RESMM’14, 12./15.May 2014

High energy proton irradiation of Nb_3Sn wires for LHC Upgrade quadrupoles

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Radiation damage in Nb_3Sn quadrupoles

Nb_3Sn quadrupoles in the LHC Upgrade accelerator at CERN will be submitted to high energy irradiation, produced by

Photons	Neutrons	Protons
Electrons		Pions

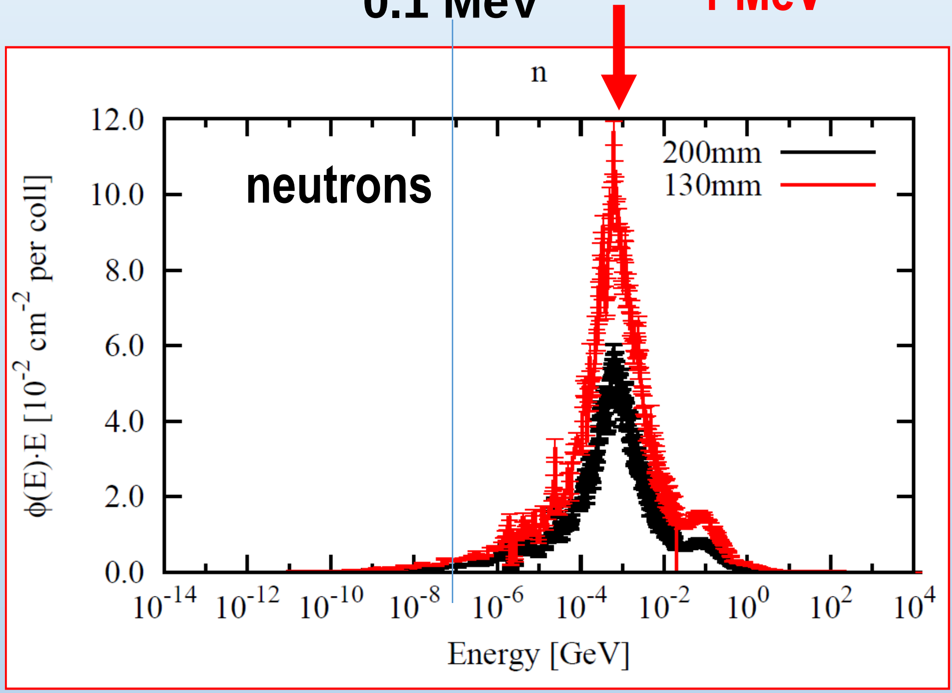
Integrated luminosity: 3000 fb^{-1} (Estimated lifetime: ~ 10 years)

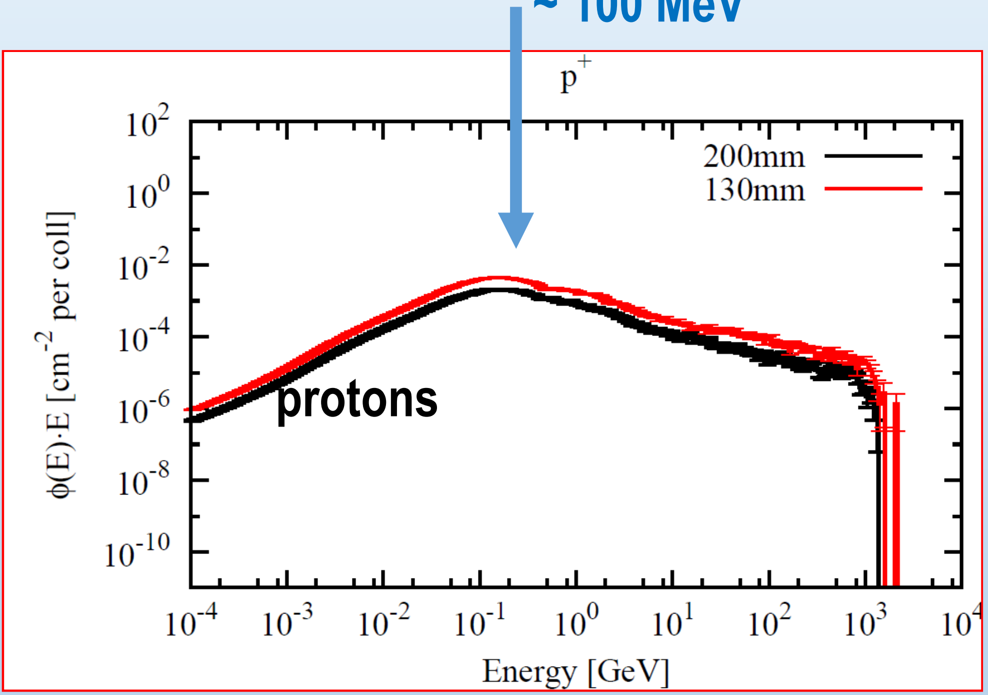
Major questions for the superconductor :

- Effects caused by neutrons and by charged particles on J_c
- Stability of magnetic field produced by the quadrupoles

→ Damage caused by protons (present work) is compared to that of neutrons on the same wires (collaboration with Atominstitut Vienna)

Particle spectra in the LHC Upgrade coils



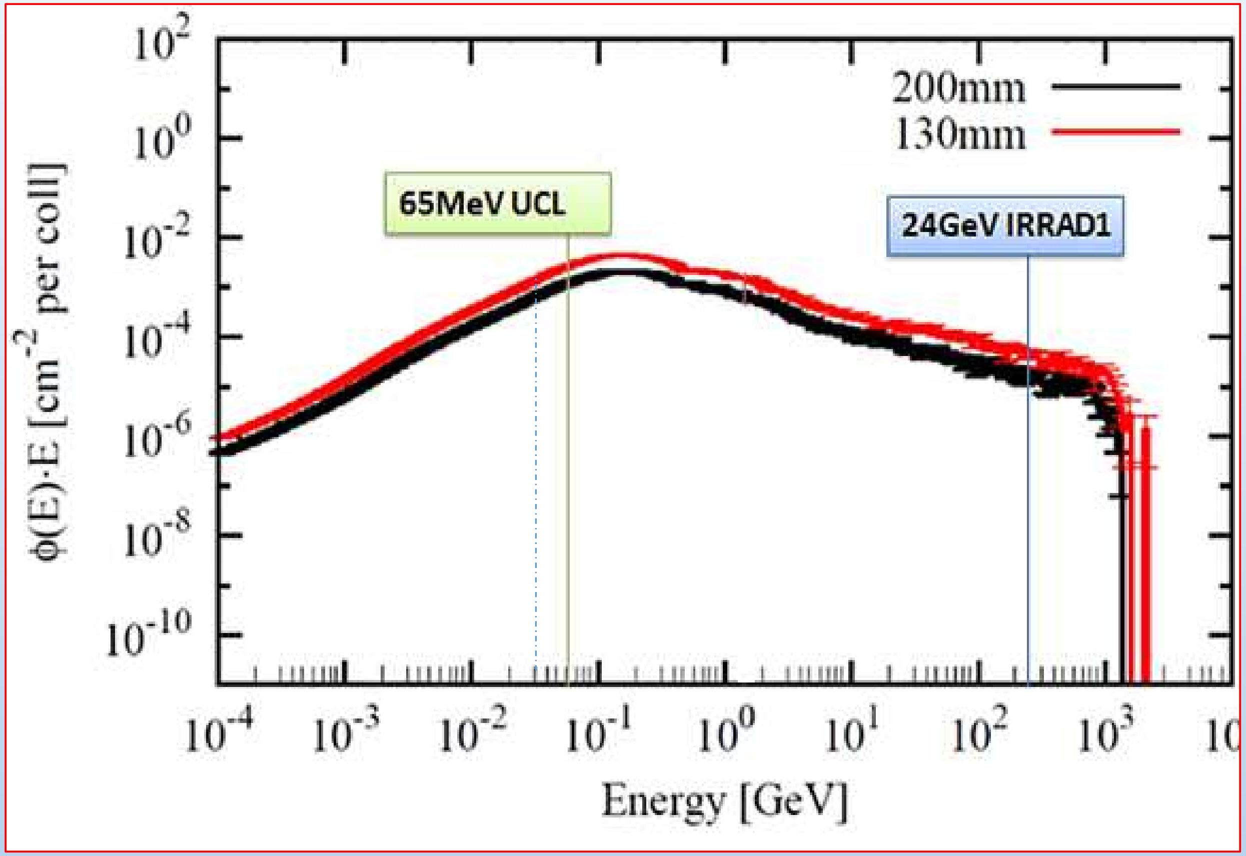


1.5×10^{21} n/m²

> 1×10^{20} p/m²

Calculations: F. Cerutti, CERN

Proton energies in the present work



Proton spectrum
in the Q2a Quadrupole
(LHC Upgrade)

Investigated alloyed Nb_3Sn wires:

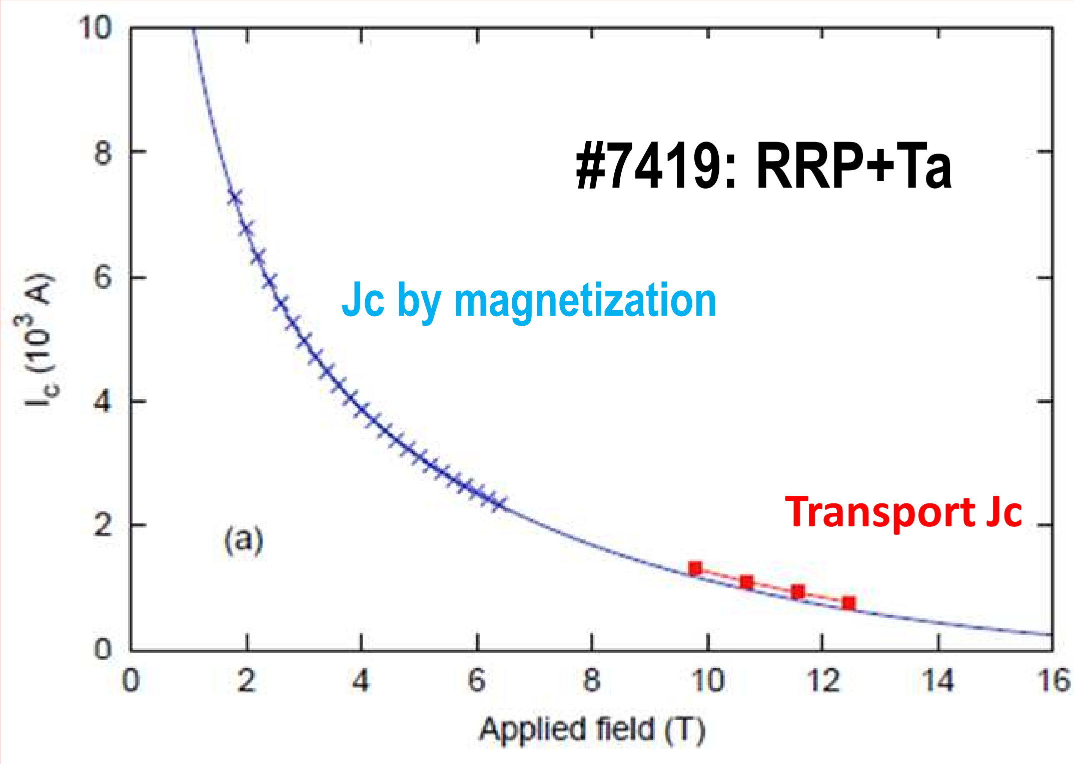
RRP + Ta	**Oxford**
RRP + Ti	**Oxford**
PIT + Ta	**Bruker**

Energies

24 GeV protons, IRRAD1 (CERN); ϕt ≤ ×10^{21} p/m^2

65 MeV protons, Louvain-la-Neuve (B), ϕt ≤ 1×10^{21} p/m^2

Scaling between J_c(magn) and J_c(transport)



.

