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Summary of the RADSUM workshop at CERN

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CCA, CERN, March 12th 2025

RADiation effects in **SU**perconducting **M**agnets

Motivation

- Aim and objectives

Review of the workshop

- Radiation environments
- Modelling of radiation effects
- Irradiation experiments
- Design of magnets and shielding

Problem with coated conductors: competing effects

- Favorable effect: increase in flux pinning („large defects“)
- Harmful suppression of superfluid density („small defects“)



Aim of the workshop

Bring together **scientists and engineers** designing **superconducting magnets for high-radiation environments** such as beam lines, accelerators, colliders and detectors, for physics and other applications, particle production sources (hadrons and leptons), as well as fusion facilities.

- Overview of activities, **experimental data** and **modelling work** on radiation effects in superconductors;
- Quantify and contrast **radiation environments** for different applications;
- Advance the understanding of radiation-induced degradation for establish **radiation damage limits** for magnet materials;
- Discuss R&D directions for enlarging the material database, and improving the radiation resistance of magnets;
- Foster synergies among communities.



Synergy of communities

Common problem: Use of superconductors in a radiation environment.

- How do the material properties change?
- Damage limit to be used for the design?



????: Ideal experiment

Envisaged
application
in a radiation
environment

Experiment
in the known
radiation
environment

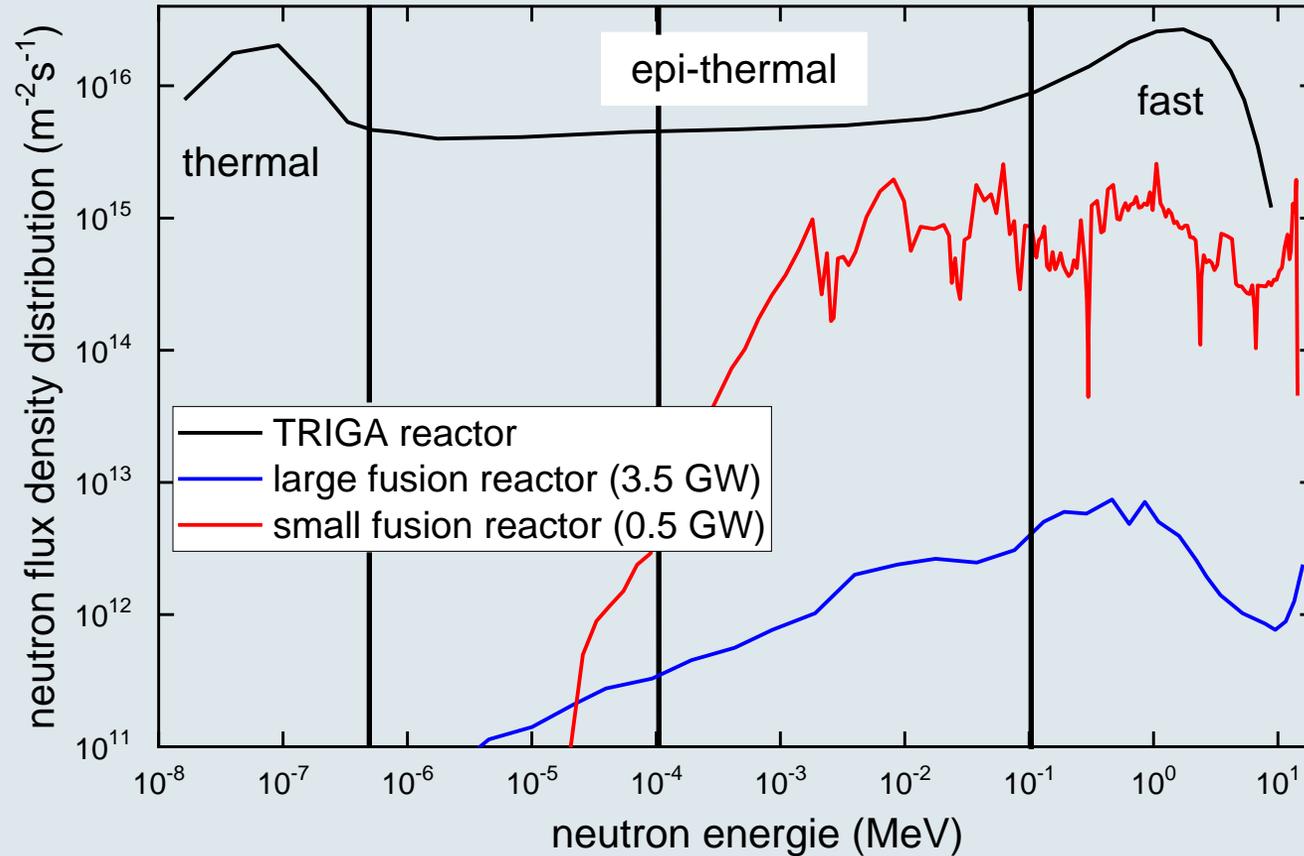
Change of
properties

Real world: radiation environment

- not known exactly
- not available for experiments
- higher flux is needed



Neutron energy distributions



F. Ledda et al., IEEE TAS 34 (2024) 4206105
 D. Torsello et al., WB5-4-INV, 11:15, Dec.5

Baker et al., STARFIRE — A Commercial Tokamak Fusion
 Power Plant Study, ANL/FPP-80-1 (1980).

