Repetitive Irradiation Tests at Cryogenic Temperature by Neutrons and Protons on Stabilizer Materials of Superconductor

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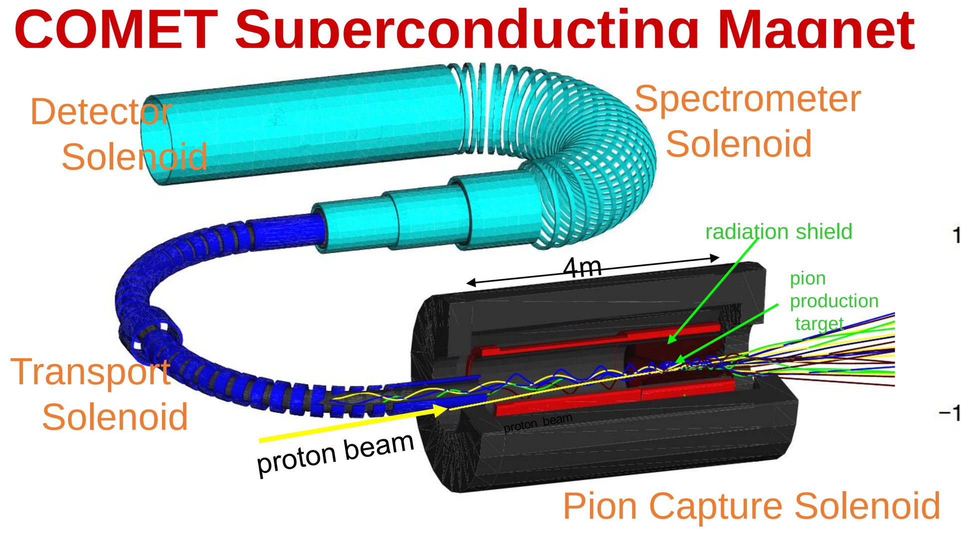
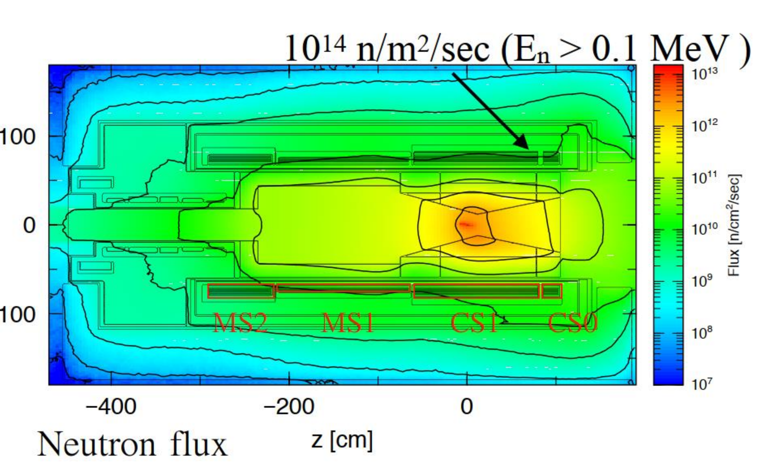
ABSTRACT

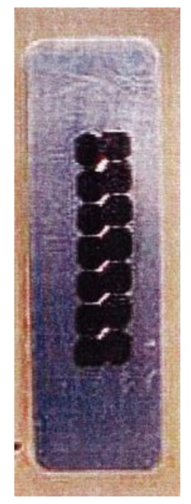
Superconducting magnets for high-intensity accelerators and secondary particle sources are being required to operate in the high radiation environment by beam collisions and beam losses. Neutron fluence in the high-luminosity LHC and the COMET experiment is expected to exceed 10^{21} n/m^2. The stabilizer of superconductor is made of pure copper and aluminum and should degrade by such high radiation. Series of irradiation tests were accomplished to evaluate the degradation at cryogenic temperature. The effect of repetitive cycles of irradiation at cryogenic temperature and anneal at room temperature on stabilizer materials of copper and aluminum were measured using reactor neutrons at KUR. Also, pure metals are irradiated at cryogenic temperature by high-energy protons at J-PARC. This paper will review the results of repetitive irradiation tests on copper and aluminum with reactor neutrons and accelerator protons.