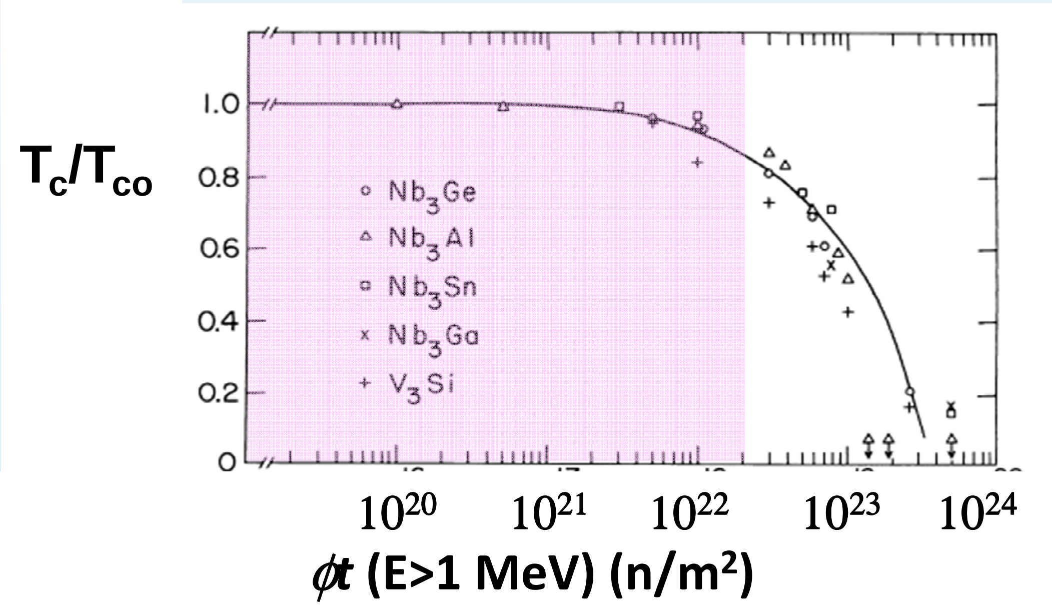
Satisfactory scaling: The study on irradiated RRP an PIT wires can be performed by means of magnetization measurements

T. Baumgartner, M. Eisterer, H.W. Weber, R. Flükiger, B. Bordini, L. Bottura, C. Scheuerlein, IEEE Trans. Appl. Supercond., vol. 22, 6000604, 2012.

2. High energy irradiation damage

Known data and their interpretation

T_c of A15 compounds after neutron irradiation



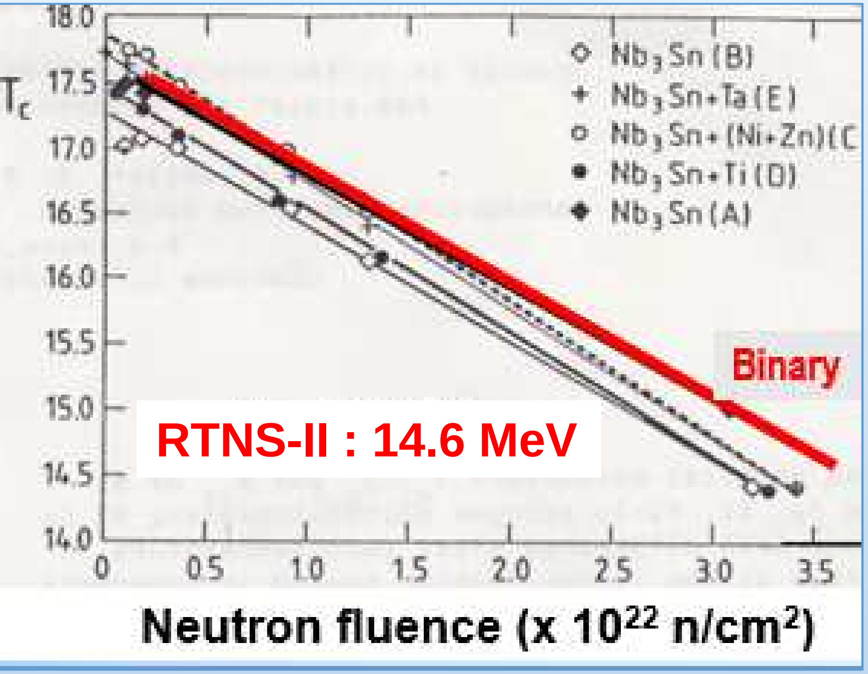
Sweedler et al. 1983:

Variation of T_c with neutron fluence
Attributed to a lowering of the Bragg
Williams long-range atomic order parame

However: Two different regions, below and above ~ 2 x 10^{22} n/m^2 !
Order parameter alone cannot explain both behaviors

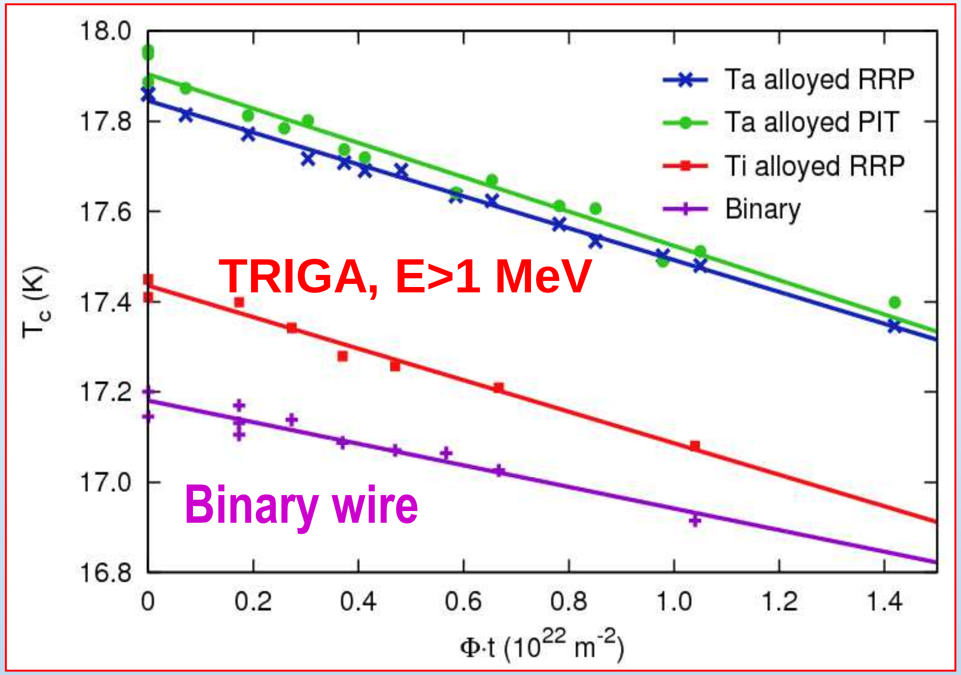
New interpretation of the Sweedler rule in the fluence region ~ 2 x 10^{22} n/m^2:
The fluence region of both ITER and LHC Upgrade is included in this low fluence ran

Linearity of T_c vs. ϕt < $2x10^{22}$ n/m^2



Binary

RTNS-II : 14.6 MeV



TRIGA, E>1 MeV

Binary wire

Weiss, R. Flükiger, W. Maurer, P.A. Hahn, M.W. Guinan,
EE Trans. Magn., MAG-23,976(1987) et al. 1987

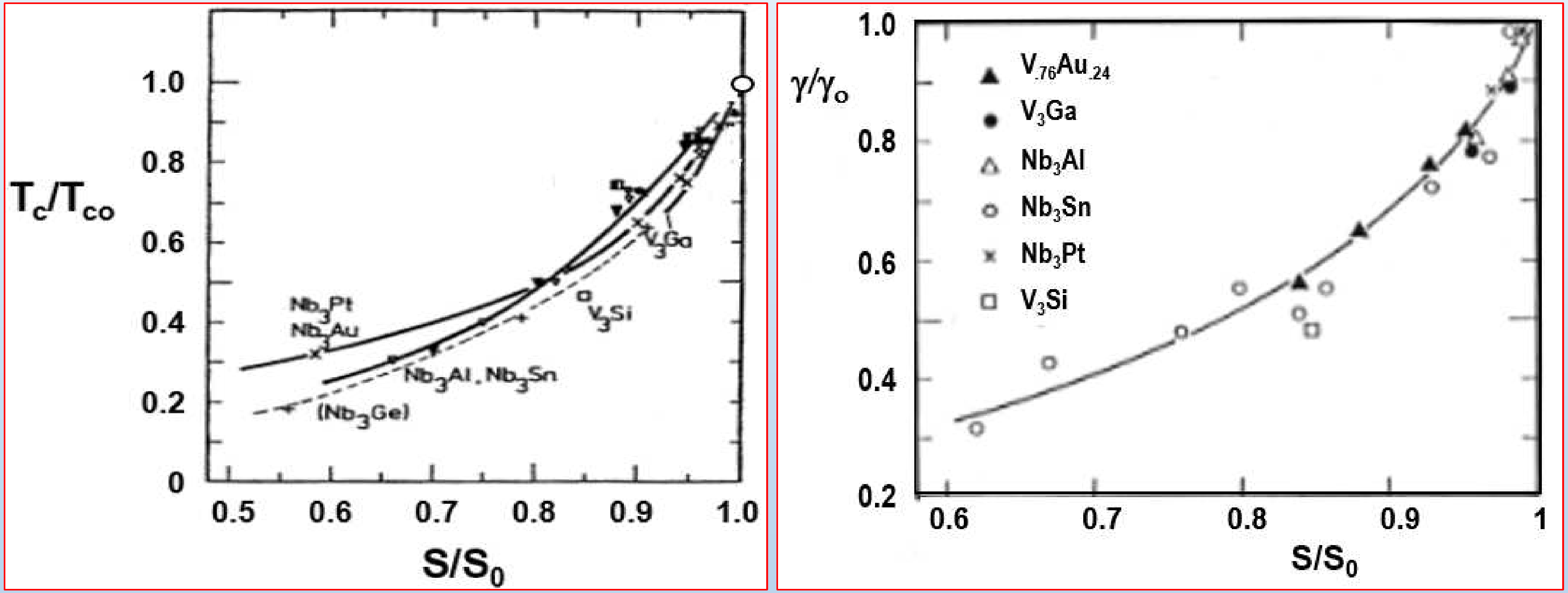
R. Flükiger, T. Baumgartner, M. Eisterer, H.W. Weber, T. Spina, C.
Scheuerlein, C. Senatore, A. Ballarino, L. Bottura, *Trans. App. Sup.* 2

inearity of T_c vs. ϕt is observed up to ~ 2 x 10^{22} n/cm^2 : Aronin rule not fulfilled

maller slope dT_c/dϕt for binary Nb_3Sn wire: Difference attributed to different damage energ

Correlation T_c vs. order parameter S in A15 compounds

S: Bragg-Williams atomic order parameter



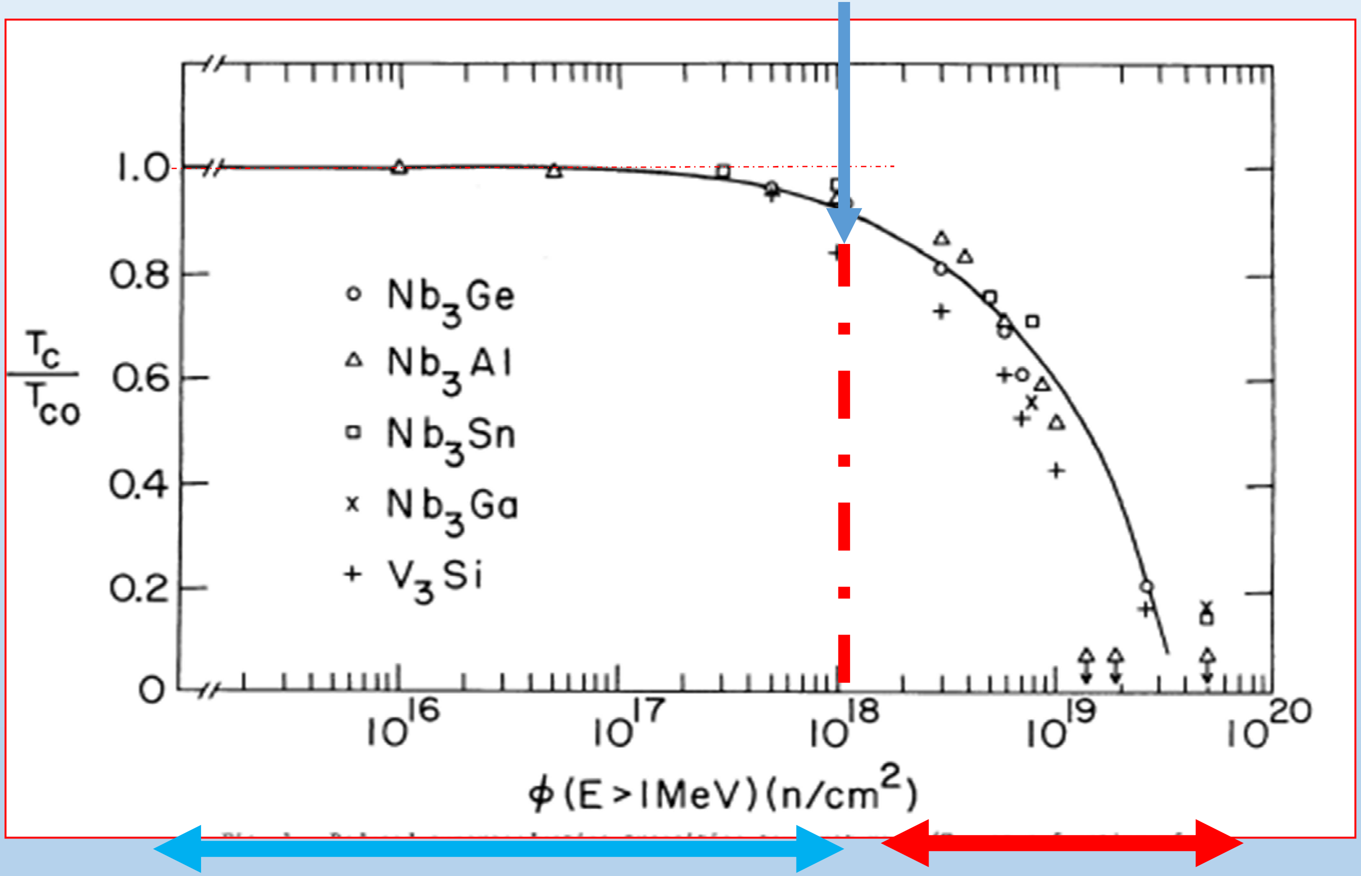
Data collection from irradiation and quenching: R. Flükiger, KfK 4204 Report, Karlsruhe, 1987

