WAMSDO 2008

Workshop on Accelerator Magnet, Superconductor, Design and Optimization

Irradiation Effects in Low T_c Superconductors

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Outline

Introduction

Radiation damage in solids

Behavior of various superconductors under irradiation

Radiation Effects in A15 type superconductors

- * Change of atomic ordering
- * Homogeneity after Irradiation
- * Irradiation temperature and recovery

Irradiated binary and alloyed Nb_3Sn wires

- * Critical field, Critical current
- * J_c under stress

Expected Radiation Spectrum in LHC

Conclusions

Introduction

Compound	T_c (K)	$B_{c2}(0)$ (T)	x (nm)
NbTi	10	14	6.3
Nb_3Sn	18	28	4.2
Nb_3Al	19	33	
MgB_2	39	35 - 65	5
V_3Ga	15	24	
$(Hf,Zr)V_2$ Laves phases	10	20	
$PbMo_6S_8$ Chevrel phases	15	50	2.2

Radiation damage in solids

The collision cascade

High energy particle: **Energy transfer**

Along the particle trajectory: local melting or continuous amorphous zone : columnar track.

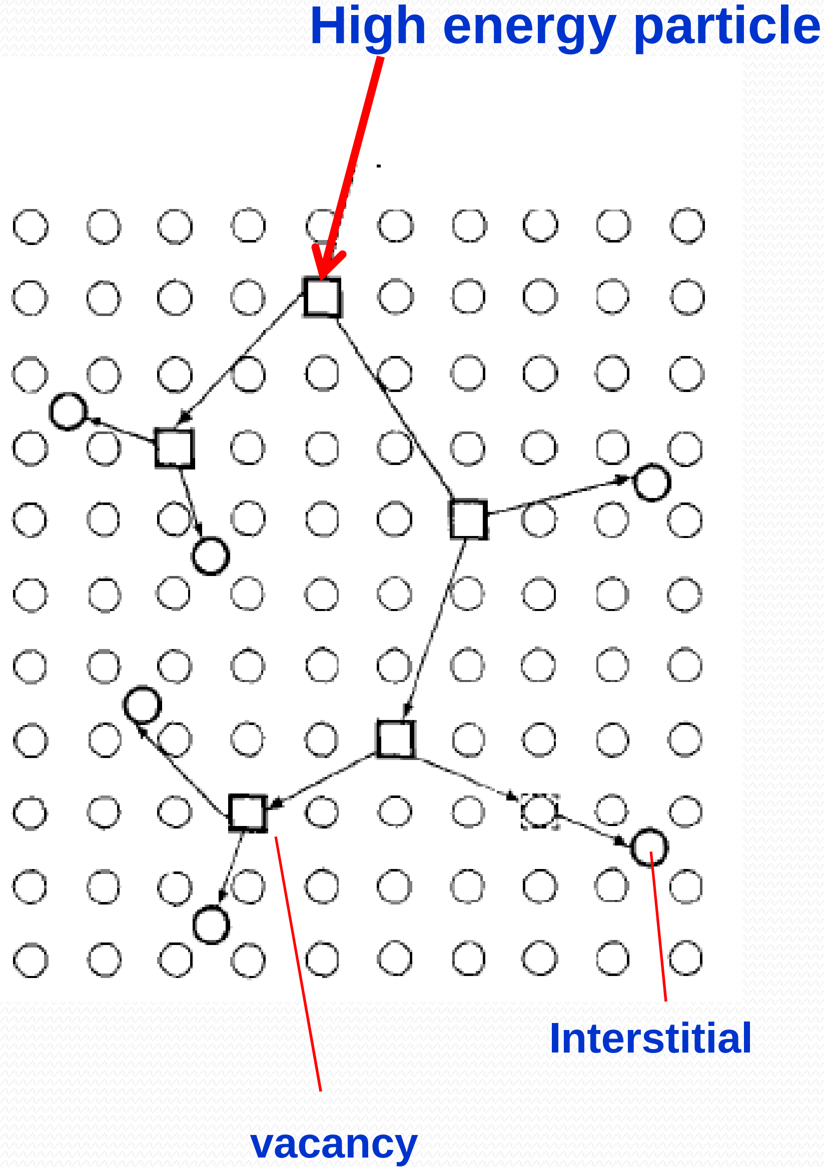
Displacement energy : **E_d**

E_d = 10 – 40 eV for most metals

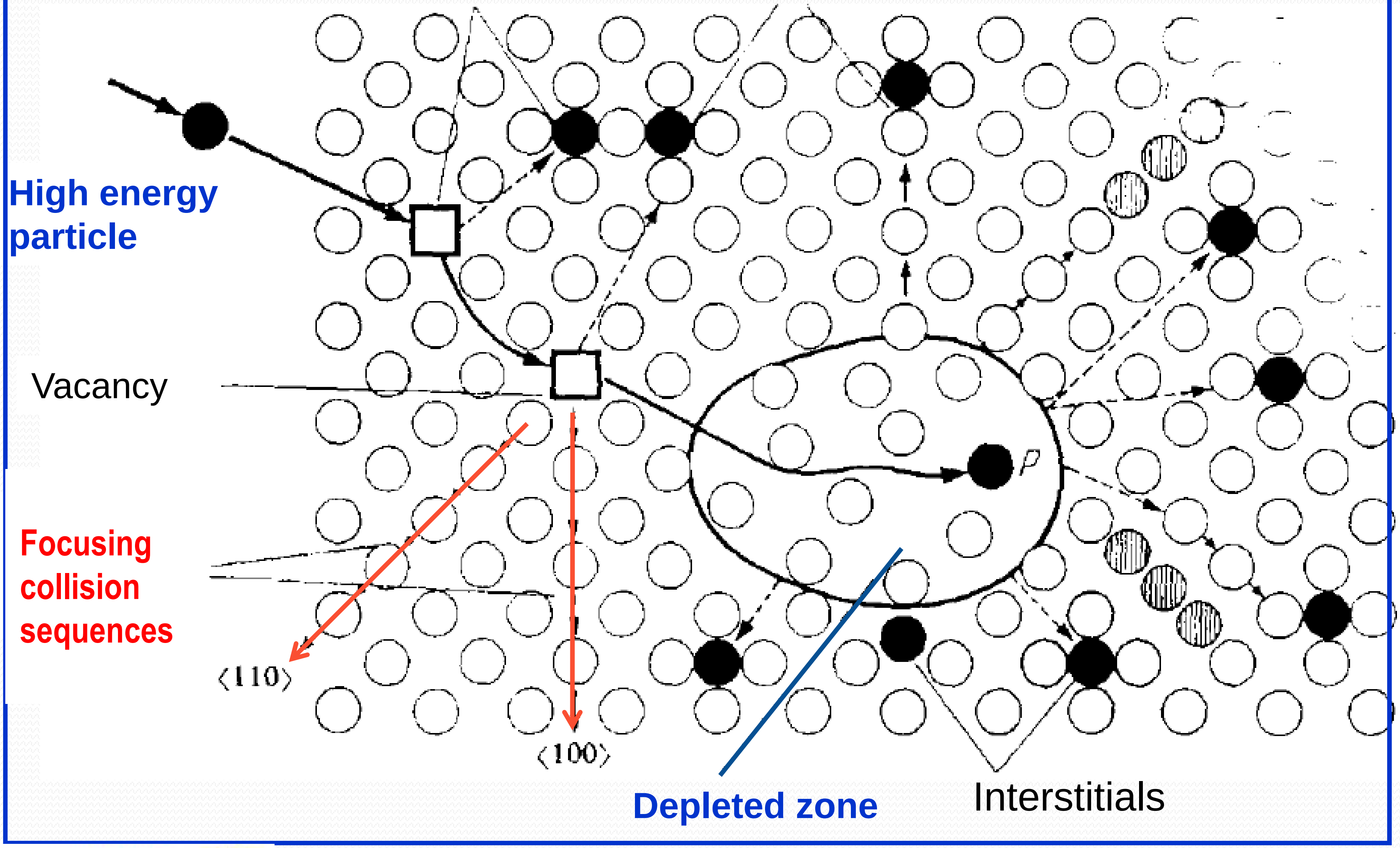
Number of displaced atoms:

$$\nu = T / 2E_d$$

At the end of the path of the irradiating particle: mean free path decreases, density of displaced atoms increases



Formation of depleted (disordered) zones



High energy particle

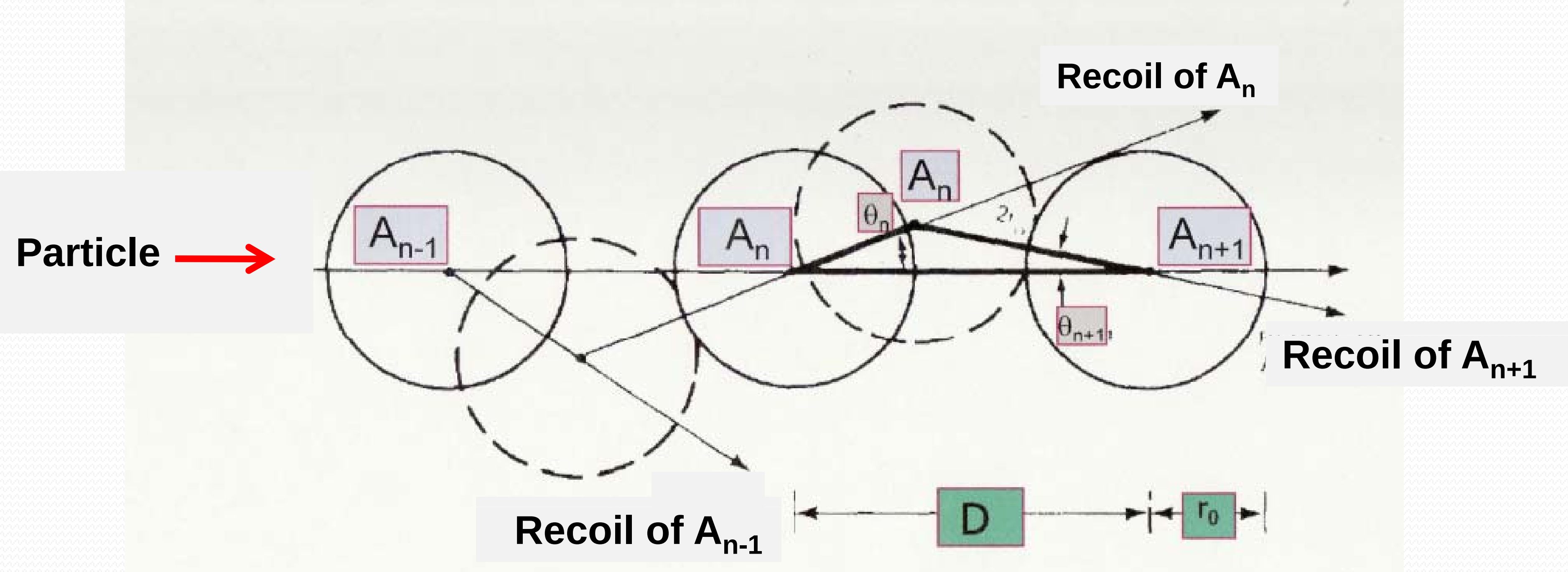
Vacancy

Focusing collision sequences

Depleted zone

Interstitials

Focusing energy transfer → Focusing Collision sequences



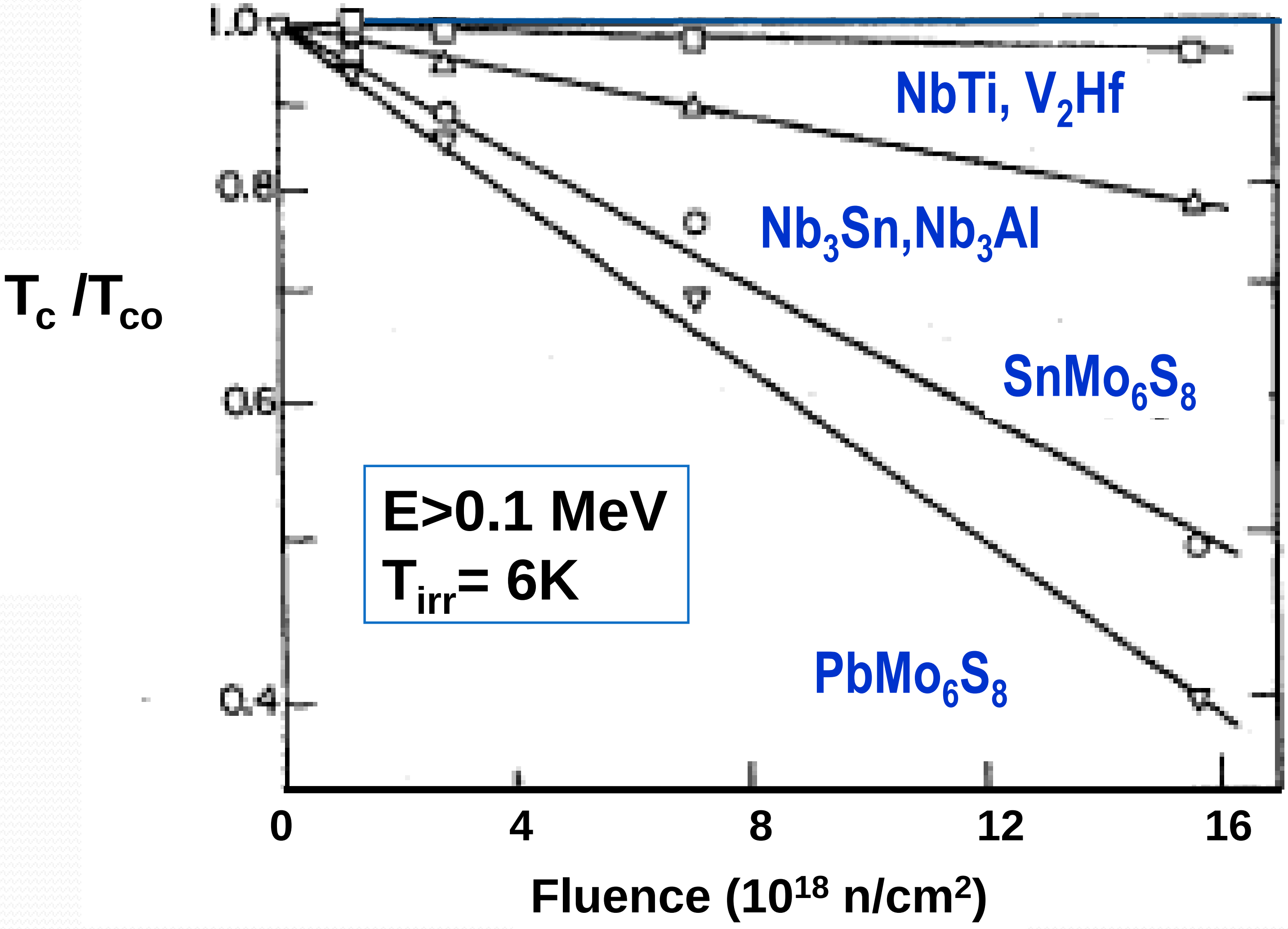
Angles must be small enough to keep collisions in a line

