

Impact of the Number of *dpa* on the Superconducting Properties in HiLumi LHC and FCC Accelerators

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Outline

1. Accelerators: HiLumi LHC, FCC
2. The «displacement per atom» or *dpa*
3. Superconducting properties of Nb_3Sn vs. *dpa*
4. Estimated T_c , B_{c2} and J_c in the accelerator quadrupoles
5. Conclusions



1. Details of Future Accelerators at CERN

	HiLumi LHC	FCC/Run1	FCC/Run2 Ultimate goal
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	55 mm	55 mm
Neutrons	70 %	80 %	90 %
Charged particles	30 %	20 %	10 %

Magnetic field	12 T	16 T	16 T
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Working strategy

CERN launched a campaign to study the variation of the superconducting properties of Nb_3Sn wires during the entire acceleration lifetime.

Same industrial multifilamentary Nb_3Sn wires

Proton irradiation
study
@ CERN
(65 MeV, 24 GeV)

Neutron irradiation study
@ Atominstitut Vienna
(T. Baumgartner,
M. Eisterer et al.)

Nb_3Sn bulk samples

Proton irradiation study
NRC Kurchatov (Russia)
(A. Ryazanov,
Y. Zubavichus et al.)



2. The «displacement per atom or *dpa*

Accelerators contain multiple high energy sources:
Neutrons, protons, pions, electrons and photons.

At the same fluence ϕt , all physical properties are very different



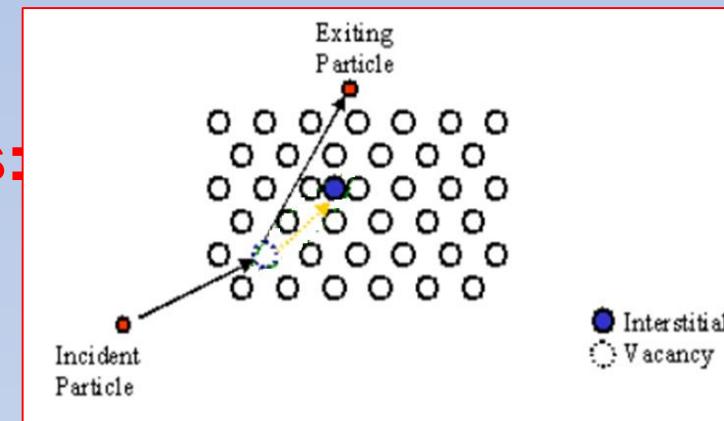
ϕt will be replaced by *dpa*

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

$$dpa \equiv \frac{A}{VN_A\rho} N_F$$

Frenkel pairs:



A: molar mass (g/mol), V: vol. (cm³), N_A: Avogadro number (mol⁻¹), ρ: mass density (g/cm³)