The variation of T_c/T_{co} : empirical correlation $T_c/T_{co} \sim e^{-k'(1-S/So)}$

Reflects e variation of the electronic density of states ($\gamma/\gamma_o \sim e^{-k'(1-S/So)}$)

Empirical “Sweedler curve” T_c vs. ϕt for neutrons

Maximum of J_c/J_{co} and of B_{c2}



Linear

Double exponential

edler, 1980

Question:

is T_c/T_{c0} vs. Φt the same for protons (except Bragg peak region?

1) $T_c/T_{co} \sim e^{-k'(1-S/So)}$

2) $S \sim e^{-\phi t}$ (Aronin)

Is atomic ordering effective in ITER?

Fluence region below 2 x 10^{22} n/m^2 is the region of operation for ITER

Below 2 x 10^{22} n/m^2 : the Aronin rule does not hold (linear decrease of T_c vs. fluence)

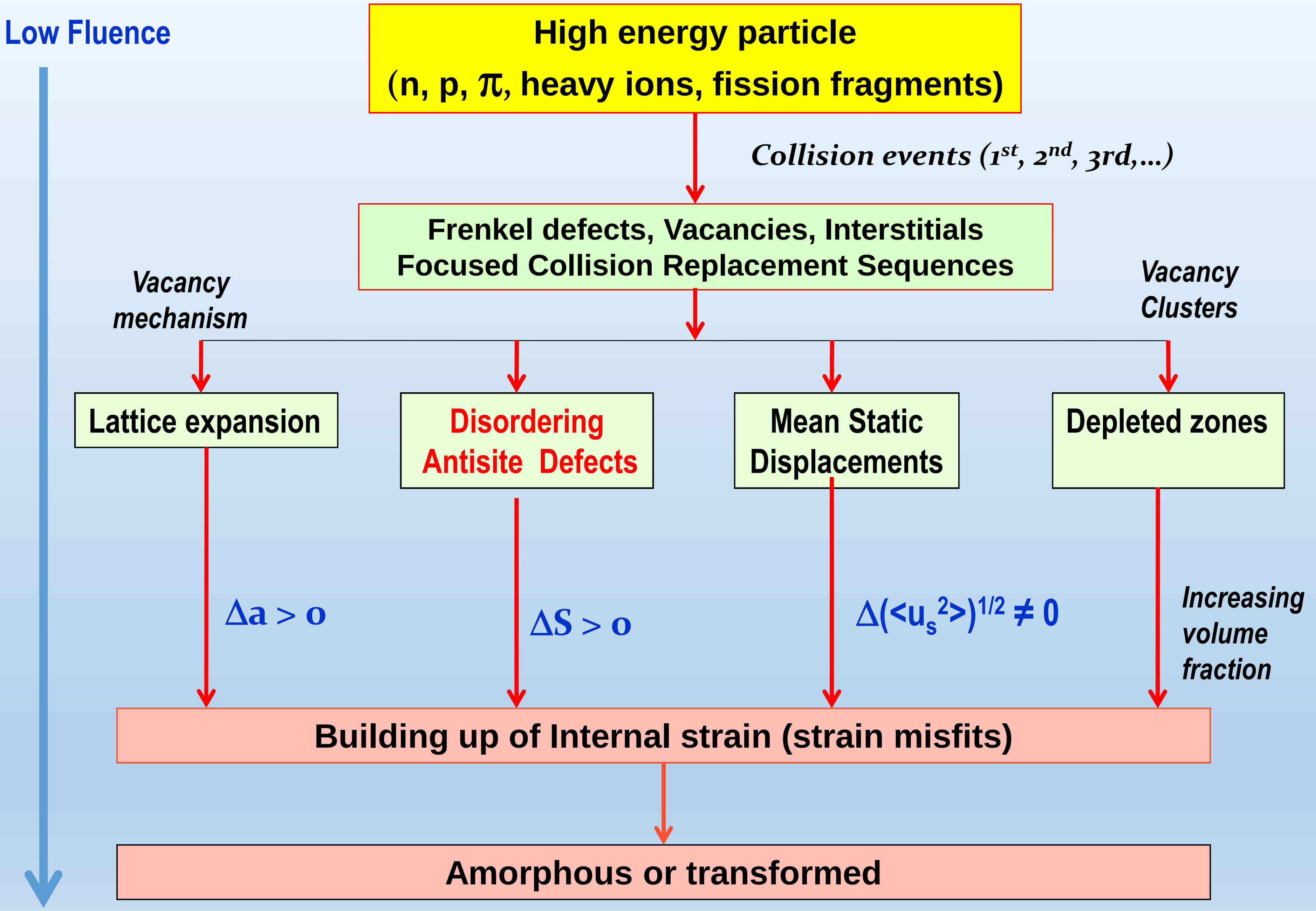
→ the decrease of T_c cannot be explained by a change of the Bragg-Williams atomic order parameter S

→ the variation of J_c is uniquely due to radiation induced point pinning (APC)

Note: the expected change of order parameter in this region is of the order of 1 - 2 %, which below the precision of the order parameter measurement.
Recent precise determination (PhD work at CERN, T. Spina): S = 0.97 ± 0.03 for Nb_3Sn.

Other observed changes for this low fluence range mechanism:

- Lattice expansion
- Mean static displacements around the equilibrium position
- Mechanical stresses due to presence of defect clusters?



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, KfK Report 4204, 1989

How is atomic ordering affecting the s.c. properties of LHC Upgrade ?

eutrons : negligible up to 2 x 10^{22} n/cm^2: Analogy to ITER

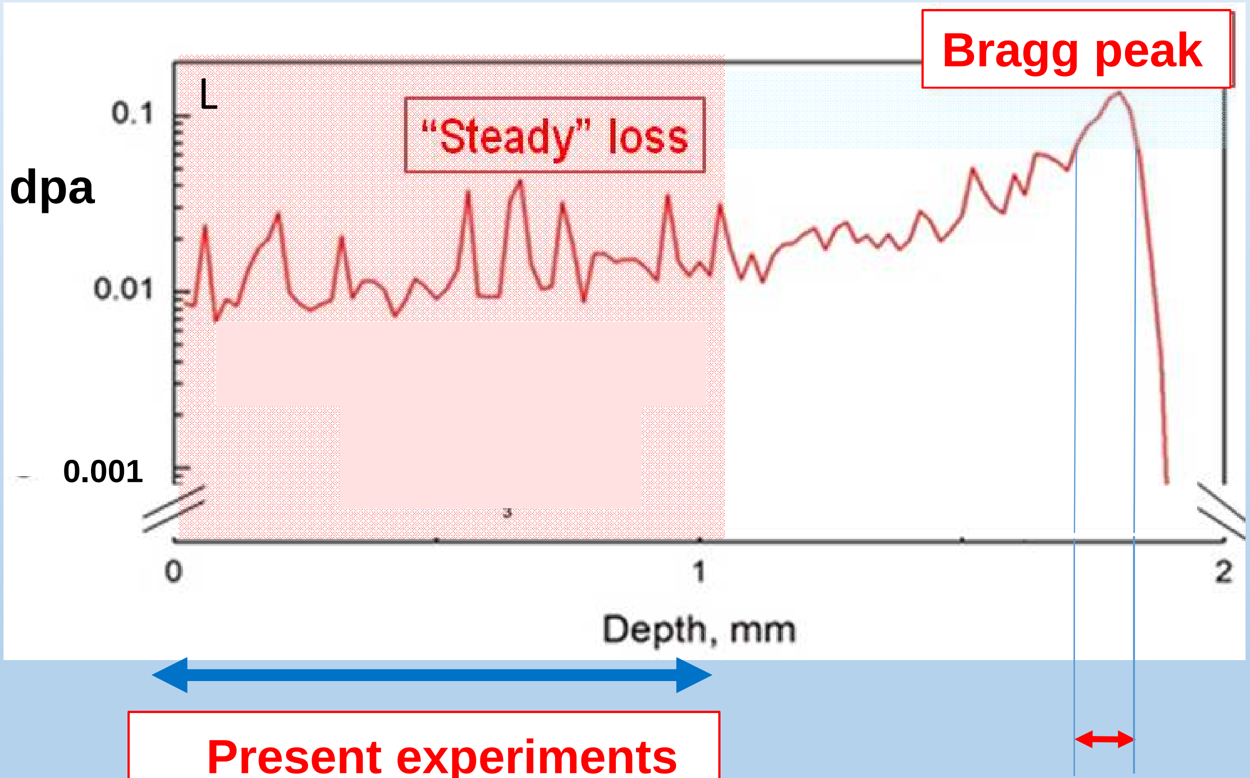
rotons, pions (charged particles): 1) Steady losses: negligible ordering effects
2) Bragg peak: strong ordering effects expe

ectrons, Gammas: Much smaller effects than neutrons, proto

3. Effect of high energy protons on J_c of Nb_3Sn wires

Visualization of Artificial Pinning effects in Nb_3Sn wires

Penetration of high energy protons in Nb_3Sn



Present experiments
Wire diameter Φ = 1 mm

DPA calculation for 30 MeV
protons and ϕt = 1 x 10^{22} p/
(A. Ryazanov, Kurchatov) 2013, unpubli

LHC Upgrade: most protons
pions have their Bragg peak
inside the quadrupoles !
Strong ordering effects expe

