Neutron Irradiation Tests at KUR and Design Update of COMET Magnet

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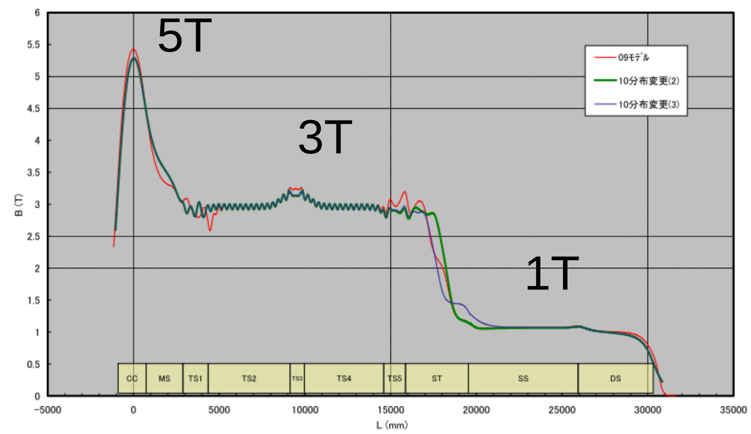
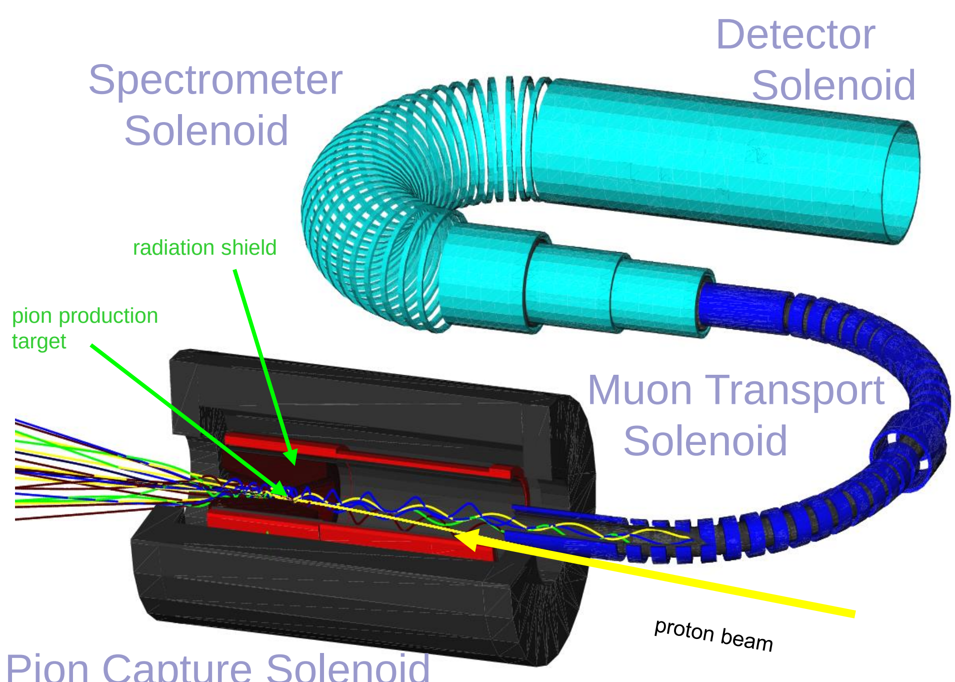
Contents

- Introduction to Superconducting magnet for COMET
- Preliminary results of irradiation test of stabilizer material, thermosensor
- Estimation of irradiation effects on COMET magnet

COMET Magnet System

- J-PARC E21
- 8GeVx7μA
- 10^{11} μ^{-}/sec
- A series of long solenoids from end to end
  - pion capture & decay
    - *High field on Target*
  - muon transport
  - electron focus
  - spectrometer
  - detector

