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Radiation damage effects on RRR

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Radiation conditions at LHC Upgrade

Fundamental aspects of irradiation

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Proton irradiation of Cu

Comparing fluences between various reactors

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Introduction

The electrical resistivity ρ of the Cu stabilizers (or the RRR value) in superconducting magnets is strongly affected by high energy irradiation.

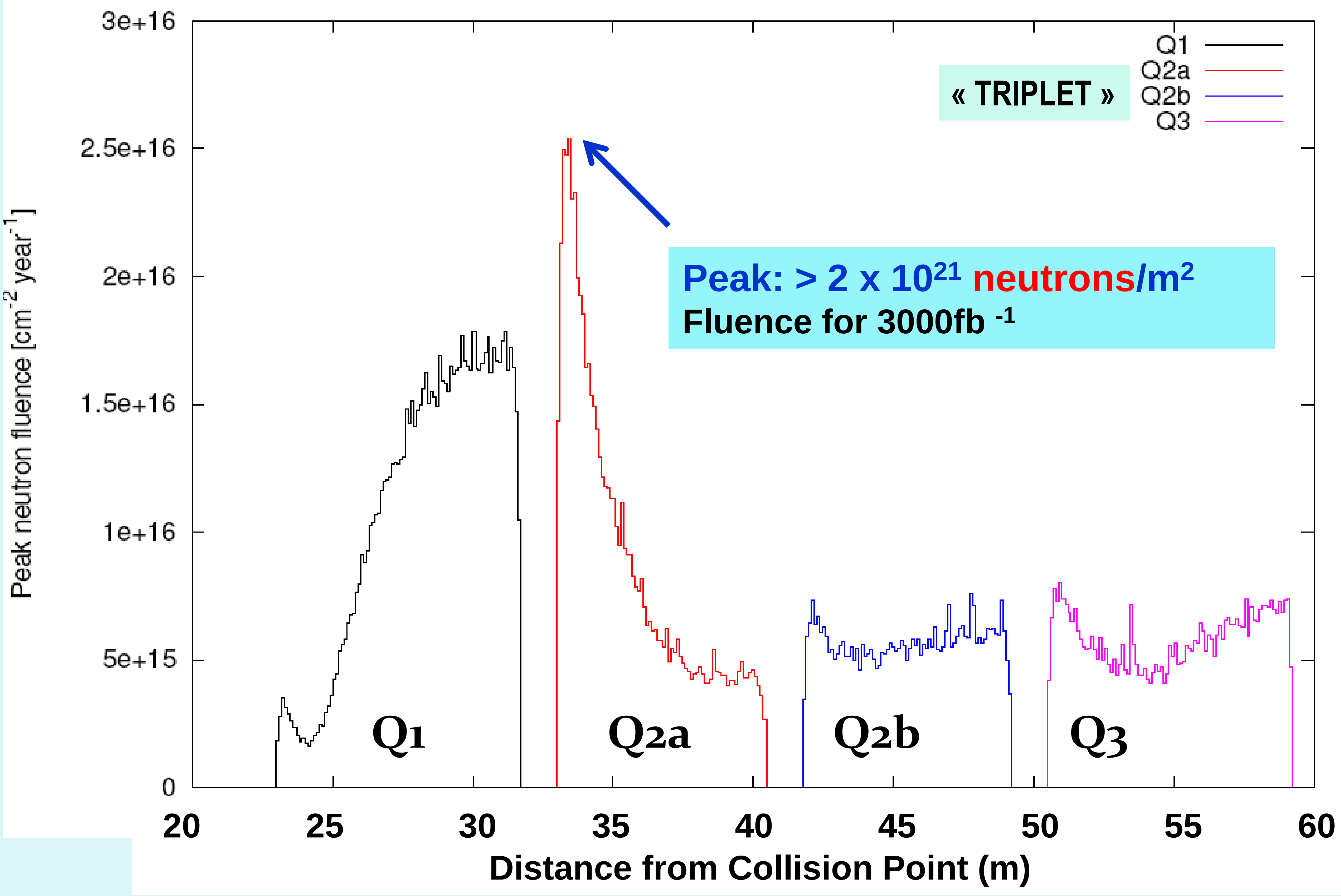
The lowering of RRR after irradiation will affect the quench stability and the protection scheme.

It is known that

- The enhancement of resistivity (or decrease of RRR) of Cu is stronger for irradiations at lower temperatures
- RRR is recovered with increasing temperature, starting already at 20K

Radiation conditions at LHC Upgrade

Neutron fluence in the inner winding of LHC Quadrupoles



Preliminary FLUKA calculations (without cold shielding)

Over the High Lumi LHC target: integrated luminosity (3000 fb^{-1}).
Triplet quadrupole cables and insulators will undergo the following radiation peak values:

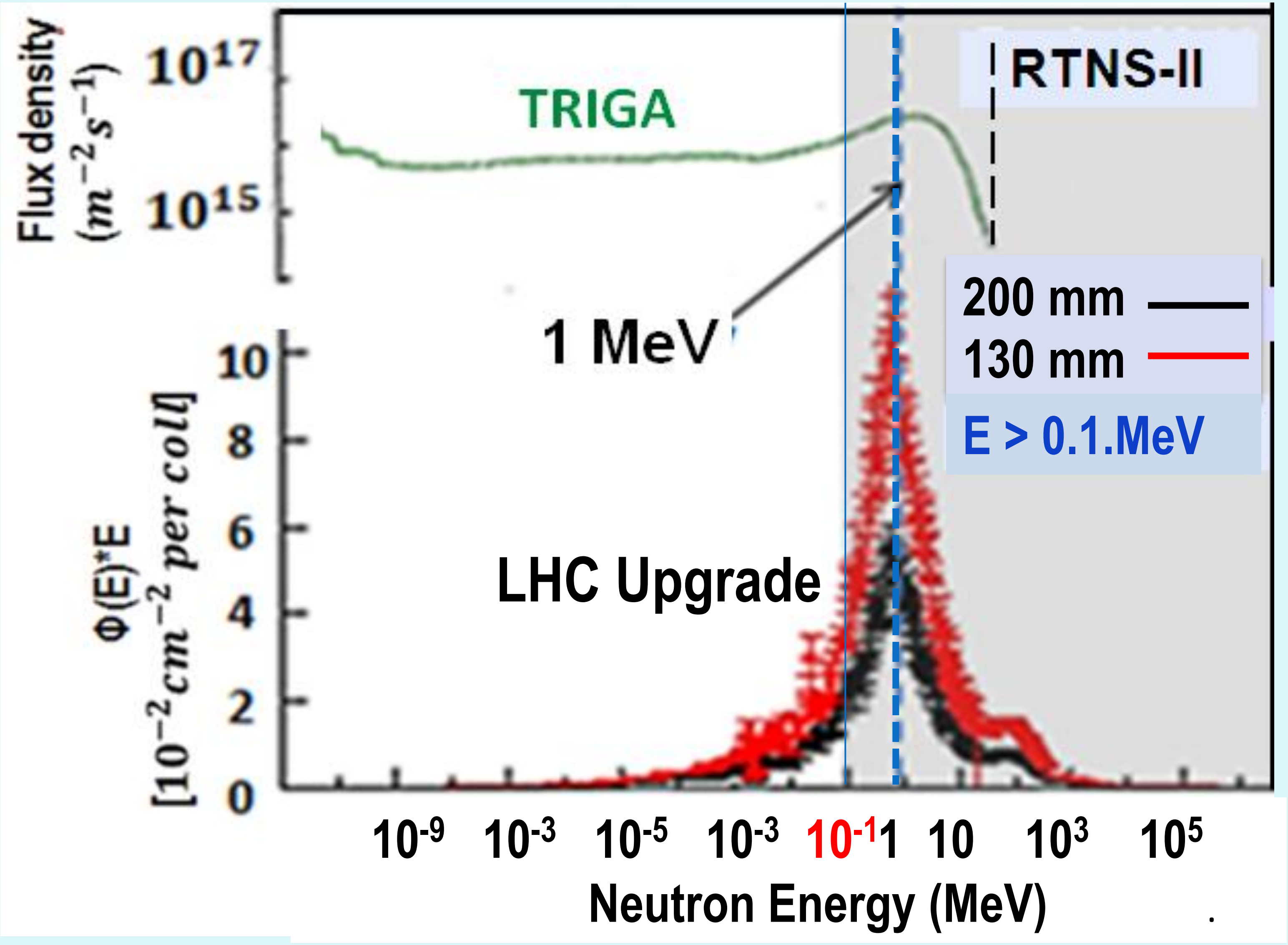
- ~ 100 MGy (dose)
- ~ 10^{16} pions/cm^2
- ~ 2 x 10^{17} neutrons/cm^2

Track length fraction [%]	
photons	88
electrons/positrons	7
neutrons	4
pions	0.45
protons	0.15

