Neutron Irradiation Measurement for Superconducting Magnet Materials at Low Temperature

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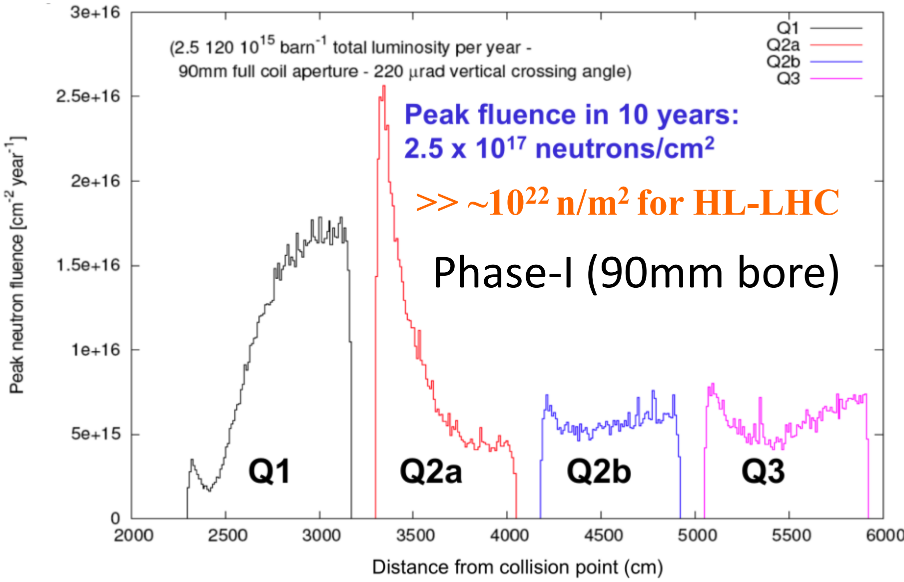
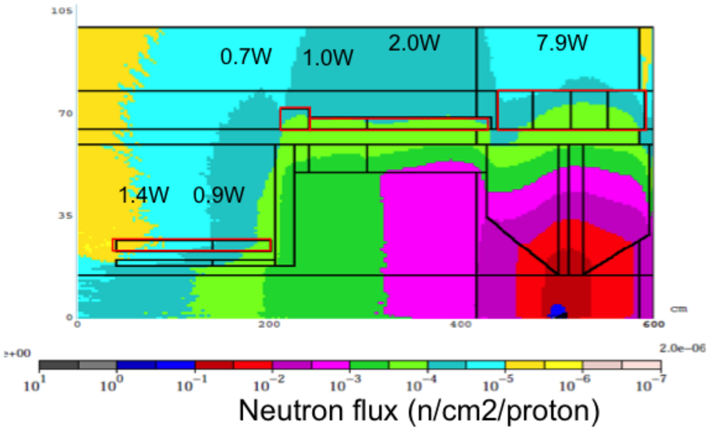
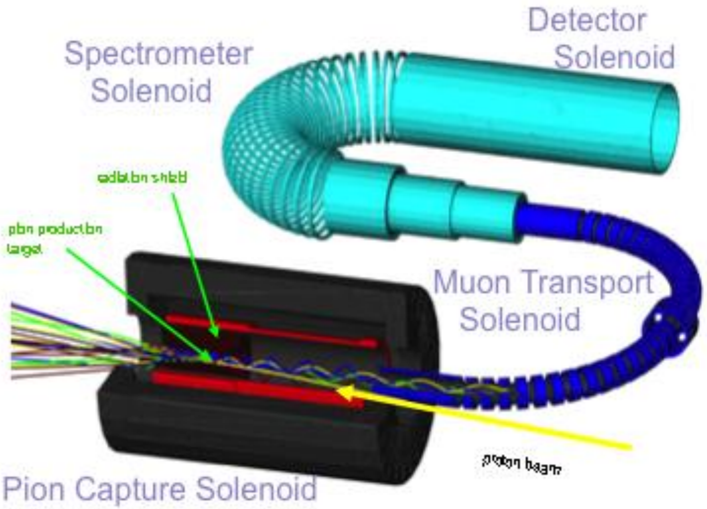
[CERN]	G.D. Rijk, E. Todesco, L. Bottura, L. Rossi.

High Radiation Environment for SC Magnets

- HiLumi LHC: 10^{21}-10^{22} n/m^2
- COMET & Mu2e experiments (J-PARC, Fermilab)
  - Search for μ-e conversion
  - Pion capture solenoids w/ Al stabilized NbTi SC cable.
    - Same spec as ATLAS-CS.
  - Neutron fluence: > 10^{21} n/m^2







COMET Superconducting Magnet System

Neutron irradiation effects at low temperature need be studied.

Why ρ of stabilizer? Why at low temperature?

- Electrical resistivity ρ of stabilizers (aluminum, copper) is one of the most sensitive property in the SC magnet materials with respect to the radiation.
  - Induced resistivity is remarkable at LT.
  - Recovery effect starts at 20 K or higher.
- The induced ρ by the radiation will compromise the quench stability and protection scheme. Coil temperature will be increased in the in-direct cooling magnets.
- Anneal effect and full-recovery during warm-up to RT would be expected in aluminum, but only 80-90% recovery in copper (??).
- Questions to be studied:
  - Samples from the practical SC wire/cable: RRR of 100 to 500.
  - Degradation may start even below 10^{20} n/m^2 ?
  - Fluence threshold ?
  - Full recovery by full thermal cycle?
  - Accumulated resistivity after multiple irradiation?

Previous Work in Literature: $\Delta\rho_{irr}$

Neutron irradiation at 4K, and warm-up stepwise.

Horak et.al., J. Nucl. Materials, 49, p161 (1973&74)

Guinan et.al., J. Nucl. Materials, 133&134, p357 (1985)

Reactor n on Al

ρ_0: 0.0102
$\Delta\rho_{irr}$: 3.823
(nΩm)

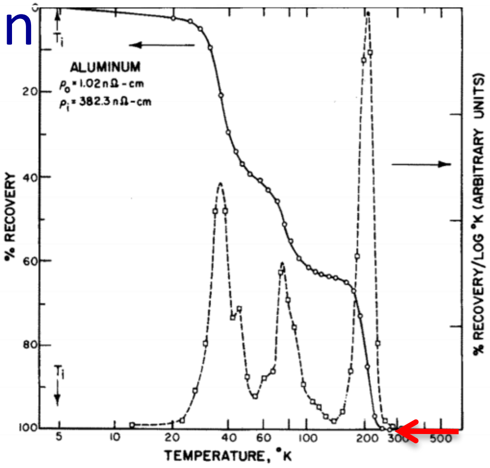
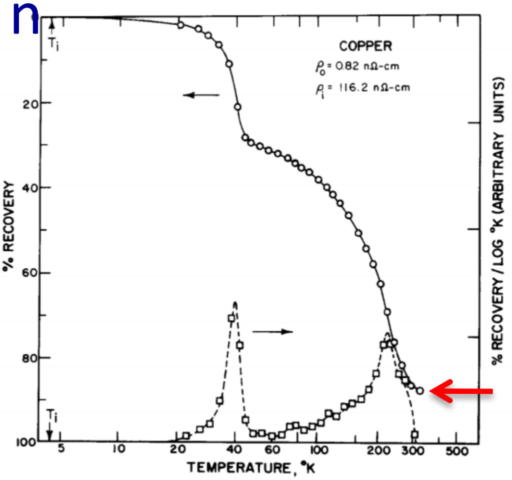


Fig. 3. Recovery and differential recovery versus logarithm of absolute temperature for aluminum irradiated at 4.5 K to 2 × 10^{18} n/cm^2 of $E > 0.1$ MeV.

