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Properties of Nb_3Sn magnets in the accelerators HiLumi LHC and FCC

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and CERN, TE-MSC**

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Tiziana Spina, for the work during her PhD thesis

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Amalia Ballarino and **Luca Bottura,** for their constant support during the work

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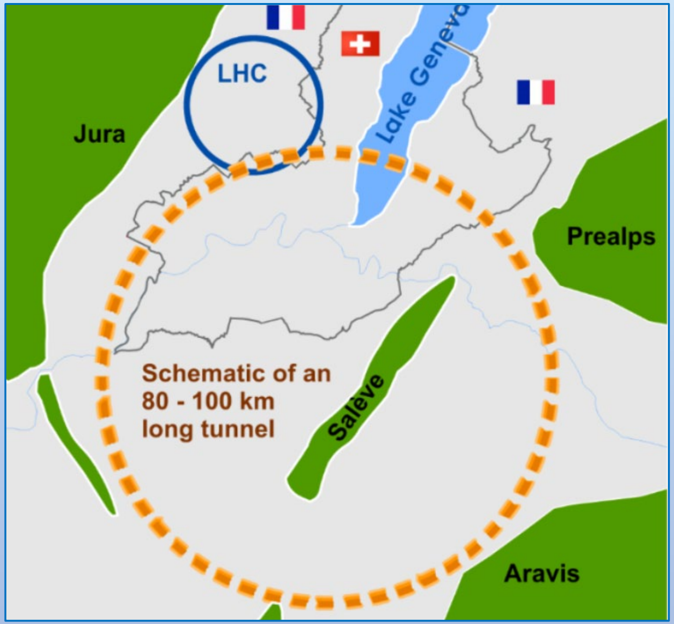
VII. Remarks about recent progress in Nb_3Sn

VIII. Conclusions

1. Introduction

The FCC Accelerator



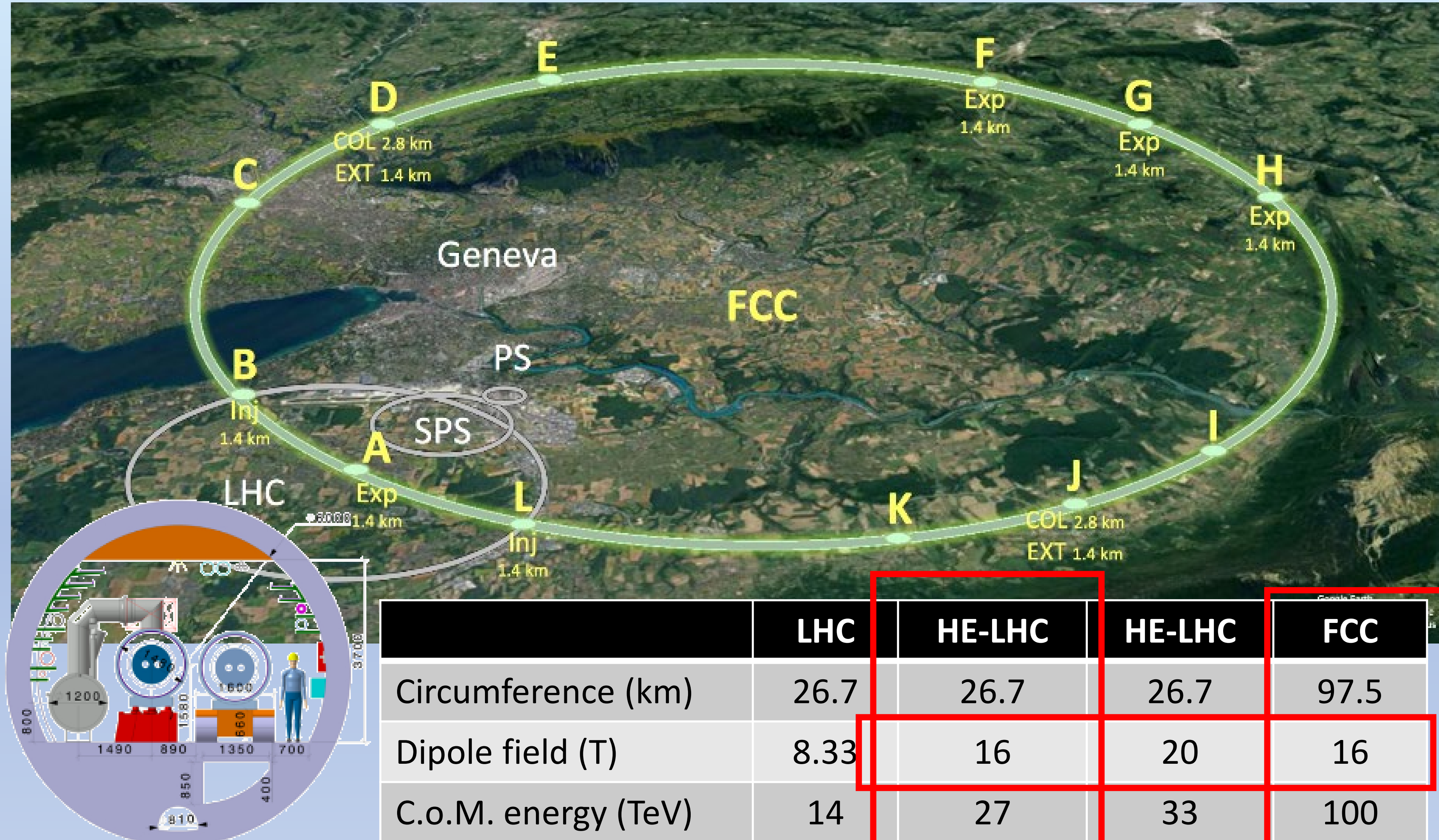
Future Circular Collider (FCC) study:
100-TeV hadron collider in a 100 km long tunnel

Magnetic field in the dipoles: 16 T

Presently envisaged superconductor: Nb_3Sn

1. Required value of J_c = 1'500 A/mm^2 at 16T/4.2K before irradiation (has not yet been reached in industrial Nb_3Sn wires, but very close to it): new challenge !

2. The radiation in FCC will affect the superconducting properties. To compensate them, even higher pristine J_c values are required (will be estimated in this talk)



	LHC	HE-LHC	HE-LHC	FCC
Circumference (km)	26.7	26.7	26.7	97.5
Dipole field (T)	8.33	16	20	16
C.o.M. energy (TeV)	14	27	33	100

Data considered in the present study

FLUKA Calculations have been performed at CERN for the values of

- * the quadrupole/dipole magnets
- * the *dpa* values for the magnets in HiLumi LHC and FCC

➡ the thickness of the W shield and

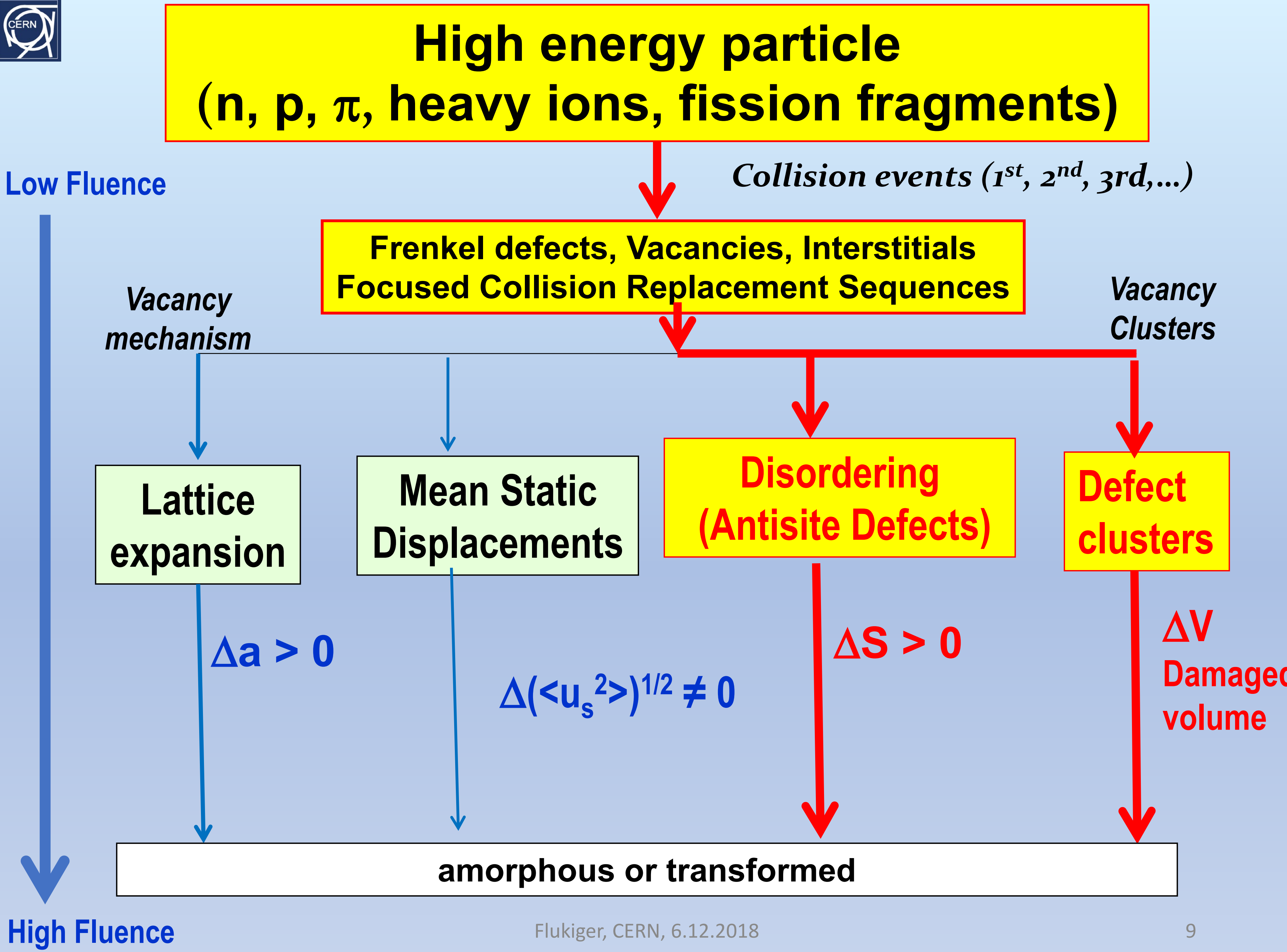
The change of superconducting properties presented here are determined assuming the following parameters:

	HiLumi LHC	FCC/RUN1	FCC/Run2
Luminosity	3'000 fb^{-1}	5'000 fb^{-1}	30'000 fb^{-1}
Coil ID	150 mm	205 mm	205 mm
dpa	2.5×10^{-4}	5×10^{-4}	3×10^{-3}
W thickness	6-12 mm	15 mm	55 mm

Chosen for the present estimation

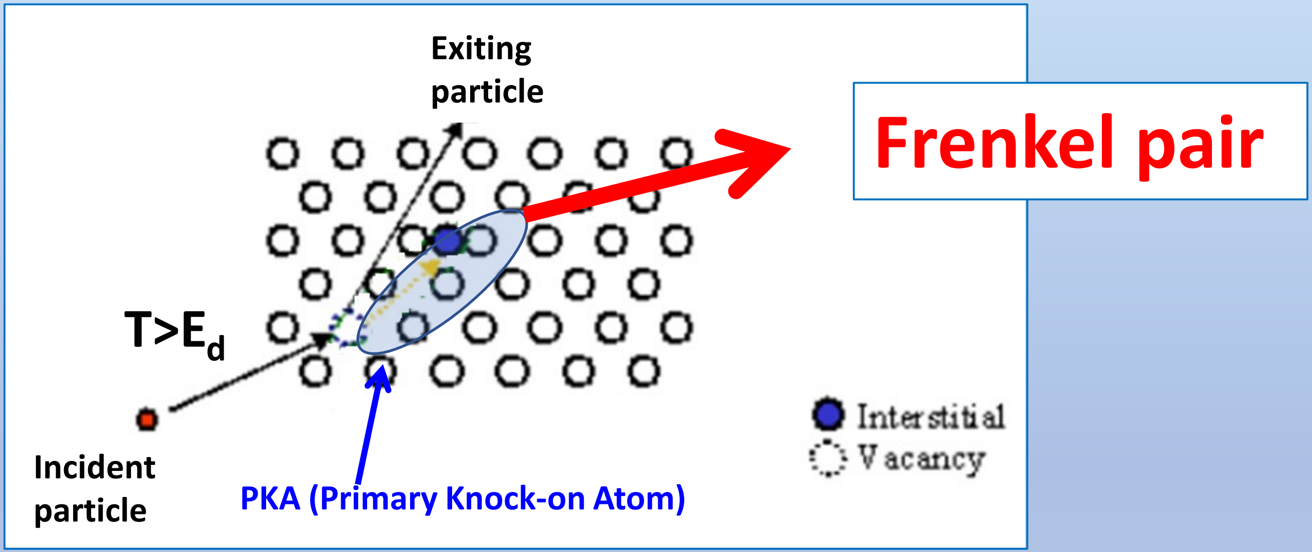
R. Flükiger et al., EUCAS 2017

II. What happens in the Nb_3Sn structure during high energy irradiation?


High energy particle
(n, p, π, heavy ions, fission fragments)
Collision events (1st, 2nd, 3rd,...)
Low Fluence
Frenkel defects, Vacancies, Interstitials
Focused Collision Replacement Sequences
Vacancy mechanism
Vacancy Clusters
Lattice expansion
Mean Static Displacements
Disordering (Antisite Defects)
Defect clusters
Δa > 0
Δ(<u_s²>)^1/2 ≠ 0
ΔS > 0
ΔV
Damaged volume
amorphous or transformed
High Fluence

Radiation damage: Frenkel pairs

Transfer of the kinetic energy, T, from projectile to the solid and the resulting distribution of target atoms (*displacement cascade*)



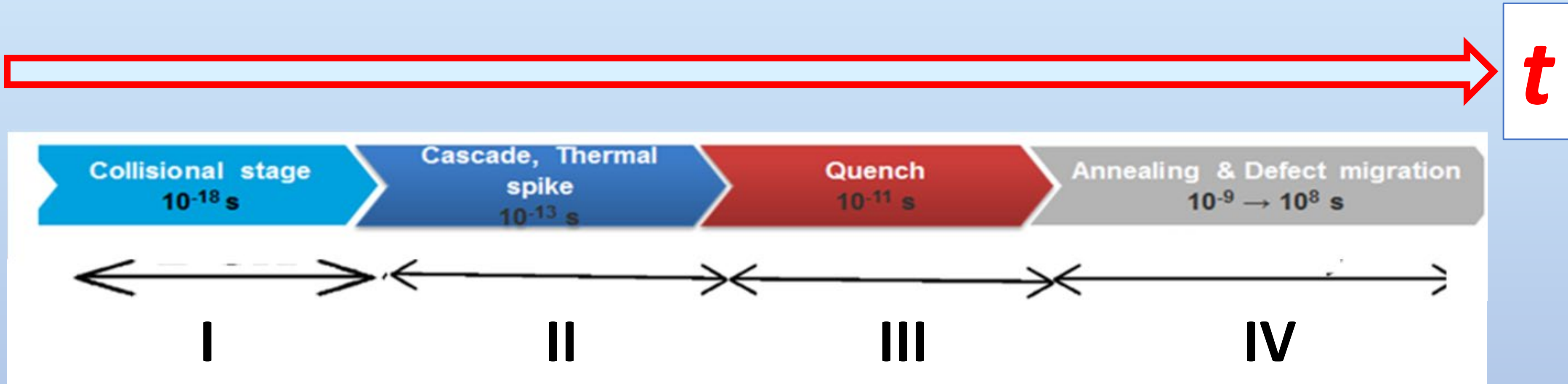
The radiation damage event is concluded when the PKA (Primary Knock Atom) comes to rest in the lattice as an interstitial (stage III)

Stable Frenkel pairs (stage III):

- additional pinning centers (higher J_c)
- determine the value of *dpa* (displacement per atom)

Time evolution of the radiation damage in a crystal

Time evolution comprises 4 stages:



Incident particle collisions: Primary Knock Atom (PKA), Creation of **Frenkel pairs**

«**Thermal spikes**» Local melting, cascades, point defects of nm size

«**Quench**»: solidification, creation of stable **Point Defects** or **Defect Clusters**

↓ dpa

Stable Frenkel defects

«**Annealing stage**» Thermal diffusion, No new vacancies, but **Displacement Collision Sequences**

