Responsibility of small defects for the low radiation tolerance of coated conductors

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[5]PSFC, MIT, Cambridge, Massachusetts, United States

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Collaborations and Funding

EUROfusion

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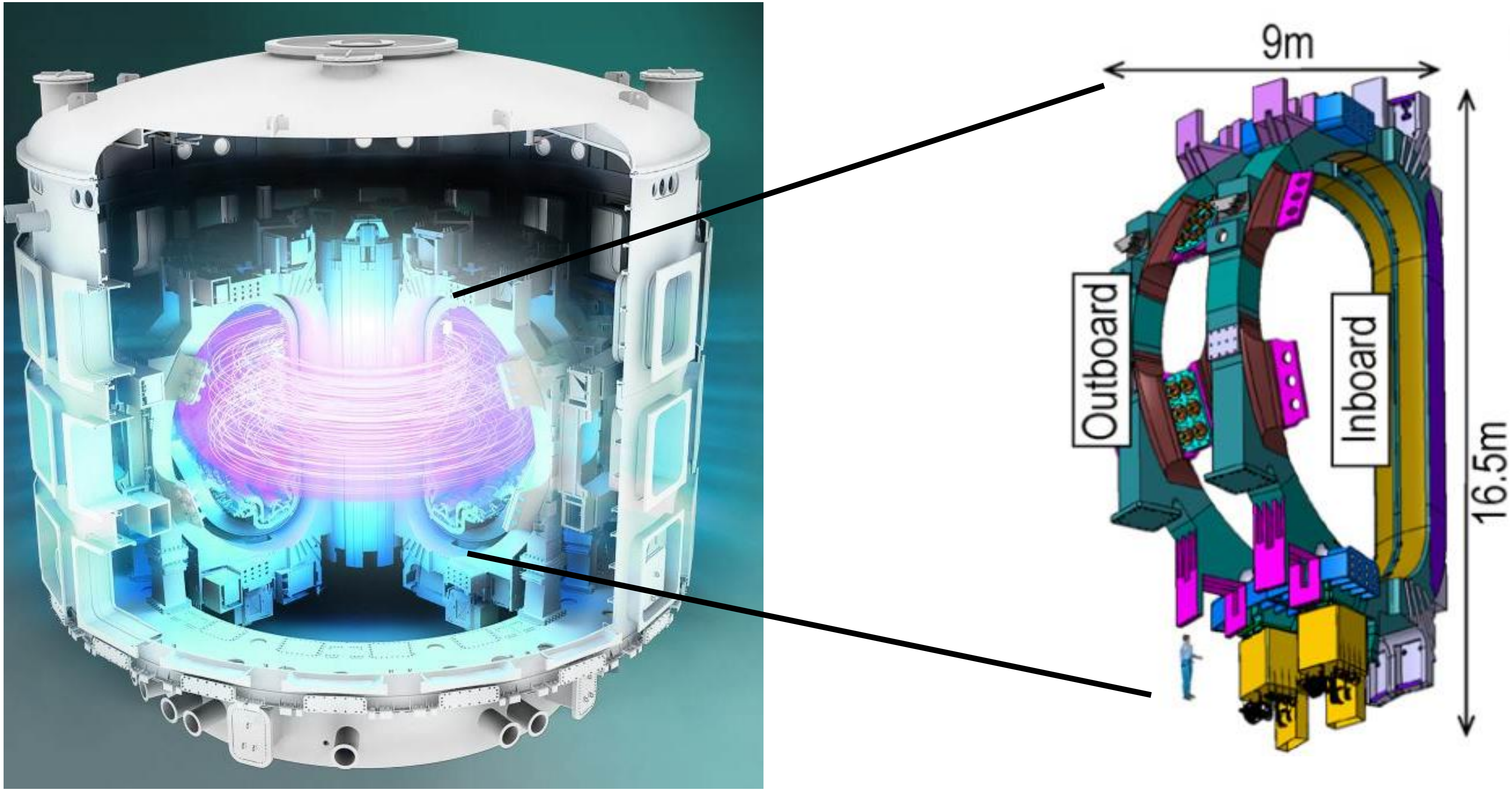
Irradiation Damage



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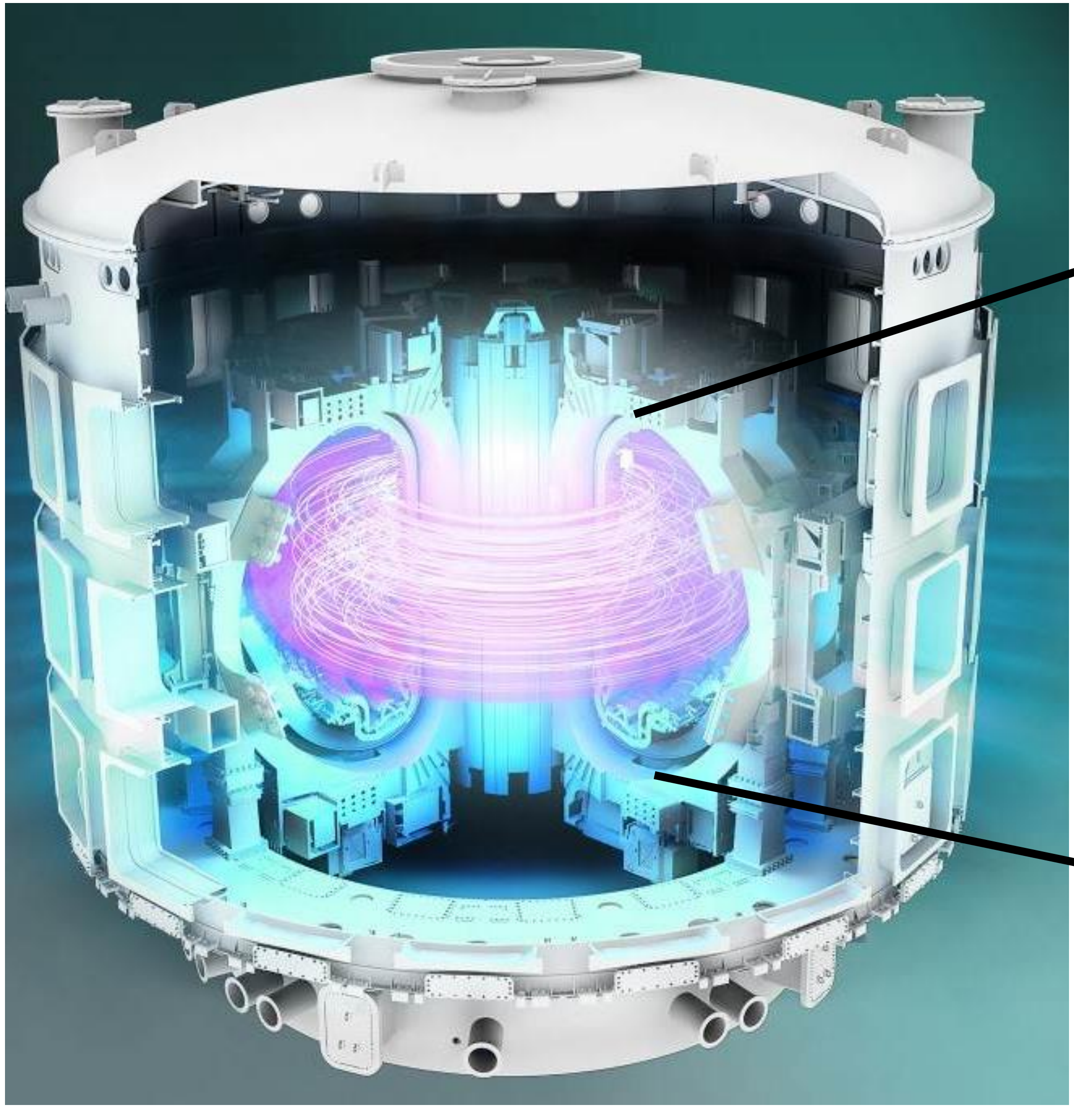

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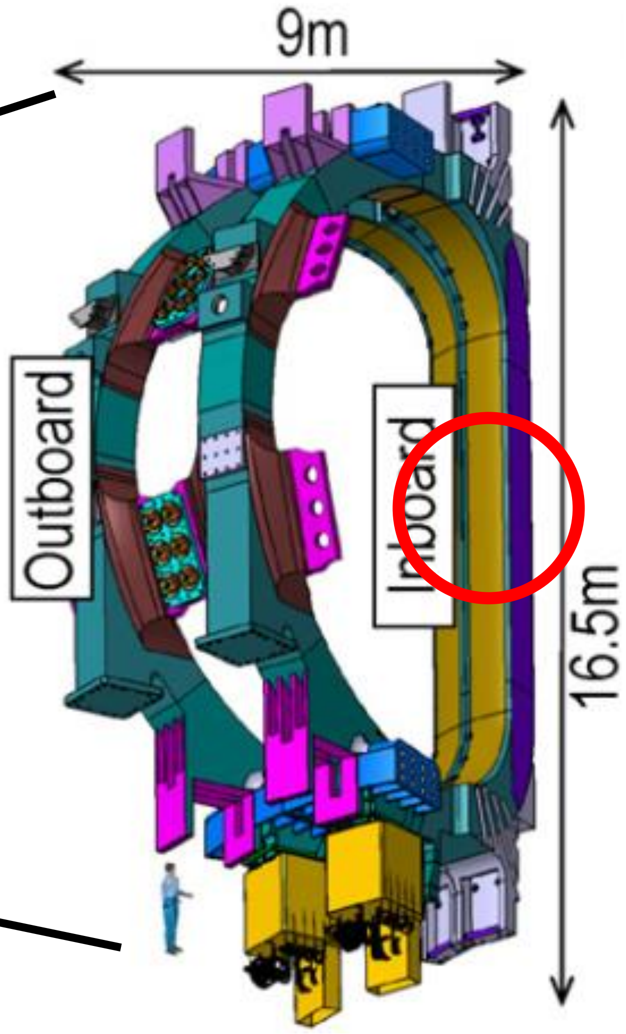

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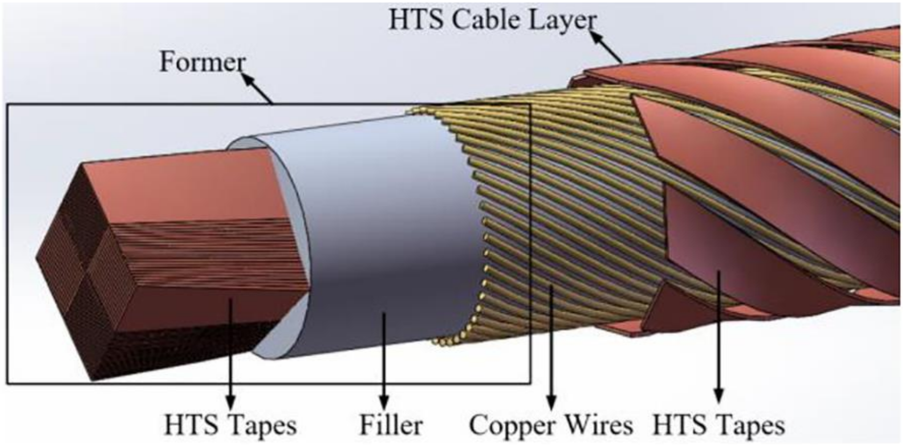

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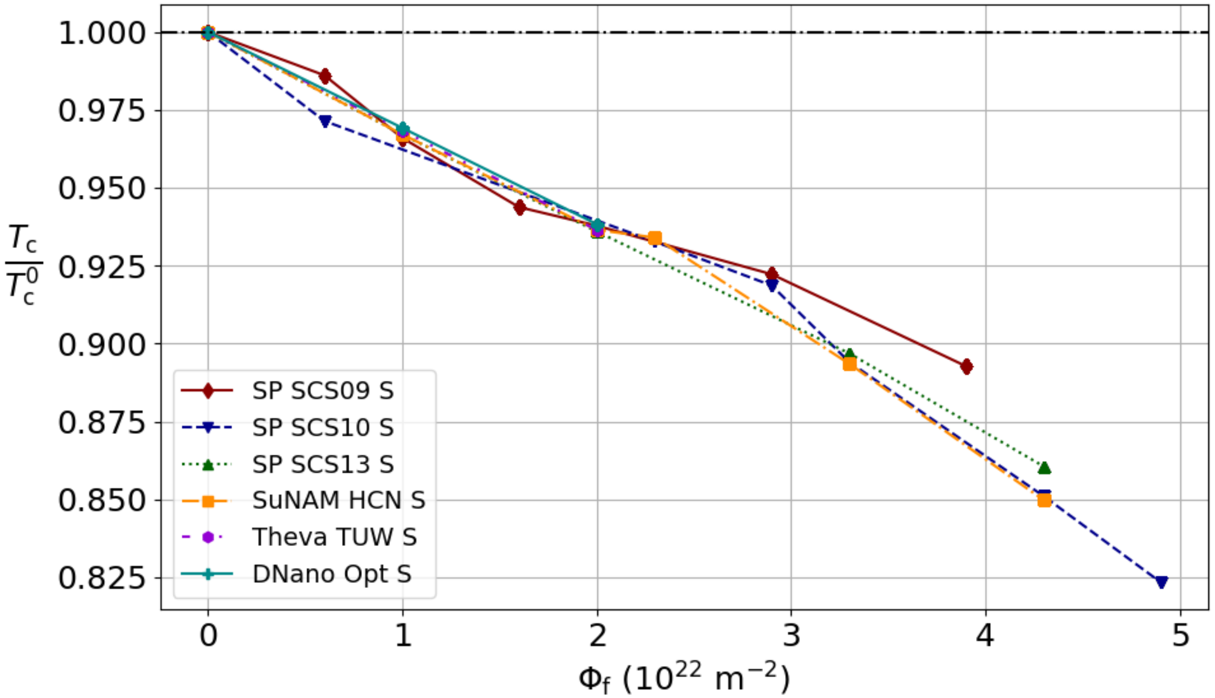
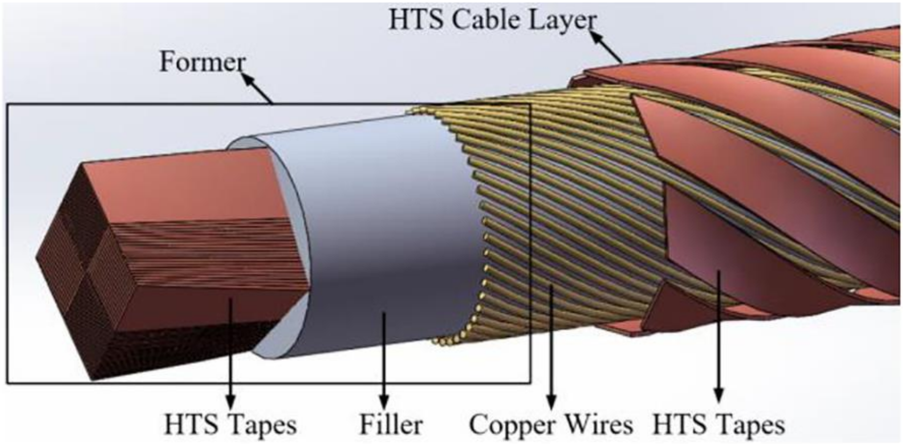


