Superconducting Magnet R&D for COMET

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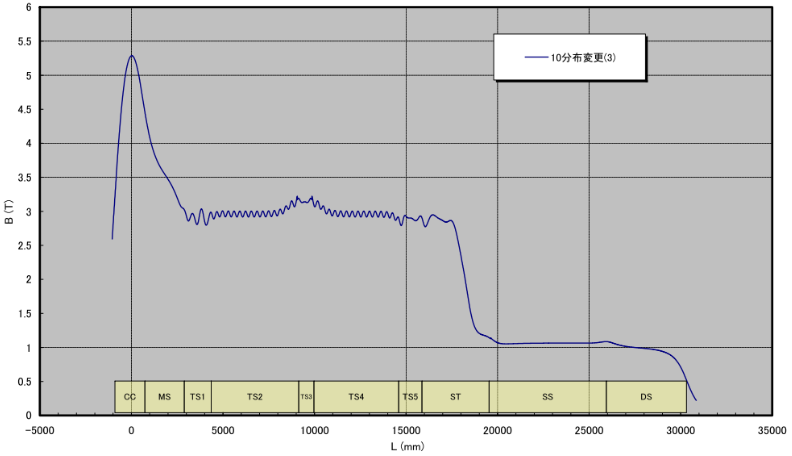
Issues in Superconducting Magnet R&D

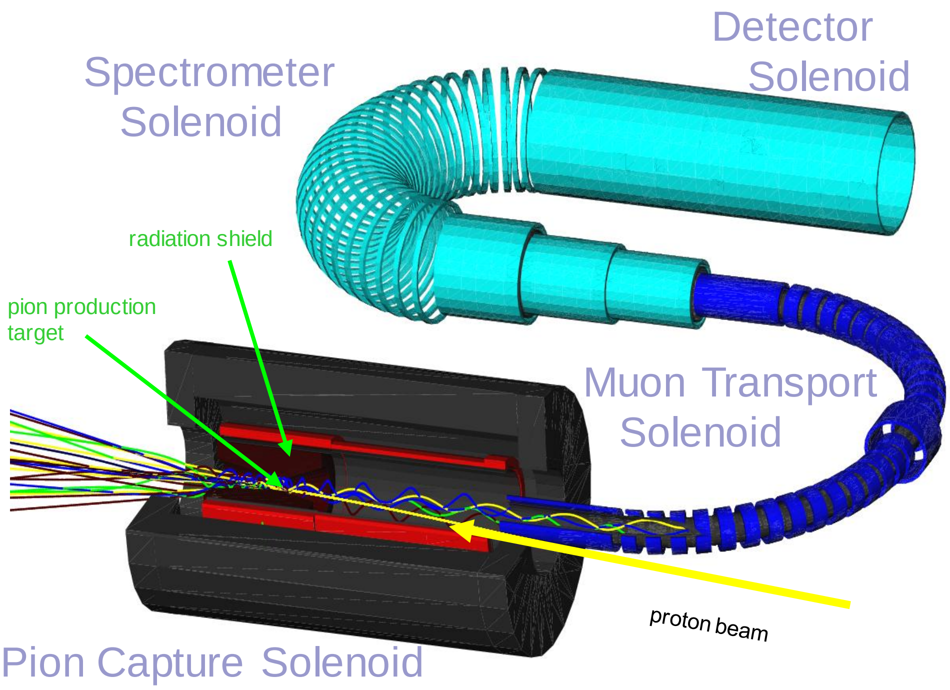
- Solenoid capture scheme is proposed in Neutrino Factory and intense muon (μ^-) source for mu-e conversion experiments, COMET at J-PARC and Mu2e at FNAL.
- Higher magnetic field is needed for better collection efficiency of pions.
- Superconducting magnets will provide 5T on the target in COMET/Mu2e, 20T in NF
- Magnet components are irradiated by severe radiation from the embedded target.

- Radiation issues should be considered in a magnet design.
- Investigation of irradiation effects on magnet materials has been initiated in 2010 with reactor neutrons

COMET@J-PARC

- Searching for muon-electron conversion
  - J-PARC E21
- 8GeVx7microA pulse protons from MR
- Aims at 10^{18} negative muons for 10^{21} protons
- Superconducting solenoid magnets from end to end;
  - Pion capture
  - Muon Transfer
  - Spectrometer
  - Detector

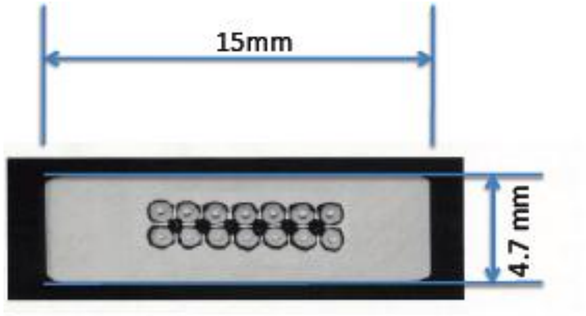




COMET Superconducting Magnet System

Al-stabilized superconductor

- NbTi Rutherford cable with aluminum stabilizer
  - Less nuclear heating than with Cu stabilized cable
- Doped, cold-worked pure aluminum
  - Good residual resistance
    - RRR~500 (ρ_0=0.05nΩm@4K)
  - Good yield strength
    - 85MPa@4K