Reactor n on Cu

ρ_0: 0.0082
$\Delta\rho_{irr}$: 1.162
(nΩm)



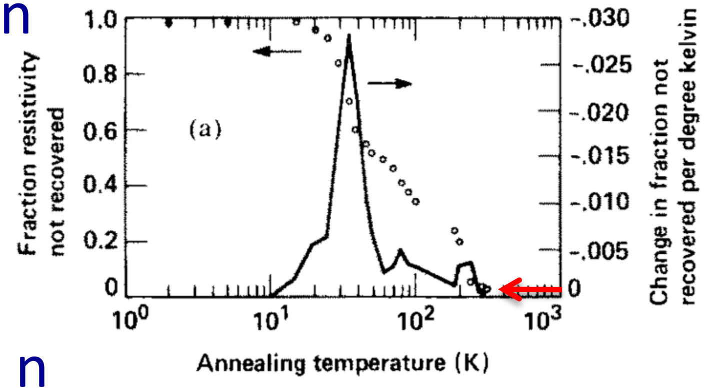
90% recovery

Fig. 5. Recovery and differential recovery versus logarithm of absolute temperature for copper irradiated at 4.5 K to 2 × 10^{18} n/cm^2 of $E > 0.1$ MeV.

- fluence up to $2*10^{22}$ n/m^2 (En>0.1MeV)
- RRR of ~2000

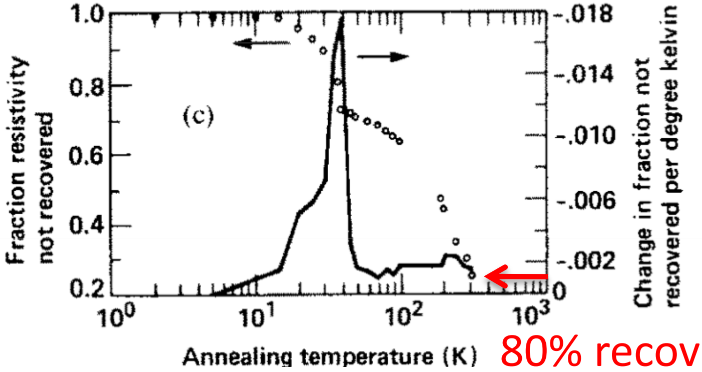
14MeV n on Al

ρ_0: 0.386
$\Delta\rho_{irr}$: 0.336
(nΩm)



14MeV n on Cu

ρ_0: 0.098
$\Delta\rho_{irr}$: 0.191
(nΩm)



80% recovery

Fig. 2. Post-irradiation, isochronal annealing results for (a) Al, (b) Ni, (c) Cu and (d) Pt. Annealing results below 50 K for Ni and Pt were lost because of warming.

- fluence up to $1*10^{21}$ n/m^2
- RRR of ~100

- Double of resistivity observed at 10^{21} n/m^2.
- Full recovery in Al expected by T.C.
- Degradation in Cu will be accumulated even after T.C.

Neutron Irradiation at KUR

- Kyoto Univ. Research Reactor Institute
- 5MW max. thermal power
- Irradiation cryostat close to reactor core
- Sample cool down by He gas loop: 10K – 20K
- Fast neutron flux (En>0.1MeV): 1.4x10^{15} n/m^2/s@1MW

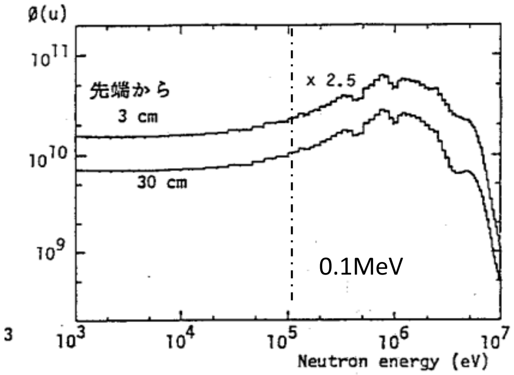
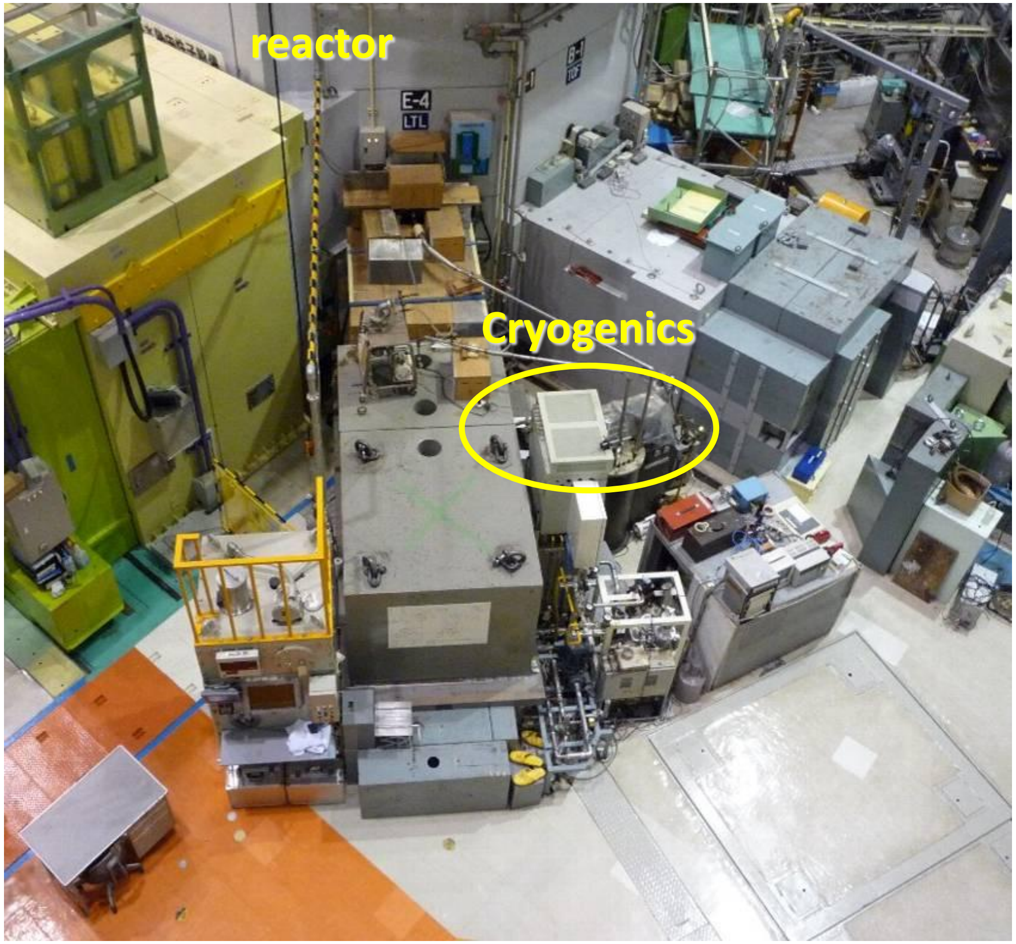
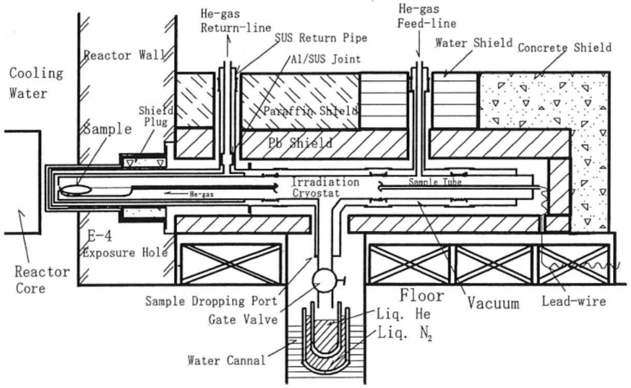