- Compact fusion devices – high fields for confinement
  - Currently REBCO coated conductors most promising
  - High quality, long lengths (800+ m)
  - Change of properties under irradiation conditions “well” known

Irradiation Damage



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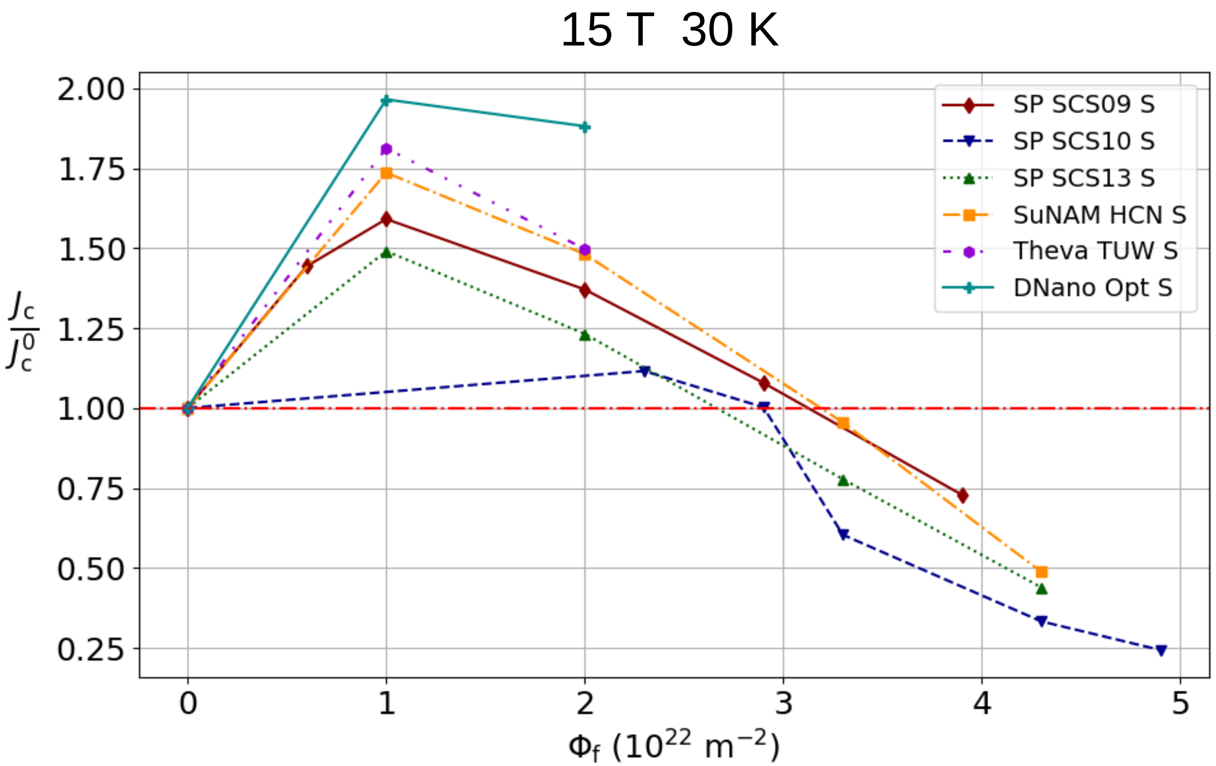

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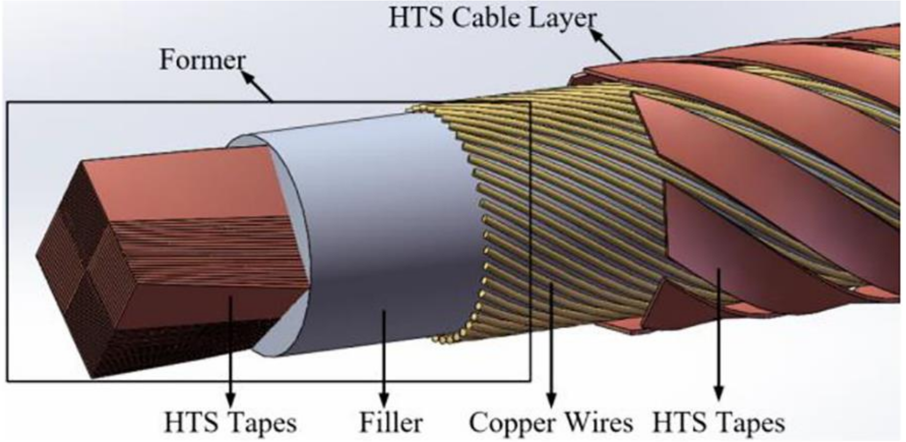

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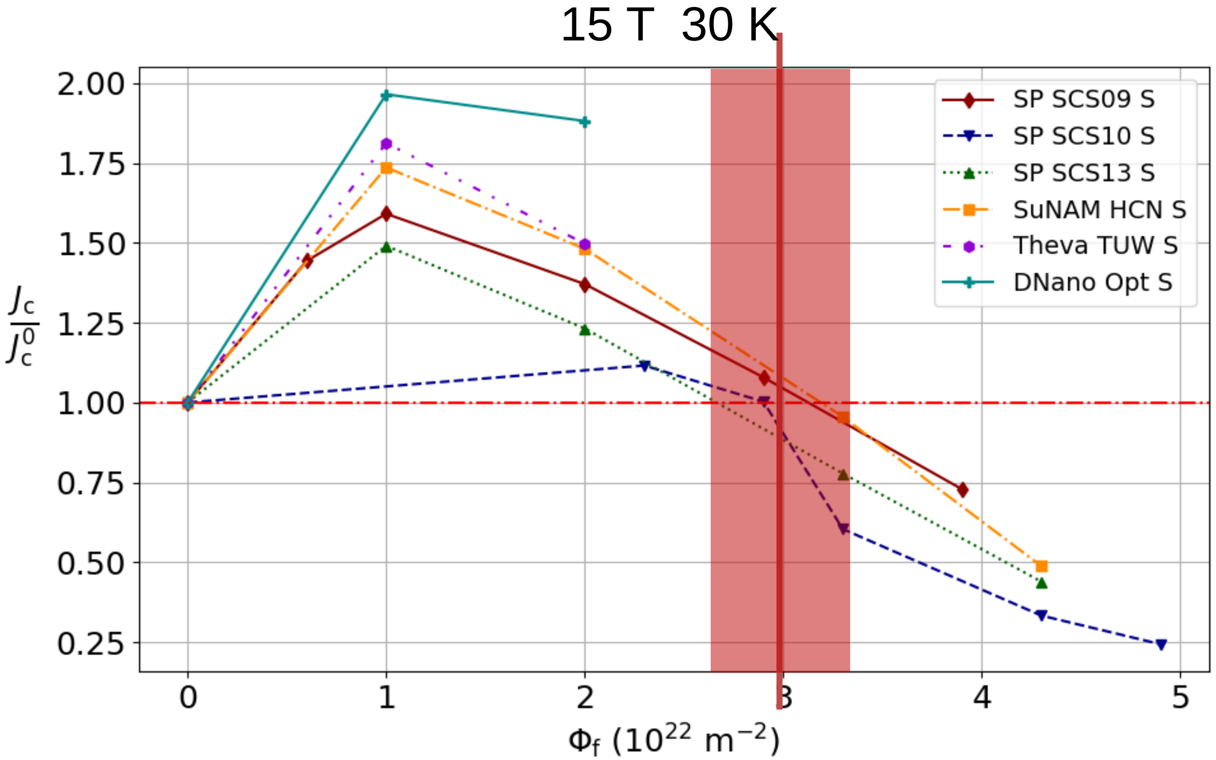

Compact devices

- Much higher neutron flux at the magnets
- Magnets reach EOL at approx. 3-3.3 · 10^{22} m^{-2}

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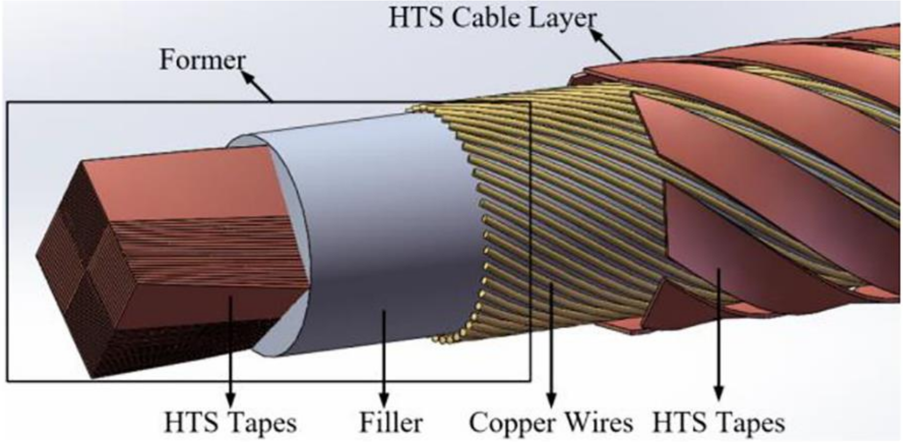

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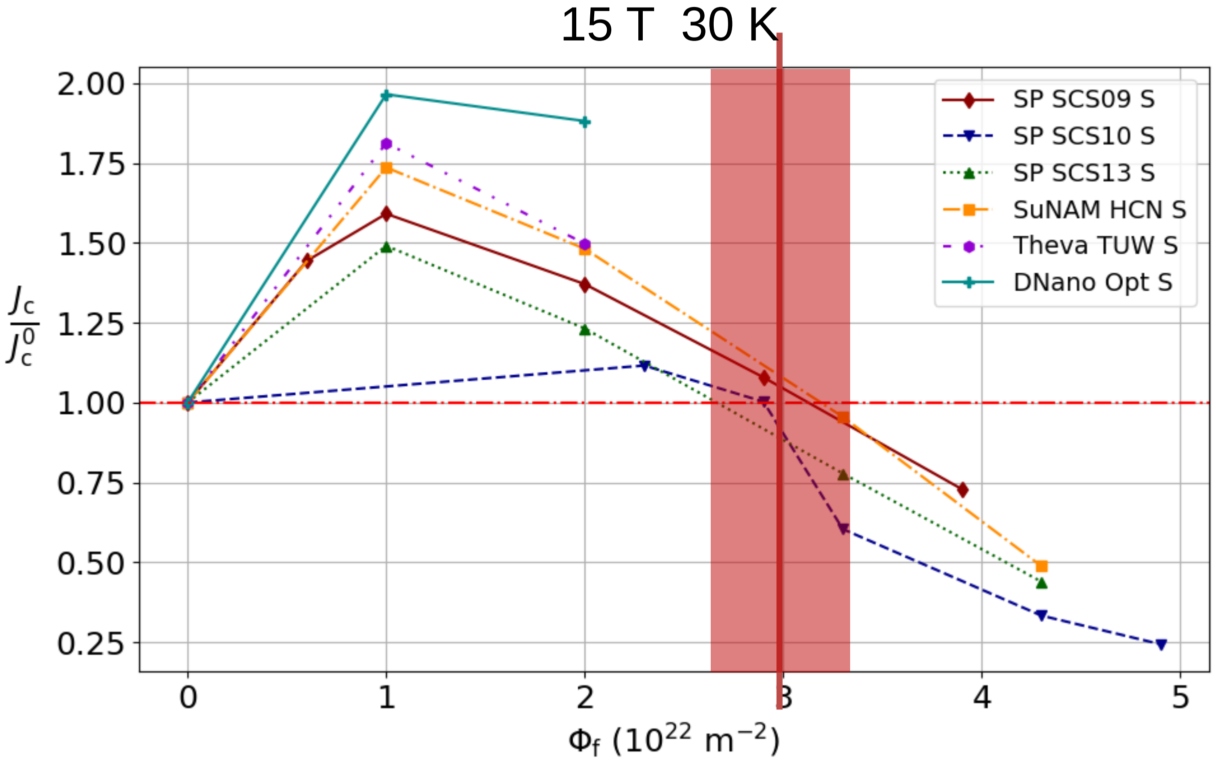
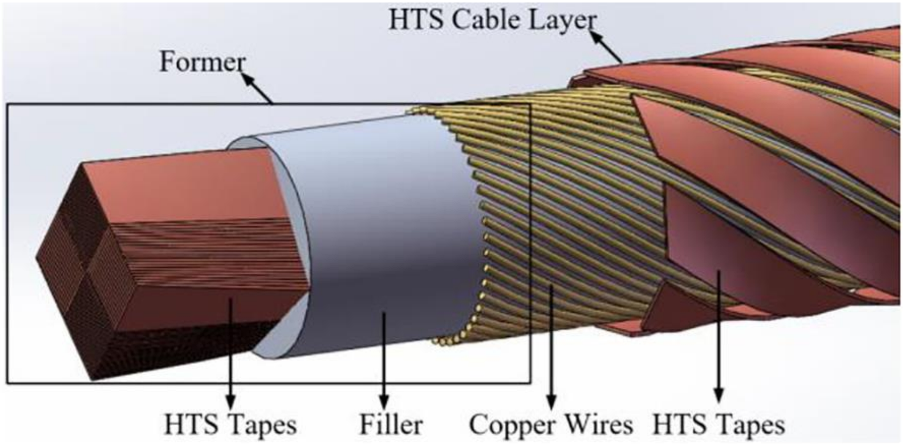


Compact devices

- Much higher neutron flux at the magnets
- Magnets reach EOL at approx. 3-3.3 · 10^{22} m^{-2} ← Environment dependent!