COMET Superconducting Magnet



Neutron flux on PCS





Aluminum Stabilized Superconductive Cable

- Higher strength by additives and cold work
- Less interaction by radiation particles
- Capable to recover from irradiation damage by a thermal cycle

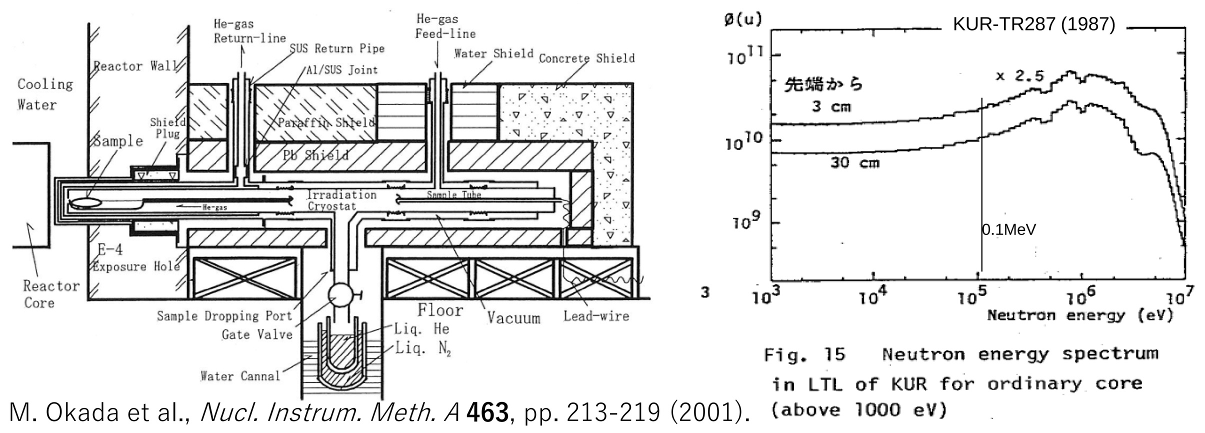
Design parameters for COMET

- Rutherford type NbTi cable with Al stabilizer
- Al/Cu/SC: 7.3/0.9/1
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500

Neutron Irradiation Tests at KUR

Low Temperature Lab. (LTL) at Kyoto Univ. Research Reactor (KUR)

- Thermal Power 1 MW~5MW
- Cryostat installed near reactor core
- Cool by He gas loop down to 10K
- Neutron flux : 1.4x10^{15} n/m^2/sec (>0.1MeV)