↓ s

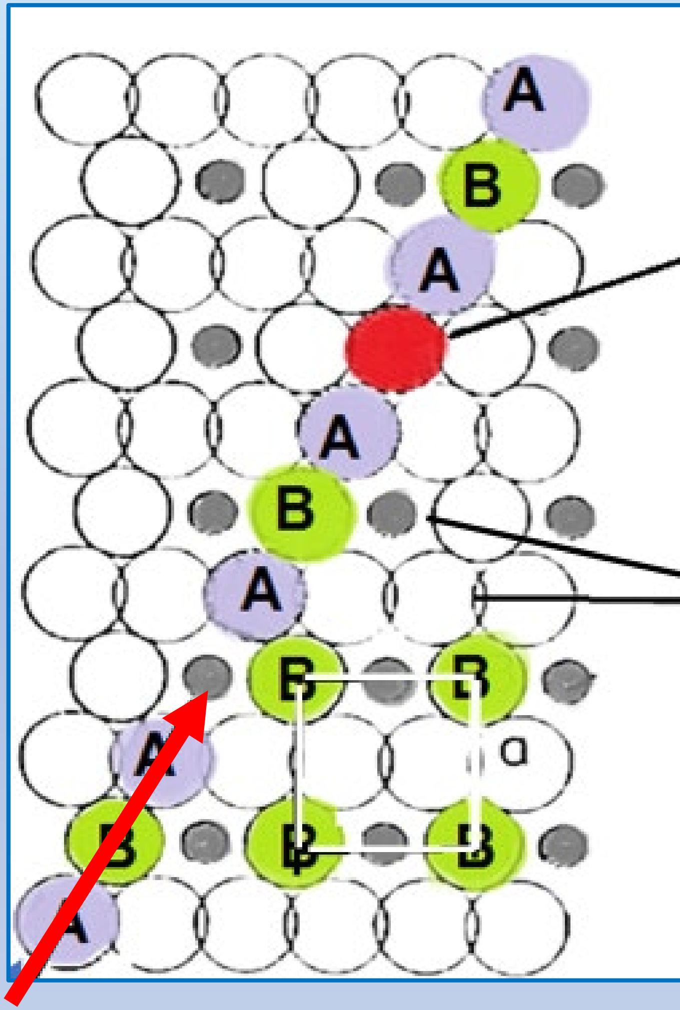
Mobile Frenkel defects

III. Definition of the *dpa* (displacement of atoms)

Stage IV: Decreasing atomic order parameter

Mechanism: Focusing Displacement Collision Sequence along <102>

A15 structure



A: Nb atoms
B: Sn atoms

Occupied «virtual» site

Overlapping of Nb atoms in A15 structure

Step IV: Mobile Frenkel defects

Change of the order parameter S

***dpa* unchanged**

<102> **Focusing Displacement Collision Sequence**

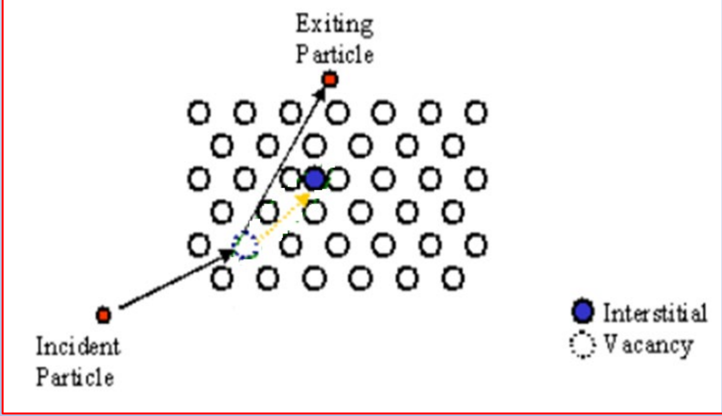
The «displacement per atom» or *dpa*

dpa: **calculated by the FLUKA code:** http://www.fluka.org

Multipurpose interaction, incl. a Monte Carlo simulation, taking into account secondary ions

$$dpa \equiv \frac{A}{V N_A \rho} N_F$$

Frenkel pairs



A: molar mass (g/mol), V: vol. (cm^3), N_A: Avogadro number (mol^{-1}), ρ: mass density (g/cm^3)

dpa : **proportional to the fluence, different for each reactor and particle**

Essential property of dpa: Treatment of multiple sources

$$dpa = \Sigma\, (dpa)_j$$

j: different energy sources

Formulation of tasks

Evaluation of the damage caused by high energy irradiation on the superconducting properties of Nb_3Sn wires in the magnets of HiLumi-LHC (quadrupoles) and FCC (dipoles) during lifetime

What is known: **Number of total *dpa* (displacement per atom) during lifetime of HiLumi-LHC and FCC**

*From **FLUKA** MonteCarlo simulations:*
A. Lechner, F. Cerutti et al. 2014

Tasks: * Determination of the changes *dpa* vs. T_c and *dpa* vs. J_c
*** Evaluate the changes of T_c, B_{c2} and J_c during lifetime**

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IV. Expected radiation load in Future Accelerators:

HiLumi LHC, FCC

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* the *dpa* values for the magnets in HiLumi LHC and FCC

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Chosen for the estimation

Radiation damage in Nb_3Sn magnets in accelerators

The Nb_3Sn superconducting magnets in these accelerators will be submitted to high energy irradiation, produced by multiple particles:

* Photons,
* Electrons

Photons are the major cause of damage for the insulator; Little effect on the superconductor (not treated here)

* Neutrons
* Protons
* Pions

These sources cause almost all the effect on

- the Cu stabilizer and
- the superconducting properties

In order to describe the cumulated radiation damage, these individual quantities have to be replaced by a more general quantity: the number of displacements per atom, or *dpa*.

$$dpa = \Sigma (dpa)_i$$

dpa: appropriate parameter for irradiation by multiple sources in accelerators

Remarks: radiation induced effects in accelerator magnets

All magnet components are sensitive to radiation effects.
However, their importance differs for the various materials:

Material	Reversibility	Remarks
1. Insulator	Irreversible	Most sensitive part to high energy irradiation
2. Cu stabilization	≥ 90% reversible at 300 K	High initial RRR required
3. Nb_3Sn wires	Irreversible at 300K	Only reversible at ≥700°C: not suitable for magnets

Nb_3Sn wires: No recovery at 300K: The initial values of T_c, B_{c2} and J_c of Nb_3Sn wires must be sufficiently high to fulfill stability requirements, even after irradiation during the whole lifetime (10 years and more)

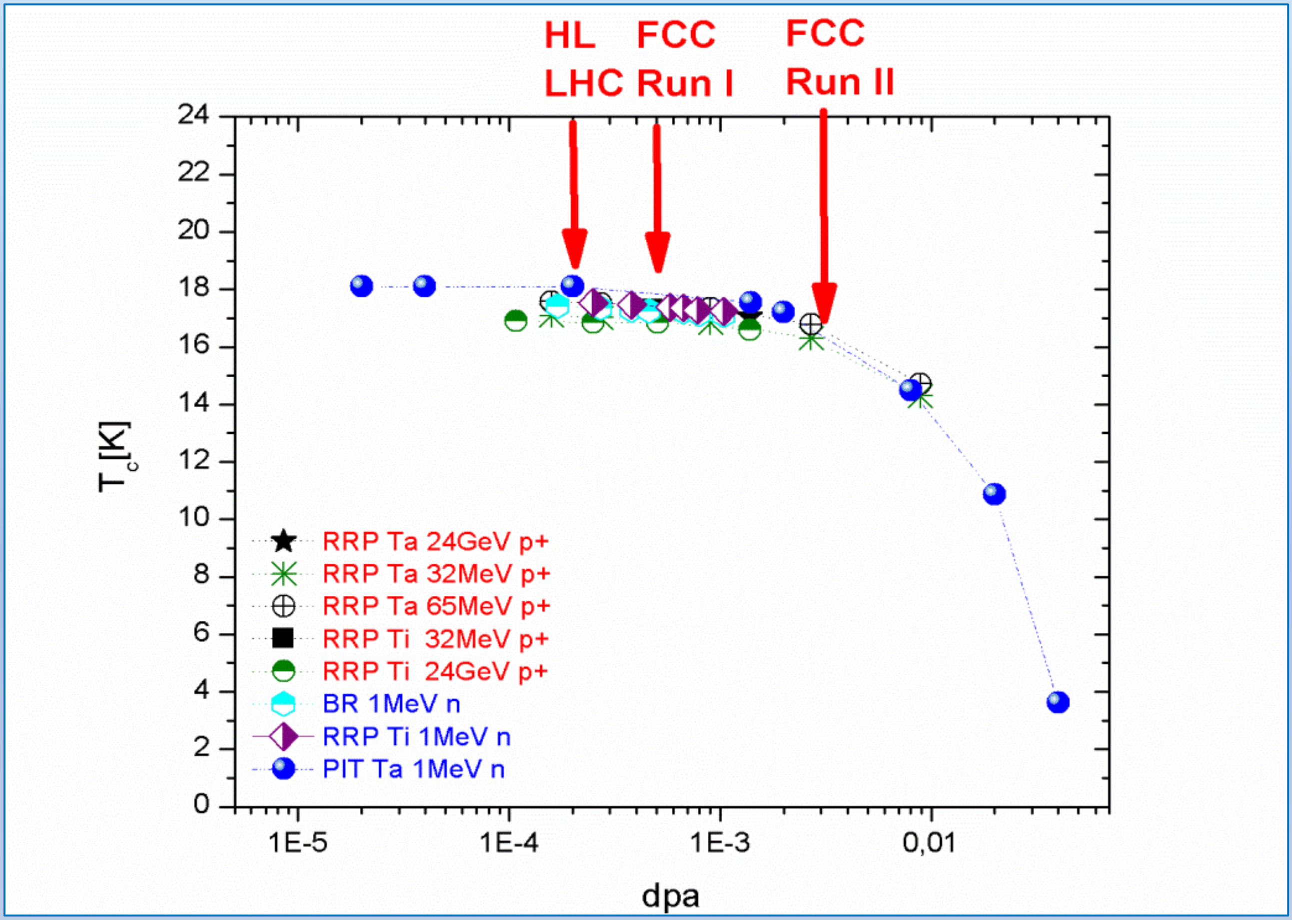
Contribution of neutrons and charged particles to dpa of HL-LHC and FCC

	HiLumi LHC	FCC/Run1	FCC/Run2
Neutrons	~ 70 %	~ 80 %	~ 90 %
Charged particles	~ 30%	~ 20 %	~ 10 %

Neutron contribution for FCC/Run 2 is as high as 90%!
However, protons cause a 10 x higher radiation damage on J_c than neutrons (thus higher dpa values):

The effect of protons must in any case be taken into account

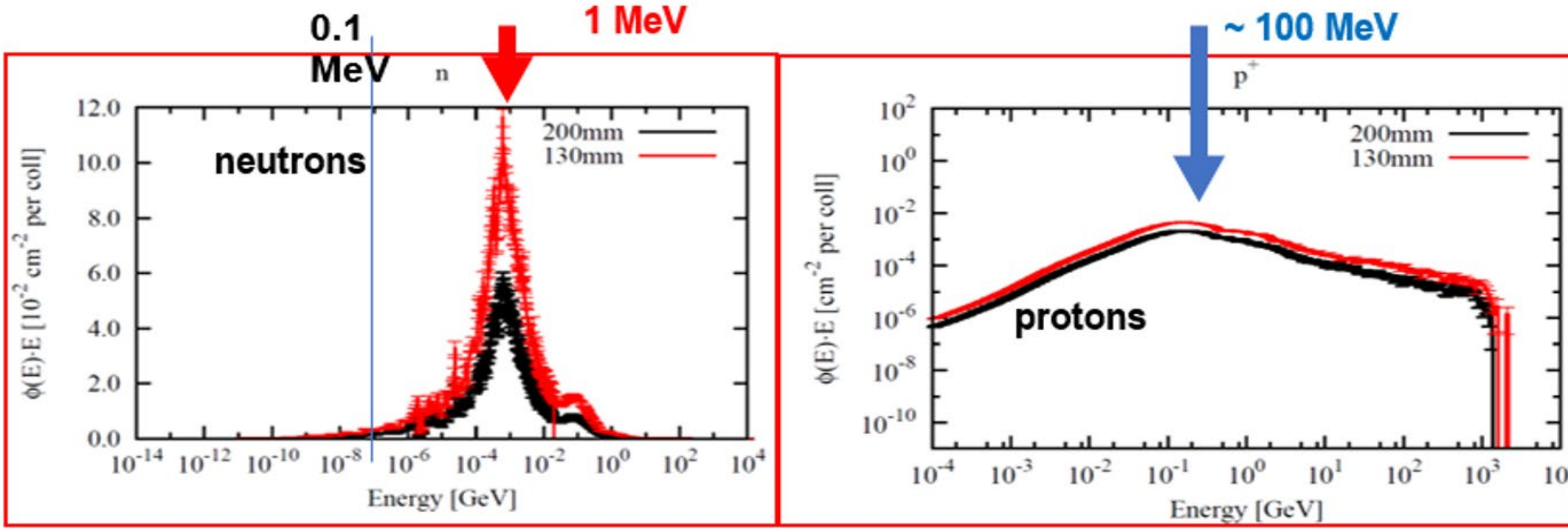
dpa values for various accelerator types



T. Spina, R. Flükiger et al., to be published

Comparison : neutron and proton irradiation fluences

Example: particle spectra acting on quadrupoles (HiLumi LHC)



Where can the Nb_3Sn wires in preliminary studies be irradiated under conditions approaching those in accelerators?

Neutrons: ATI (Atominstitut) in Vienna (Austria): E > 0.1 MeV

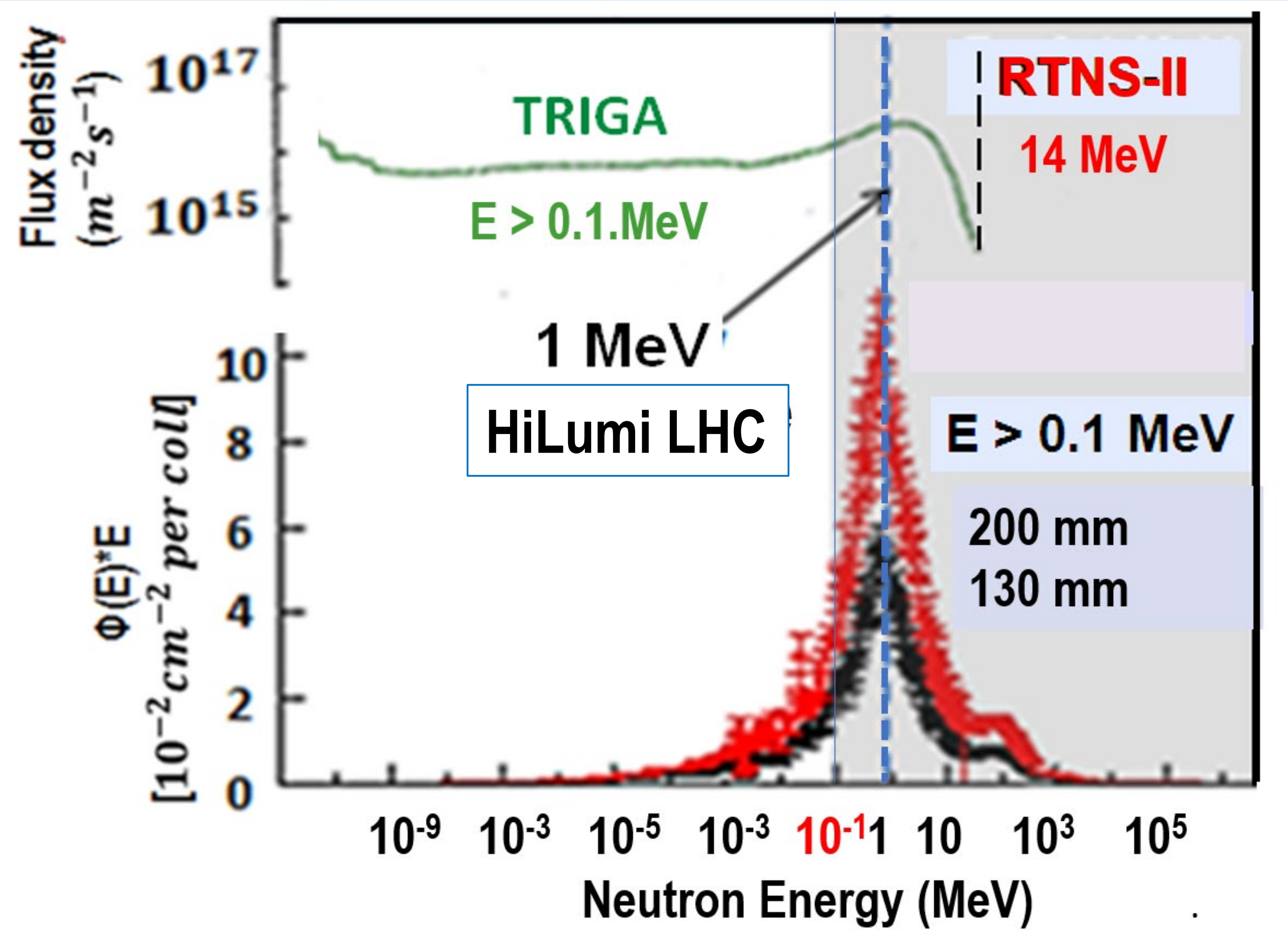
Protons: Kurchatov Institute, Moscow: E =12 – 32 MeV

Cyclotron, Louvain la Neuve, Belgium; E = 63 MeV

CERN, IRRAD1 (PS beam), E= 24 GeV

The Neutron Energy spectra in various reactors

Present work: TRIGA (>0.1 MeV) RTNS-II(14 MeV)