Irradiation Damage



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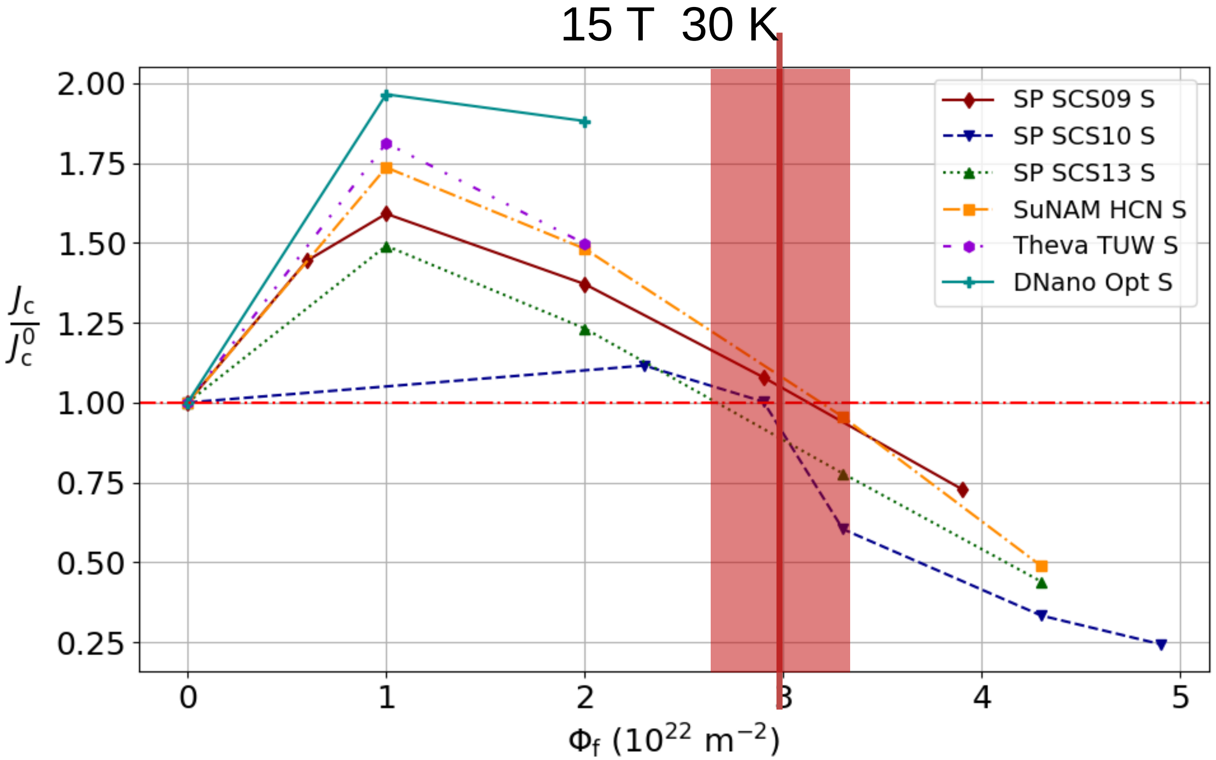
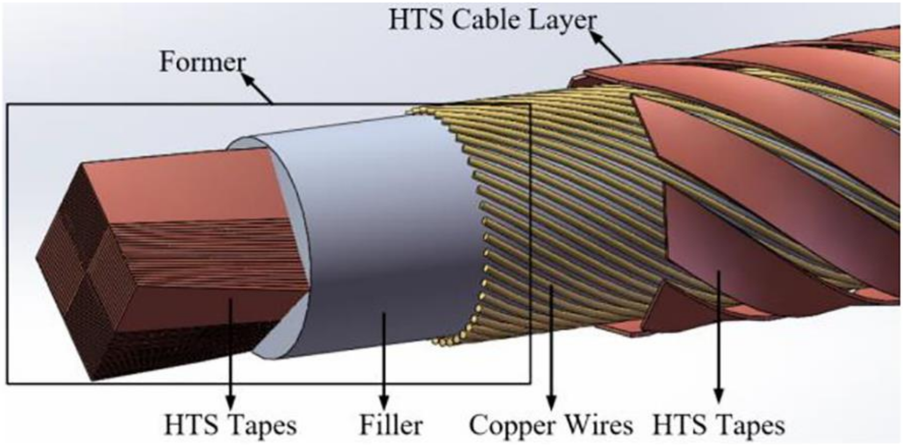


Lifetime is field, temperature, radiation environment and tape dependent

Q: How can we predict the lifetime? – What has to be done?

Irradiation Damage



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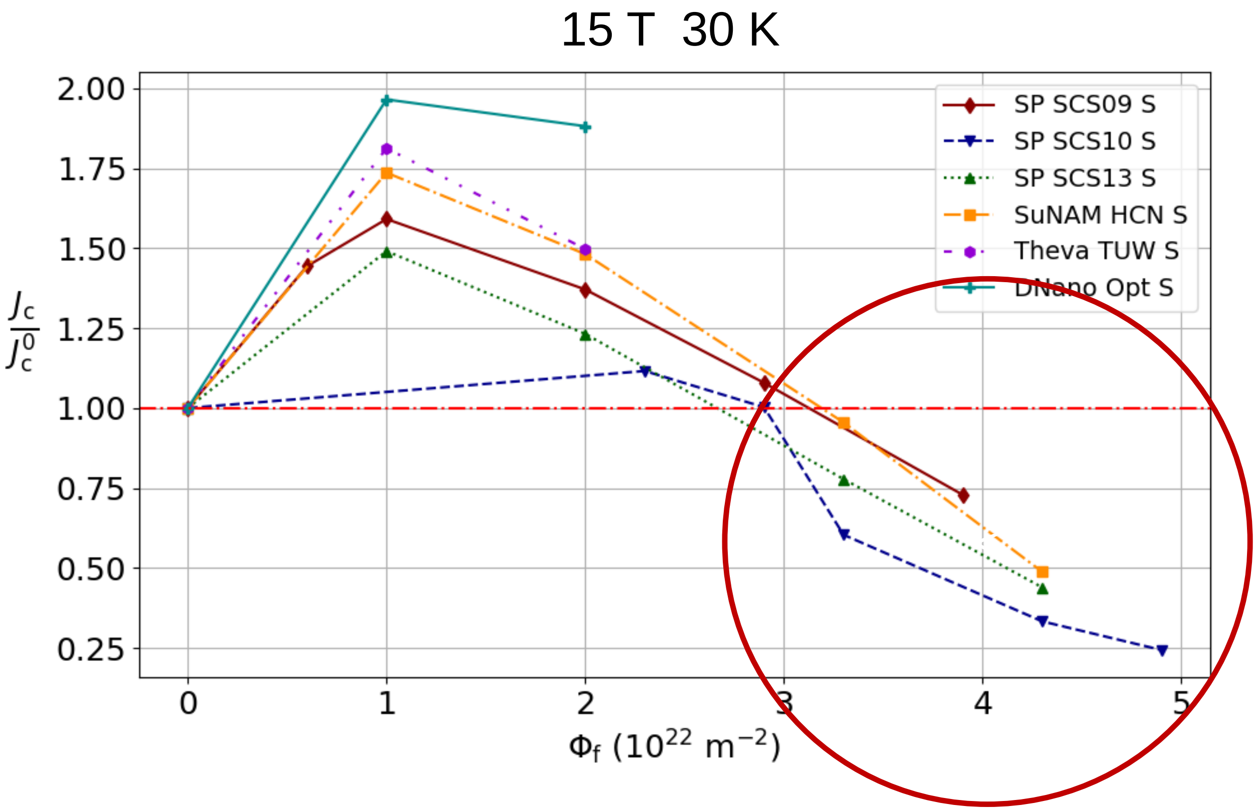
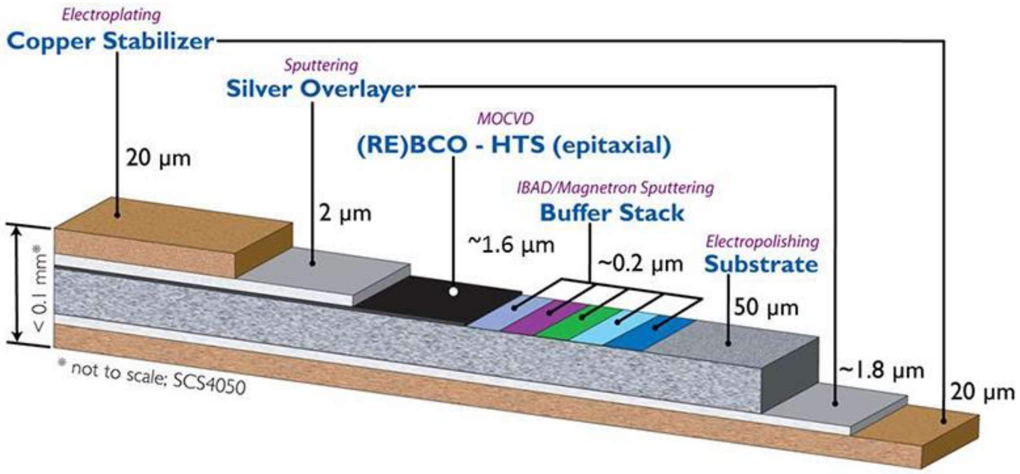


First we need to answer: **What drives the degradation?**

Irradiation Methods

Samples



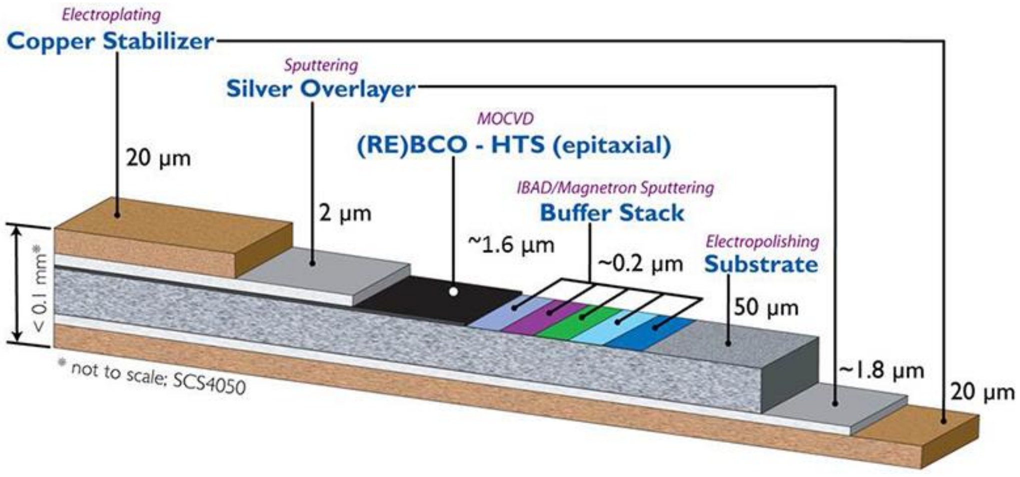
[1] SuperPower®, superpower-inc.com

- chem. stabilized: 1 µm Ag
- el. stabilized: Cu
- substrate: Hastelloy
- HTS thickness: ~1 µm

Thorough pre-characterization!