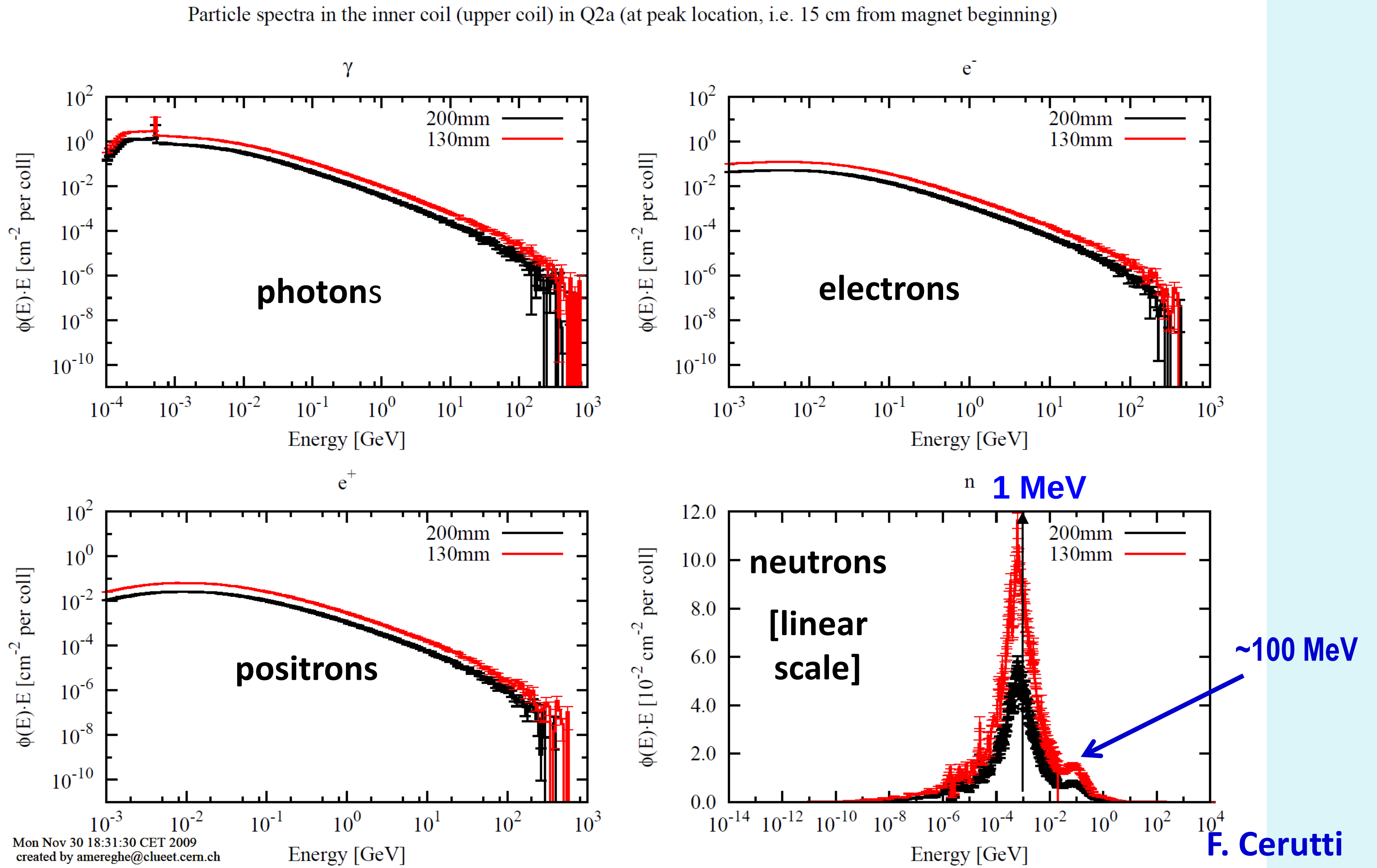
Neutrons	87.0 %
Protons	3.2%
Pions (+/-)	9.8%

F. Cerutti

Neutron Energy spectra



Particle spectra in the coils



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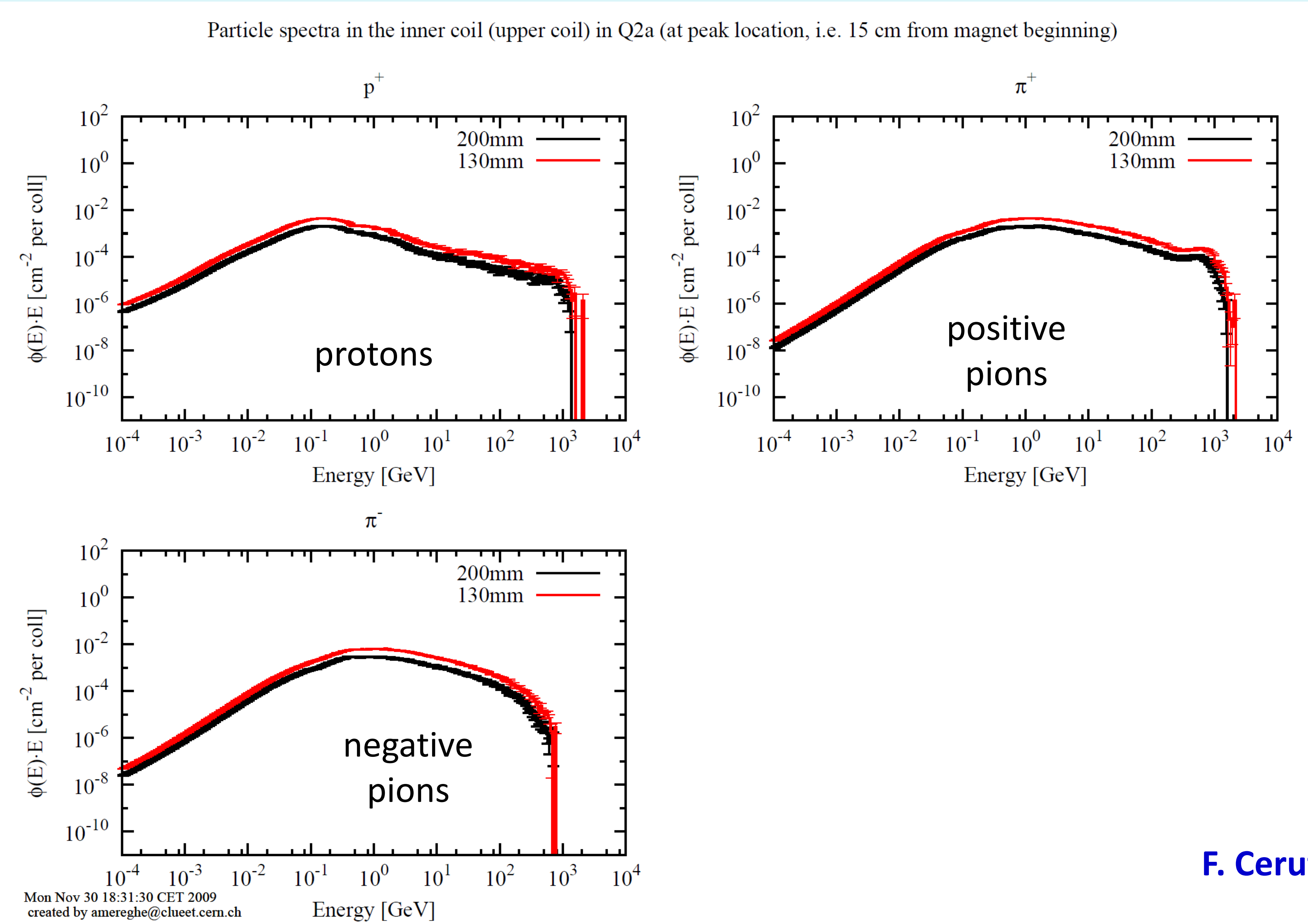
Particle spectra in the coils



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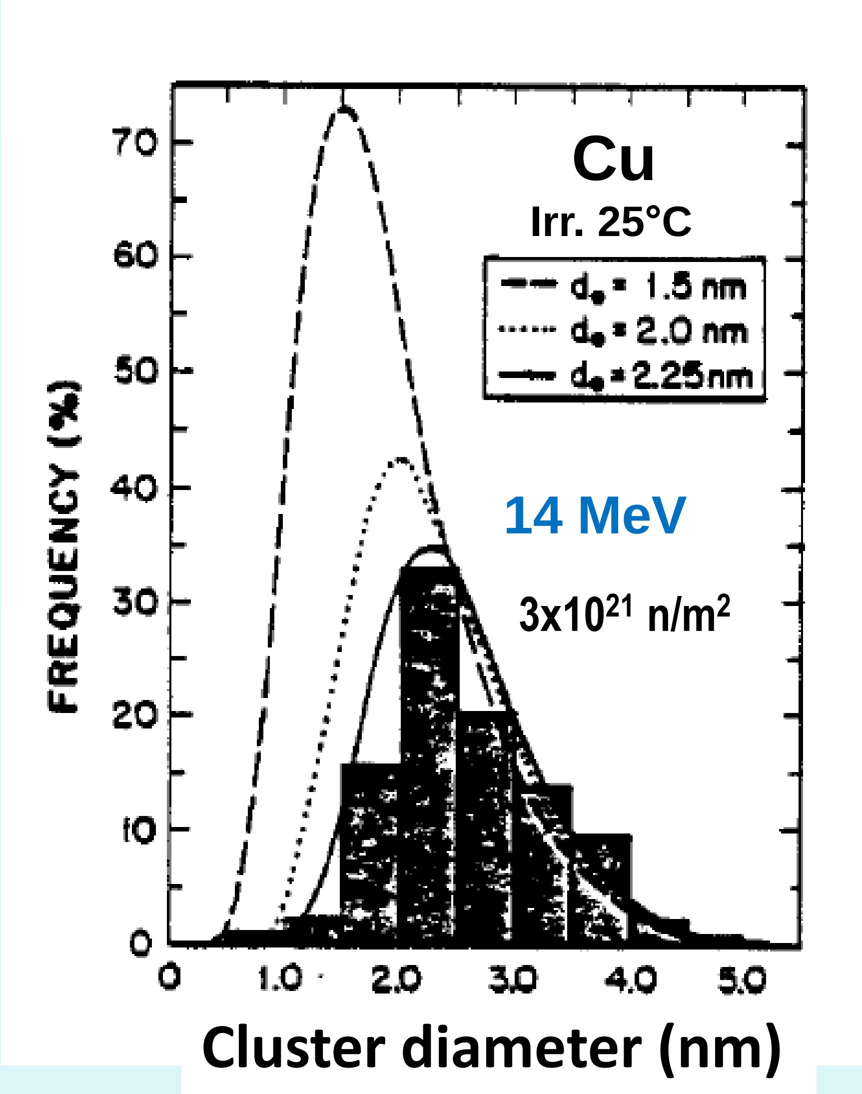
Fundamental aspects of irradiation effects