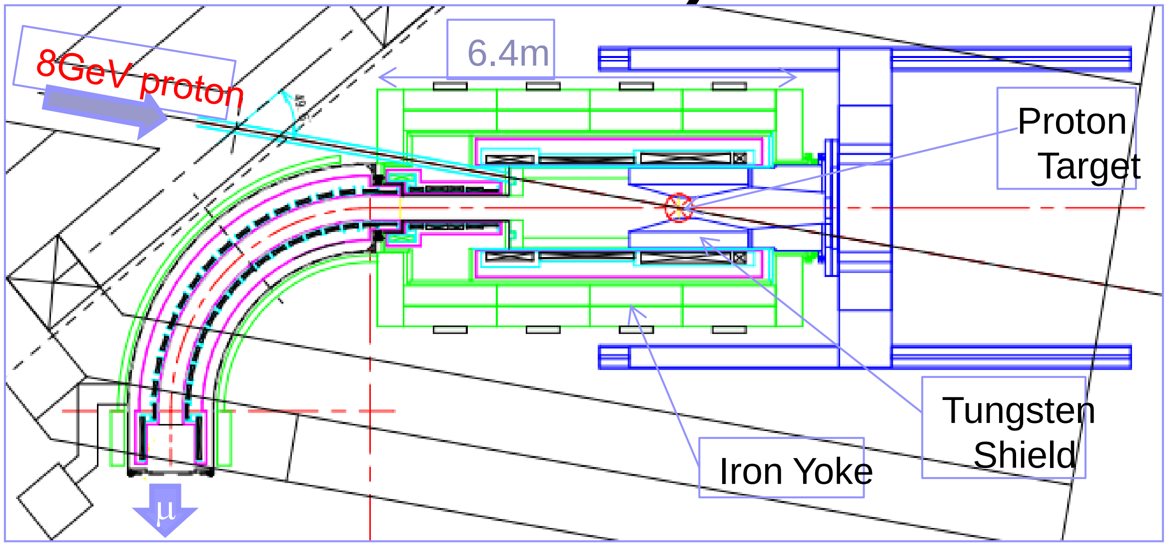


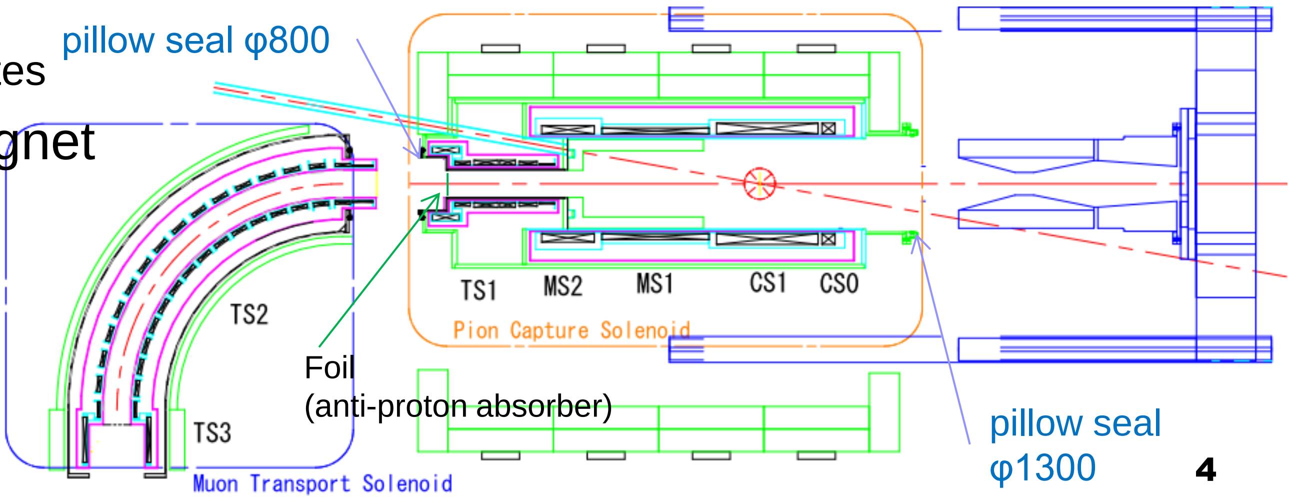


COMET Superconducting Magnet System

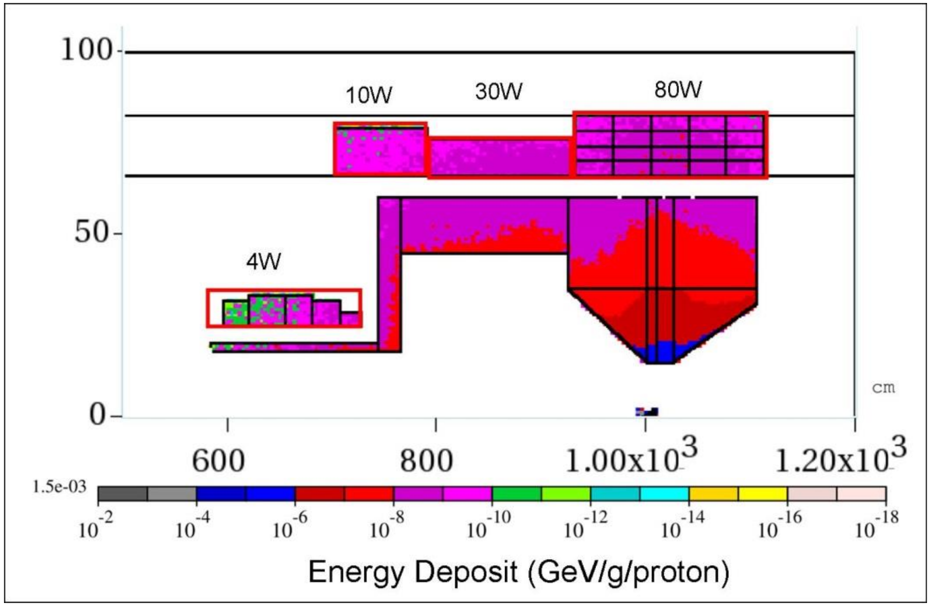
Components of the Magnet System (muon beam line)

- Pion Capture Solenoid
  - warm bore
  - pillow seal at both ends
- Transport Solenoid
  - 80K bore
- Iron yoke
  - Stack of iron plates
- Shield inside magnet bore
  - Slide into bore





Radiation Dose



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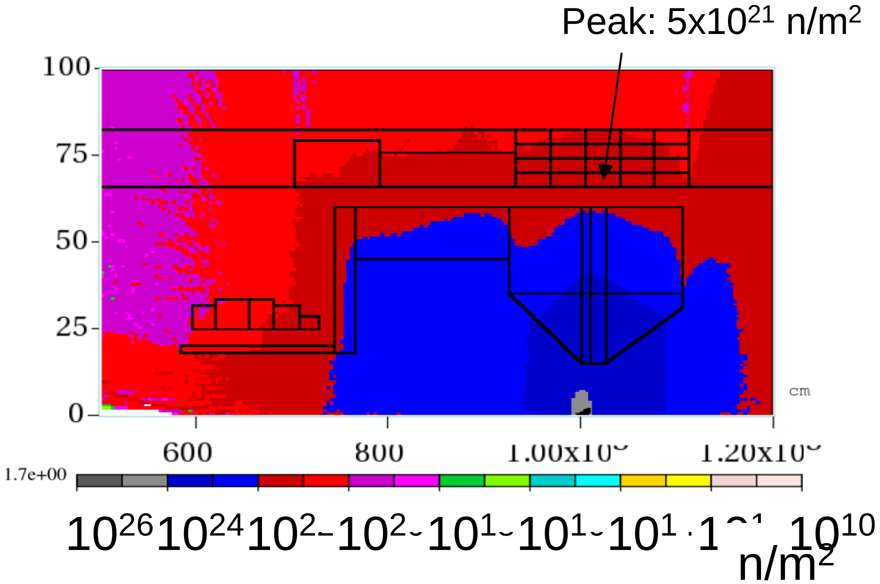
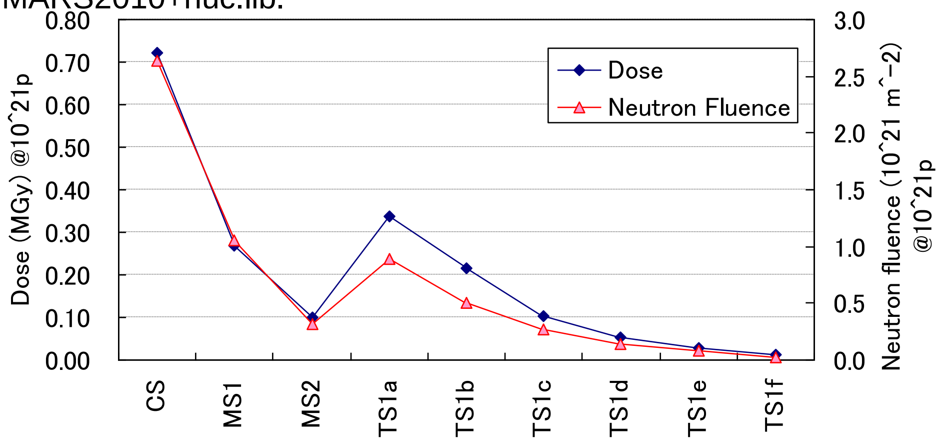