***dpa* : proportional to the fluence ϕt**

Essential property of *dpa*: **$dpa = \sum (dpa)_j$** j: various particles

3. Superconducting properties as a function of *dpa*

Properties measured after **neutron** and **proton** irradiation

T_c vs. dpa

S atomic order parameter vs. *dpa*

B_{c2} vs. *dpa*

J_c vs. *dpa*

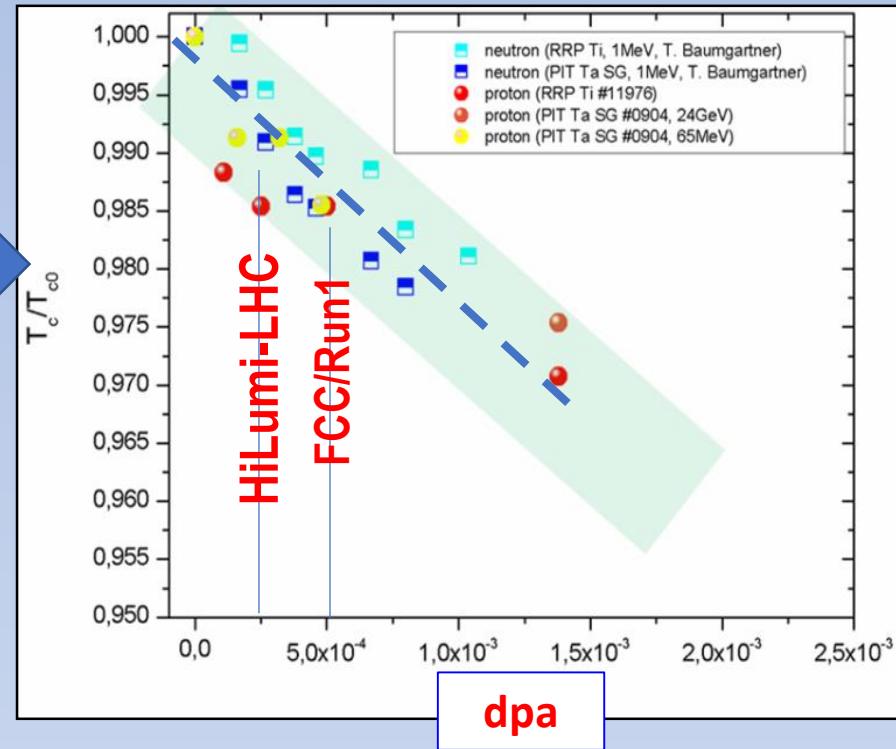
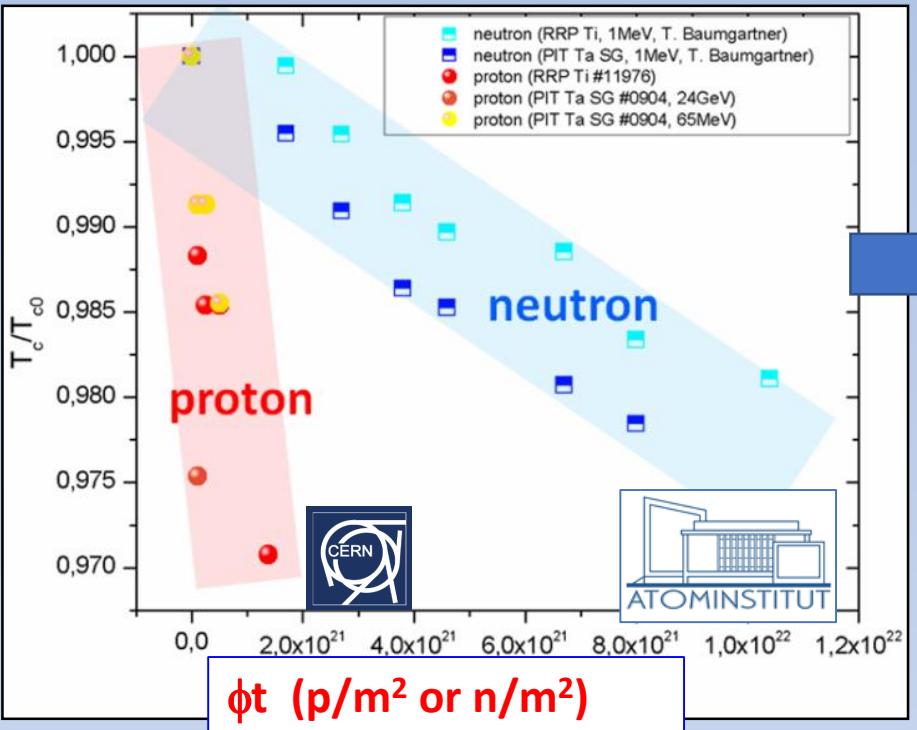
Lattice parameter a vs. *dpa*

These properties depend on the same way on N_F (nb. of Frenkel defects)
Exception: J_c (Special discussion)



Decrease of T_c after high energy irradiation

Different PROJECTILES (protons, neutrons) and ENERGIES



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

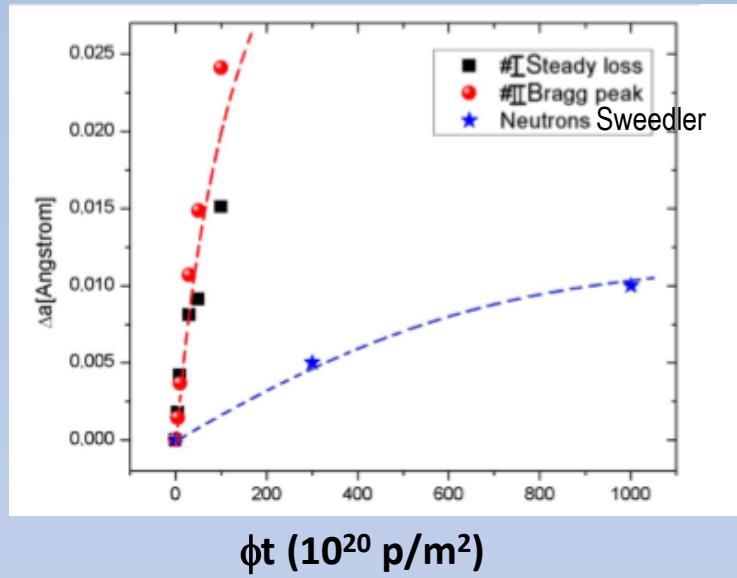
Neutrons: T Baumgartner et al., *Supercond. Science and Technol.*, 27,1(2014)

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.