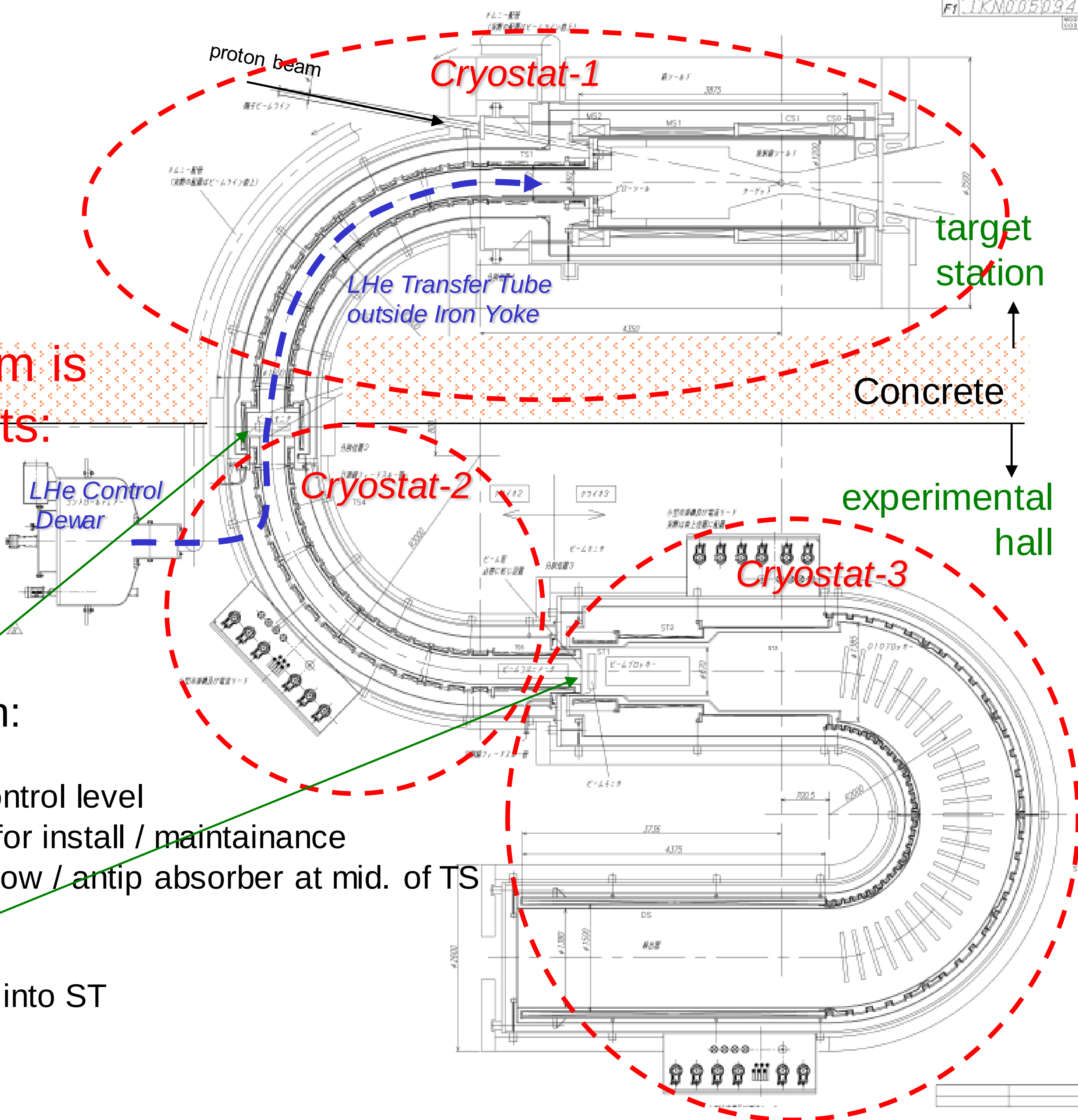
COMET design value

- 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.

COMET Magnet Design

The magnet system is separated in 3 parts:

Cryostat-1: CS+UpstreamTS
Cryostat-2: DownstreamTS
Cryostat-3: ST+SS+DS

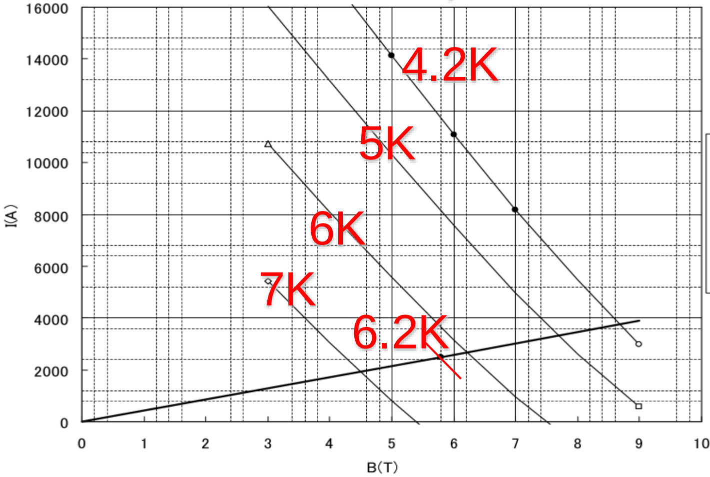


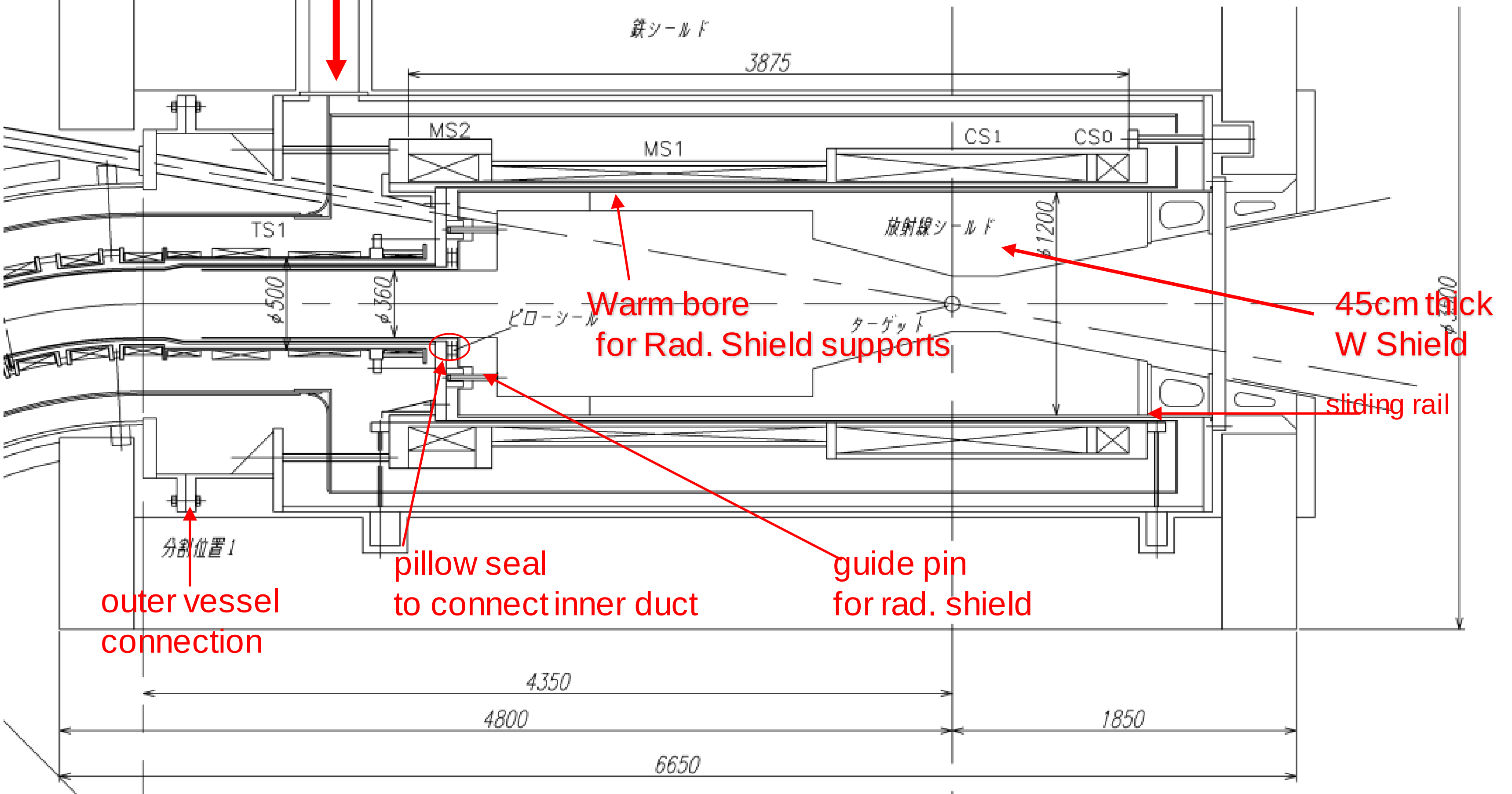
Purpose of separation:

- At concrete wall
    - Different radiation control level
    - Movable Cryostat-2 for install / maintainance
    - Vac. separation window / antip absorber at mid. of TS
    - Beam monitors
- At stopping target
    - inject electron beam into ST
    - Muon beam monitor