Presently under work with Kurchatov I

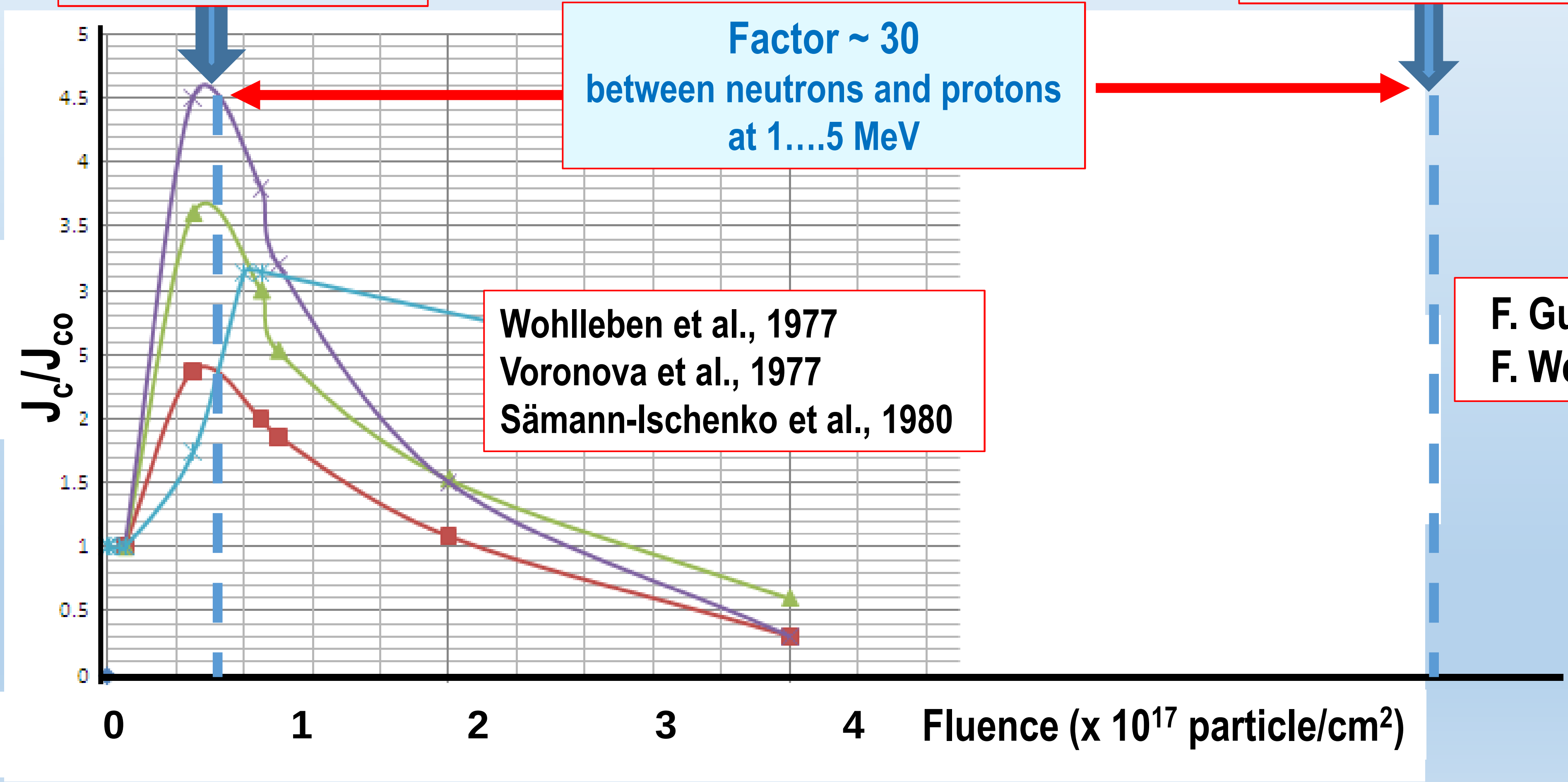
$I_{c(max)}$ for binary Nb_3Sn after n and p irradiation

$J_{c(max)}$ for Protons

0.6×10^{21} p/m^2

$J_{c(max)}$ for Neutrons

~ 2×10^{22} n/m^2



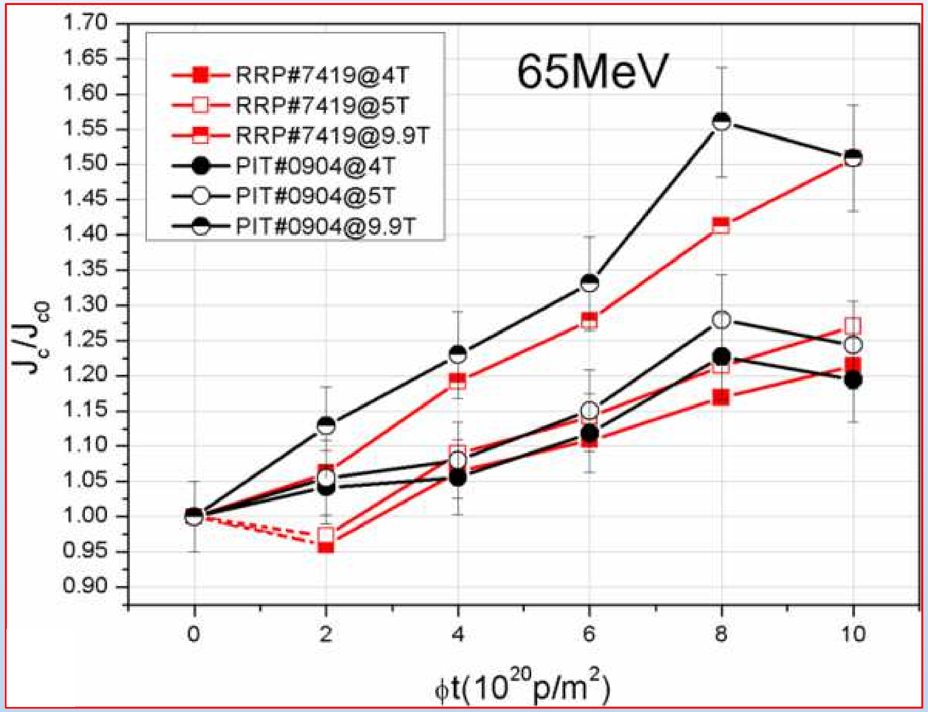
Factor ~ 30
between neutrons and protons
at 1….5 MeV

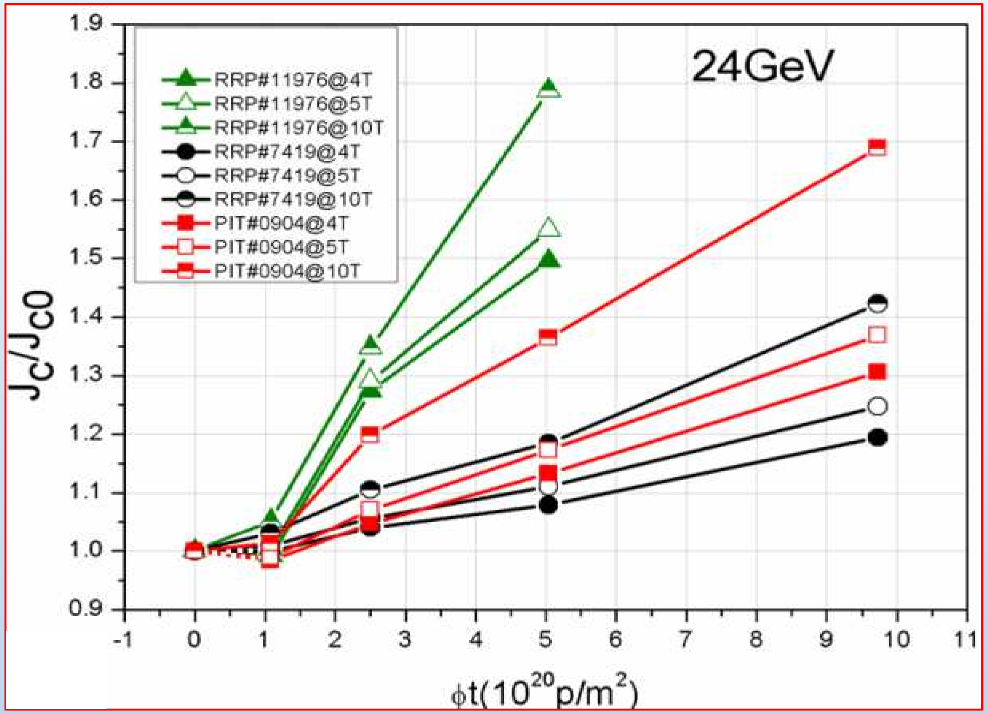
Wohlleben et al., 1977
Voronova et al., 1977
Sämann-Ischenko et al., 1980

F. Guinan et a
F. Weiss et al.

Steady loss zone

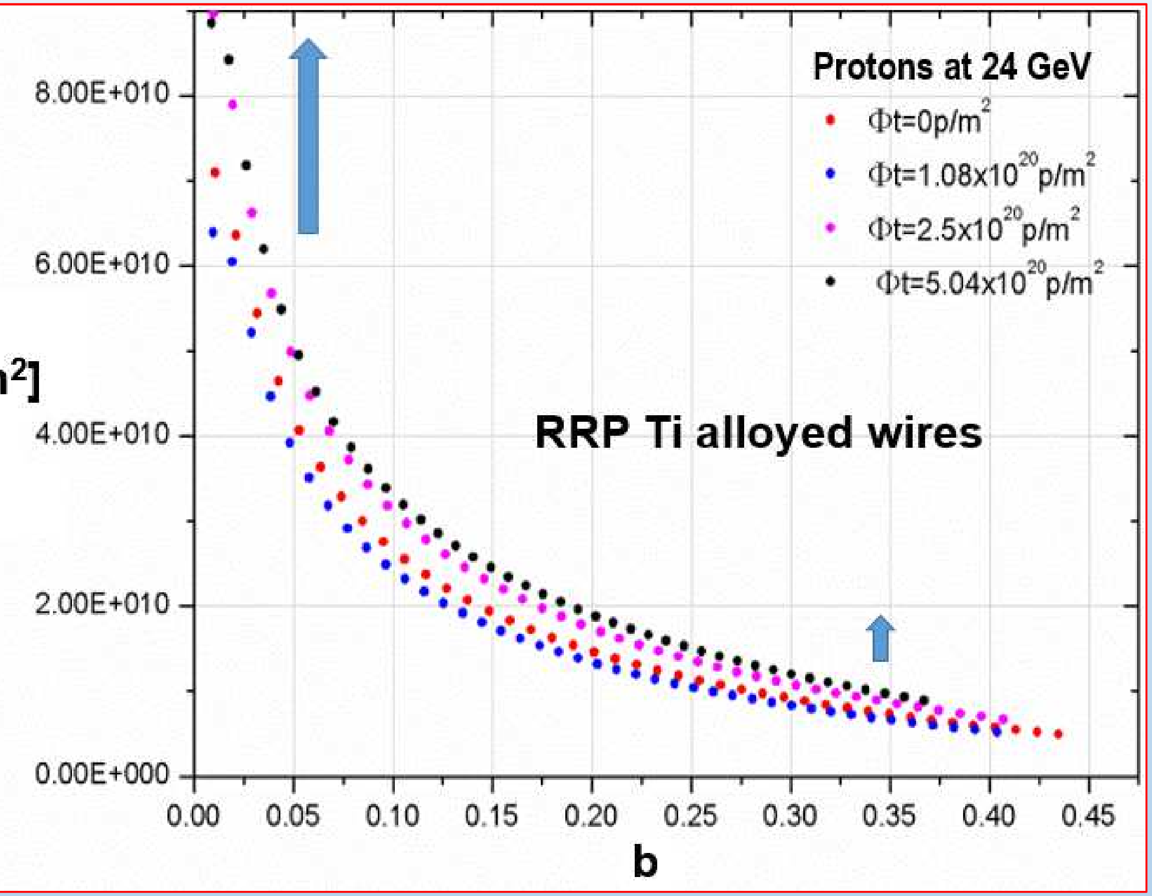
Enhancement of J_c in Nb_3Sn wires after proton irradiation





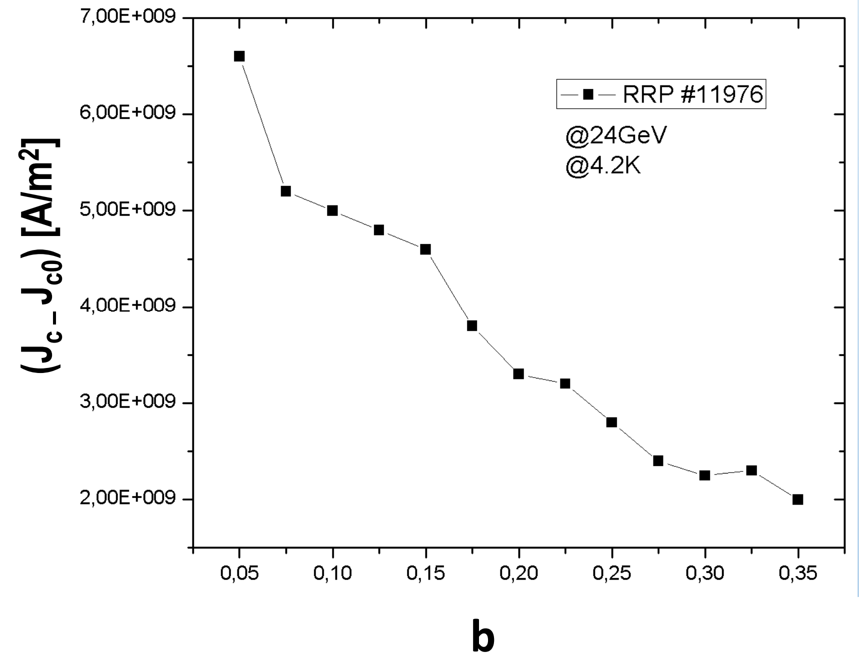
Up to 1 x 10^{21} p/m^2, no clear maximum of J_c can be recognized (for 65 MeV, more data are necessary)