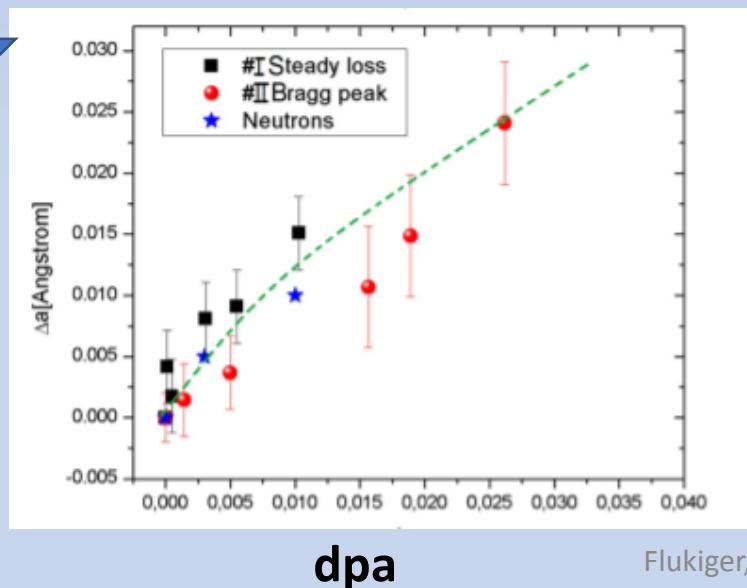
«Universal relation» between T_c and dpa

Enhancement of lattice parameter a for Nb_3Sn



dpa: universal parameter for lattice expansion

This confirms the direct dependence of the lattice parameter on the number of Frenkel pairs.



R. Flükiger, T. Spina, F. Cerutti, A. Ballarino, C. Scheuerlein, L Bottura, Y. Zubavichus, A. Ryazanov, R. Svetogorov, S. Shavkin, P. Degtyarenko, Y. Semenov, C. Senatore and R. Cerny,
Supercond. Sci. Technol., 30, 054003 (2017)

The case of J_c after irradiation

Different mechanism for changes of T_c and J_c , from recovery experiments on V_3Si

Recovery of T_c : 500 – 620 °C

Decrease of J_c : 590 – 680 °C

Meier-Hirmer, IEEE Trans. Magn., MAG-17, 1981

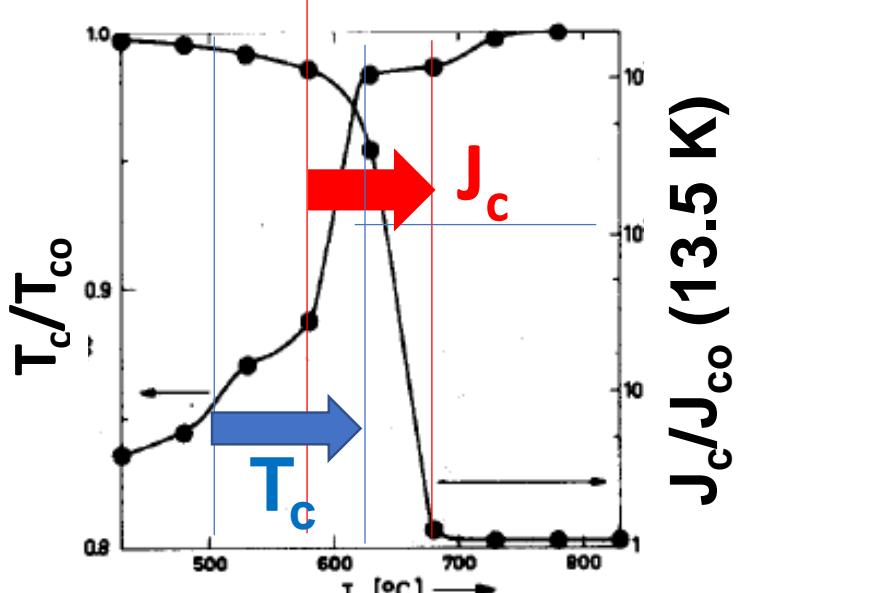
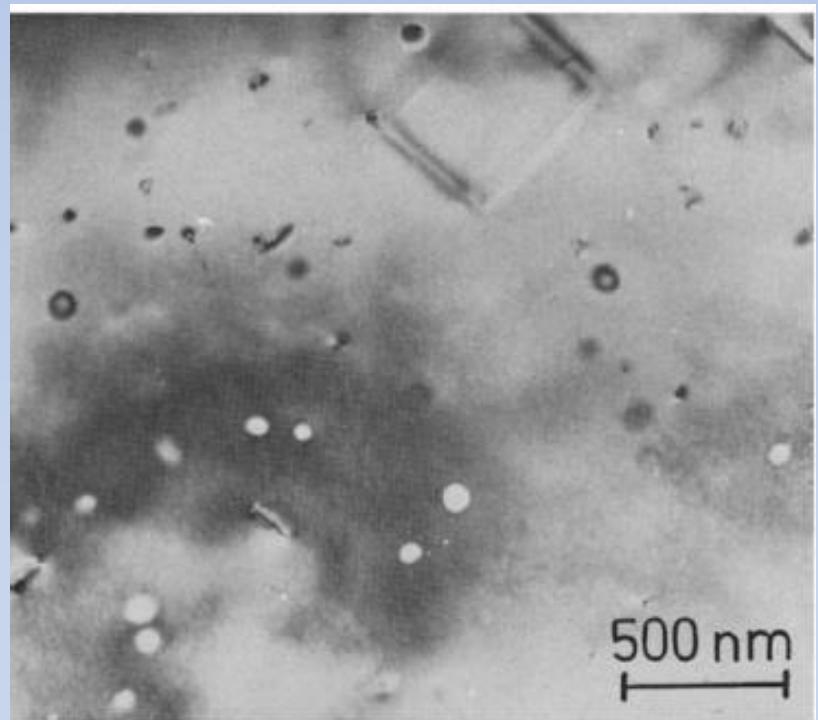


