What do we need?

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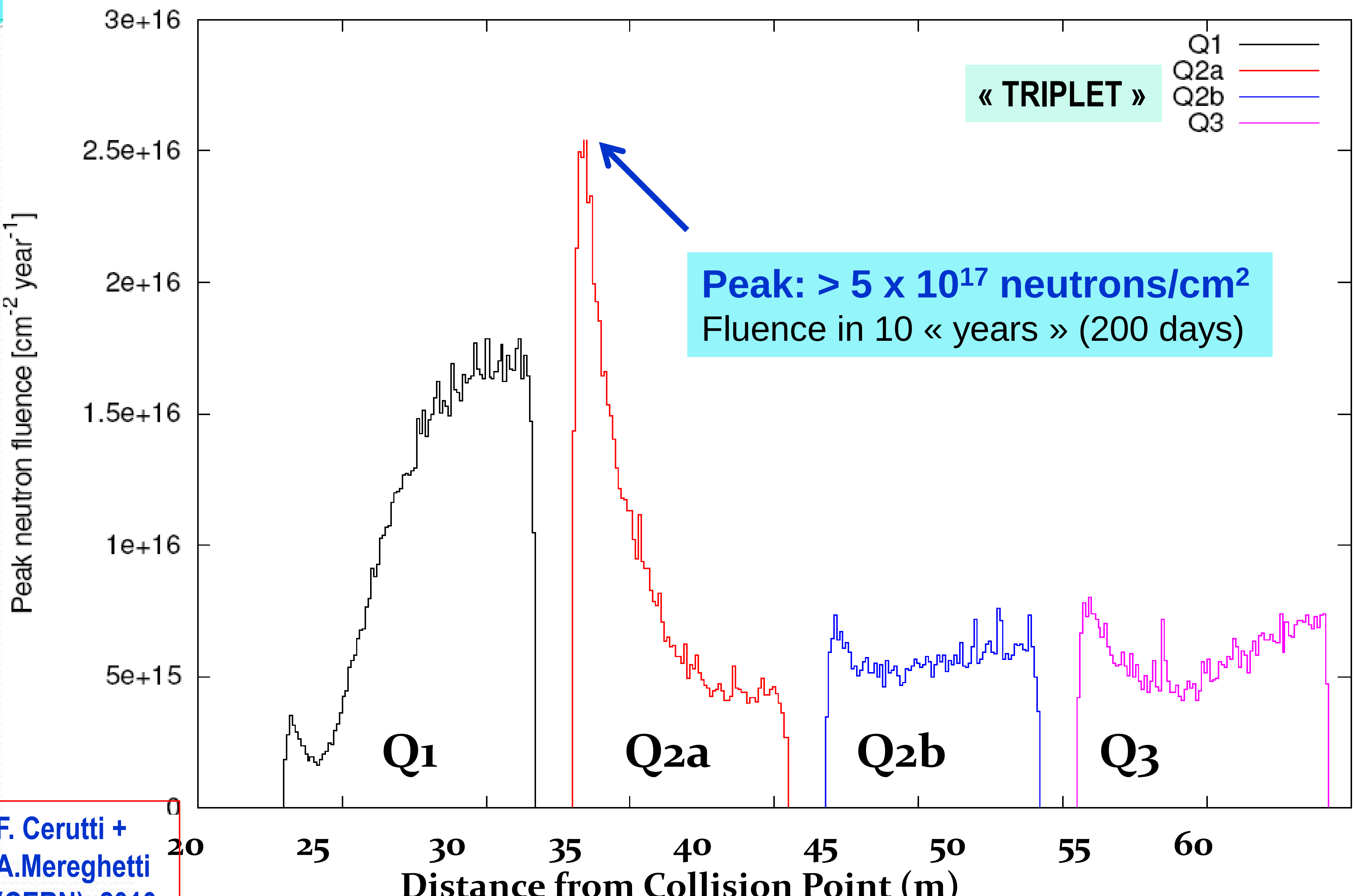
In the following, analysis will be restricted on Nb_3Sn (quadrupoles)

MgB_2 for current leads: talk of M. Putti

BI-2212: not yet developed at an industrial level.

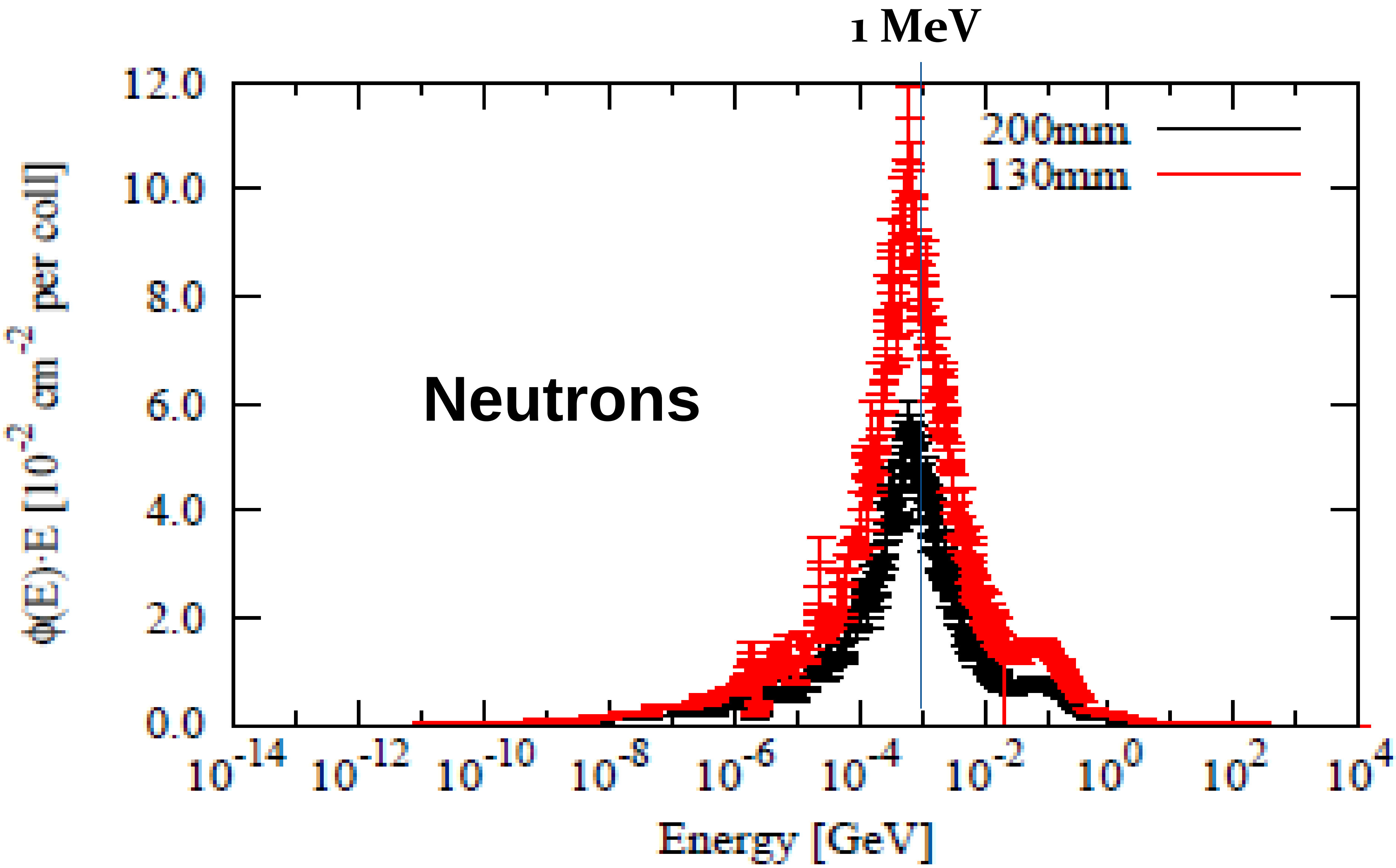
Starting point of the present considerations:
Calculations of F. Cerutti (CERN), 2010
(newer calculations in his presentation, today)

Neutron fluence in the inner winding of Quadrupoles (LHC Upgrade)