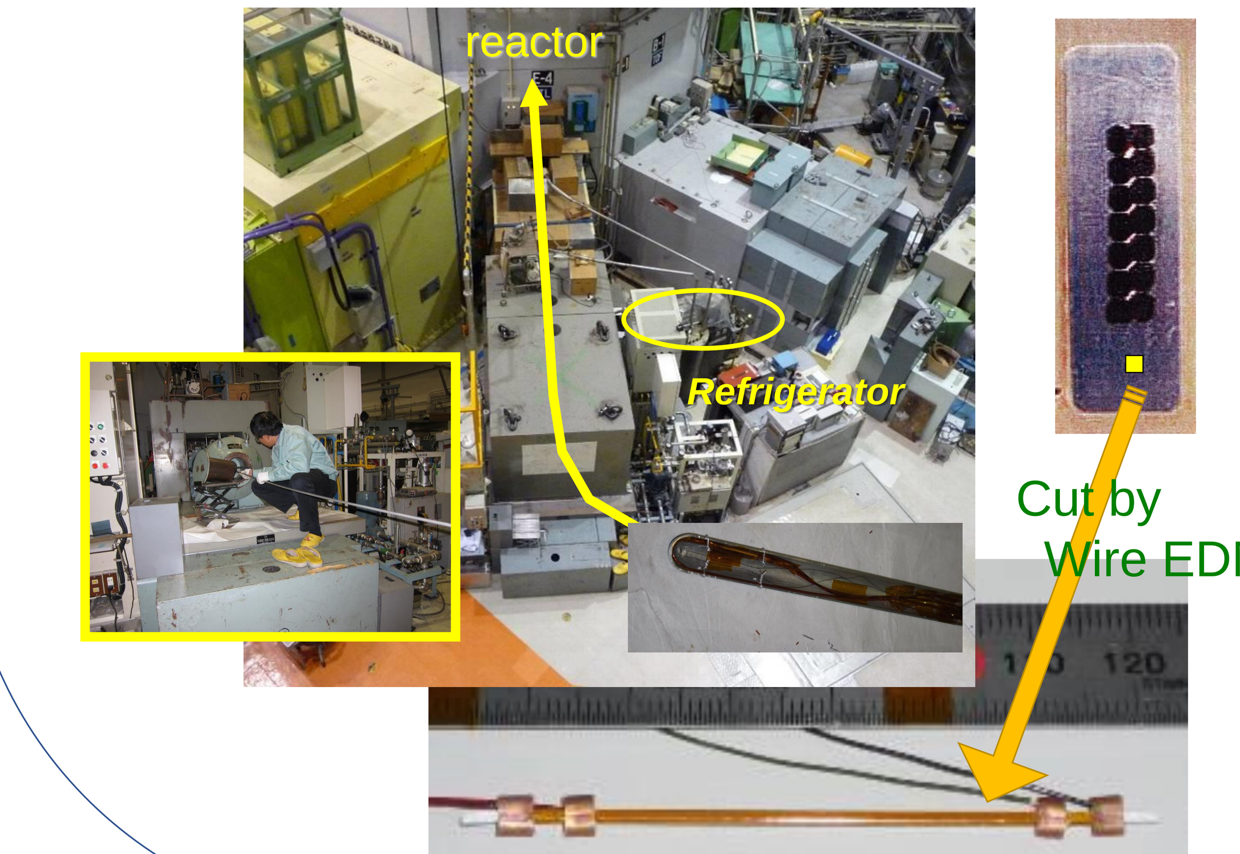


M. Okada et al., *Nucl. Instrum. Meth. A* **463**, pp. 213-219 (2001).

- Irradiation sample is fixed at the top of ~7m long Al pipe.
- The sample pipe is inserted into the cryostat of LTL
- Electrical resistivity of samples were measured in situ in a cycle of reactor operation.