Fig. 9. T_c/T_{c0} and j_c/j_{c0} (13.5 K, $b=0.5$) versus annealing temperature T_a for sample LS5.

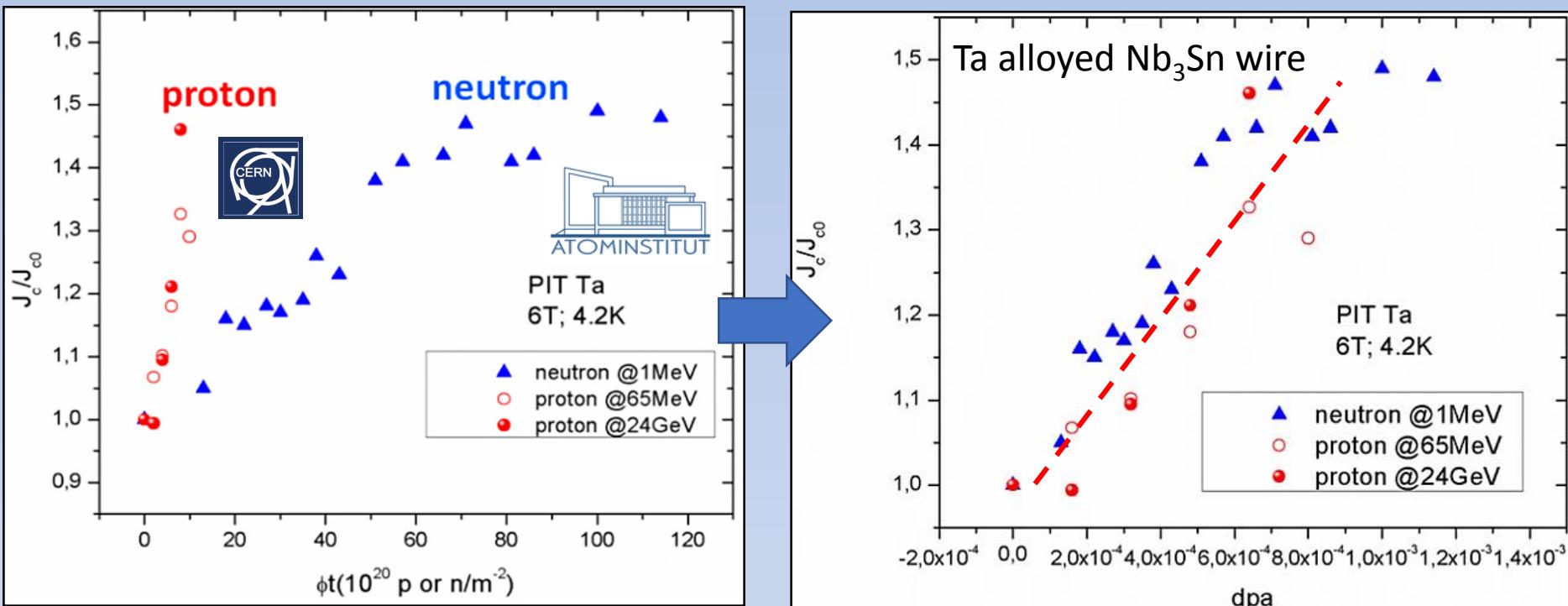
R. Meier-Hirmer, H. Küpfer,
J. Nucl. Mater. 108 - 109, 593 (1982)



Dislocation loops are dissolved at 680°C

Enhancement of J_c for a Nb_3Sn PIT wire

In contrast to T_c , the link between the variation of J_c and dpa is not established by S but by other radiation induced defects (point pinning)