Fig. 15 Neutron energy spectrum in LTL of KUR for ordinary core (above 1000 eV) KUR-TR287 (1987)

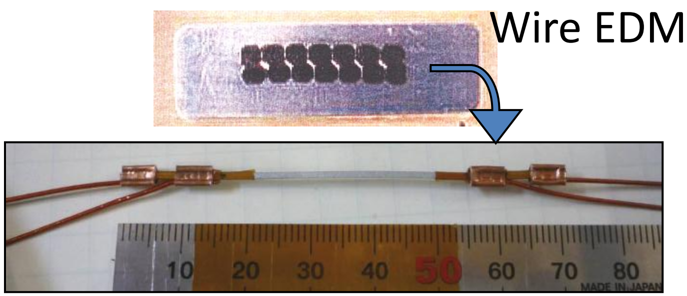


M. Okada et al., NIM A463 (2001) pp213-219

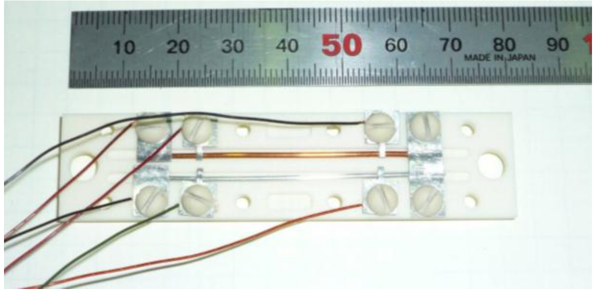


Sample and Measurement

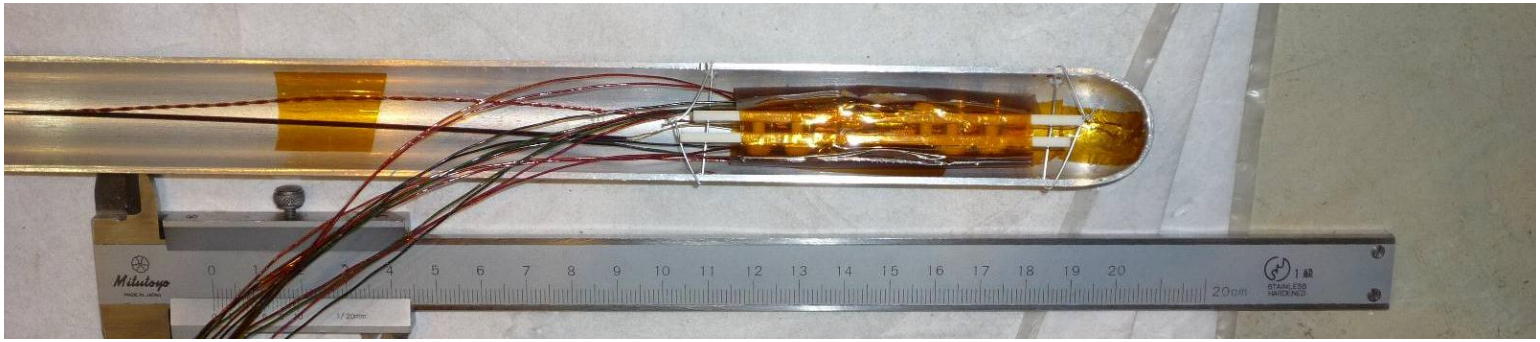
- Aluminum:
  - Cut by EDM from Al stabilized NbTi cable.
  - 5N Al + Cu(20ppm), Mg(40ppm) with 10% cold work. RRR of ~500.
  - 1mmx1mmx70mm, $L_{v\text{-taps}}$ =45 mm
- Copper:
  - Provided by Hitachi Cable. Material for SC wire. RRR of ~300.
  - ϕ1mmx60mm, $L_{v\text{-taps}}$ =32 mm
- 5N Aluminum (for reference):
  - Provided by Sumitomo Chemical. RRR of ~3000.
  - ϕ1mmx60mm, $L_{v\text{-taps}}$ =32 mm
- 4 wire resistance measurement by nano-voltmeter: Keithley 6221+2182A
- Thermometers: CERNOX CX-1050-SD, TC (AuFe-Chromoel)
- Neutron fluence determined by Ni foil activation method.