Collisions along a row of close-packed atoms

- * Larger distances covered
- * More probable at low energies

Behavior of various superconductors submitted to high energy irradiation

Irradiation of various Low T_c superconductors



B.S. Brown, J.W. Hafstrom, T.E. Klippert, J. Appl. Phys., 48(1977)1759

Radiation Effects in A15 Type Compounds:

Change of Atomic Ordering

The Long Range Bragg-Williams Atomic Order Parameter

S: The degree of atomic ordering in an A15 type compound A_3B

S=1: perfect ordering

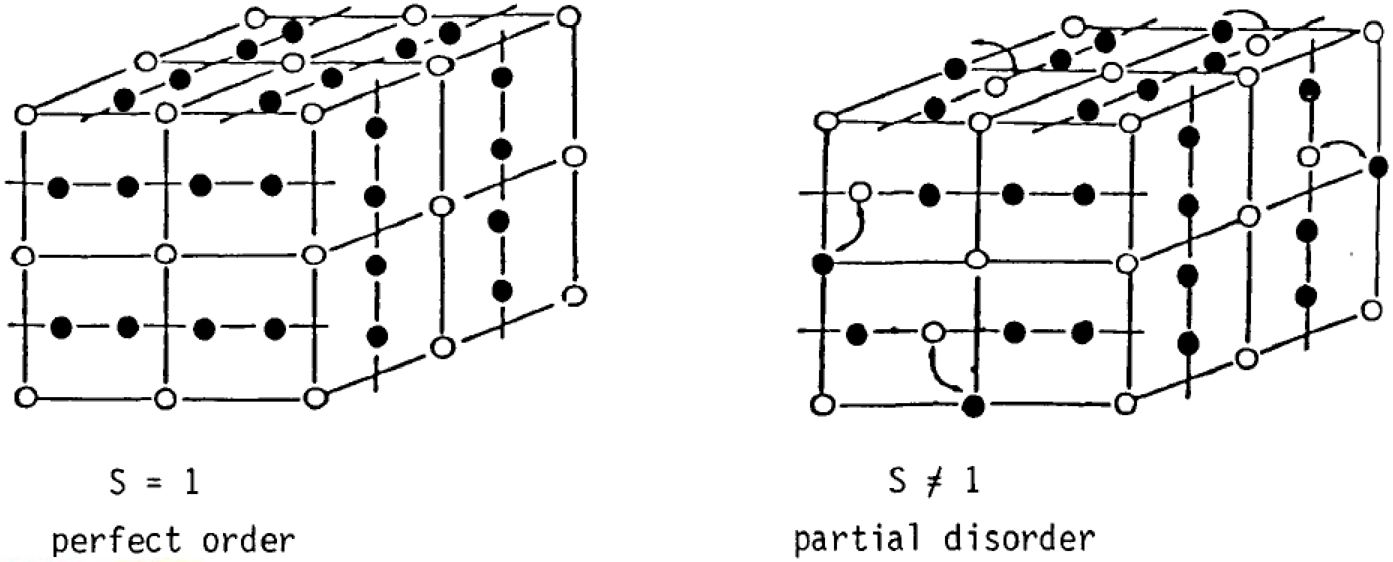
Probability to find atom A on 6c sites: 1

Probability to find atom B on 2a sites: 1

S = 0: complete disorder

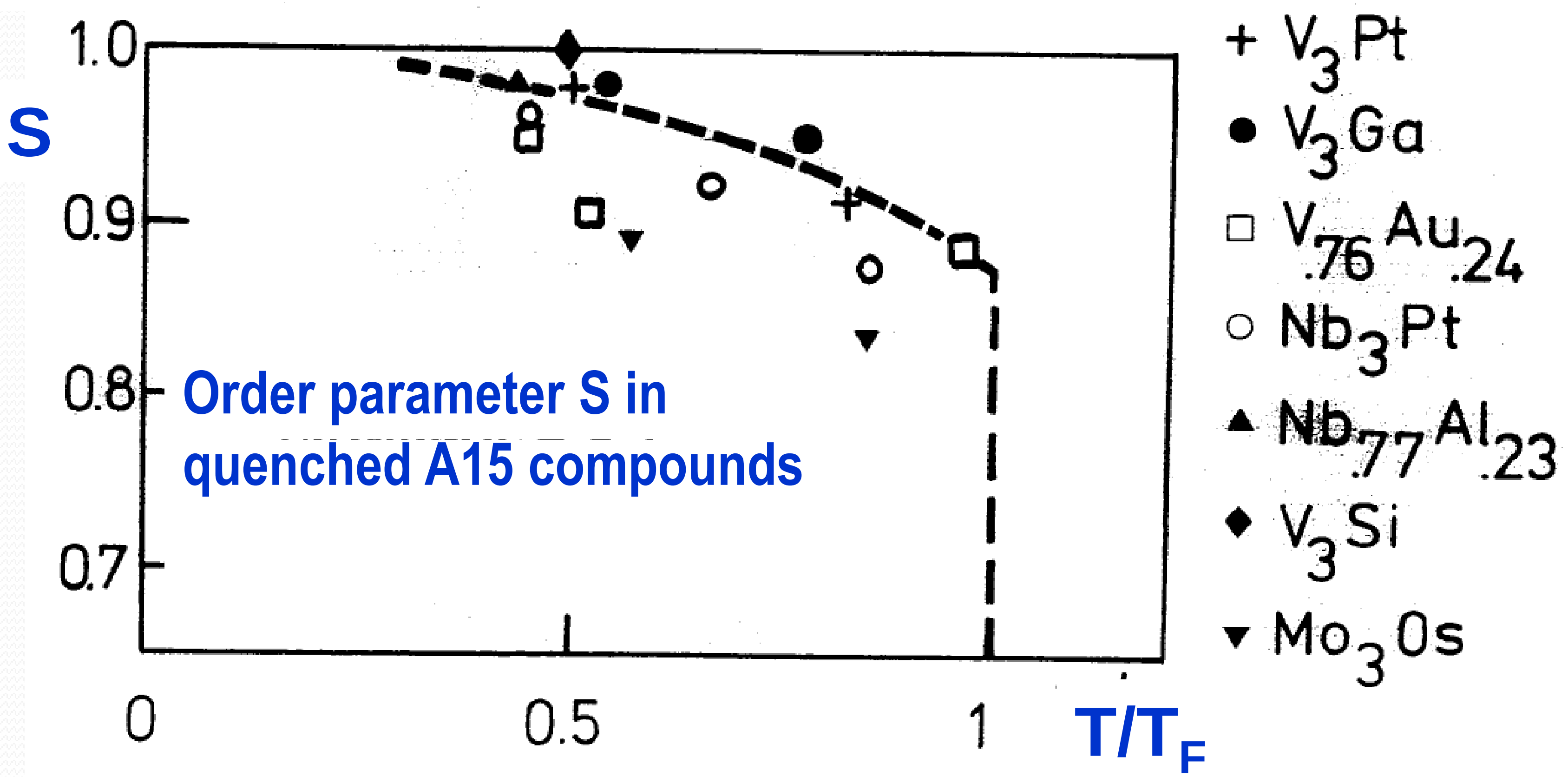
Probability to find atom A on 6c sites: 0.75

Probability to find atom B on 2a sites: 0.25



Irradiation has the same effect as quenching from high temperatures:

→ **Reduction of the Bragg Williams order Parameter**



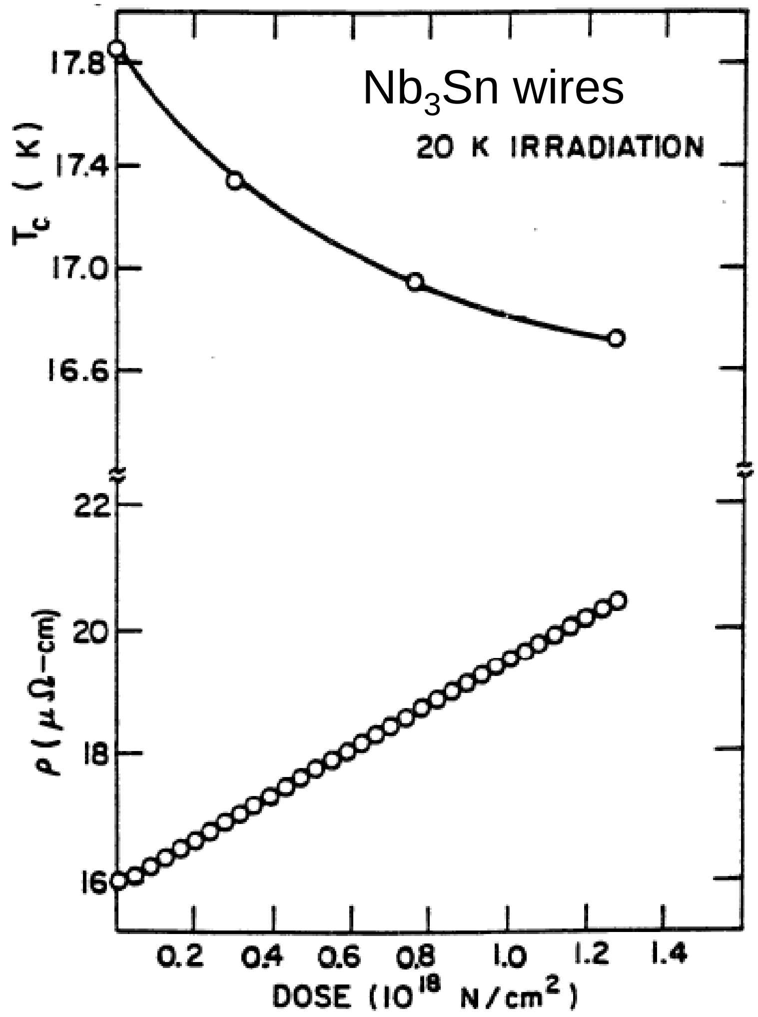
Order parameter S in quenched A15 compounds

R. Flükiger, 1989

T_F: fusion temperature

Effects observed after High Energy Irradiation

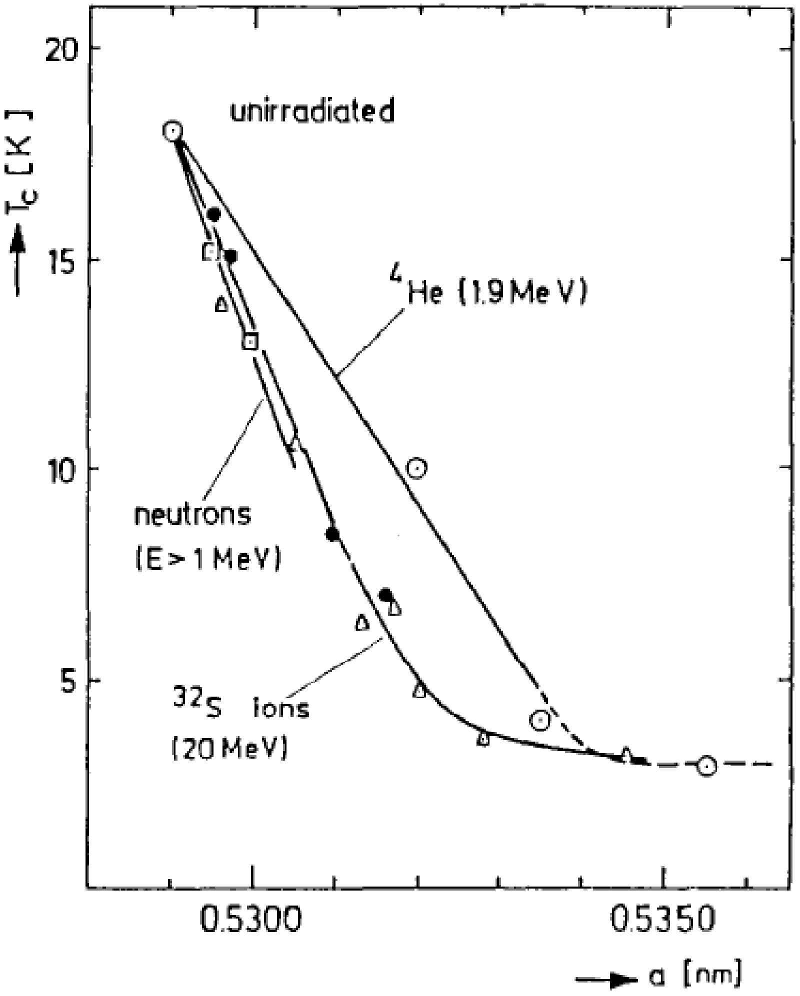
Enhancement of normal state electrical resistivity ρ_o