Microscopic effects during irradiation

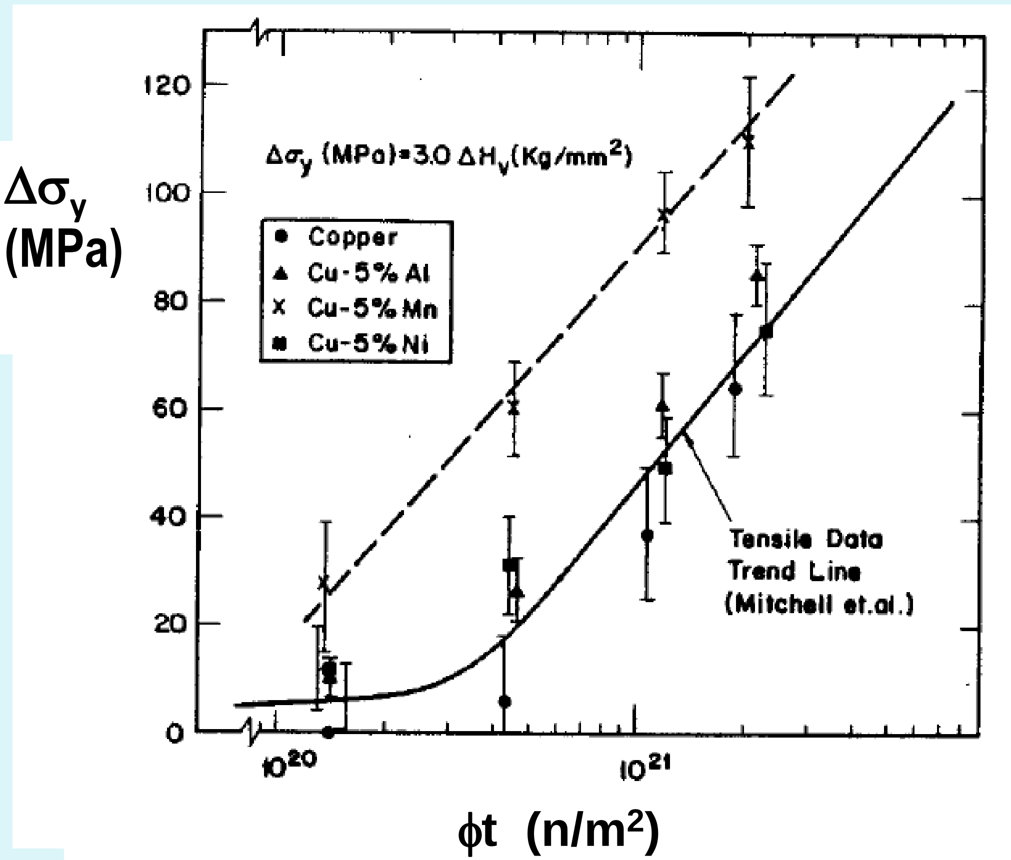
TEM analysis:
Formation of disordered zones, or defect clusters of nanometer size

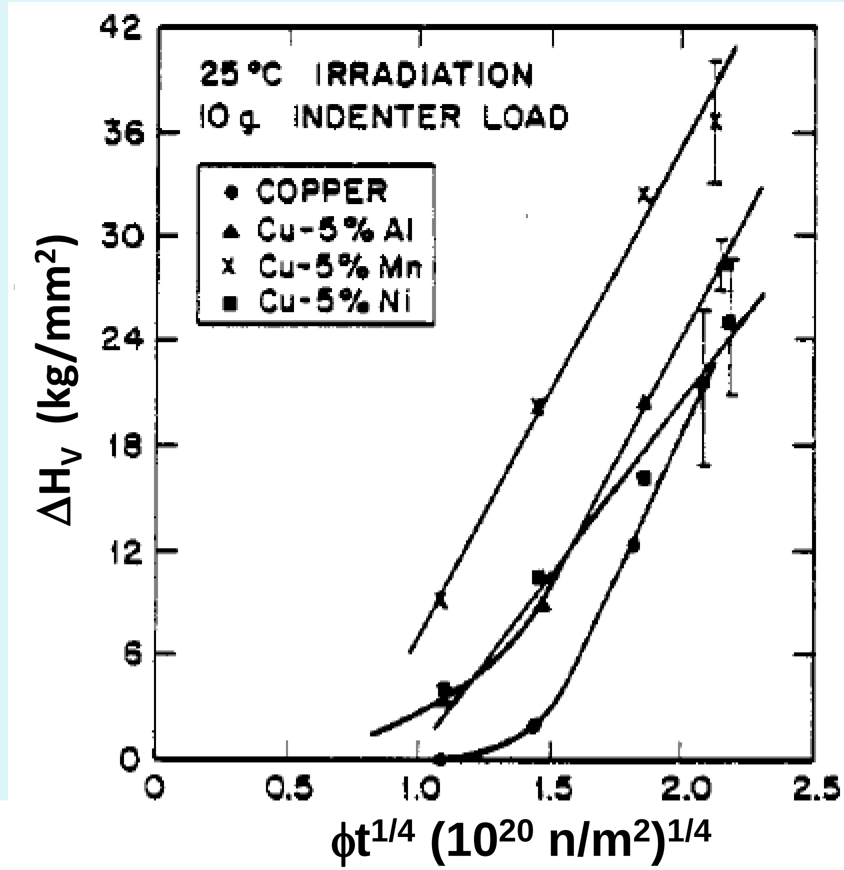
Number of clusters highest for the smallest sizes



S.J. Zinkle, G. L. Kulcinski, J. Nucl. Mater., 122&123, 449(1984)