Supplier	Type	REBCO	APCs	method	nomenclature
SuperPower	SCS4050 2009	GdBCO	None	MOCVD	SP SCS09
SuperPower	SCS4050 2013	(Y,Gd)BCO	$BaZrO_3$	MOCVD	SP SCS13
SuNAM	HCN04150	GdBCO	None	RCE-DR	SuNAM HCN

Samples



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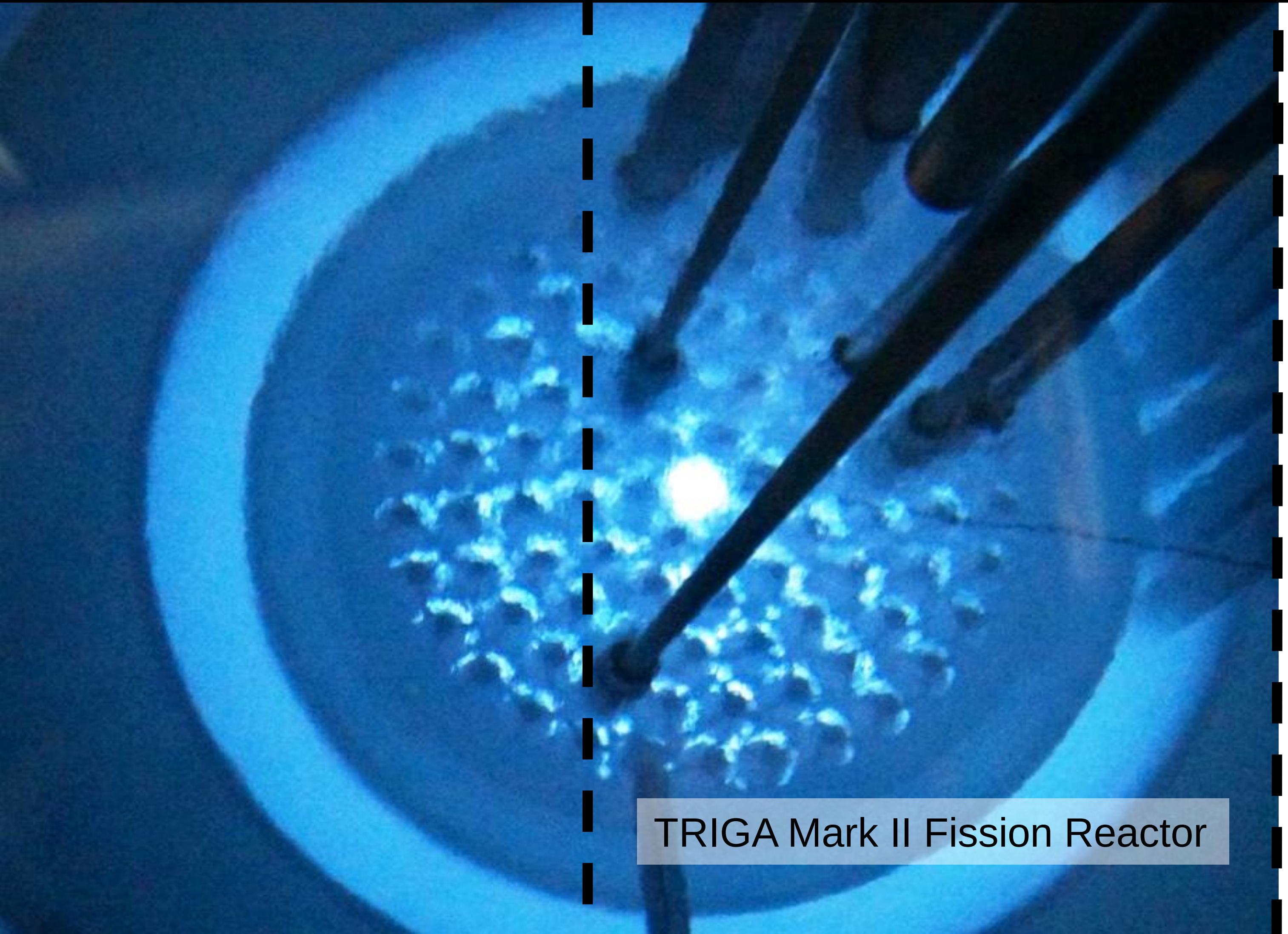
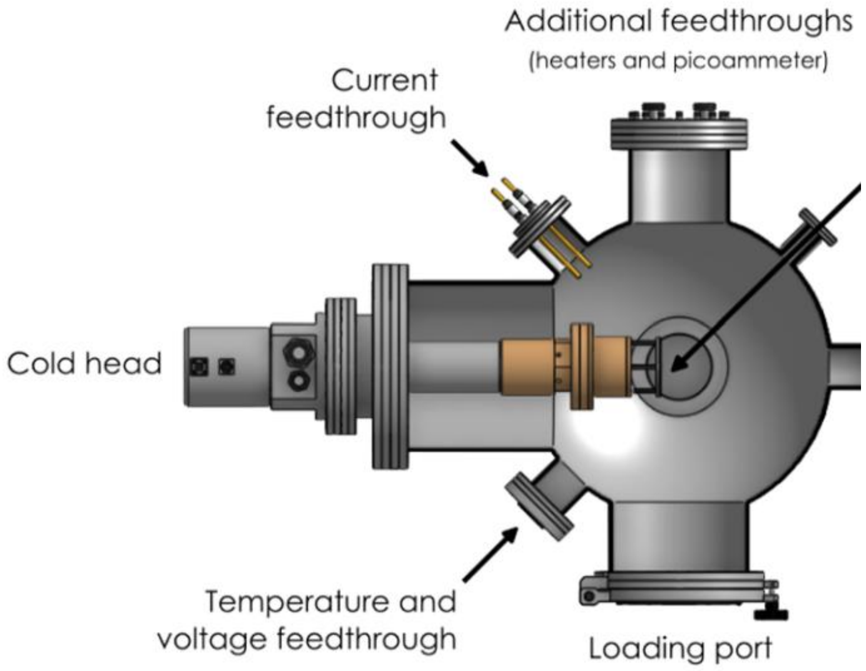
Irradiation Environments

Neutron irradiation at TU Wien



TRIGA Mark II Fission Reactor

Irradiation at MIT



General Ionix 1.7 MV Acc.

Irradiation Environments

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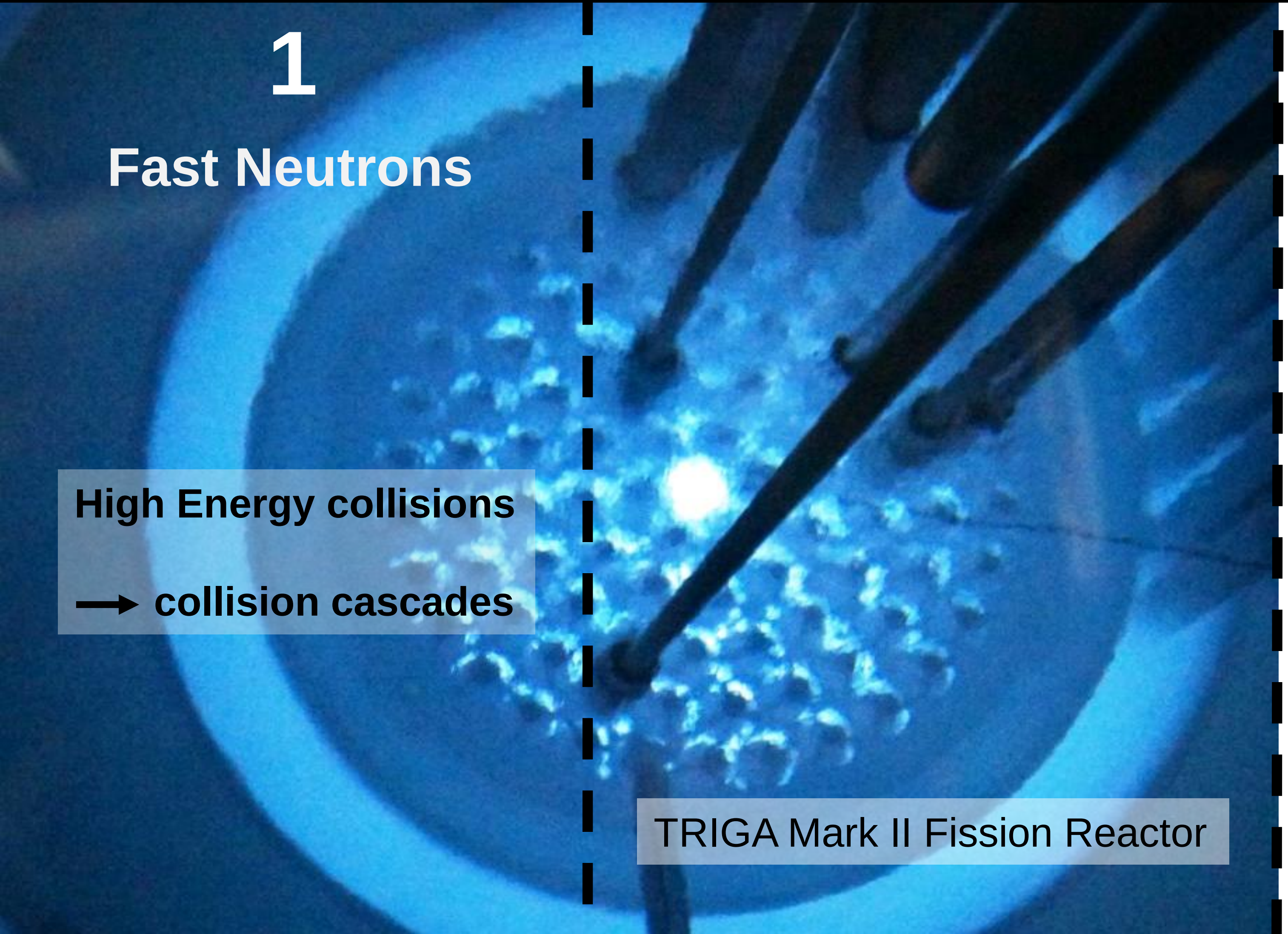


1

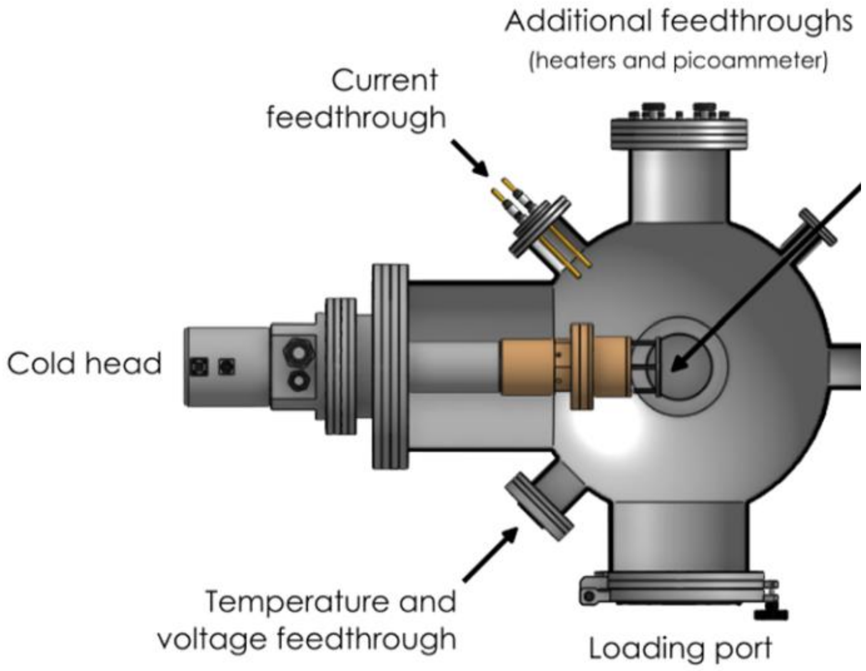
Fast Neutrons

High Energy collisions

→ collision cascades

TRIGA Mark II Fission Reactor

Irradiation at MIT



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Irradiation Environments

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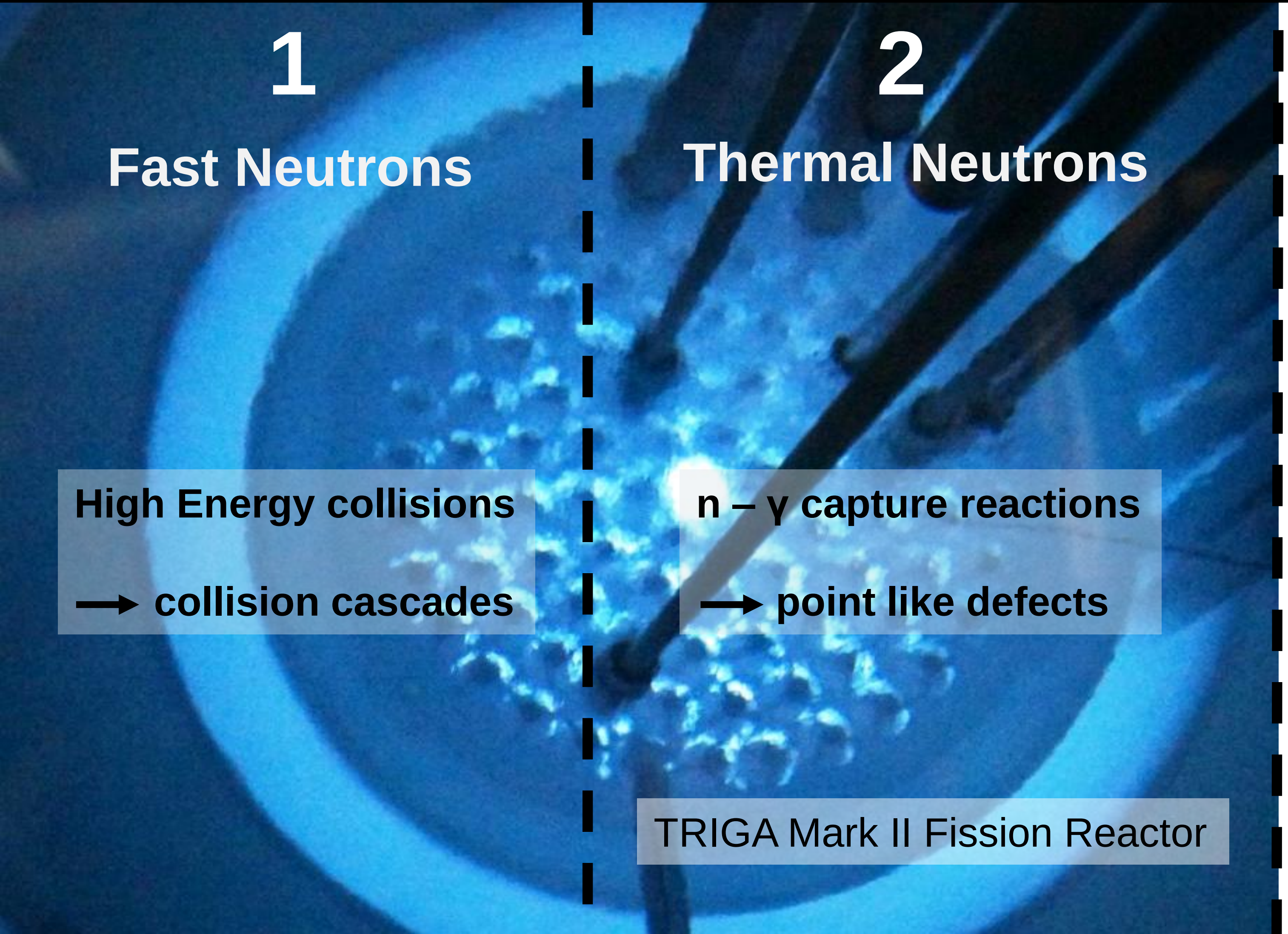