Irradiation at various proton energies

Irradiation at various proton energies, covering the proton spectrum

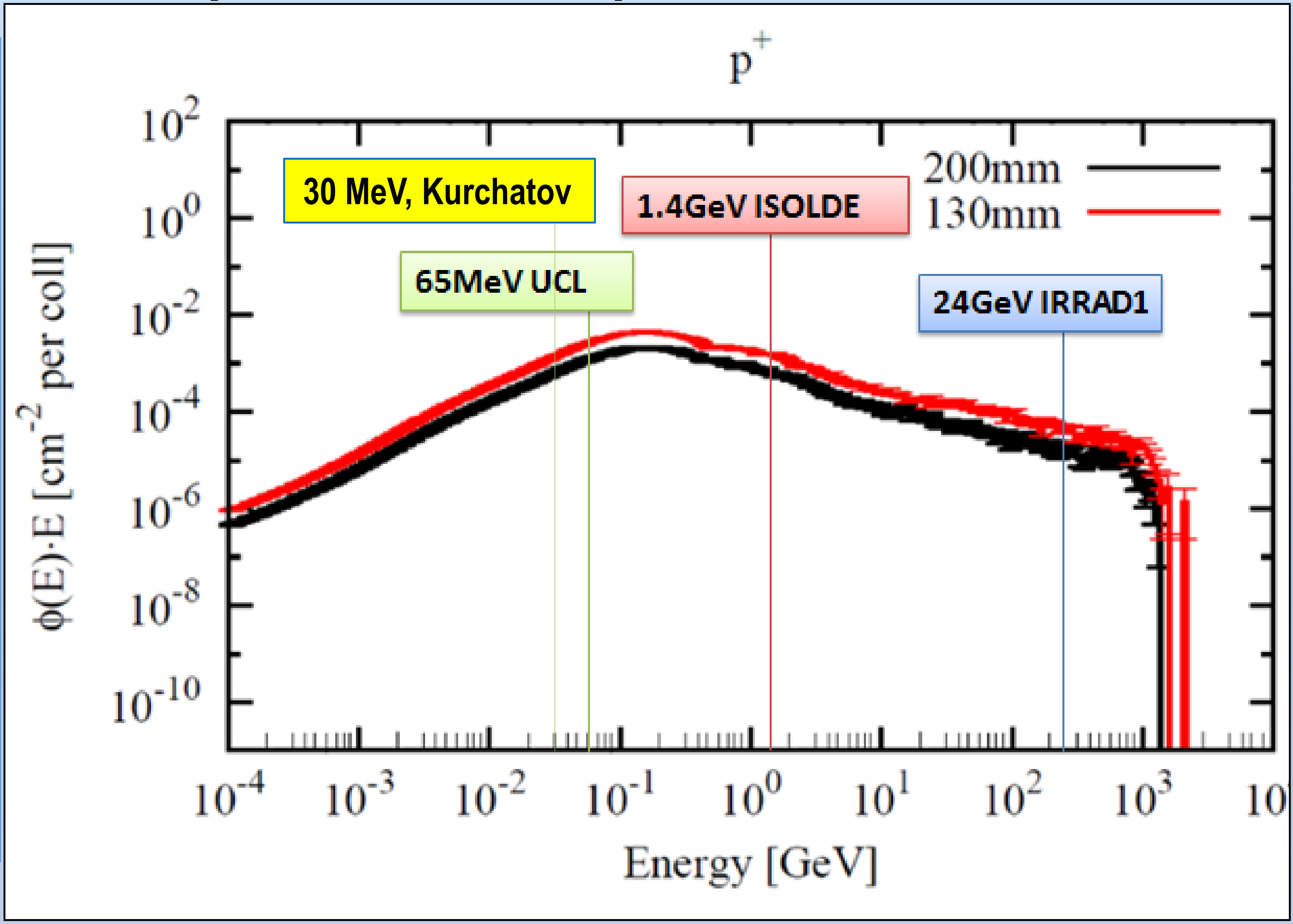
Example: Q2a Quadrupole of HiLumi LHC

24 GeV protons
IRRAD1 (PSbeam),CERN

1.4 GeV protons, **ISOLDE (booster beam), CERN**

65 MeV protons, **Cyclotron of University Louvain la Neuve, Belgium**

10 - 30 MeV protons, **Cyclotron of Kurchatov Moscow (Russia)**



V. The irradiation research program at CERN

Comprises both: Nb_3Sn wires and
Nb_3Sn bulk samples

The Irradiation Program at CERN

Same set of Nb_3Sn wires

Nb_3Sn wires

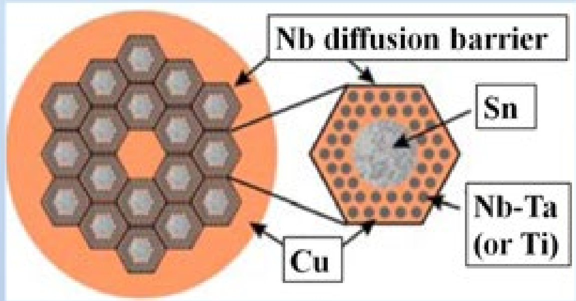
- Proton irradiation @ CERN (24 GeV)
- Neutron irradiation ATI Vienna, Austria > 0.1 MeV
- Proton irradiation Louvain Cyclotron, Belgium (65 MeV)

Nb_3Sn wires + bulk samples

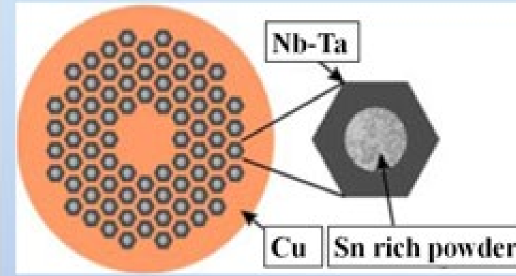
- Proton irradiation NRC Kurchatov (Russia)

Industrial Nb_3Sn wires for the CERN irradiation study

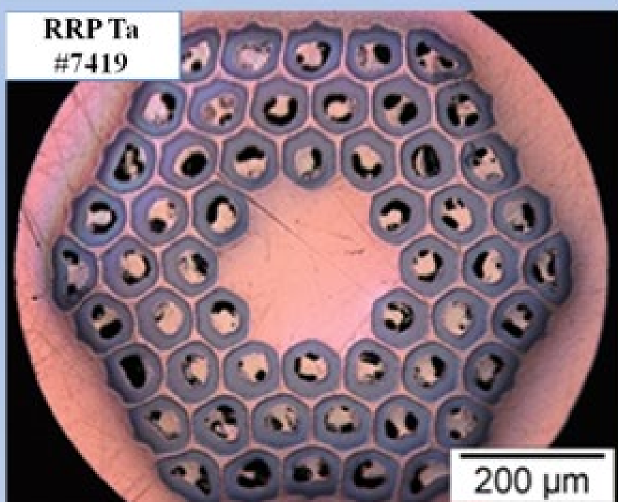
Internal Tin (RRP)

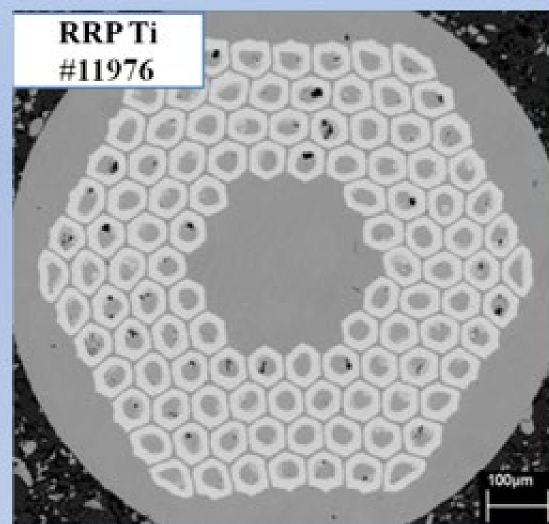


Powder In Tube (PIT)

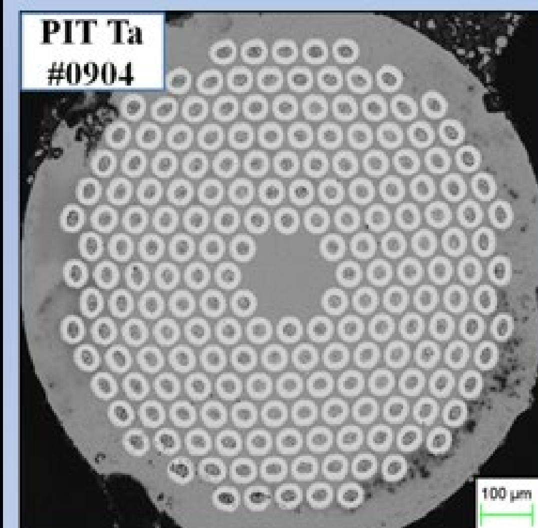


Oxford Instruments





Bruker



Characterization of the Nb_3Sn wires (at 12 T)

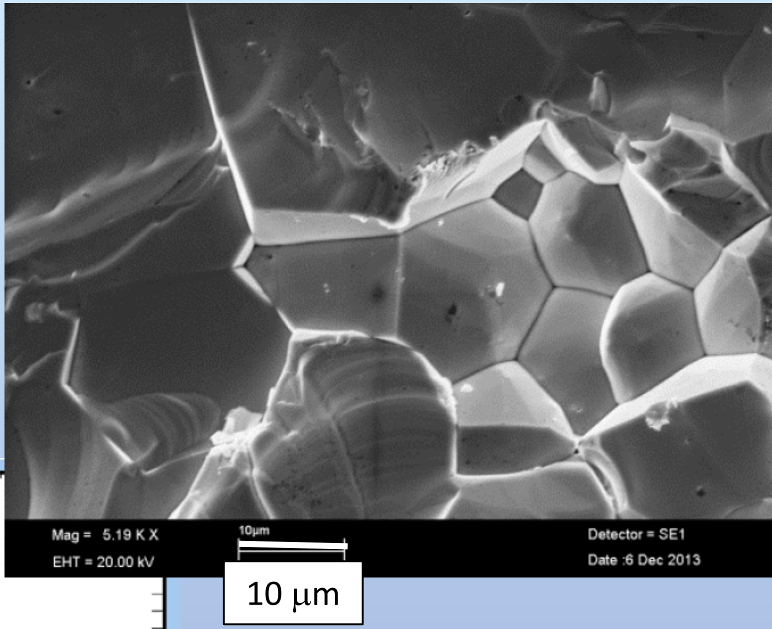
Wire	Diameter (mm)	Type	Sub-elements	Twist pitch (mm)	T_c (K)	$J_{c,A15}$ at 4.2K/12 T (A/mm^2)
#7419	0.8	RRP+Ta	54	12	17.84	4843
#0904	1.0	PIT+Ta	192	24	17.93	3930
#11976	0.8	RRP+Ti	108	14	17.44	4135
#63468	1.25	IT	246	55	17.16	2057

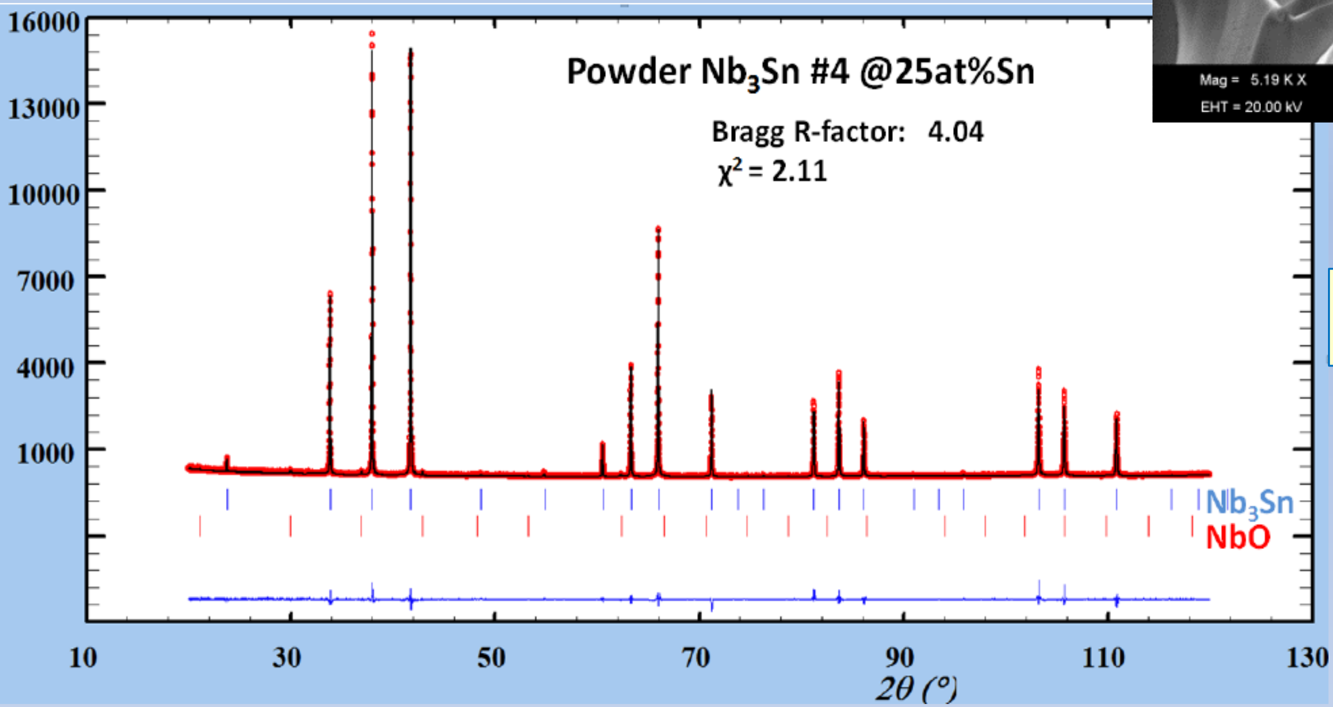
Annealing conditions:
#7419: 695 °C/17 h,
#0904: 625 °C/250 h,
#11976: 210 °C/48 h + 400 °C/48 h + 665 °C/50 h,
#63468: 215°C/24 h + 340°C/24 h + 400°C/24 h + 645 °C/50 h.

Characterization of the bulk Nb_3Sn samples (Kurchatov)

Nb_3Sn platelets: d = 0.090 – 0.15 mm

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





> 98% single phase

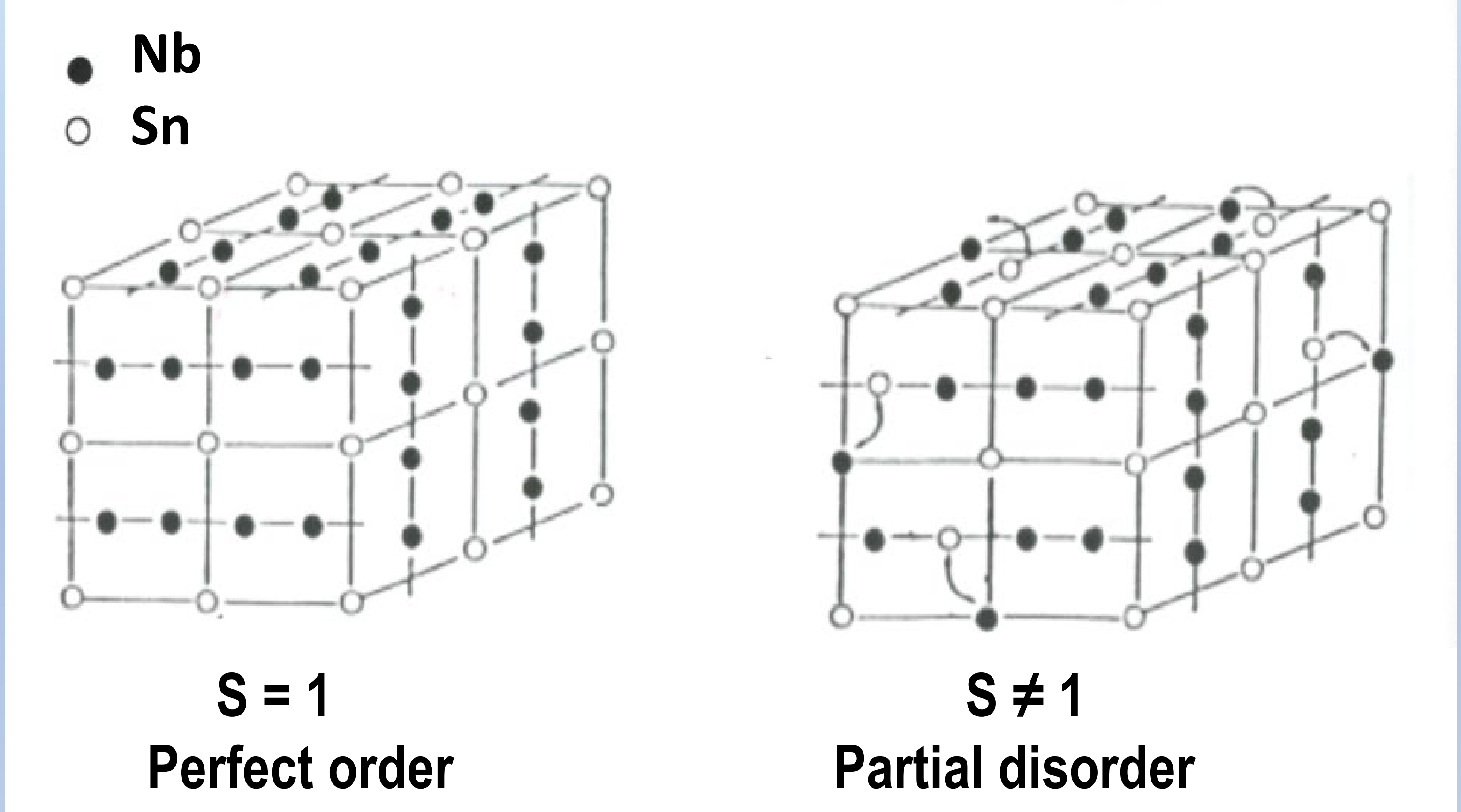
R. Flükiger et al, SuST 30,101979 (2017)