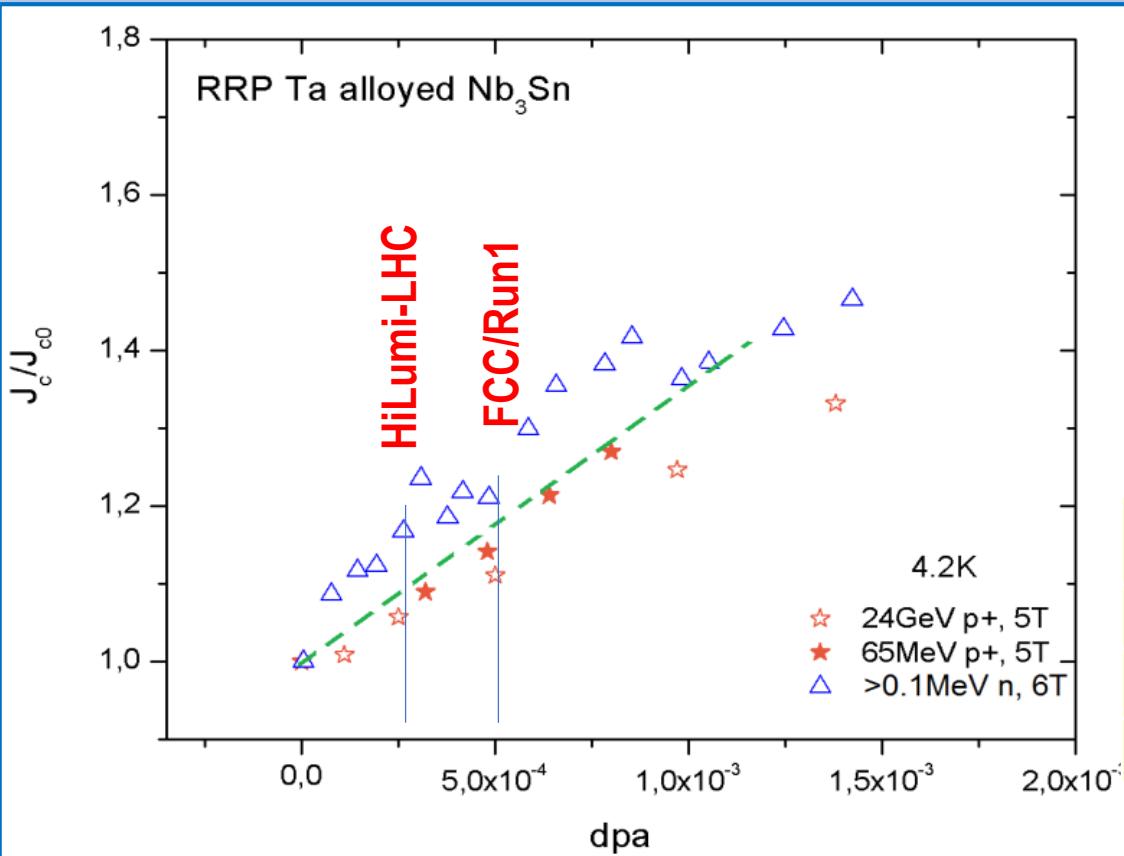


T. Spina et al, *IEEE Trans.Appl.Supercond.*, 25,6000505 (2015)

T. Baumgartner et al., *Supercond. Science Technol.*, 27,1,2014

Increasing the dpa number enhances the quantity of stable point defects
(depending on the number of Frenkel Pairs)

Enhancement of J_c for a Nb_3Sn RRP wire



Both PIT and RRP Nb_3Sn wires with **Ta** alloying show the same behavior:

J_c depends essentially on only one parameter: **dpa**

Changes	HiLumi LHC	FCC/RUN1
ΔT_c	< - 0.20 K	< - 0.40 K
ΔJ_c	$\leq + 30 \%$	$\geq + 60 \%$
ΔB_{c2}	$< +1 \%$	$< 2 \%$

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

Neutrons: T Baumgartner et al., *Supercond. Science and Technol.*, 27,1(2014)