Defect clusters : Effects on the mechanical properties



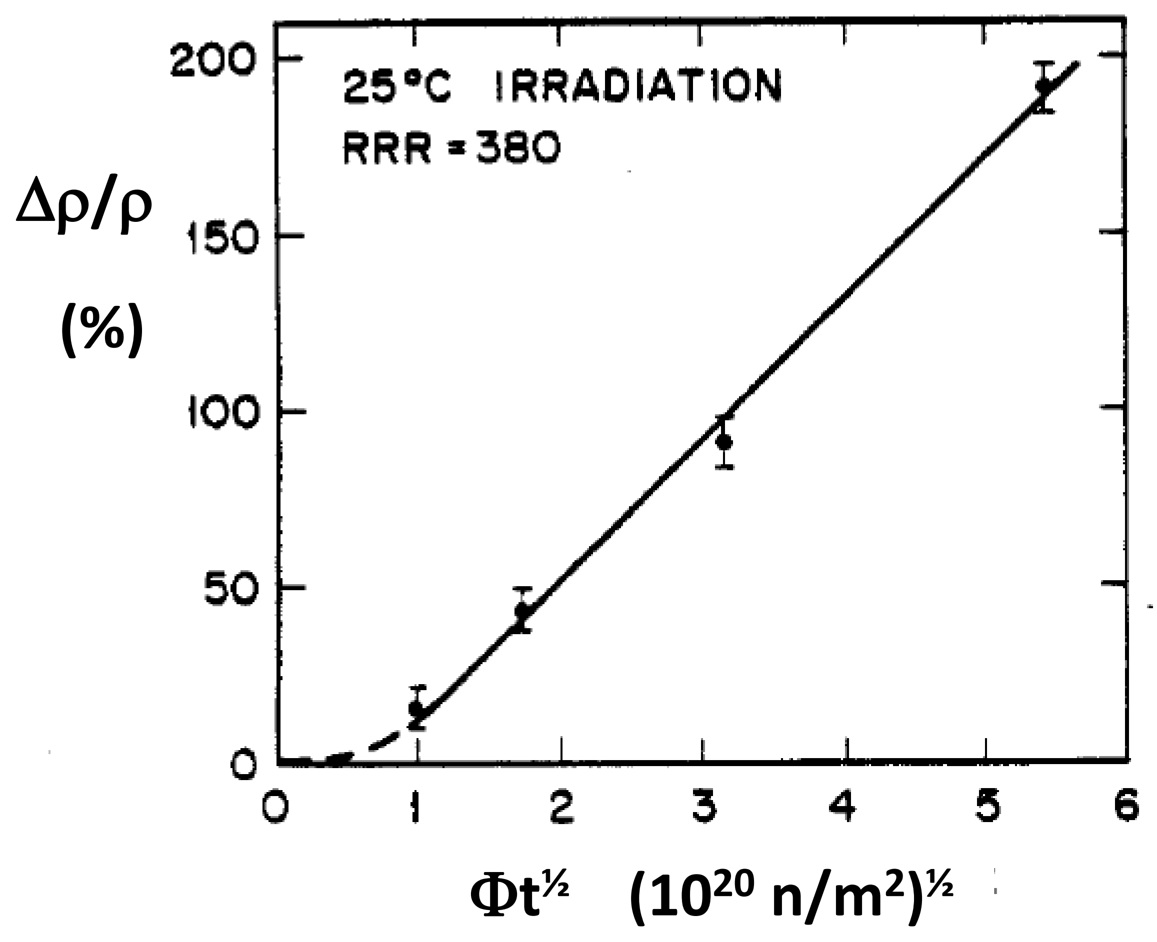


Change of yield strength at 14 MeV

Change of Vickers microhardness

S.J. Zinkle et al. (1984)

Defect clusters : Effects on electrical resistivity



S.J. Zinkle et al. (1984

Analogy with superconductors

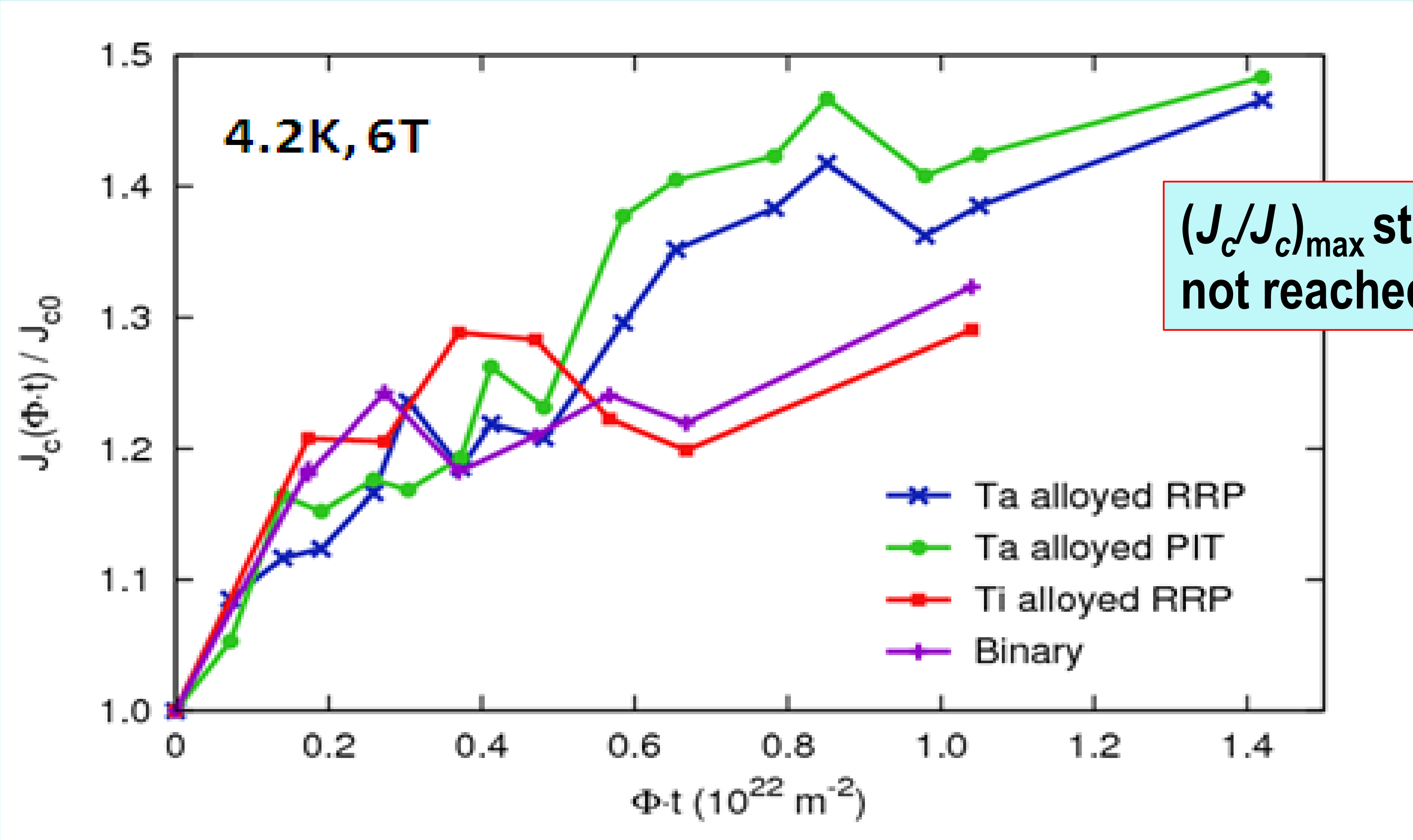
Formation of defect clusters at nanoscale is a general effect in solids after high energy irradiation:

- **Mainly caused by neutrons, protons, (pions)**
- **To a smaller extent: by electrons and photons (more data are needed)**

In superconductors, defect clusters are the reason for the observed enhancement of J_c after irradiation

Theoretically, the pinning behavior caused by defect clusters can be treated as «point defects»
(Main result of the collaboration with the Vienna group)

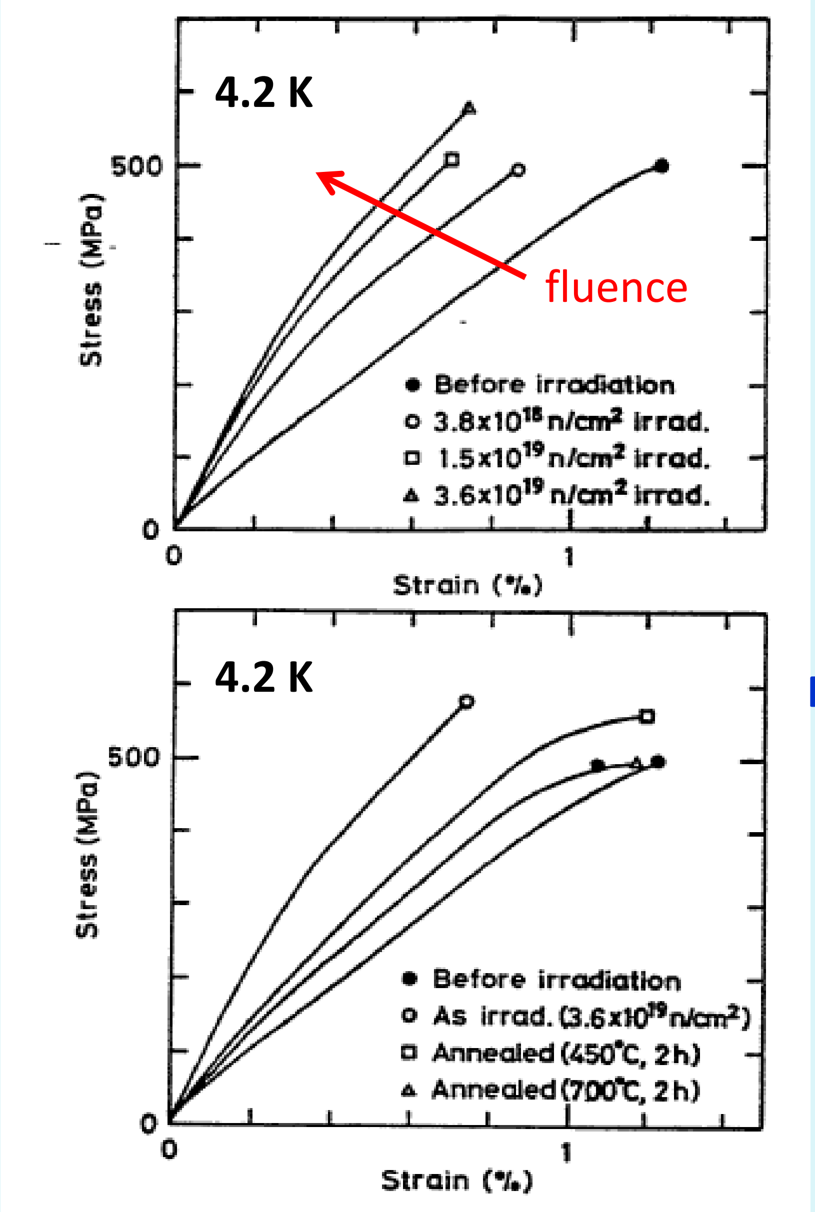
Variation of J_c with increasing neutron fluence



$(J_c/J_c)_{max}$ still not reached!