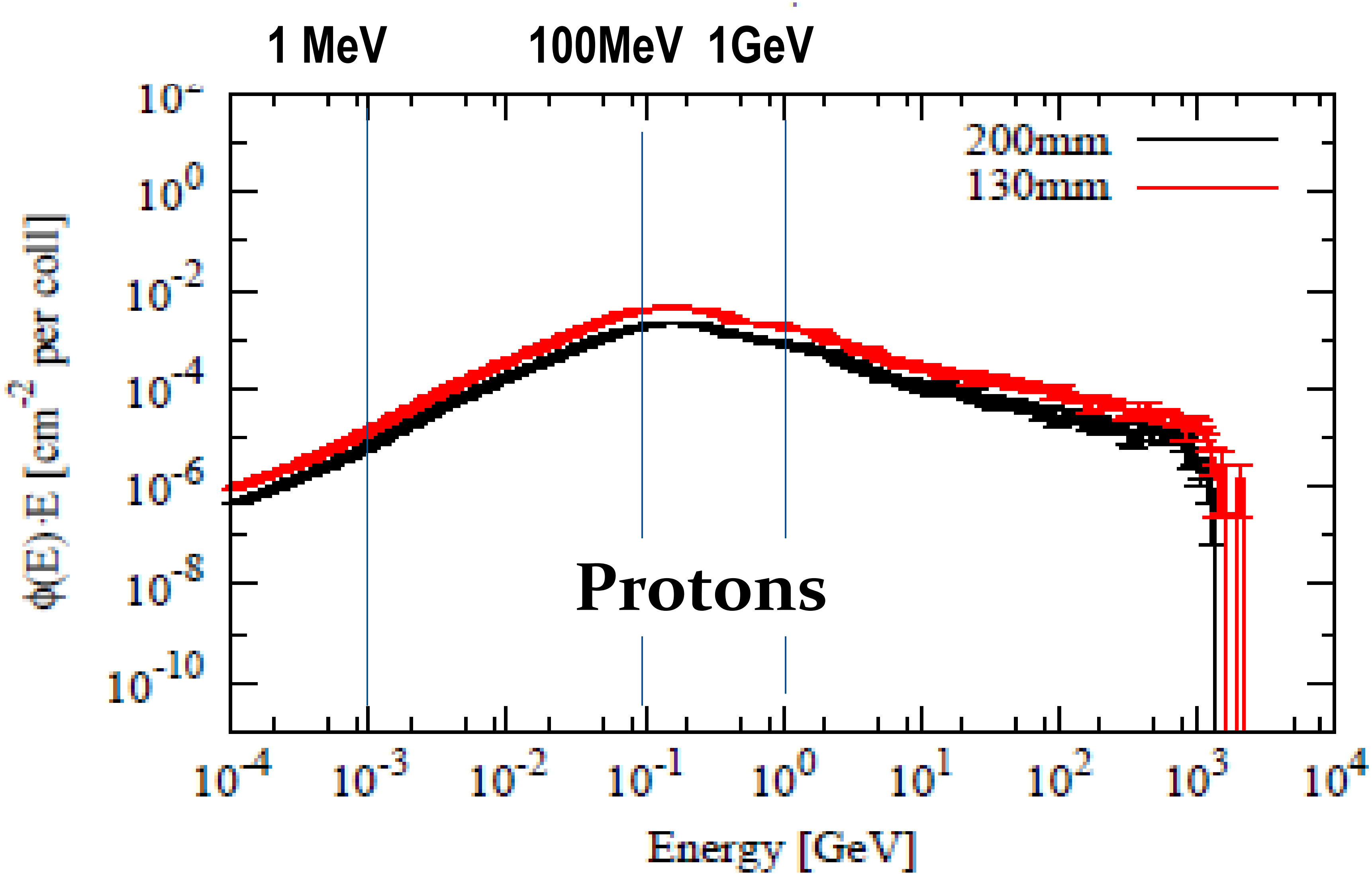


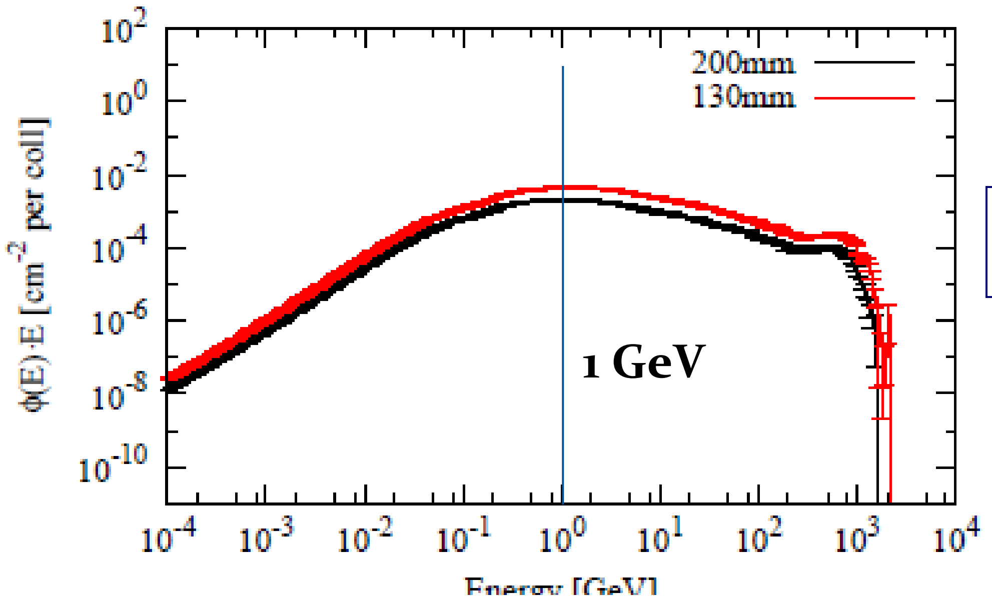
F. Cerutti + A.Mereghetti (CERN), 2010

Neutron spectrum in the inner coil of Q2a at peak location

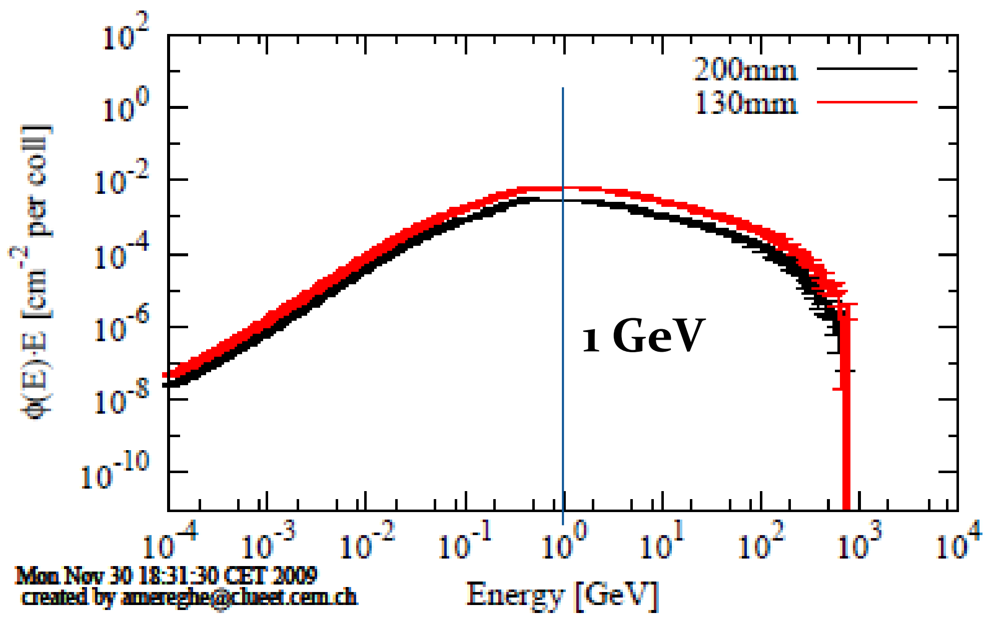


Proton spectrum in the inner coil of Q2a at peak location





Pions +



Pions -

Pion spectrum in the inner coil of Q2a

Peak Fluence, LHC Upgrade (5 x 10^{34} cm^{-2} s^{-1})

Radiation spectrum at Q2a: 35m from Collision Point

Aperture	200mm	130mm	130 mm	
Photons	88.93	89.00%		
Neutrons	4.82	4.04%	4.04%	
Protons	0.14	0.13%	0.13%	
Pions+	0.19	0.19%	0.19%	0.57%
Pions-	0.26	0.25%	0.25%	
Electrons	4.31	4.63%		
Positrons	2.23	2.45%		

$$\frac{\text{Protons + Pions(+) + Pions(-)}}{\text{Neutrons}} \approx 14\ \%$$

Question: How do the magnets (quadrupoles) behave after 10 years of operation?

Study to be carried out for each high energy source:

- **the superconductor** — T_c, J_c, H_{c2}
- **the stabilizing Cu** — ρ (T)
- **the insulator** — mechanical properties, electrostatic charges,….
- **the magnet** — combined effects, quench behavior, volume changes (expansion of Nb_3Sn, Cu and insulator)

Keep in mind:

* all high energy sources act simultaneously

* there is no experience on a combined effect of several high energy sources

* subsequent irradiations with different sources should be carried out on selected samples

* calculations must be carried out to study combined irradiations
(taking into account the small values of dpa, this may be possible

Known effects of radiation on superconductors

Neutrons : Strong source of damage for superconductors

Protons: From known data, even stronger effect (charge)

Pions: Nothing is known yet. Effects expected to be comparable to those of protons (charges +/-)

Electrons: Very little is known. Much smaller effects expected (in contrast to insulators). More data needed

Photons: Nothing is known. Smaller effects expected. Data needed

What should be analyzed about irradiation of the superconductor?