Pion Capture Solenoid

Load Line of CS,MS





LHe Transfer from TOP

Warm bore for Rad. Shield supports

45cm thick W Shield

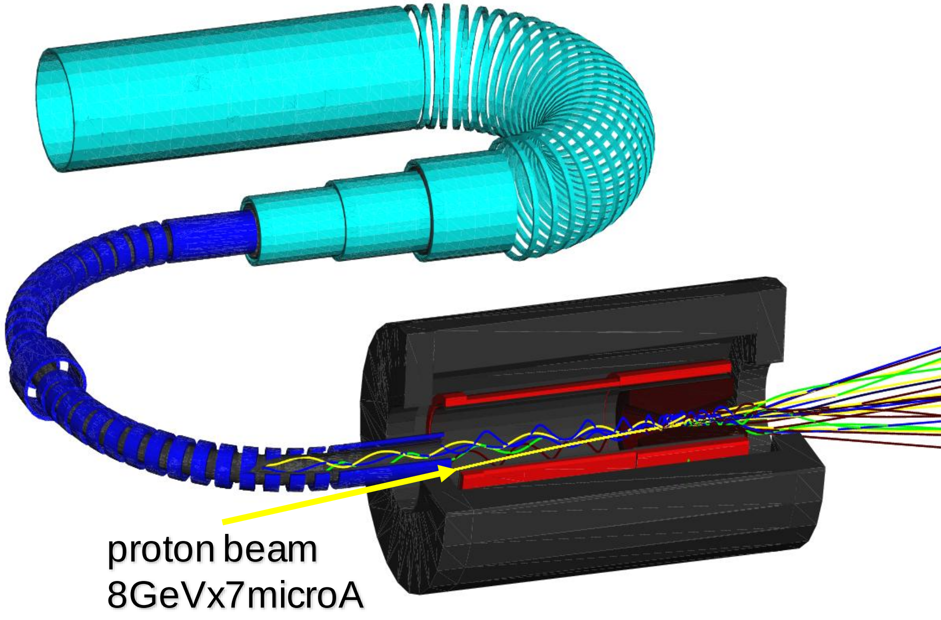
sliding rail

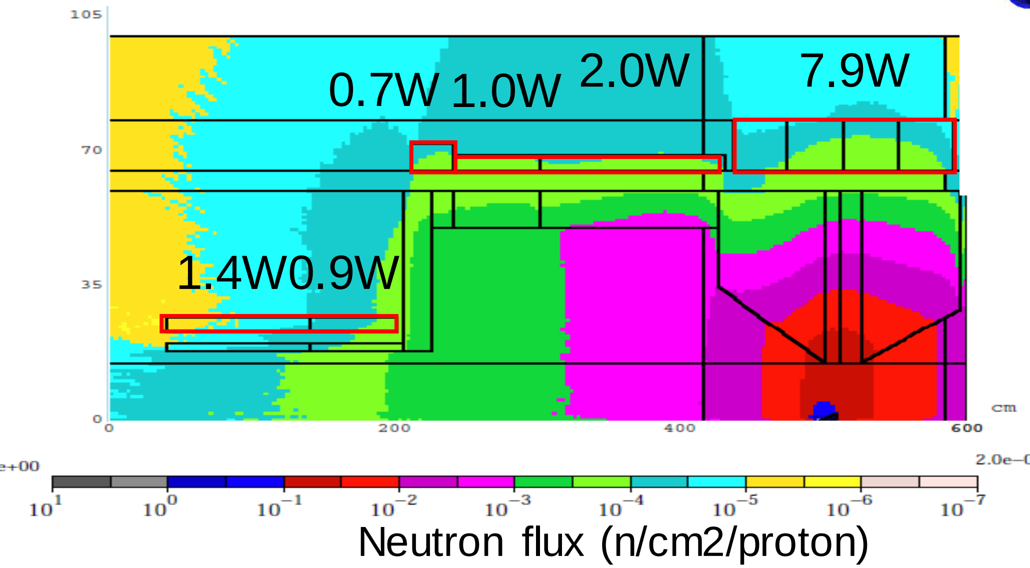
outer vessel connection

pillow seal to connect inner duct

guide pin for rad. shield

Capture Solenoid of COMET





- Maximum heat deposit
  - 10 mW/kg
- Maximum dose
  - 0.07 MGy/10^{21}p
- Neutron flux
  - 1×10^{21} n/m^2/10^{21}p
  - fast neutrons 6×10^{20} n/m^2/10^{21}p (>0.1MeV)

Neutrons penetrates thick 45cm tungsten shield surrounding the target

Neutron fluence for experimental life-time (~10^{21} p) approaches a level of ITER magnets (ITER requirement: <10^{22} n/m^2)

What's the effects on magnet properties?

Radiation hard magnet material

- Insulator, resin
  - BT-resin, Cyanate ester
  - Polyimide/Glass composite
- Thermal insulator
  - Al-coated polyimide film; Less outgas
- Support structure
  - GFRP, Titanium rod
- Superconductor
  - NbTi, Nb3Sn would be OK up to 10^{22} n/m^2

Problematic components

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

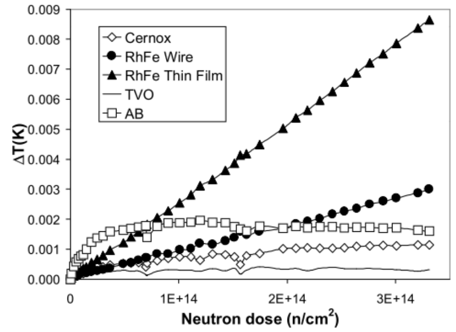
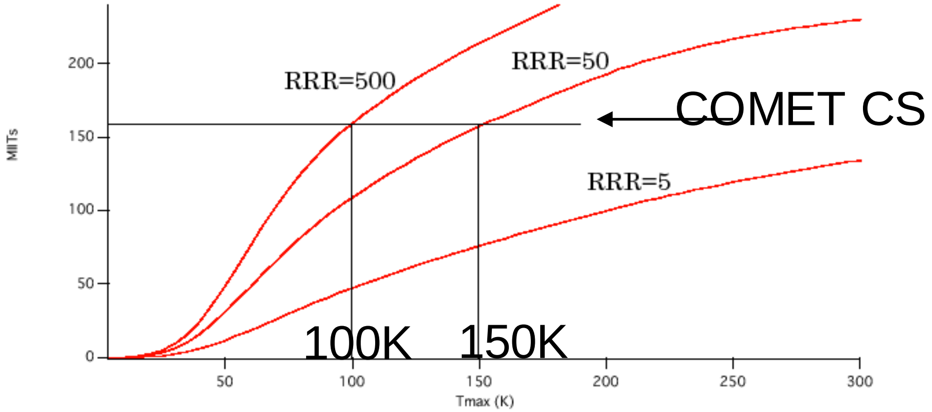


Figure 3 Error on temperature measurement on some sensors during irradiation (Tbath=1.8 K)

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



Irradiation effects on Al, Cu in literature

- pure Al (RRR=2000)
  - Fast neutron 2×10^{22} n/m^2 Induces ρ_i=3.8nΩ.m [1]
  - Perfect recovery by annealing at RT
- pure Cu
  - ρ_i=1.2nΩ.m [1]
  - 10% damage remains after annealing at RT

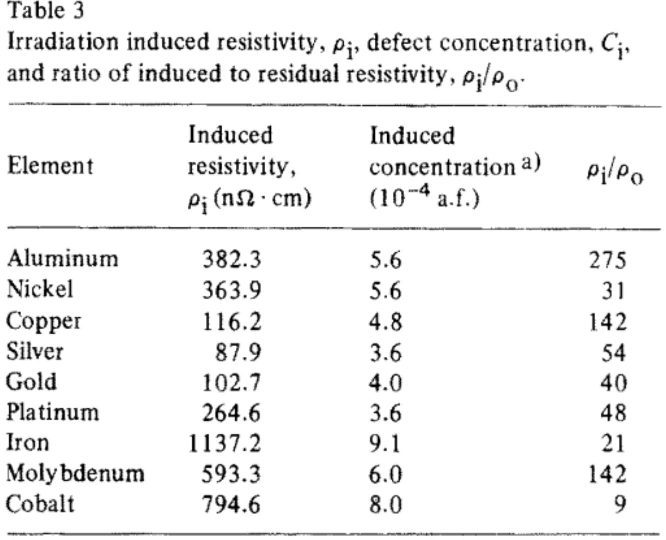
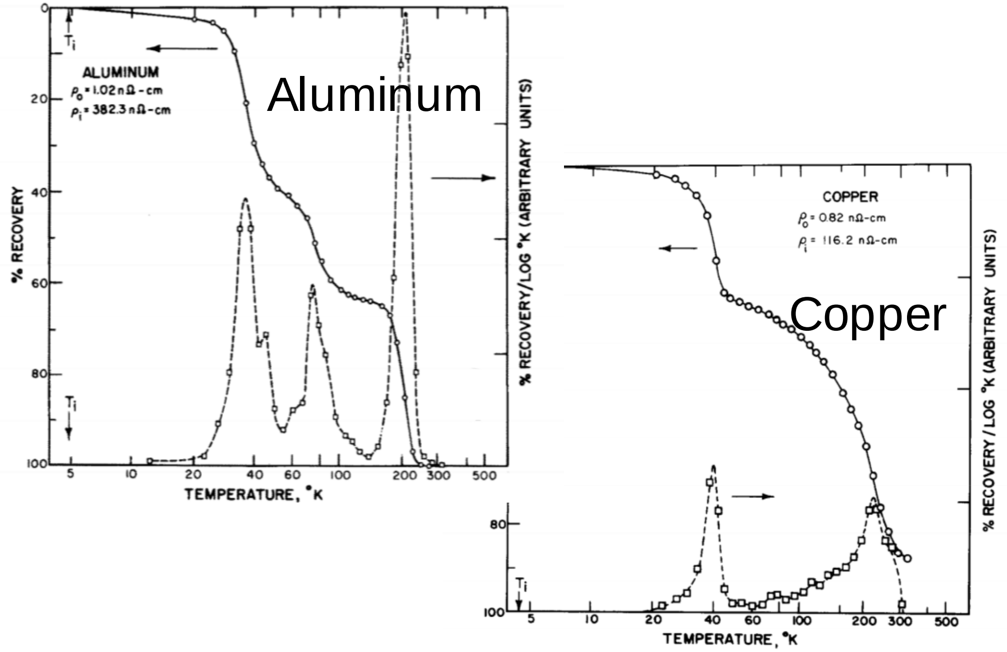