1

Fast Neutrons

High Energy collisions

⟶ collision cascades

2

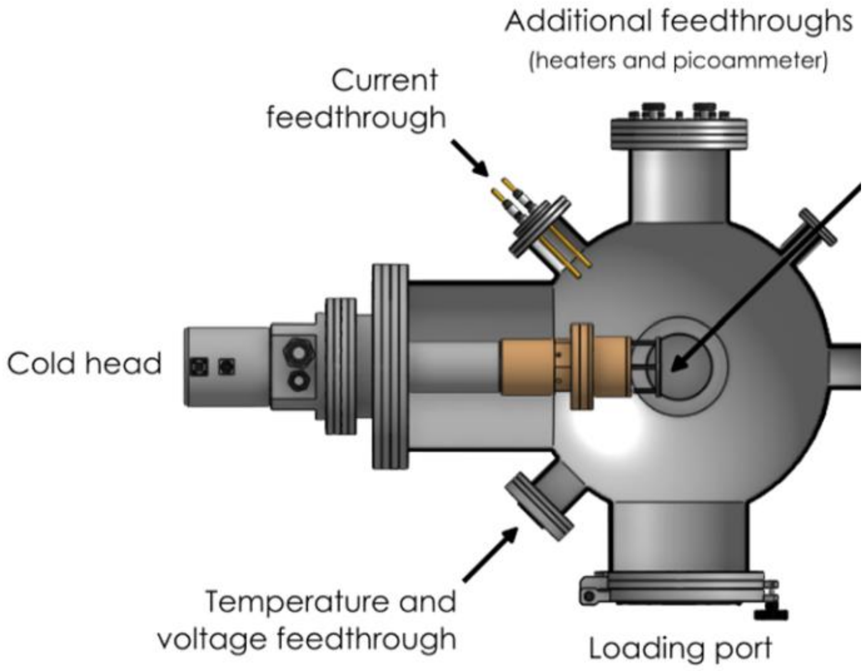
Thermal Neutrons

n – γ capture reactions

⟶ point like defects

TRIGA Mark II Fission Reactor

Irradiation at MIT



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Irradiation Environments

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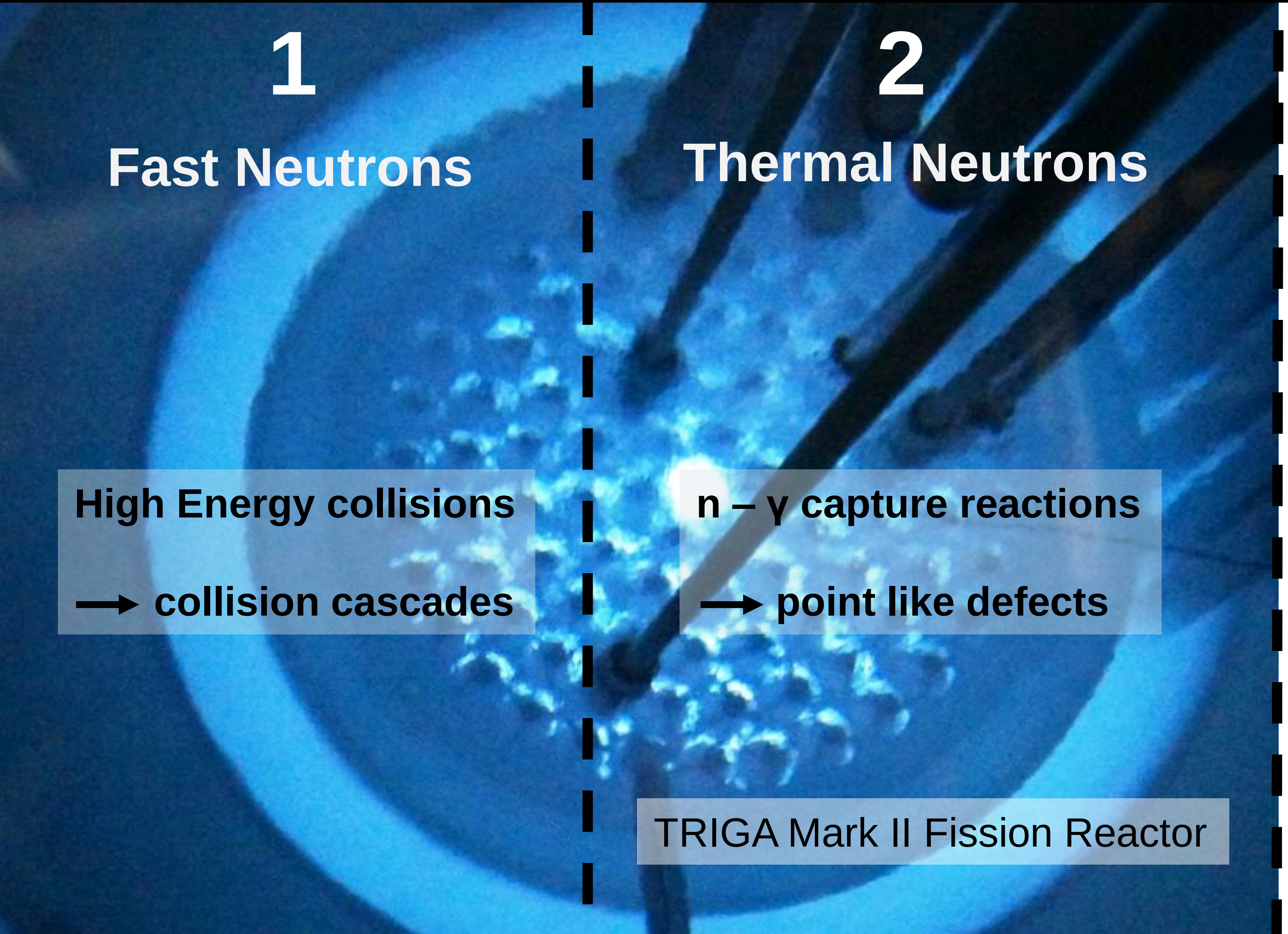

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Fast Neutrons

High Energy collisions

→ collision cascades

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Thermal Neutrons

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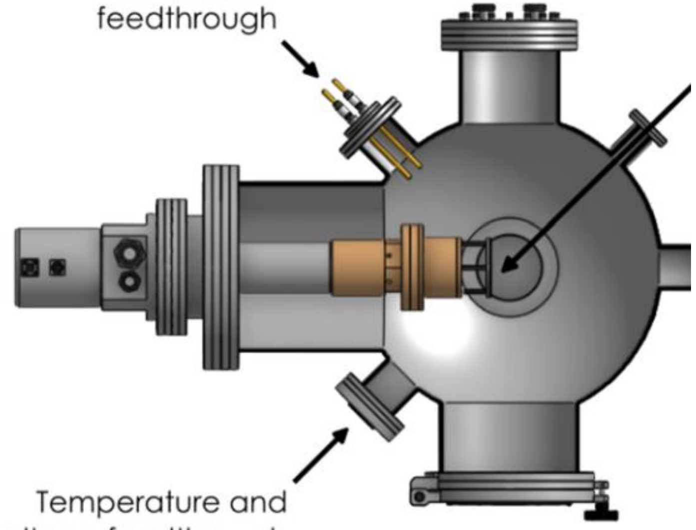
→ point like defects

TRIGA Mark II Fission Reactor

Irradiation at MIT

3

1.2 MeV p^+ Control Experiment



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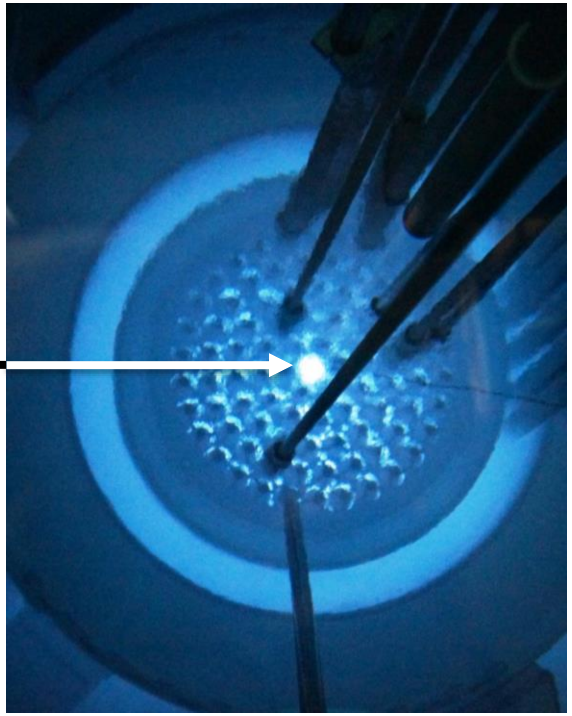
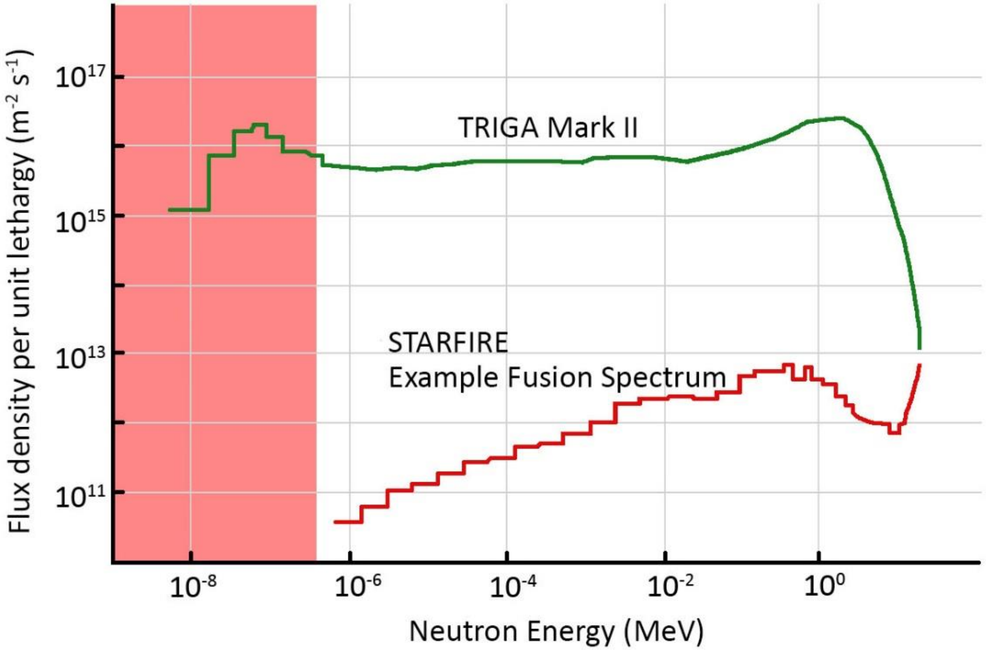
Neutron Irradiation – Shielded

TRIGA MARK II at TU Wien

- Irradiation in the central irradiation facility
- Fast / thermal **neutron** flux 3.2 / 4 x 10^{16} m^{-2} s^{-1}
- Irradiation with and **without** thermal (< 0.55 eV) neutrons
- Sample identifiers denoted with “S”