Damage Mechanism (atomic ordering); Comparison with heavy ion irradiation

Effect of various energy sources

Number of displacement per atoms

Summation of single irradiations (small dpa numbers)

Irradiation at 4.2K and 300K

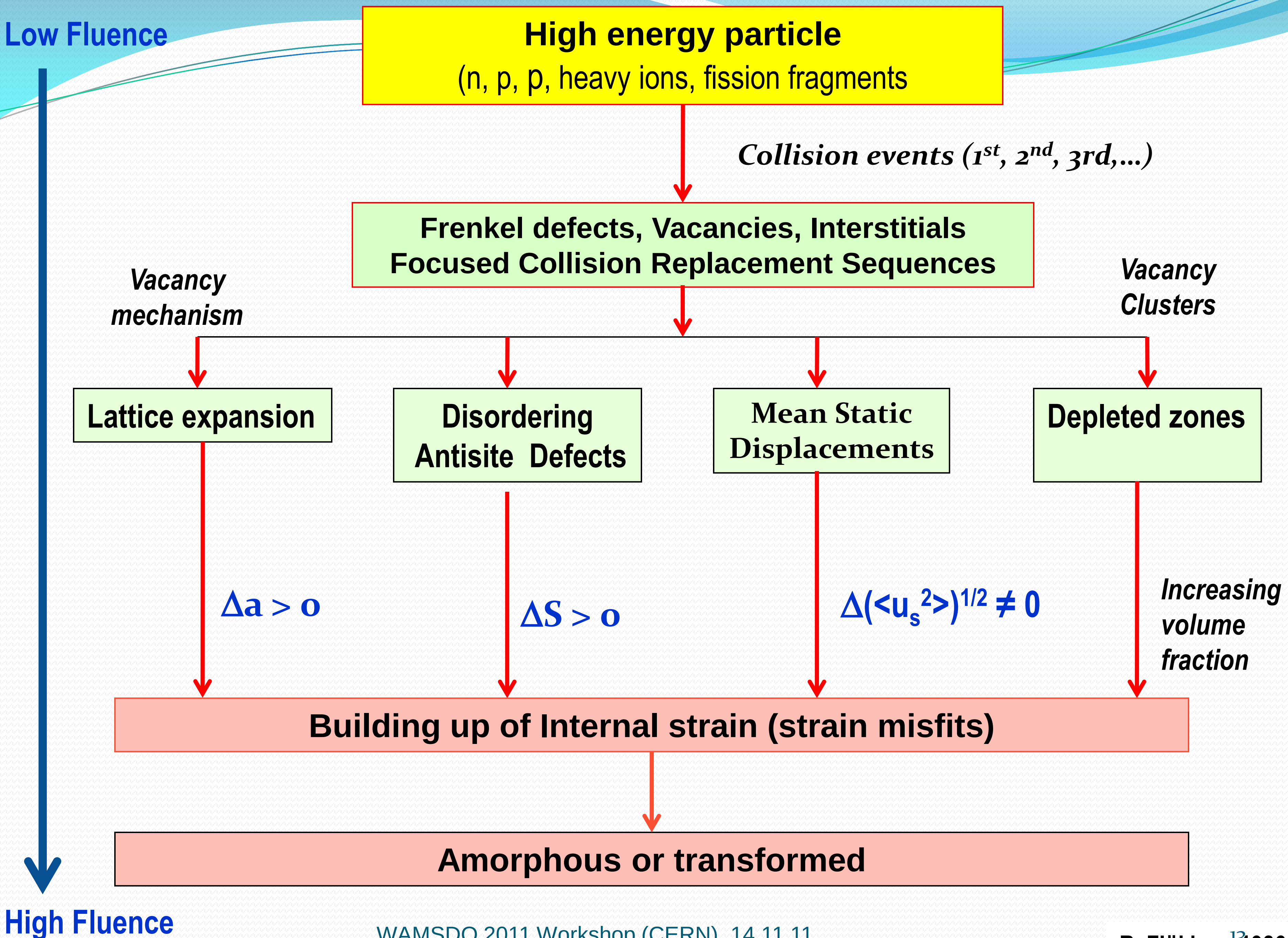
Volume expansion of Nb_3Sn; Effect of repeated warming up and cycling on irradiated superconductors

Thermal stabilization: Recovery behavior of Cu?

Mechanical properties of the superconductor after irradiation

Mechanisms of irradiation damage

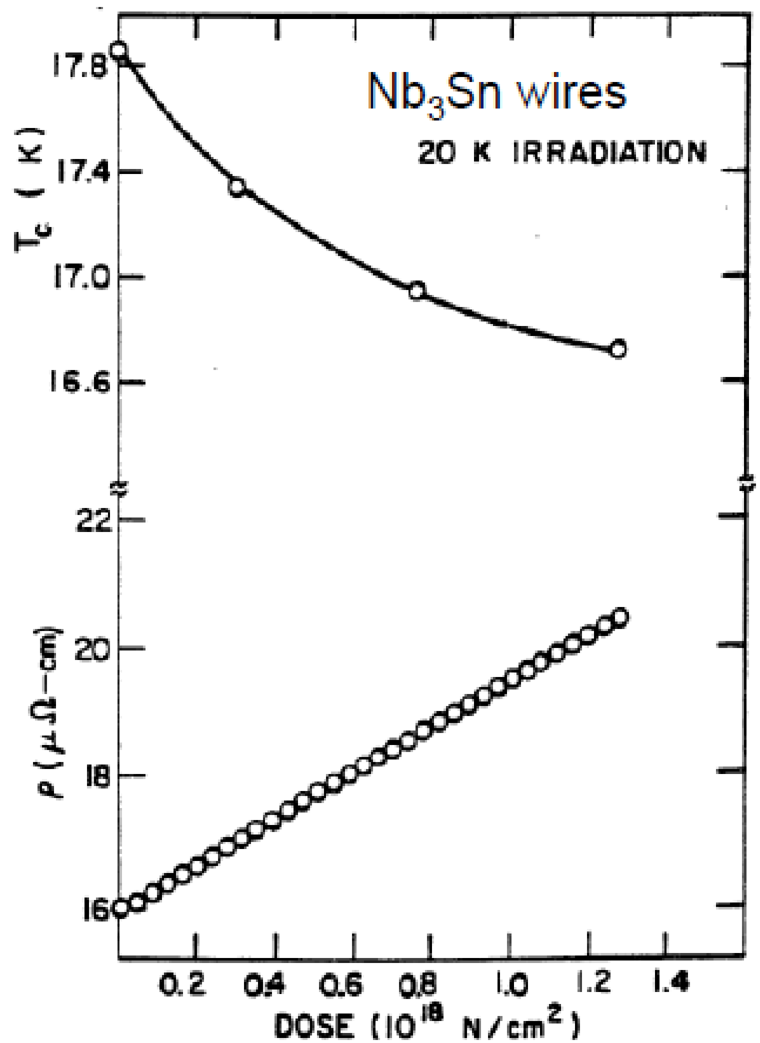
Due to limited data, results from heavy ion irradiation are also taken into account