R. Flükiger, T. Baumgartner, M. Eisterer, H.W. Weber, C. Senatore, T. Spina, C. Scheuerlein, A. Ballarino and L. Bottura , ASC 2012

Stress – strain curves before and after irradiation



Bronze Route multifilamentary wire
T_{irr} = 350 K

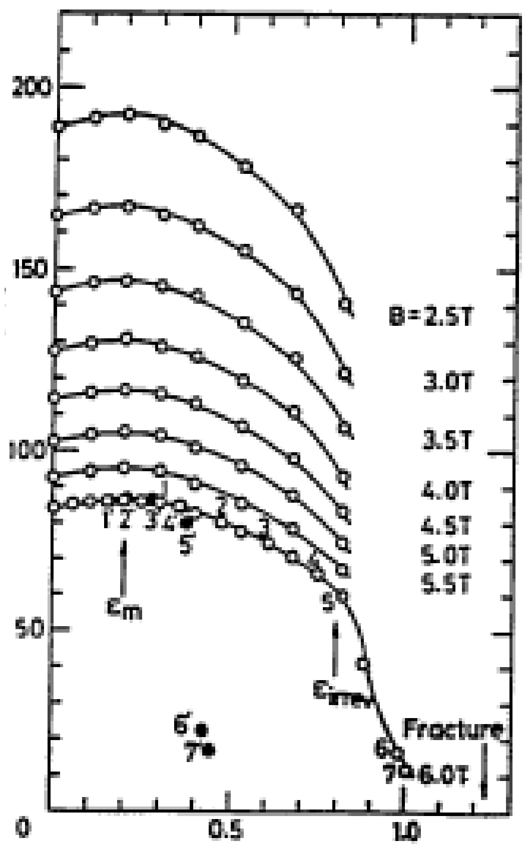
Hardening with higher fluence

Recovery after annealing at 450 and 700 °C

T. Okada, M. Fukumoto, K. Katagiri, K. Saito, H. Kodaka, H. Yoshida, IEEE Trans. Magn., MAG-23(1987)972

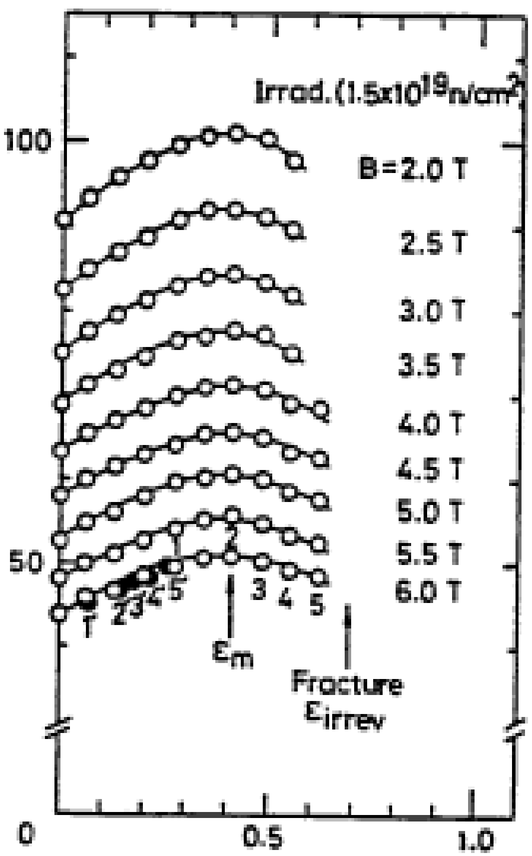
Effect of uniaxial tensile strain after irradiation

I_c (A)



Strain (%)

I_c (A)



Strain (%)

Bronze Route Multifilamentary Nb_3Sn wire

Before Irradiation
$\varepsilon_m = 0.2\%$

After Irradiation
$\varepsilon_m = 0.4\%$

T. Okada, M.Fukumoto, K.Katagiri,K.Saito, H.Kodaka, H.Yoshida, IEEE Trans.Magn. MAG-23(1987)972

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

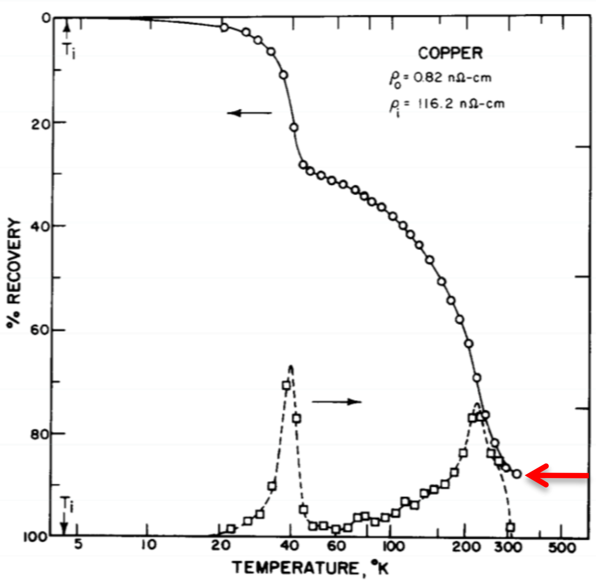
Horak et.al., J. Nucl. Materials, 49, p161 (1973&74)

Guinan et.al., J. Nucl. Materials, 133&134,357(1985)

Reactor neutrons (>0.1 MeV)

ρ_0: **0.0082 nΩm**

$\Delta\rho_{irr}$: **1.162 nΩm**

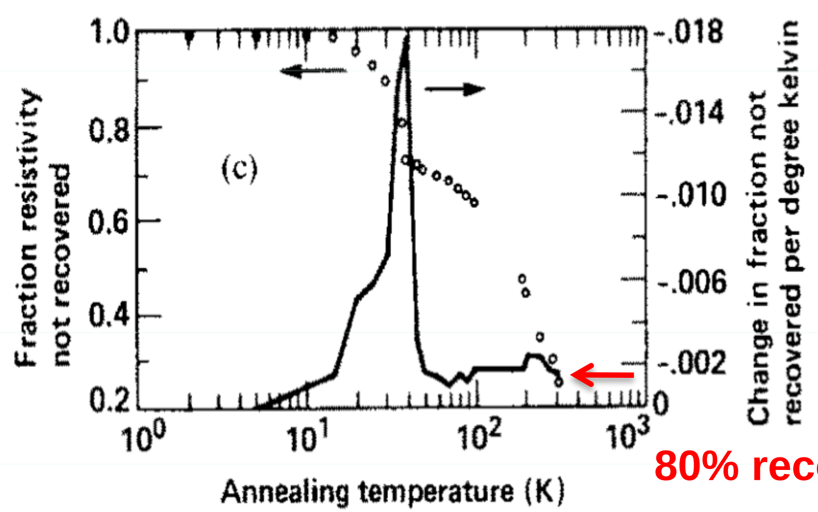


90% recovery

RTNSII neutrons (14 MeV)

