Properties of Nb$_3$Sn magnets in the accelerators HiLumi LHC and FCC

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DQMC, University of Geneva
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
Outline

I. Introduction
II. What happens in the Nb$_3$Sn structure during high energy irradiation?
III. Definition of dpa (displacement per atom)
IV. Expected radiation load in Future Accelerators (HiLumi LHC, FCC)
V. The irradiation program at CERN
VI. Radiation damage mechanism in Nb$_3$Sn
   A. dpa, a «universal» parameter for T$_c$ changes after irradiation
   B. Effect of irradiation on B$_{c2}$
   C. Effect of irradiation on J$_c$ of Nb$_3$Sn wires
      Expected effects in HiLumi-LHC and in FCC
VII. Remarks about recent progress in Nb$_3$Sn
VIII. Conclusions
1. Introduction
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$_3$Sn

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$_3$Sn 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)
<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HE-LHC</th>
<th>HE-LHC</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (km)</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>97.5</td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>8.33</td>
<td>16</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>C.o.M. energy (TeV)</td>
<td>14</td>
<td>27</td>
<td>33</td>
<td>100</td>
</tr>
</tbody>
</table>
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:

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<td>3'000 fb⁻¹</td>
<td>5'000 fb⁻¹</td>
<td>30'000 fb⁻¹</td>
</tr>
<tr>
<td>Coil ID</td>
<td>150 mm</td>
<td>205 mm</td>
<td>205 mm</td>
</tr>
<tr>
<td>dpa</td>
<td>2.5 × 10⁻⁴</td>
<td>5 × 10⁻⁴</td>
<td>3 × 10⁻³</td>
</tr>
<tr>
<td>W thickness</td>
<td>6-12 mm</td>
<td>15 mm</td>
<td>55 mm</td>
</tr>
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Chosen for the present estimation
II. What happens in the Nb$_3$Sn structure during high energy irradiation?
High energy particle 
(n, p, π, heavy ions, fission fragments)

Collision events (1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd},...)

Frenkel defects, Vacancies, Interstitials
Focused Collision Replacement Sequences

Vacancy mechanism

Lattice expansion

\(\Delta a > 0\)

Mean Static Displacements

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

Disordering (Antisite Defects)

\(\Delta S > 0\)

Defect clusters

\(\Delta V\) Damaged volume

amorphous or transformed
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:

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

II. «Thermal spikes»: Local melting, cascades, point defects of nm size

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

IV. «Annealing stage»: Thermal diffusion, No new vacancies, but Displacement Collision Sequences

- dpa
- Stable Frenkel defects
- Mobile Frenkel defects

Flukiger, CERN, 6.12.2018
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

<102> Focusing Displacement Collision Sequence

Step IV: Mobile Frenkel defects

Occupied «virtual» site

Overlapping of Nb atoms in A15 structure

Change of the order parameter $S$

$dpa$ unchanged
The «displacement per atom» or \( dpa \)

dpa: calculated by the FLUKA code:  [http://www.fluka.org](http://www.fluka.org)
Multipurpose interaction, incl. a Monte Carlo simulation, taking into account secondary ions

\[
dpa \equiv \frac{A}{VN_A \rho} N_F
\]

A: molar mass (g/mol), V: vol. (cm\(^3\)), \( N_A \): Avogadro number (mol\(^{-1}\)), \( \rho \): 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$_3$Sn 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

* 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

From FLUKA MonteCarlo simulations:
A. Lechner, F. Cerutti et al. 2014
Evaluation of the damage caused by high energy irradiation on the superconducting properties of Nb$_3$Sn wires in the magnets of HiLumi-LHC (quadrupoles) and FCC (dipoles) during lifetime.