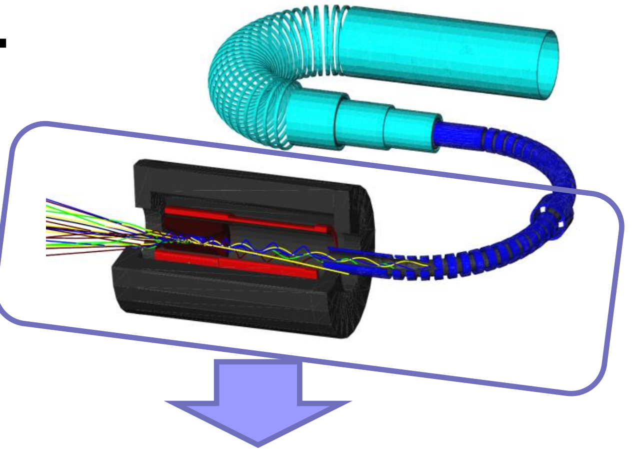


Averaged in circumferential direction

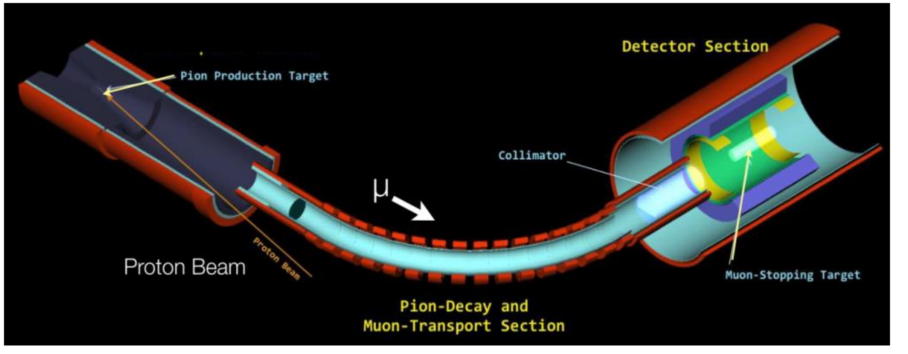
Nuclear Heating : >100W
Peak dose rate in Al : >1MGy
Neutron fluence : >10^{21} n/m^2

Status of the COMET experiment

- Construction for the COMET phase-I has been started in 2014
- Civil construction of experimental hall for the COMET experiment is underway.
- Production of magnet coils are slowly initiated

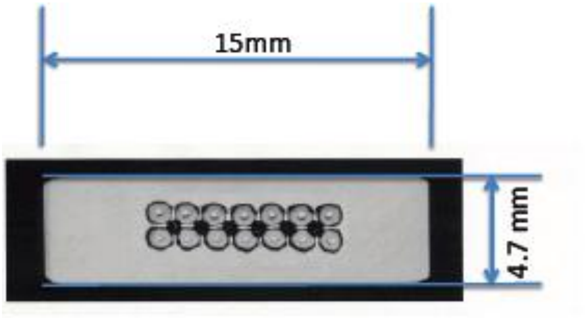


Phase-I



Al-stabilized superconductor

- NbTi Rutherford cable with aluminum stabilizer
- "TRANSPARENT" to radiation
  - Less nuclear heating
- Ni doped, cold worked aluminum
  - Good residual resistance
    - RRR>500
  - Good yield strength
    - 85MPa@4K



COMET design value

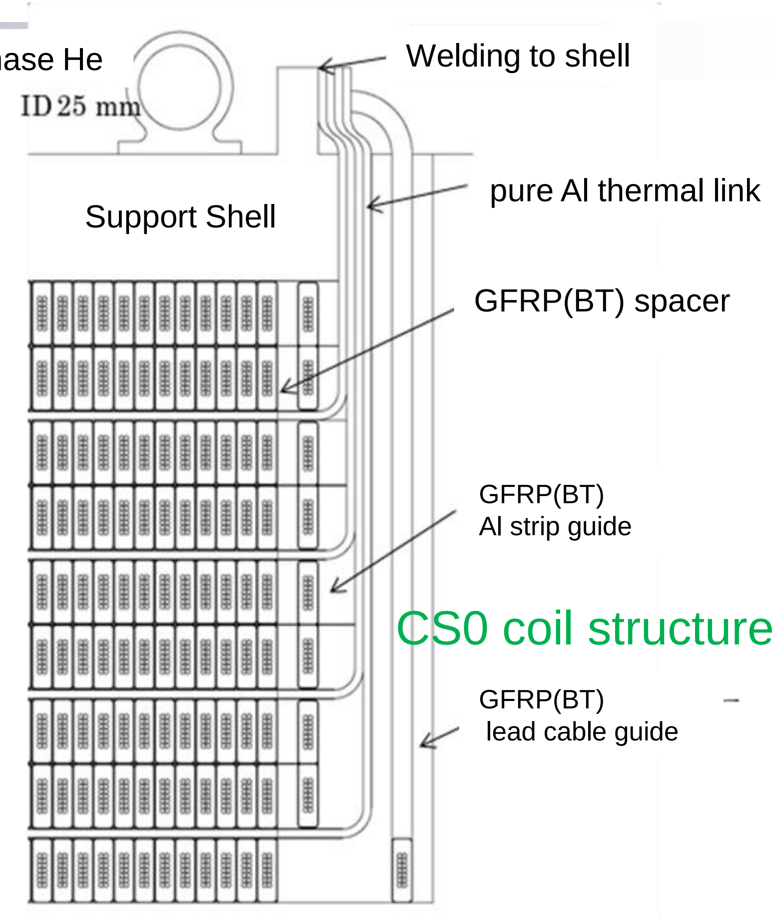
- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