Table 3

Irradiation induced resistivity, ρ_i, defect concentration, C_i, and ratio of induced to residual resistivity, ρ_i/ρ_o.

Element	Induced resistivity, ρ_i (nΩ · cm)	Induced concentration a) (10^{-4} a.f.)	ρ_i/ρ_o
Aluminum	382.3	5.6	275
Nickel	363.9	5.6	31
Copper	116.2	4.8	142
Silver	87.9	3.6	54
Gold	102.7	4.0	40
Platinum	264.6	3.6	48
Iron	1137.2	9.1	21
Molybdenum	593.3	6.0	142
Cobalt	794.6	8.0	9

Recovery after irradiation 2×10^{22} n/m^2 (E>0.1MeV)



[1] J.A. Horak and T.H. Blewitt, J. Nucl. Materials, Vol. 49 (1973) p161

Indirect Cooling of Capture Solenoid

- Possible problem with Helium bath cooling of Capture Solenoid, due to Tritium production by $^3He(n,p)^3H$
- Propose conduction cooling to reduce irradiation of LHe
- Remove nuclear heating (max. 20W) by pure aluminum strip in between coil layers
- Thermal conduction can be degraded by neutron irradiation

- Temperature gradient in coil
  - 0.5mm thick, λ=4000W/m-K (RRR=2000) → ΔT=0.12K
  - If irradiation makes λ=400W/m-K → ΔT=1.2K
- Taking into account margin for irradiation damage, thick aluminum will be used
  - 2mm, λ=400W/m-K → ΔT=0.3K

ATLAS CS

NIMA584, p53 (2008)

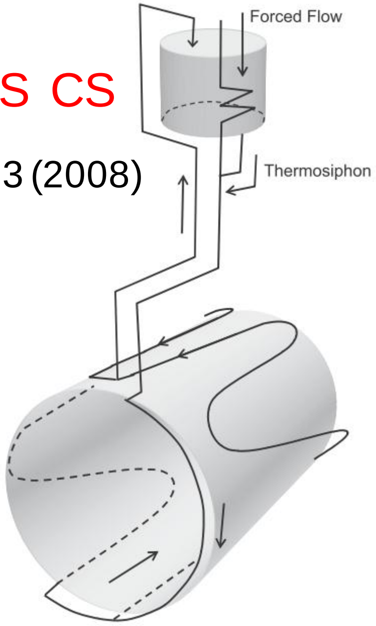
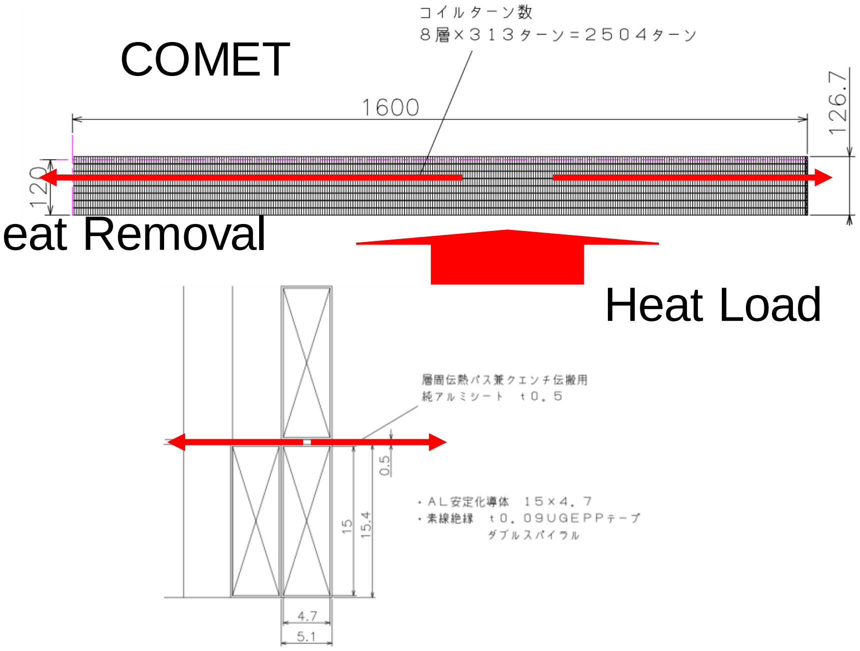


Fig. 11. Sketch showing the showing the concept of the thermosiphon and indicating where the cooling pipes are fixed to the cold mass.