ρ_0: **0.0098 nΩm**

$\Delta\rho_{irr}$: **0.191.162 nΩm**



80% recovery

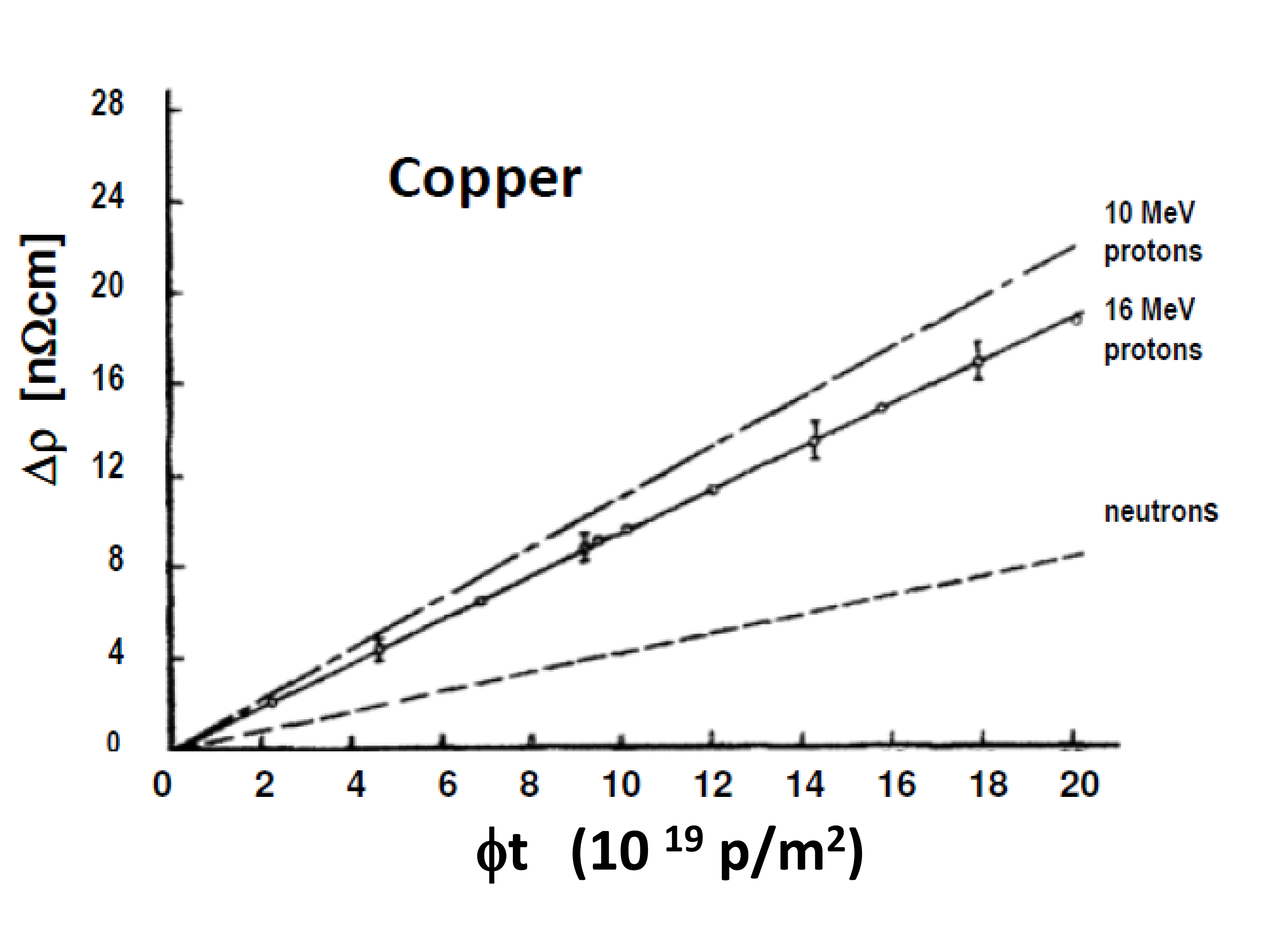
Isochronal annealing to 320K

2×10^{22} n/m^2 at E > 0.1 MeV

1×10^{21} n/m^2 at 14 MeV

- **RRR of ~2000**
- **RRR of ~100**

Effect of proton irradiation on the electrical resistance of Cu



D.A. Thompson, A.M. Omar, J.E. Robinson, J. Nucl. Mater., 85,509(1979)

Electron irradiation of Copper:

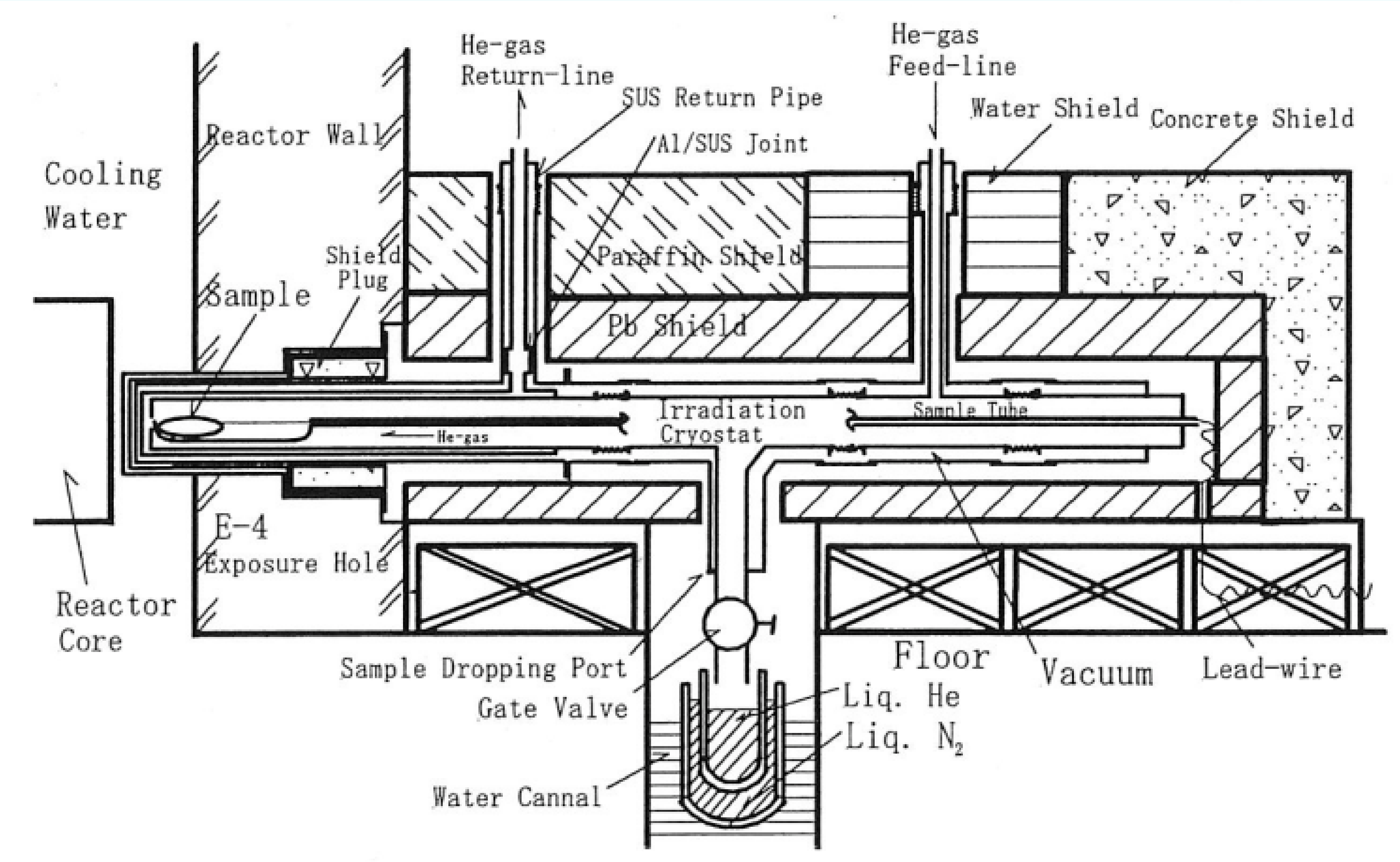
2.8 MeV electrons, T = 9K (RRR = 2'800)
ρ_o = 15.7 x 10^{-9} Ωcm $\longrightarrow$ 590 x 10^{-9} Ωcm (factor 37.5)

Enhancement factors of ρ_o after irradiation (Sassin et al.)
Lowering of RRR:

Cu, 9K:	**Factor 37.5**
Cu, 77K:	**Factor 5**
Cu, 300K:	**Factor 2.**

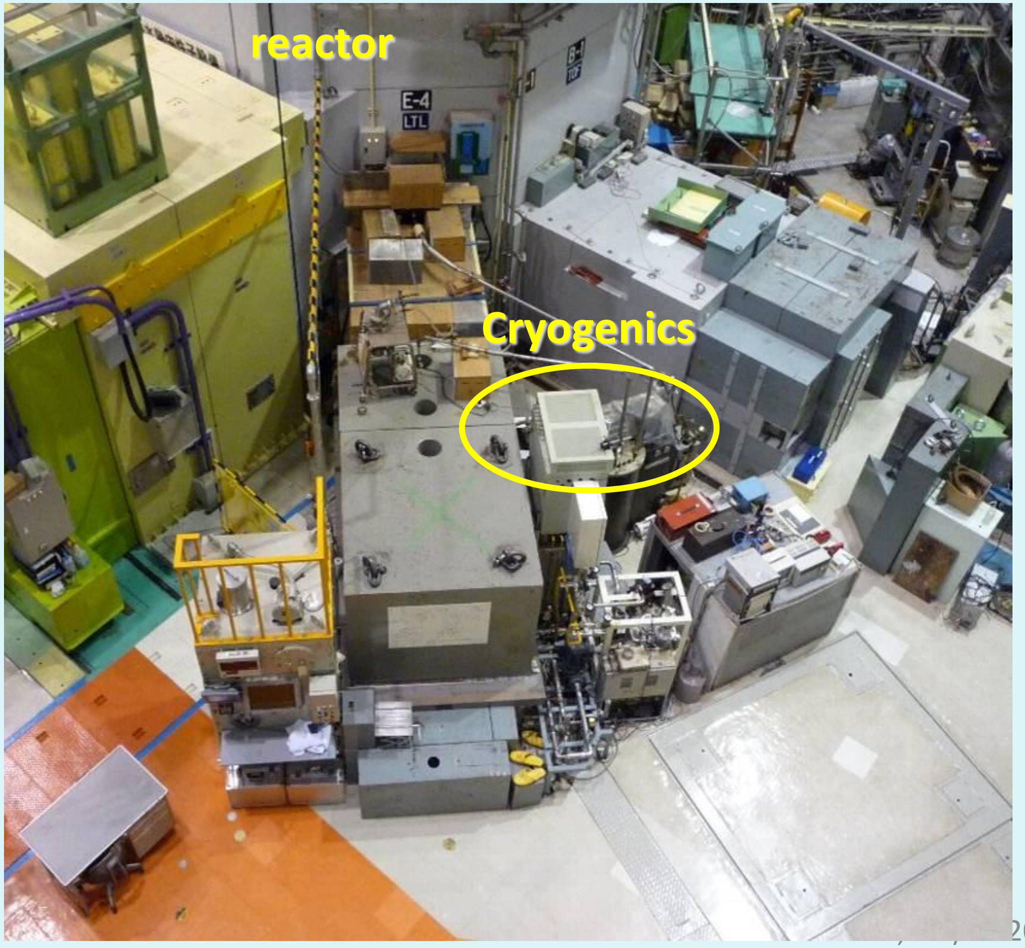
Reason for this difference: recovery of Cu at T well below 300K