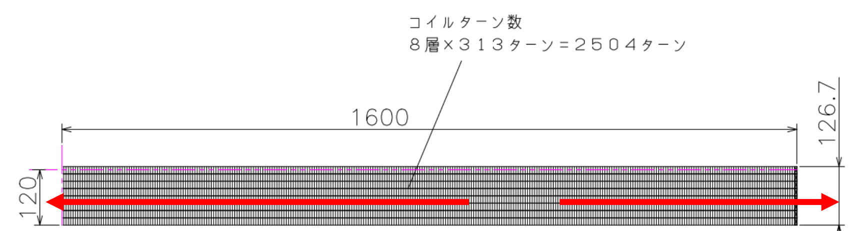
Capture Solenoid Coil Structure

- Bath cooling could cause helium activation
  - Tritium production by $^{3}He(n,p)^{3}H$
  - Larger cold mass for LHe vessel -> Larger refrigerator

→ Conduction cooling

  - Remove nuclear heating by pure aluminum strip in between coil layers





Heat transfer

Problematic components

- Stabilizer
  - Aluminum alloy
  - Copper
- Thermal conductor
  - Pure aluminum
  - Copper
  - Aluminum alloy
- Thermo sensor
  - No experience at 10^{21} n/m^2

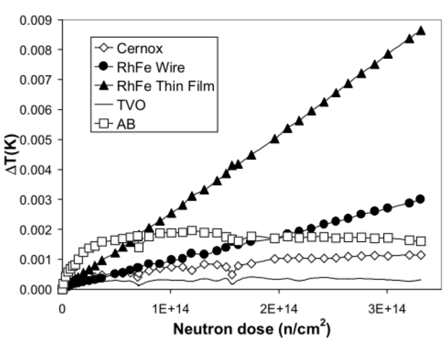


Figure 3 Error on temperature measurement on some sensors during irradiation (Tbath=1.8 K)

LHC Project Report 209

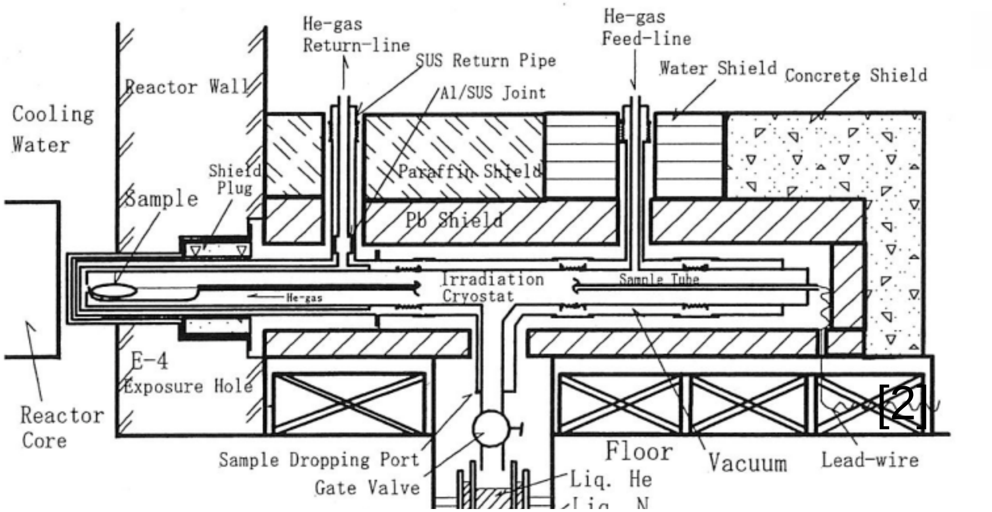
- Fast-neutron irradiation induces defects in metal.

- Defects could be accumulated at Low temperature,
- and causes degradation of electrical/thermal conductivity