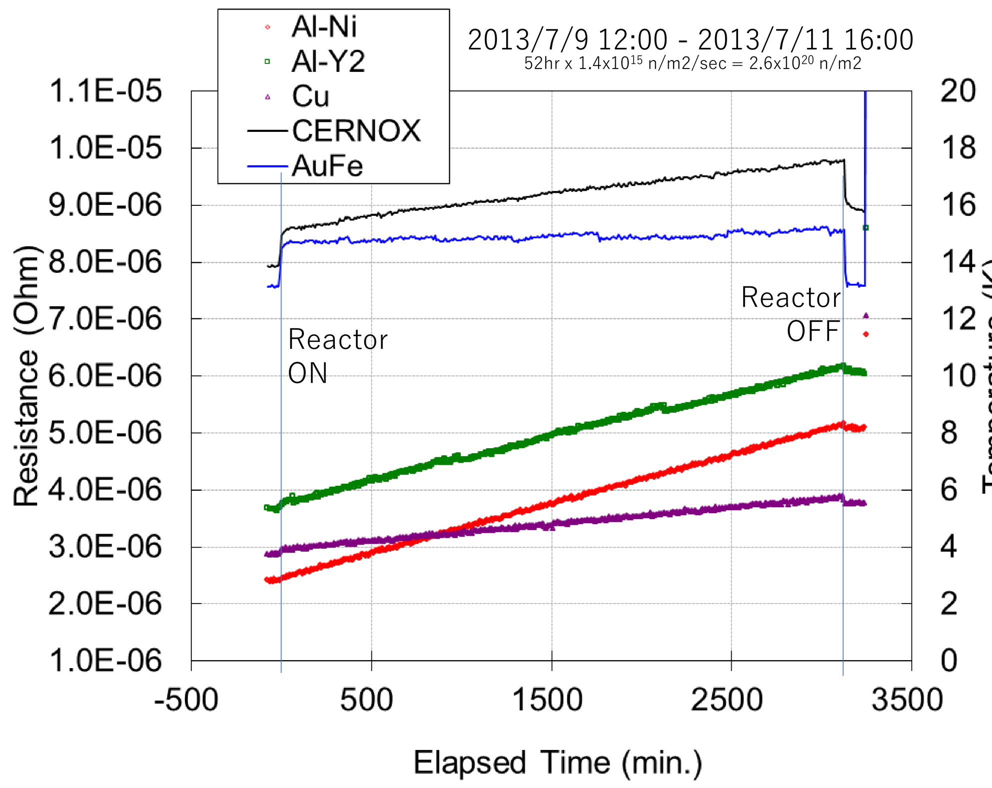
Irradiated samples

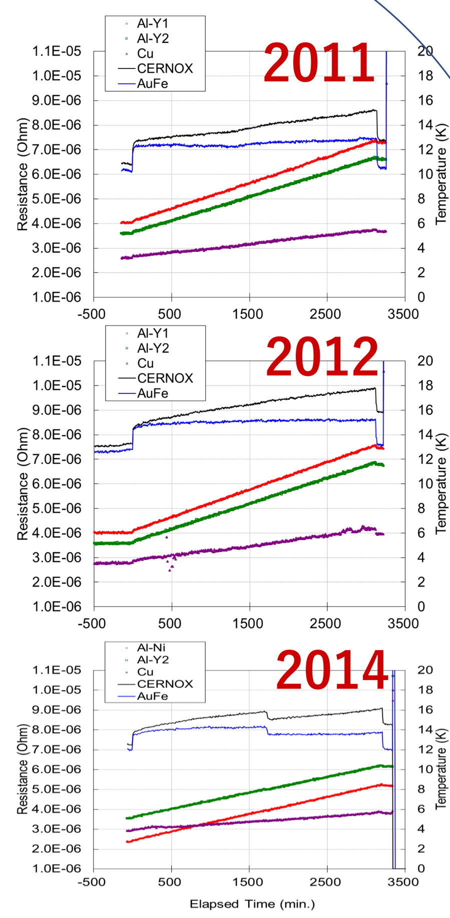
Sample Name	Composition	RRR	Shape	Irradiation Period
Al-CuMg	Al(5N)+Cu(20ppm)+Mg(40ppm)	455	1x1x45	2010
Al-5N	Al(5N)	~3000	ϕ 1x32	2011-1
Al-Y1	Al(5N)+Y(0.2%)	341	1x1x45	2011-2,2012
Al-Y2	Al(5N)+Y(0.2%)	366	1x1x45	2011-2,2012,2013,2014
Al-Ni	Al(5N)+Ni(0.1%)	541	1x1x45	2013,2014
Cu	OFHC	308	ϕ 1x32	2011,2012,2013,2014