COMET



Heat Removal

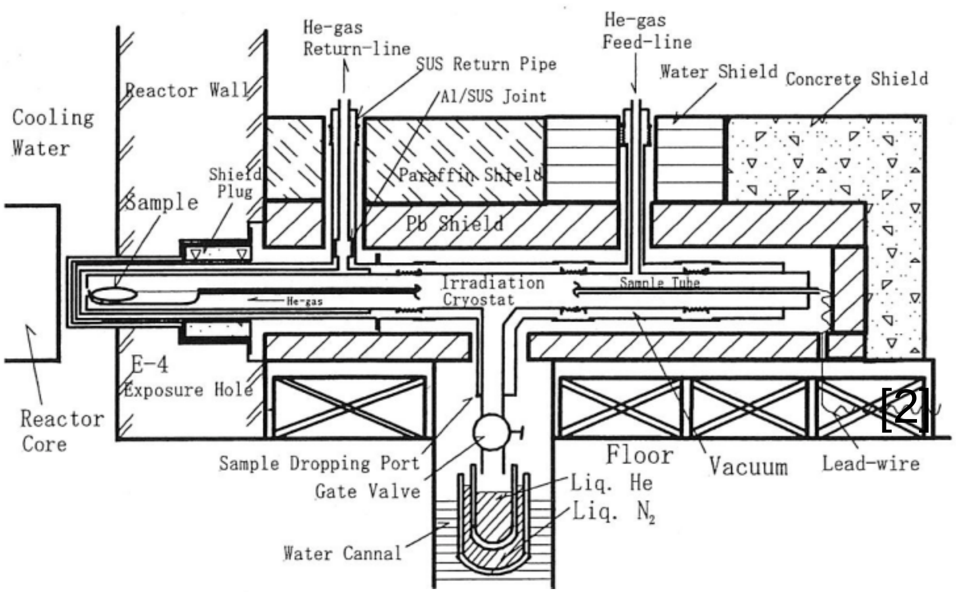
Heat Load

Irradiation test with reactor neutron

- Fast neutrons can degrade electrical/thermal conduction of Al, Cu
- Cold-worked Al-stabilizer and CERNOX sensor was irradiated by reactor neutrons
- Irradiation and measurement must be performed in low temperature to reproduce magnet operation situation

Low Temperature Irradiation Facility

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



[2]

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

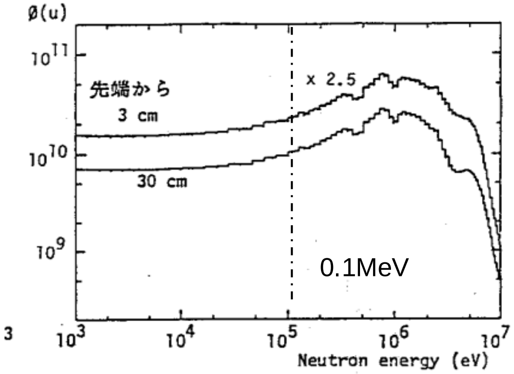


Fig. 15 Neutron energy spectrum in LTL of KUR for ordinary core (above 1000 eV)

KUR-TR287 (1987)

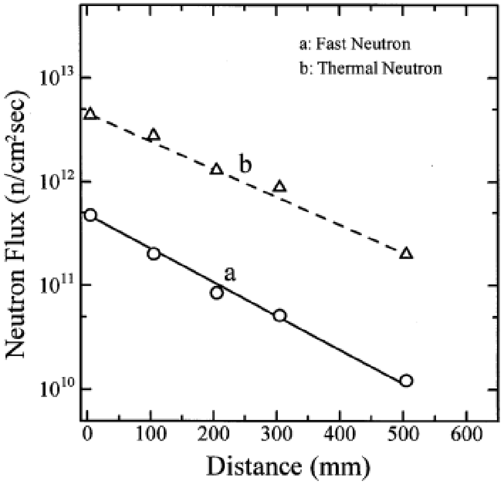
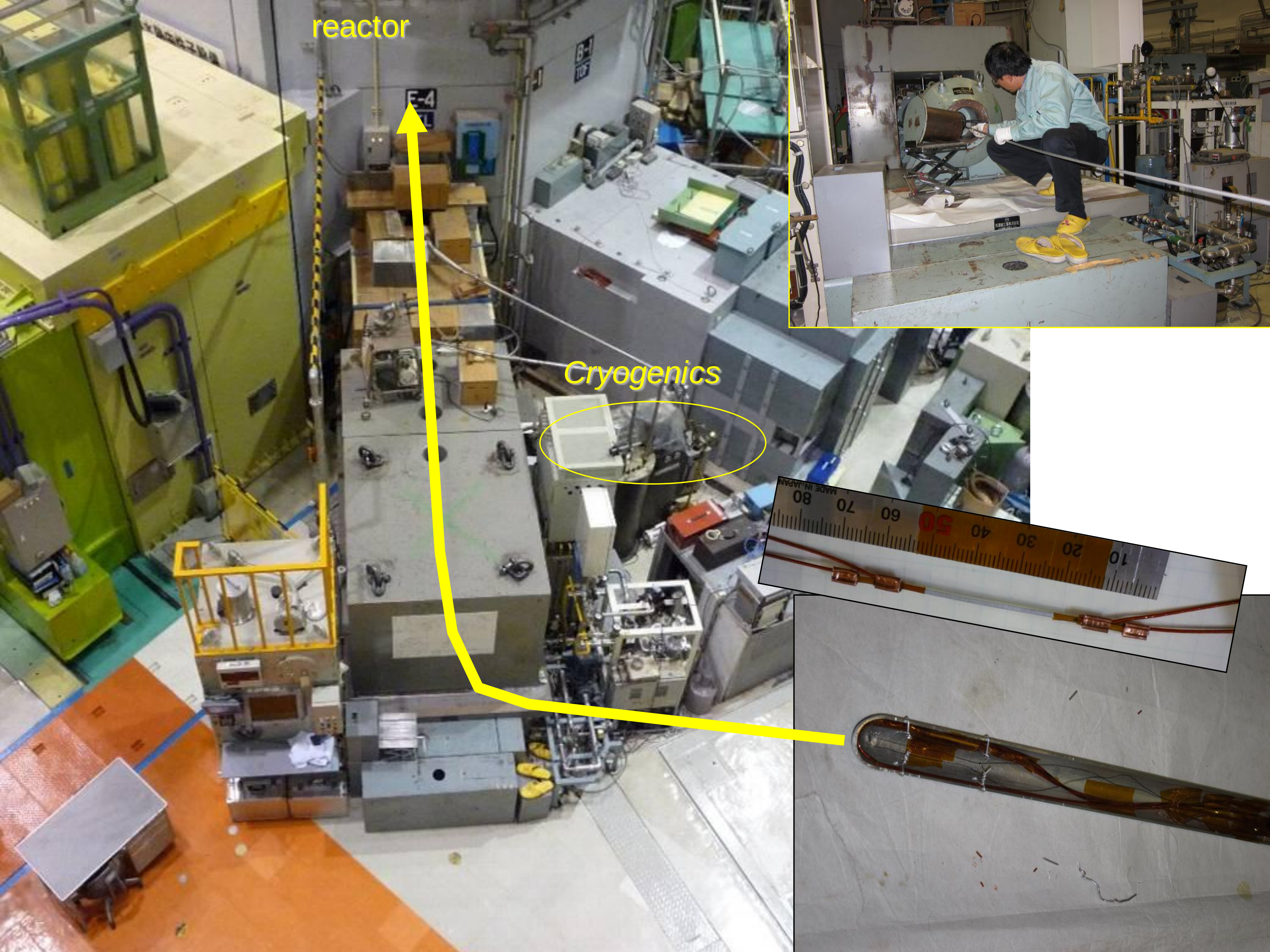