Low temperature irradiation facility at Kyoto University



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



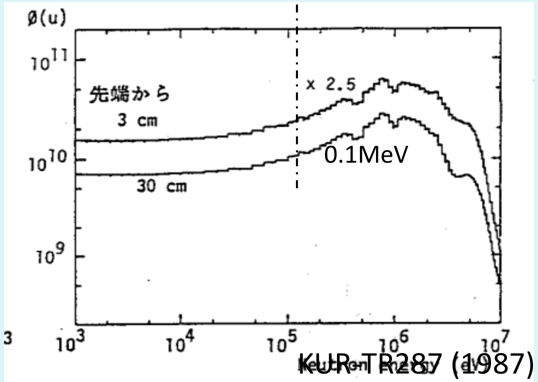
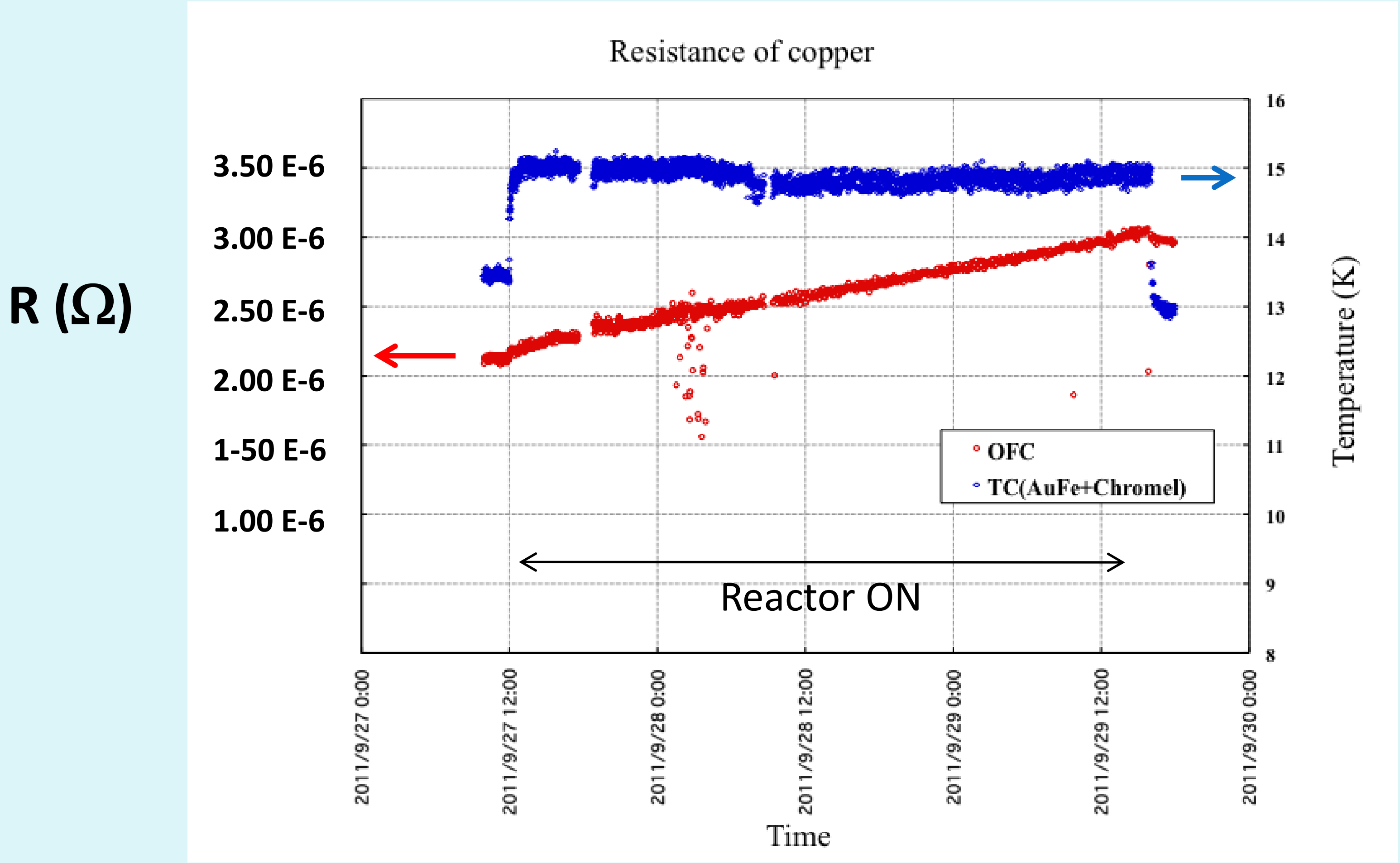


Fig. 15 Neutron energy spectrum in LTL of KUR for ordinary core (above 1000 eV)

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

Recent data : $\Delta\rho_{irr}$ for Copper



- **Fast neutron exposure at 14K (Sep. 2011)**
- **Resistance increased proportionally to neutron fluence in the range of 10^{19}-10^{20} n/m^2**

Nakamoto et al.

Comparison between data on neutron irradiated Copper

Materials	Copper		
	Horak	Guinan	Nakamoto
RRR	2280	172	319
T_{irr} (K)	4.5	4.2	14
Neutron Source	Reactor E > 0.1 MeV	14 MeV	Reactor E > 0.1 MeV
ϕt (n/m^2) (>0.1MeV)	2×10^{22}	$1\text{-}2 \times 10^{21}$	2.7×10^{20}
$\Delta\rho_{irr}/\phi t$ $\times 10^{-31} (\Omega m^3)$	0.58	2.29	0.82
Recovery by thermal cycle	90%	80%	TBD

Degradation rate: $\Delta\rho/\phi t$

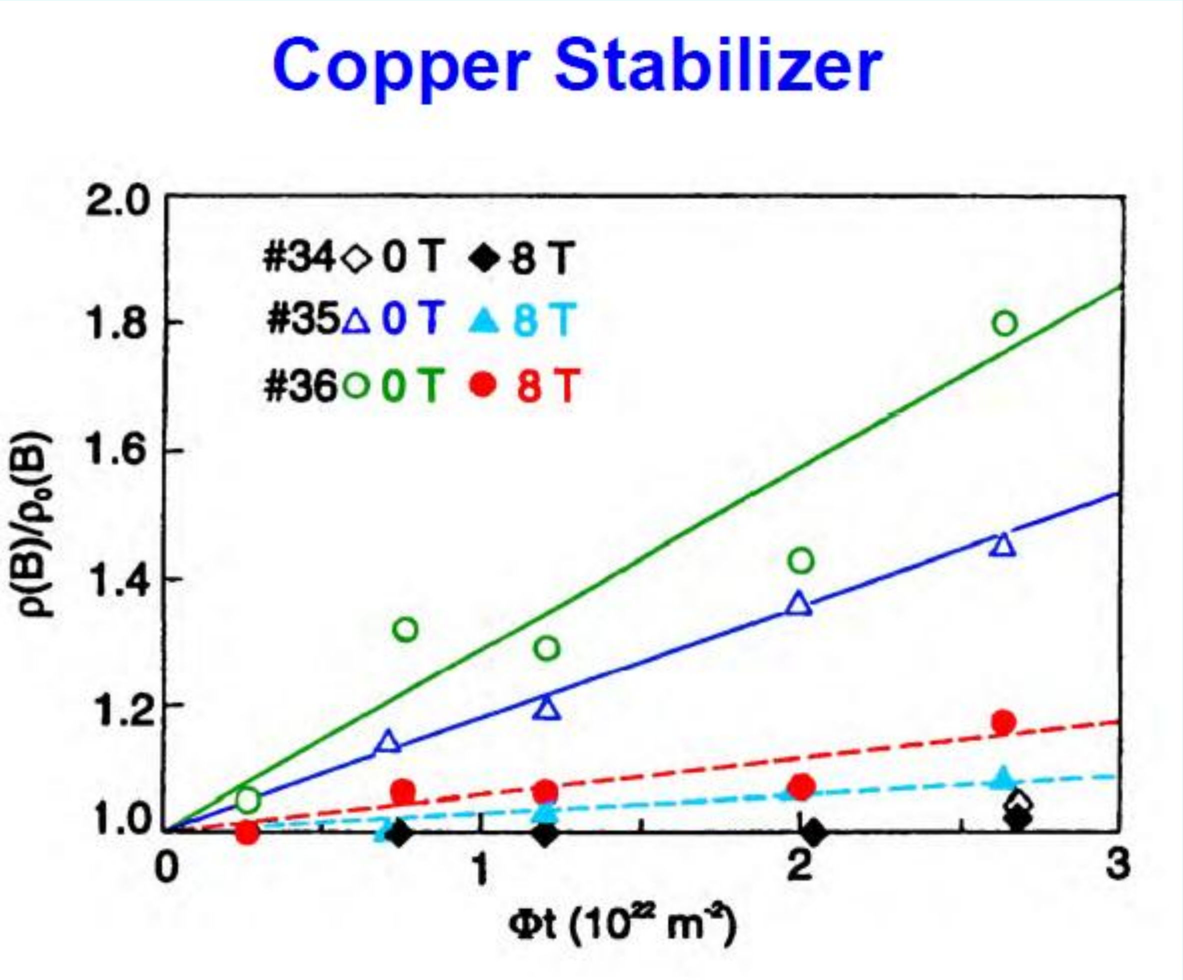
Under work at KURR

From the data of Nakamoto et al.:

Degradation rate ($\Delta\rho_{irr}/\Phi_{tot}$) seems to be higher for Cu after irradiation with neutrons of 14 MeV (with respect to > 0.1 MeV)

However, taking into account the different damage energies E_D in the different reactors, the degradation rates seem to be comparable.