R. Flükiger, 1986

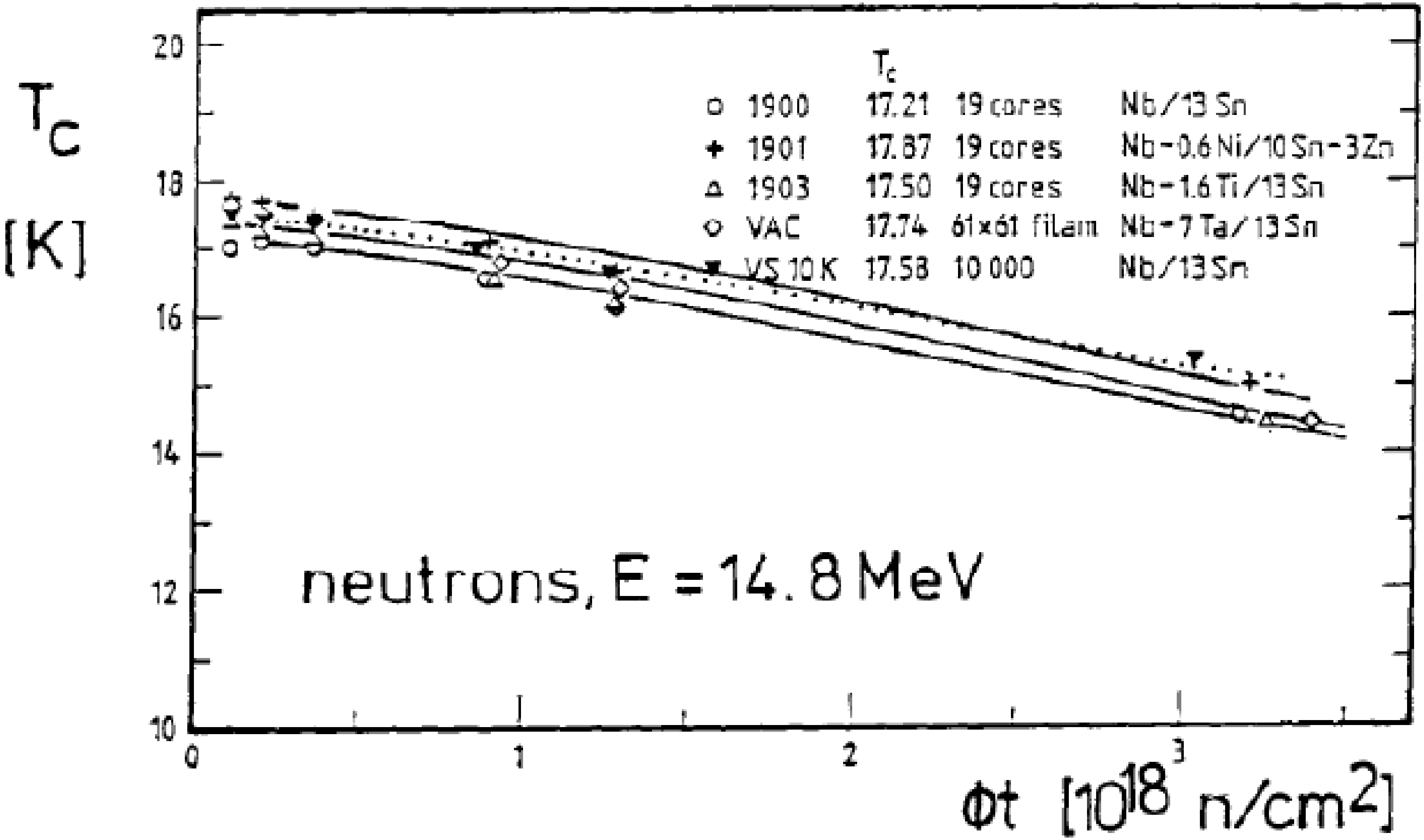
Effect of neutron irradiation on T_c

Enhancement of normal state electrical resistivity ρ_o



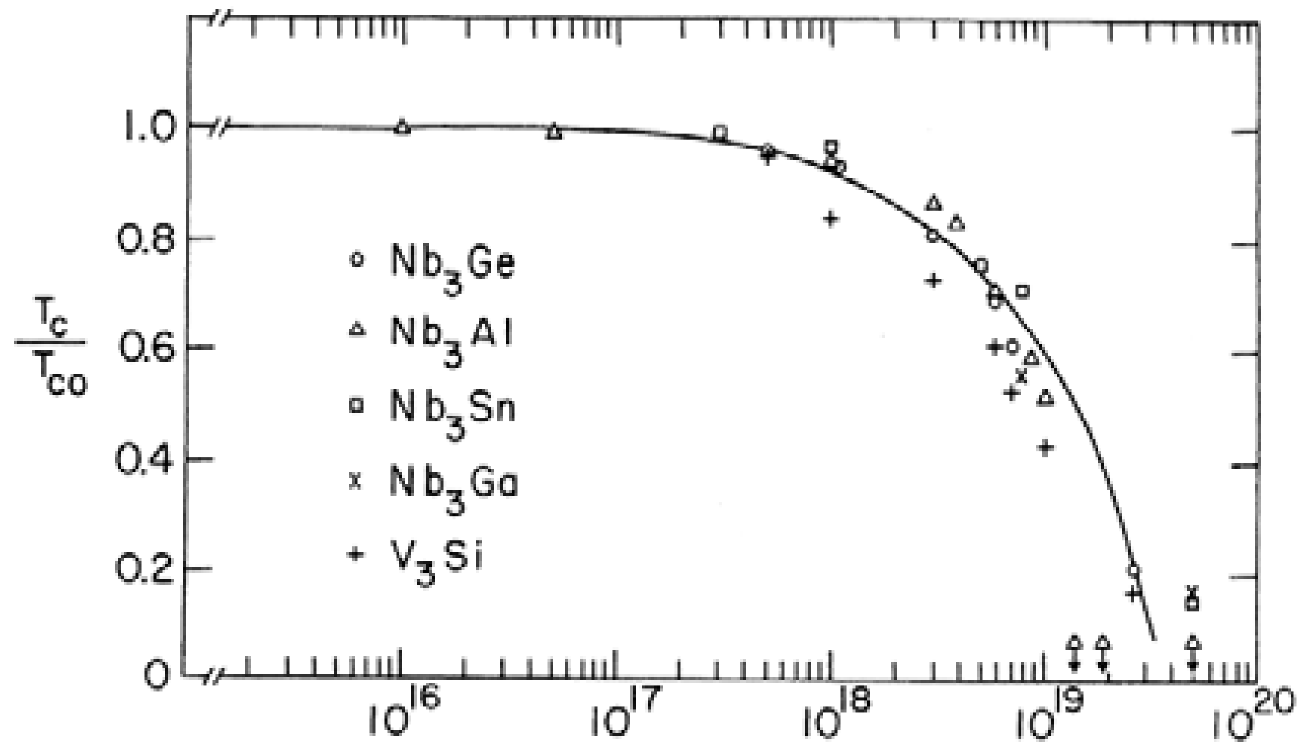
$B_{c2} \sim T_c \gamma \rho_o$

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

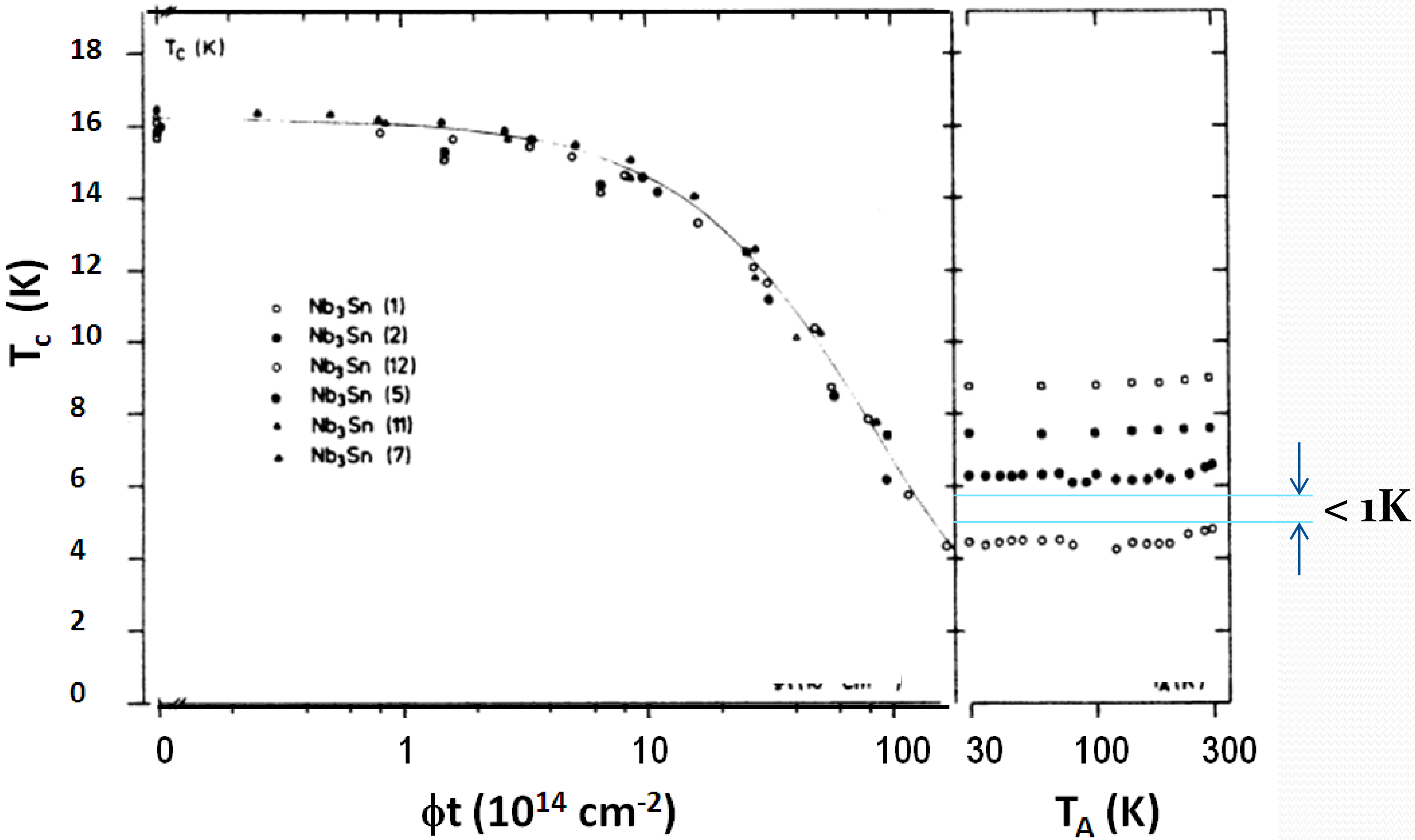


F. Weiss, R. Flükiger, W. Maurer, IEEE Trans. Magn., MAG-23(1987)976

T_c of Nb_3Sn after 1 MeV neutron irradiation

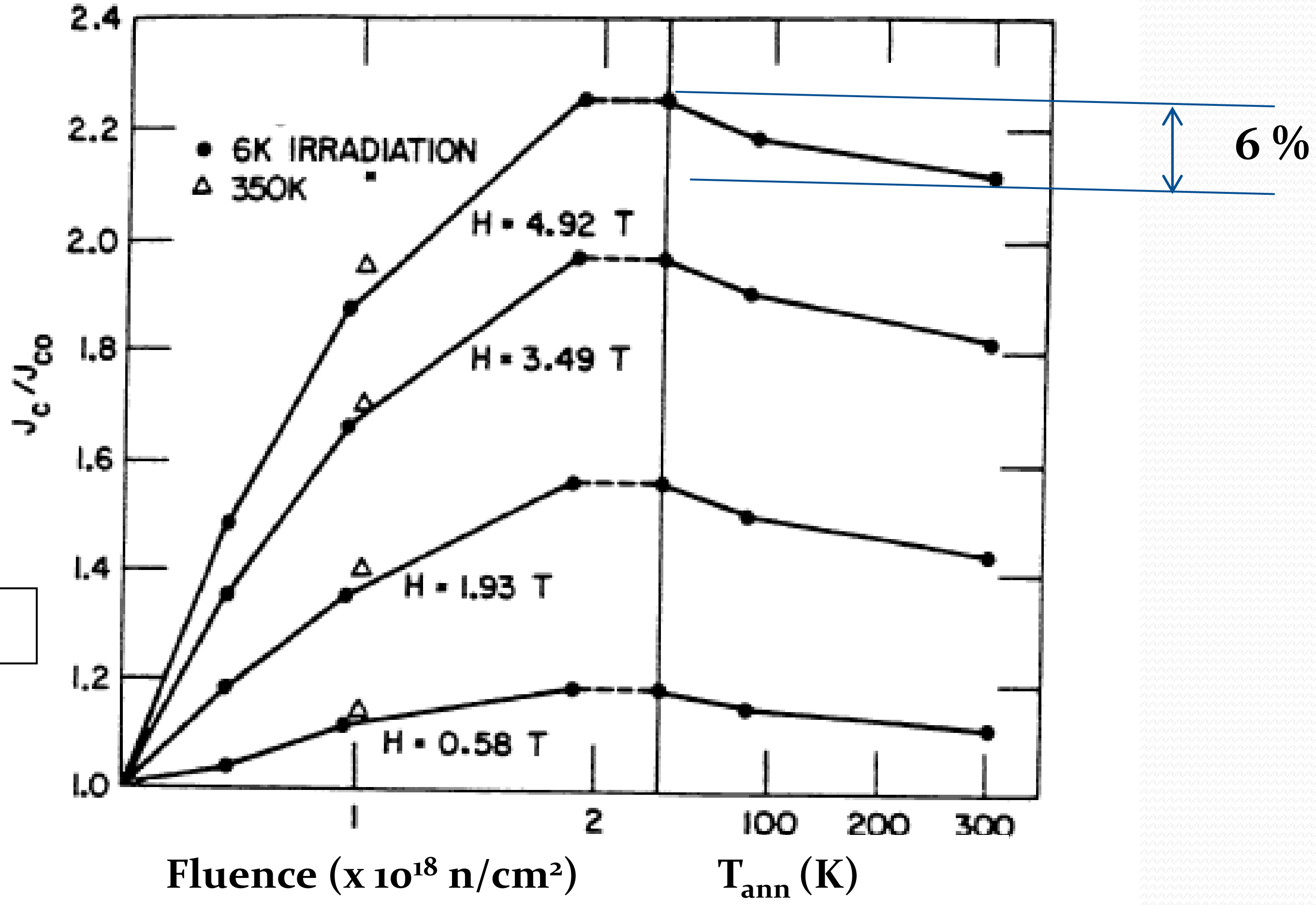


A.R. Sweedler, D.G. Schweizer, G.W. Webb, Phys. Rev. Lett. 33 (1974) 168