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

\textit{From FLUKA} MonteCarlo simulations:
A. Lechner, F. Cerutti et al. 2014

Tasks: * Determination of the changes \textit{dpa} vs. $T_c$ and \textit{dpa} vs. $J_c$
* Evaluate the changes of $T_c$, $B_{c2}$ and $J_c$ during lifetime
IV. Expected radiation load in Future Accelerators:
HiLumi LHC, FCC
FLUKA Calculations have been performed at CERN for the values of

* the quadrupole/dipole magnets
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The Nb$_3$Sn superconducting magnets in these accelerators will be submitted to high energy irradiation, produced by multiple particles:

- Photons
- Electrons
- Neutrons
- Protons
- Pions

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

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:

<table>
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<tr>
<th>Material</th>
<th>Reversibility</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Insulator</td>
<td>Irreversible</td>
<td>Most sensitive part to high energy irradiation</td>
</tr>
<tr>
<td>2. Cu stabilization</td>
<td>$\geq 90%$ reversible at 300 K</td>
<td>High initial RRR required</td>
</tr>
<tr>
<td>3. Nb$_3$Sn wires</td>
<td>Irreversible at 300K</td>
<td>Only reversible at $\geq 700^\circ$C: not suitable for magnets</td>
</tr>
</tbody>
</table>

**Nb$_3$Sn wires:** No recovery at 300K: The initial values of $T_c$, $B_{c2}$ and $J_c$ of Nb$_3$Sn 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

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<th>FCC/Run1</th>
<th>FCC/Run2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>~ 70 %</td>
<td>~ 80 %</td>
<td>~ 90 %</td>
</tr>
<tr>
<td>Charged particles</td>
<td>~ 30%</td>
<td>~ 20 %</td>
<td>~ 10 %</td>
</tr>
</tbody>
</table>

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
Where can the Nb$_3$Sn 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)

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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: $\text{Nb}_3\text{Sn}$ wires and $\text{Nb}_3\text{Sn}$ bulk samples
The Irradiation Program at CERN

Same set of Nb₃Sn wires

Nb₃Sn wires

Proton irradiation @ CERN (24 GeV)

Neutron irradiation
ATI Vienna, Austria
> 0.1 MeV

Proton irradiation
Louvain Cyclotron, Belgium (65 MeV)

Nb₃Sn wires + bulk samples

Proton irradiation
NRC Kurchatov (Russia)
Industrial Nb$_3$Sn wires for the CERN irradiation study

**Internal Tin (RRP)**
- Nb diffusion barrier
- Sn
- Nb-Ta (or Ti)
- Cu

**Powder In Tube (PIT)**
- Nb-Ta
- Cu
- Sn rich powder

**Oxford Instruments**
- RRP Ta
  - #7419

**Bruker**
- RRP Ti
  - #11976
- PIT Ta
  - #0904

200 µm

100 µm
## Characterization of the Nb$_3$Sn wires (at 12 T)

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

### 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 Nb₃Sn samples (Kurchatov)

Nb₃Sn platelets: $d = 0.090 - 0.15$ mm

- Nb₃Sn melted under 2 kbar at UniGe
- Cut by spark erosion
- Polished
- Flash annealed to remove stresses

> 98% single phase

VI. Radiation damage mechanism in Nb$_3$Sn

VI.A. $dpa$: «Universal» parameter for the change of $T_c$
The A15 crystal structure of Nb$_3$Sn

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

$S = 1$

Perfect order

$S \neq 1$

Partial disorder

$S$ depends on the fluence $\phi t$

$S = S_0 \cdot \exp (-k \cdot \phi t)$
Atomic ordering and $T_c$ in Nb$_3$Sn

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

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


$T_c/T_{c0}$ vs. $S$ very similar, for both, neutron and proton irradiation
In the region of interest for accelerators, $T_c$ vs. $\phi t$ is linear. It reflects the **damage energy** of the incident particle.

Well-known data:

$$T_c = T_c(\phi t)$$
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.
The dependence $T_c$ vs. $\phi t$ for protons and neutrons in binary Nb$_3$Sn

For binary Nb$_3$Sn, 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.