VI. Radiation damage mechanism in Nb_3Sn

VI.A. *dpa*: «Universal» parameter for the change of T_c

The A15 crystal structure of Nb_3Sn

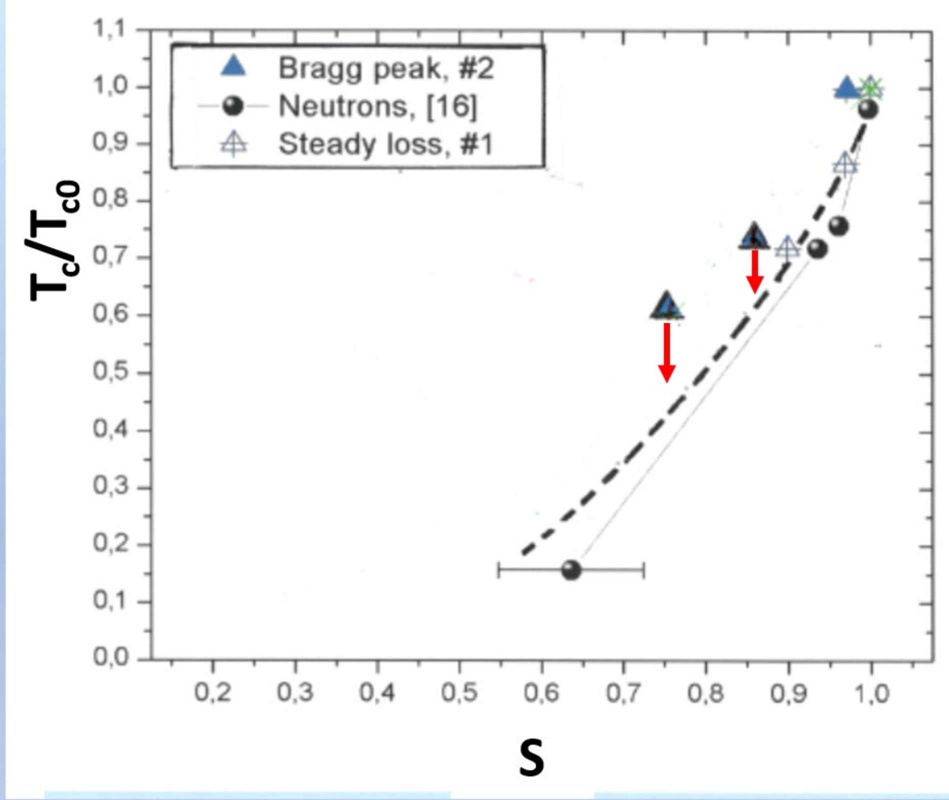
The long-range atomic order parameter S: occupation of the atomic sites



S depends on the fluence ϕt

$$S = S_0 \cdot \exp(-k \cdot \phi t)$$

Atomic ordering and T_c in Nb_3Sn



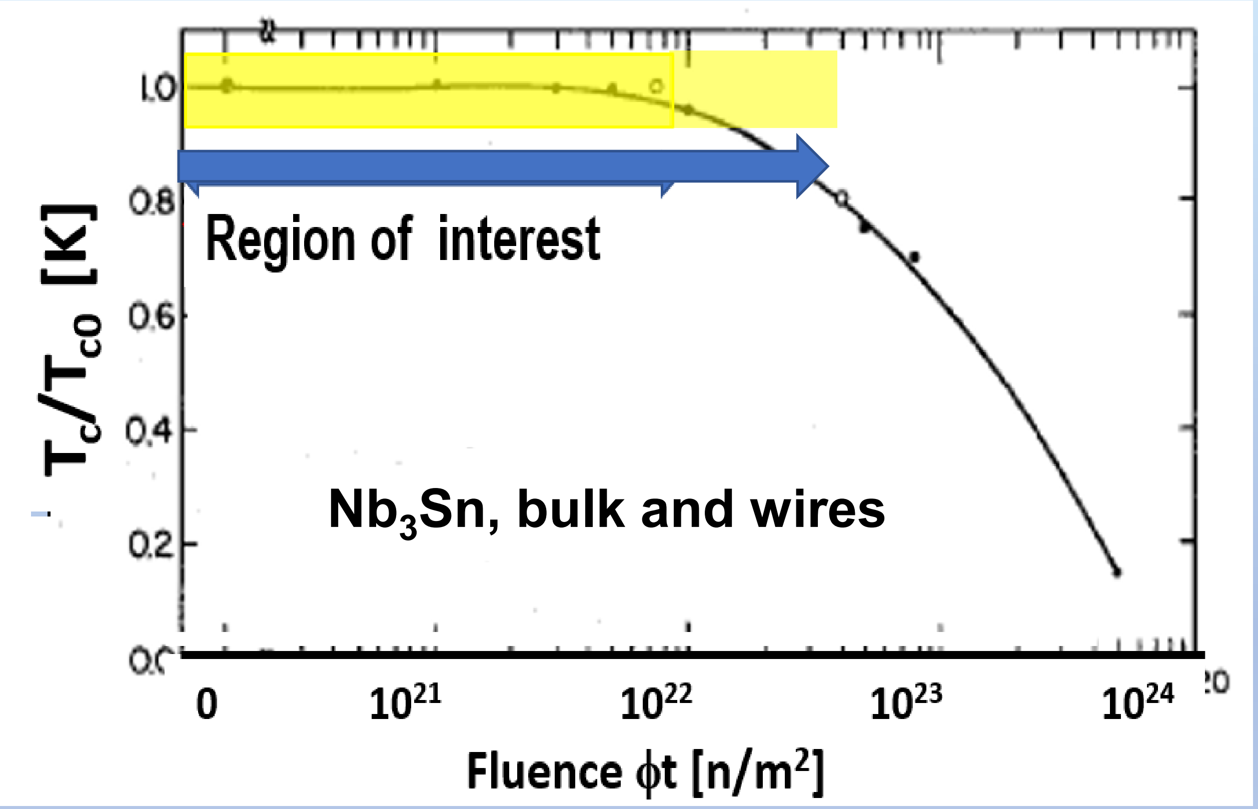
S : Atomic order parameter: indicates occupation of the Nb sites in the A15 structure

The dependence of T_c vs. fluence ϕt is directly correlated to the variation $T_c = T_c(S)$

R. Flükiger et al, SuST 30,101979 (2017)

T_c/T_{c0} vs. S very similar, for both, neutron and proton irradiation

The dependence T_c vs. ϕt: literature results



Well-known data:

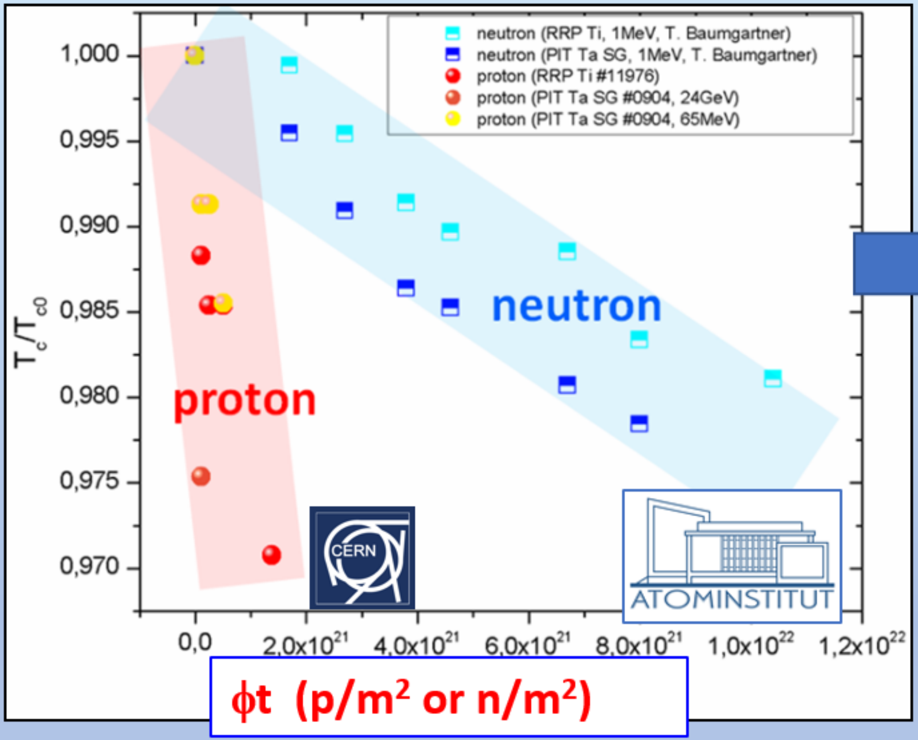
A.R. Sweedler, D.E. Cox and S. Moehlecke, J. Nucl. Mater., 72, 50 (1978)

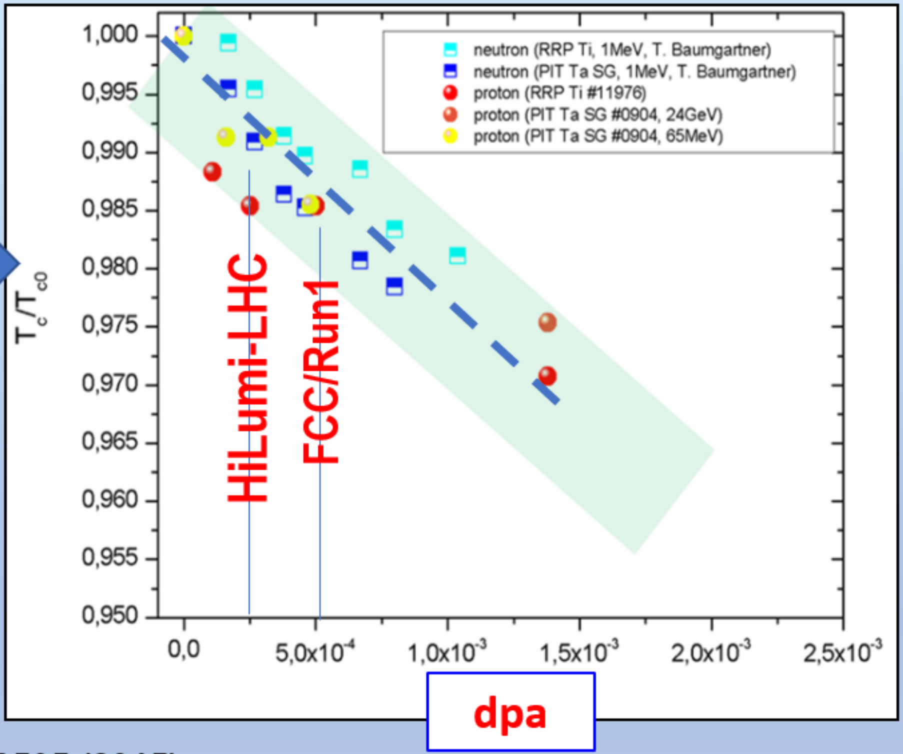
$$T_c = T_c(\phi t)$$

In the region of interest for accelerators, T_c vs. ϕt is linear. It reflects the damage energy of the incident particle.

Neutron and proton irradiation

Different PROJECTILES (protons, neutrons) and ENERGIES



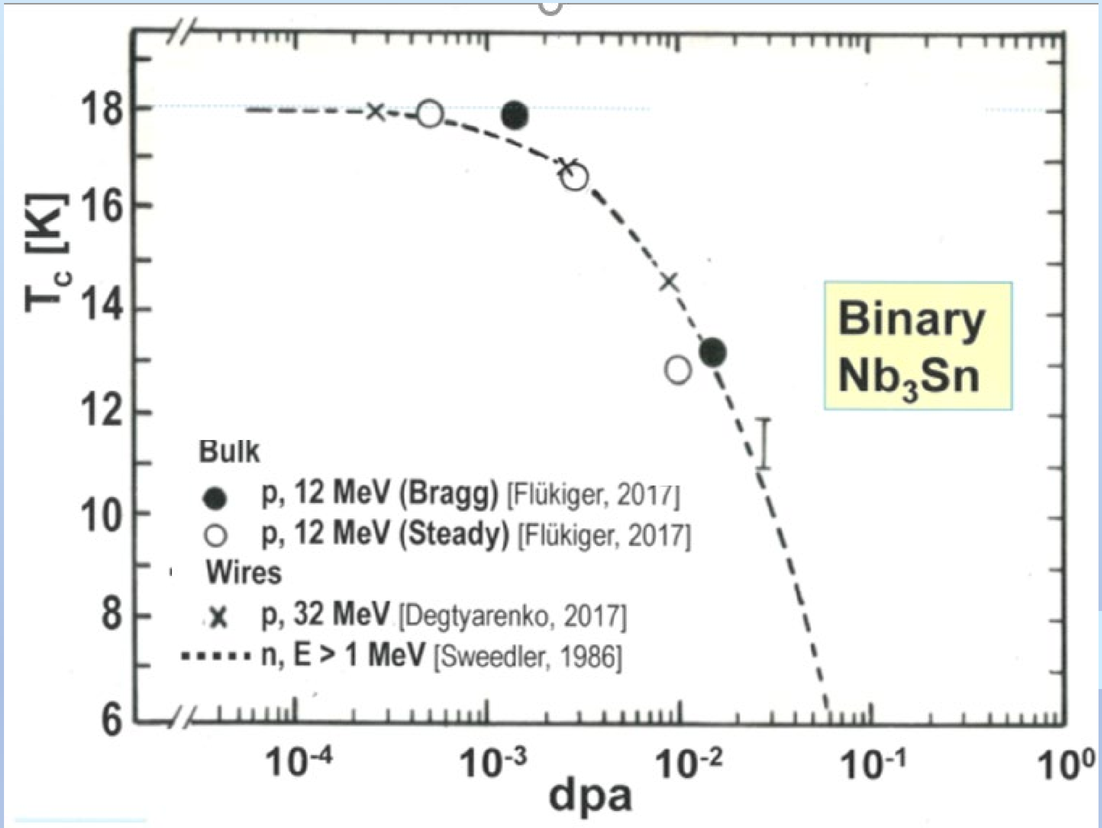


Protons: T. Spina et al, *IEEE Trans.Appl.Supercond.*, 25,6000505 (2015)
Neutrons: T Baumgartner et al., *Supercond. Science and Technol.*, 27,1(2014)

For a given value of dpa the decrease of T_c is the same regardless of the type of projectile and the different energy during irradiation.