Recovery of Nb_3Sn films after irradiation at T < 30K with 25 MeV O-ions (B. Besslein, 1976)

Recovery Effects after warming up



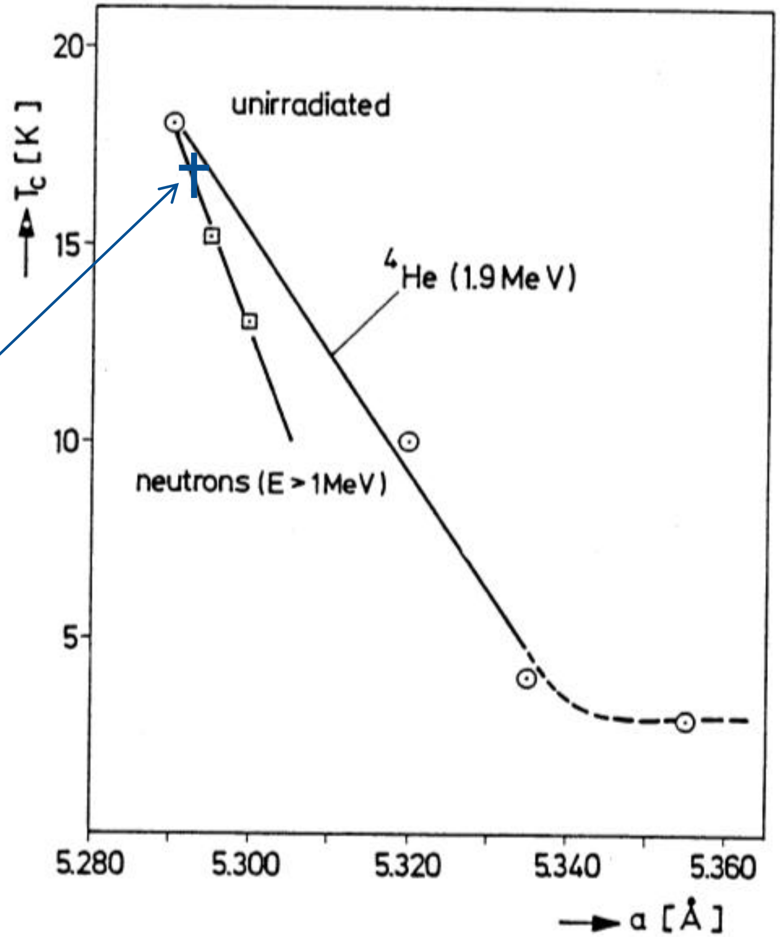
E > 0.1 MeV

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

Volume expansion of irradiated Nb_3Sn

Analogy between neutron and heavy ion irradiation

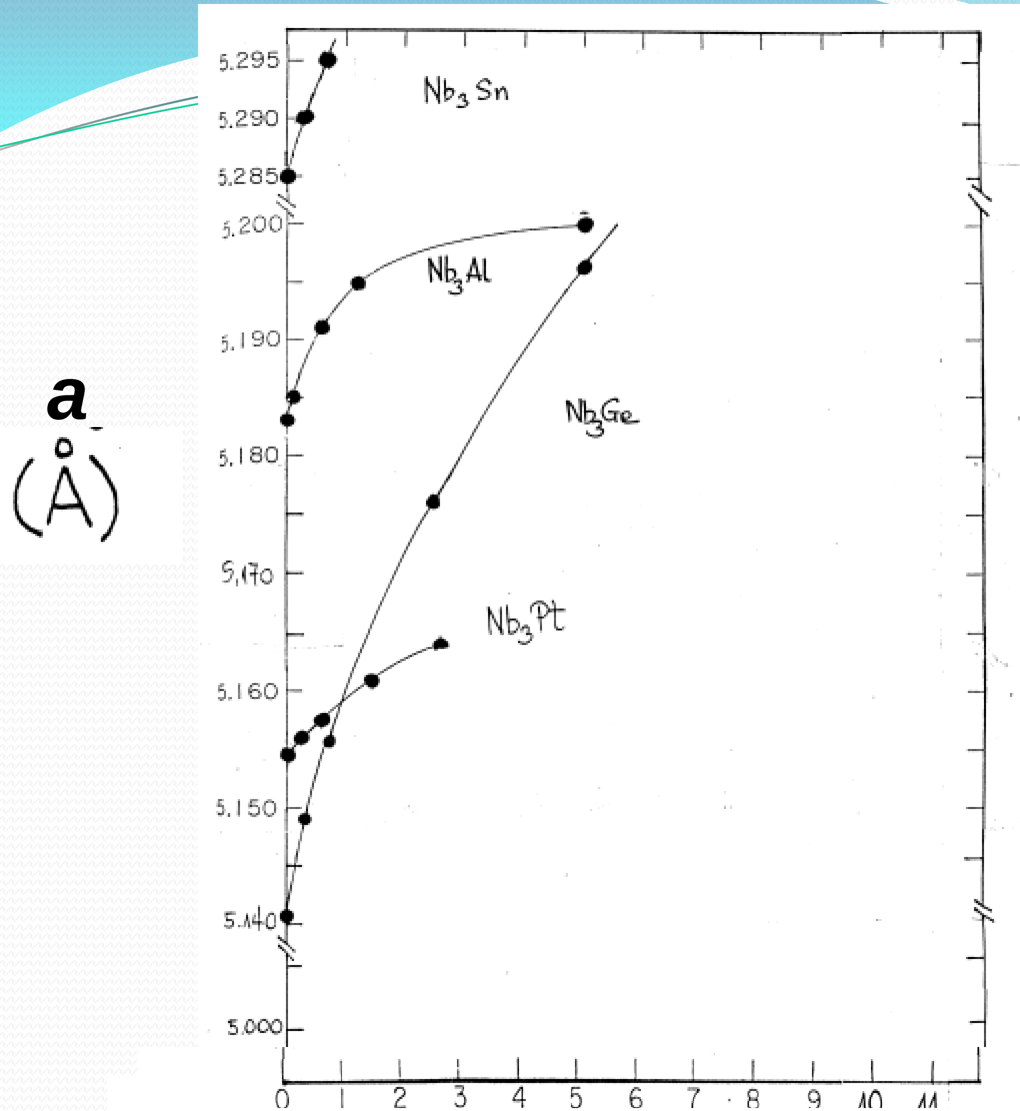


1x 10^{18} n/cm^2

$\Delta V \approx 1\%$

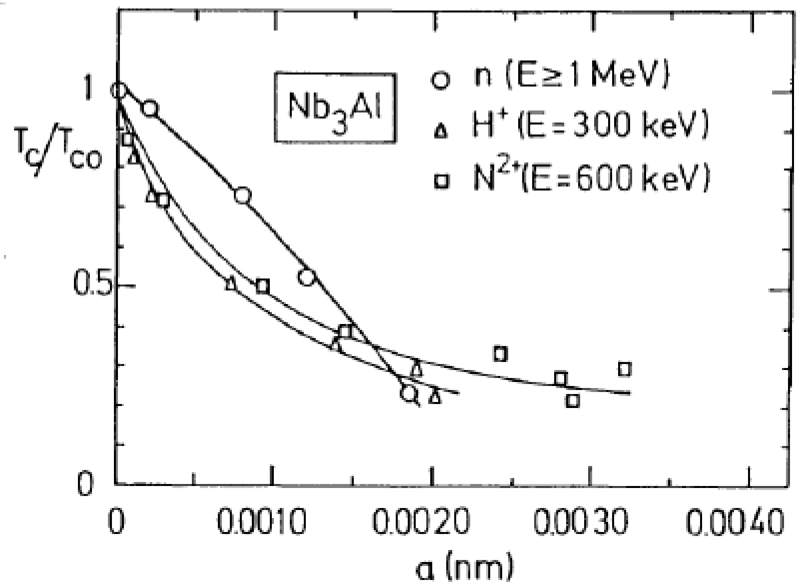
Scaling law between various sources not yet investigated

At 1 x 10^{18} n/cm^2, volume expansion of Nb_3Sn is ≈ 1%: * internal stresses?
* effects on J_c?