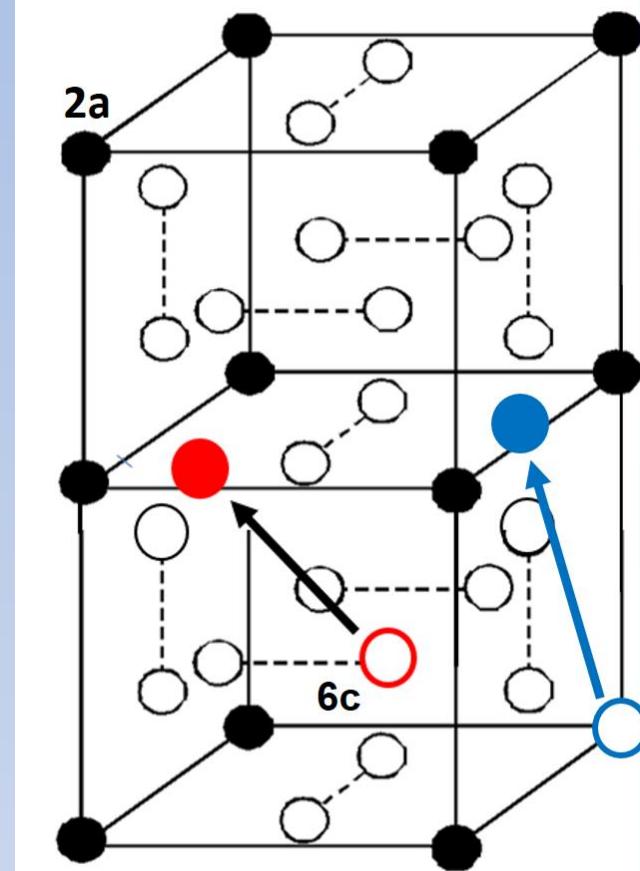
Frenkel pairs in the A15 structure

- T_c is governed by the Frenkel defects
6c-vacancy/interstitial only

Neighbouring Frenkel defects are closer than 2 nm and act as point pinning centers

- J_c is governed by both:
6c-vacancy/interstitial and
2a-vacancy/interstitial

This would explain why annealing effects after irradiation show a different behavior



○ Nb
● Sn

Frenkel defects:
6c-vacancy/interstitial
2a-vacancy/interstitial

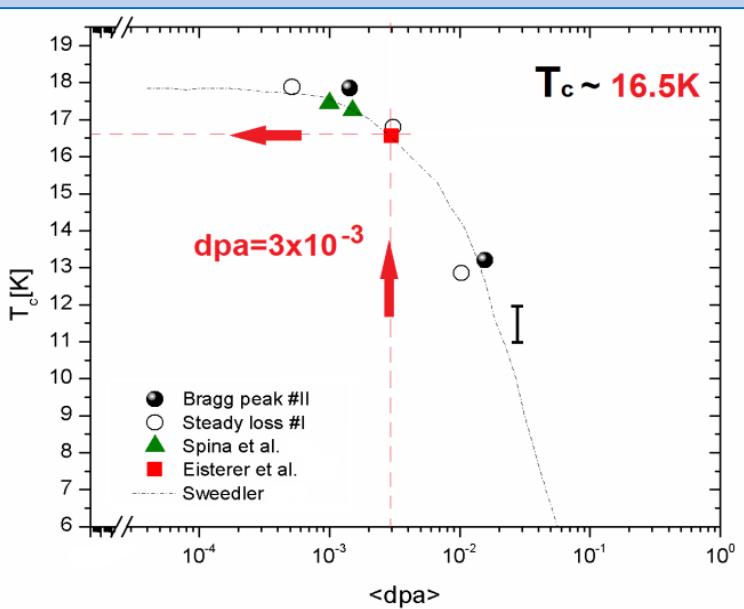
Estimation of the changes in FCC/Run2, with $dpa = 3 \times 10^{-3}$

dpa value for FCC/Run1: * well beyond than the maximum of J_c vs. dpa
* higher than the values presently reached

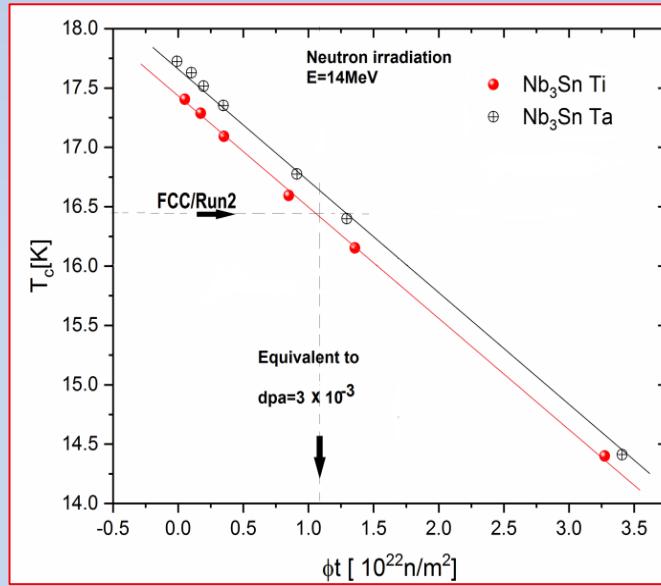
→ Estimation: on the basis of **14 MeV neutron** data on 19-core **Nb₃Sn wires** (resistive measurements up to 20T, no dpa known)