«Universal relation» between T_c and *dpa*

The dependence T_c vs. ϕt for protons and neutrons
in binary Nb_3Sn



All known data fall on the same curve: $T_c \longleftrightarrow$ dpa

dpa :«universal» parameter for binary Nb_3Sn

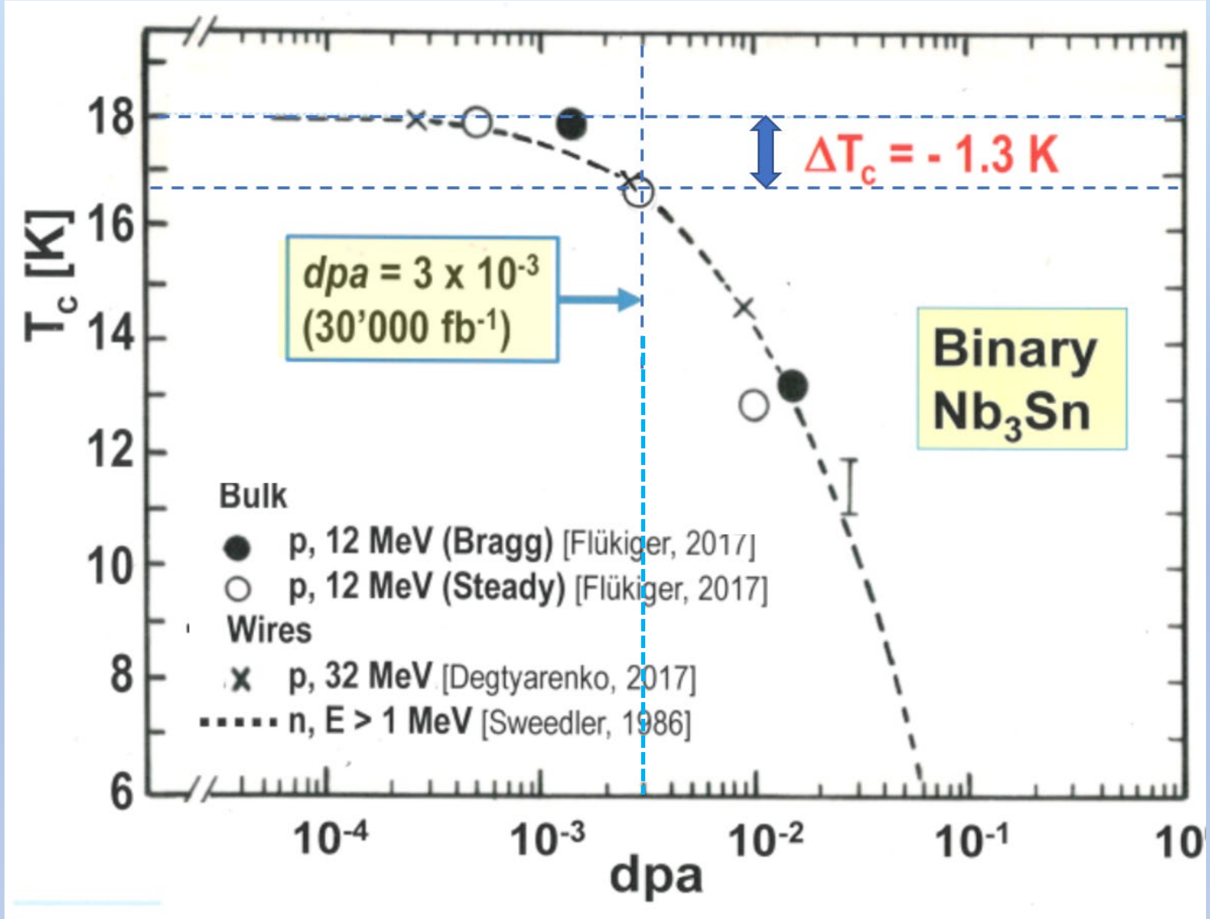
R. Flükiger et al., SuST, 30, 101979 (2017)

For binary Nb_3Sn, each *dpa* corresponds to one value of T_c

Linear variation of T_c vs. ft : reflects the damage energy of the incident particle → it is now possible to compare the data obtained with very different reactors.

Determination of ΔT_c for FCC/Run2 for binary Nb_3Sn

FCC/Run2: *dpa* = 3 x 10^{-3} → ΔT_c



Recent result: For binary Nb_3Sn, there is a direct correlation between T_c and *dpa* (or protons and neutron irradiation)

Situation in alloyed Nb_3Sn?

FCC/Run2: dpa = 3 x 10^{-3} → ΔT_c = - 1.3 ± 0.2 K

R. Flükiger et al. SuST 30, 101979 (2017)

Difference between binary and alloyed Nb_3Sn

In accelerators, only alloyed Nb_3Sn wires will be used.

Binary : Nb_3Sn
Alloyed: $(Nb_{1-x}Ti_x)_3Sn$ or $(Nb_{1-x}Ta_x)_3(Sn_{1-y}Ta_y)$

A given fluence ϕt corresponds to a value of *dpa:*

$$dpa = N_d\, \sigma\, \phi t$$

N_d: Number of displacements per cascade vs. the damage energy E_d
σ: Scattering cross section

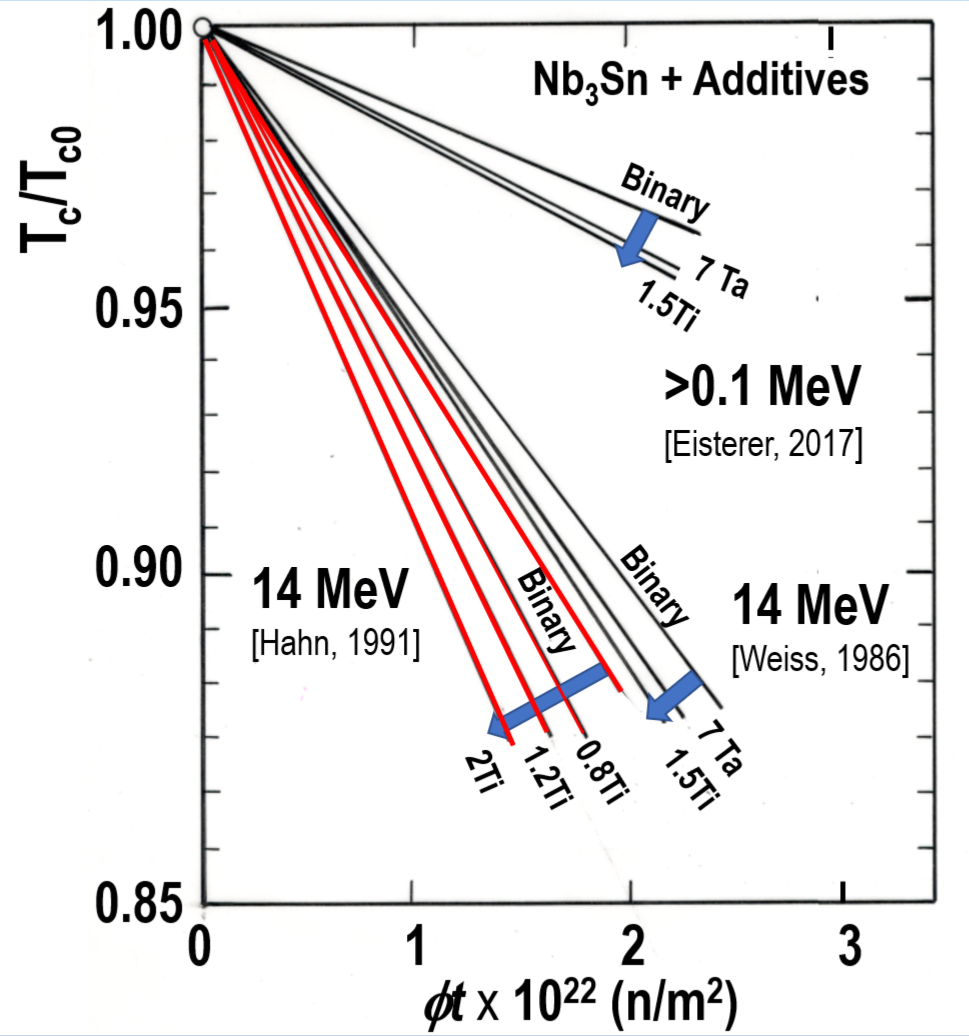
Small amount of alloy Ta or Ti (≤ 3 %), the *dpa* at a given fluence is very similar for binary and ternary alloyed Nb_3Sn.

However, binary and alloyed Nb_3Sn samples with the same *dpa* do not exhibit the same value of T_c.

This is illustrated by the known values of T_c vs. ϕt

dpa values for binary and alloyed Nb_3Sn wires

After irradiation at a given fluence ϕt, *dpa* for binary and alloyed Nb_3Sn wires is essentially the same, but a certain difference ΔT_c still subsists.



Data from two reactors: ATI: >0.1 MeV
RTNS-II: 14 MeV

Stronger decrease of T_c for alloyed Nb_3Sn wires

E = 14 MeV:

*P.A Hahn, M.W. Guinan, I. T. Summers, T. Okada, D.B. Smathers, J. Nucl. Mater., 179, 1127 (1991)

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

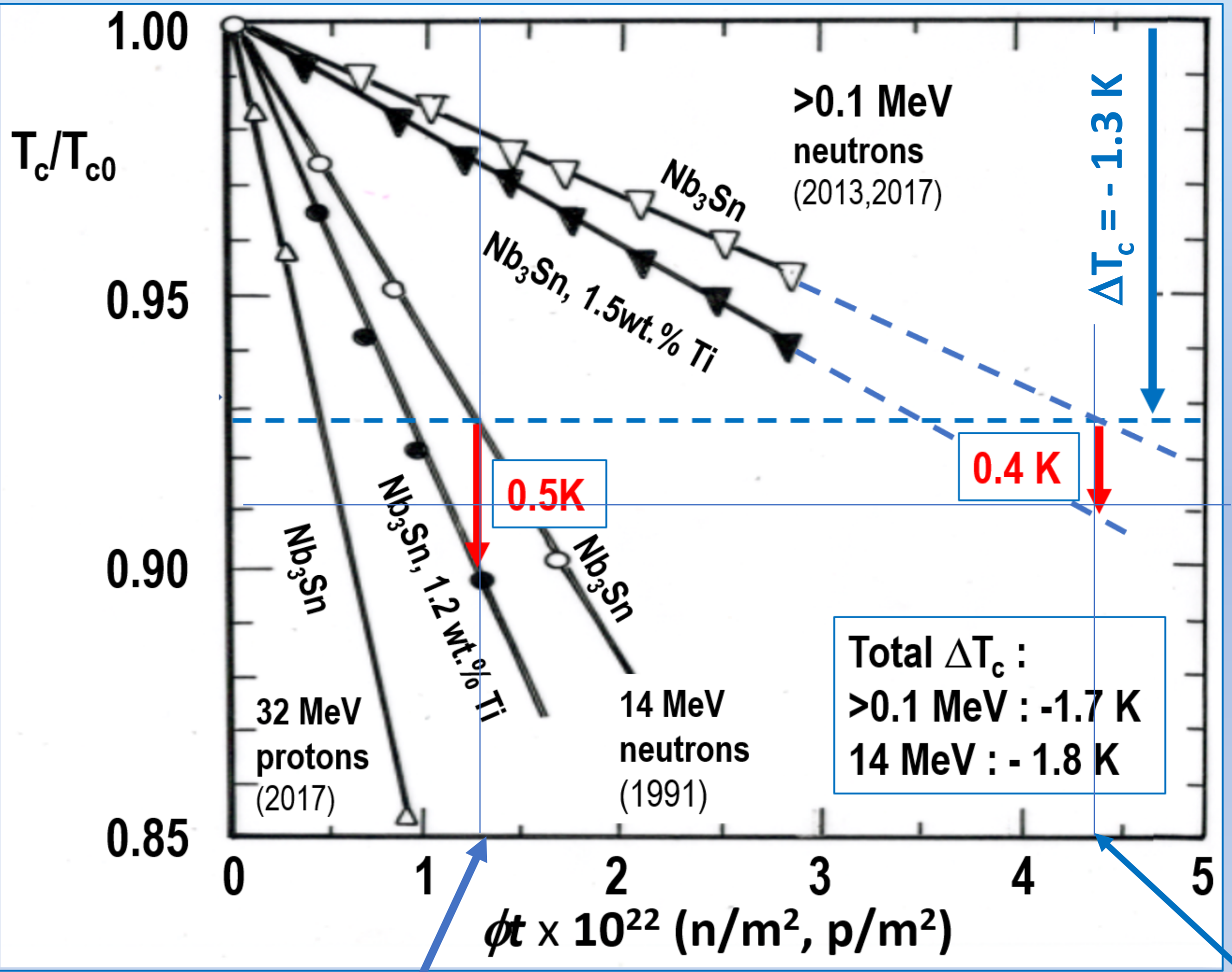
E > 0.1 MeV:

*M. Eisterer, T. Baumgartner et al., ICMC 2017

*Flükiger et al., IEEE Trans. Appl. Supercond., 23, 8001404 (2013)

Determination of ΔT_c for alloyed Nb_3Sn wires

FCC/Run2: Binary Nb_3Sn: ΔT = -1.3 K ± 0.2 K



1.3 x 10^{22} n/m²

4.3 x 10^{22} n/m²

E > 0.1 MeV:

*Flükiger et al., IEEE Trans. Appl. Supercond., 23, 8001404 (2013)
*M. Eisterer, T. Baumgartner et al., ICMC 2017

E = 14 MeV:

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*F. Weiss, et al., IEEE Trans Magn. MAG 23, 976,1987

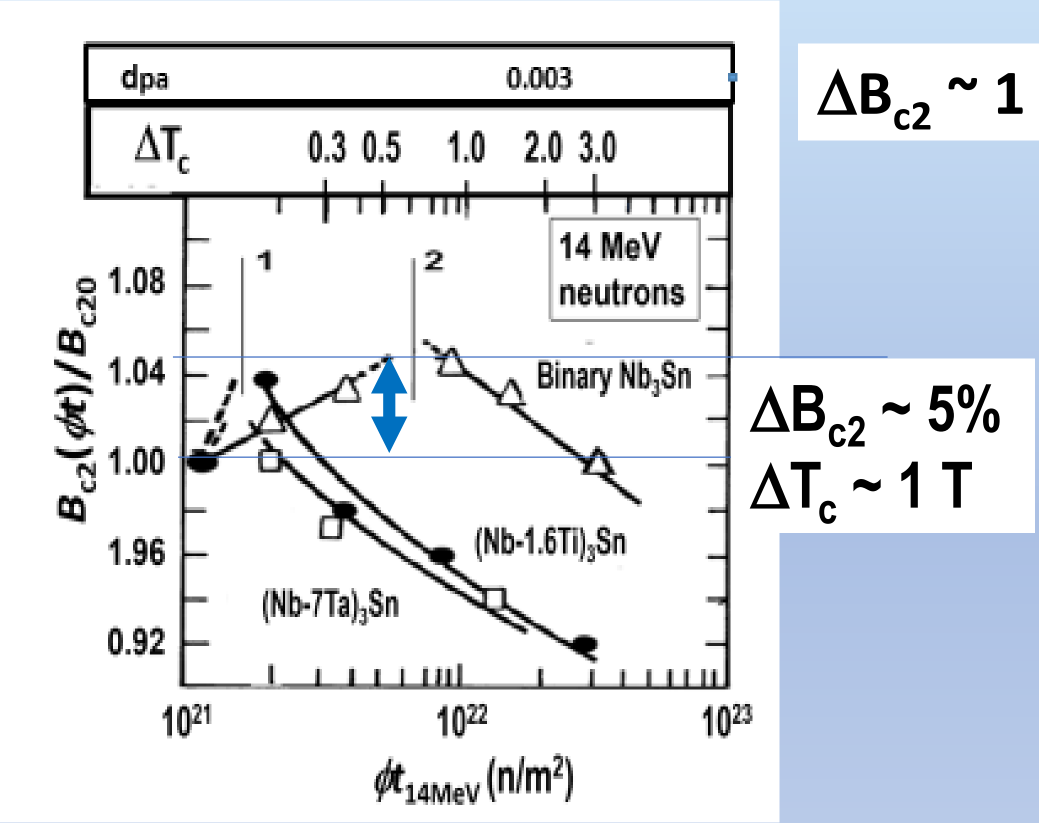
Estimation for FCC/Run2, for alloyed Nb_3Sn

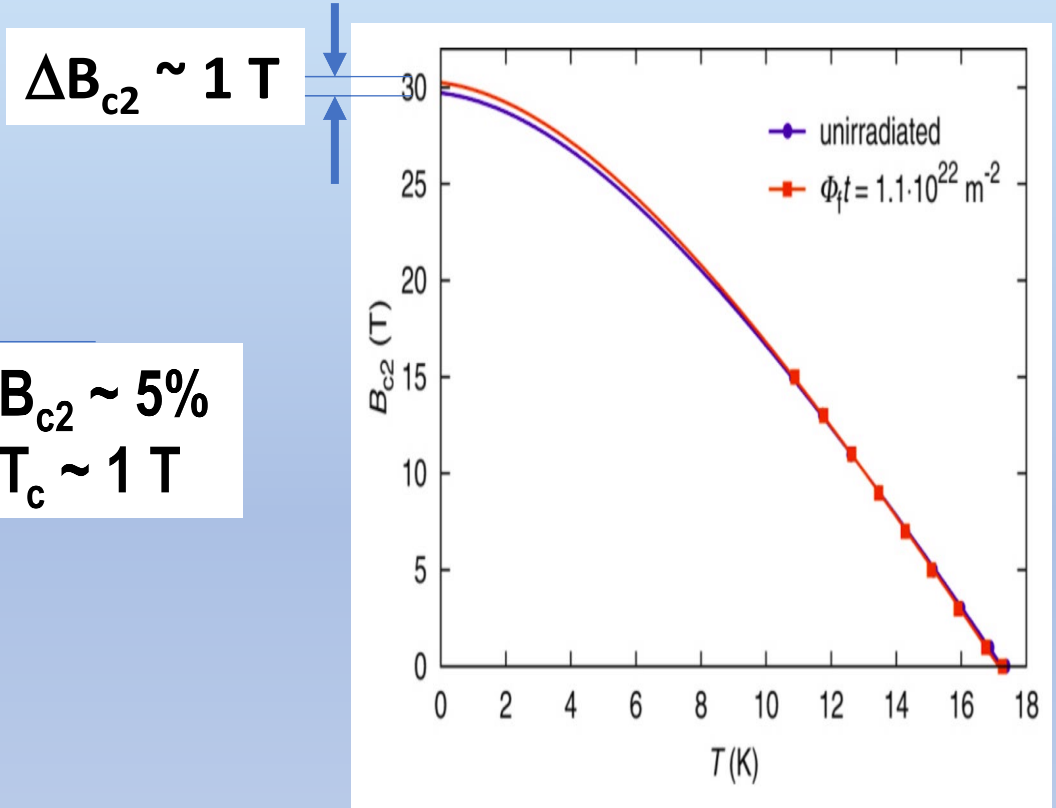
$\Delta T_{c,total}$ = -1.8 ± 0.2 K

VI.B: Effect of Irradiation on B_{c2}

Upper critical field after irradiation

Small number of investigations, lead to the same result $\Delta B_{c2} \sim +1$ T





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

T. Baumgartner, M. Eisterer, H.W. Weber, R. Flükiger, C. Scheuerlein, L. Bottura, SuST, 27, 015005 (2014)

Properties depending only on the number Frenkel pairs

We have experimentally proven by independent measurements that

- The transition temperature T_c,
- the order parameter *S* and
- the lattice parameter *a*

of Nb_3Sn depend only on the number of Frenkel pairs N_F, and thus of *dpa*.