< 70 °C at sample



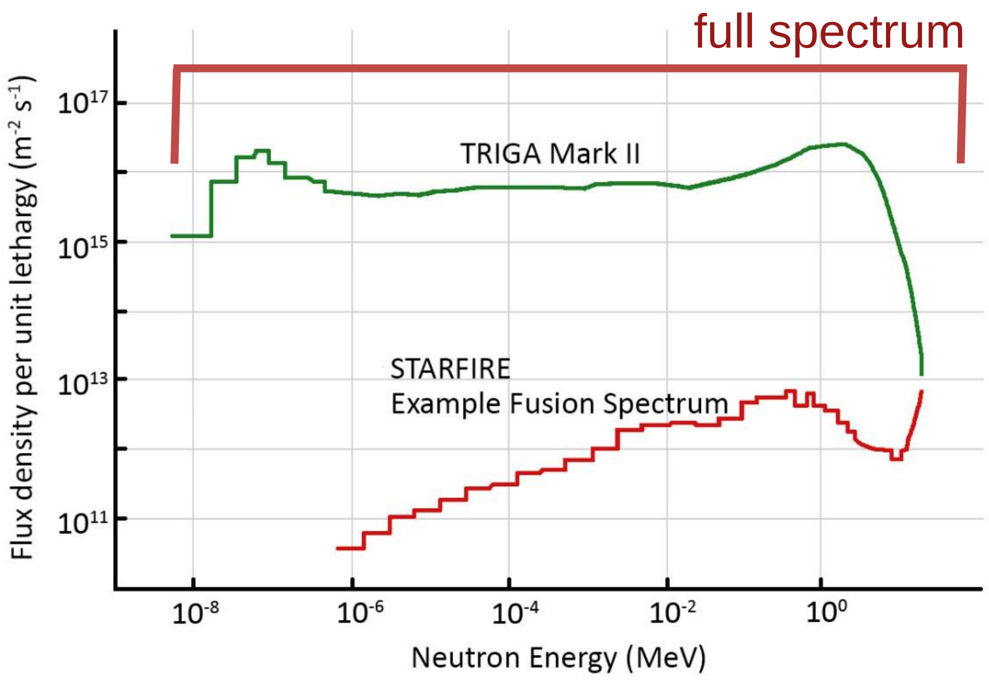


- can be shielded with Cd

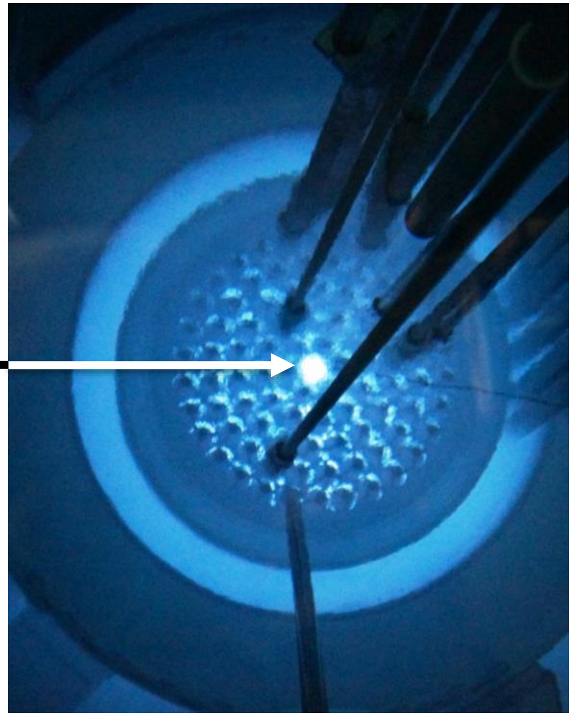
Neutron Irradiation – Unshielded

TRIGA MARK II at TU Wien

- Irradiation in the central irradiation facility
- Fast / thermal **neutron** flux 3.2 / 4 x 10^{16} m^{-2} s^{-1}
- Irradiation **with** and without thermal (< 0.55 eV) neutrons
- Sample identifiers denoted with "U"



< 70 °C at sample

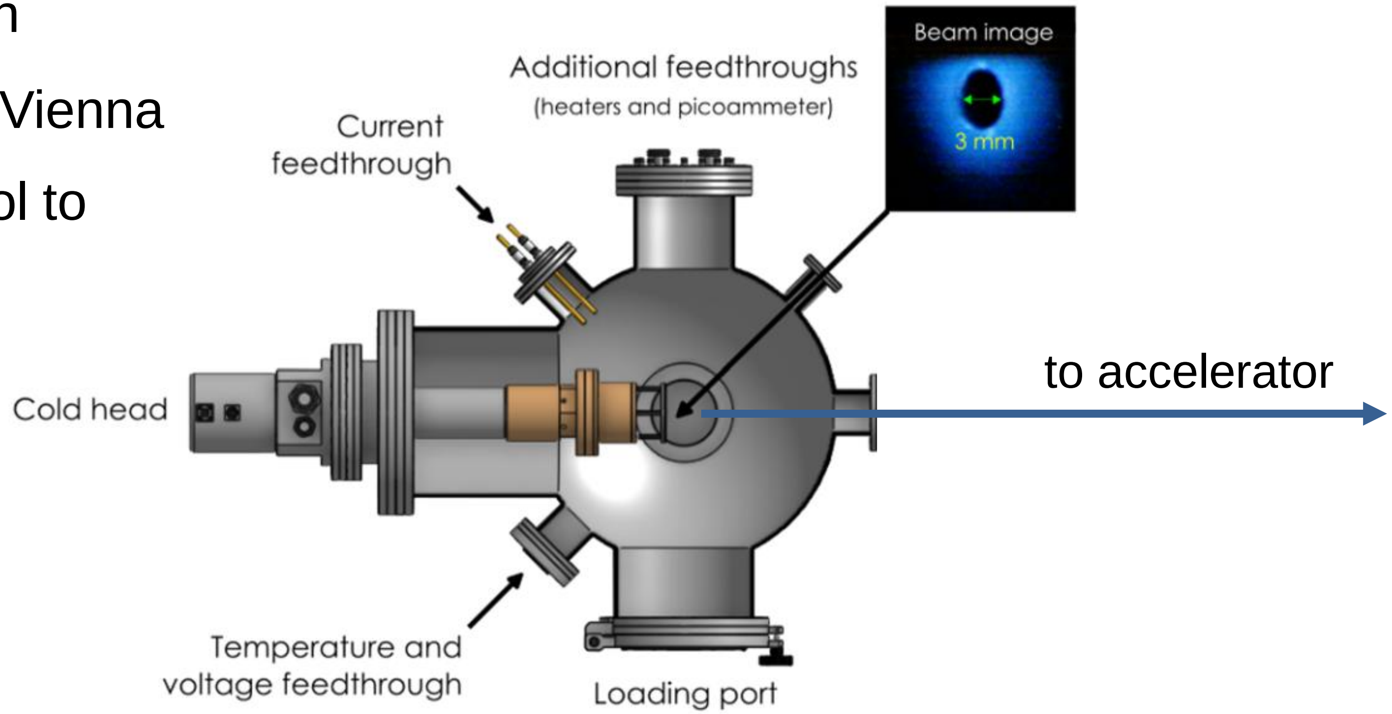


p^+ Irradiation - Bridged

AR Devitre 2024

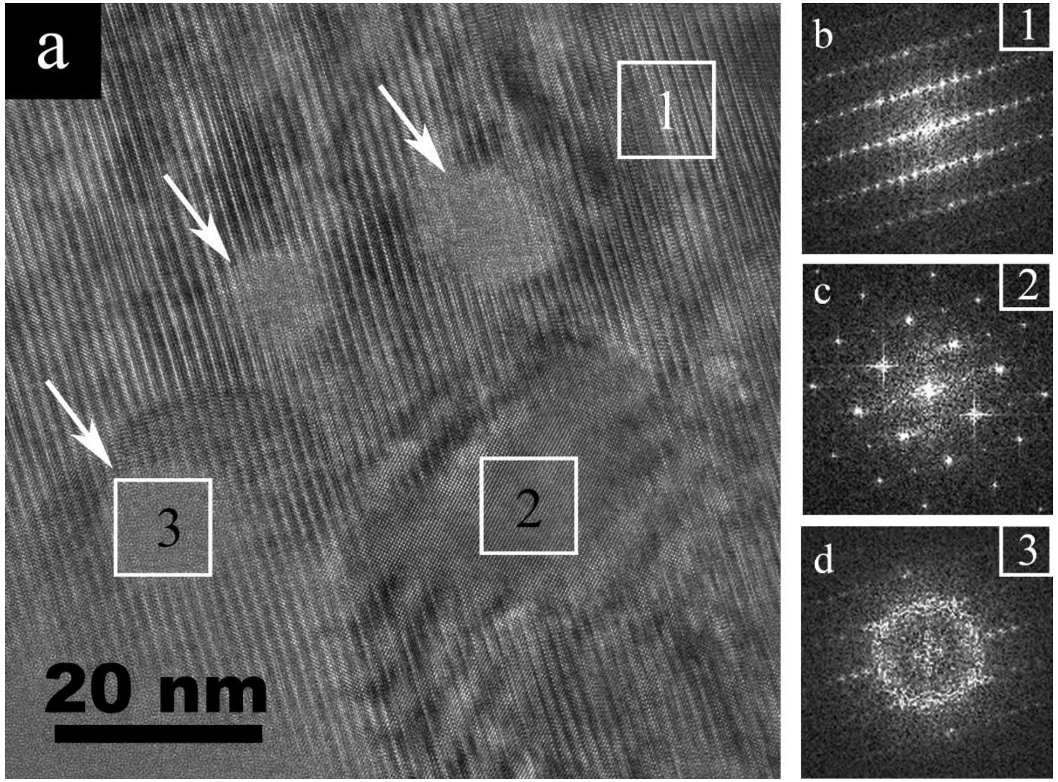
General Ionix 1.7 MV tandem accelerator

- Irradiation with 1.2 MeV protons
- Room temperature irradiation
- Bridged samples 0.2 mm width
- Samples pre-characterized in Vienna
- On-sample temperature control to monitor beam heating



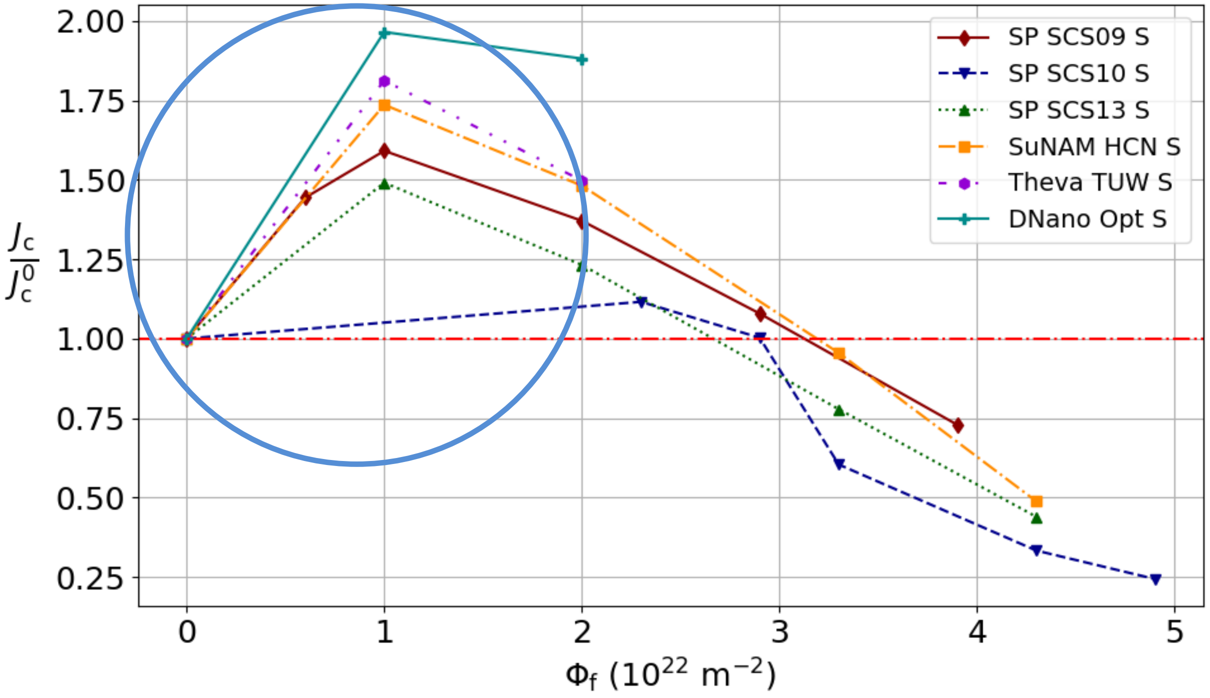
Defect Formation

Fast Neutron Irradiation



left – TEM picture of neutron induced defects
right – FFT of selected regions [1]

15 T 30 K



Cascades Enhance Pinning

[1] with friendly permission by Yatir Linden, *Analysing neutron radiation damage in YBa2Cu3O7–x high-temperature superconductor tapes,* https://doi.org/10.1111/jmi.13078
Department of Materials, University of Oxford, Oxford, UK

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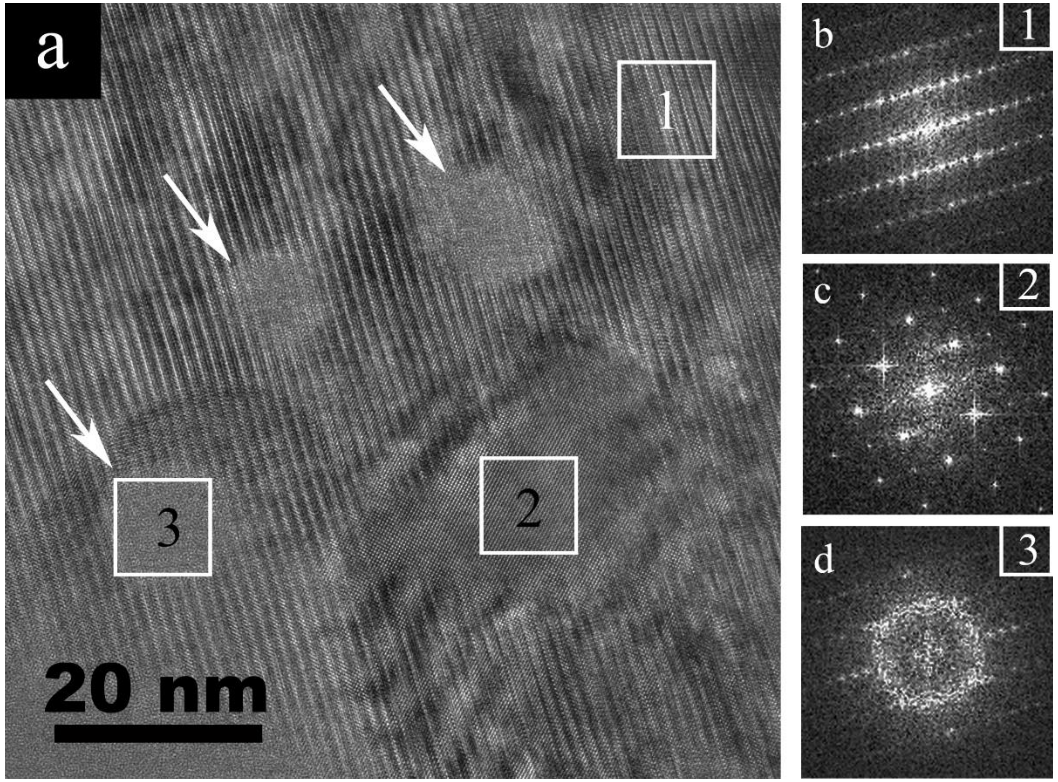