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

1st step: find T_c from $dpa = 3 \times 10^{-3}$



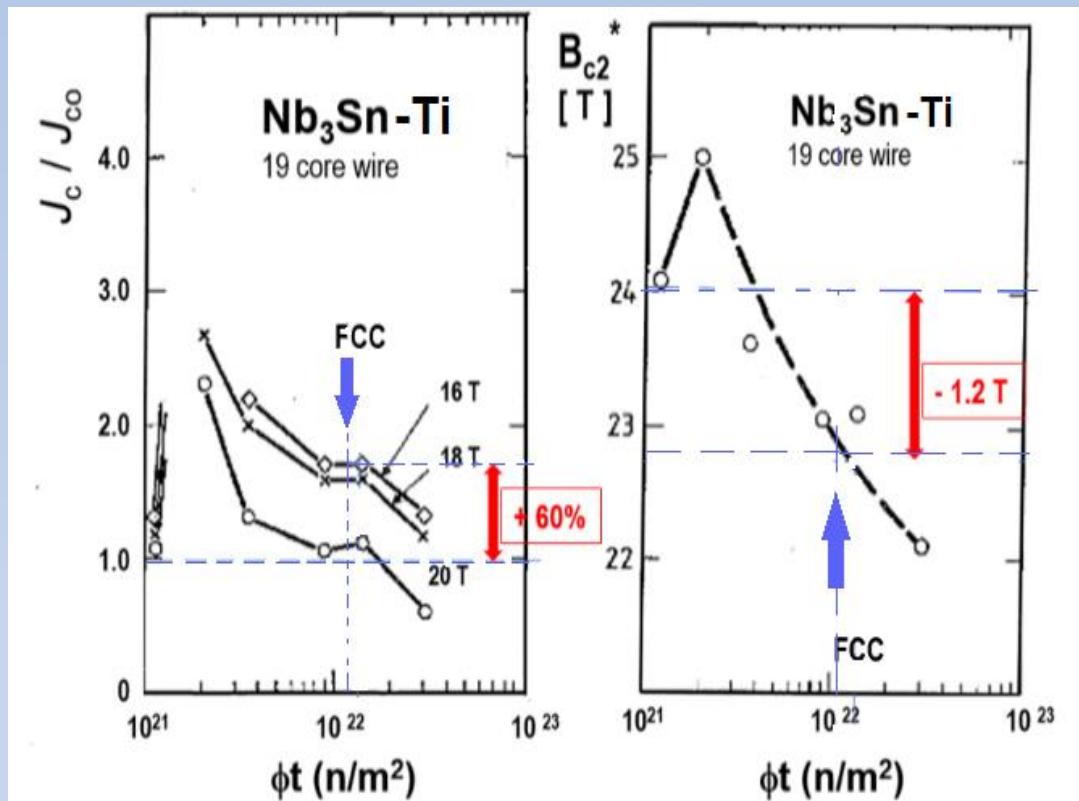
2nd step: find corresponding dpa for 14MeV neutrons