Aluminum sample

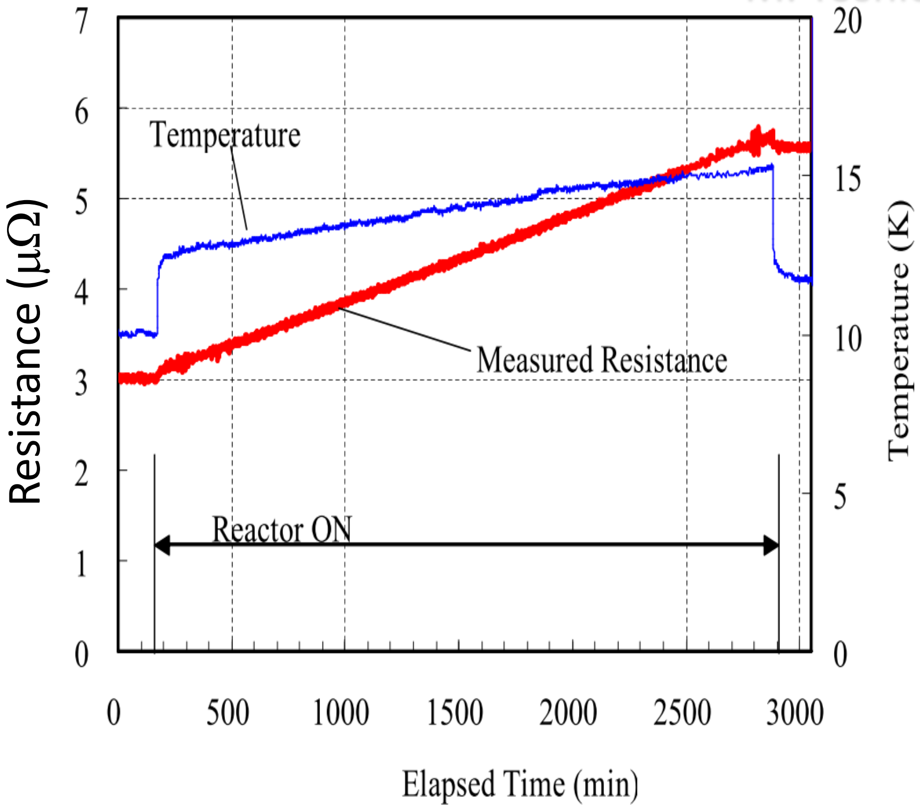


Copper and 5N-Aluminum samples



Result: $\Delta\rho_{irr}$ for Aluminum

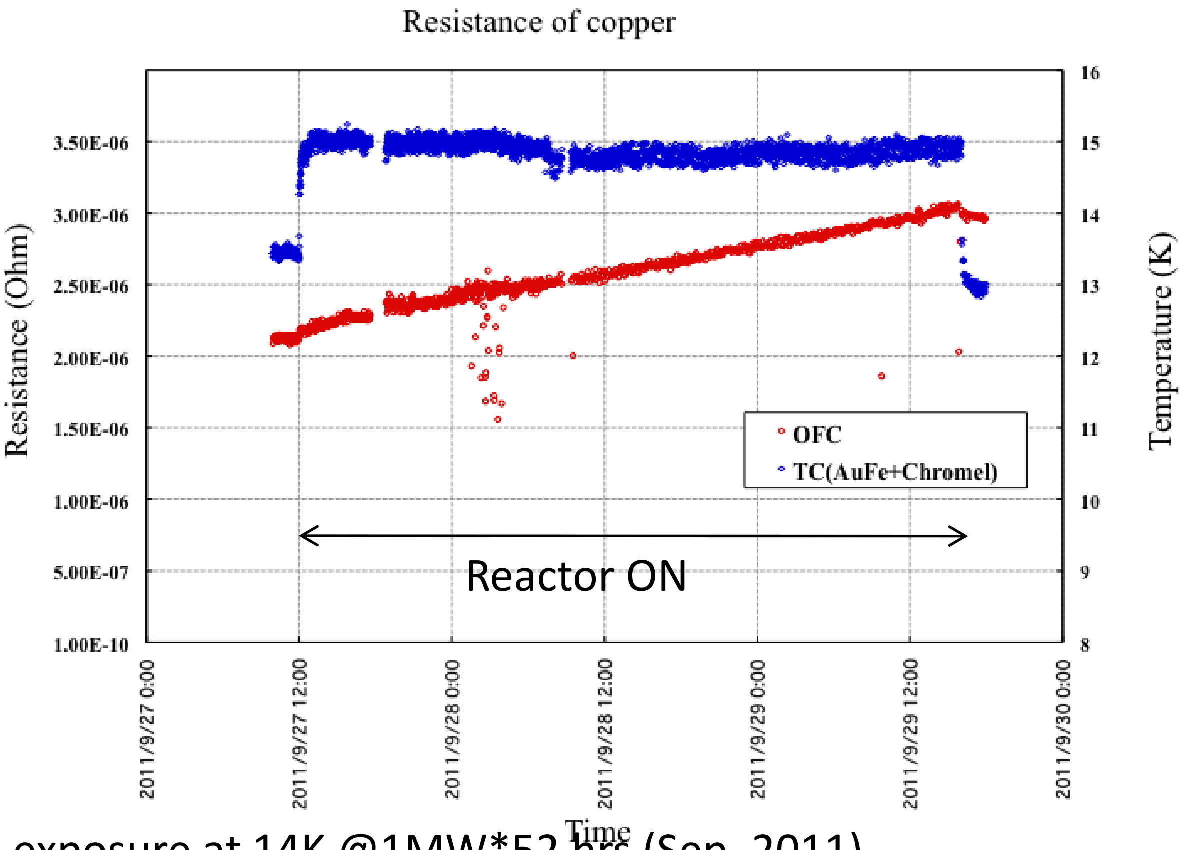
M. Yoshida et al., ICMC2011



- Fast neutron exposure at 12K @1MW*45 hrs (Nov. 2010)
- 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 $\Delta\rho_{irr}$ = 0.056 nΩ.m for 2.3x10^{20} n/m^2 (>0.1MeV)
  - Fairly good agreement with the previous work.
    - Present work: $\Delta\rho_{irr}/\Phi_{tot}$= 2.4x$10^{-22}$ nΩm^3 (RRR 500, 2.3x10^{20} n/m^2)
    - Previous: $\Delta\rho_{irr}/\Phi_{tot}$= 1.9x$10^{-22}$ nΩm^3 (RRR 2000, 2x10^{22} n/m^2)

Result: $\Delta\rho_{irr}$ for Copper

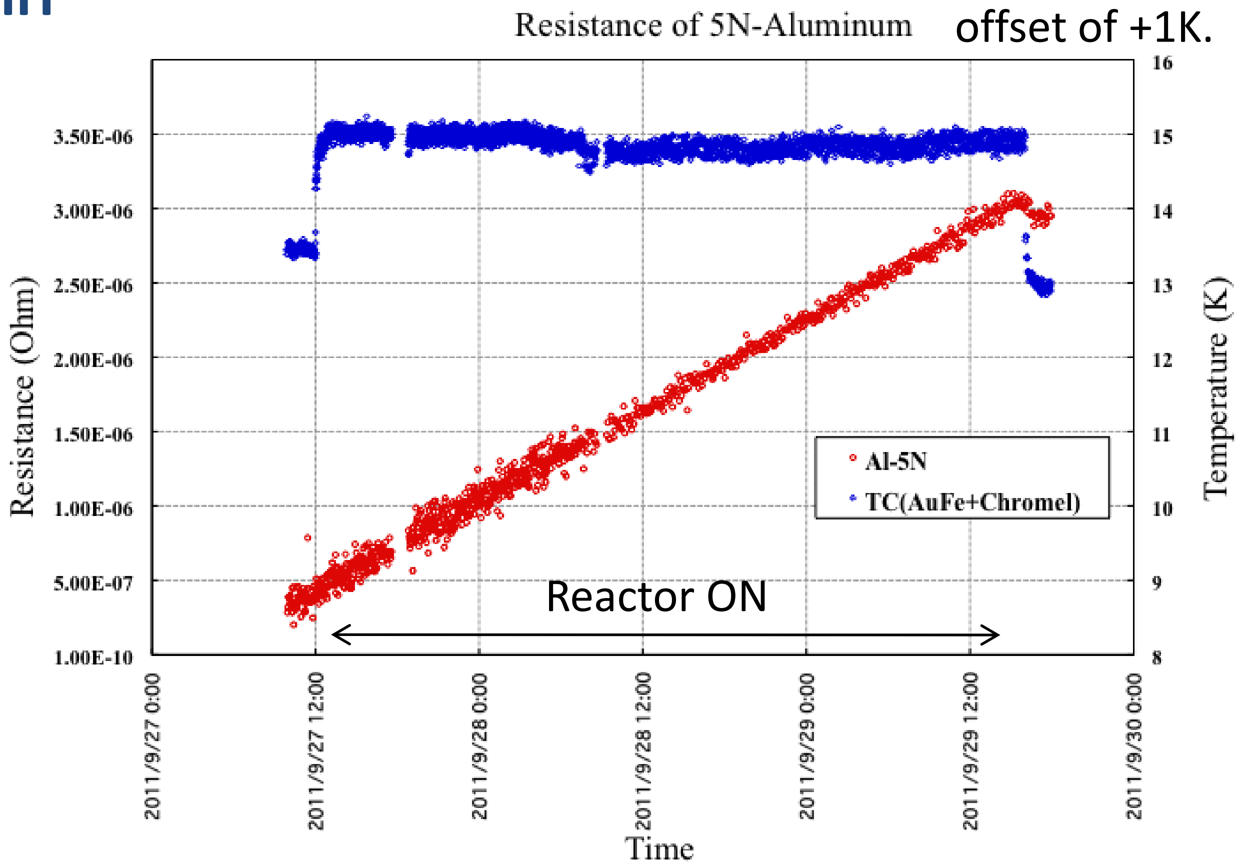
*TC reading includes the offset of +1K.



- Fast neutron exposure at 14K @1MW*52 hrs (Sep. 2011)
- 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 $\Delta\rho_{irr}$ = 0.022 nΩ.m for 2.7x10^{20} n/m^2 (>0.1MeV)
  - Agreed with the previous work within a factor of 2.
    - Present work: $\Delta\rho_{irr}/\Phi_{tot}$= 0.82x$10^{-22}$ nΩm^3 (RRR 300, 2.7x10^{20} n/m^2)
    - Previous: $\Delta\rho_{irr}/\Phi_{tot}$= 0.58x$10^{-22}$ nΩm^3 (RRR 2000, 2x10^{22} n/m^2)