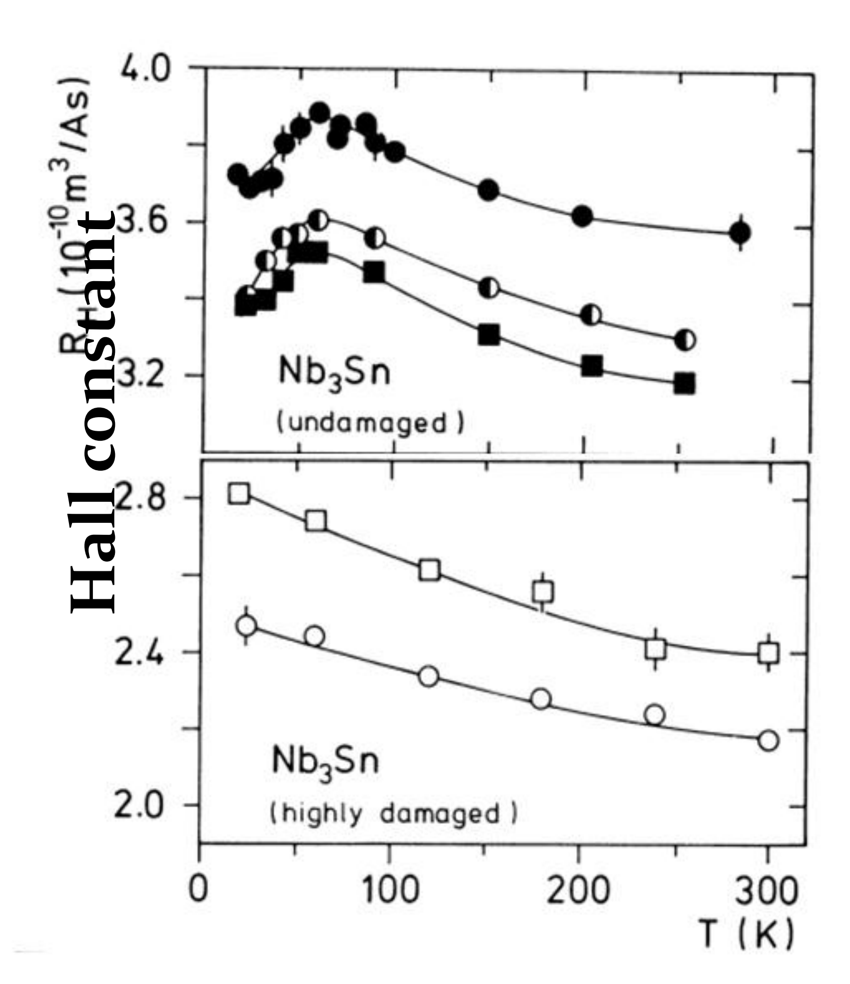
Φt (x 10^{19} n/cm²)

A. Sweedler, 1978



Schneider, 1982

Volume expansion after irradiation

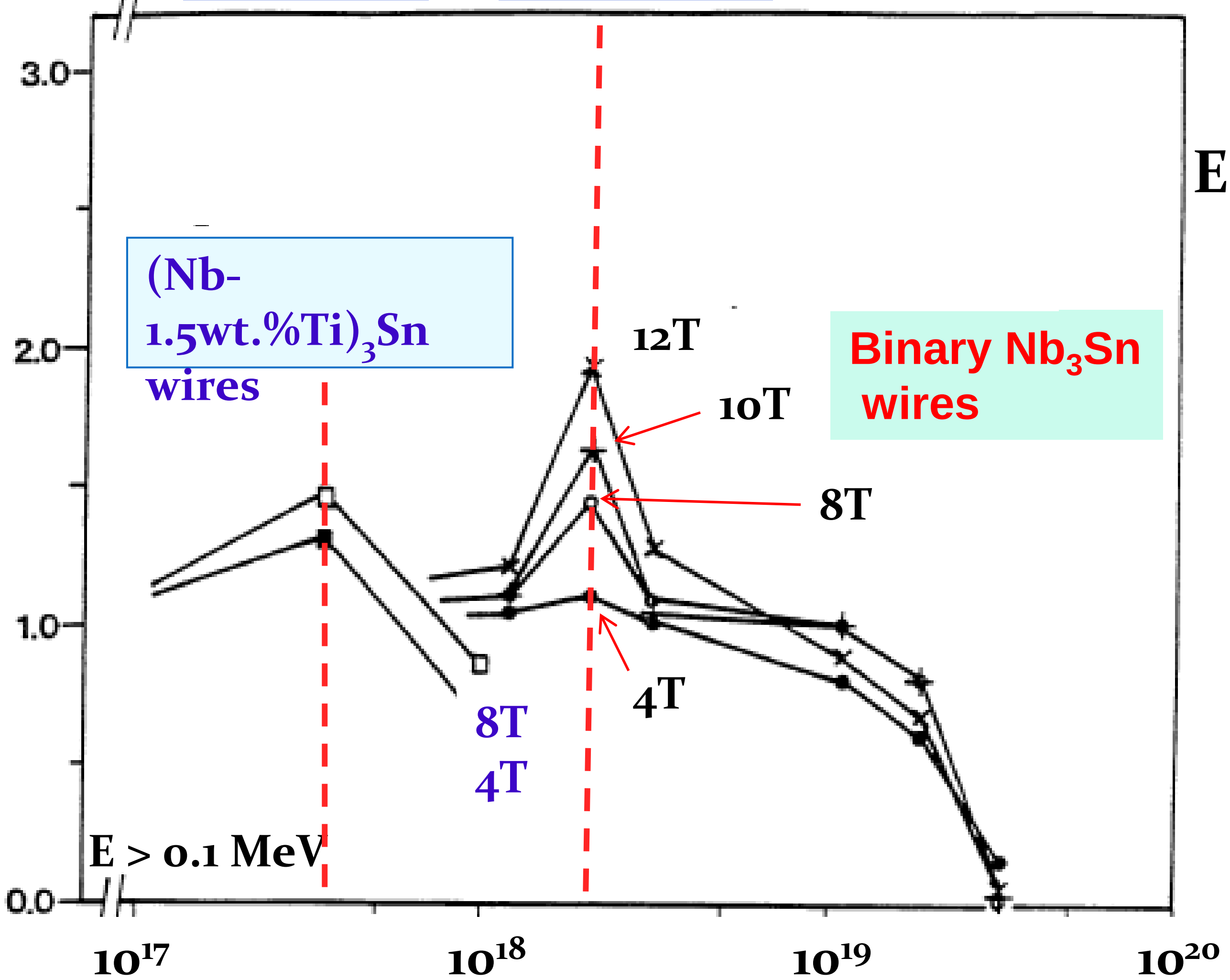


Suppression of martensitic transformation in Nb_3Sn films irradiated with 20 MeV ^{32}S ions at < 30 K (2×10^{15} cm^{-2}) (C. Nölscher, 1984)

Irradiation of binary and ternary alloyed Nb_3Sn

~ 3 x 10^{17}

1.5 x 10^{18}



E > 0.1 MeV

H.W. Weber et al., 1986, Adv. Cryo. Eng., 32, 853

Neutron irradiation
E = 14 MeV

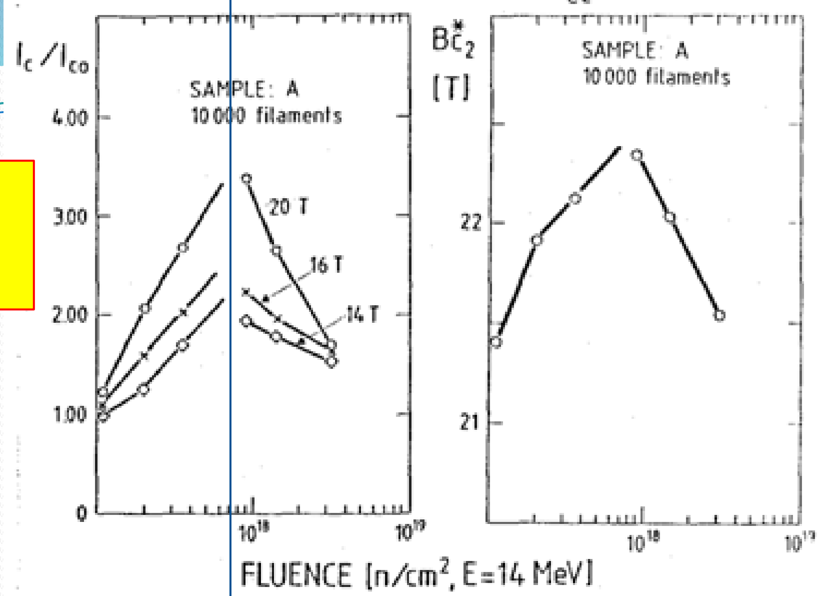


Figure 5. I_c/I_{co} and B^*_{c2} of a 10000 core bronze processed binary Nb_3Sn wire after neutron irradiation at 25°C.

