- Thicker Al at innermost layer
- Thicker Al to LHe pipe

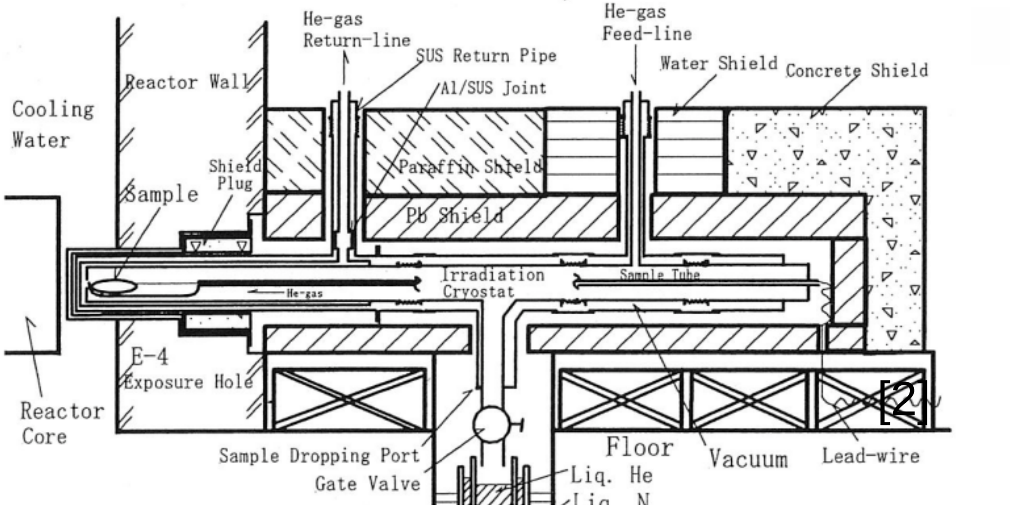
Optimization of coil design is in progress

Summary

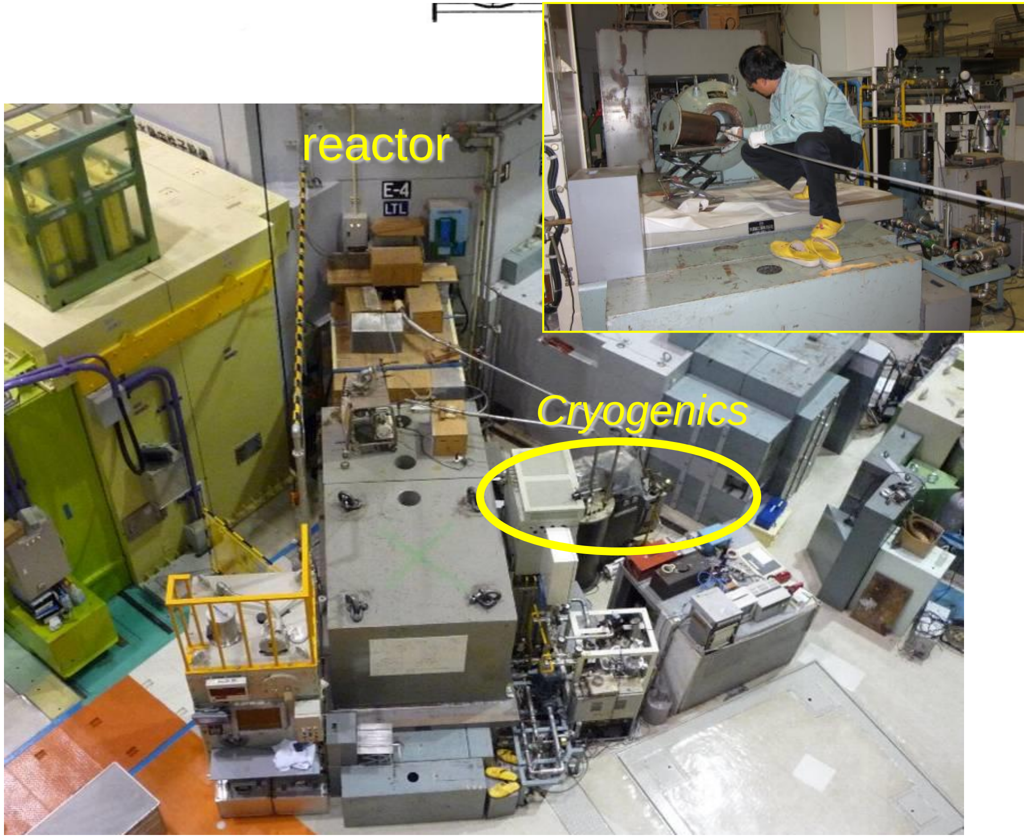
- Construction for COMET experiment started in FY2013.
  - New building was constructed at J-PARC Hadron Experiment Facility
  - Muon Transport Solenoid (90 degree) was deivered
  - Coil winding is in progress
- Irradiation tests was performed on Stabilizer, Insulation tape, Diode
- Design improvements for more radiation tolerance is in progress

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)
  - $1.4\text{x}10^{15}$ n/m^2/s@1MW