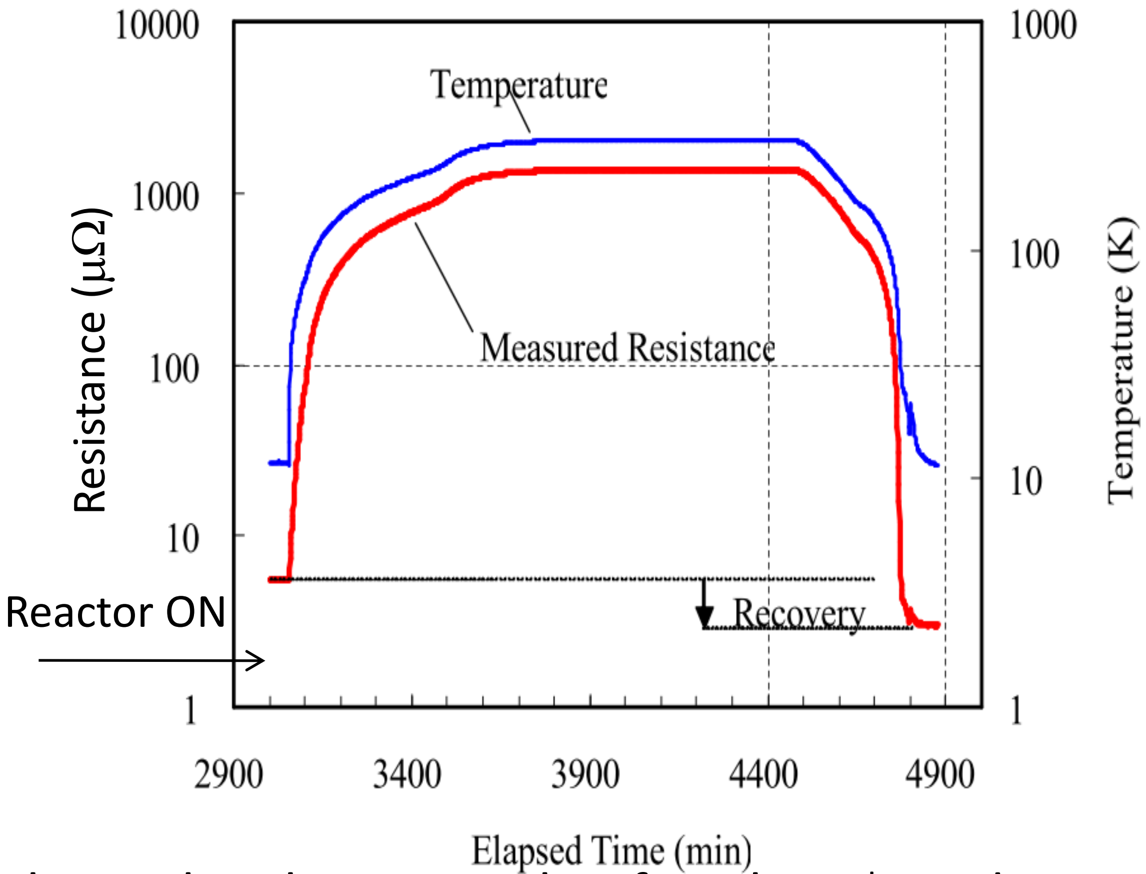
Result: $\Delta\rho_{irr}$ for 5N-Aluminum

*TC reading includes the offset of +1K.



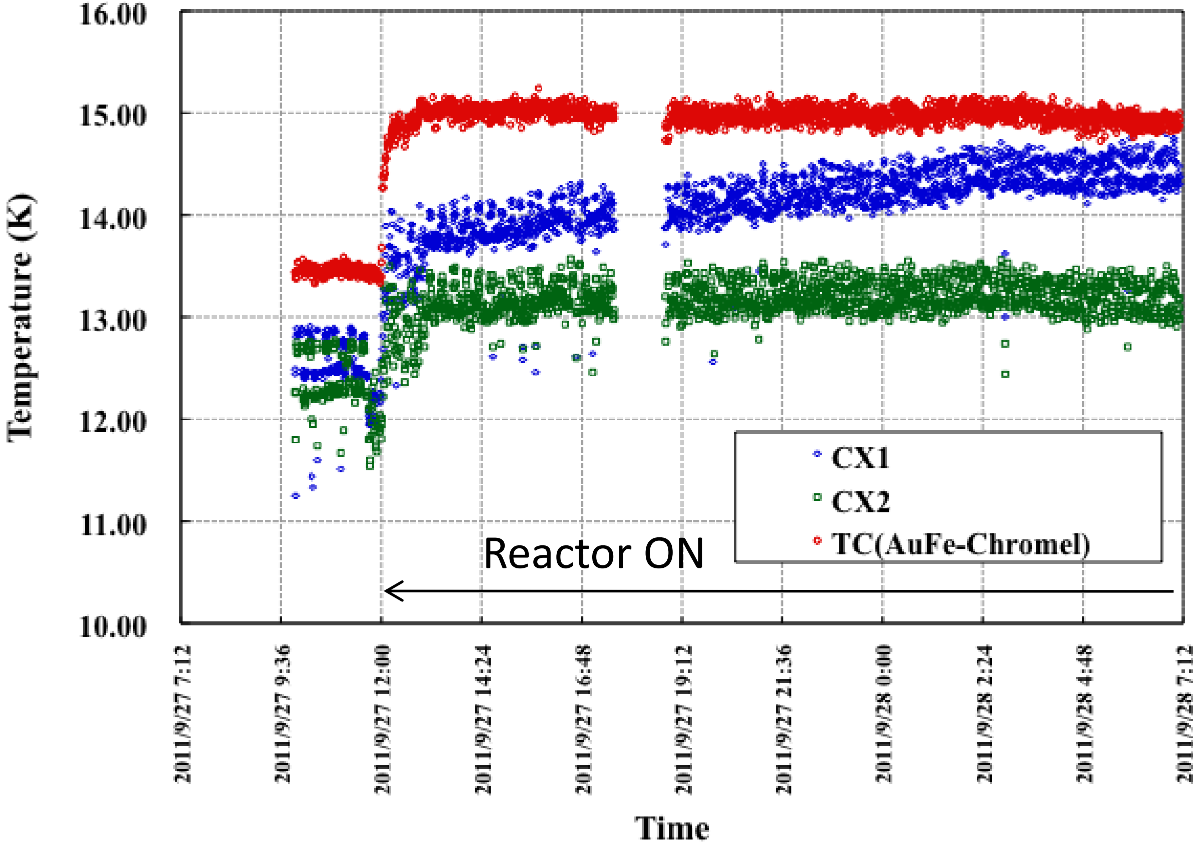
- Fast neutron exposure at 14K @1MW*52 hrs (Sep. 2011)
- Resistance increased in proportional to neutron fluence in the range of 10^{19}-10^{20} n/m^2
  - No threshold at low neutron fluence
- Observed $\Delta\rho_{irr}$ = 0.064 nΩ.m for 2.7x10^{20} n/m^2 (>0.1MeV)
  - Agreed with the previous work within a factor of 2.
    - Present work: $\Delta\rho_{irr}/\Phi_{tot}$= 2.4x$10^{-22}$ nΩm^3 (RRR 3000, 2.7x10^{20} n/m^2)
    - Previous: $\Delta\rho_{irr}/\Phi_{tot}$= 1.9x$10^{-22}$ nΩm^3 (RRR 2000, 2x10^{22} n/m^2)