Artificial pinning: J_c enhancement at low magnetic fields



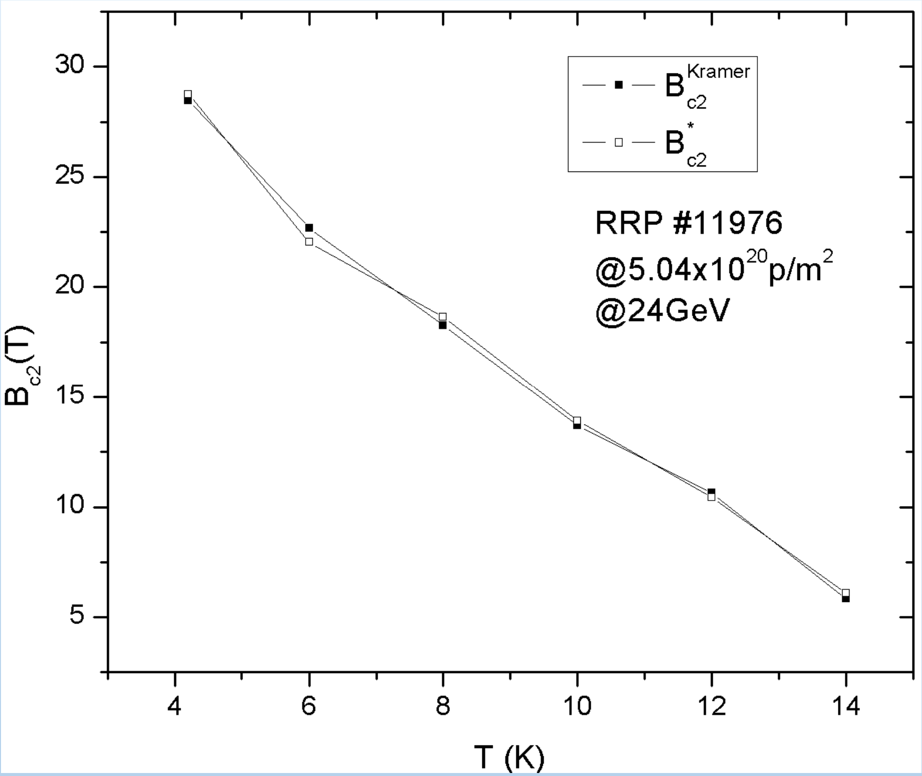
Regardless of B_{c2}:

- **Main enhancement of J_c : at low fields**
- **Smaller increase of J_c at high fields**

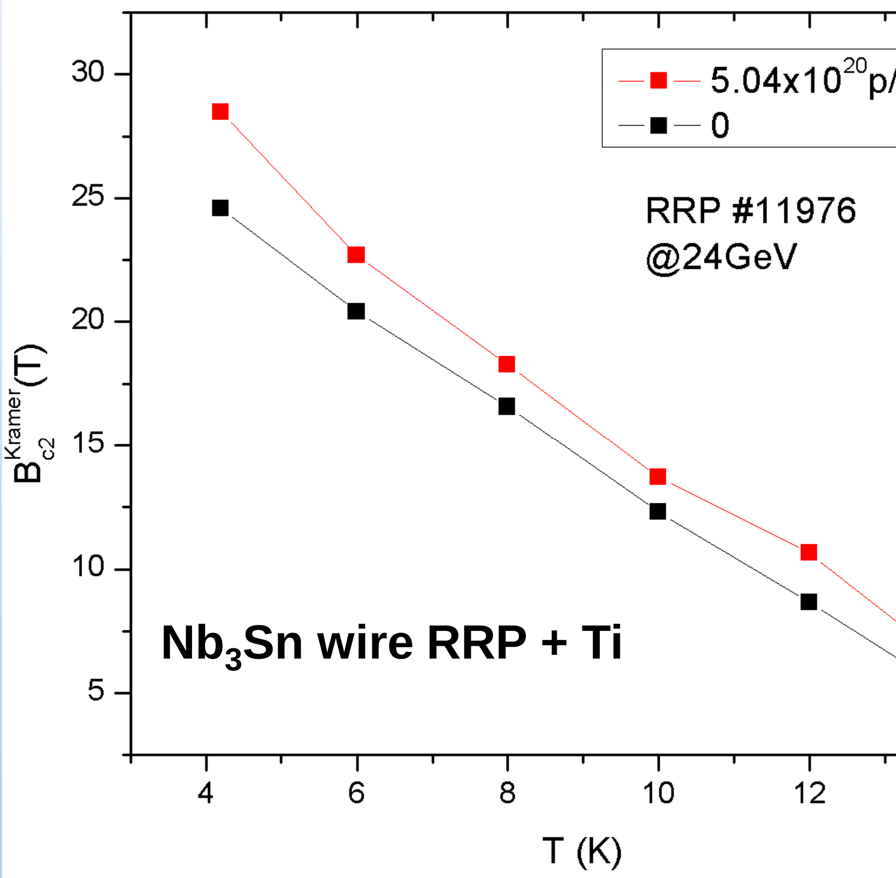


Artificial pinning by the radiation induced defects

Variation of B_{c2} under proton irradiation



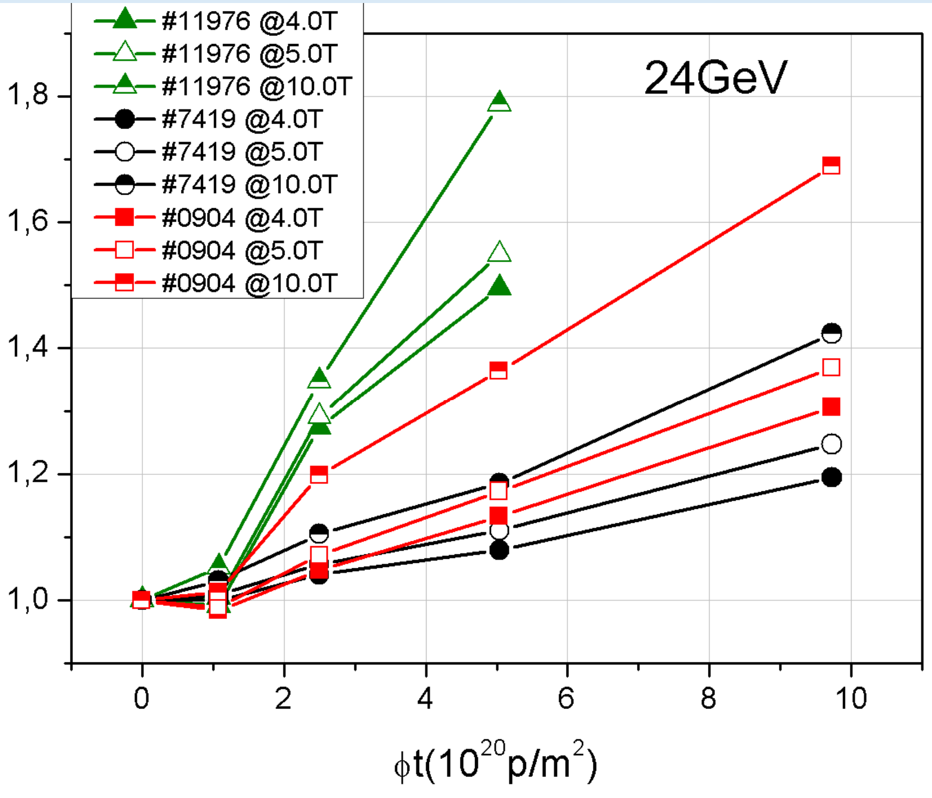
and B_{c2}^{Kramer} are very similar, before and after diation

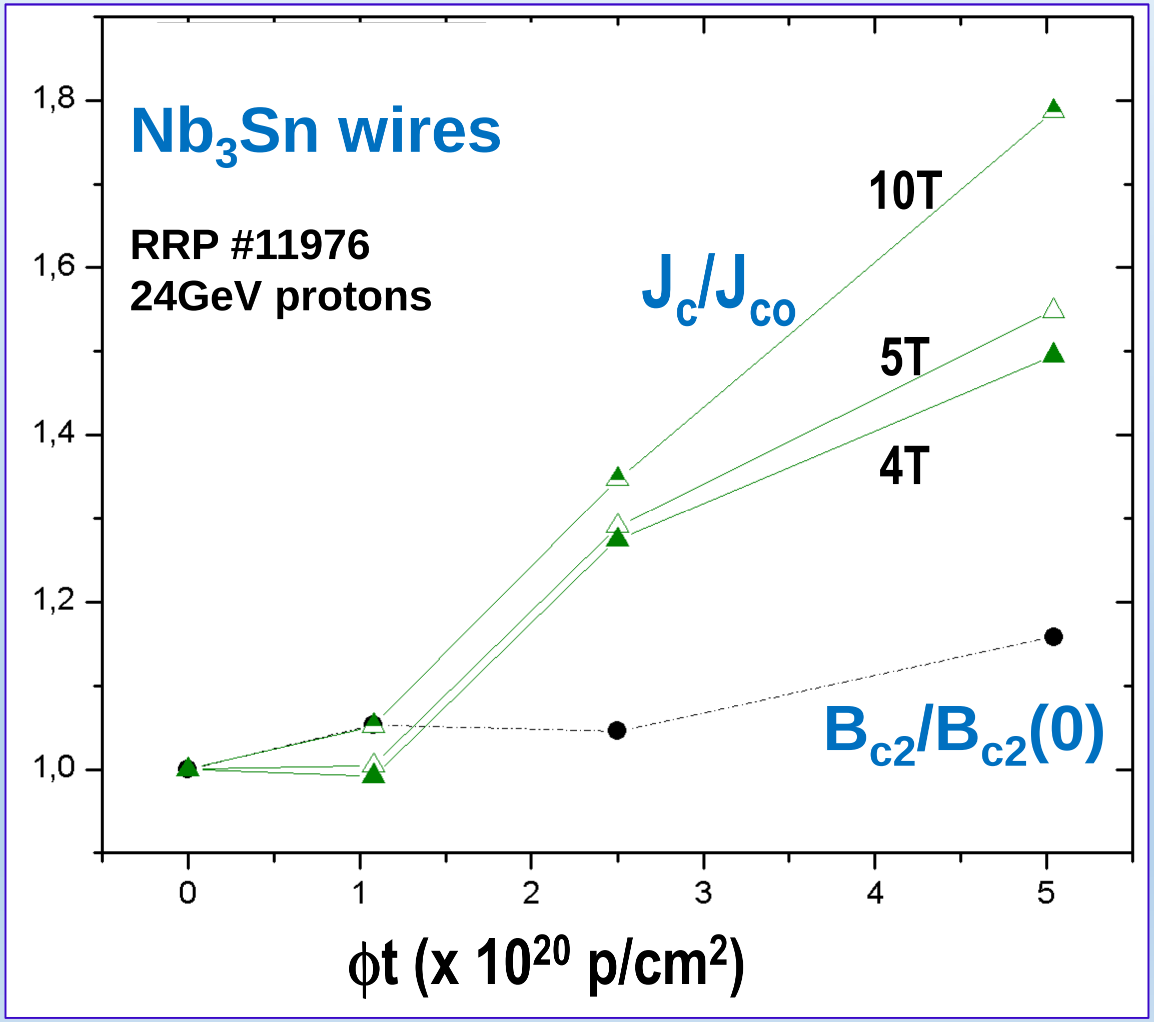


Enhancement of B_{c2} with irradiatio

Effect of proton fluence on J_c and B_{c2}

Nb_3Sn wire RRP + Ti





Model for the pinning force after irradiation

- **Observation of «defect clusters»: new, nanosize pinning centers (Pande 1978)**
- **The variation ΔB_{c2} is not sufficient for explaining the increase of J_c (Brown, 1976; Colucci 1977, Fähnle 1977)**
- **Two pinning mechanisms: $F_p = F_p(\text{grains}) + F_p(\text{defect clusters})$ (H. Küpfer et al., 1979)**
- **Quantitative two-mechanism model (neutrons: T. Baumgartner, ATI, Vienna, Austria, PhD Thesis 2012) protons: T. Spina, et al., EUCAS 2013, Genoa, Italy**