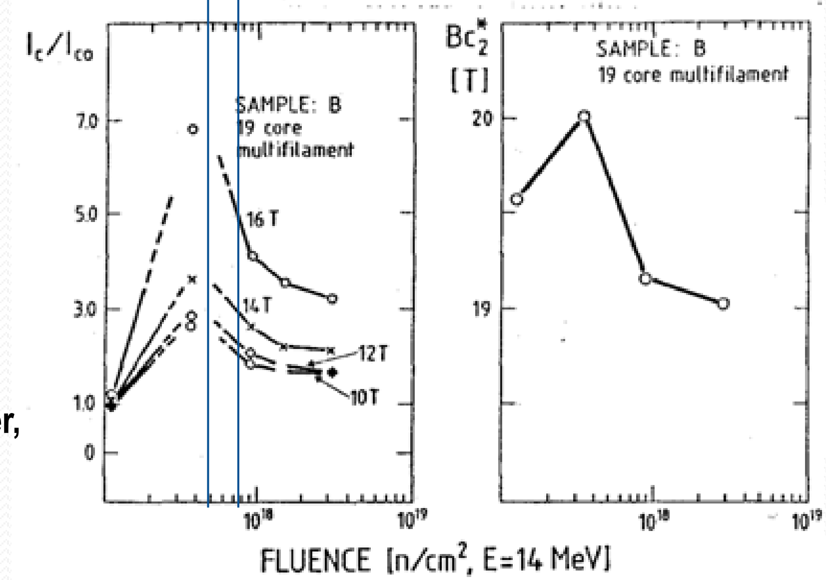


Figure 6. I_c/I_{co} and B^*_{c2} of a 19 core binary Nb_3Sn wire after neutron irradiation at 25°C.

Binary Nb_3Sn
Bronze route
10'000 filaments

Binary Nb_3Sn
Bronze route
19 filaments

F. Weiss, R. Flükiger, W. Maurer, P.A. Hahn, M.W. Guinan, IEEE Trans. Magn., MAG 23(1987)976

I_c(max) varies for different wire configurations

I_c(max) are different for different neutron sources:

When comparing the effect of irradiation for different neutron sources e.g. 1 MeV and 14 MeV, the fluences have to be considered carefully, and the appropriate corrections have to be made

E = 14 MeV

Binary Nb_3Sn wire (19 filaments)

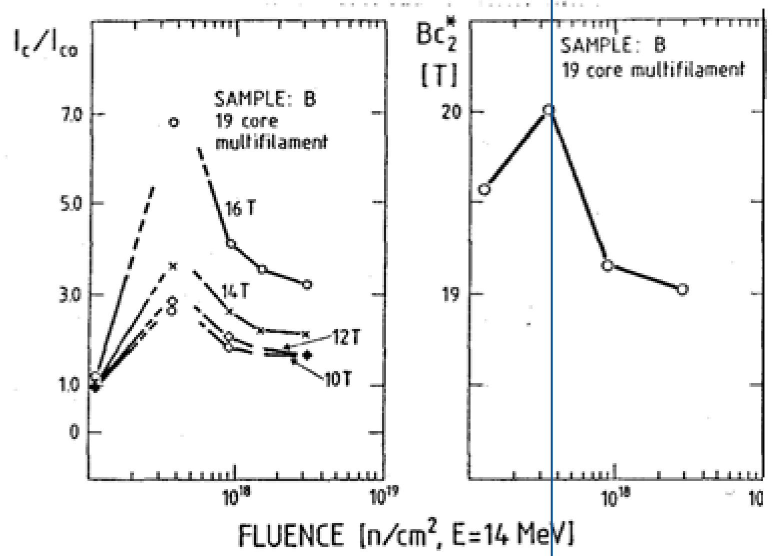


Figure 6. I_c/I_{co} and B_{c2}^* of a 19 core binary Nb_3Sn wire after neutron irradiation at 25 °C.

Ti alloyed Nb_3Sn wire (19 filaments)

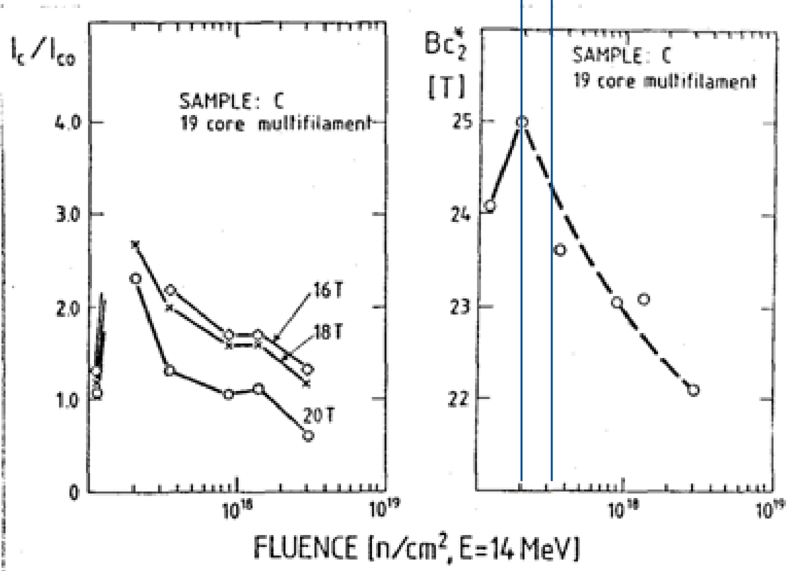
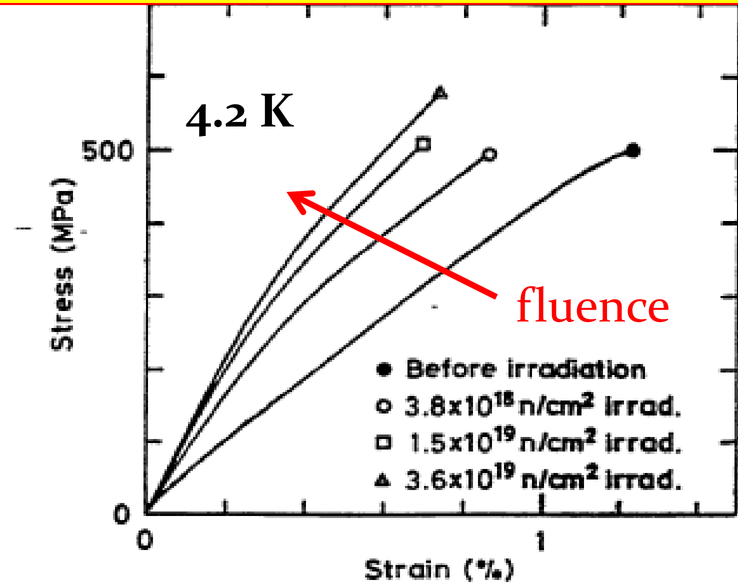


Figure 7. I_c/I_{co} and B_{c2}^* of a 19 core Ti alloyed Nb_3Sn wire after neutron irradiation at 25 °C.

This effect does not depend on the neutron source, but on the Nb_3Sn wire configuration

Behavior of J_c under stress after irradiation

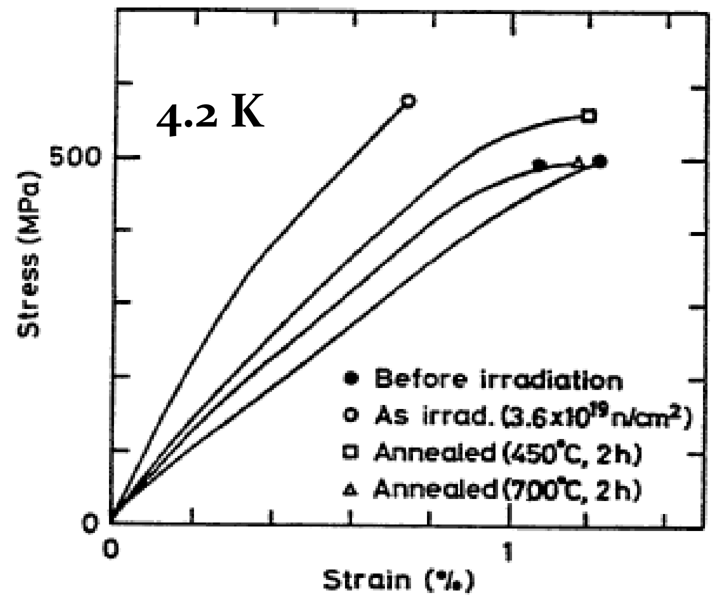
Stress – strain curves before and after irradiation