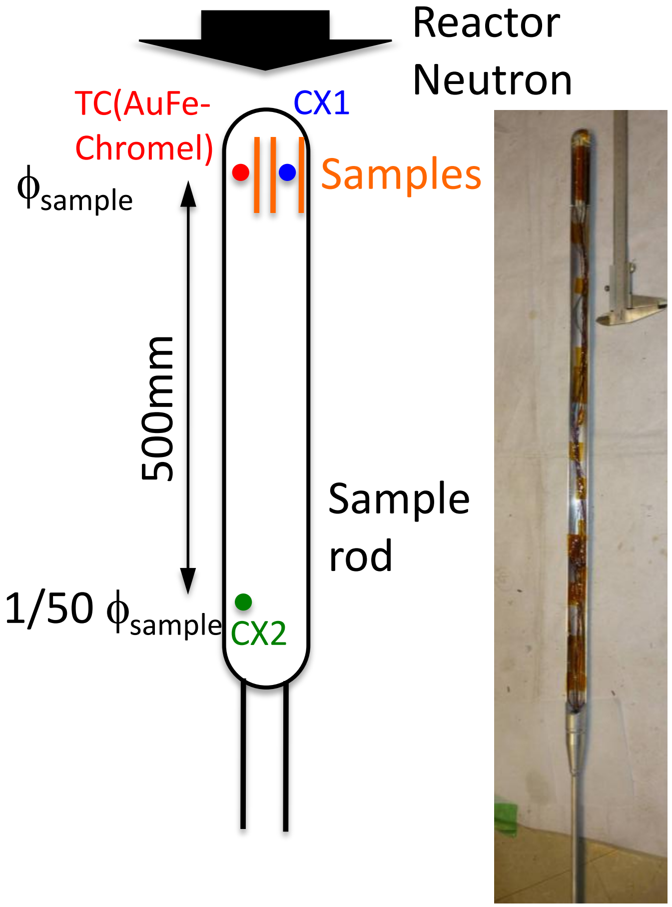
Result: Anneal and Recovery for Aluminum



- A thermal cycle to RT right after the 1st irradiation ($2.3\text{x}10^{20}$ n/m^2) in Nov. 2010.
  - Before irradiation: 3.0 μΩ @10K
  - After irradiation: 5.7 μΩ @12-15K
  - After TC: 3.0 μΩ @12K
- **Full recovery of $\Delta\rho_{irr}$ was confirmed.**

Result: Thermometers





- 2 Cernox sensors and TC (AuFe-Chromel) irradiated together with samples in Sep. 2011.
- Sudden jump right after the reactor start is due to energy deposition by gamma rays and neutrons.
- CX1 reading seems to drift with a rate of 1K/day while TC at the same position shows constant temperature.
  - Likely cause of temperature reading rise in CX1 was degradation.
- Temperature rise in CX2 under low neutron flux is negligibly small.

Discussion

Materials	Aluminum				Copper		
	Horak	Guinan	**Present**	**Present**	Horak	Guinan	**Present**
RRR	2286	74	**450**	**3007**	2280	172	**319**
T_{irr} (K)	4.5	4.2	**12**	**14**	4.5	4.2	**14**
Netutron Source	Reactor	14 MeV	**Reactor**	**Reactor**	Reactor	14 MeV	**Reactor**
Φ_{tot} (n/m^2) (>0.1MeV)	2 x 10^{22}	1-2 x 10^{21}	**2.3 x 10^{20}**	**2.7 x 10^{20}**	2 x 10^{22}	1-2 x 10^{21}	**2.7 x 10^{20}**
$\Delta\rho_{irr}/\ \Phi_{tot}$ x10^{-31}(Ωm^3)	1.9	4.09	**2.4**	**2.4**	0.58	2.29	**0.82**
Recovery by thermal cycle	100%	100%	**100%**	**TBD**	90%	80%	**TBD**

- Degradation rate ($\Delta\rho_{irr}/\ \Phi_{tot}$) seems to be higher in 14 MeV neutron irradiation. Evaluation using a common index such as DPA would be necessary.
- Present work shows that difference in RRR of Al doesn't influence the degradation rate.
- For copper, degradation rates ($\Delta\rho_{irr}/\ \Phi_{tot}$) are ranged from 0.58 to 2.29 10^{-31} Ωm^3. What if SC cables with the initial RRR of 200 are irradiated to 10^{20} or 10^{21} n/m^2?
  - 10^{20} n/m^2 : RRR of 160 – 190
  - 10^{21} n/m^2 : RRR of 50 – 120
- Recovery by annealing in cooper sample and its multiple irradiation are planned in 2012.

Summary and Further Plan

- Reactor neutron irradiation tests for SC stabilizers (Al, Cu) at low temperature have been carried out to study the degradation behavior. Recovery by annealing to RT have been also studied.

- Irradiation of aluminum and copper samples up to 2-3 x 10^{20} n/m^2 below 20 K showed that the degradation rates ($\Delta\rho_{irr}/\Phi_{tot}$) agreed with the previous work within a factor of 2.

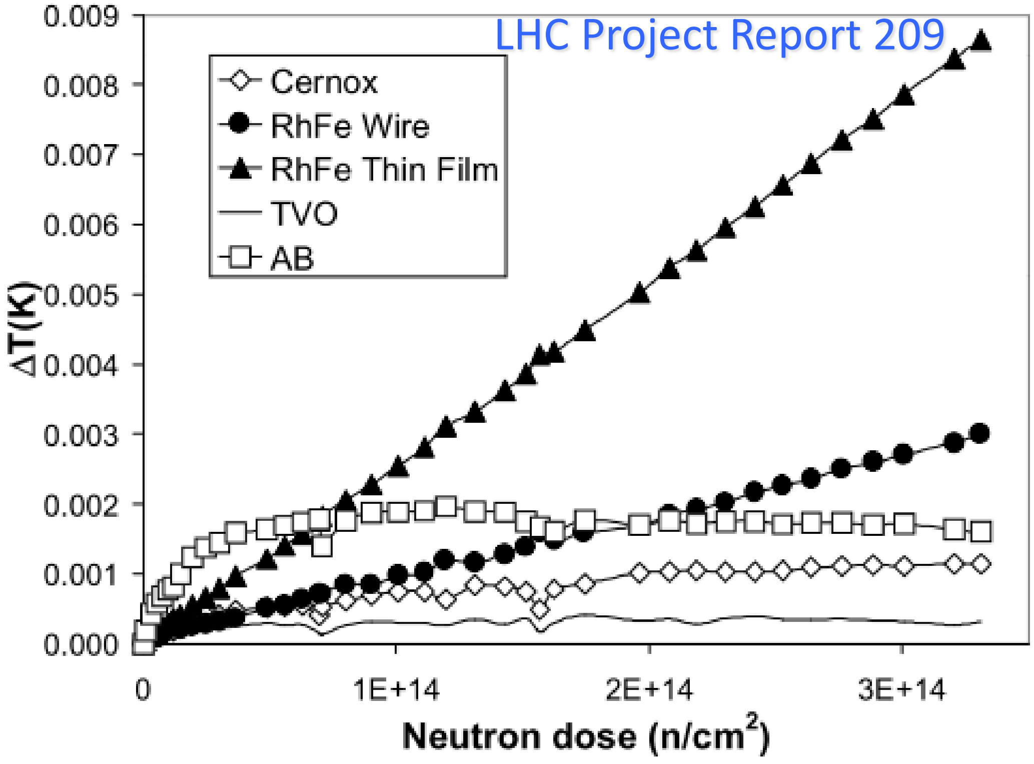
- Full recovery of resistivity degradation by annealing was confirmed in the aluminum sample.
  - For the copper sample, the recovery behavior during the repeated irradiation and annealing will be studied in 2012.

- Cernox thermometers irradiated up to 2-3 x 10^{20} n/m^2, which is 20 times as high as that for the previous work. The induced resistance per neutron fluence was consistent with the previous work.

- Further neutron irradiation tests for other SC magnet materials will be made at KUR.

Why thermometers?

- Irradiation effects of thermometer including Cernox studied for the LHC at 1.8 K. Fluence up to 10^{19} n/m^2.
  - What happens at the level of 10^{20} or higher?