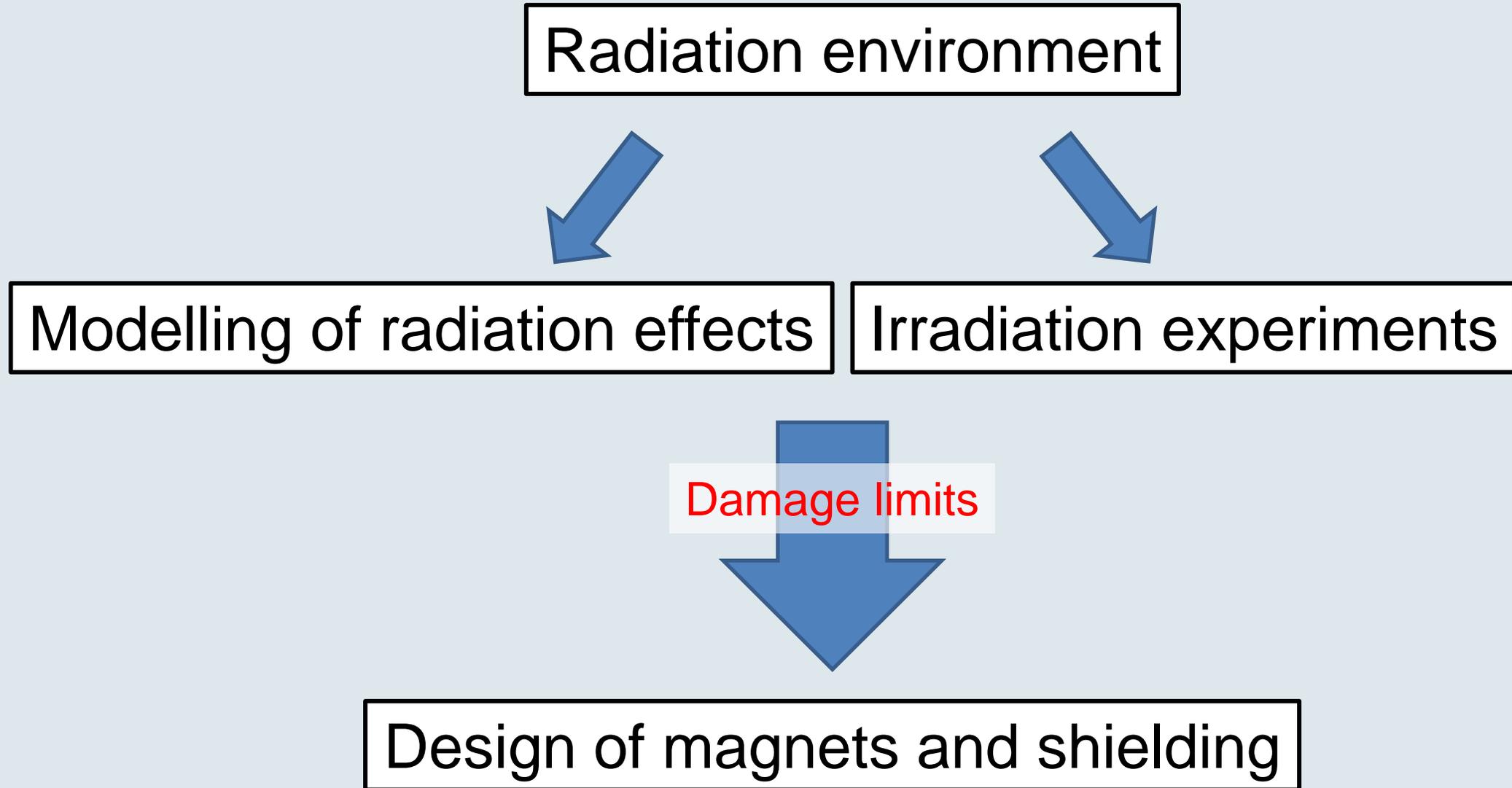


We have to understand what is going on!

- Can we quantify radiation damage independent from the particular radiation it results from?
- Established: Displacements per atom (dpa)
 - Obtained from damage calculations
 - Useful for structure materials (stainless steel): a few dpa
 - Sufficient for Nb_3Sn (?), anti-site defects and dislocation loops stable (?)
 - Applicable for coated conductors? (Many different types of defects ?)
 - A few mdpa



Structure of workshop



- **Accelerator Magnets**

- Future colliders at CERN (HL-LHC, FCC, Muon Collider); [Anton Lecher](#)
- Magnets at J-PARC; [Tatsushi Nakamoto](#)
- HiMB project at PSI; [Eric Forton](#)

- **Fusion Magnets**

- ARC; [Danielle Torsello](#)
- STEP; [Tim Eade](#)
- ITER; [Davide Langhi](#)

- **Medical Applications;** [Vincent Nuttens](#)



My personal summary/conclusions

- Reliable prediction is possible with state-of-the-art modelling.
- Radiation at the magnet location is very different from the primary radiation.
 - Moderation
 - Secondary particles
- Neutrons make most damage in most applications.



Modelling of radiation effects

- **Superconducting properties**
 - Pinning versus scattering; [Michael Eisterer](#)
 - Time dependent GL theory for change in pinning; [Roland Willa](#)
- **Damage and Defect structure**
 - Molecular Dynamics; [Davide Gambino](#)
 - DFT; [Rebecca Nichols](#)
 - Defect formation energies and mobility; [Li Yang](#), [Ashley Dickson](#)
 - dpa calculations; [Fredric Granberg](#), [Francesc Pujol](#), [Yosuke Iwamoto](#)



My personal summary/conclusions

- Still significant differences between different dpa codes or models.