Bronze Route multifilamentary wire

T_{irr} = 350 K

Hardening with higher fluence

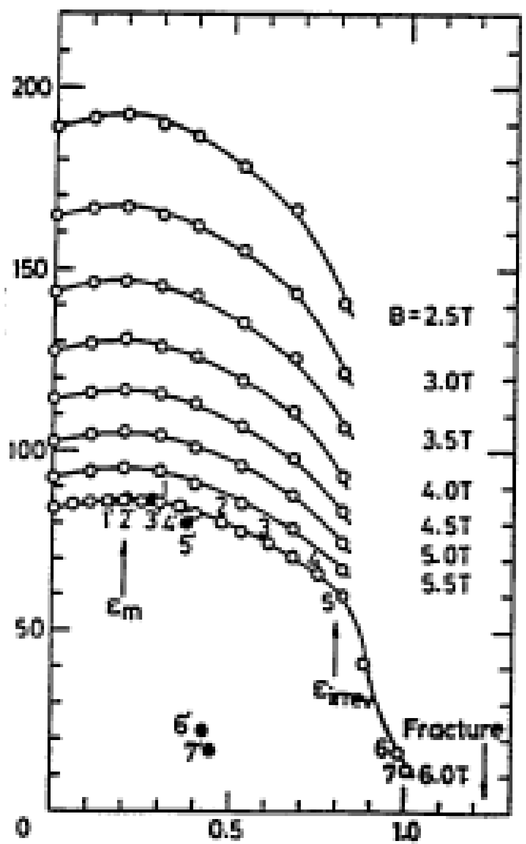


Recovery after annealing at 450 and 700 °C

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

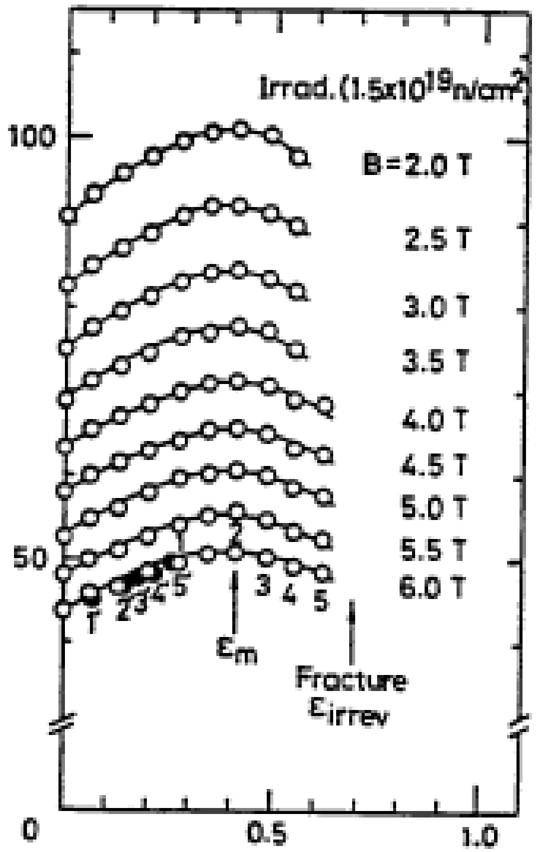
Effect of uniaxial tensile strain after irradiation

I_c (A)



Strain (%)

I_c (A)



Strain (%)

Bronze Route Multifilamentary Nb_3Sn wire

Before Irradiation
$\varepsilon_m = 0.2\%$

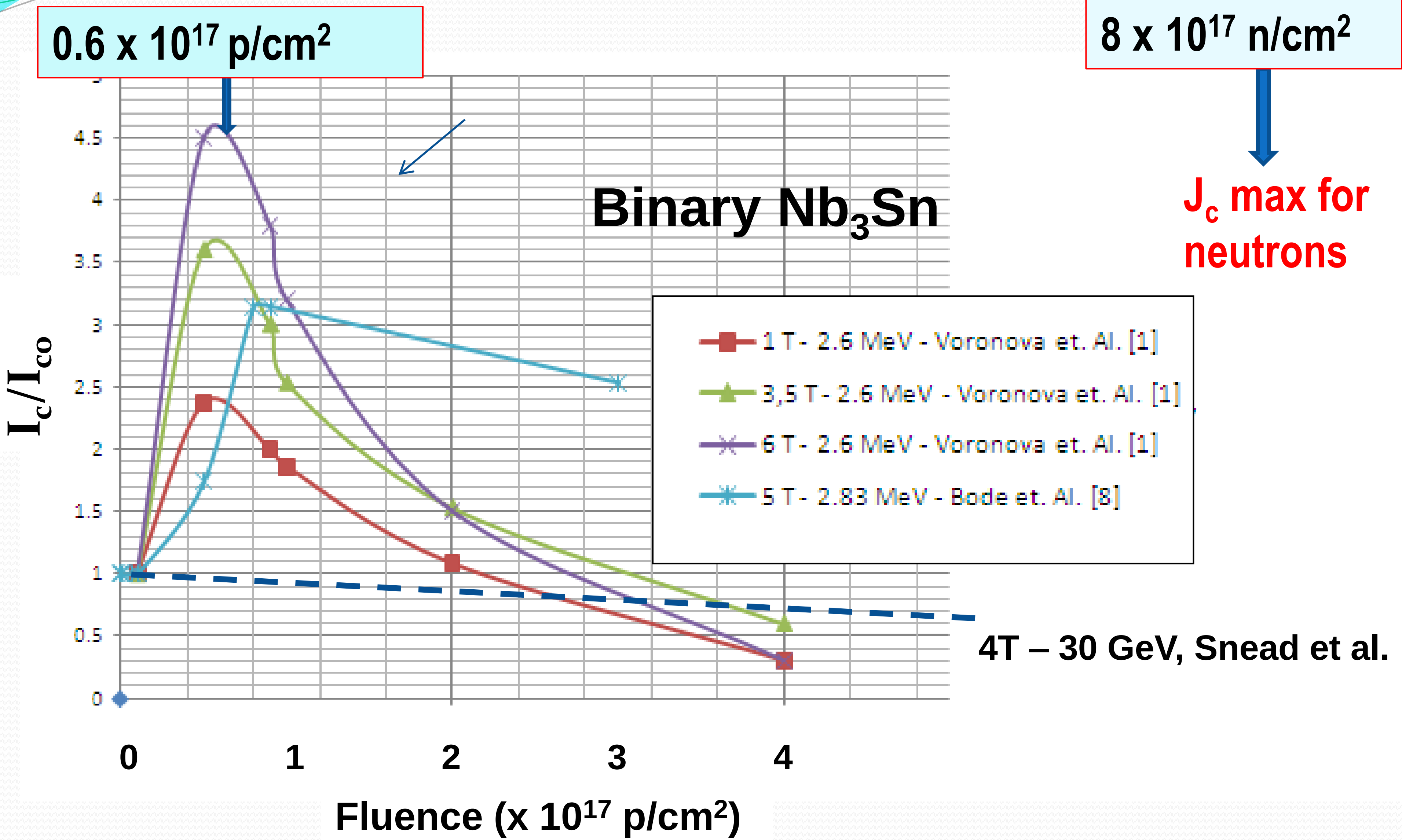
→

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

The effect of proton irradiation on Nb_3Sn (thin films)

Maximum of I_c after proton irradiation



Binary Nb_3Sn wires (and films):

Maximum of I_c: neutrons: **8×10^{17}** n/cm^2

protons: **6×10^{16}** p/cm^2

Ternary Nb_3Sn wires:

Maximum of I_c: neutrons: **2×10^{17}** n/cm^2

protons: **?**

Still necessary to know behavior after proton irradiation, in spite of 3% fluence with respect to neutrons !

Even more necessary: behavior under pion irradiation. Total damage of protons + pions becomes comparable to that caused by neutrons

Planned operations at CERN

L. Bottura
A. Ballarino
G. De Rijk

C. Scheuerlein
T. Spira PhD, will start January 2012
R. Flükiger

Calculations: Collaboration with F. Cerutti (CERN)
F. Broggi, Milano)

Planned operations at CERN - 1

Neutron irradiation, 1 MeV,
Collaboration with Atominstitut Vienna

Material: Nb_3Sn with additives (Internal Sn, PIT)
Ti
Ta (activation!)

Neutron irradiation of Nb_3Sn wires at 1 MeV and 14 MeV has already been performed 20 years ago

However, new investigation on high J_c wires with precisely determined neutron fluence at 300K (see the presentation of Harald Weber)

Goal of the collaboration with Atominstitut Vienna:

1: Confirm the systematic difference between binary and ternary alloyed Nb_3Sn wires after neutron irradiation

2: Establish the maximum of J_c vs. fluence; find out at which fluence the values of J_c and H_{c2}

2: Comparison between resistive and inductive J_c measurements on Internal Sn and PIT wires
T. Baumgartner et al., MT22 (H. Weber's talk)

Advantage: once the scaling is established, J_c can be determined on 3 mm wire pieces by magnetization.
This result will be used for measuring J_c in proton irradiated wires

Planned operations at CERN - 2

Proton Irradiation at various energies

Material: Nb_3Sn Internal Sn and PIT wires, with Ta and Ti additives

Collaborations with:

* Kurchatov Institute (Russia)	35 MeV	10^{18} p/cm^2
* Université catholique, Louvain la Neuve, Belgique	65 MeV	10^{17} p/cm^2
* CERN:		
IRRAD1	24 GeV	10^{17} p/cm^2
ISOLDE	1.4 GeV	10^{18} p/cm^2

First magnetization measurements of wires after decay: after mid 2012

Proton irradiations at Kurchatov Institute: Program

Duration :	24 months
Proton energy:	35 MeV
Temperature:	300K (+ heating due to proton impact)
Maximum fluence:	$1x\ 10^{18}$ p/cm^2
Tasks on irradiated wires:	J_c by magnetization measurements*)**) Electrical resistivity vs. T T_c TEM Lattice parameters
Tasks on irradiated bulks:	Long range atomic order parameter*)
Calculations:	dpa calculations for proton irradiation

*) Measurements will be performed at CERN

**) Transport J_c on proton irradiated wires: will be done later

Conclusions (superconductors)

We are still at the beginning of our investigations:

*Need for proton and pion irradiations of Nb_3Sn wires

*Are binary or ternary alloyed Nb_3Sn wires better?

*How has the volume expansion (1% at 10^{18} n/cm^2) to be taken into account?

*Irradiations at 4.2K still necessary (very small number, for comparison)

*Warming up and cooling cycles needed for reliability tests

*New devices for testing at 15 T needed

*New devices for mechanical testing needed

*Calculations needed: dpa, but also combined irradiations