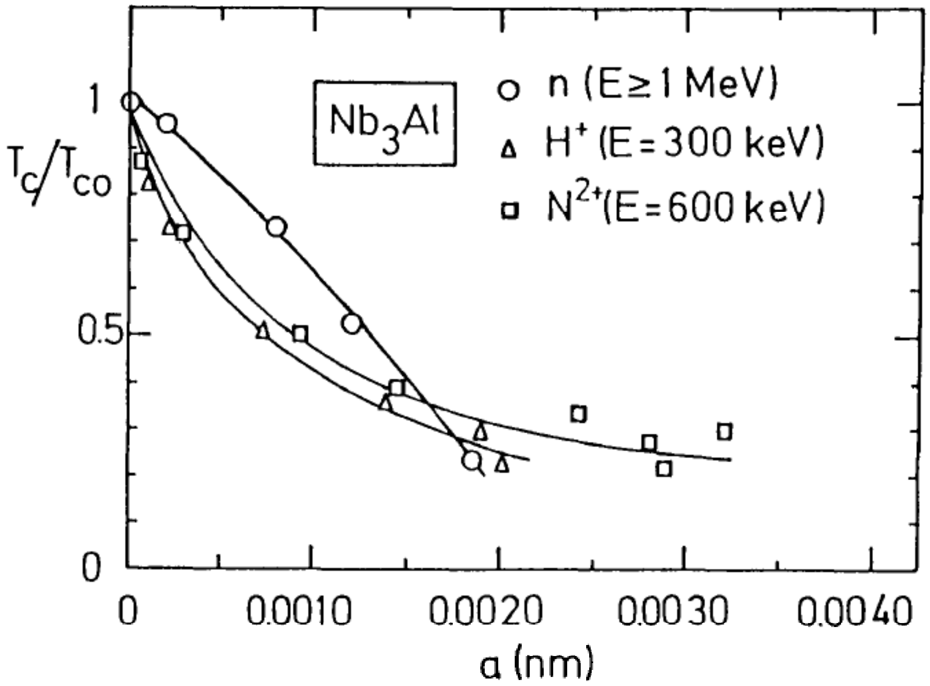


$B_{c2} \sim T_c \, \gamma \, \rho_o$

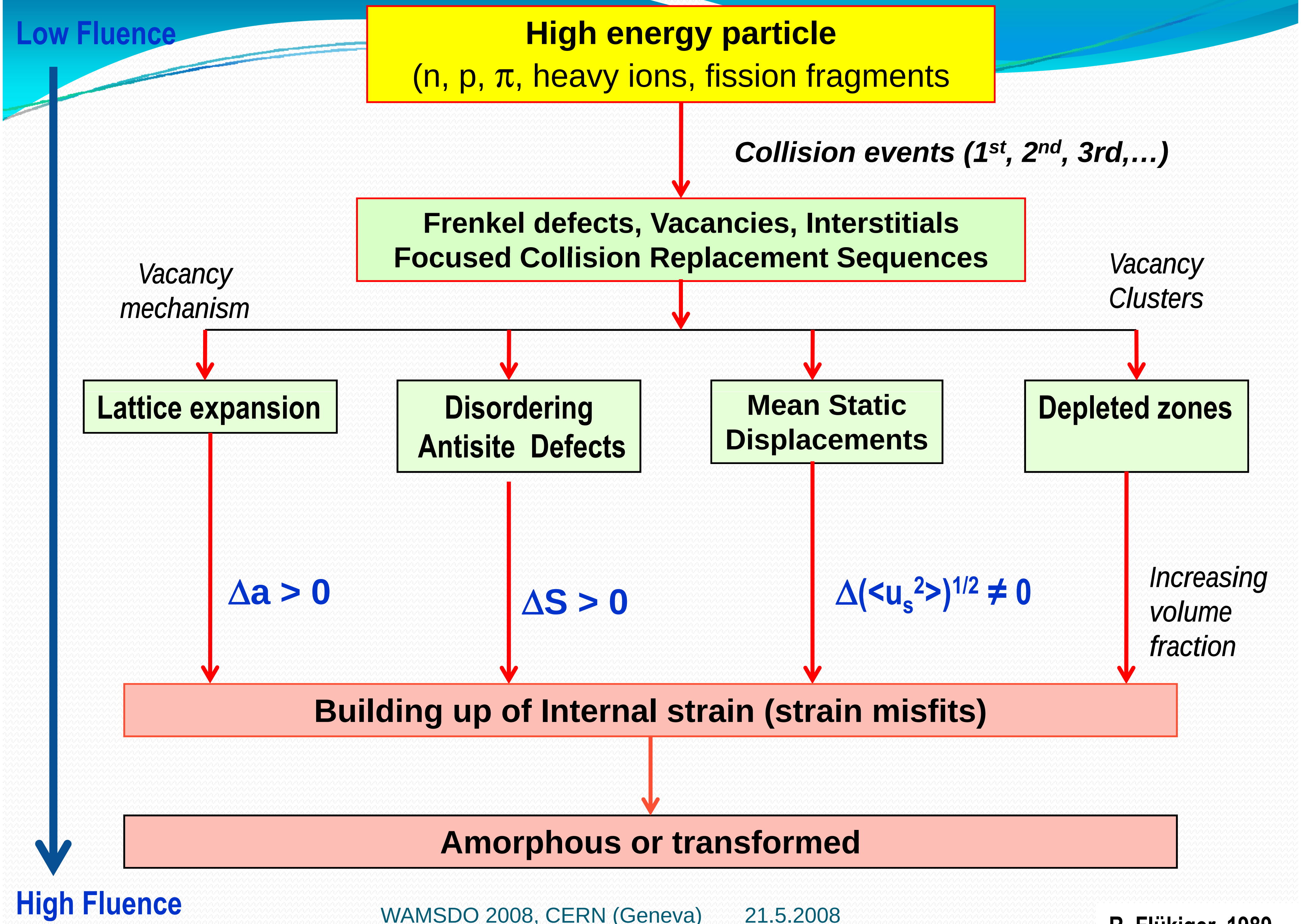
B.S. Brown, R.C. Birtcher, R.T. Kampwirth, T.M. Blewitt, J. Nucl. Materials 72(1978)76

Decrease of T_c and lattice expansion after irradiation with various particles





Neutrons: Sweedler, 1978, H$^+$, N^{2+}: Schneider, 1982, ^{4}He: Burbank, 1979, ^{32}S: Nölscher, 1985.



Low Fluence

High energy particle
(n, p, π, heavy ions, fission fragments

Collision events (1st, 2nd, 3rd,…)

Frenkel defects, Vacancies, Interstitials
Focused Collision Replacement Sequences

Vacancy mechanism

Vacancy Clusters

Lattice expansion

Disordering Antisite Defects

Mean Static Displacements

Depleted zones

$\Delta a > 0$

$\Delta S > 0$

$\Delta(\langle u_s^2 \rangle)^{1/2} \neq 0$

Increasing volume fraction

Building up of Internal strain (strain misfits)

Amorphous or transformed

High Fluence

R. Flükiger, 1989

In A15 Compounds: Homogeneos Degree of Ordering after Irradiation

Consequence of the Vacancy Diffusion Mechanism

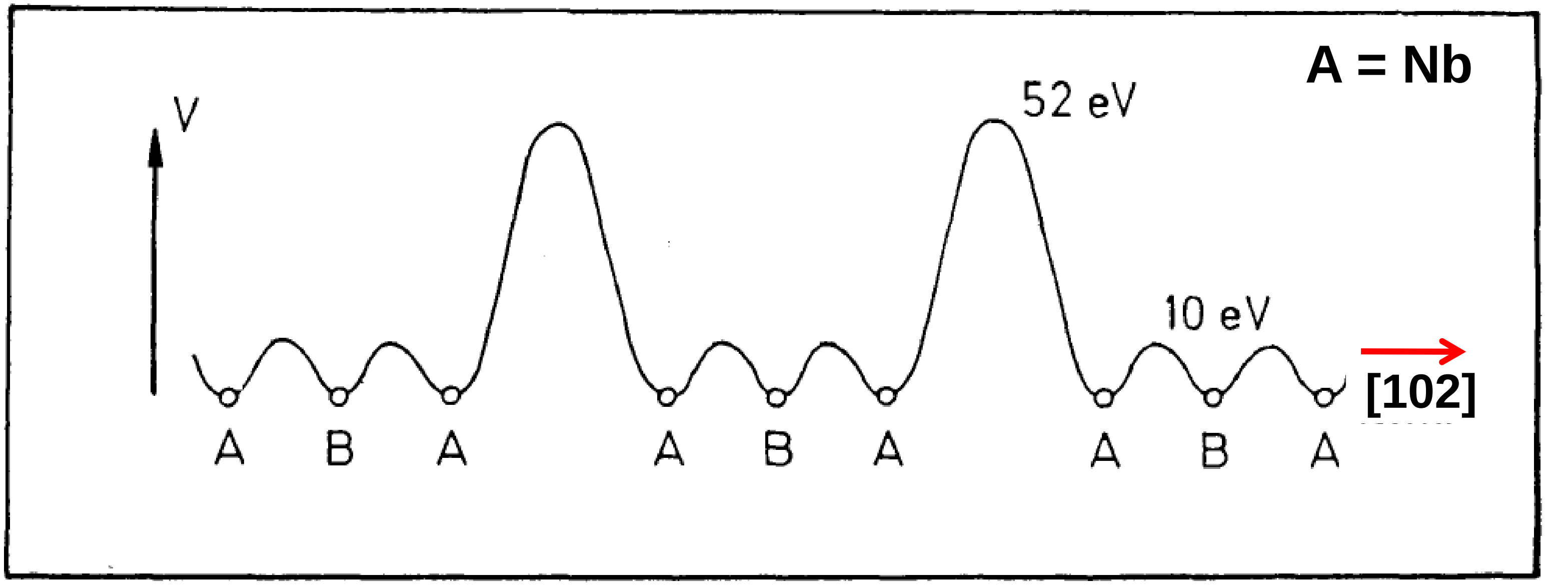
Arguments:

- **Analogy between effects of irradiation and of fast quenching**
- **Correlation between radiation fluence and atomic order parameter**
- **Homogeneity of T_c, proven by specific heat measurements**

Unirradiated state

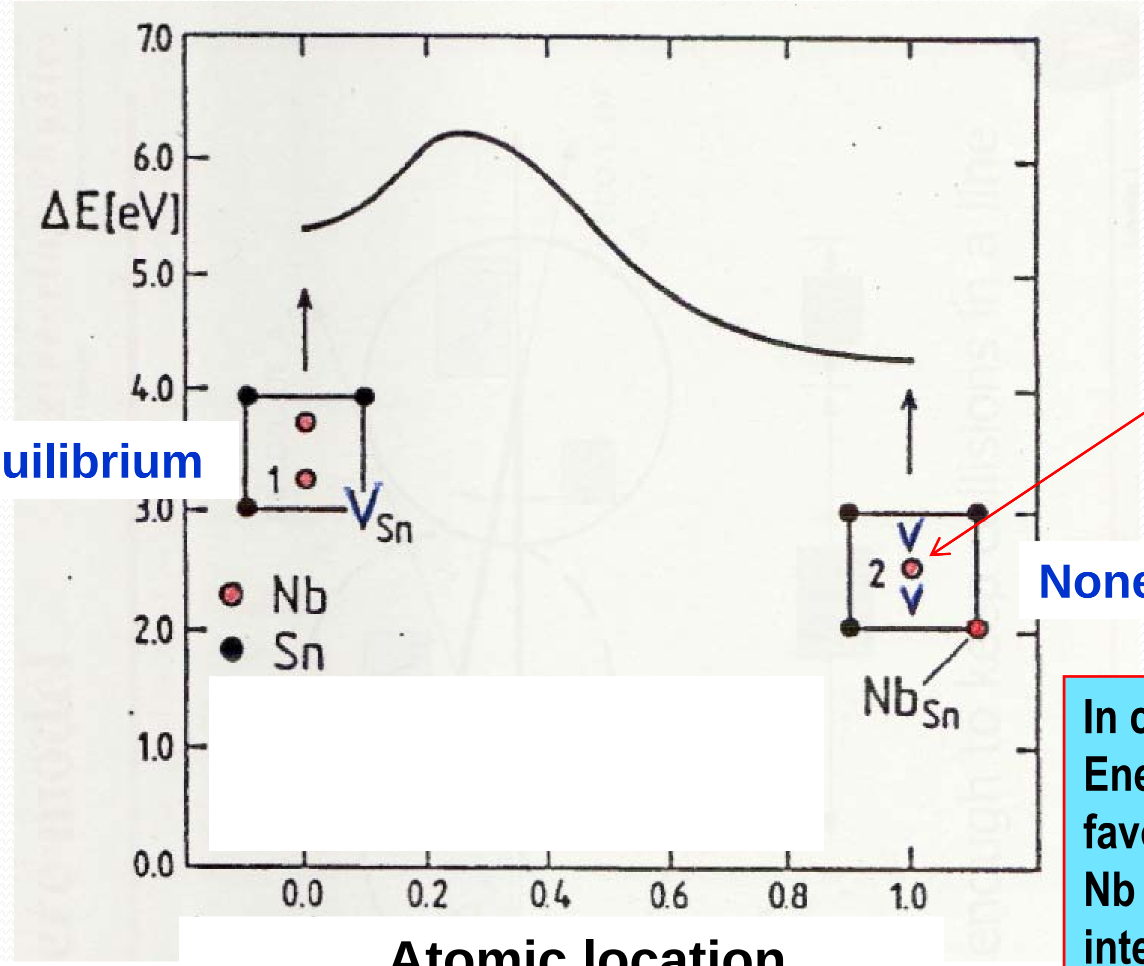
Potential encountered by a Nb atom on its way along the focusing <102> direction Nb_3Sn

D. Welch, G. Dienes, O. Lazareth, R. Hatcher, Phys. Lett., 29A(1984)1225



At low temperature: no vacancies: Site exchange highly improbable!

Presence of vacancies: The "virtual" lattice site



Virtual lattice site

Equilibrium

Nonequilibrium

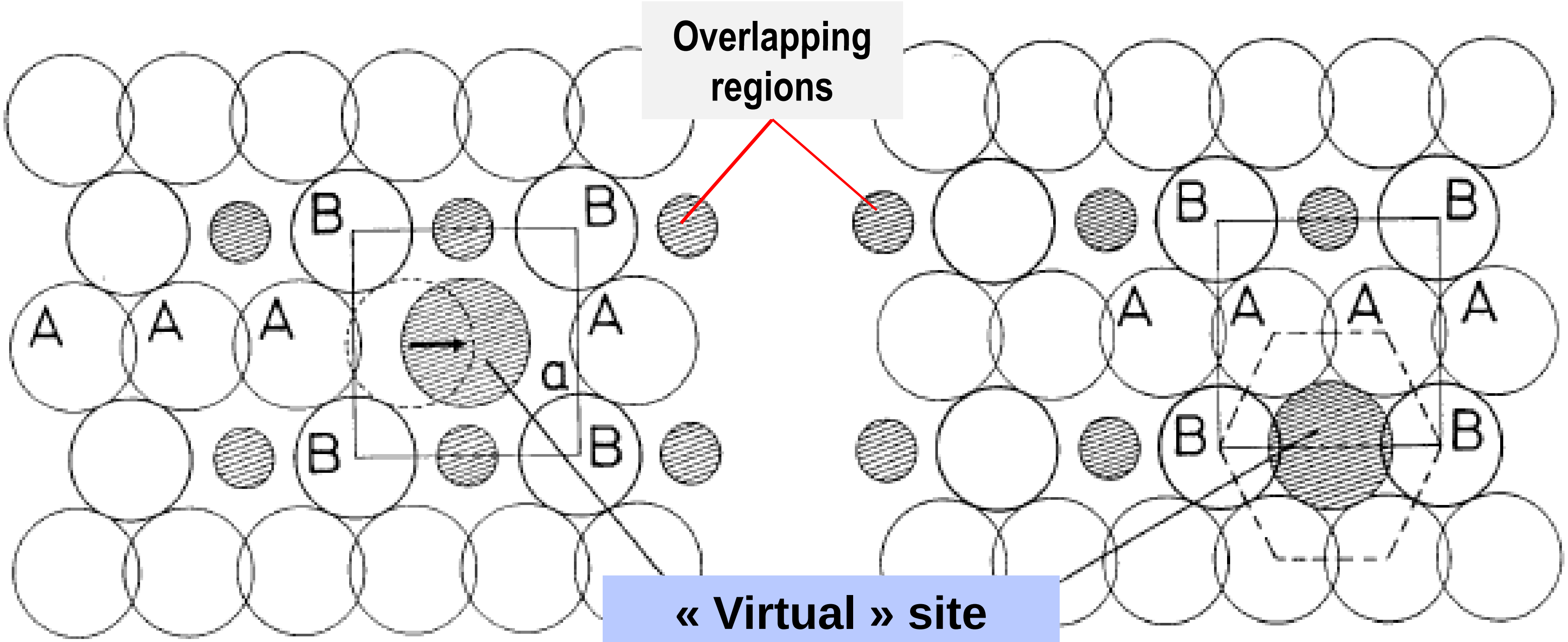
Atomic location

D. Welch, G. Dienes, O. Lazareth, R. Hatcher, Phys. Lett., 29A(1984)1225

In case of a Nb vacancy:
Energetically more favorable for neighbour Nb to occupy the intermediate position
New « virtual » site