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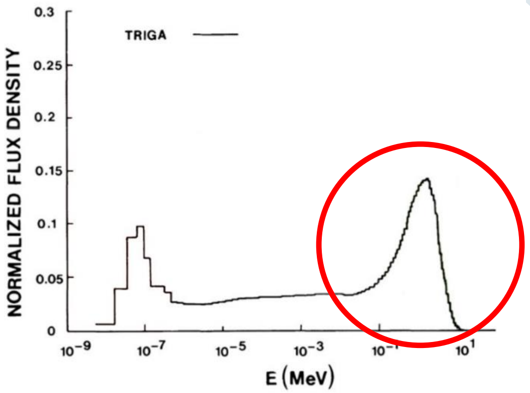
1. Undisturbed GdBCO
2. Crystalline BZO rod
3. Amorphous cascade



Defect size	≤ 10 nm
Mean	~ 4 nm
ξ^{0}_{ab}	~ 1.4 nm
ξ^{77}_{ab}	~ 3 nm

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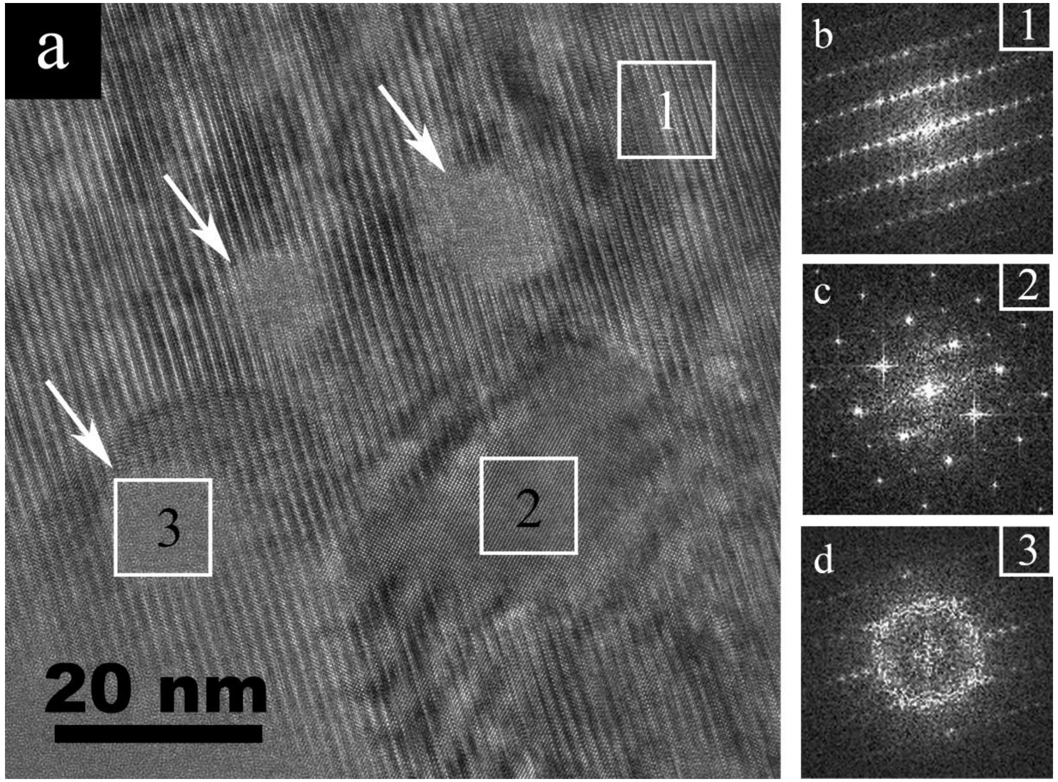

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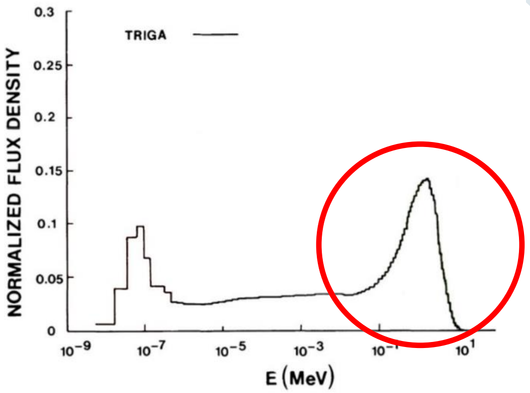

- $3.3 \times 10^{19} – 5 \times 10^{22}$ cascades per 10^{22}
- ~ 0.01 % reduction of superconducting cross-section

What drives the degradation?

➡ **Must be small (invisible) defects**

[1] with friendly permission by Yatir Linden, *Analysing neutron radiation damage in YBa2Cu3O7–x high-temperature superconductor tapes,* https://doi.org/10.1111/jmi.13078
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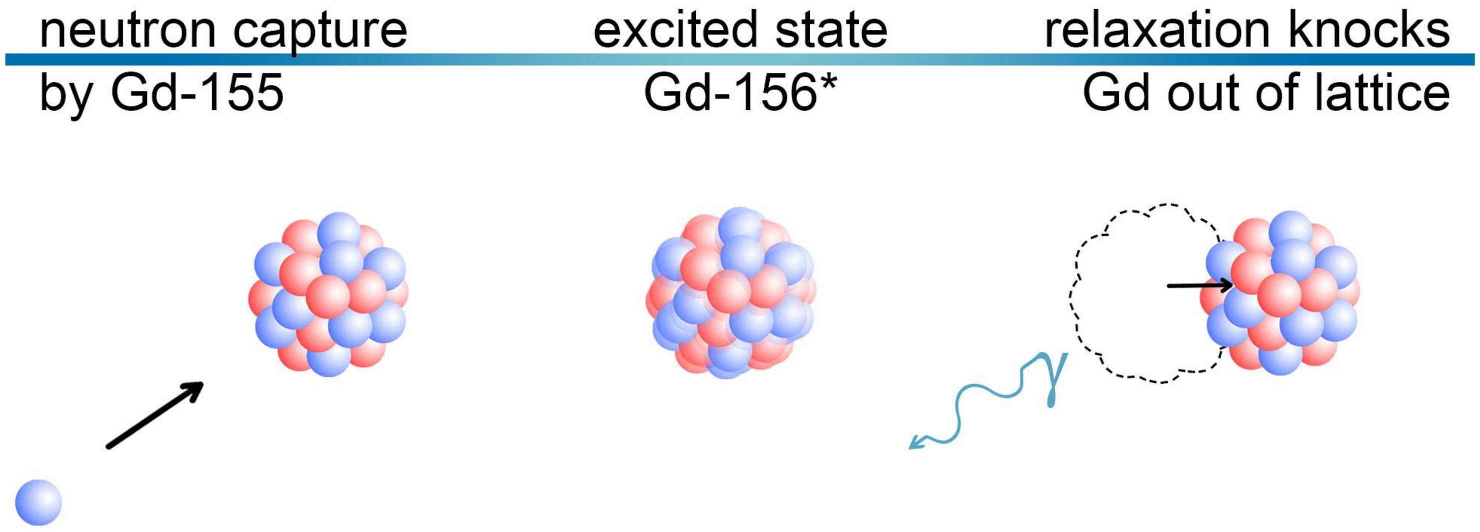
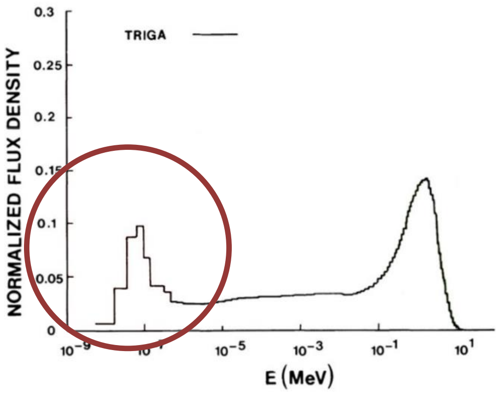
Thermal Neutron Irradiation



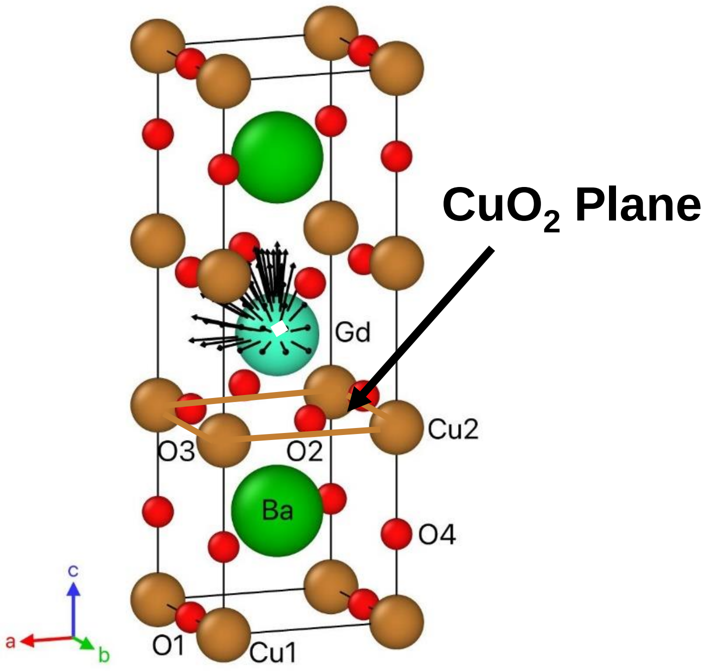
K.E. Sickafus et al., Phys. Rev. B **46** (1992) 11862



Thermal neutrons excite Gd → Recoil of 29 – 32 eV gamma emission displaces the nucleus

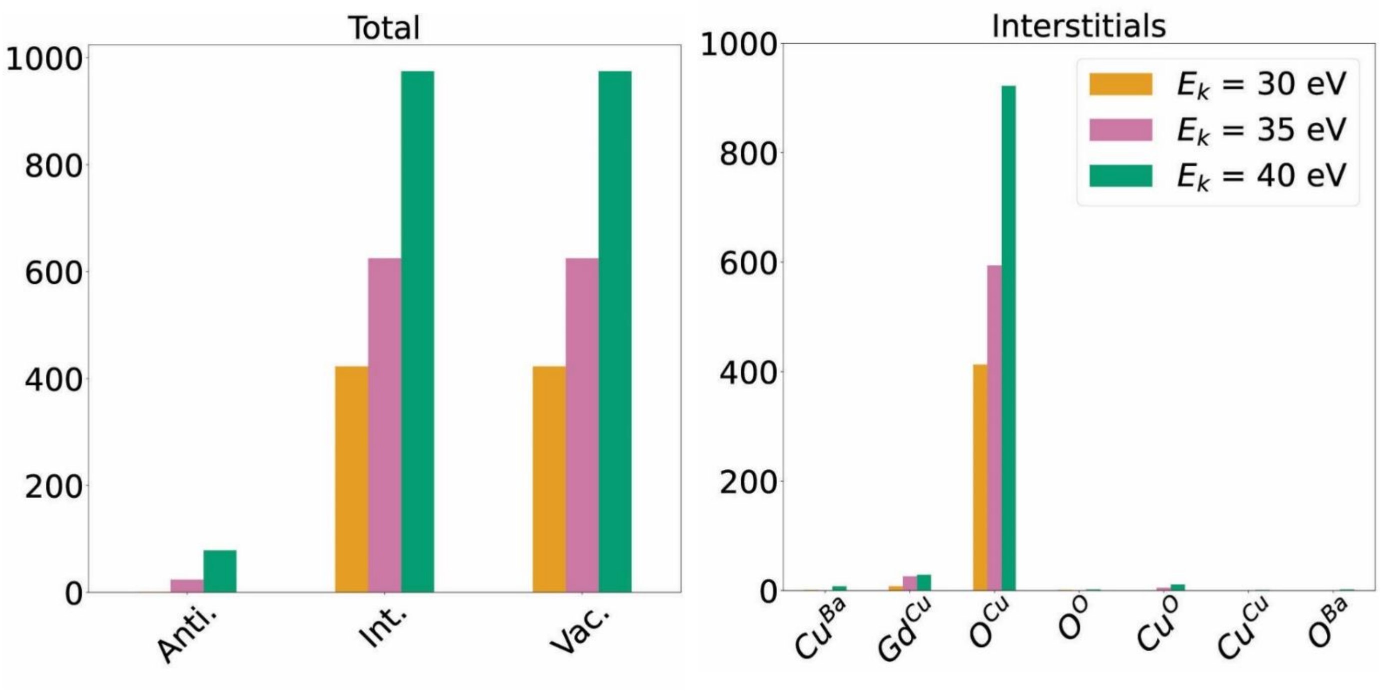
- Very high defect densities achievable
- Add to fast neutron induced defects