LHC Project Report 209

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

X60947
R_0=1960Ω @12K
$\Delta R/\Delta T$=-170 Ω/K
ΔR_{irr}=340 Ω @2*10^{20} n/m^2

R_0=12600 Ω
$\Delta R/\Delta T$=-12000 Ω/K
ΔR_{irr}=24 Ω @10^{19} n/m^2

>> 480 Ω for 2*10^{20}

SC: NbTi (1)

Degradation on Tc: 0.15 K to 0.6 K @up to 10^23/m2

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

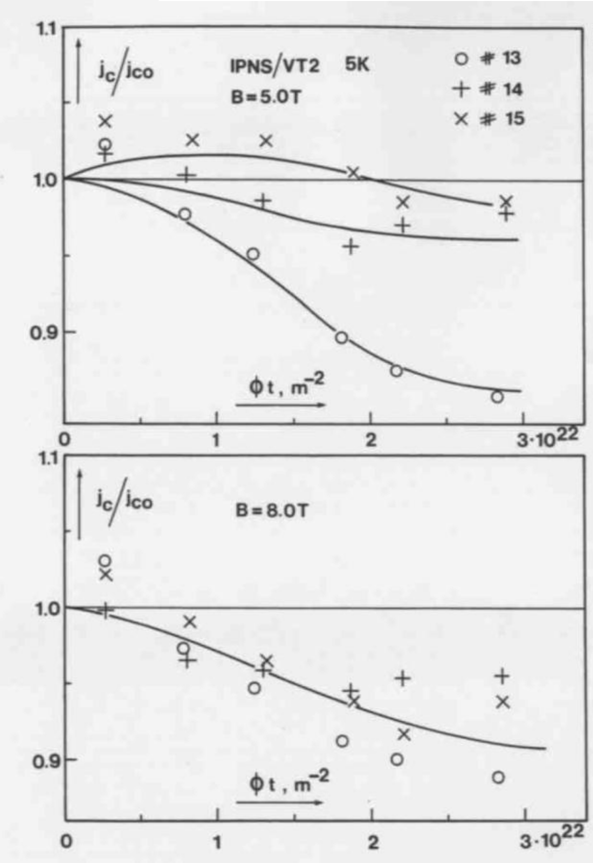


Fig. 2. Change of critical current densities with fast neutron fluence (E >0.1MeV) at 5 and 8 T. #13,14,15: 42,49,54 wt%Ti; annealing temperature: 350°C; final cold work: 71%.

5K

Jc: < 10% reduction up to 10^22/m2

J. Nucl. Materials, 271&272, p505 (1999)

20K

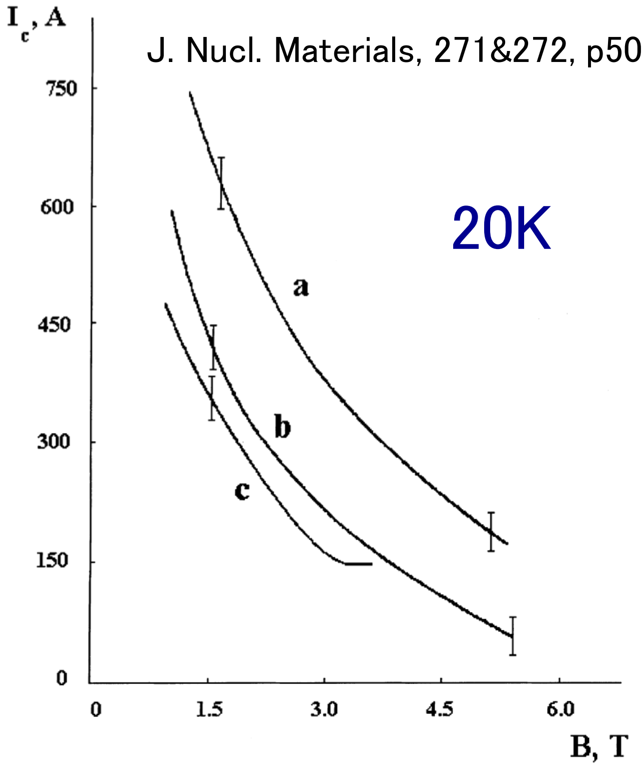


Fig. 2. Dependence of critical current vs magnetic field for 37-core industrial superconducting NbTi wire: (a) before irradiation; (b) after irradiation by the neutron fluence of 8.6×10^{17} cm^{-2}; (c) after irradiation by the neutron fluence of 1.6×10^{18} cm^{-2}.

I: Significant reduction at 5T @ 10^22/m2

SC: NbTi (2)

RT, 77K w/ T.C.

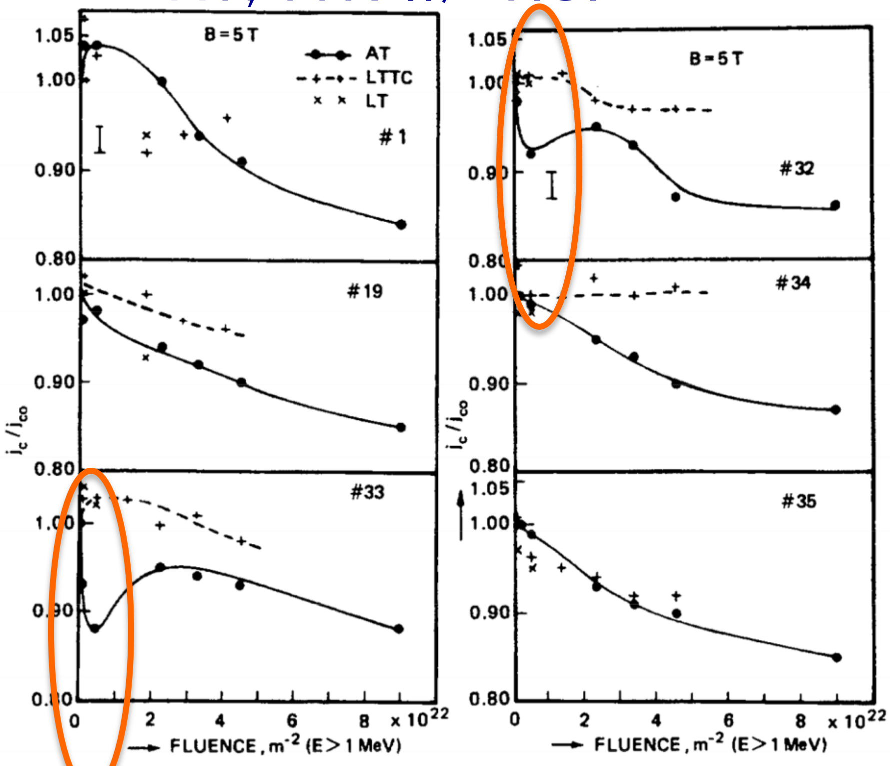


Fig. 11. Changes of critical current densities measured at 5 T with fast neutron fluence. AT, LT: irradiation at ambient temperatu and 77 K, respectively; LTTC: irradiation at 77 K and thermal cycle to room temperature. No. 1: Nb–42 wt% Ti, lowest j_{c0}; Nos. 1 32, 33: Nb–42, 49, 54 wt%Ti, highest j_{c0} of each series; Nos. 34, 35: Nb–49 wt%Ti, Multifilamentary conductors [41].