- Predicting the density and morphology of defects is demanding (Molecular dynamics calculations are most promising)
 - Many different defects are possible
 - Different particles with wide energy distributions
- Oxygen vacancies/interstitials/anti-sites seem most important (highest density)
- Stability of defects?
- dpa as a damage limit seems questionable.
- Scattering is the main driver for the degradation of superconducting properties.



Irradiation experiments

- **Neutrons;** [Mukesh Dhakarwal](#), [Michael Eisterer](#),
- **Charged particles**
 - Protons; [Shin-ichiro Meigo](#), [David Fischer](#)
 - Oxygen ions; [Susie Speller](#)
- **Gamma radiation;** [Simon Chislett-McDonald](#)
- **Microstructure**
 - Microscopy, spectroscopy etc. [Susie Speller](#)



My personal summary/conclusions

- A proxy for neutrons is highly desired.
 - Similar overall behavior (T_c , J_c) of neutron, proton and ion irradiation.
- Defect annealing starts at cryogenic temperatures.
 - Larger degradation at cryogenic temperatures (operation conditions)
 - A thermal cycle to room temperature leads to very similar results than irradiation at room temperature.
 - Stable defects?
- TEM is a powerful tool for assessing large defects
- Nanoscale disorder is very hard to assess/quantify (main reason for degradation)



Magnet design and shielding

- **Accelerator Magnets**
 - Future colliders at CERN; [Daniele Calzolari](#)
 - COMET at J-PARC; [Makoto Yoshida](#)
 - HIPA accelerator at PSI; [Ciro Calzolaio](#)
 - Ceramic insulation; [Masami Iio](#)
- **Fusion Magnets**
 - DEMO; [Lorenzo Giannini](#)
 - Tokamak Energy; [Gurdeep Kamal](#)
 - ARC; [Ashleigh Francis](#)
- **Hadron Therapy (C-ions);** [Giulia Tosetti](#)