A15 (A_3B): A ↔ B site exchanges by vacancy diffusion

Chain parallel to plane — **Chain perpendicular to the plane**



Overlapping regions

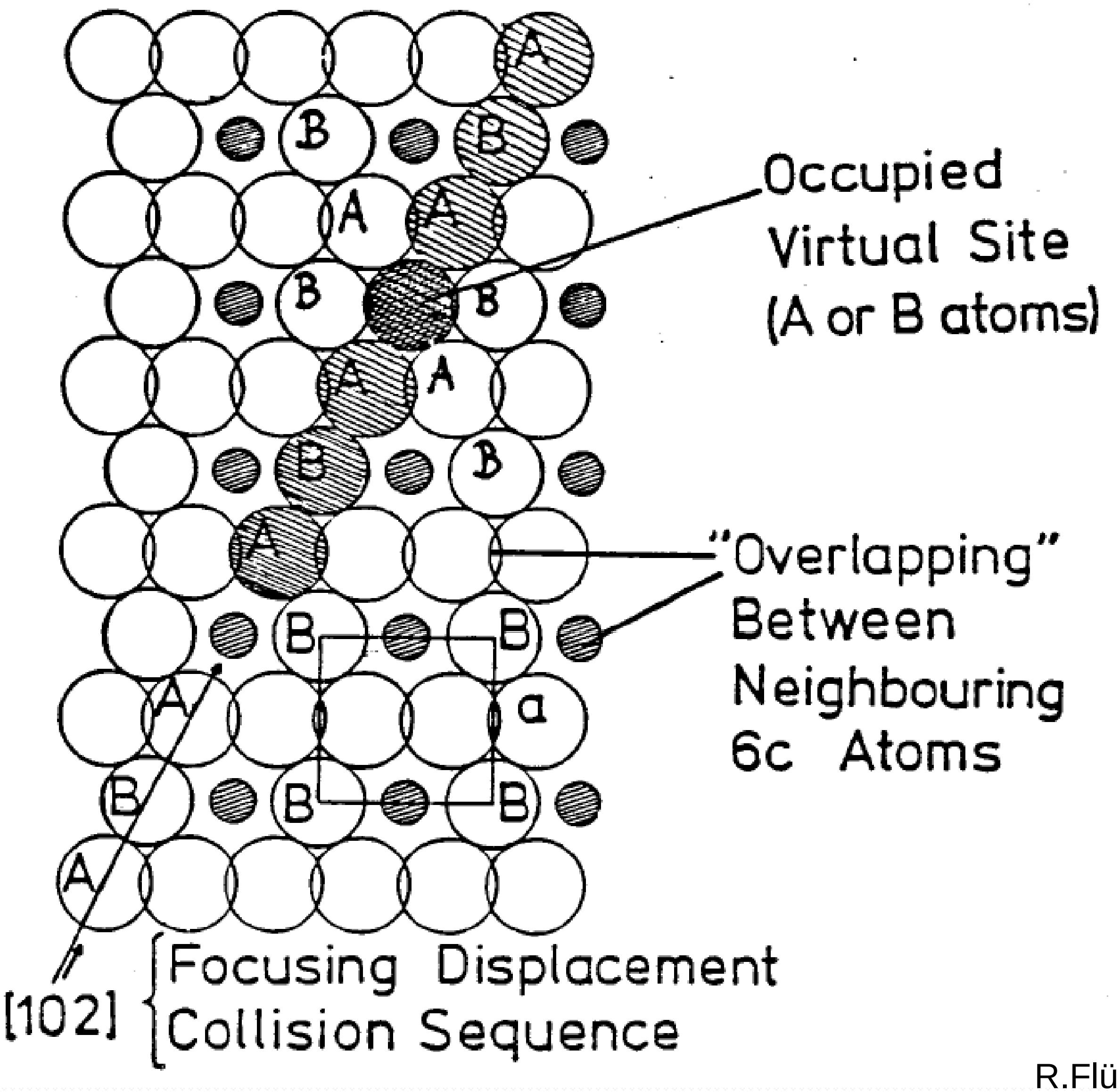
« Virtual » site occupied by A or B

Jump of an A atom into a « virtual » vacancy

Jump of an A atom into a *2a* vacancy

R. Flükiger, 1989

Site exchanges through Focusing Collision Sequences



R.Flükiger, 1989

Mechanisms for explaining “homogeneous” irradiation effects on T_c

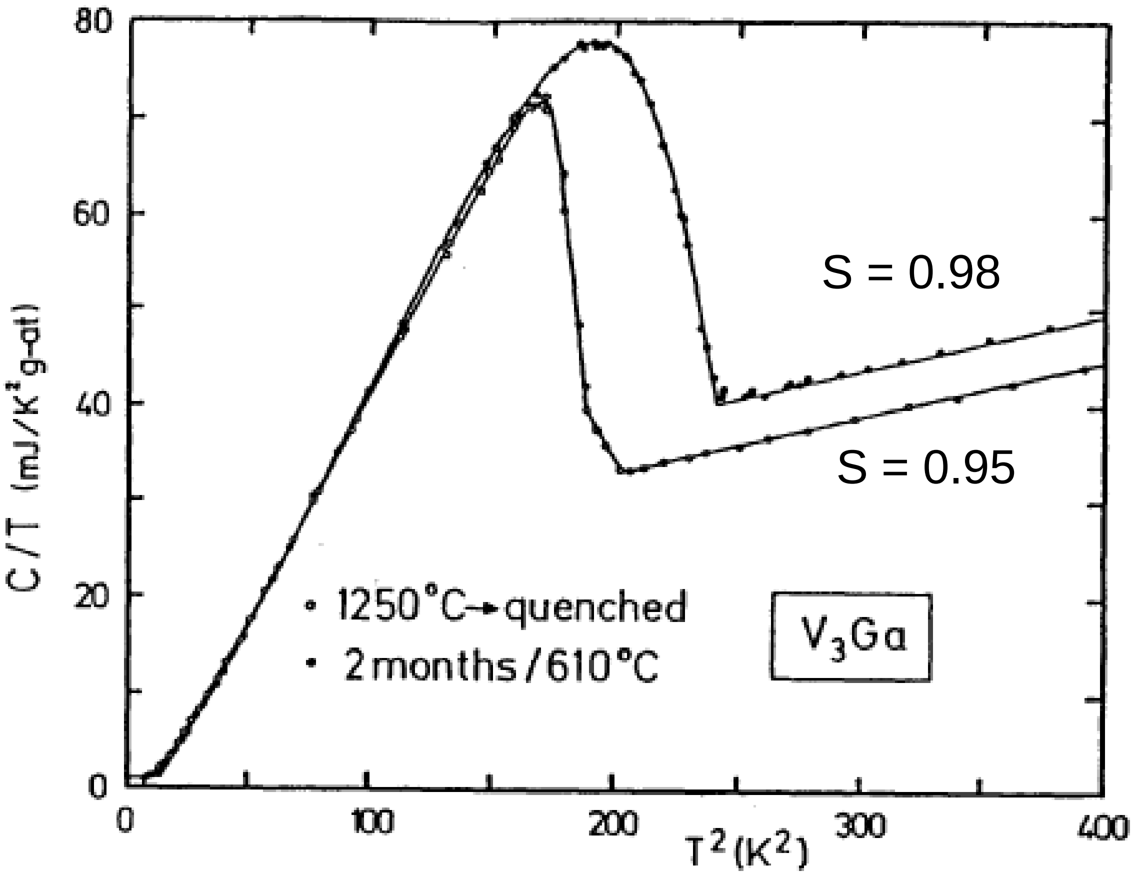
Dominant mechanism:

Decrease of atomic ordering due to focused collision sequences

(Sweedler et al., 1975, 1978, Söll et al., 1976, Snead et al., 1980, 1986, Hahn et al., 1991, Guinan et al., 1984, Weiss et al., 1987, Flükiger et al., 1989)

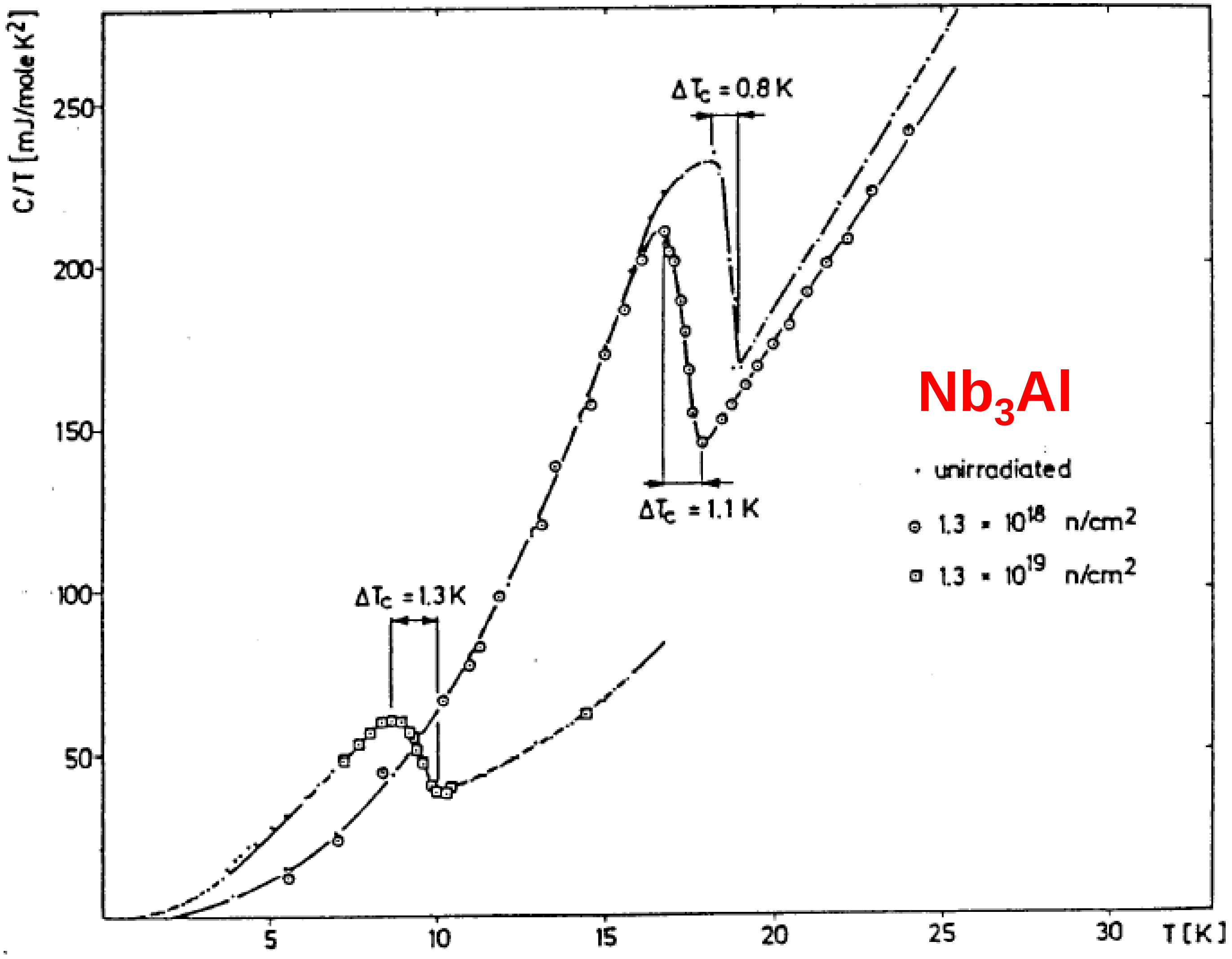
Another mechanism: Proximity effects due to deleted zones with lower T_c cannot explain the homogeneity of the observed effects

Homogeneity of T_c on quenched V_3Ga



P. Fischer, R. Flükiger, 1980

Homogenenity of T_c distribution (Specific Heat Measurements)



B. Cort, G.R. Stewart, C.L. Snead, A.R. Sweedler, Phys. Rev. B24(1981)379

Irradiation Temperature:
Radiation Damage and Recombination

*** Highest damage: at lowest T_{irr}**

*** Increase of T_{irr} : recombination**

*** Even T_{300K} causes partial recombination**

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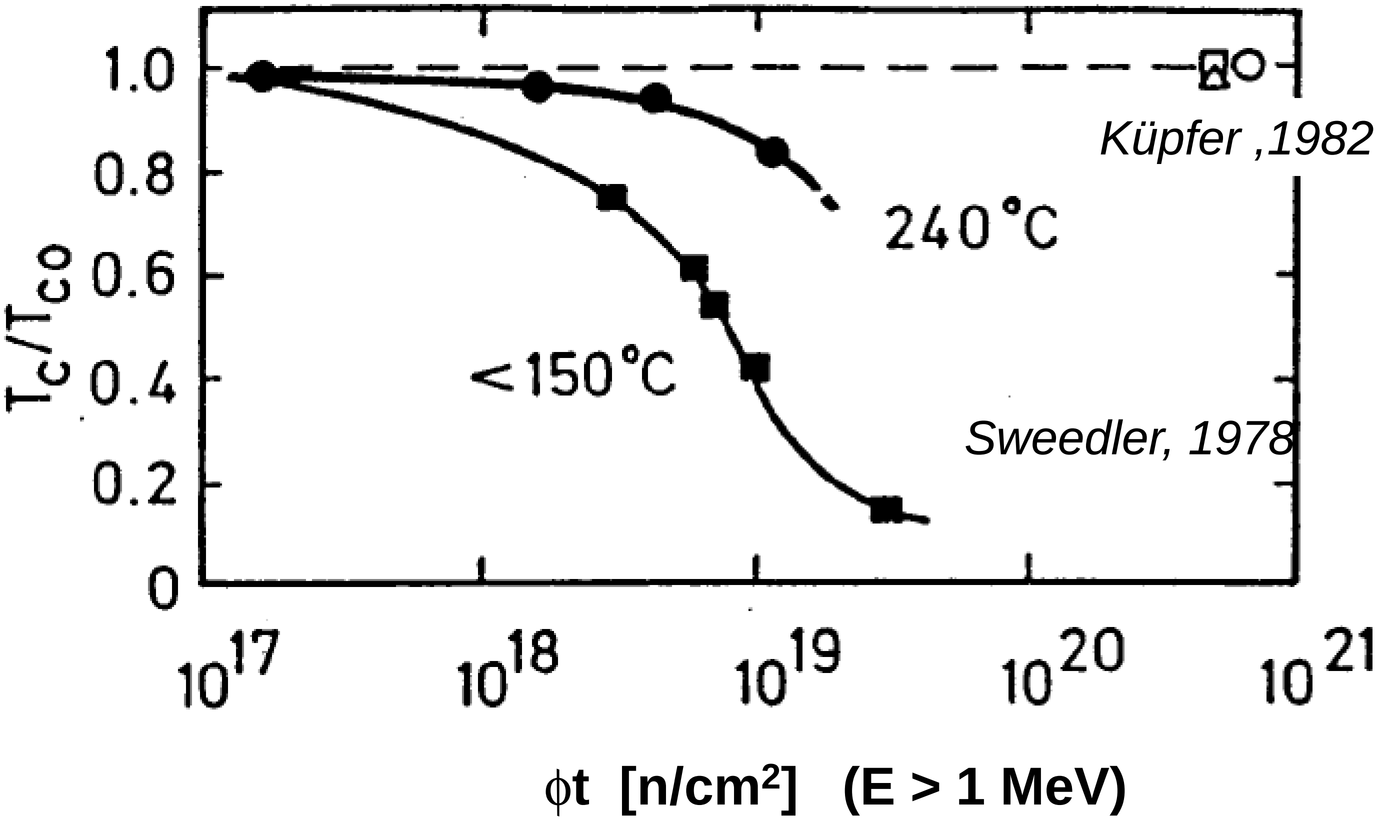
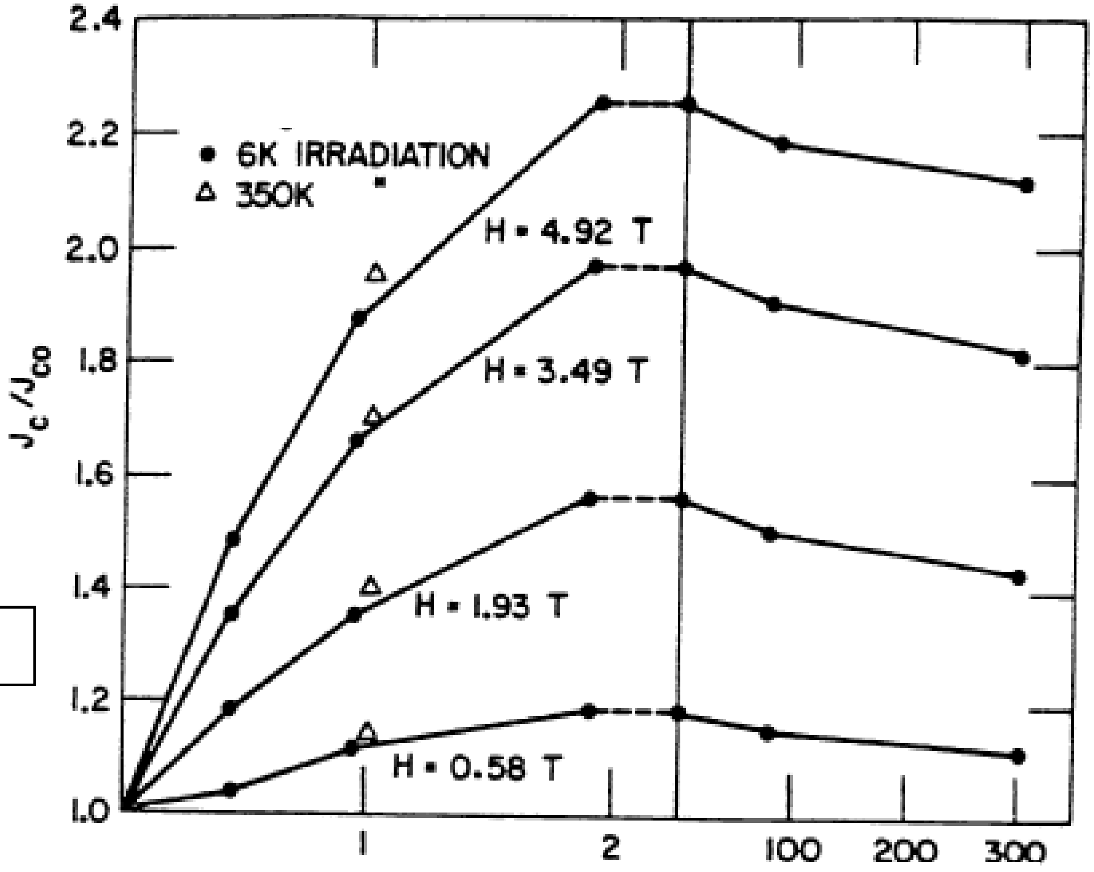
Effect of Irradiation Temperature