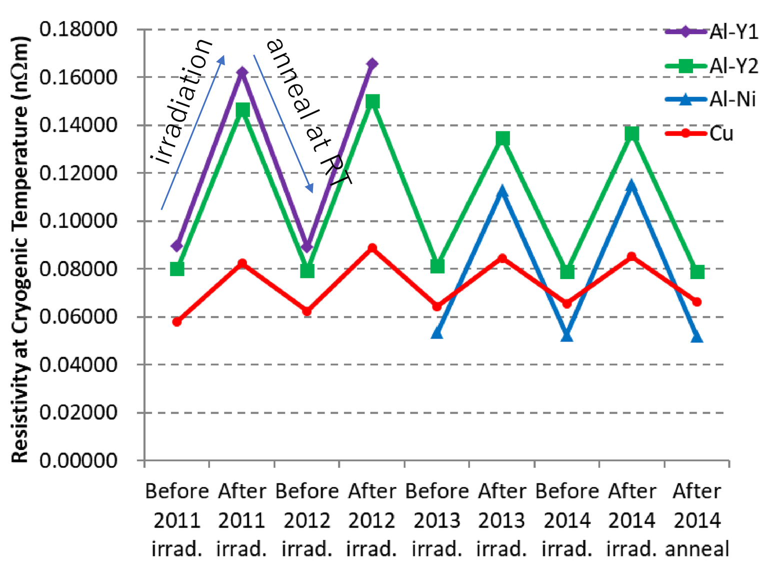
Al Sample 1mmx1mmx70mm

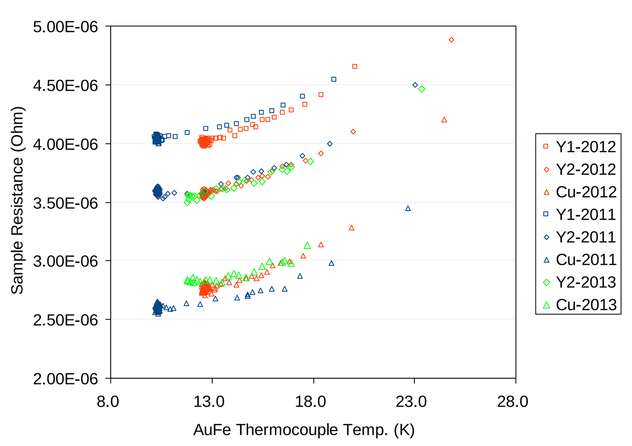
Irradiation results





Irrad. Period		2010Nov	2011Sep	2011Nov	2012Nov	2013July	2014Apr
Neutron Fluence		2.3E+20	2.6E+20	2.6E+20	2.6E+20	2.6E+20	2.7E+20
Irrad. Temp.		12K	15K	12K	15K	15K	14K
Damage Rate (Ωm^3/n)							
	Al-CuMg	2.4E-31					
	Al-5N		2.5E-31				
	Al-Y1			2.8E-31	2.9E-31		
	Al-Y2			2.6E-31	2.7E-31	2.3E-31	2.2E-31
	Al-Ni					2.3E-31	2.3E-31
	Cu			9.4E-32	1.0E-31	7.7E-32	7.3E-32