$dpa(14 \text{ MeV})$
 $= 1.1 \times 10^{-3}$

Estimation of the changes in FCC/Run2, with $dpa = 3 \times 10^{-3}$

3rd step: Find J_c and B_{c2} for the corresponding $dpa(14 \text{ MeV})$



$$\Delta J_c = + 60\%$$
$$\Delta B_{c2} = - 1.2 \text{ T}$$

Conclusions

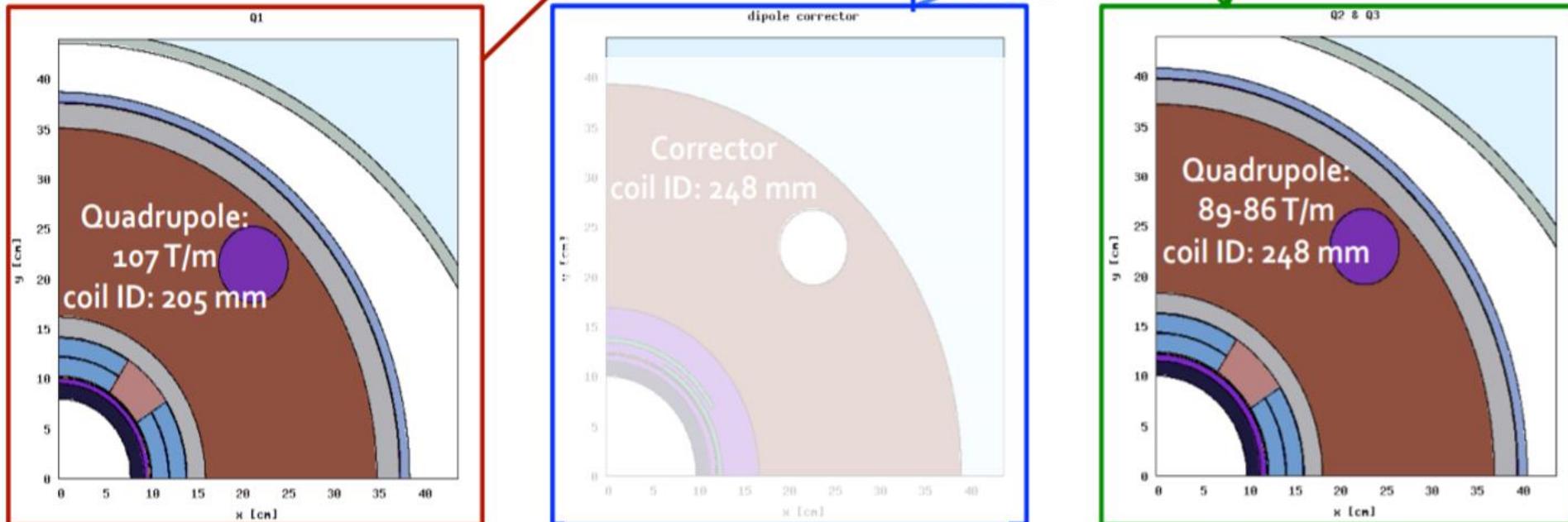
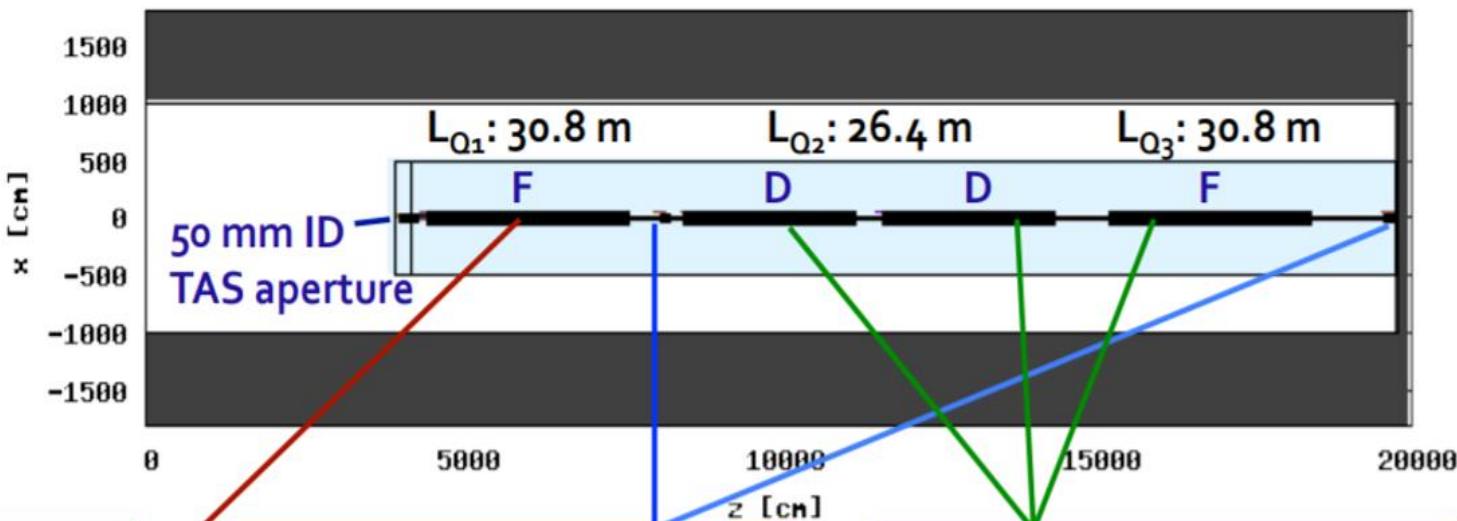
- The change of T_c , S , a and J_c in Nb_3Sn after irradiation can be described by only a single parameter: **dpa** (displacement per atom)
- The mechanism for the change of T_c and J_c is different :
- T_c is governed by the Frenkel defects **6c-vacancy/interstitial** only
- J_c is governed by both **6c-vacancy/interstitial** and **2a-vacancy/interstitial**
Neighbouring Frenkel defects are closer than 2 nm and act as point pinning centers
- Based on the present considerations, the change of the superconducting properties in 3 types of accelerators is estimated:

Changes at 4.2 K	HiLumi LHC	FCC/RUN1	FCC/Run2
ΔT_c	$< -0.20 \text{ K}$	$< -0.40 \text{ K}$	-1.5 K
ΔJ_c	$\leq +30 \%$	$\geq +60 \%$	$\leq +60 \%$
ΔB_{c2}	$< +1 \%$	$< 2 \%$	-1.20 T

Thank you for the attention !

FCC Accelerator: Quadrupoles

Half crossing
angle: $89.15 \mu\text{rad}$



Inner W shield: **15 mm** and **55 mm** (ultimative FCC goal)