T_c vs. fast neutron irradiation dose for V_3Si

E > 0.1 MeV

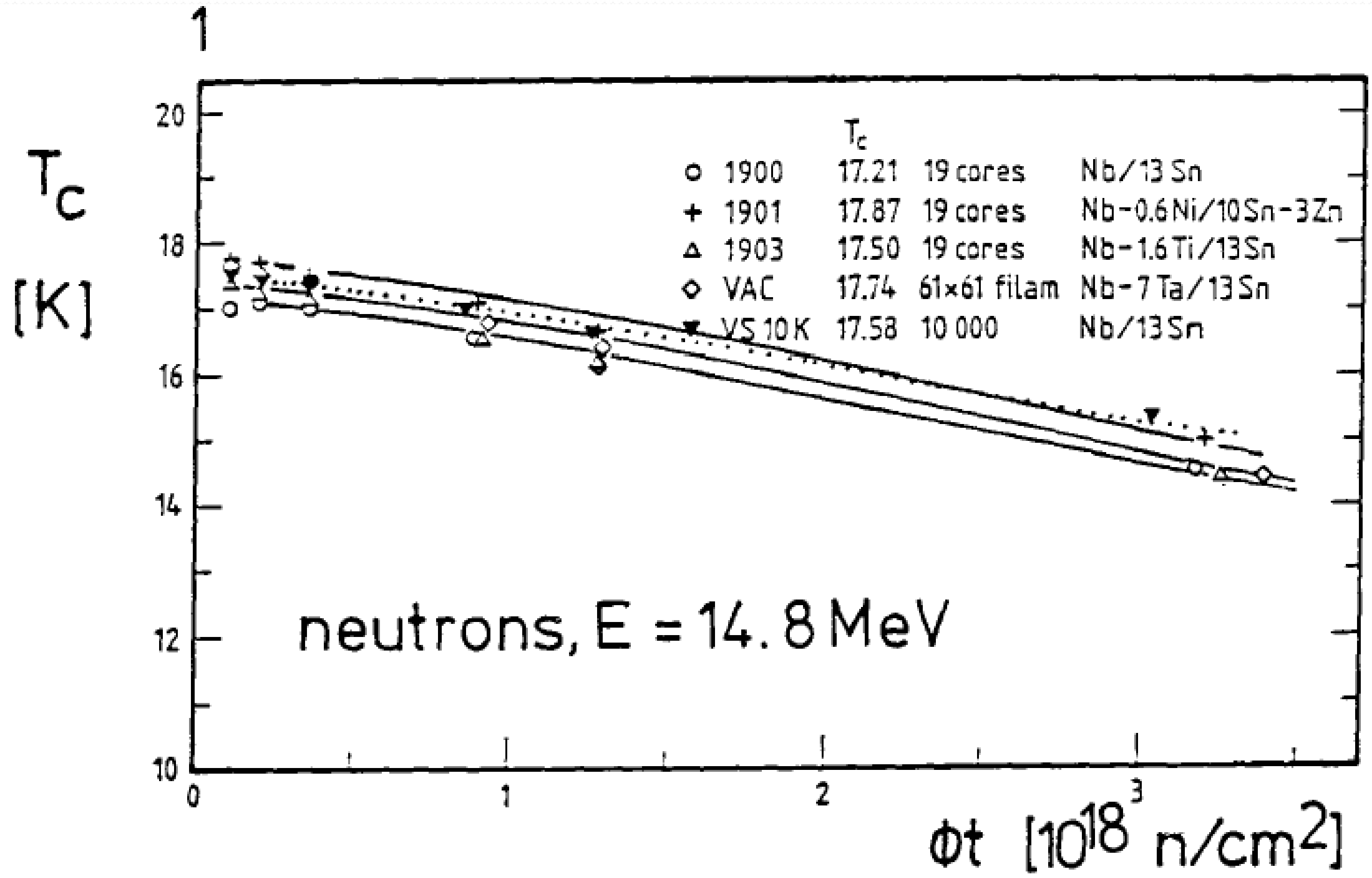


Fluence (x 10^{18} n/cm^2) T_{ann} (K)

Neutron irradiation of a multifilamentary Nb_3Sn wire, followed by an anneal of 5 min. at T_{ann}.

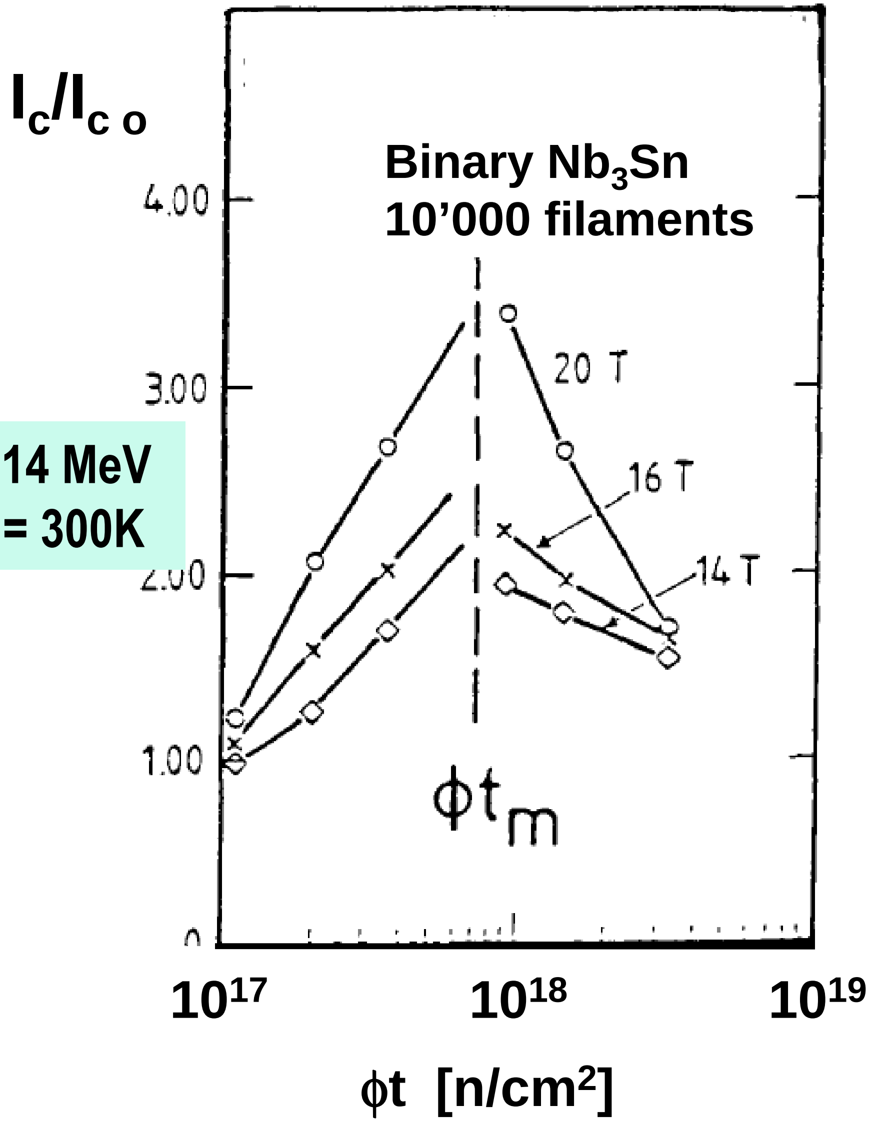
B.S. Brown, T.H. Blewitt, T.L. Scott, D.G. Wozniak,, J. Appl. Phys.49(1978) 4144

Irradiation of binary and ternary Nb_3Sn wires with 14 MeV neutrons

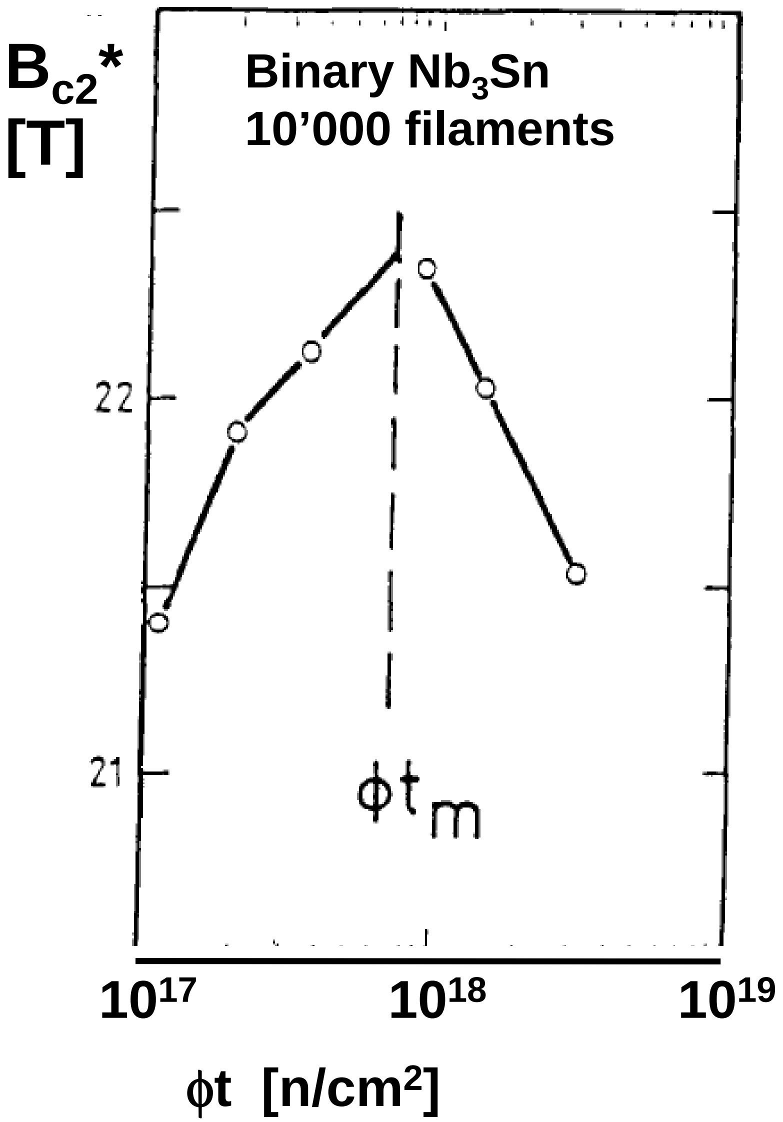


F. Weiss, R. Flükiger, W. Maurer, IEEE Trans. Magn., MAG-23(1987)976

Binary Nb_3Sn wire (10’000 filaments)