$$f(b) = \alpha * b^{p_1}(1-b)^{q_1} + \beta * b^{p_2}(1-b)^{q_2}$$

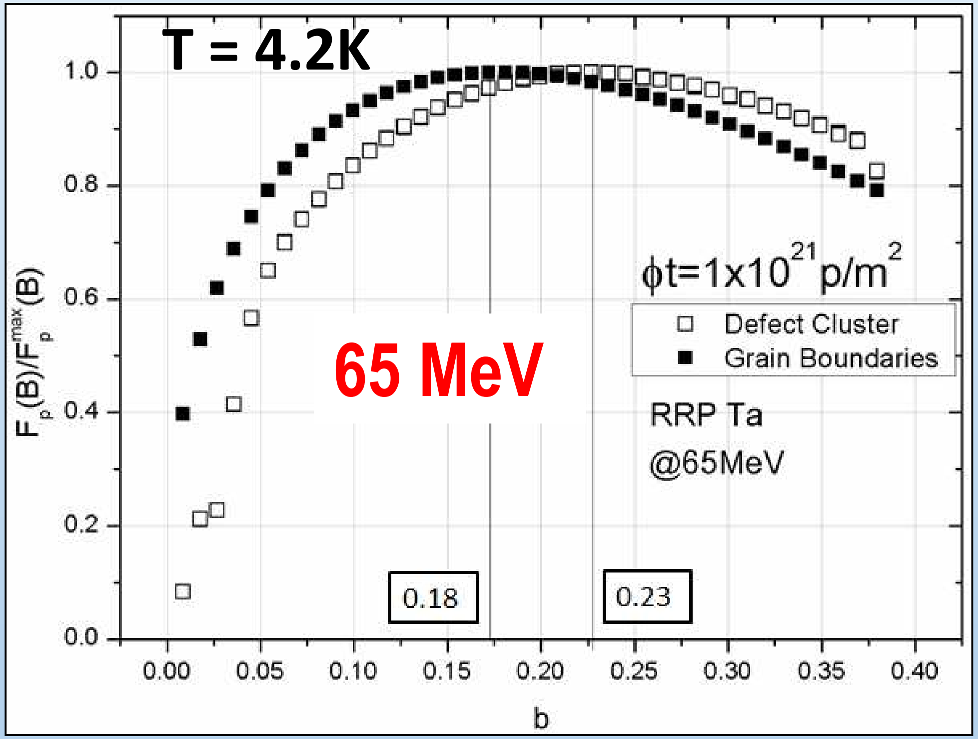
Grain boundary pinning

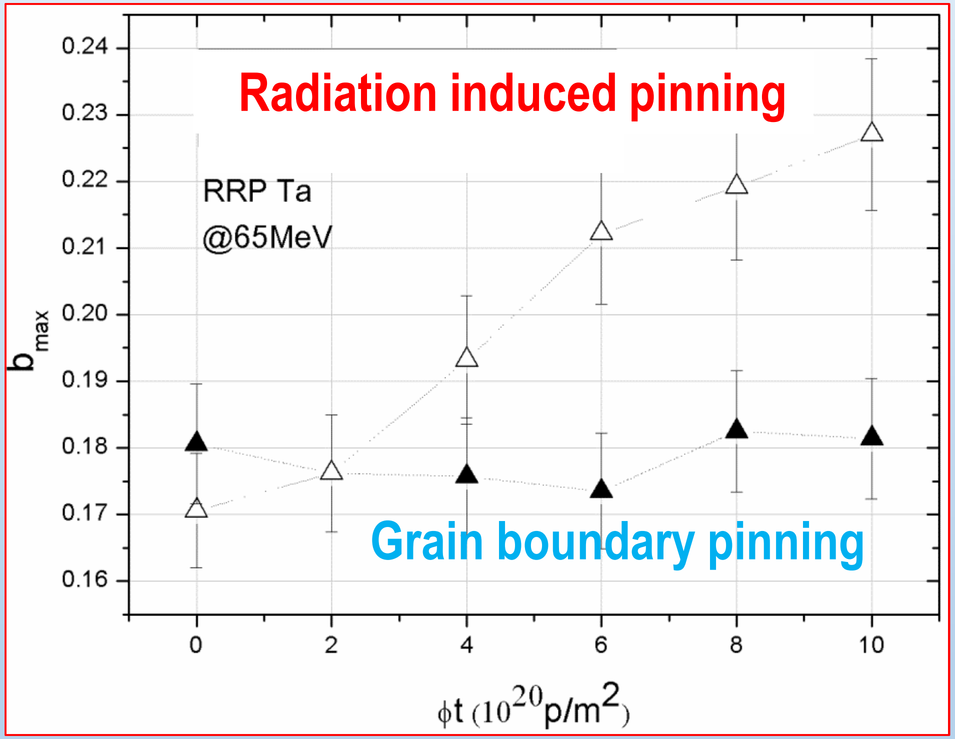
Point defect pinning (Defect clusters)

Pinning force in proton irradiated Nb_3Sn wires

$$f(b) = \alpha * b^{p_1}(1-b)^{q_1} + \beta * b^{p_2}(1-b)^{q_2}$$

p_1, q_1 equal to the values p and q found for non irradiated wires (b, p_2, q_2: fit parameters)



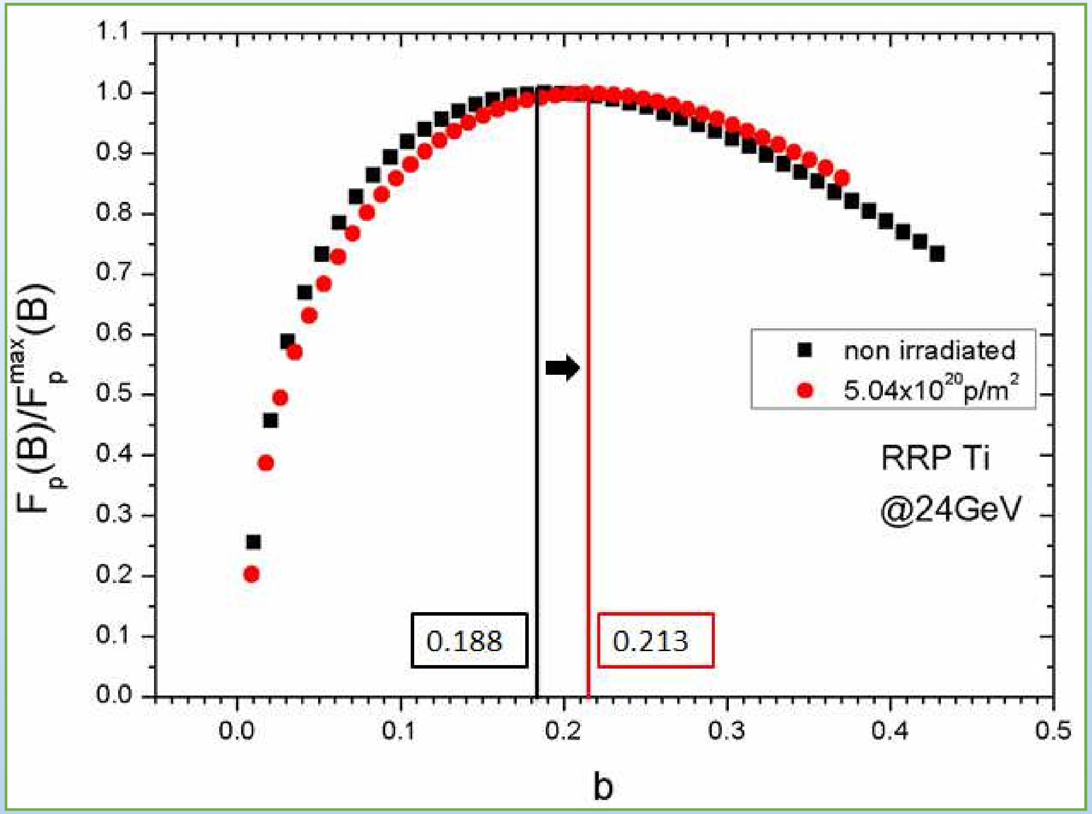


- Shift of F_p(max) towards higher fluences
- Peak due to grain boundaries doesn't change after irradiation
- Enhanced pinning uniquely due to the radiation induced effects

T. Spina et al.,
EUCAS 2013

Pinning force after irradiation at various energies

E = 24 GeV

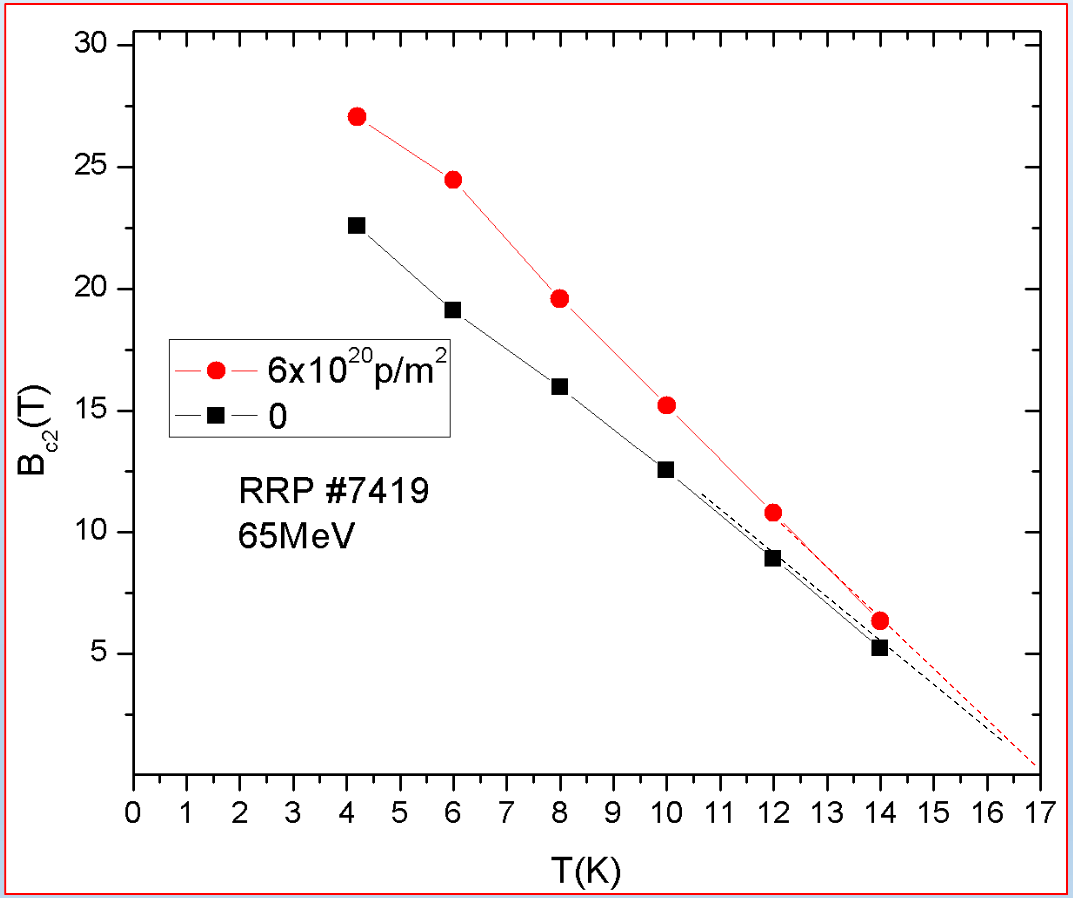


The two component pinning model is valid for all measured RRP and PIT wires, regardless of the proton energy and of the fluence