Fig. 7. Neutron flux distribution as a function of distance from top of sample chamber, (a) fast-neutron and (b) thermal neutron.

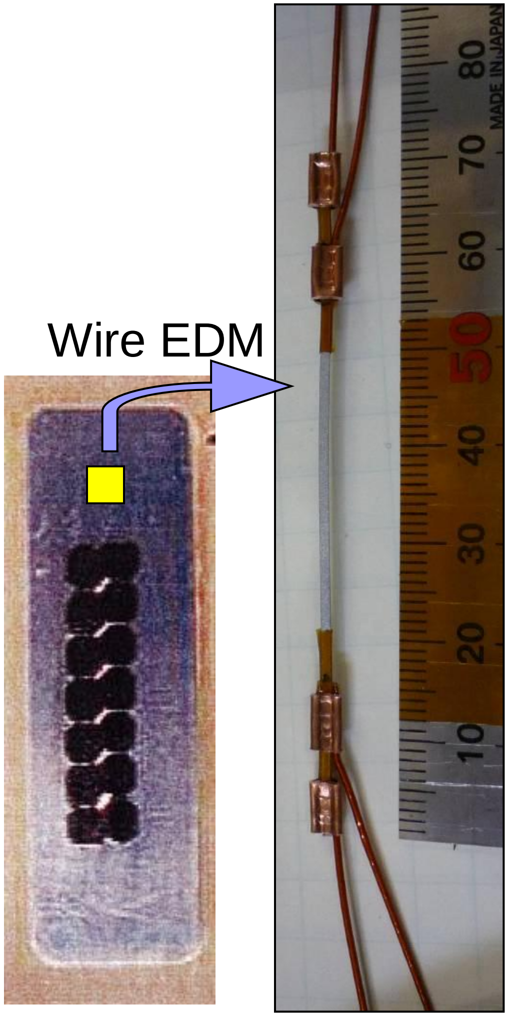

reactor
Cryogenics

Irradiation sample

- Aluminum stabilizer sample from the superconductor by wire electrical discharge machining in KEK
  - ☐ Keep defects by cold-work
- Size: 1mmx1mmx70mm
- Voltage taps with 45mm spacing
- 4 wire resistance measurement by nano-voltmeter
- CERNOX CX-1050-SD close to sample temperature (also irradiated)