T_c and *S* and are directly correlated, this constitutes an additional proof!

The prediction of these three quantities in future accelerators can be performed with a good precision.

What about J_c?

As expected, the prediction of J_c vs. *dpa* shows a considerably higher uncertainty, but a prediction can be done within certain limits

VI.C: Effect of Irradiation on J_c

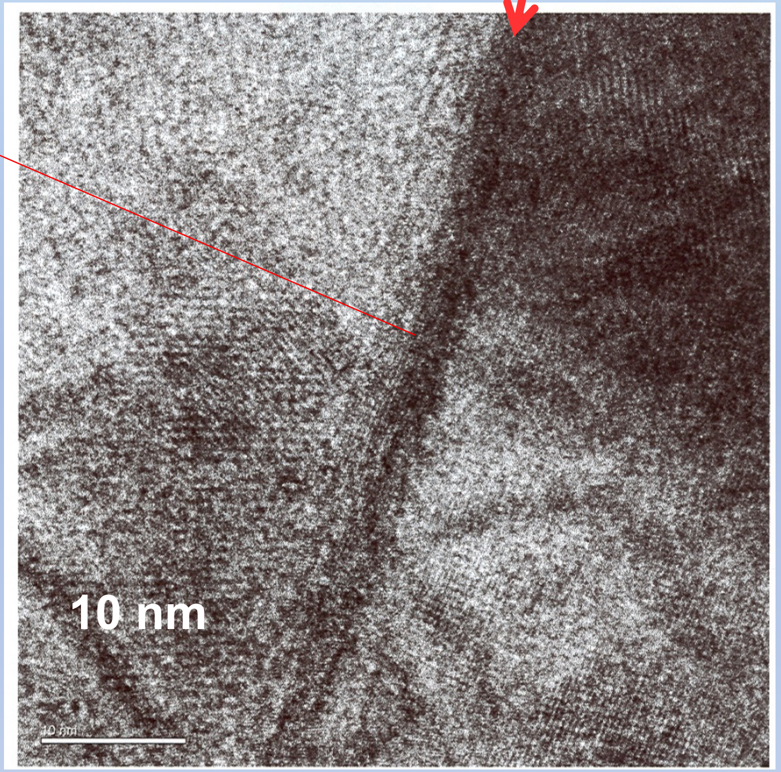
J_c: Phenomenon at nanometric scale

Before irradiation:

Intergrain boundaries between neighbouring A15 grains

Boundary between Nb_3Sn grains

M. Cantoni et al., 2006



4 nm: ~ Coherence length ξ_o

Nb_3Sn:

Defects at grain boundaries:
breakage of periodicity creates normal conducting regions
Vortices will pin the flux lines

→ J_c

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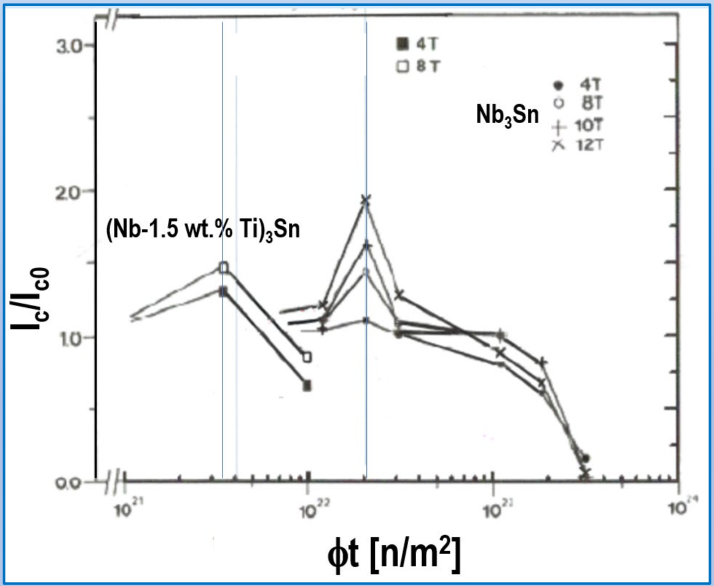
J_c in binary and alloyed Nb_3Sn

Two kinds of irradiation/measurement cycles have been applied:

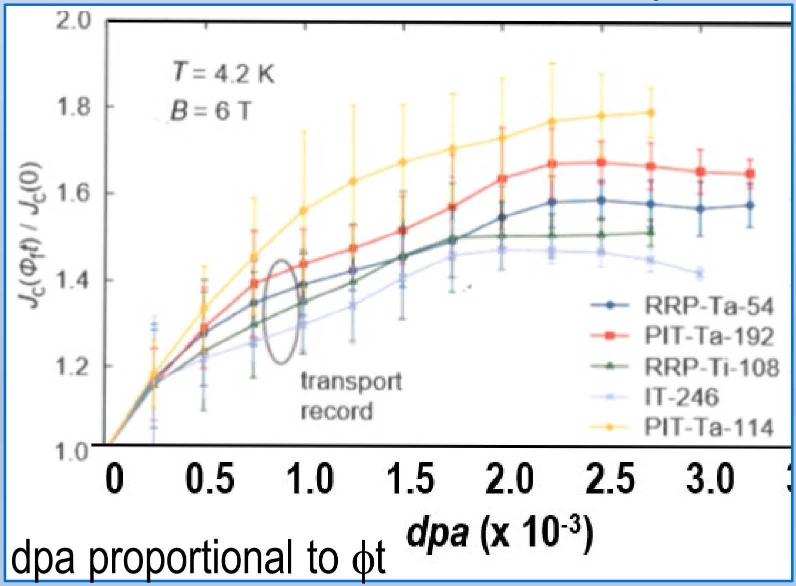
Only one irradiation: each wire undergoes only one Irradiation/measurement cycle (All data before 2013)



H. W. Weber, Int. J. Modern Phys., E 20 (2011)

All known data J_c vs. ϕt show a marked peak. $J_{c,max}$ occurs at different fluences for binary and alloyed Nb_3Sn

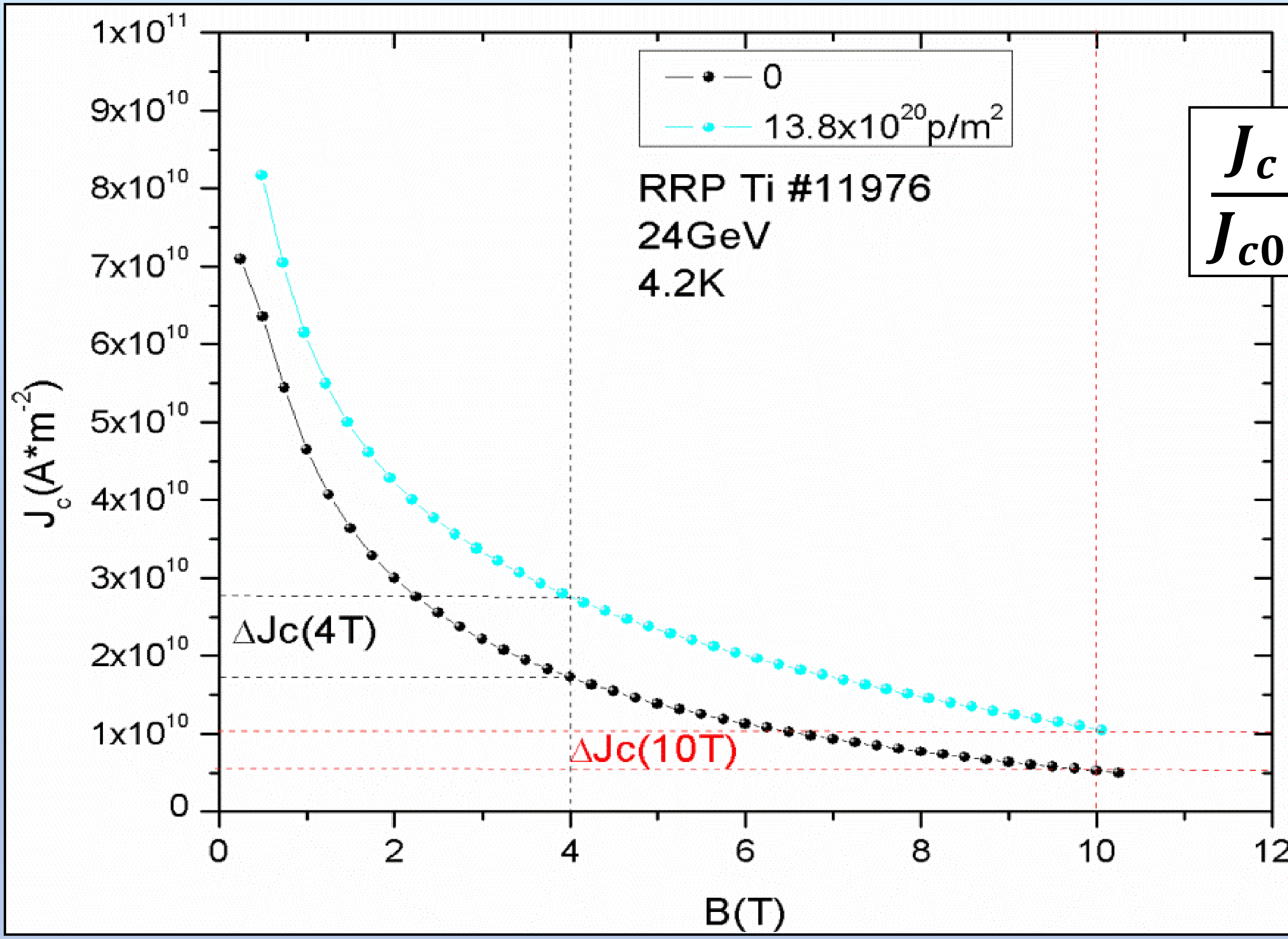
Repeated irradiation: The same wire is submitted to all irradiation/measurement cycles (Measurements at ATI, after 2013)



M. Eisterer et al., ongoing work

Current results at ATI: no clear peak. Is there diffusion at 300 K, after irradiation? Answer later in this talk

Irradiation: Larger enhancement of J_c/J_{c0} at higher fields



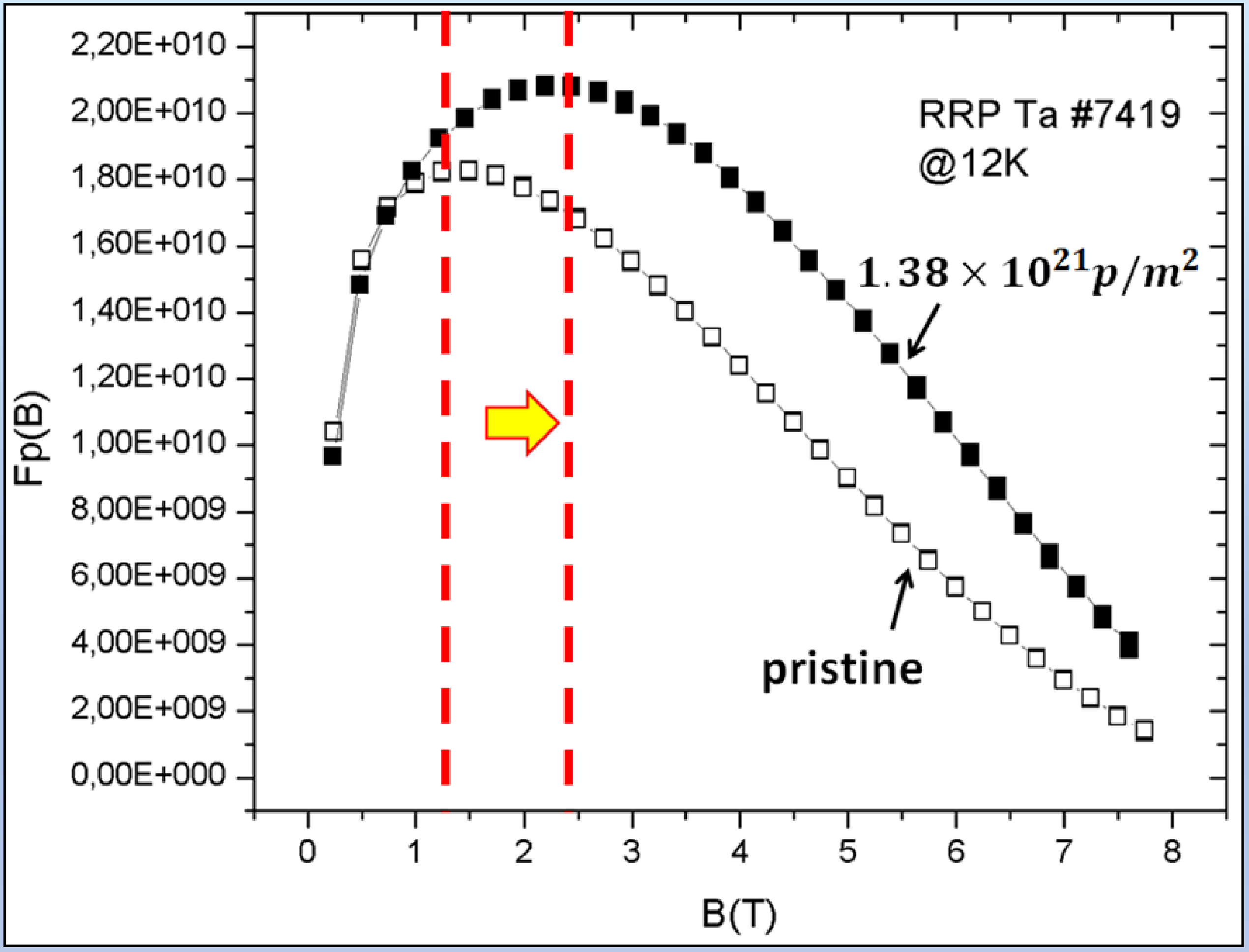
$$\frac{J_c}{J_{c0}}(4T) < \frac{J_c}{J_{c0}}(10T)$$

ΔB_{c2} = ~ +1 T

T. Spina, C. Scheuerlein, D. Richter, L. Bottura, A. Ballarino, R. Flükiger, J. Physics: Conference Series, 507, 022035 (2014)

Shift of the maximum $F_{p,max}$ after irradiation

Proton irradiation:



T. Spina et al., IEEE Trans. Appl. Supercond.,, 25, 6000505 (2015)

What is the nature of the enhancement of J_c after irradiation?