Comparison between proton and neutron irradiation

Enhancement of B_{c2} after proton irradiation

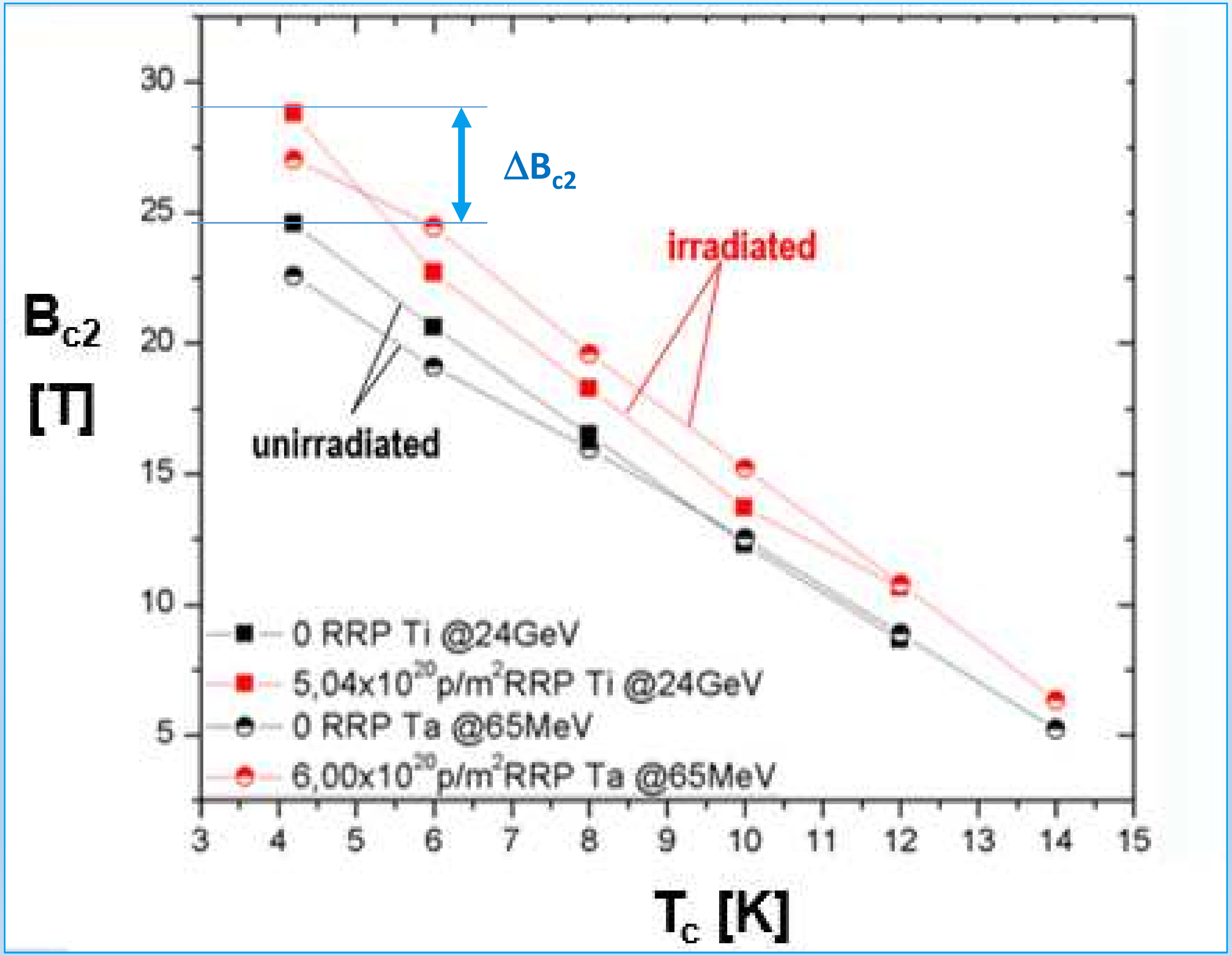
RRP Ta alloyed @65MeV



Kramer extrapolation from data at > 10T:

Precise B_{c2}*: only for T > 12K

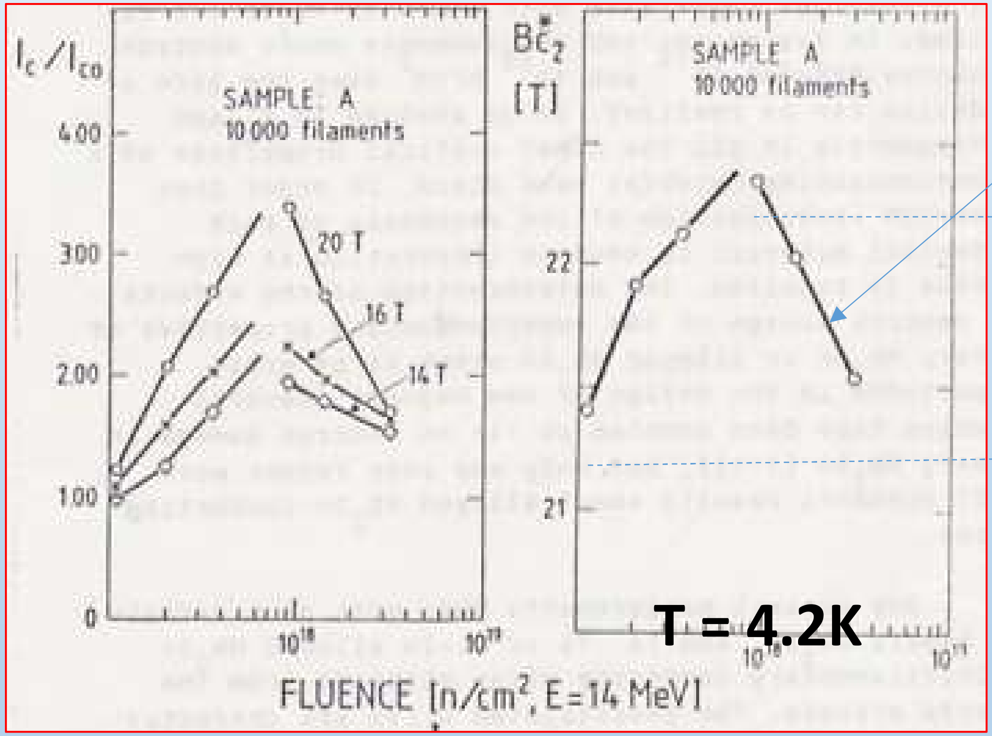
B_{c2} at various temperatures, after proton irradiation



ΔB_{c2} ~ 3.5 T (1

Comparison with ΔB_{c2} after neutron irradiation

Analysis of the measurements at T > 4.2K



Bc2* determined by Kramer extrapolation from measurements up to 21 T in Grenoble

ΔB_{c2} ~ 1 T (4.5 %)

F. Weiss et al., 1987: 4.5 % on Bronze Route wires
T. Baumgartner et al., 2012: 3 % on RRP and PIT wires

The variation of B_{c2} with proton irradiation

Present proton irradiation data at 4.2K	ΔB_{c2} ~ 14 - 20 % (ΔT_c ~ 0.1 K)

Neutrons:

F. Weiss et al, 1987	ΔB_{c2} ~ 4.5 %
T. Baumgartner et al., 2013	ΔB_{c2} ~ 3 % (ΔT_c ~ 0.5 K)

ΔB_{c2} markedly higher than after neutron irradiation.

The same tendency is observed in irradiated V_3Si (S.A. Alterowitz et al., 1981, D.E. Cox et al., 1978)

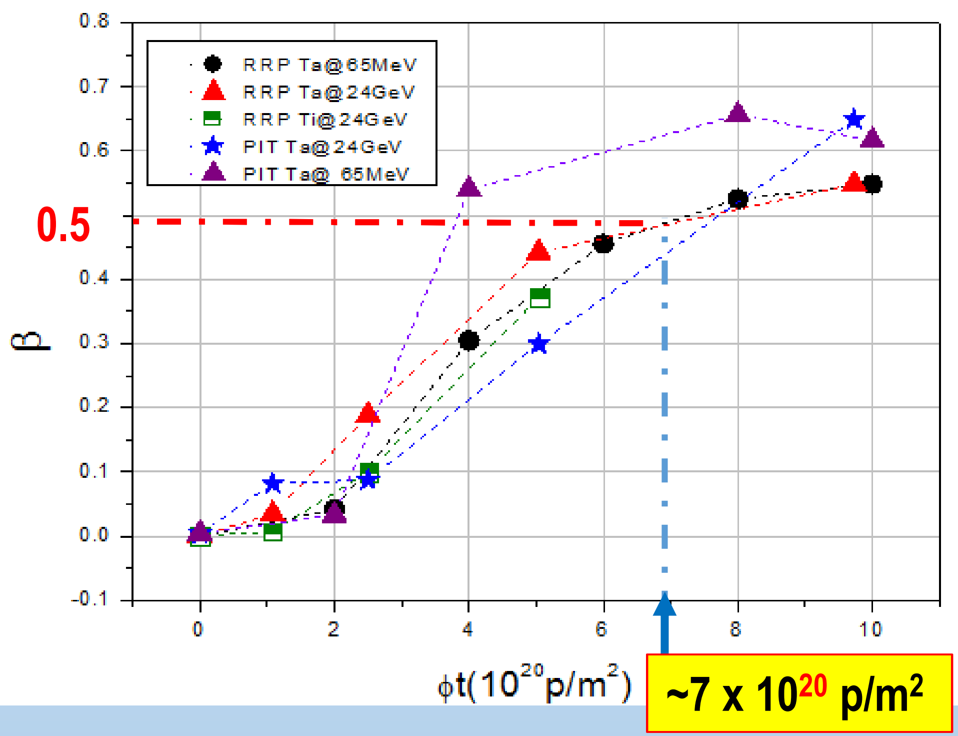
Reason for this difference between neutron and proton irradiation?

- It is not an ordering effect
- Possibly different mean static displacement between neutral and charged particles (?)

neutrons: V_3Si single crystals, : $\Delta\langle u^2\rangle$ ~0.001 A^2 (Cox et al., 1978)
protons: no data; should be studied

Comparison between the damage caused by neutrons and by protons

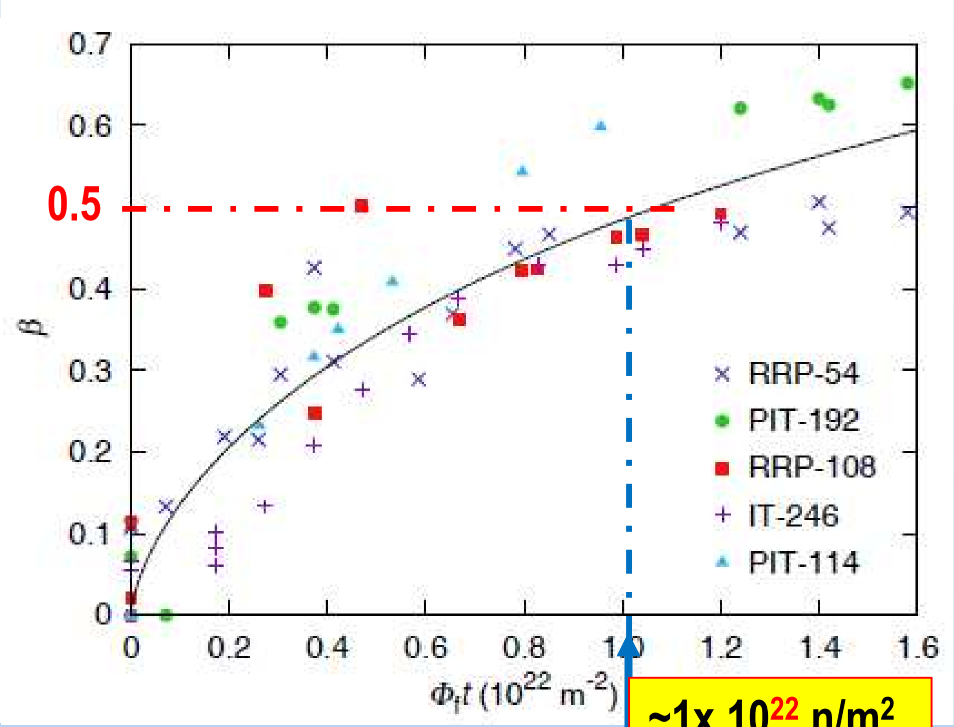
Proton irradiation



~7 x 10^{20} p/m^2

Neutron irradiation

(*T. Baumgartner, PhD thesis, to be published*)



~1x 10^{22} n/m^2

Comparison: fluences at the same β value: for example $\beta = 0.5$.

E > 60 MeV: Neutron fluence ~15 X proton fluence!