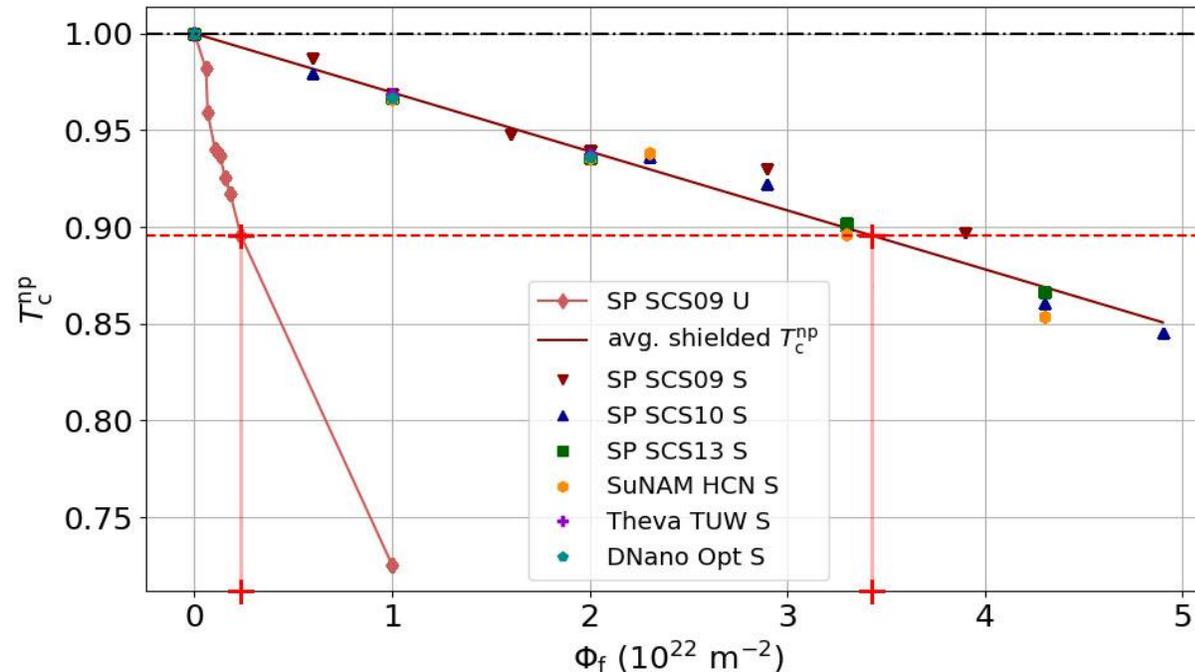
Discussion

Damage limits/quantification



Competing effects of defects

- **Any** defect breaks translational symmetry of the crystal lattice
→ **scattering of charge carriers**
 - **Decrease in superfluid density**
 - Pair breaking in the cuprates (**decrease of T_c**)
 - Most efficient: high density of **small defects (dpa)**