- Problems in
  - Quench protection, Stability
  - Cooling

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



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

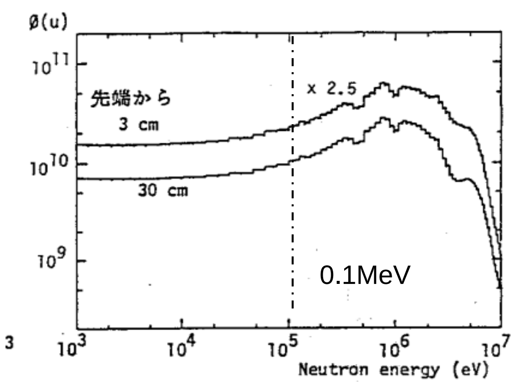
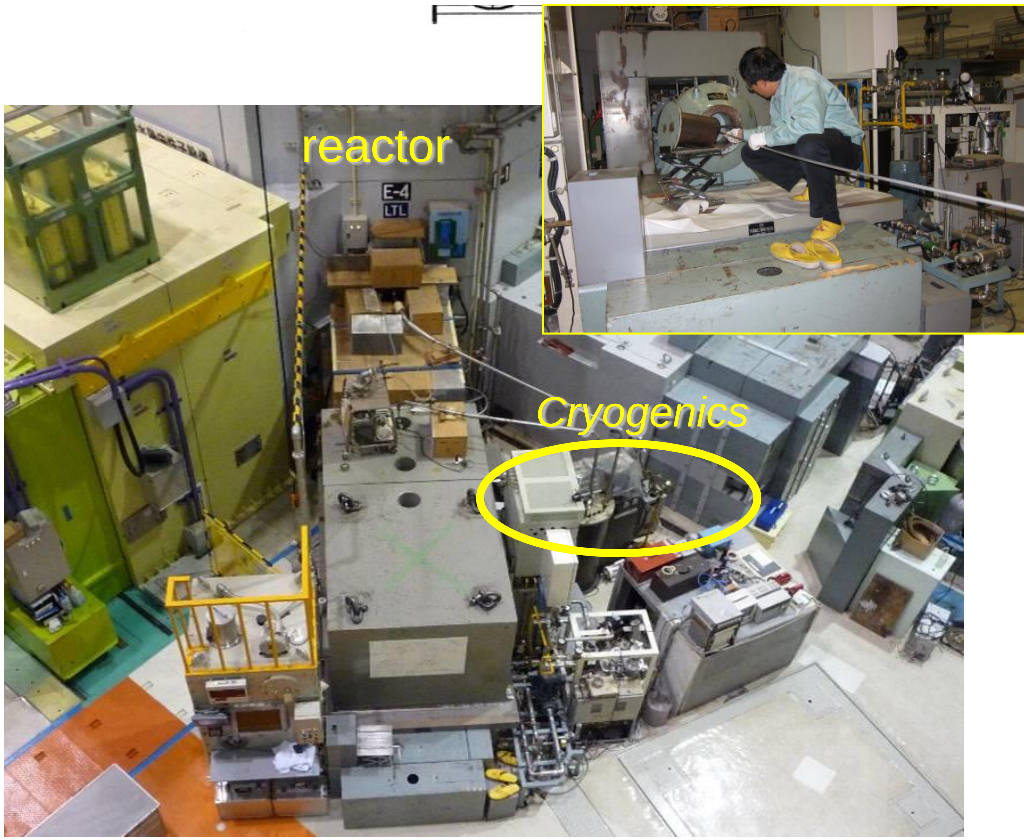
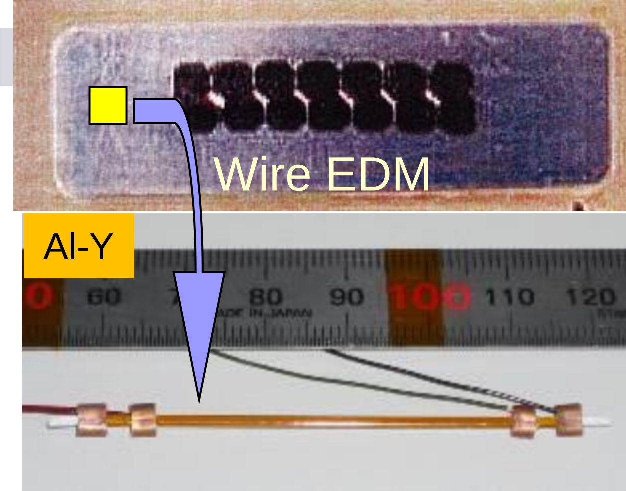


Fig. 15 Neutron energy spectrum in LTL of KUR for ordinary core (above 1000 eV)

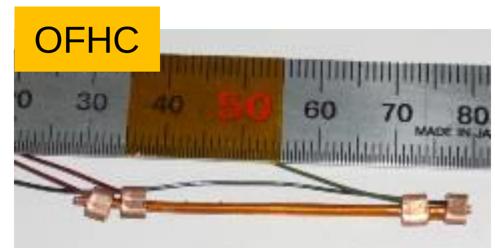
KUR-TR287 (1987)



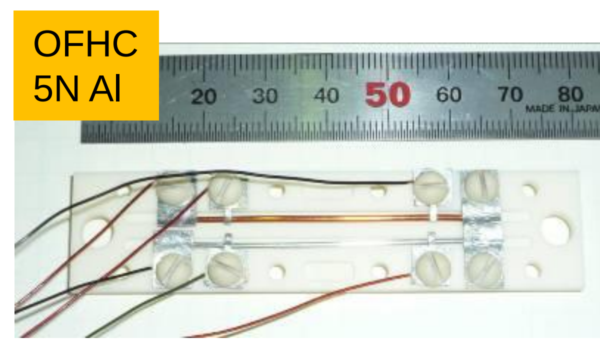
Irradiation Sample



- 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)