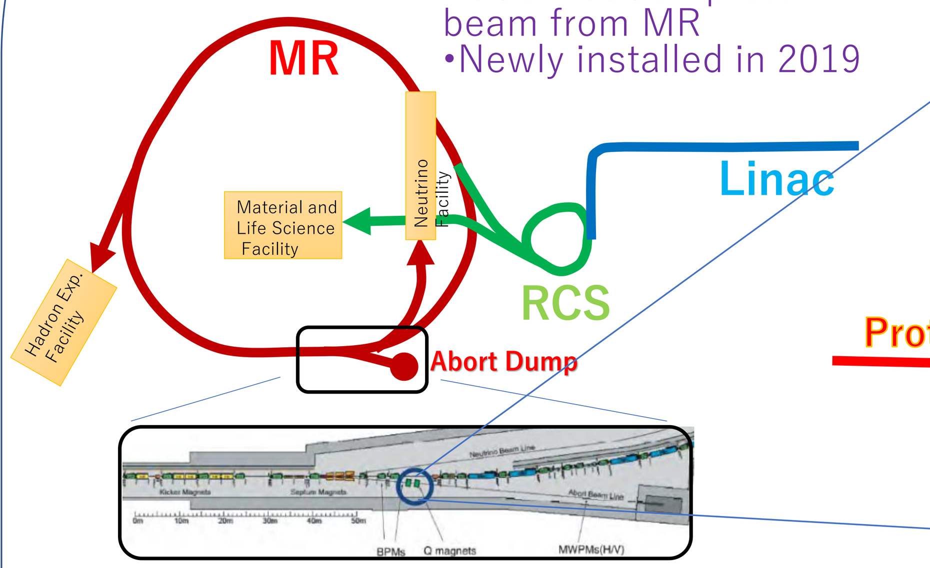


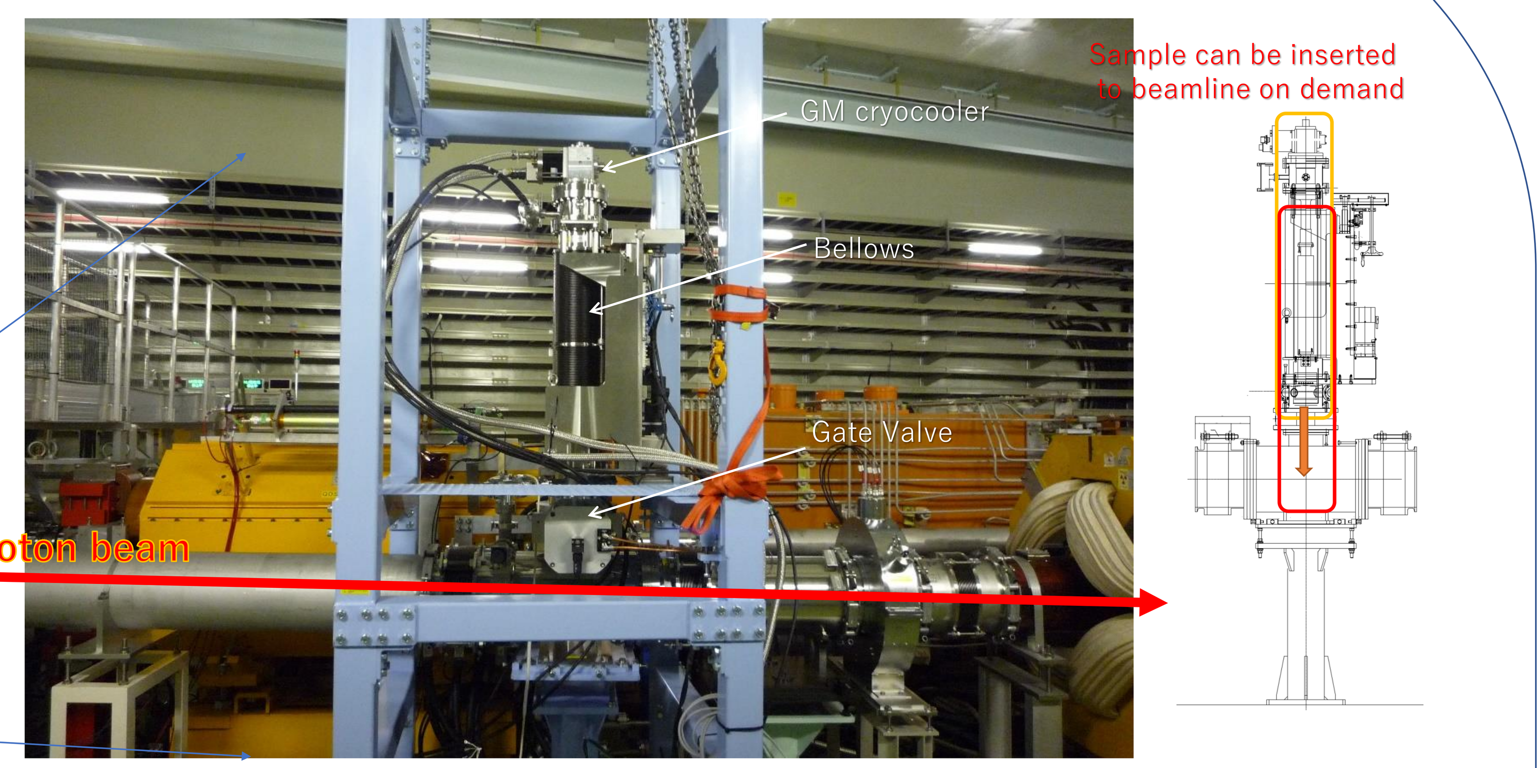
- Irradiation/annealing were repeated in max. 4 times for aluminum and copper samples
- Damage in aluminum samples is 3 times larger than copper.
- Perfect recovery after annealing at RT was observed on aluminum.
- Residual damage in Cu after RT anneal seems to pile up.