The two-mechanism model

Separation of contributions due to grain boundary and to point pinning:

T. Baumgartner, M. Eisterer, H. Weber, R. Flükiger, B. Bordini, L. Bottura, C. Scheuerlein, *SuST*, 27, 1, 2014

$$F_p(b) = c_1 * b^{0.5}(1-b)^2 + c_2 * b^1(1-b)^2$$

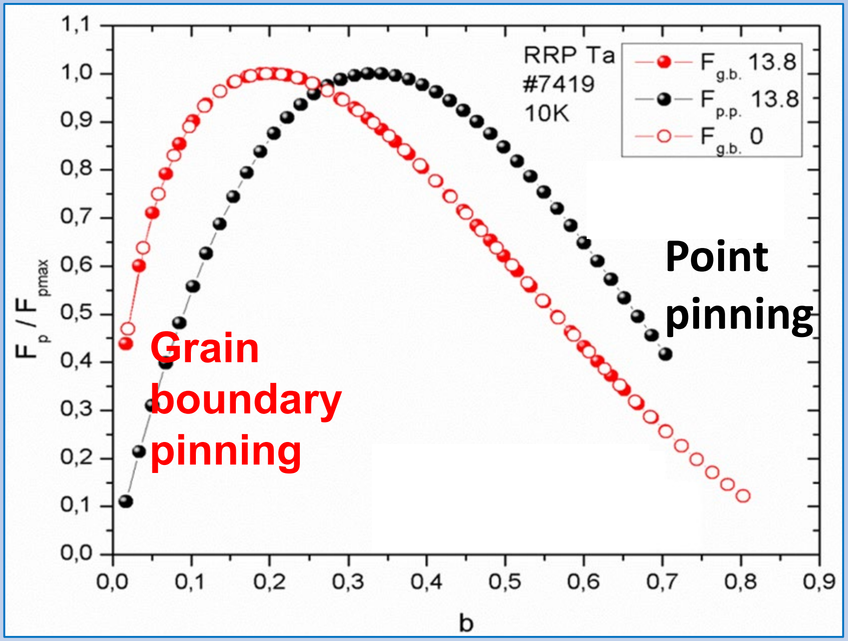
Grain boundary pinning

$c_1 \equiv c_{unirr}$

Point defect pinning

c_2 and B_{c2}: Fitting parameters

Grain boundary pinning: essentially unchanged after irradiation

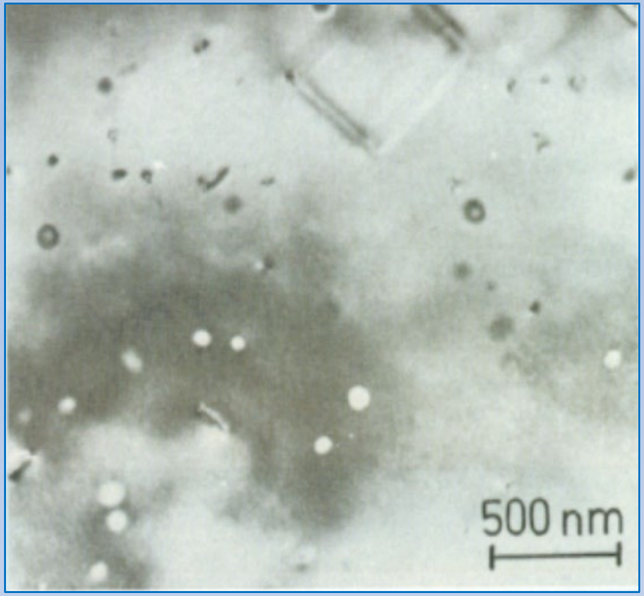


Origin of the enhancement of J_c after irradiation

The variation ΔB_{c2} is not sufficient for explaining the increase of J_c
(Brown, 1976; Colucci 1977, Fähnle 1977, Baumgartner, 2016)

Mechanisms leading to new pinning centers (additional to grain boundary pinning):

* **Observation of defect clusters** (Pande 1978)
* **Observation of dislocation loops** (H. Meier-Hirmer, H. Küpfer, J. Nucl. Mater., 108, 593 (1982)



- **Are defect clusters or dislocation loops responsible for the radiation-induced effects on J_c?**

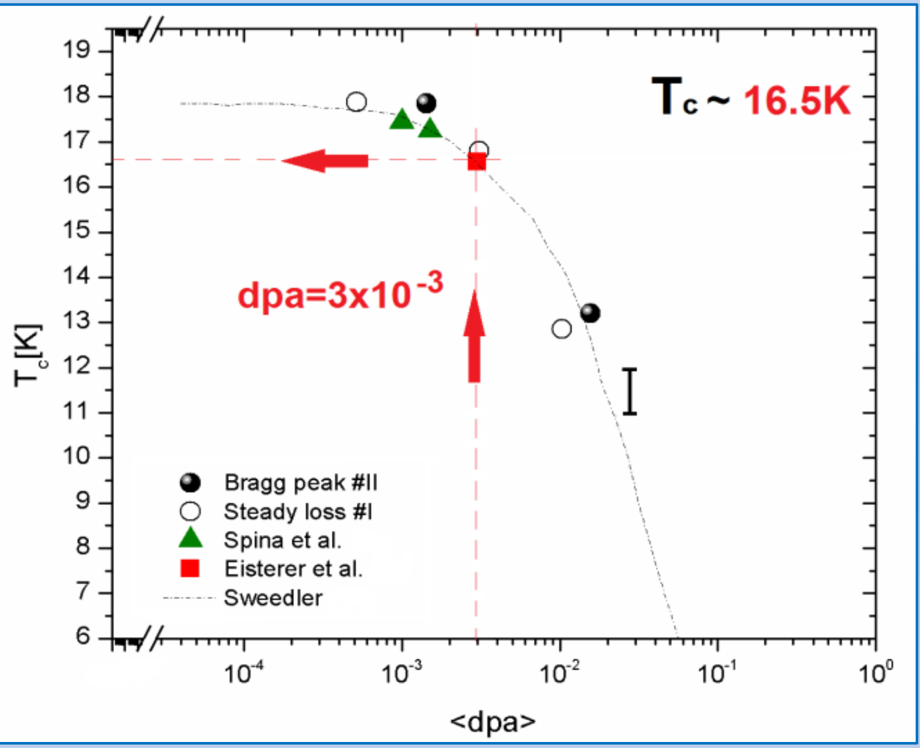
* **Are there other effects?**

More research is needed to fully answer these questions

Estimation of the changes in FCC/Run2 at *dpa* = 3 x 10^{-3}

Change of T_c for *dpa* = 3 x 10^{-3} value is extracted from the relationship between T_c and *dpa*

R. Flükiger et al., SuST, 30, 101979 (2017)



«Universal» behavior for neutrons and protons

dpa = 3 x 10^{-3}: ΔT_c = 1.3 ± 0.2 K

Two estimations, based on earlier 14 MeV irradiations:
A: Weiss et al, 1987,
B: Hahn et al., 1991

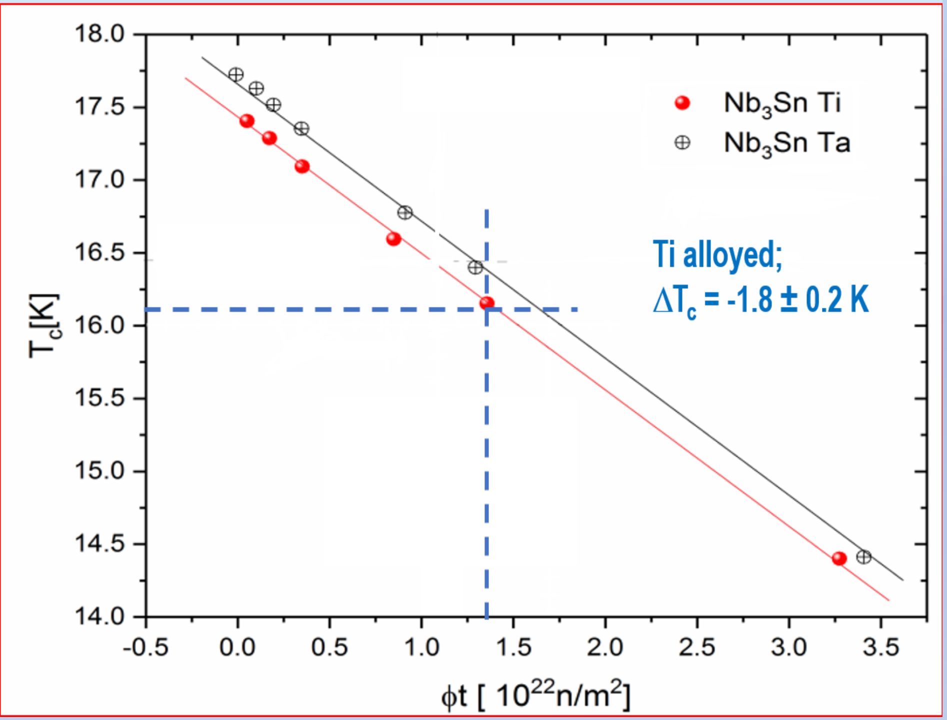
It is expected that the «universal» behavior is also valid for other particles: This question is being studied

Estimation of the changes in FCC/Run2, with *dpa* = 3 x 10^{-3}

A. First estimation:

Based on T_c vs. ϕt, 14 MeV neutron data on 19-core Nb_3Sn wires (resistive J_c measurements up to 20 T):

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



1st step: find T_c from *dpa* = 3x10^{-3}

2nd step: find corresponding *dpa* for 14MeV neutrons

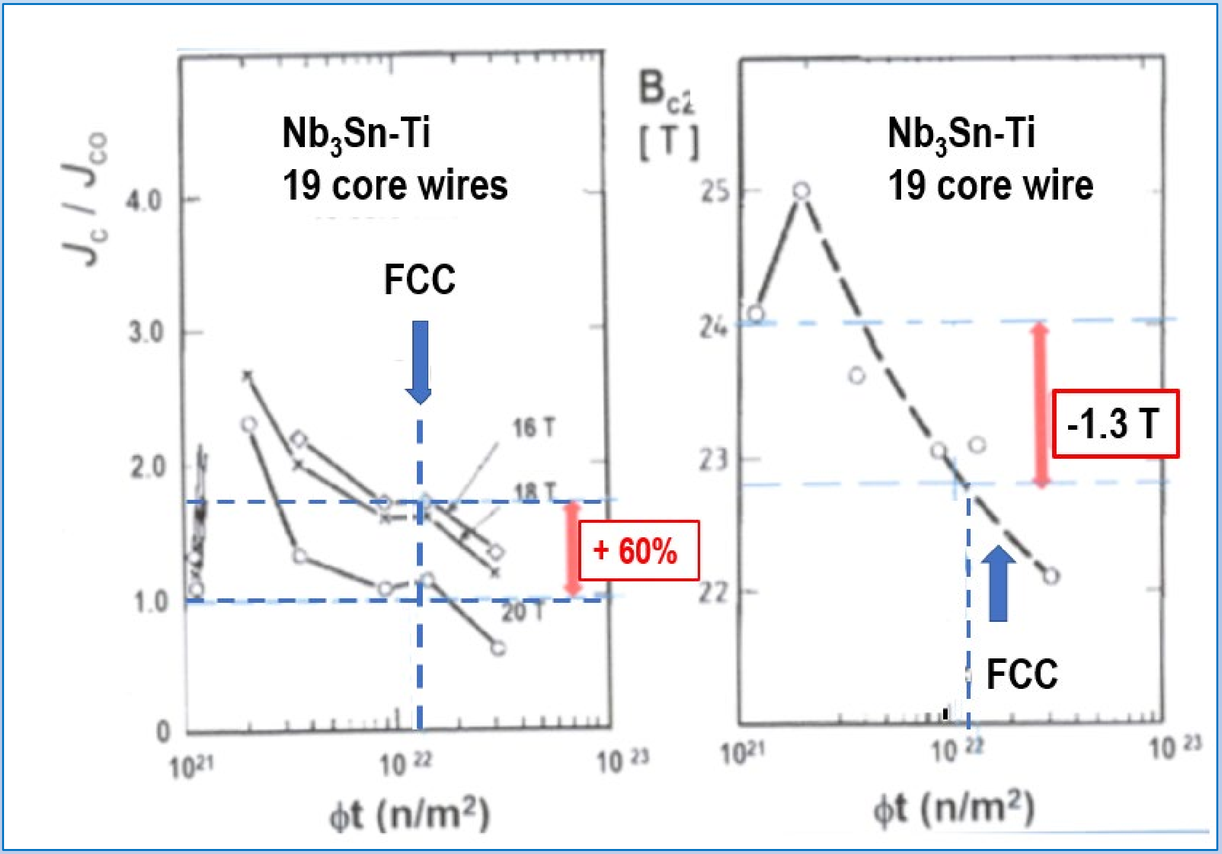
→ ***dpa*** **value for FCC/Run2:**

Φt(14 MeV) = 1.3 x10^{22}n/m^2

Estimation of the changes in FCC/Run2, with *dpa* = 3 x 10^{-3}

3rd step:

Find J_c and B_{c2} for the corresponding fluence at 14 MeV: 1.3 x 10^{22} n/m^2



At 16T/4.2K:

ΔJ_c = + 60%
ΔB_{c2} = - 1.3 T

For alloyed Nb_3Sn wires, we had found:

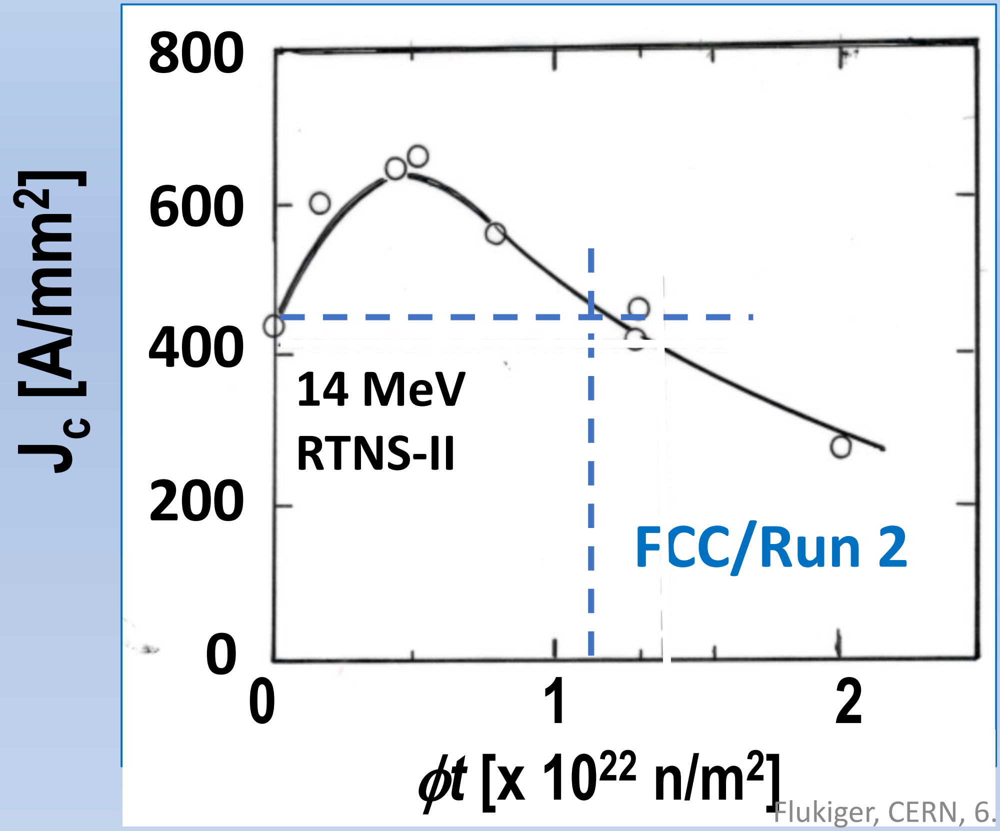
Total ΔT_c = - 1.8 ± 0.2K

F. Weiss et al, 1987

Estimation of the changes in FCC/Run2, *dpa* = 3 x 10^{-3}

B: Second estimation: **Based on T_c vs. ϕt, 14 MeV neutron data on 19-core Nb_3Sn wires (resistive J_c measurements up to 20 T)**

P.A. Hahn, M.W. Guinan, L.T. Summers, T. Okada, D.B. Smathers, J. Nucl. Materials, 179-181, 1127 (1991)



At 16T/4.2K:

ΔJ_c ~ 0
ΔB_{c2} not given

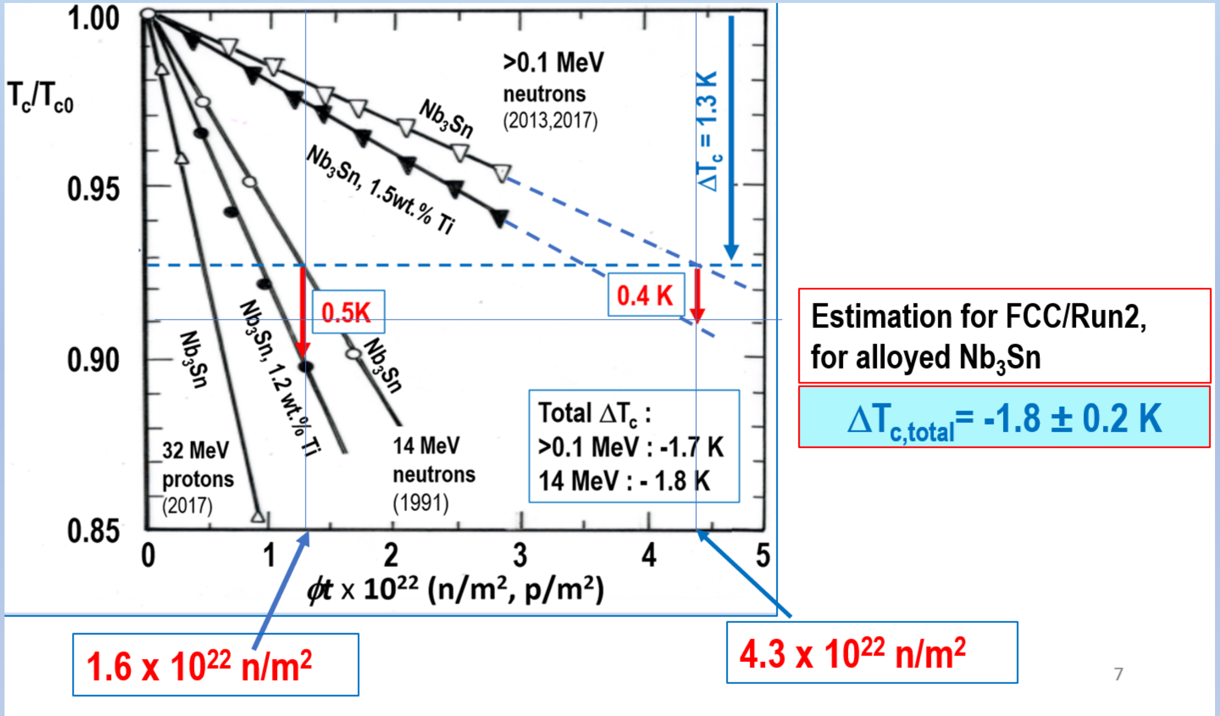
For alloyed wires, we had already found: ΔT_c = -1.8K ± 0.2 K:

Total ΔT_c = - 1.8 ± 0.2K

How will J_c vary with higher ϕt in TRIGA ?