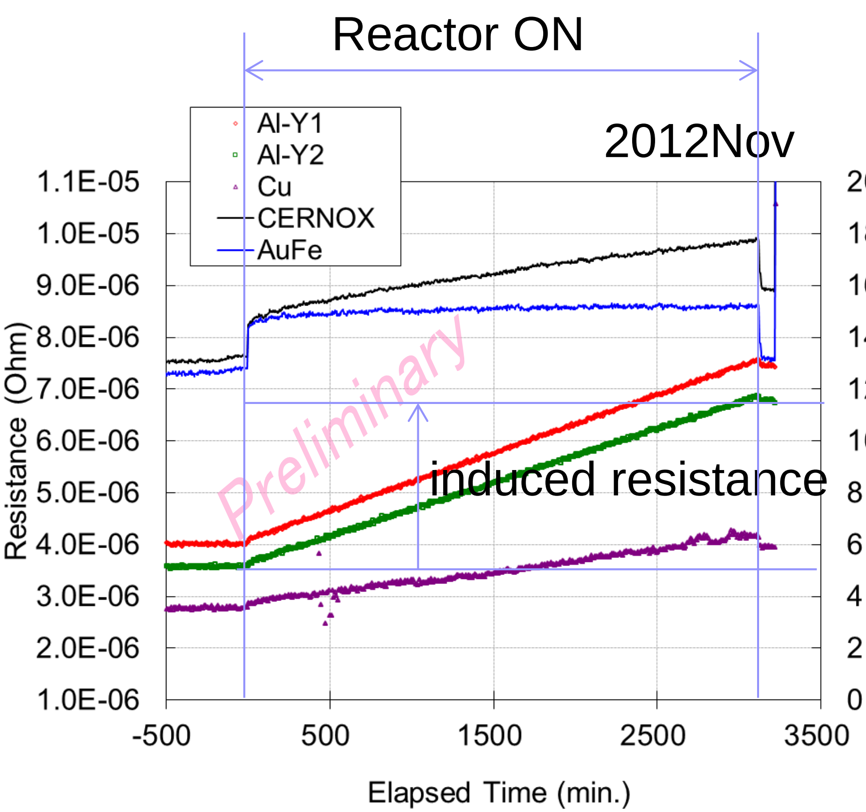


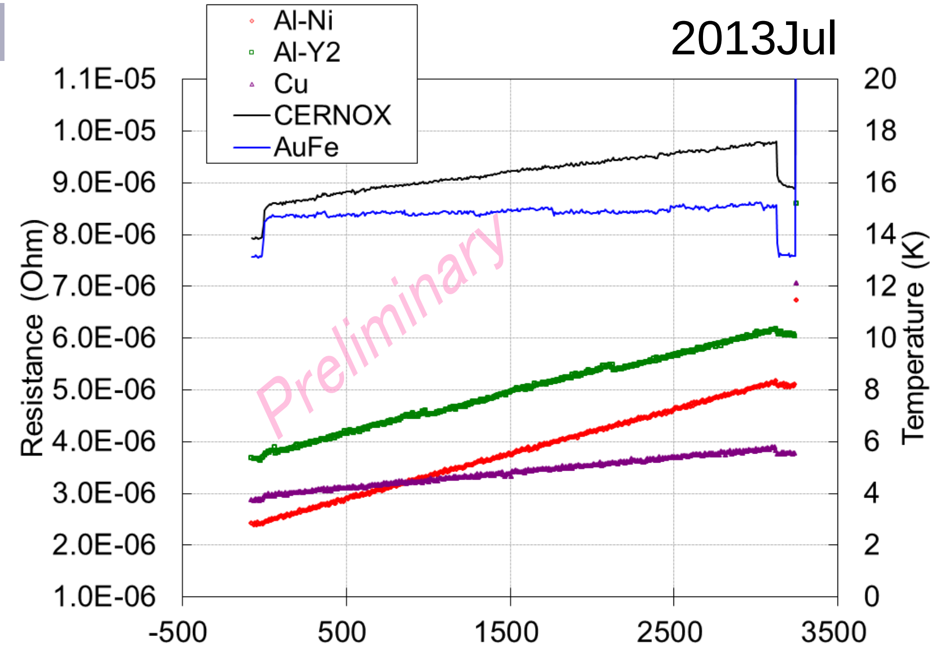
Neutron Irradiation Tests

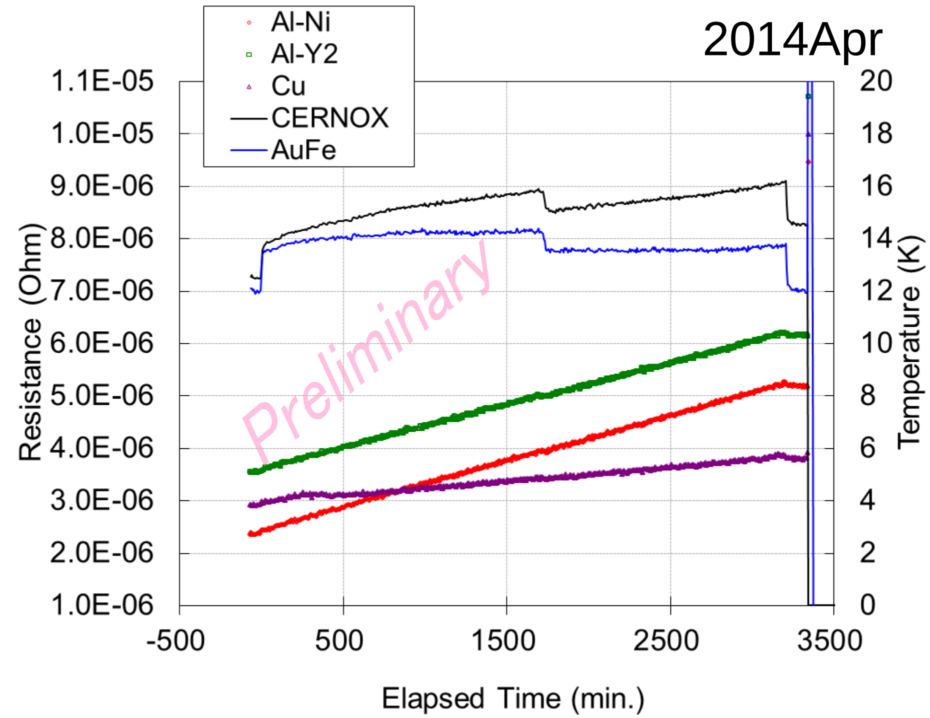
- Neutron exposure at 13K-15K
- 4 wire resistance measurement by nano-voltmeter (Keithley 2182A+6221)
- Temperature near sample measured by CERNOX and TC
- Flux measured by Ni foil activation ; 58Ni(n,p)58Co

  - 2010 Nov.: Al-CuMg(#1), CX-1050 , Ni foil
  - 2011 Jan.: Al-CuMg(#2) , CX-1050
  - 2011 Sep.: 5N-Al, OFHC(#1) , CX-1050, TC(AuFe)
  - 2011 Nov.: Al-Y(#1,#2) OFHC(#2), CX-1050, TC(AuFe)
  - 2012 Nov.: Al-Y(#1,#2), OFHC(#2), CX-1050, TC(AuFe)
  - 2013 Jul.: Al-Ni, Al-Y(#2), OFHC(#2), CX-1050, TC(AuFe)
  - 2014 Apr.: Al-Ni, Al-Y(#2), OFHC(#2), CX-1070, TC(AuFe) , Ni foil