Lower energies: this factor increases

Bragg peak experiments

e irradiation will be performed on Nb_3Sn platelets of 0.09 to 0.15 mm thickness.

nce the grain boundary pinning does not change with irradiation, experiments will udy the effects of the radiation induced part only. They will be carried out at the Kurchatov stitute, Moscow

particular importance, as a function of fluence (at 10 and 20 MeV):

Decrease of atomic order parameter S (correlation between S and dpa ?)

Decrease of T_c

Enhancement of lattice parameter a

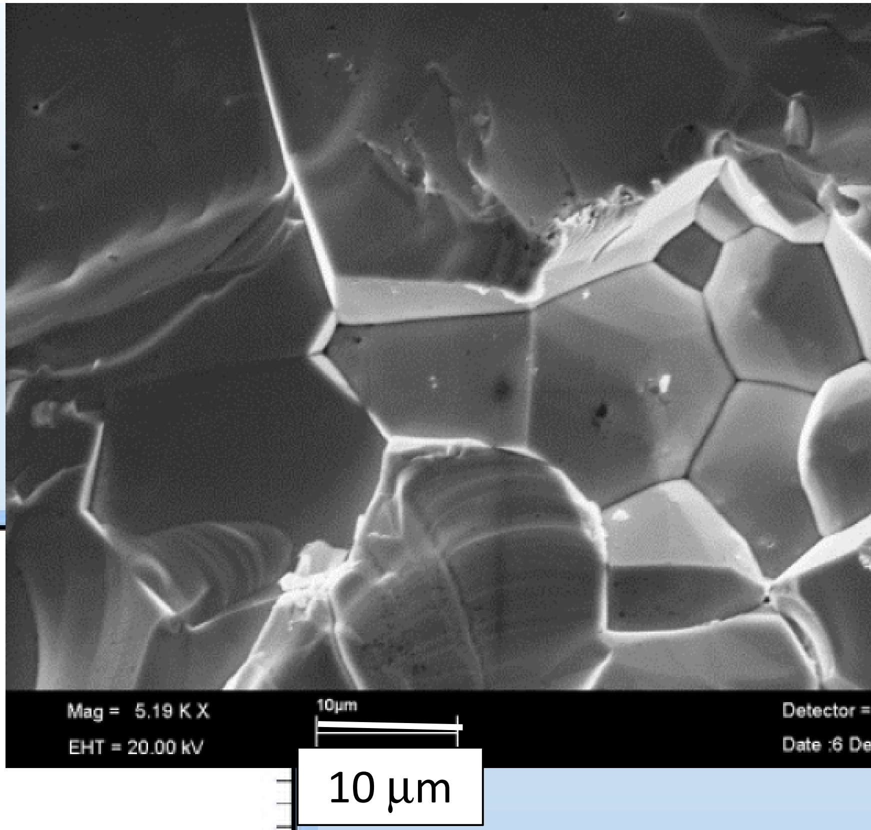
Development of the defect cluster size by TEM

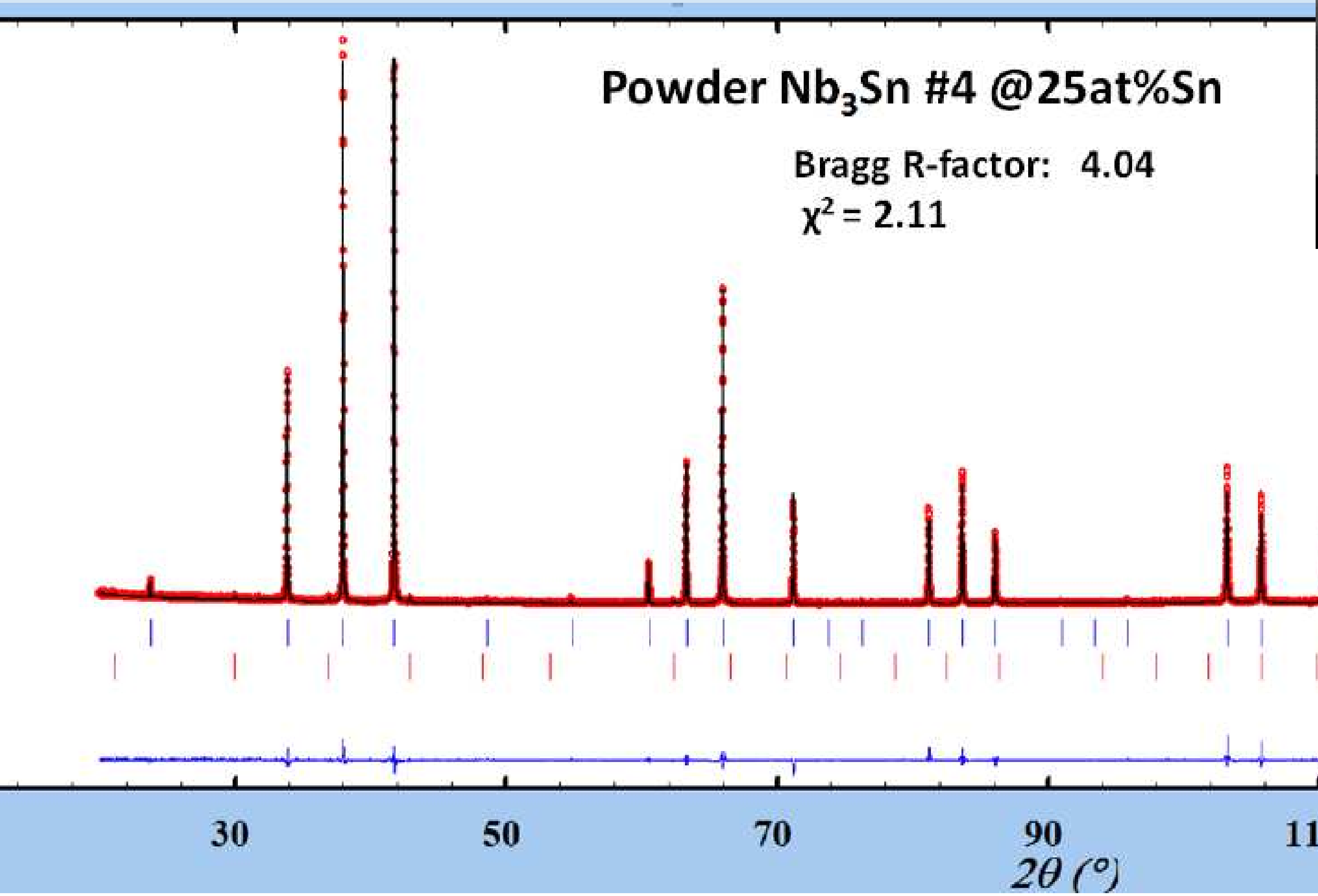
The variation of J_c

(the ratio of point pinning force with respect to grain boundary pinning force can be approximated by using the facto β defined above.

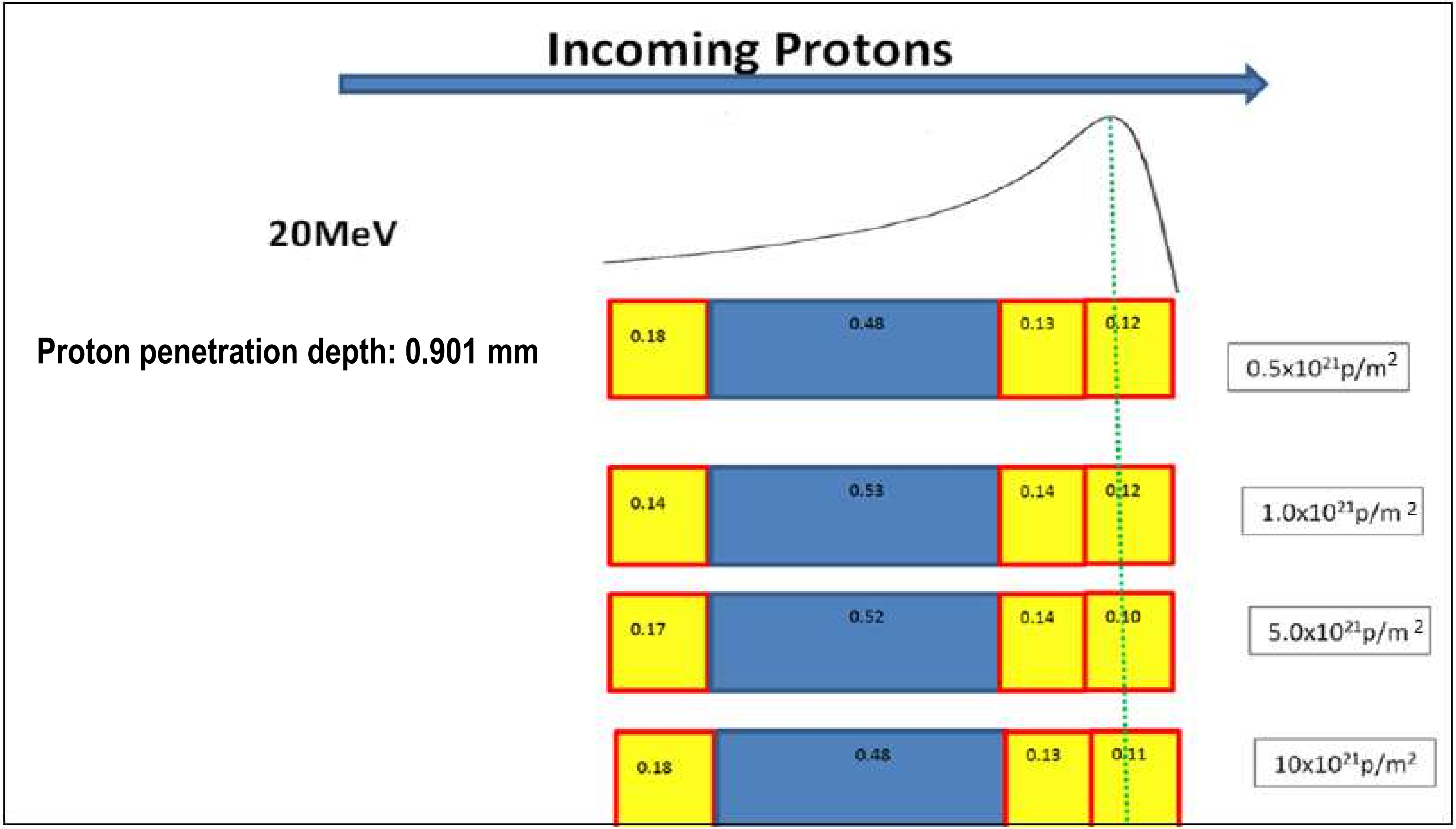
Nb_3Sn platelets: d = 0.090 – 0.15 mm

Nb_3Sn melted under 2 kbar pressure
Cut by spark erosion
Polished
Flash annealed to remove stresses





The Bragg peak experiment



Proton penetration depth: 0.901 mm

Conclusions I

Enhancemente of J_c after high energy proton irradiation at 24 GeV and 65 MeV up to a fluence of $1x10^{21}p/m^2$:

- Similar enhancement of J_c at different proton energies and different fabrication techniques (RRP and PIT), for the same additive (Ta)
- J_c of the Ti alloyed wires exhibits a stronger increase than Ta alloyed wires
- The enhancement of B_{c2} with proton irradiation is much higher than for neutron irradiation: 14 - 20%, compared to 3-4.5%.
  Order parameter effects excluded (very small ΔT_c). Mean static displacements?
- Pinning force can be described as a sum: 1) grain boundary pinning, 2) point pinning
- The contribution of radiation induced defects to the pinning force (factor β) does not vary for the various Nb_3Sn wires

Conclusions II

vo different regions have to be studied for the total damage due to charged particles:

teady loss region:

he same amount of radiation induced pinning due to defect clusters is reached after 15 times lower proton
ience (at E > 60 MeV).

⇨ in the quadrupoles of LHC Upgrade, the effect of protons corresponds to > 50% when compared to neutrons. Together with the 8% pions in LHC Upgrade (not measured here):

⇨ Effect of charged particles on J_c is at least as high as that due to neutrons (Nb_3Sn, MgB_2)

ragg peak region:

ost of the Bragg peaks of protons and pions will be located in the quadrupole. *No data are available about*
fects on J_c. This damage is additive to those of the “steady loss region”.

study about the effects at the Bragg Peak in Nb_3Sn is under work (Nb_3Sn wires) in collaboration with Kurcha
stitute.