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



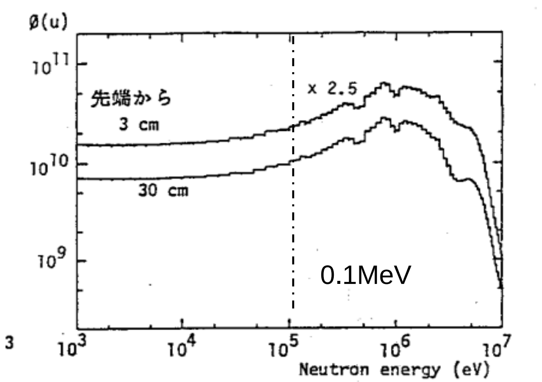
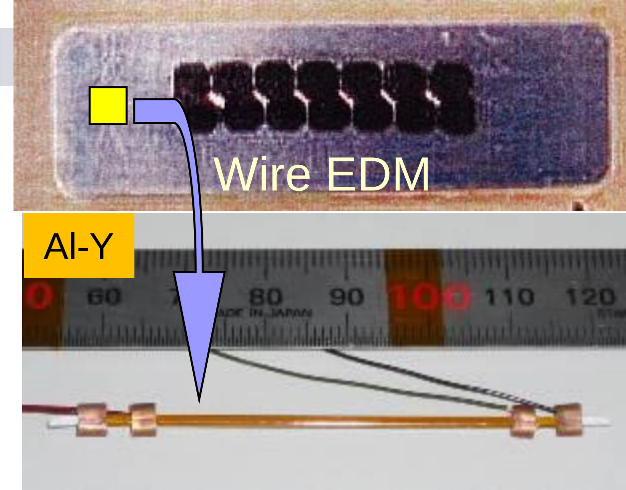


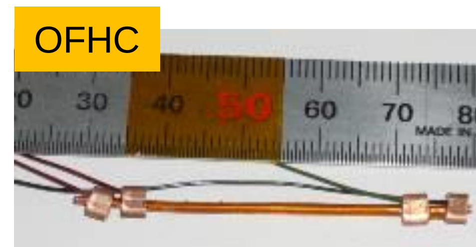
Fig. 15 Neutron energy spectrum in LTL of KUR for ordinary core (above 1000 eV)

KUR-TR287 (1987)

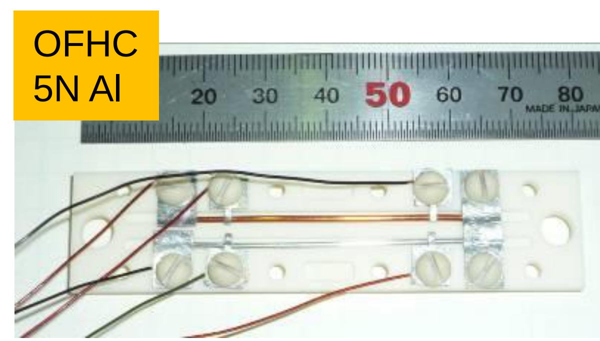
Irradiation Sample



- Aluminum
  - 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 Cable Ltd.
  - 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)



Summary of Neutron Irradiation

	Aluminum										Copper					
	Horak	Guinan	Al-5N	Al+CuMg	Al+Y 2011	Al+Y 2012	Al+Y 2013	Al+Y 2014	Al+Ni 2013	Al+Ni 2014	Horak	Guinan	OFHC 2011	OFHC 2012	OFHC 2013	OFHC 2014
RRR	2286	74	3000	450	341, 360	342, 360	-, 368	-, 367	561	566	2280	172	308 (10K)	291 (13K)	285 (13K)	277 (12K)
T_{irr} (K)	4.5	4.2	15	12	12	15	15	14	15	14	4.5	4.2	12	15	15	14
Neutron Source	Reactor	14 MeV	Reactor								Reactor	14 MeV	Reactor			
Φ_{tot} (n/m^2) (>0.1MeV)	2 x 10^{22}	1-2 x 10^{21}	2.6 x 10^{20}	2.3 x 10^{20}	2.6 x 10^{20}	2.6 x 10^{20}	2.6 x 10^{20}	2.7 x 10^{20}	2.6 x 10^{20}	2.7 x 10^{20}	2 x 10^{22}	1-2 x 10^{21}	2.6 x 10^{20}	2.6 x 10^{20}	2.6 x 10^{20}	2.7 x 10^{20}
$\Delta\rho_{irr}/\Phi_{tot}$ x10^{-31}(Ωm^3)	1.9	4.1	2.5	2.4	2.6, 2.8	2.7, 2.9	2.5	2.2	2.3	2.3	0.58	2.29	0.93	1.02	0.77	0.73
Recovery by thermal cycle	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	90%	80%	82%	92%	95%	96%

- Degradation rate ($\Delta\rho_{irr}/\Phi_{tot}$) seems to be consistent with the previous reactor neutron irradiation.
    - higher in 14 MeV neutron irradiation.
- Present work shows that difference in RRR (300-3000) of Al doesn't influence the degradation rate or recovery behavior.
- Partial recovery observed in Cu, but would be saturated after multiple irradiation??