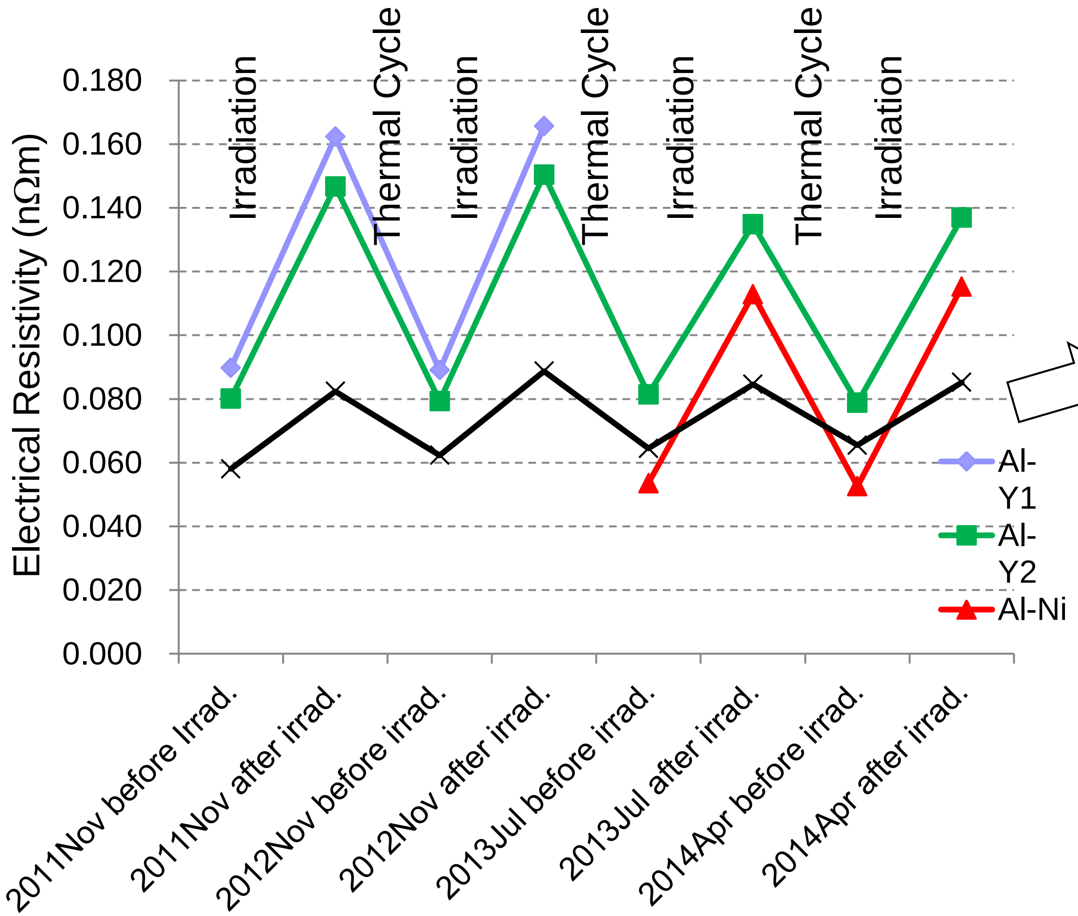
Preliminary Results (2012-2014)

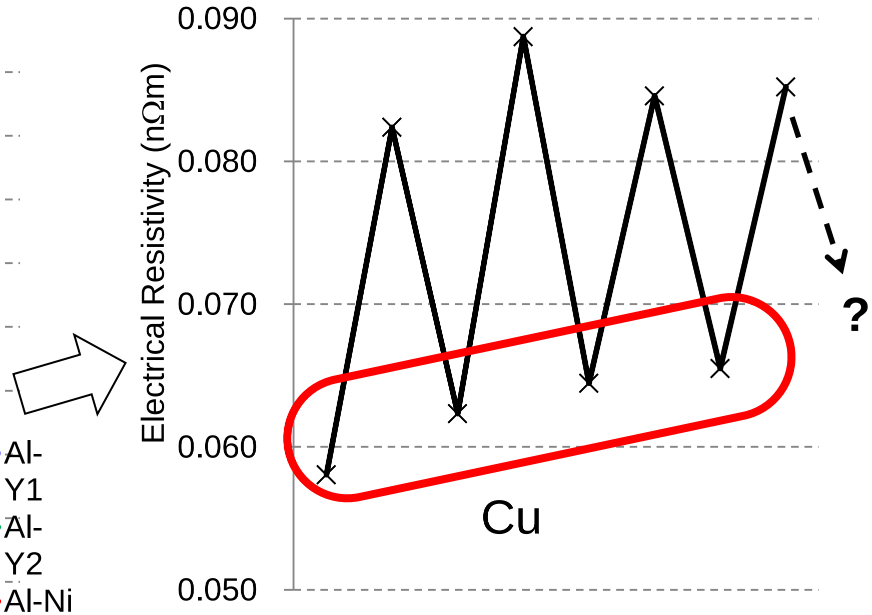






Recovery by Anneal Effect





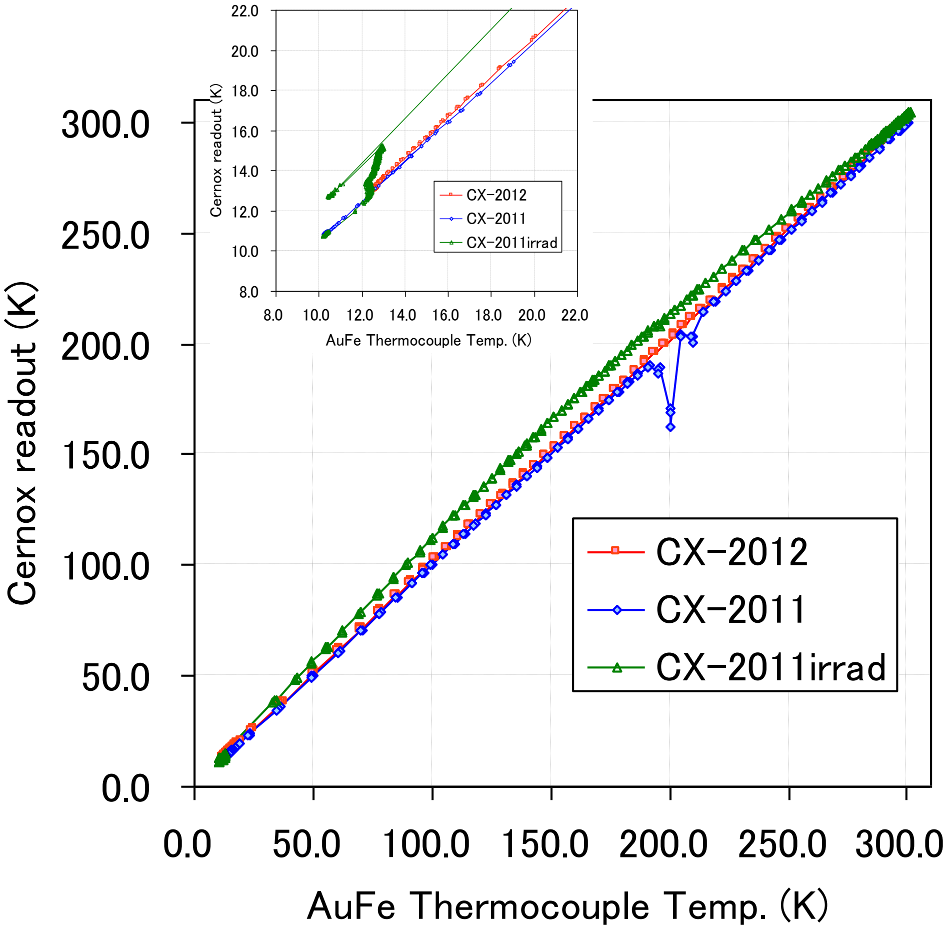
- All Al samples show "full" recovery of electrical resistivity after thermal cycle to RT.
- Nevertheless, Cu sample shows "partial" recovery of 82%~95%.