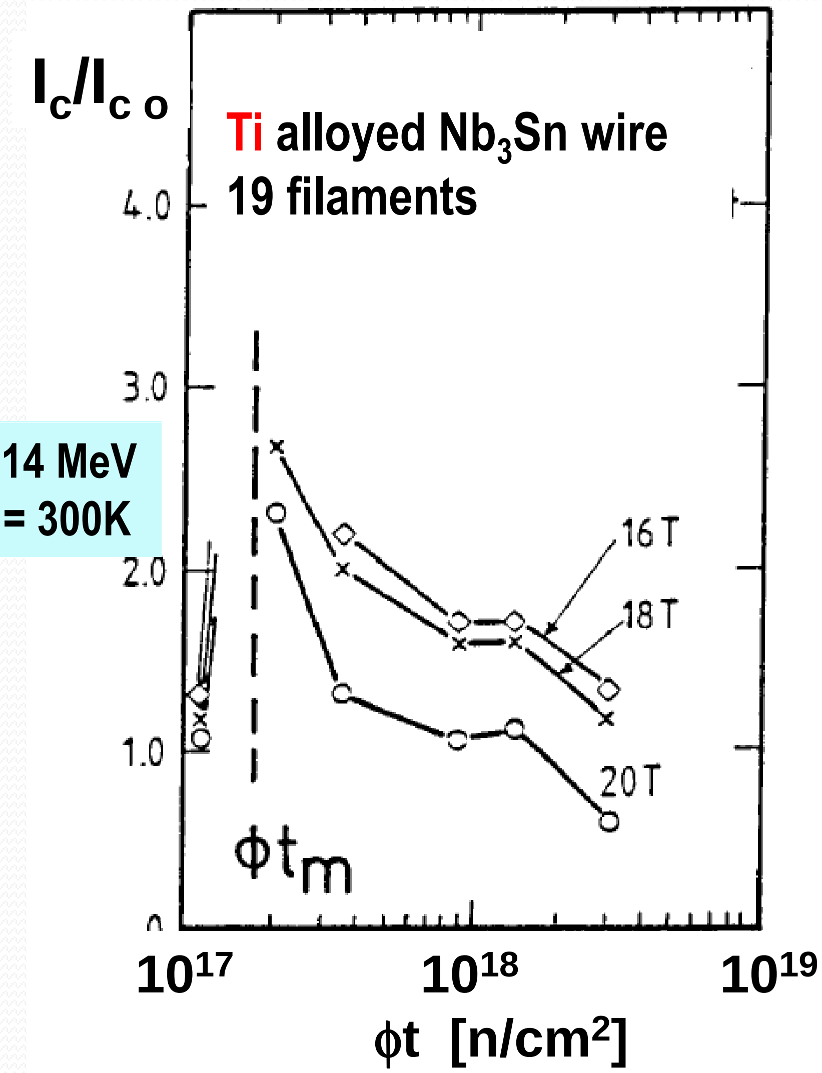
E =14 MeV
T_{irr} = 300K

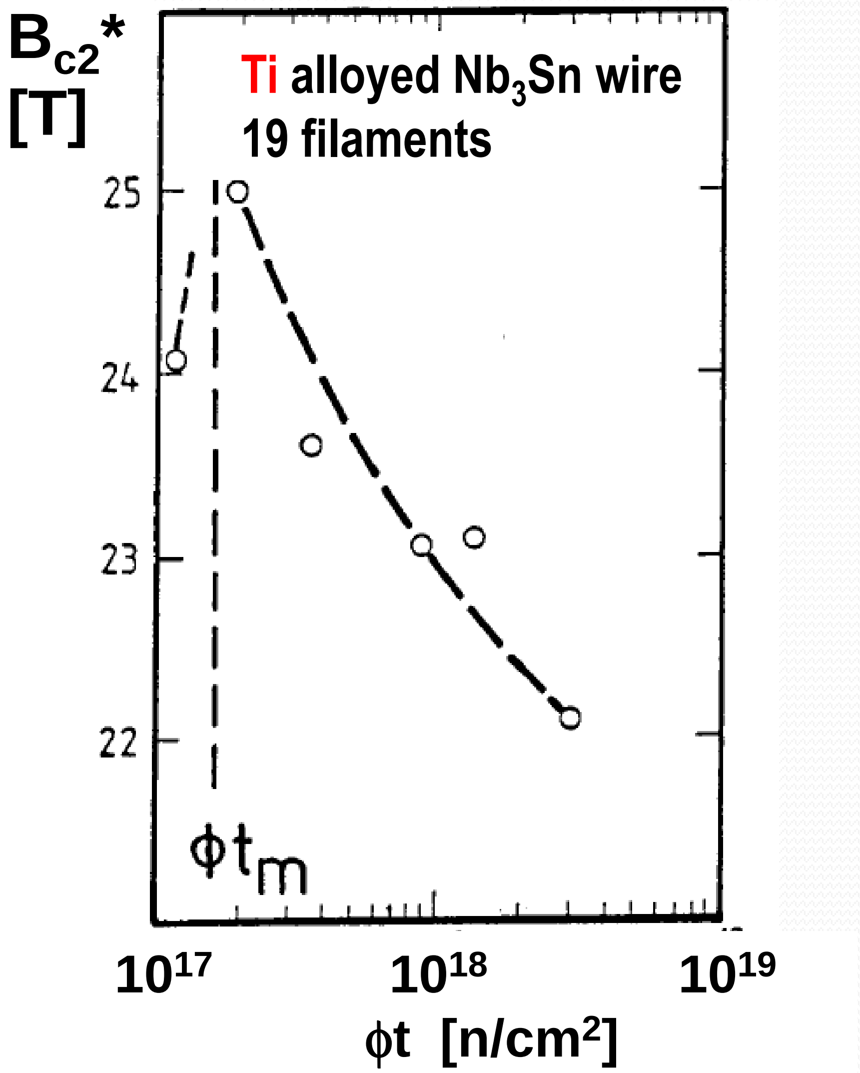


F. Weiss et al. IEEE Trans. Magn., MAG-23(1987)976

Ti alloyed Nb_3Sn wires

E =14 MeV
T_{irr} = 300K

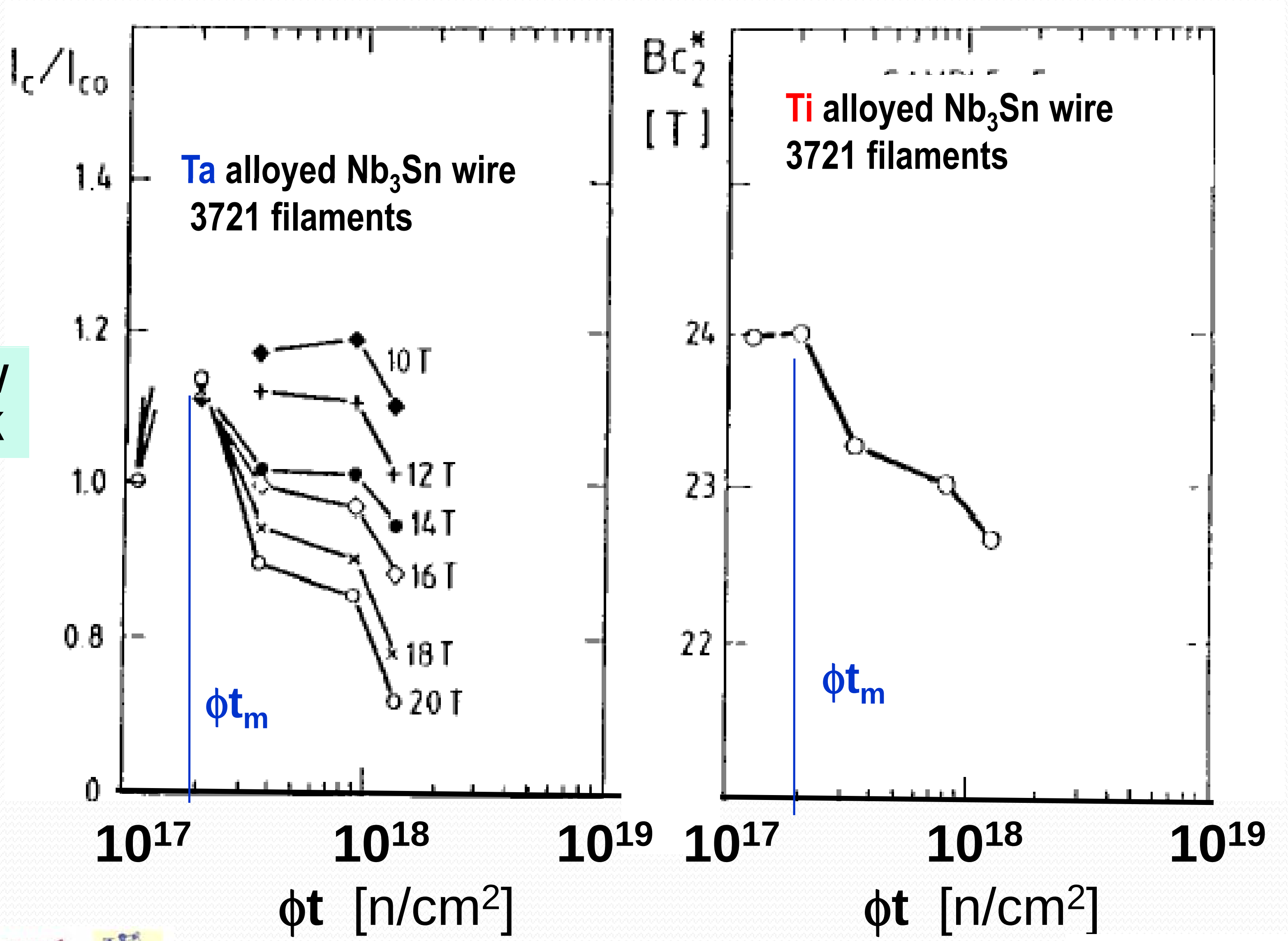




F. Weiss et al. IEEE Trans. Magn., MAG-23(1987)976

Ta alloyed multifilamentary Nb_3Sn wires

E =14 MeV
T_{irr} = 300K



Ta alloyed Nb_3Sn wire
3721 filaments

Ti alloyed Nb_3Sn wire
3721 filaments

F. Weiss et al. IEEE Trans. Magn., MAG-23(1987)976

Alloyed Nb_3Sn wires: J_c more sensitive to irradiation

1) Maximum of I_c/I_{co} and B_{c2} at lower fluences for alloyed Nb_3Sn wires

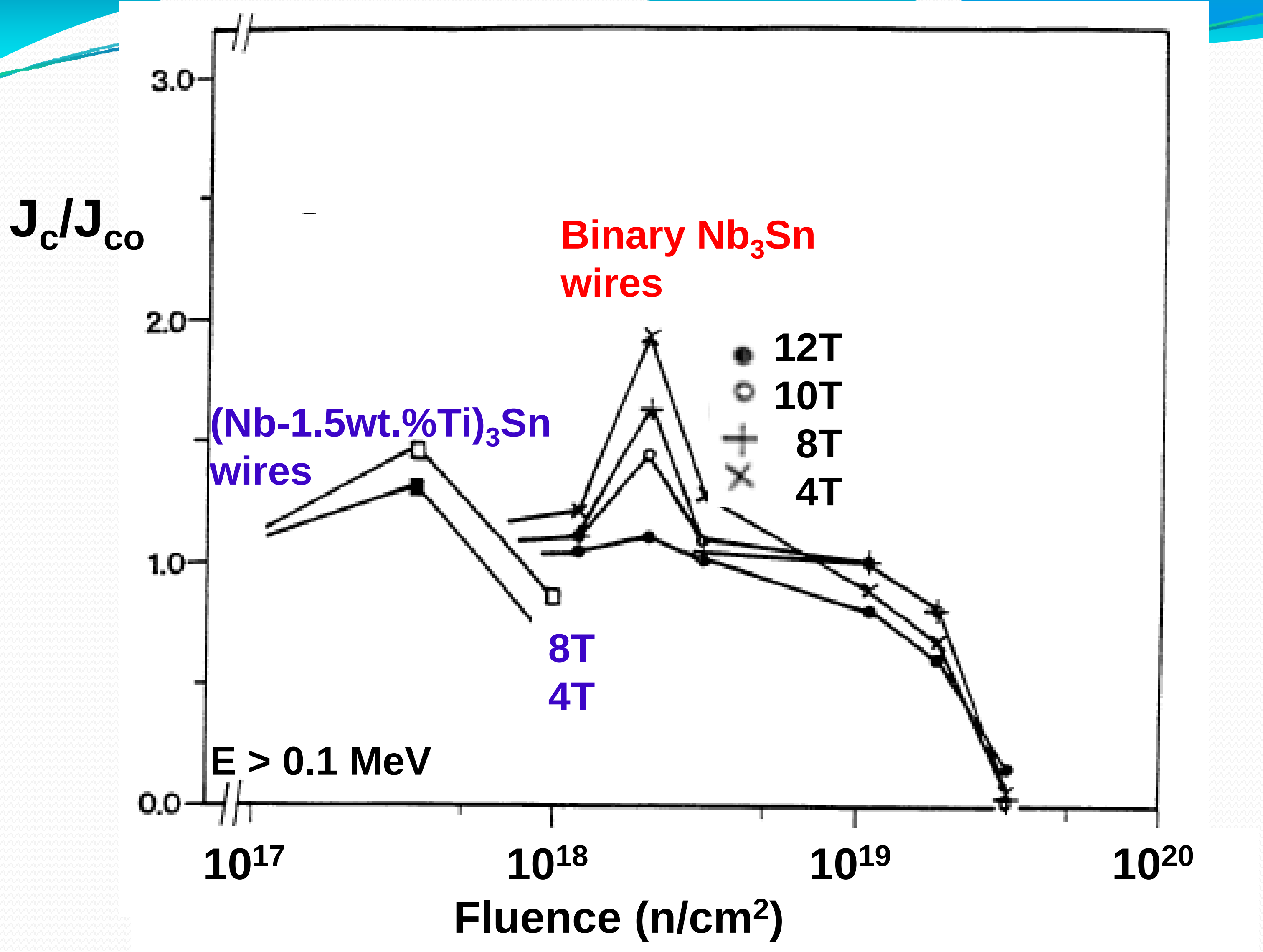
Wire	ϕt_m
Binary Nb_3Sn wire	8 x 10^{17} n/cm^2
Ti alloyed Nb_3Sn wire	1.8 x 10^{17} n/cm^2
Ta alloyed Nb_3Sn wire	1.8 x 10^{17} n/cm^2

2) At ϕt_m the increase $\Delta(I_c/I_{co})$ and $\Delta(B_{c2})$ is lower for alloyed Nb_3Sn wires

3) At ϕt = 3 x 10^{18} n/cm^2:

I_c/I_{co} for binary Nb_3Sn wire higher than before irradiation
but:
I_c/I_{co} for to alloyed Nb_3Sn wires lower than before irradiation

E > 0.1 MeV



H.W. Weber, 1986, Adv. Cryo. Eng., Vol. 32, 853

Why Stronger Radiation Effects in Alloyed Nb_3Sn wires ?