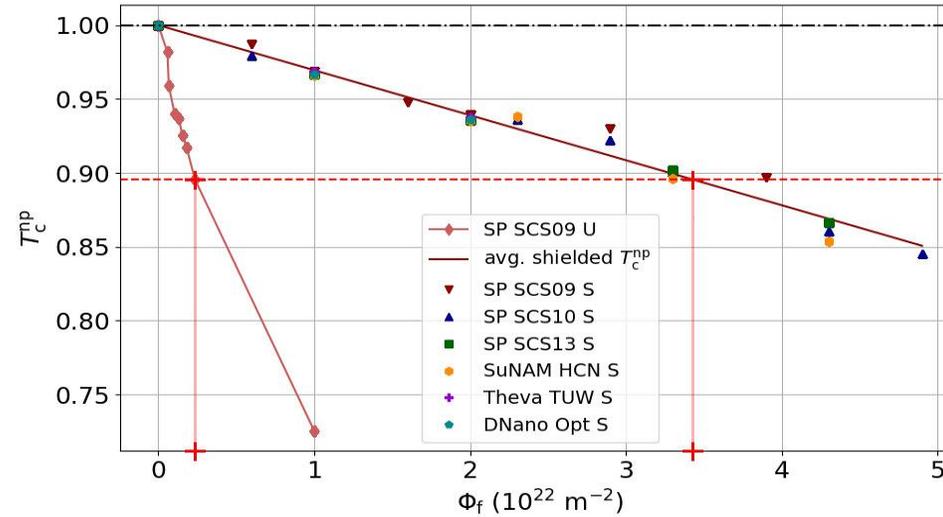
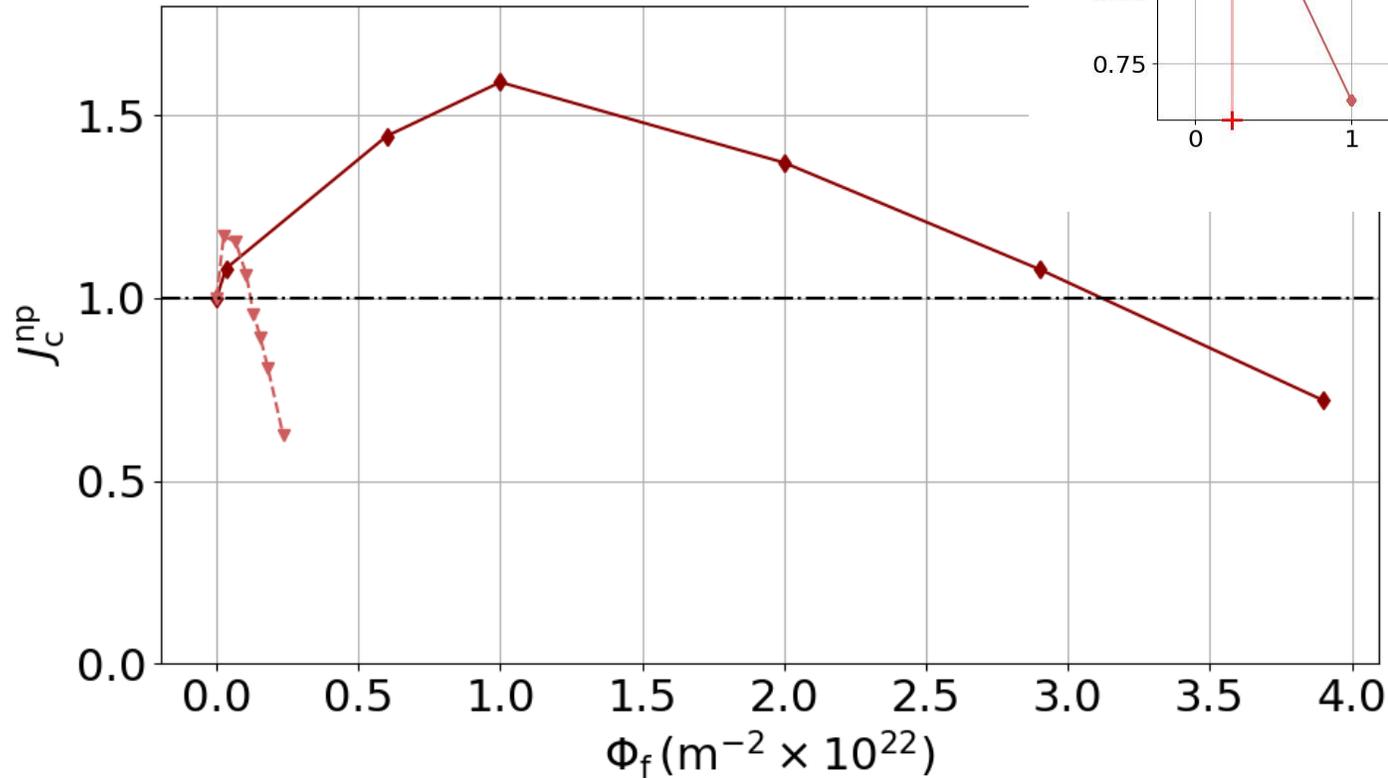


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 - **Decrease in superfluid density**
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 - Most efficient: high density of **small defects (dpa)**
- **Any** defect contributes to **pinning**
 - Small defects: δI -pinning (less efficient, in particular at high temperatures)
 - **Large defects:** δT_c -pinning
(one defect corresponds to many displaced atoms; → dpa?)