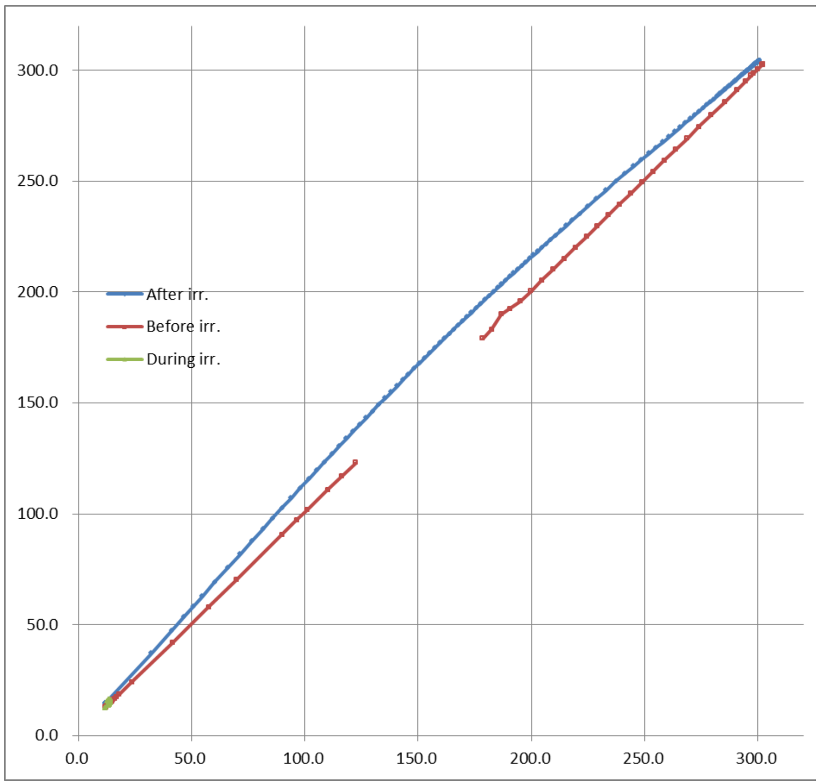
Summary of Neutron Irradiation

	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 %	TBD	100 %	TBD	90%	80%	82%	92%	95%	TBD

- 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??

Irradiation effects in Cernox™ sensor

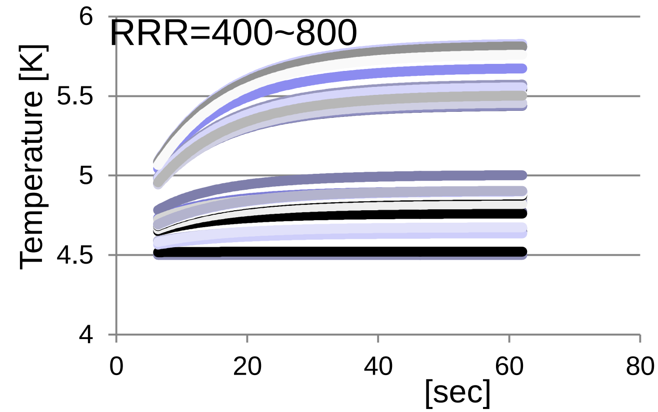




- Cernox sensor show degradation by neutron irradiation
- Almost recover by thermal cycle to RT
- CX-1050 and CX-1070 show same tendency

Irradiation effects on quench protection / cooling

- Electrical/thermal conductance can be degraded by neutron irradiation
- Assumption
  - Peak fast neutron fluence ~5×10^{21} n/m^2 for 10^21 protons (COMET PhaseII)
  - Neutron induced resistance : 0.03 nOhm.m for 10^{20} n/m^2



Al stabilizer

Month		0	1	3	12	24
Neutron fluence(peak)	n/m2	0.00E+00	2.08E+20	6.25E+20	2.50E+21	5.00E+21
RRR (Original)		400	400	400	400	400
Neutron-induced Resistivity	nOhm-m	0.00E+00	6.25E-02	1.88E-01	7.50E-01	1.50E+00
Total resistivity @4K		0.0675	0.13	0.255	0.8175	1.5675
RRR		400	208	106	33	17

Tmax>150K

Coil can be protected at RRR>100

Al thermal conductor

Month		0	1	3	12	24
Neutron fluence (phi-averaged)	n/m2	0.00E+00	1.04E+20	3.13E+20	1.25E+21	2.50E+21
RRR (Original)		2000	2000	2000	2000	2000
Neutron-induced Resistivity	nOhm-m	0.00E+00	3.13E-02	9.38E-02	3.75E-01	7.50E-01
Total Resistivity @4K		0.0135	0.04475	0.10725	0.3885	0.7635
RRR		2000	603	252	69	35
Thermal Conductivity	W/m/K	8167	2464	1028	284	144

Tcoil>6K

Temperature margin will be short at RRR<200

Need to be updated including degradation distribution

Summary

- A series of neutron irradiation tests on stabilizer material has been done.
- No effects of multiple cycles of irradiation and annealing ware observed in aluminum
- Copper shows drift of residual resistance after annealing.
- Operation of COMET magnet could be limited by degradation of thermal conduction.
  - Temperature gradient in a coil will exceed margin in a few month. Need more study (more cooling path?).