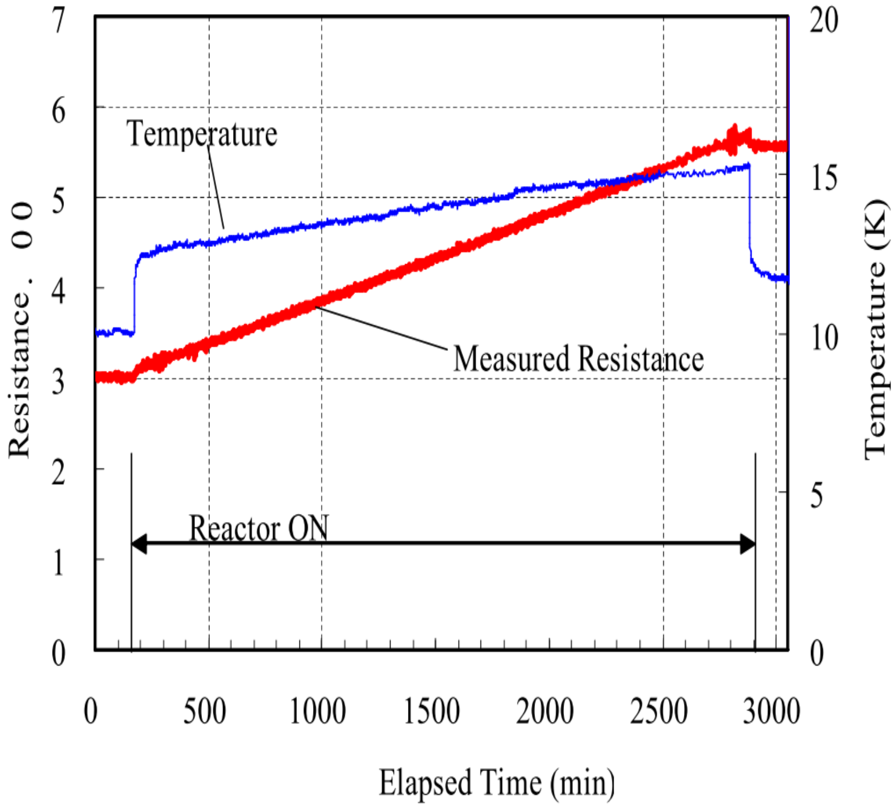
Irradiation sample

- 5N pure aluminum + Cu, Mg with 10 % cold work
- 1.35mΩ @RT, 3μΩ @10K



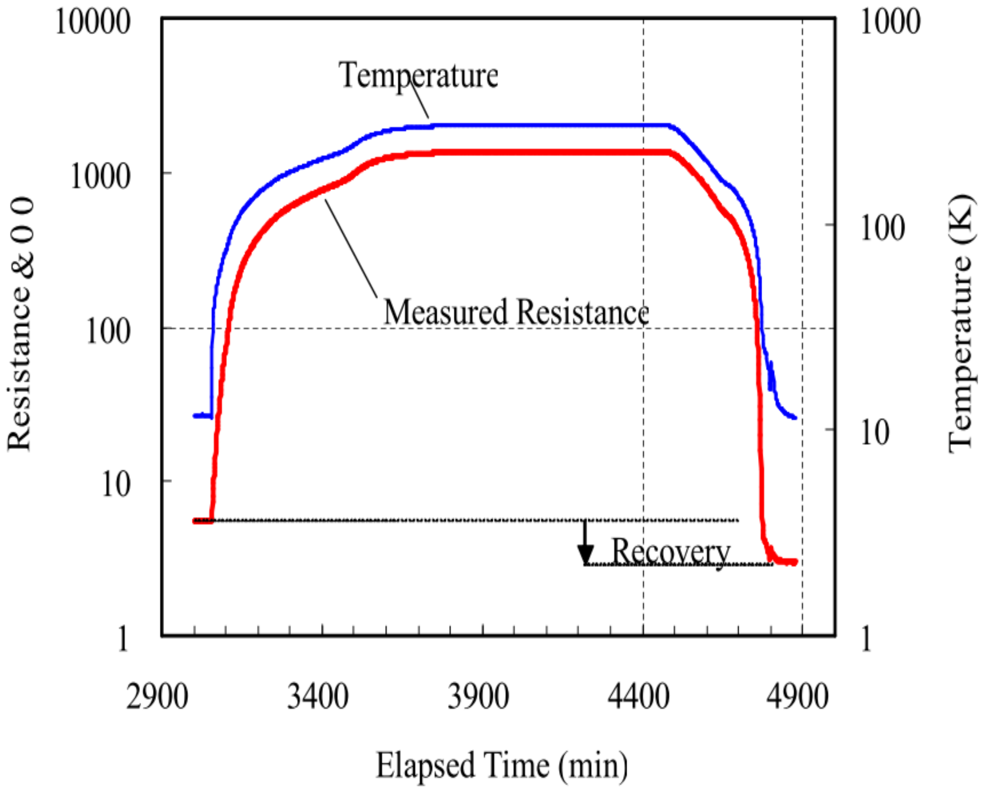
Result

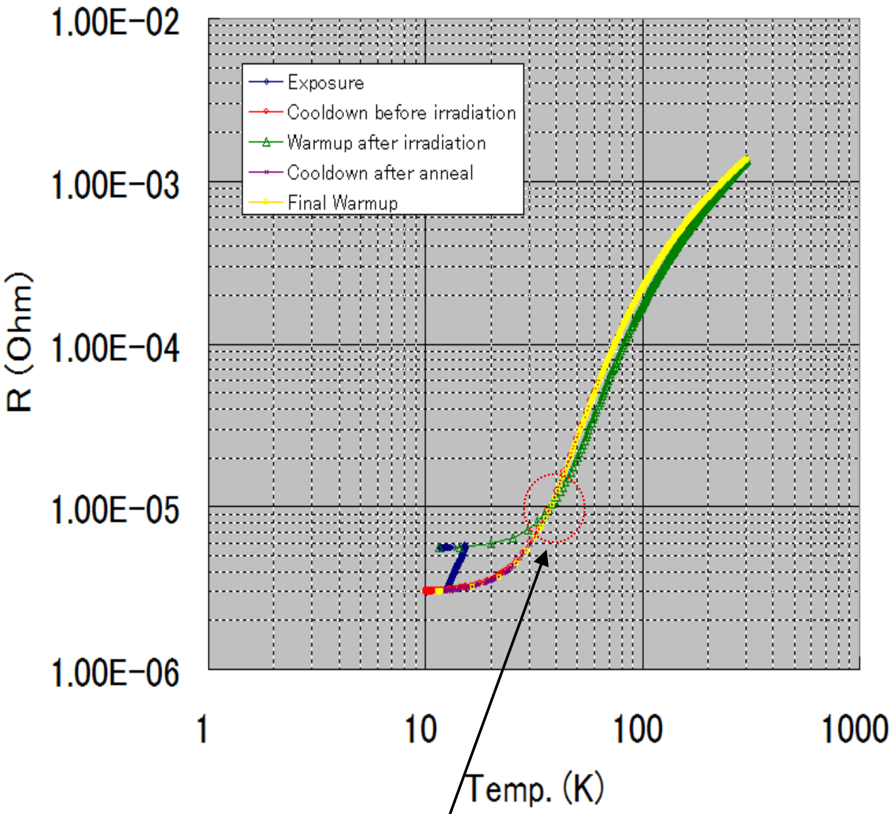
- Fast neutron exposure at 12K-15K
- Resistance was measured *in situ*.
- Resistance increased in proportional to neutron fluence in the range of 10^{19}-10^{20} n/m^2
  - No threshold at low neutron fluence
- Observed ρ_i = 0.056 nΩ.m for 2.3x10^{20} n/m^2 (>0.1MeV)
  - Good agreement with pure aluminum results (cf. [1])
- In COMET life time, resistivity of stabilizer will increase by a factor of 4 for neutron fluence of 6x10^{20} n/m^2 →Seasonal warmup would be necessary



M. Yoshida et al., ICMC2011

Recovery by annealing at RT





- Perfect recovery is observed
- Temperature drift due to CERNOX sensor degradation?

Summary

- Solenoid capture scheme is employed in NF/MC, mu-e conversion experiments
- Conceptual design of coil support, cryostat and cryogenics was carried out for COMET
- Radiation issues are most important for the feasibility
  - Indirect cooling
  - Radiation hard organic materials
  - Irradiation effects on electrical and thermal properties
- Active R&D on irradiation effect is underway
  - First tests successfully done in 2010 Nov.-2011 Feb.
  - Degradation of electric resistivity of Al-CuMg was observed from ~10^{20} n/m^2.
  - Full recovery by thermal cycle to room temperature was also confirmed.
  - Will investigate different additives, copper, pure aluminum for thermal conduction.