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

RT

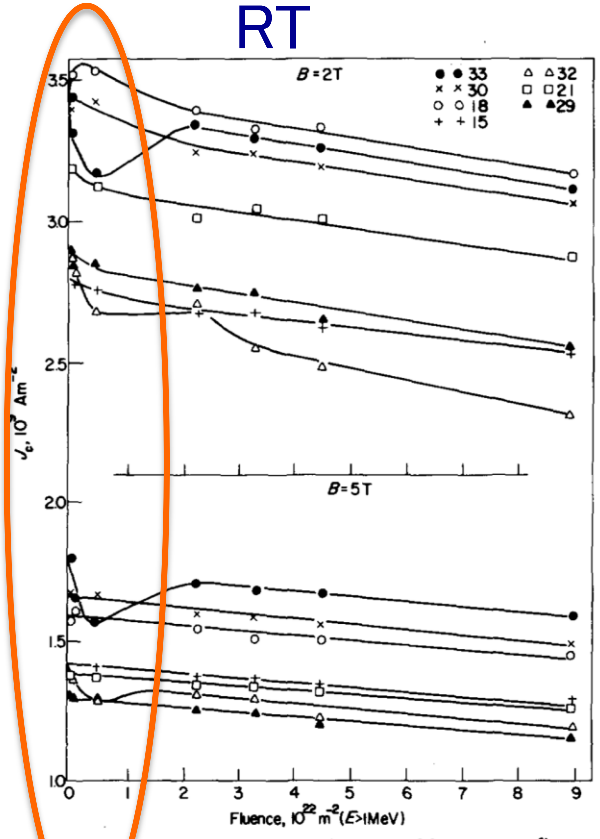


Fig. 9 Critical current densities as a function of fast neutron fluence for the seven highest j_c conductors of the present investigation

Cryogenics, 21, No.4, p223 (1981)

Jc: Drop and recovery observed to 10^22/m2.
10-20% reduction up to 10^23/m2.
Recovery by annealing to RT is observed.

NbTi would be OK up to 10^22/m2.

SC: Nb3Sn

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

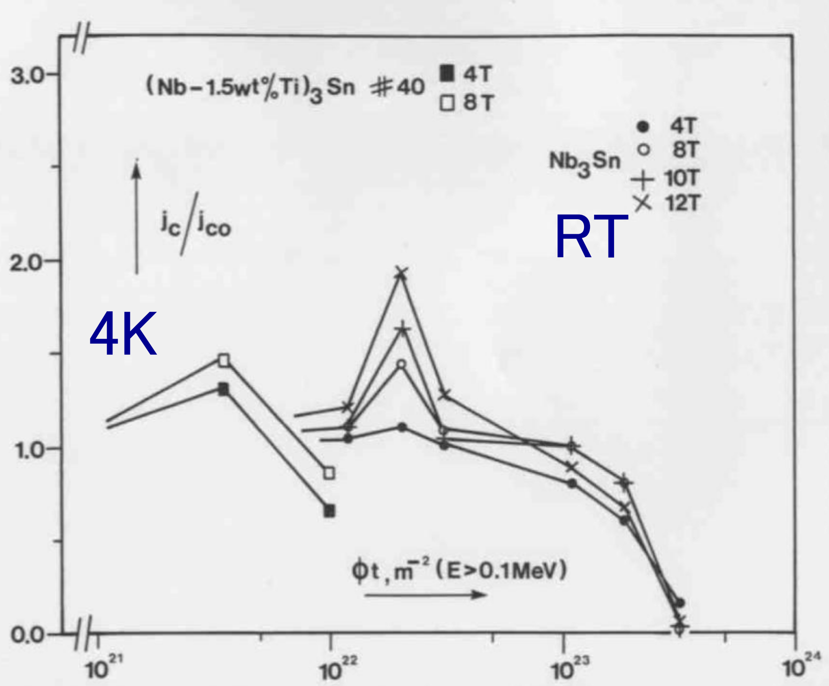
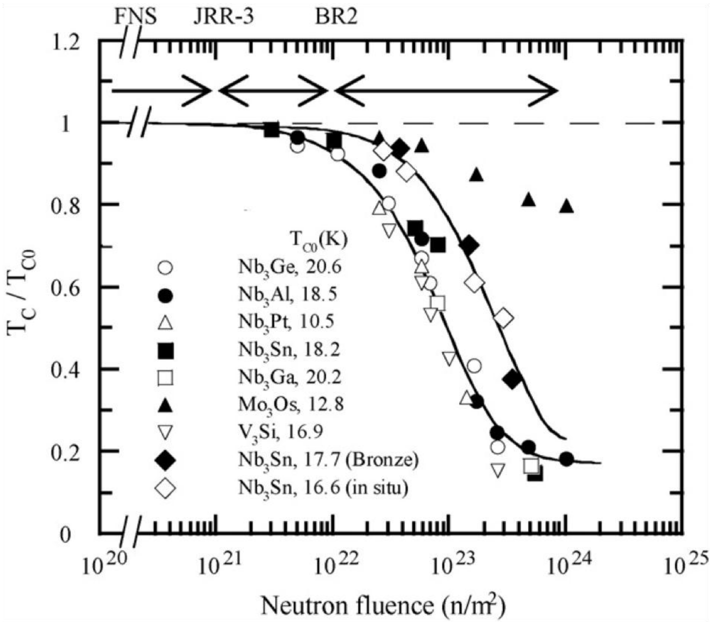


Fig. 6. Change of critical current densities with neutron fluence. The scaling is not completely accurate because of slight differences in damage energy cross sections. Low temperature irradiations on an alloyed conductor are compared to ambient temperature irradiations of pure Nb$_3$Sn[29].

Fusion Eng. Design, 84, p1425 (2009)



Tc: −10% @ 10^22/m2.
−30% @ 10^23/m2.

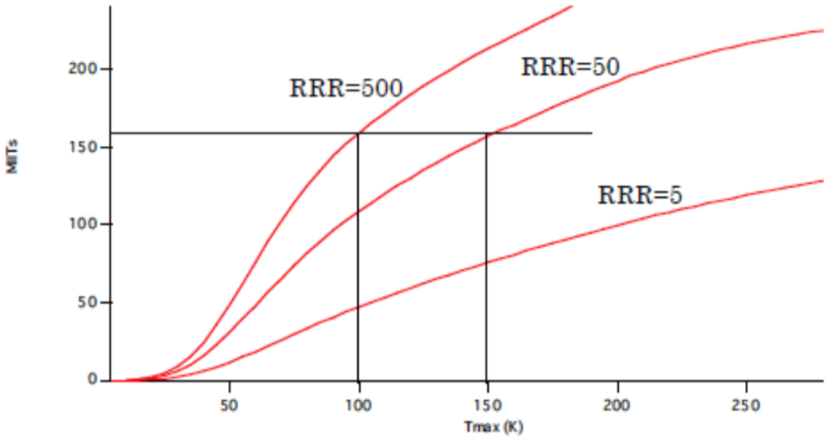
Jc: Improvement bwn 10^22 and 10^23/m2.
Significant degradation beyond 10^23/m2.

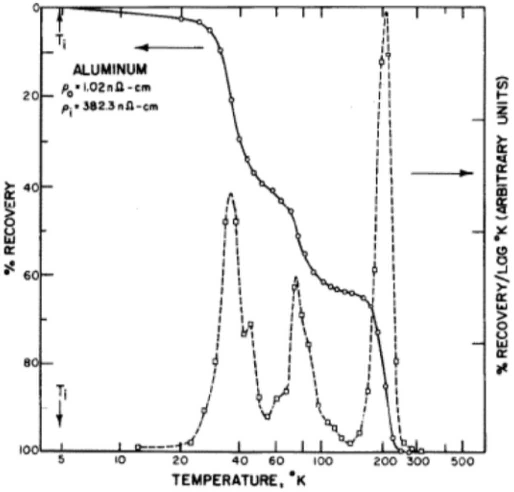
NbSn would be OK up to 10^22/m2 as well.

Why is ρ of Stabilizer Important?

>> very concerned with quench protection.

- MIITs: $\int_{t_{quench}}^{t_{end}} I^2 dt = \int_{T_0}^{T_{\max}} \frac{C_p A}{\rho / A} dT$
- ρ increase ➔ temperature increase





Neutron irradiation test for stabilizers (copper, aluminum) is undoubtedly necessary.

minimum fluence to start of degradation

anneal effect on recovery

R&D of witness sample for the operation