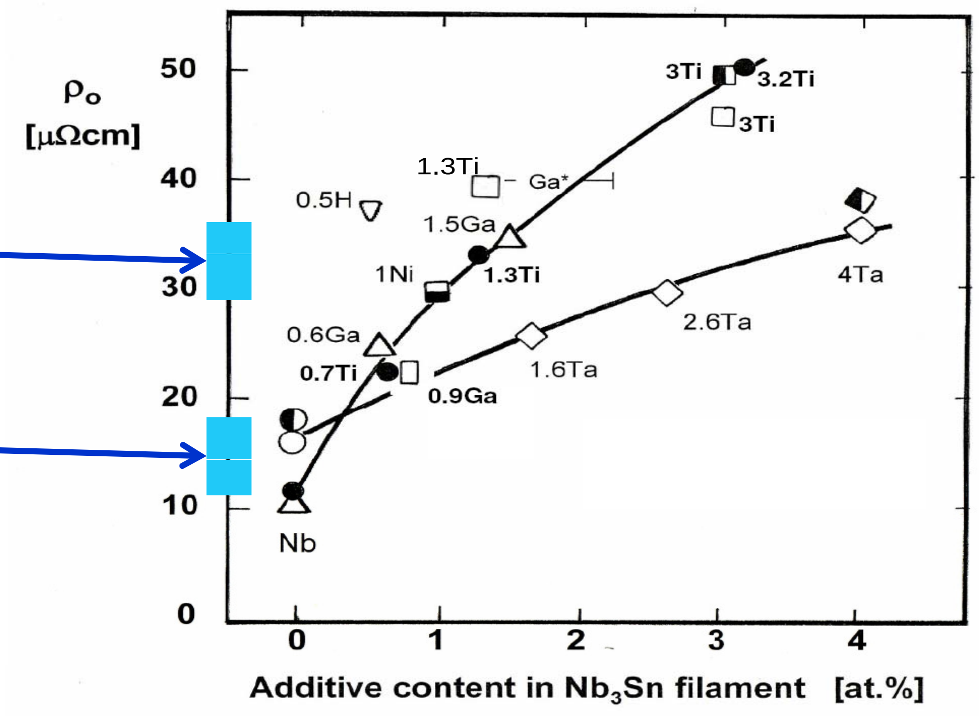
1) Normal state electrical resistivity ρ_o before irradiation:

ρ_o = 30 - 35 μΩcm

Optimized Alloyed Nb_3Sn wires

ρ_o = 10 - 15 μΩcm

Binary Nb_3Sn wires



R.Flükiger, C.Senatore, F.Buta, D.Uglietti, B.Seeber, 2007
Superc. Sci. Technol. 21 054015

After Irradiation: $\Delta\rho_o$ much lower for alloyed Nb_3Sn wires

Consequences of lower $\Delta\rho_o$ for alloyed Nb_3Sn wires

- The increase $\Delta(B_{c2})$ is smaller
- The maximum value and B_{c2} is reached at lower ϕt_m values
- The increase of I_c/I_{co} at ϕt_m is smaller
- Above fluences ~ 0.5 x 10^{18} n/cm^2, faster decrease of J_c

Conclusion

(Based on neutron irradiated Bronze Route wires of 1986, with J_c ~ 700 A/cm^2 at 12 T; has to be proven for Internal Sn or PIT wires)

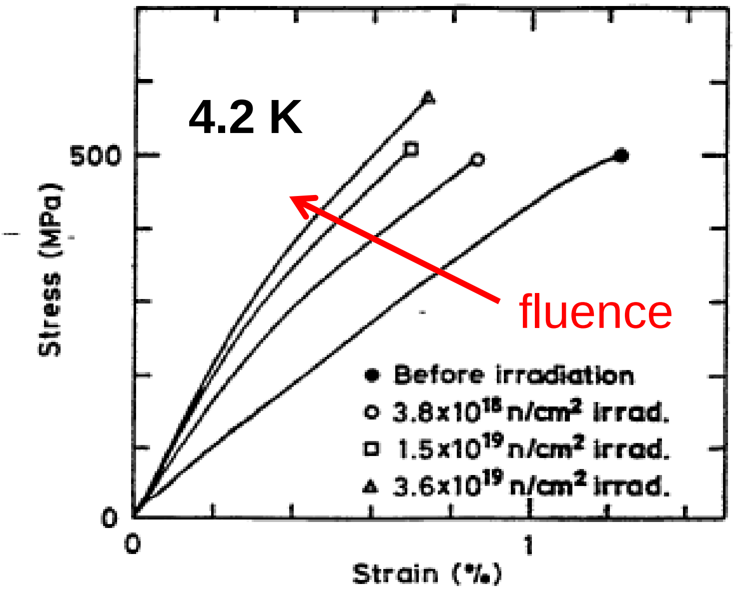
For higher fluences, J_c of alloyed Nb_3Sn wires is lower than that of binary wires.

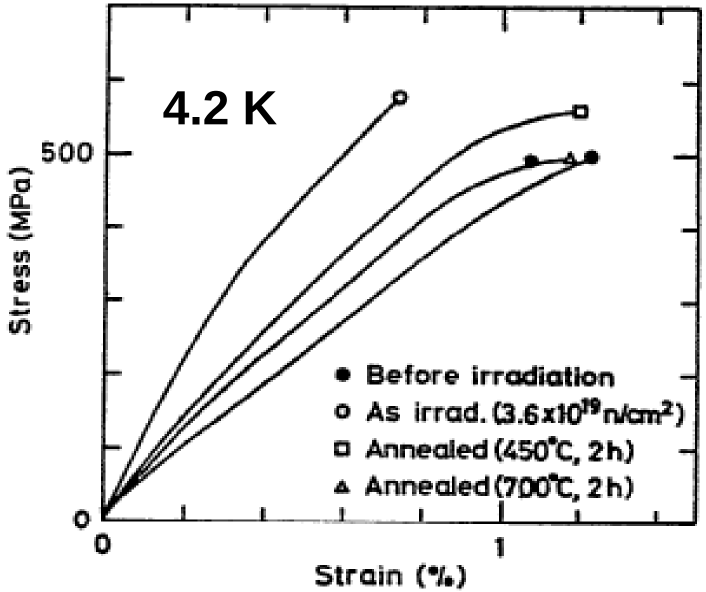
Threshold value: 3 x 10^{17} n/cm^2

This effect is stronger for higher magnetic fields; important for high field accelerators, e.g. NED

Behavior of J_c under stress after irradiation

Stress – strain curves before and after irradiation





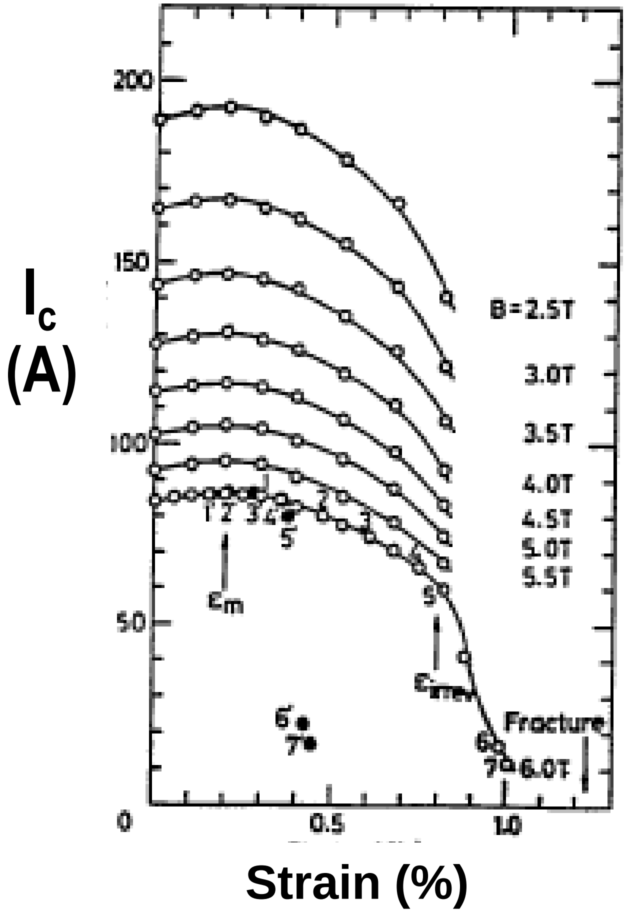
Bronze Route multifilamentary wire
T_{irr} = 350 K

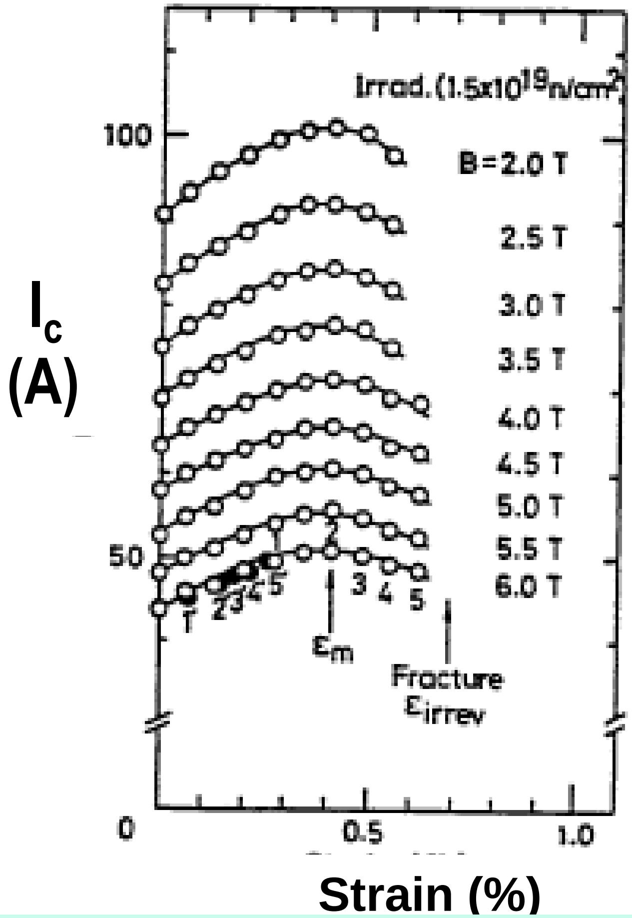
Hardening with higher fluence

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





Bronze Route Multifilamentary Nb_3Sn wire

Before Irradiation

$\varepsilon_m = 0.2\%$

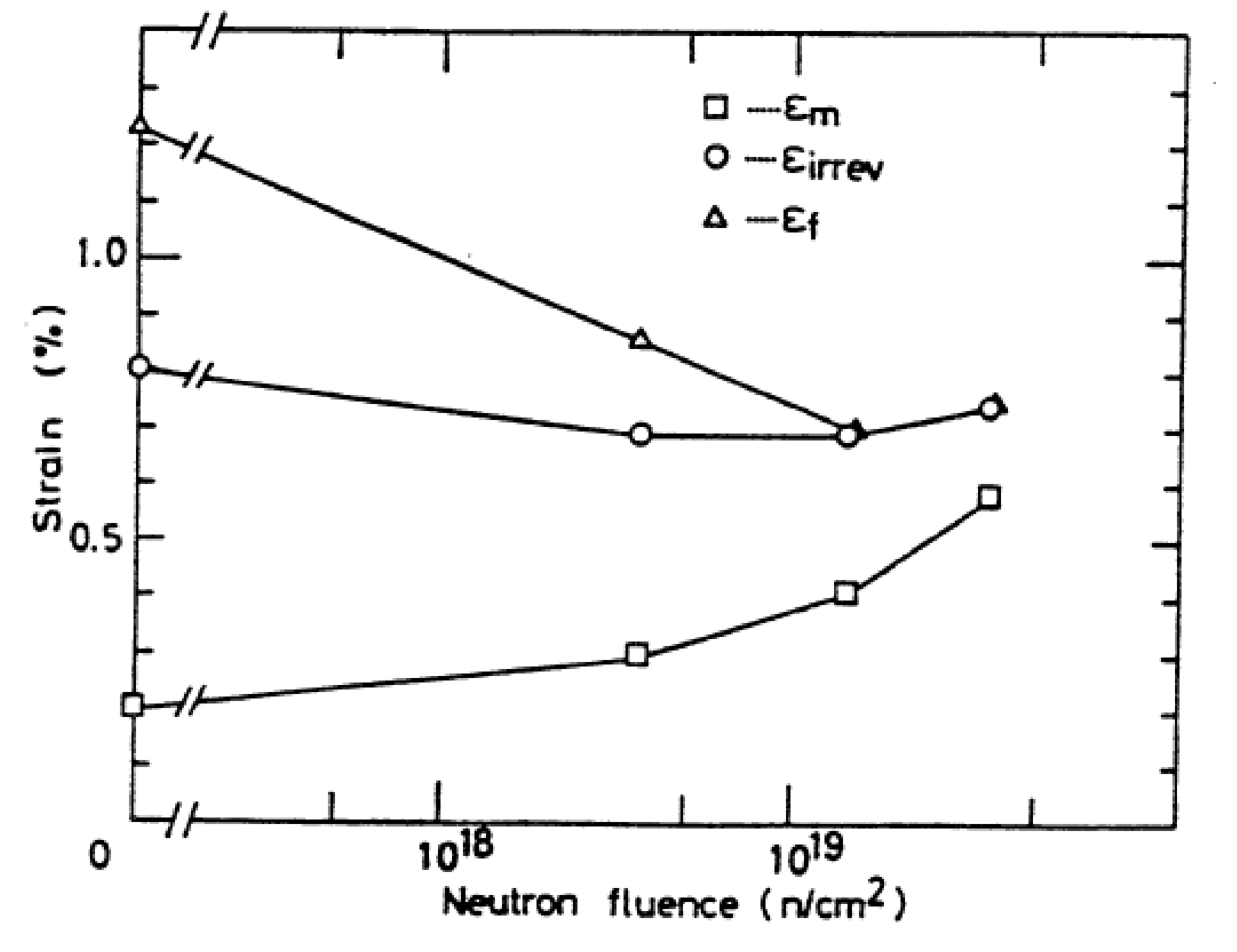
After Irradiation

$\varepsilon_m = 0.4\%$

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

Mechanical Effects of Neutron Irradiation

Binary Nb_3Sn wires



ε_m ↗

ε_{irr} → $\varepsilon_{fracture}$

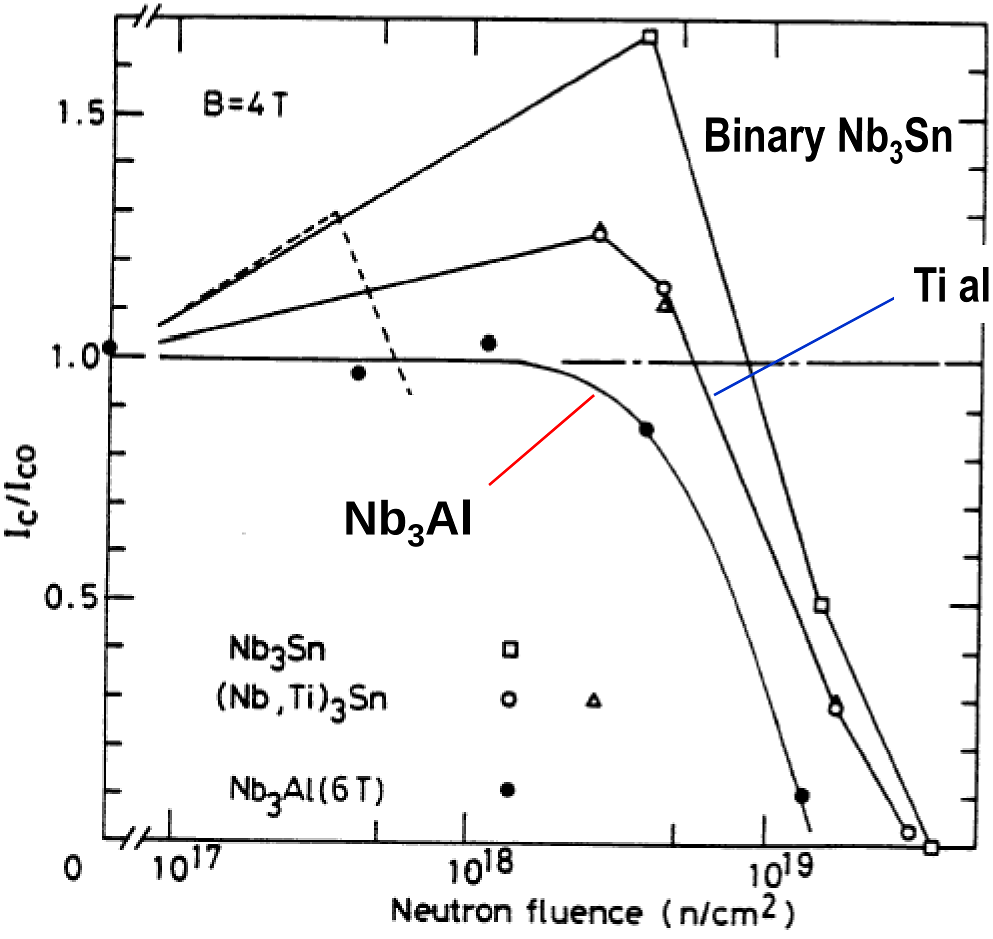
T. Okada, M. Fukumoto, K. Katagiri, K. Saito, H. Kodaka, H. Yoshida, IEEE Trans. Magn., MAG-23(1987)972