Proton Irradiation Tests at J-PARC

Cryogenic Irradiation Equip. at J-PARC MR Abort Line

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

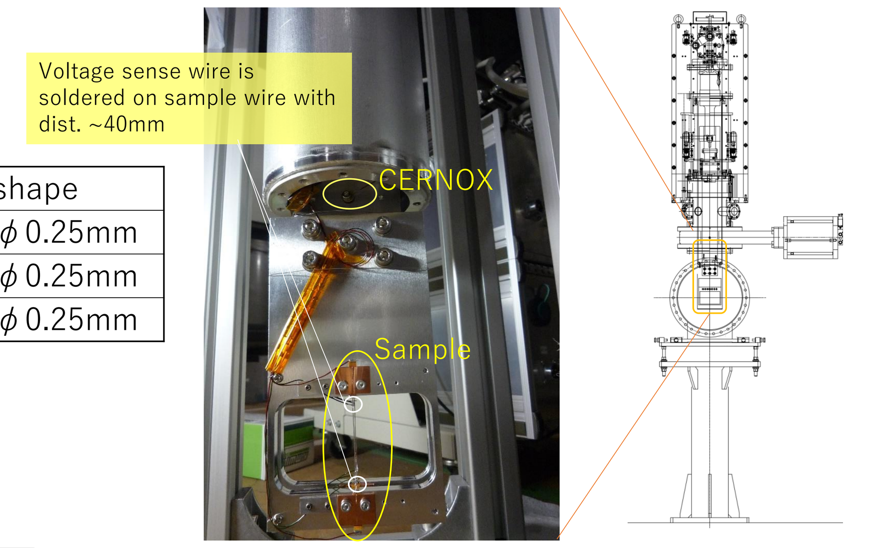




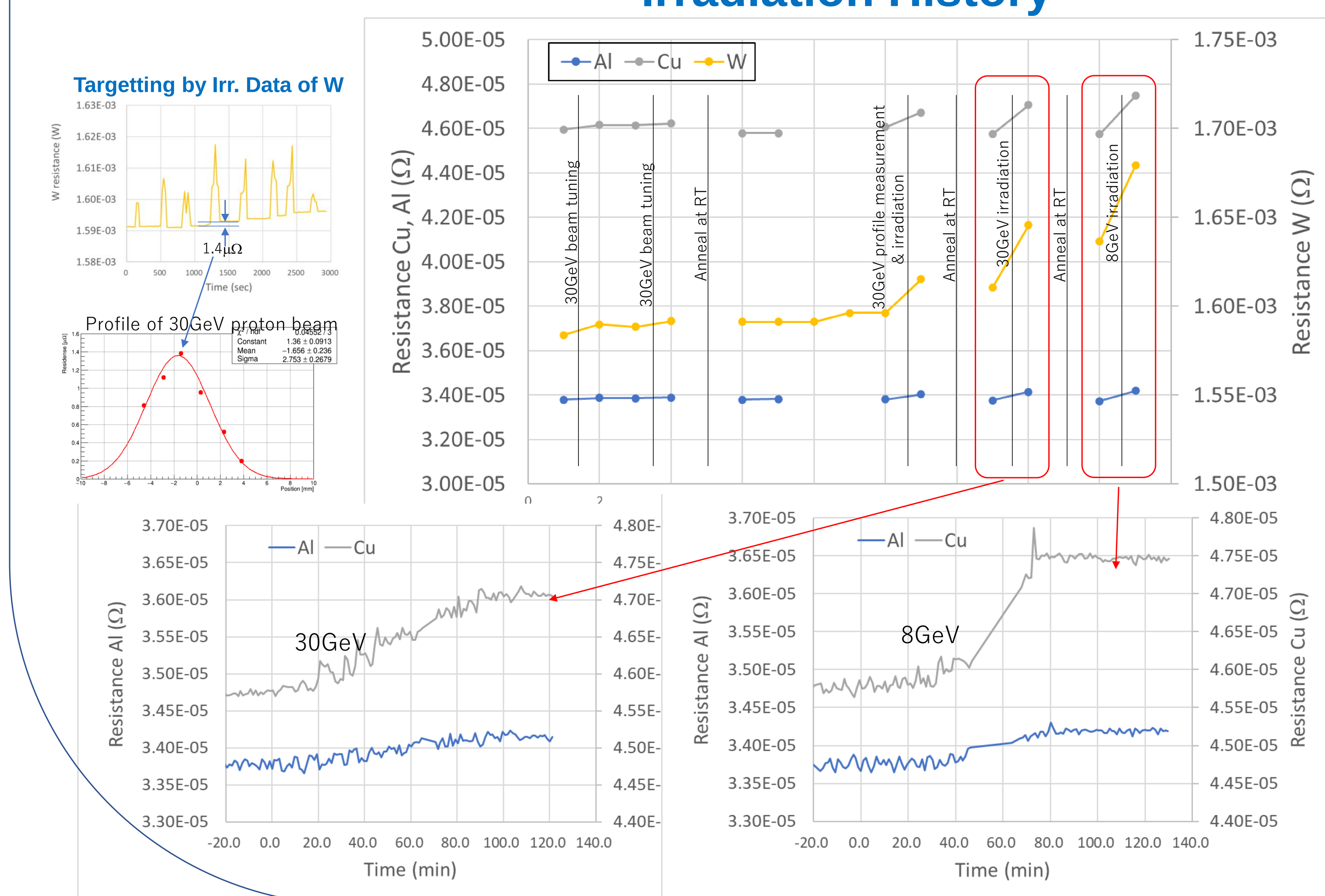
Irradiated samples

- Irradiation sample is cooled by GM cryocooler.
- Sample is fixed at the top of 60cm aluminum rod, connected to 2nd stage of cryocooler coldhead, to avoid irradiation on the coldhead.
- Temperature on the sample base is measured by CERNOX.
- Stable temperature at 3.8K-4.5K during operation.
- Beam intensity was reduced as low as possible to avoid sample heating up
  - ~2x10^{12} protons/pulse x 0.16Hz

	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



Irradiation History



Damage rate

(resistivity increase per unit proton flux)

	8GeV	30GeV
Al [x10^-31Ωm^3/p]	1.05 ±0.15	1.03 ±0.12
Cu [x10^-31Ωm^3/p]	3.88 ±0.27	3.55 ±0.23
W [x10^-31Ωm^3/p]	95.3 ±5.6	95.8 ±5.6

*error value indicates data fluctuation only

- Perfect recovery after annealing at RT was observed on aluminum.
- Damage in aluminum is 30% of copper.
- .Damage rate does not depends on proton energy in this high energy region