Question: How to compare the damage energies between different reactors?



From Minervini, 2010

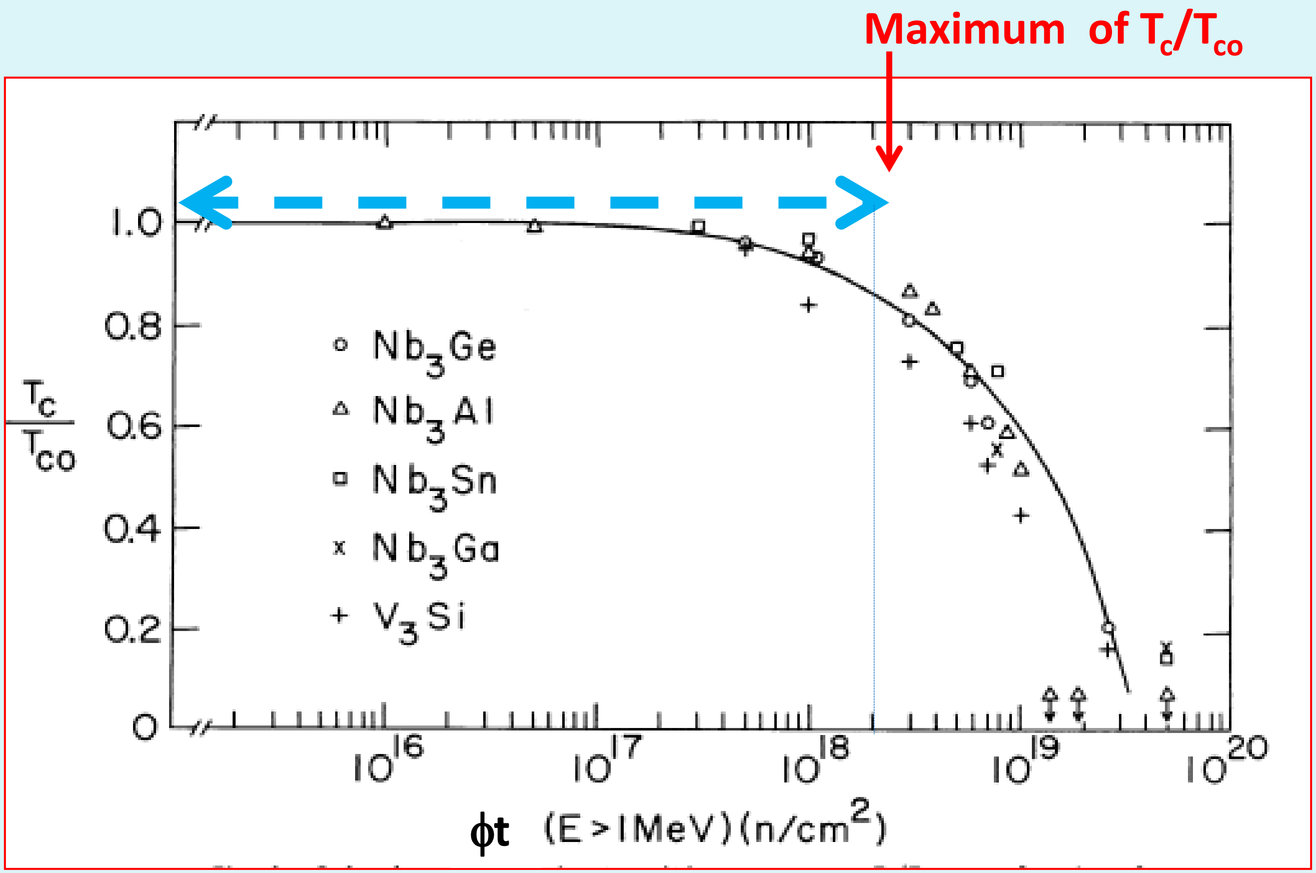
No data available, probably neutron irradiation.

The variation of RRR with fluence is smaller in the presence of magnetic fields, probably due to the additional effect of magnetoresistance

How to compare the damage energy between different reactors?

- By calculation, using codes which are very difficult to reach
- By measuring the initial, linear variation of T_c/T_{co} vs. ϕt (recently introduced : R. Flükiger et al., ASC)

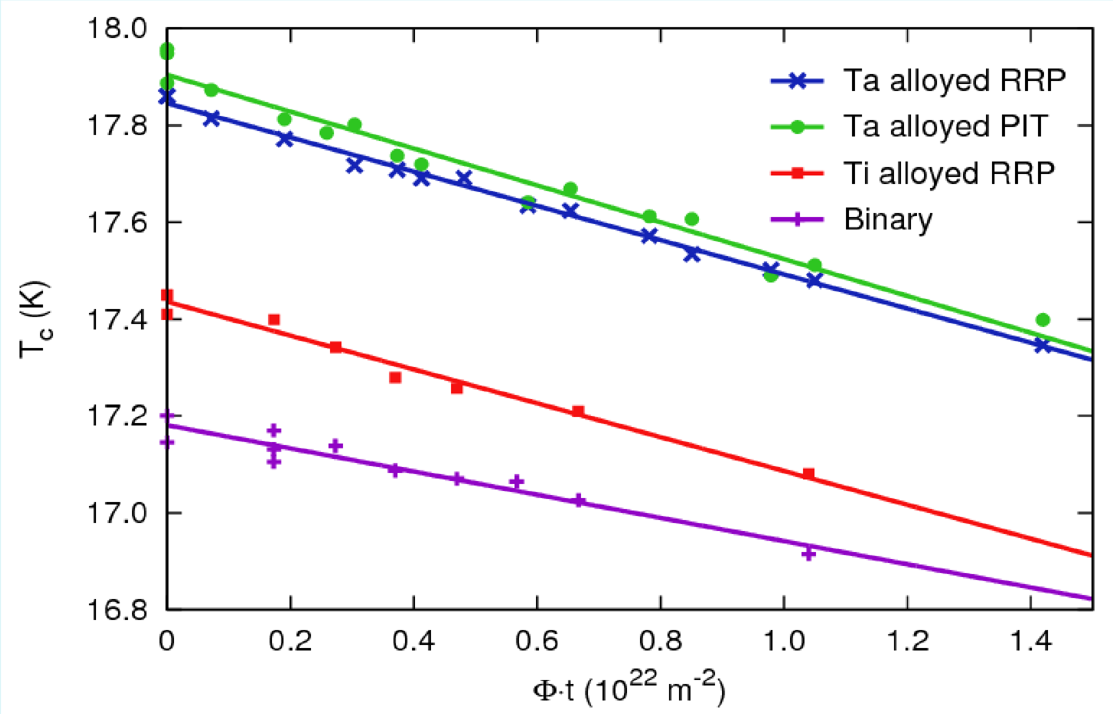
Sweedler curve



Decrease of T_c with increasing neutron fluence

Observed in TRIGA, Vienna (E > 0.1 MeV), but also in RTNSII (14 MeV) and others

Constant Slopes $dT_c/d\phi t$ at small fluences



R. Flükiger, T. Baumgartner, M. Eisterer, H.W. Weber, C. Senatore, T. Spina, C. Scheuerlein, A. Ballarino and L. Bottura , ASC 2012

Comparing the fluences of various reactors

- **Between the fluences between RTNSII and TRIGA (stays for other reactors), a factor of 3 has to be introduced for taking into account the different damage energies E_D.**

- **These considerations lead to a correction of the fluence by a factor of the order of ~ 3 have also to be applied when irradiating insulators**

Estimation for RRR, from the data of Nakamoto et al., 2012, at zero field:

- **if SC cables with the initial RRR of 200 are irradiated to 10^{20} or 10^{21} n/m^2 one expects:**

10^{20} n/m^2 : RRR of 160 – 190
10^{21} n/m^2 : RRR of 50 – 120

Conclusions

- **Irradiation of copper samples up to 2-3 x 10^{20} n/m^2 below 20 K showed that the degradation rates ($\Delta\rho_{irr}/\Phi_{tot}$) agree with the previous work within a factor of 2**
- **For Cu, the recovery at 300K is not complete: 80 – 90% of the unirradiated value**
- **Aluminum: Full recovery of resistivity degradation by annealing at 300K.**
- **Important in view of operation cycles of magnets: Behavior during repeated irradiation and annealing has still to be investigated (presently under work at KUR)**
- **The variation of RRR for Cu stabilizer should be measured in the presence of magnetic field**
- **When comparing the fluences between various reactors, the correction for the damage energy has to be applied.**