Effect of uniaxial tensile strain after irradiation

Ti alloyed Nb_3Sn wires

E > 0.1 MeV

$T_{irr} = 300$ K



Binary Nb_3Sn

Ti alloyed Nb_3Sn

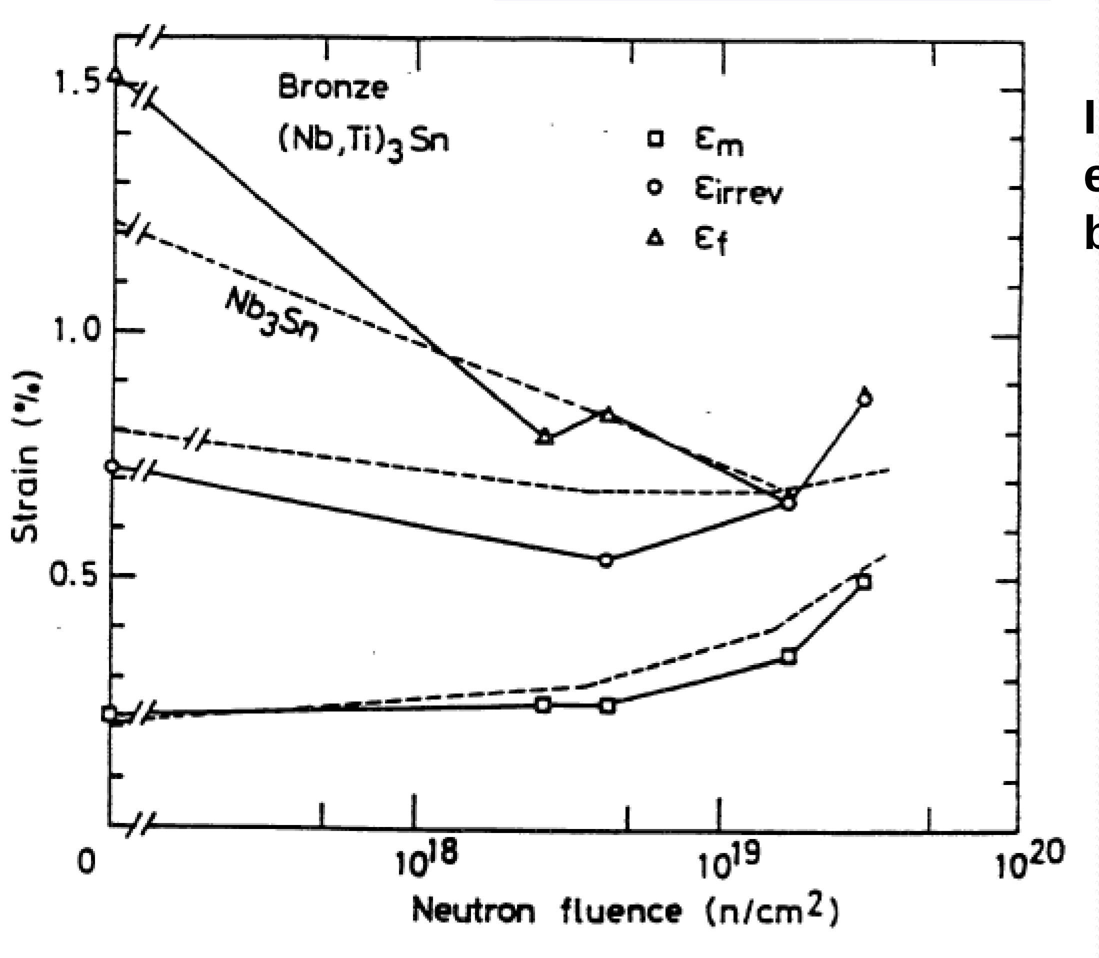
Nb_3Al

Values at $\varepsilon = \varepsilon_m$

K. Katagiri, T. Okada, K. Noto, T. Kuroda, H. Kodaka, Fusion Eng. Design, 20(1993)423

Mechanical Effects of Neutron Irradiation

Ti alloyed Nb_3Sn wires



Increase of ε_m : not fully explained by hardening of bronze matrix

$\varepsilon_m \nearrow$.

$\varepsilon_{irr} \rightarrow \varepsilon_{fracture}$

Similar to binary wires

K. Katagiri, T. Okada, K. Noto, T. Kuroda, H. Kodaka, Fusion Eng. Design, 20(1993)423

Expected Radiation Load on the LHC Quadrupoles

Calculated for the Quadrupole Inner Winding by:

Francesco Cerutti , CERN
Alessio Mereghetti, CERN
Marco Mauri, CERN
Elena Widmer, CERN

Peak Fluence during Phase 1 Upgrade (2.5 x luminosity of 10^{34} cm^{-2} s^{-1})

TRIPLET Quadrupoles (Q1, Q2a, Q2b, Q3) are closer to Collision Point than Dipoles: 23 m

Radiation spectrum close to Collision Point:

Pions, Neutrons, Photons, electrons, with energies >> 1 GeV
(Calculations of Mika Huhtinen, CERN)

Radiation spectrum at the Quadrupole site:

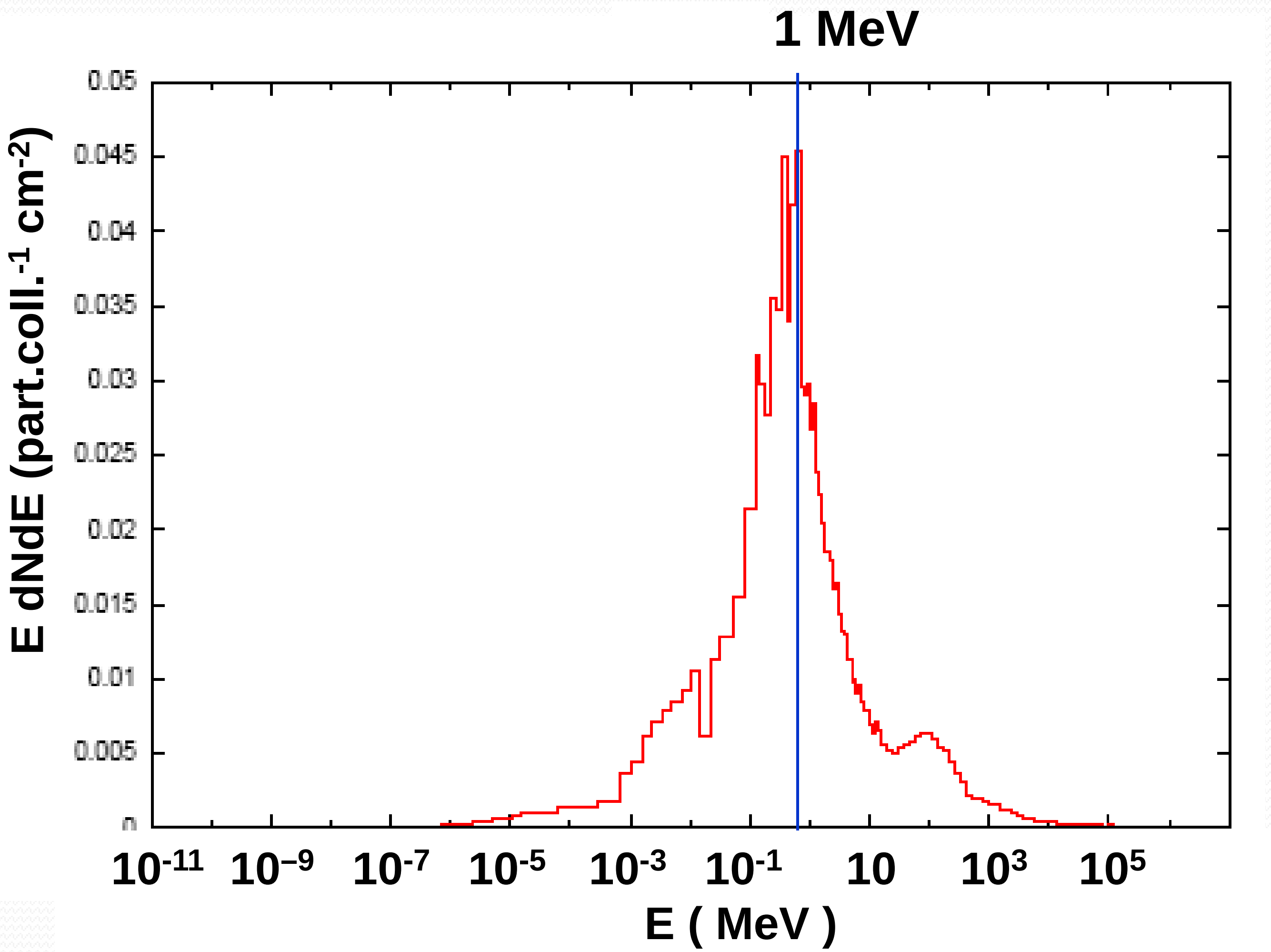
Very different, after interactions with various shielding materials:

Photons	87 %
Neutrons	6 %
Electrons	3.5 %
Positrons	2.5 %
Pions (+/-)	0.4 %
Protons	0.15 %

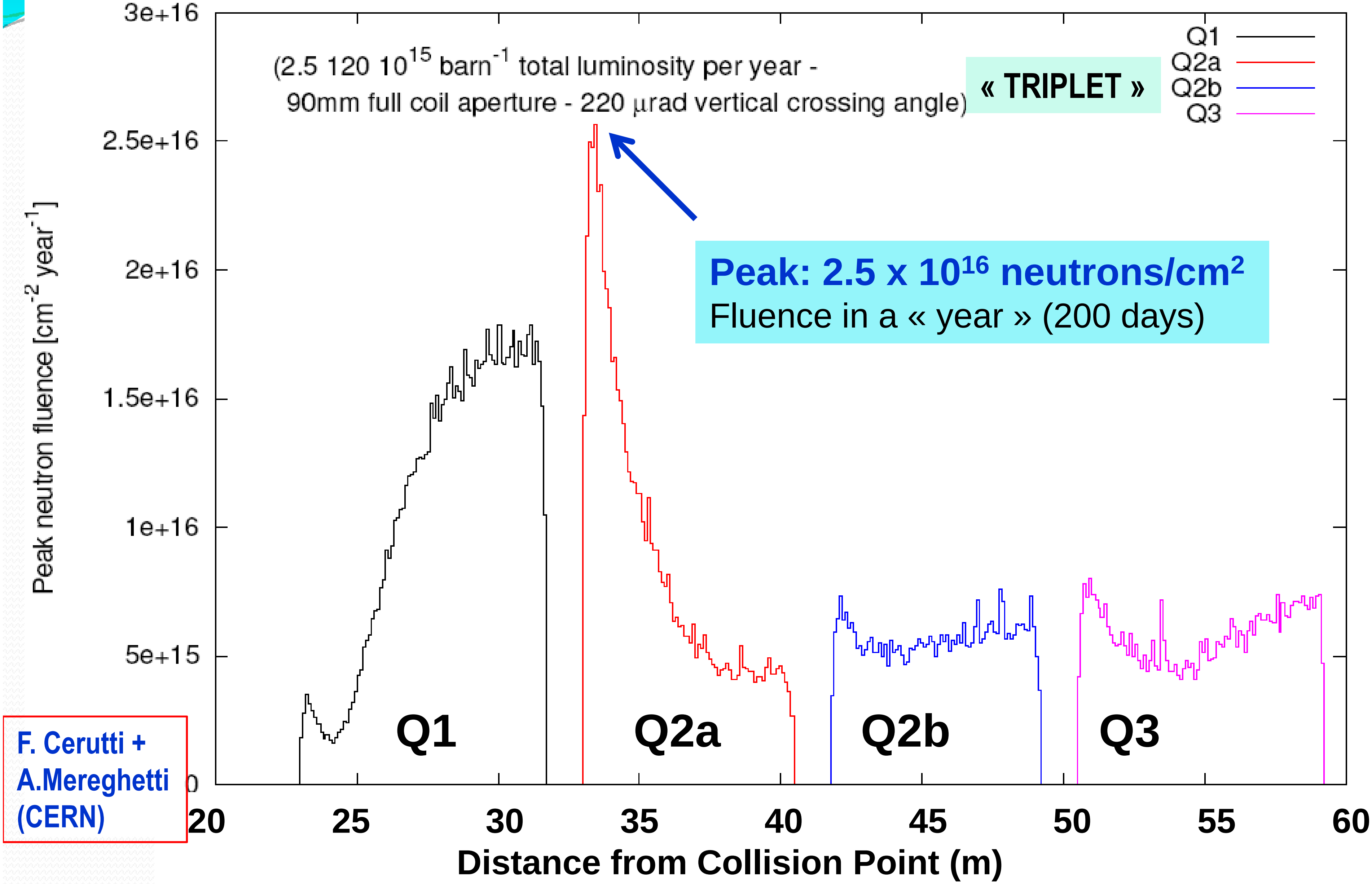
Neutrons are the main source of damage to the superconductors.
Photons have a much lower effect . Almost no pions.

Neutron spectrum in the inner winding of Quadrupole Q1

The neutron energy fully covers the possible interval, down to thermal energies



Neutron fluence in the inner winding of Quadrupoles (Phase 1 Upgrade)



« TRIPLET »

Peak: 2.5 x 10^{16} neutrons/cm^2
Fluence in a « year » (200 days)

F. Cerutti + A.Mereghetti (CERN)

Conclusions

High energy irradiation, in particular neutrons with E>0.1 MeV:

- NbTi wires are almost not affected
- Nb_3Sn wires sensitive above 3×10^{17} n/cm^2 .

Alloyed Nb_3Sn wires more sensitive to radiation than binary wires

Reason: normal state resistivity ρ_o.

Neutron Irradiation causes hardening of matrix and wire

Mechanical behavior of irradiated binary and alloyed Nb_3Sn wires is similar: ε_m increases.

Damage caused by low temperature irradiation can only partially be recovered at T = 300K

Little difference expected between irradiated Bronze Route, Internal Sn and PIT wires

Peak Fluence at Quadrupole Q2a: 2 x 10^{16} n/cm^2 after 1 year (Phase I upgrade)

For NbTi: no effect

Later, for Nb_3Sn wires:
Even after several years of operation, peak fluence remains below > 1 x 10^{18} n/cm^2.

Different fluences for Q1 – Q3: the operation conditions of these quadrupoles may have to be individually modified with time, for maintaining a constant field.

Ta is activated by neutron irradiation: For reducing induced radioactivity: minimize Ta in the wires.