Competing effects of defects



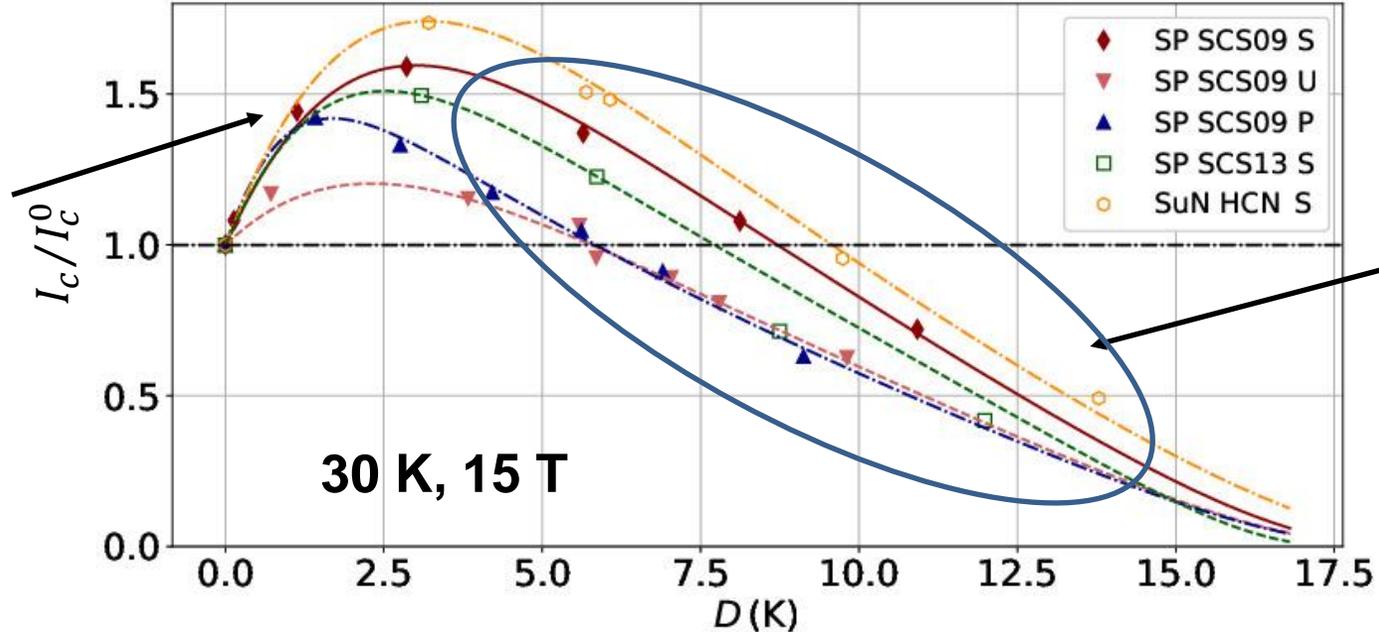
Fluence is an unsuitable disorder parameter



T_c as disorder parameter

Pinning increases

Large defects?
Good dpa?



Decrease because
of enhanced
scattering (rate)

Predictable from
changes in T_c and
 ρ_n .

Small defects?
Bad dpa?

Very similar degradation behavior:

- Same tape (SP SCS09) different irradiation techniques
 - Fast and thermal neutrons (U)
 - Fast neutrons (S)
 - 1.2 MeV protons (P)
- Different tapes (S): SP SCS09, SuN HCN, SP SCS13 (artificial pinning centers)

M. Eisterer et al., arXiv:2409.01376v1



Quantification of damage / damage limits

- The scattering rate is the intrinsic parameter for quantifying the degradation in superconductors
 - Proportional to T_c and normal state resistivity.
 - Not easy to predict from radiation damage.
 - Easier to assess experimentally.
- Increase of pinning mainly by large defects.
 - Given by size and density of defects
 - Predictable from TDGL theory?

to be continued.....





IRradiation **E**ffects on HTS for **F**usion

17 – 22 June 2025, Gallipoli, Italy

<https://www.superfusion.org/iref25/>