TRIGA in Vienna is at present the only easily available neutron reactor

We have seen earlier that *dpa* = 3 x 10^{-3} for FCC/2 corresponds to a fluence of 4.3 x 10^{22} n/m^2 (E> 0.1 MeV):

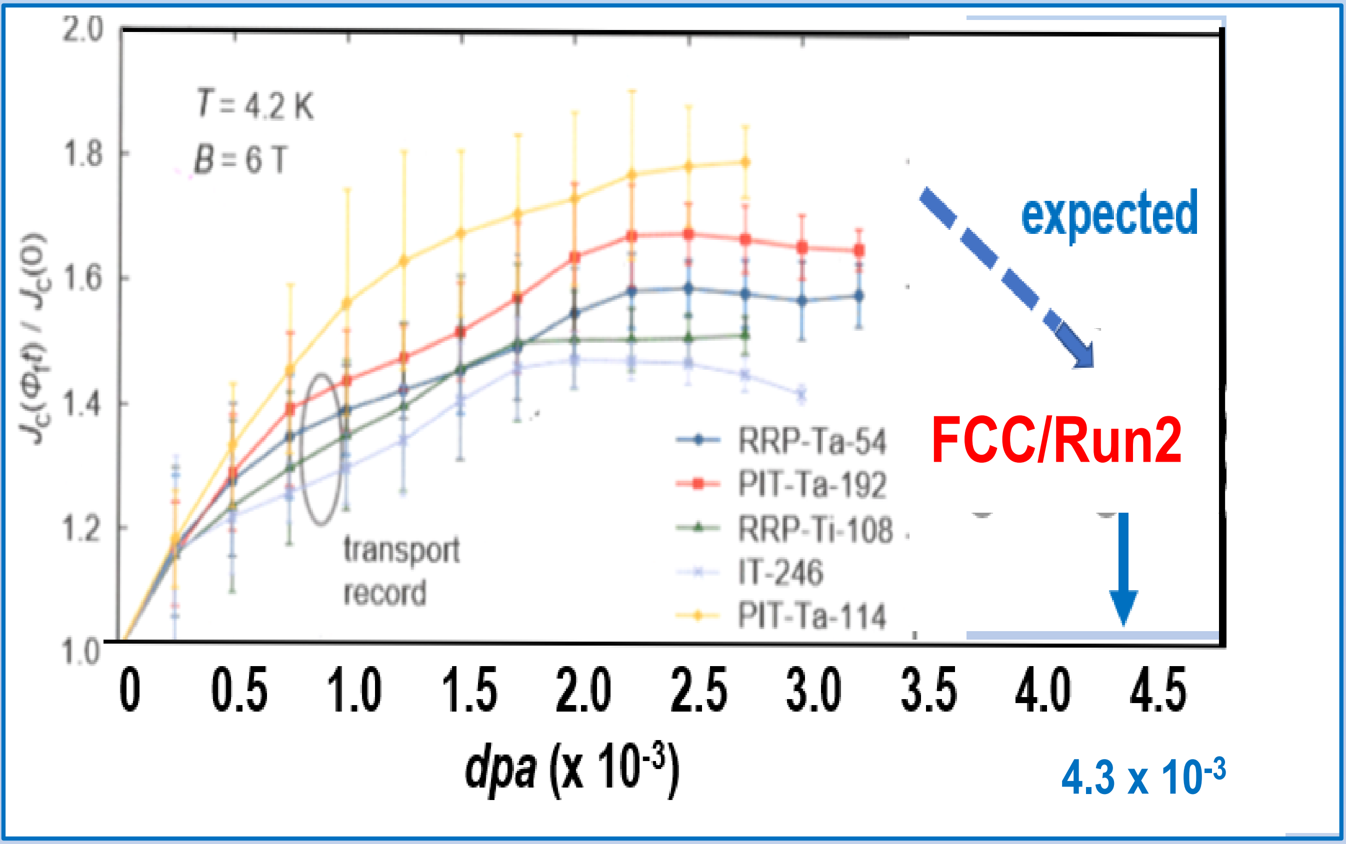


This allows to conclude about the reversibility of J_c at cycles between T_{irr} and 300K:

Expected behavior of J_c in Nb_3Sn wires in TRIGA

For E > 0.1 MeV: *ϕt* =4.3 x 10^{22} n/m^2 corresponds to *dpa* = 4.3 x 10^{-3}.

At *dpa* = 4.3 x 10^{-3}, dpa values are well beyond the maximum of J_c vs. ϕt curves for E > 0.1 MeV: this is comparable to all previous literature data

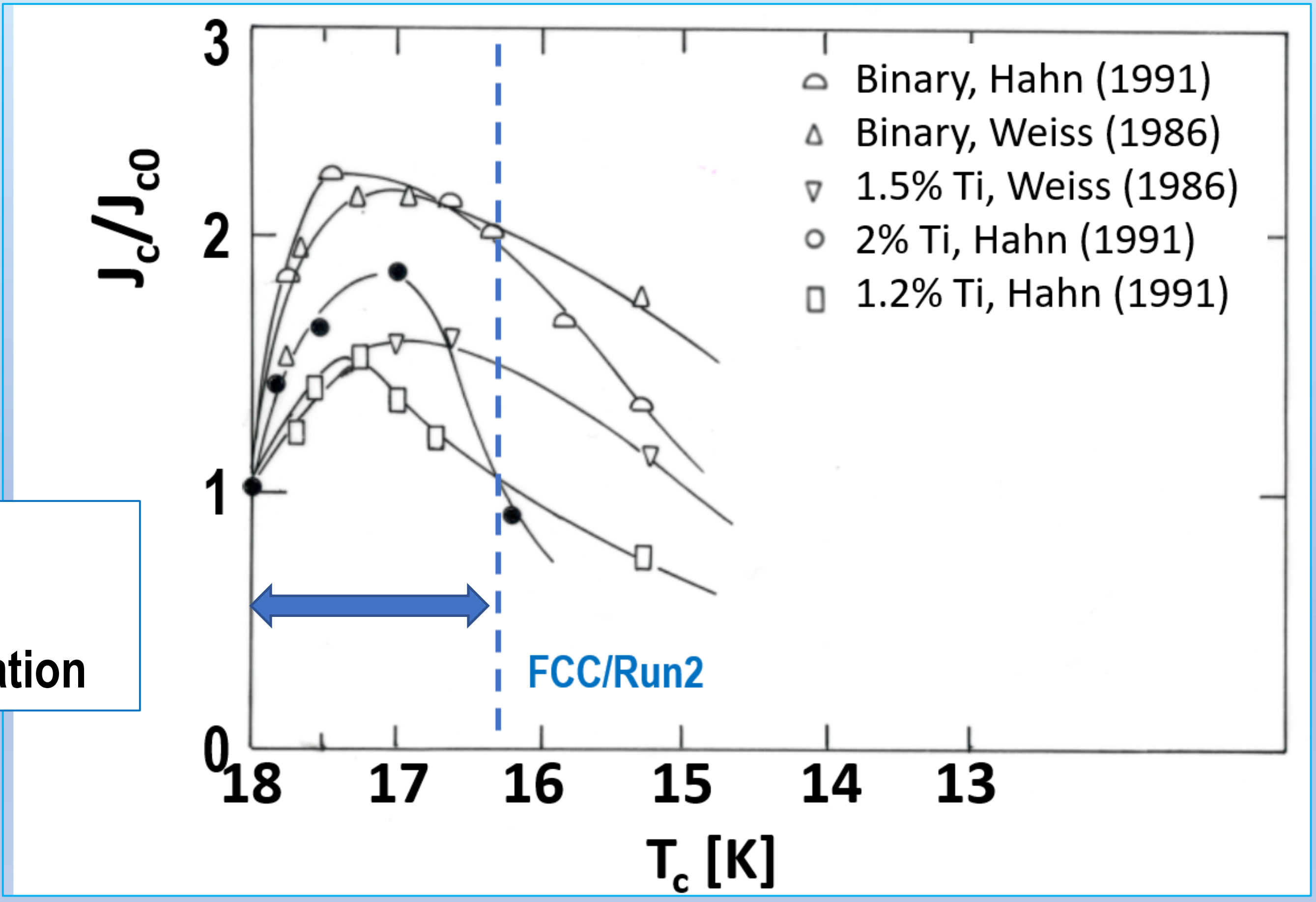


M. Eisterer,
T. Baumgartner et al.,
ICMC 2017

Starting from the data with E = 14 MeV, the data for higher fluence at E > 0.1 MeV can be predicted

1×10^{22} n/m^2 : dpa = 1 x 10^{-3}

General behavior of J_c/J_{c0} with decreasing T_c



Region of J_c enhancement prior to irradiation

VII. Remarks about recent progresses in J_c of Nb_3Sn

Will Nb_3Sn reach the required properties at 16 T ?

As mentioned in this talk, Nb_3Sn industrial wires should even overcome the limit of 1'500 A/mm^2 at 16T/4.2K, due to radiation damage, and possibly also due to stress effects.

There have been 2 very recent developments which show that Nb_3Sn has still a potential for a sizeable increase:

1: Internal oxydation (X. Xu et al., OSU, Columbus, Ohio), and
2: Nb_3Sn with Hf + Zr (S. Balachandran et al., NHMFL Tallahassee, FL)

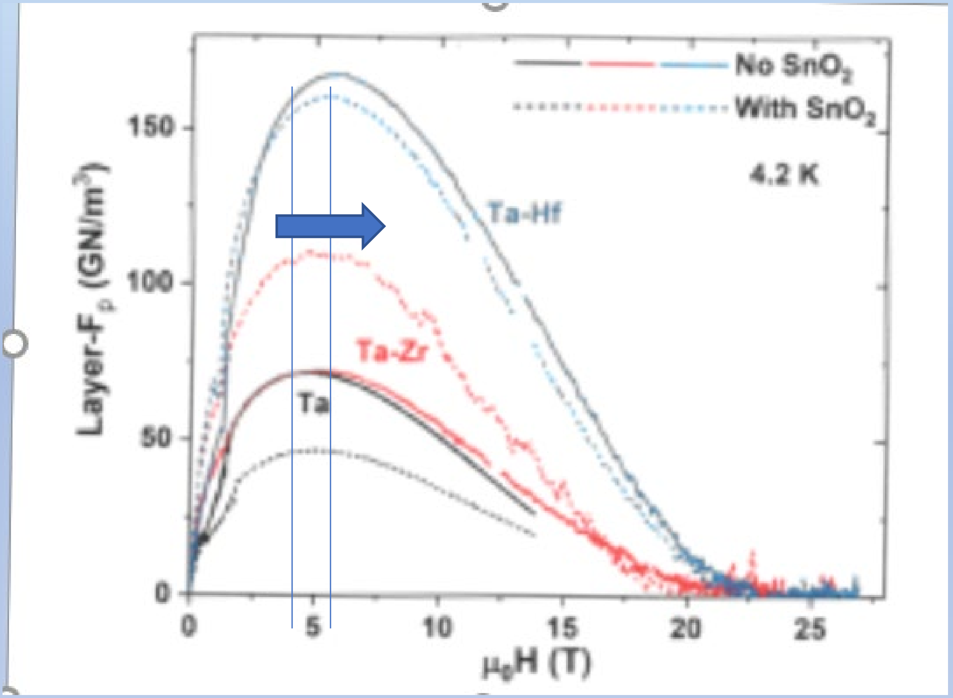
Both groups conclude that their developments may lead to non-Cu considerable above 2'000 A/mm2.
Jc What should we expect from these wires after irradiation?

Recent progress in Nb_3Sn with Zr + Hf additives

S. Balachandran et al. (group of D. Larbalestier): ArXiv 2018

Enhancement of J_c and B_{c2} by two effects:

1. **Substitution (by Ti)**
2. **Grain size reduction (attributed to Hf)**



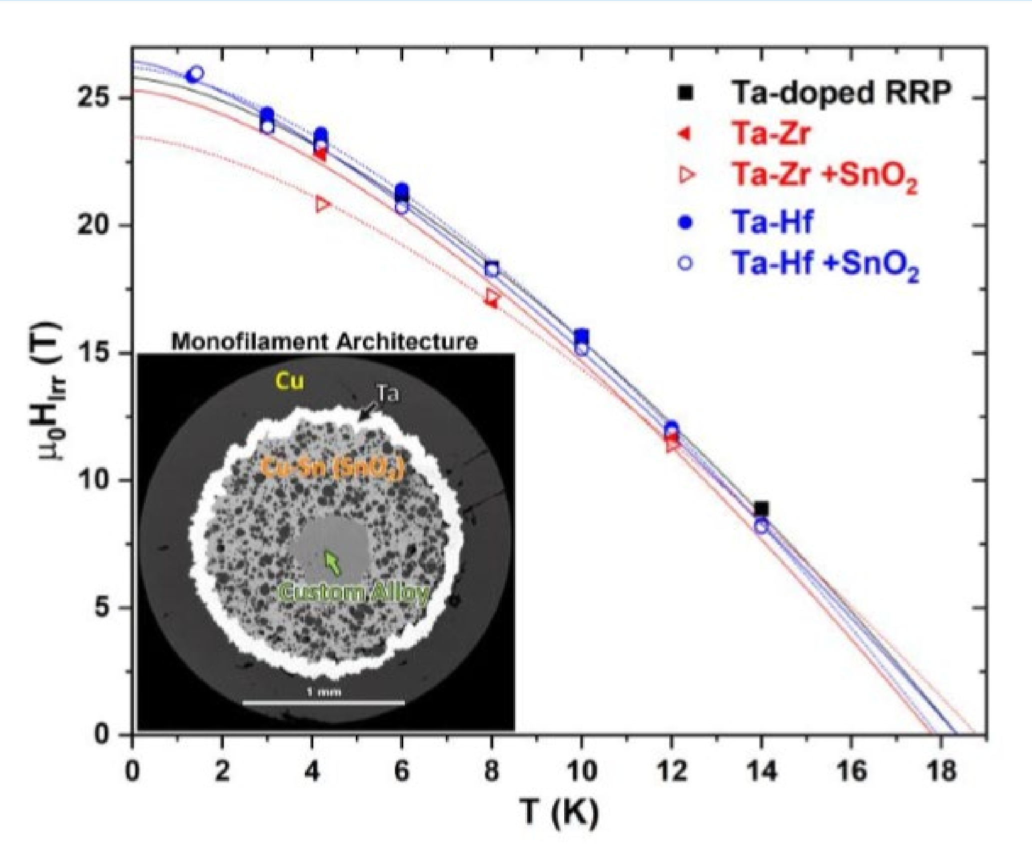
Shift of J_c(max) towards higher values of $b = B_{c2}/B_{c20}$: Additional point pinning (defect clusters?)

Also observed for Internal Oxidation

For irradiation: 1: Grain boundary pinning unchanged

2: Enhancement due to point pinning: additive? To be analyzed

Recent progress in Nb_3Sn with Zr + Hf additives



Highest B_{c2} for Hf added wires

S. Balachandran et al. Nov. 2018

Common point:

In both cases, Internal Oxidation and Hf +Zr additives, the enhancement of J_c is due to 2 effects: Grain boundary pinning + Point pinning

(the details of point pinning have still to be elucidated)

Conclusions

Conclusions (1)

- The change of T_c and J_c in Nb_3Sn after irradiation with multiple sources can be described by the parameter: *dpa* (displacement per atom)
- T_c is governed by the mobile Frenkel defects 6c-vacancy/interstitial (in the chains)
- The change of T_c and J_c after irradiation follows a different mechanism
- Based on the present considerations, the change of the super-conducting properties in the 3 types of accelerators studied here is estimated

Changes at 4.2 K	HiLumi LHC	FCC/RUN1	FCC/Run2
ΔT_c	< - 0.20 K	< - 0.40 K	- 1.8 ± 0.2 K
ΔJ_c	≤ + 30 %	≥ + 60 %	0….+ 60 %*)
ΔB_{c2}	< +1 %	< 2 %	- 1.30 T

*) depends on the type of wire

Conclusions (2)

* More work has to be done for a more precise knowledge of the behavior of the industrial wires which are foreseen for future accelerators:

* For a deeper understanding, more properties have to be studied *on the same* wire (including electrical resistivity, initial slope,….)

* Irradiations have to be performed on advanced wires using Internal Oxidation and quaternary additives, e.g. Hf +Zr.
From the present data, it follows that the higher amount of addition elements (Zr+ Hf) may lead to a decrease of T_c to values slightly below ΔT_c= – 1.8 ± 0.2 K found in the present work.