$dpa$ : «universal» parameter for binary Nb$_3$Sn

R. Flükiger et al., SuST, 30, 101979 (2017)
Determination of $\Delta T_c$ for FCC/Run2 for binary Nb$_3$Sn

FCC/Run2: \( dpa = 3 \times 10^{-3} \) \( \rightarrow \) \( \Delta T_c \)

Recent result: For binary Nb$_3$Sn, there is a direct correlation between \( T_c \) and \( dpa \) (or protons and neutron irradiation)

FCC/Run2: \( dpa = 3 \times 10^{-3} \)

\( \Delta T_c = -1.3 \pm 0.2 \) K


Situation in alloyed Nb$_3$Sn?
Difference between binary and alloyed Nb$_3$Sn

In accelerators, only alloyed Nb$_3$Sn wires will be used.

**Binary : Nb$_3$Sn**

**Alloyed: (Nb$_{1-x}$Ti$_x$)$_3$Sn or (Nb$_{1-x}$Ta$_x$)$_3$(Sn$_{1-y}$Ta$_y$)**

A given fluence $\phi t$ corresponds to a value of $dpa$:  

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

$N_d$: Number of displacements per cascade vs. the damage energy $E_d$  

$\sigma$: Scattering cross section

Small amount of alloy Ta or Ti ($\leq 3 \%$), the $dpa$ at a given fluence is very similar for binary and ternary alloyed Nb$_3$Sn.

However, binary and alloyed Nb$_3$Sn 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. $\phi t$
After irradiation at a given fluence $\phi t$, $dpa$ for binary and alloyed Nb$_3$Sn wires is essentially the same, but a certain difference $\Delta T_c$ still subsists.

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

Stronger decrease of $T_c$ for alloyed Nb$_3$Sn wires

$E = 14$ MeV:

$E > 0.1$ MeV:
*M. Eisterer, T. Baumgartner et al., ICMC 2017
Determination of $\Delta T_c$ for alloyed $\text{Nb}_3\text{Sn}$ wires

FCC/Run2: Binary $\text{Nb}_3\text{Sn}$: $\Delta T = -1.3 \text{ K} \pm 0.2 \text{ K}$

$E > 0.1 \text{ MeV}$:
* M. Eisterer, T. Baumgartner et al., ICMC 2017

$E = 14 \text{ MeV}$:

Estimation for FCC/Run2, for alloyed $\text{Nb}_3\text{Sn}$

$\Delta T_{c,\text{total}} = -1.8 \pm 0.2 \text{ K}$

1.3 x 10$^{22}$ n/m$^2$

4.3 x 10$^{22}$ n/m$^2$
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

$\Delta B_{c2} \sim 1$ T

$\Delta B_{c2} \sim 5\%$

$\Delta T_c \sim 1$ T


We have experimentally proven by independent measurements that
• The transition temperature $T_c$,
• the order parameter $S$ and
• the lattice parameter $a$

of Nb$_3$Sn 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 $J_c$
Before irradiation:
Intergrain boundaries between neighbouring A15 grains

**J_c**: Phenomenon at nanometric scale

**Nb_3Sn**:
Defects at grain boundaries:
breakage of periodicity creates normal conducting regions
Vortices will pin the flux lines

\[ J_c \]

M. Cantoni et al., 2006

10 nm

4 nm: ~ Coherence length \( \xi_o \)
Two kinds of irradiation/measurement cycles have been applied:

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

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

All known data \( J_c \) vs. \( \phi t \) show a marked peak. \( J_{c,\text{max}} \) occurs at different fluences for binary and alloyed Nb\(_3\)Sn

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

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

$\Delta B_{c2} = \sim +1 \text{ T}$

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

Proton irradiation:


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:


\[ F_p(b) = c_1 \ast b^{0.5} (1 - b)^2 + c_2 \ast b^1 (1 - b)^2 \]

Grain boundary pinning
\[ c_1 \equiv c_{\text{unirr}} \]

Point defect pinning
\[ c_2 \text{ and } B_{c2}: \text{ Fitting parameters} \]

Grain boundary pinning: essentially unchanged after irradiation

Flukiger, CERN, 6.12.2018
Origin of the enhancement of $J_c$ after irradiation

The variation $\Delta B_{c2}$ 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)

- 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

Flukiger, CERN, 6.12.2018
Estimation of the changes in FCC/Run2 at \( dpa = 3 \times 10^{-3} \)

Change of \( T_c \) for \( dpa = 3 \times 10^{-3} \) value is extracted from the relationship between \( T_c \) and \( dpa \)

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

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

«Universal» behavior for neutrons and protons

\( dpa = 3 \times 10^{-3} : \Delta T_c = 1.3 \pm 0.2 \, K \)

Two estimations, based on earlier 14 MeV irradiations:
A: Weiss et al, 1987,
B: Hahn et al., 1991
Estimation of the changes in FCC/Run2, with $dpa = 3 \times 10^{-3}$

A. First estimation:
Based on $T_c$ vs. $\phi t$, 14 MeV neutron data on 19-core Nb$_3$Sn wires (resistive $J_c$ measurements up to 20 T):


1st step: find $T_c$ from $dpa = 3 \times 10^{-3}$
2nd step: find corresponding $dpa$ for 14MeV neutrons

$\Delta T_c = -1.8 \pm 0.2 \text{ K}$

$dpa$ value for FCC/Run2:

$\phi t(14 \text{ MeV}) = 1.3 \times 10^{22} \text{n/m}^2$
Estimation of the changes in FCC/Run2, with $dpa = 3 \times 10^{-3}$

3rd step:
Find $J_c$ and $B_{c2}$ for the corresponding fluence at 14 MeV: $1.3 \times 10^{22}$ n/m$^2$

At 16T/4.2K:

- $\Delta J_c = + 60\%$
- $\Delta B_{c2} = - 1.3$ T

For alloyed Nb$_3$Sn wires, we had found:

- Total $\Delta T_c = - 1.8 \pm 0.2$K

F. Weiss et al, 1987
Estimation of the changes in FCC/Run2, \(dpa = 3 \times 10^{-3}\)

**B: Second estimation:** Based on \(T_c\) vs. \(\phi t\), 14 MeV neutron data on 19-core \(\text{Nb}_3\text{Sn}\) wires (resistive \(J_c\) measurements up to 20 T)


At 16T/4.2K:

\[\Delta J_c \sim 0\]
\[\Delta B_{c2}\] not given

For alloyed wires, we had already found: \(\Delta T_c = -1.8K \pm 0.2\) K:

Total \(\Delta T_c = -1.8 \pm 0.2K\)
How will $J_c$ vary with higher $\phi t$ in TRIGA?

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

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

This allows to conclude about the reversibility of $J_c$ at cycles between $T_{irr}$ and 300K:
Expected behavior of $J_c$ in Nb$_3$Sn wires in TRIGA

For $E > 0.1$ MeV: $\phi t = 4.3 \times 10^{22} \text{ n/m}^2$ corresponds to $dpa = 4.3 \times 10^{-3}$.

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

Starting from the data with $E = 14$ MeV, the data for higher fluence at $E > 0.1$ MeV can be predicted.
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$_3$Sn
As mentioned in this talk, Nb$_3$Sn industrial wires should even overcome the limit of 1’500 A/mm² 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$_3$Sn has still a potential for a sizeable increase:

1: Internal oxydation (X. Xu et al., OSU, Columbus, Ohio), and
2: Nb$_3$Sn 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$_3$Sn 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 $J_c(\text{max})$ 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
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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$_3$Sn 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 superconducting properties in the 3 types of accelerators studied here is estimated

<table>
<thead>
<tr>
<th>Changes at 4.2 K</th>
<th>HiLumi LHC</th>
<th>FCC/RUN1</th>
<th>FCC/Run2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_c$</td>
<td>&lt; - 0.20 K</td>
<td>&lt; - 0.40 K</td>
<td>- 1.8 ± 0.2 K</td>
</tr>
<tr>
<td>$\Delta J_c$</td>
<td>≤ + 30 %</td>
<td>≥ + 60 %</td>
<td>0....+ 60 %*)</td>
</tr>
<tr>
<td>$\Delta B_{c2}$</td>
<td>&lt; +1 %</td>
<td>&lt; 2 %</td>
<td>- 1.30 T</td>
</tr>
</tbody>
</table>

*) depends on the type of wire
* 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 $\Delta T_c = -1.8 \pm 0.2$ K found in the present work.