Thermal Neutron Irradiation



- position enables introduction of many defects close to the planes
- defects are small in comparison to coll. cascades
- defects may be modelled with MDS
- 3 energies close to experimental value simulated (30, 35, 40 eV)

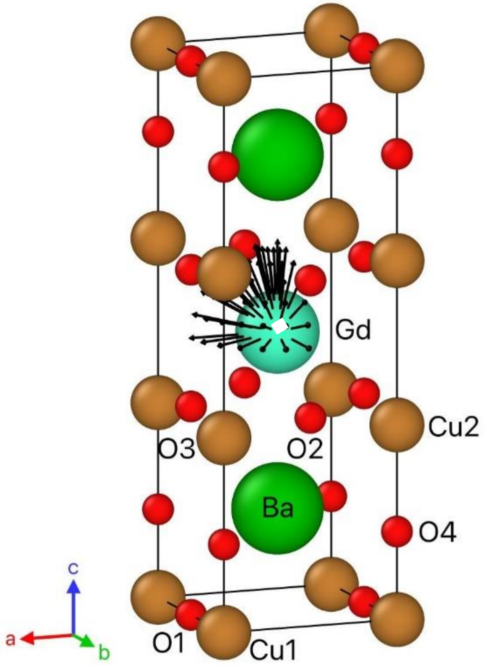
Thermal Neutron Irradiation - MDS

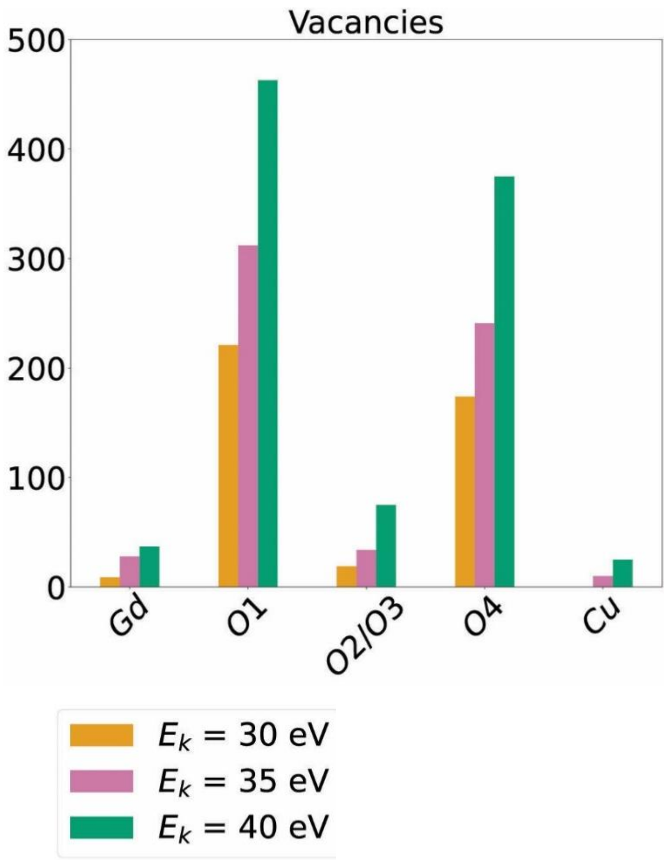


430 simulation runs per energy

- Most defects are oxygen vacancies
- Gd returns / stays in lattice position
- Different defects originating from Gd PKA (primary knock on atom)
- Defect distribution changes with energy
- 1-2 defects per incident particle

Thermal Neutron Irradiation - MDS





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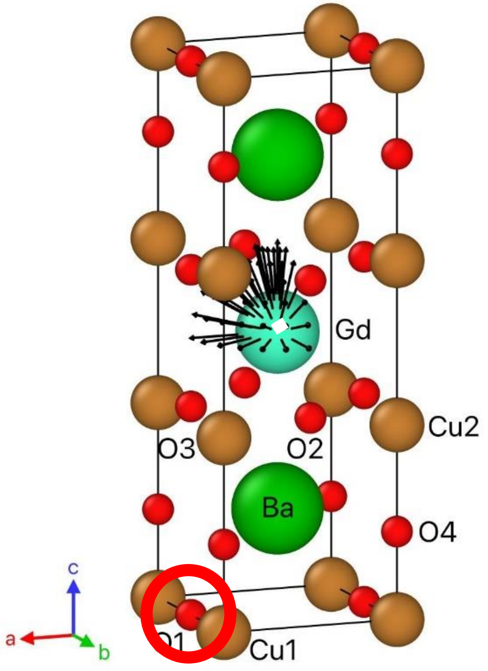

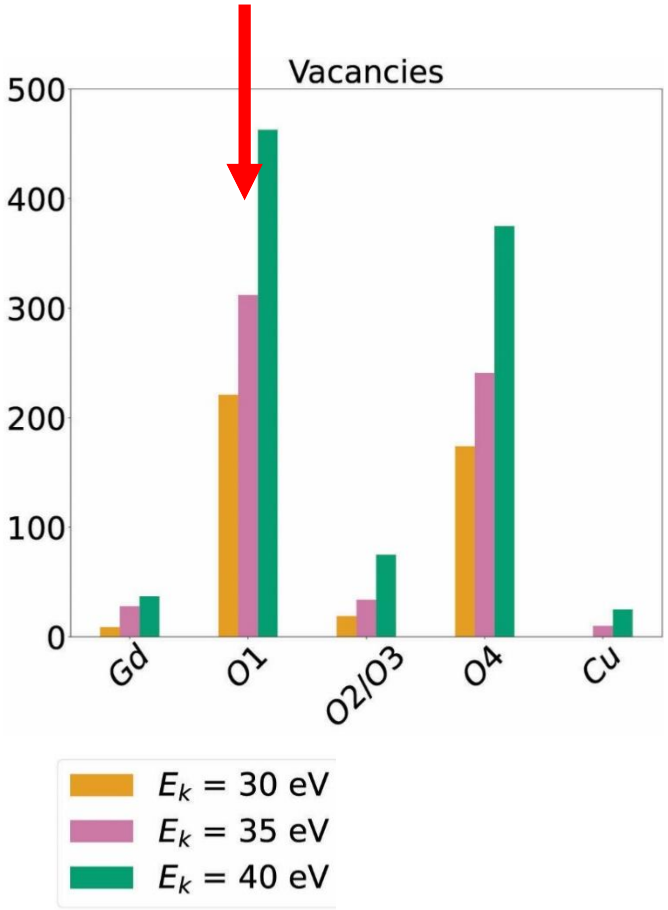

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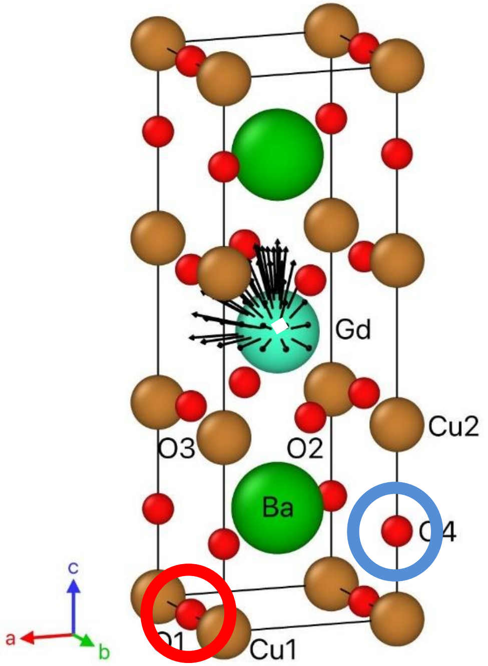

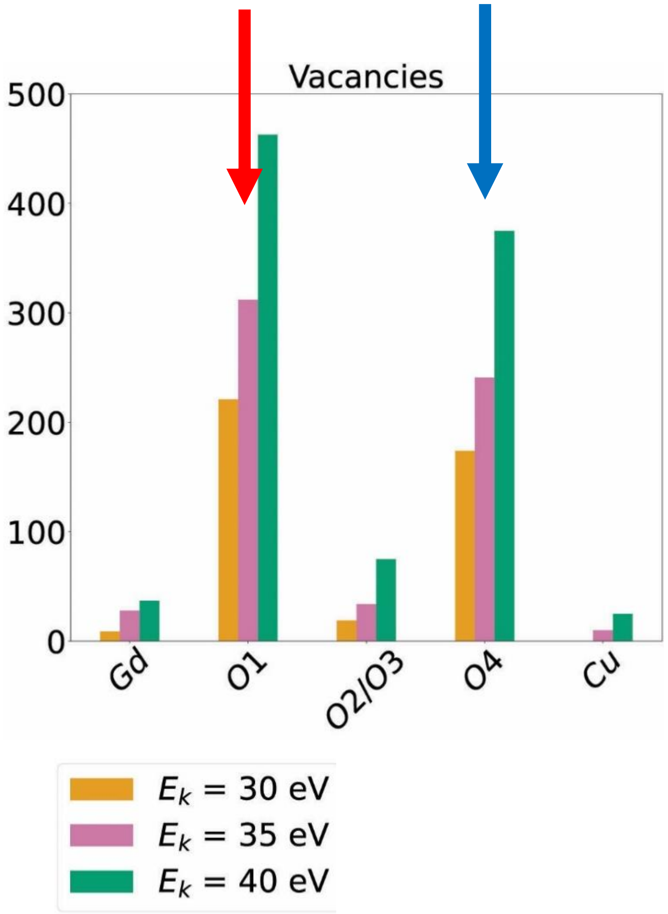

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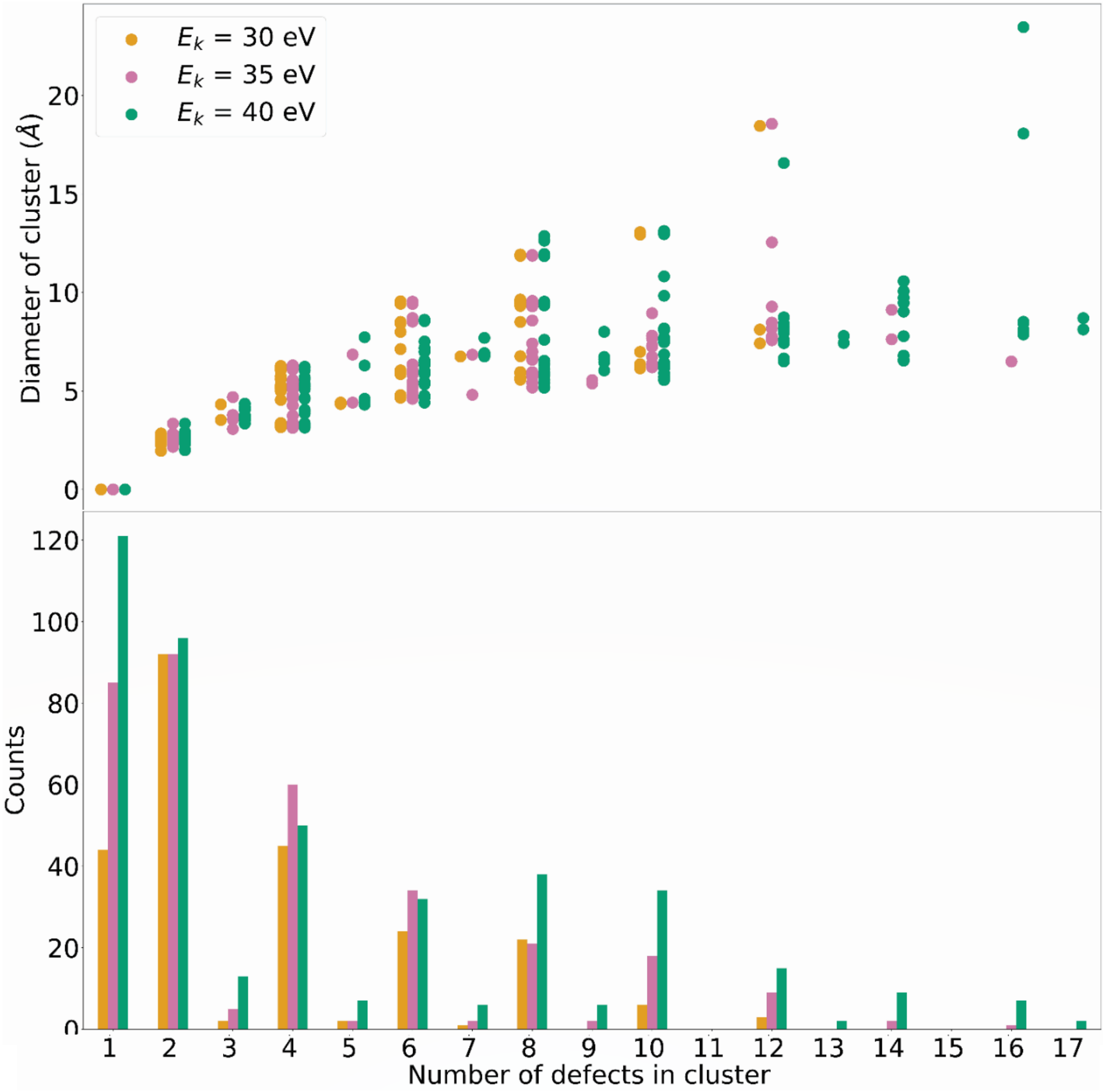
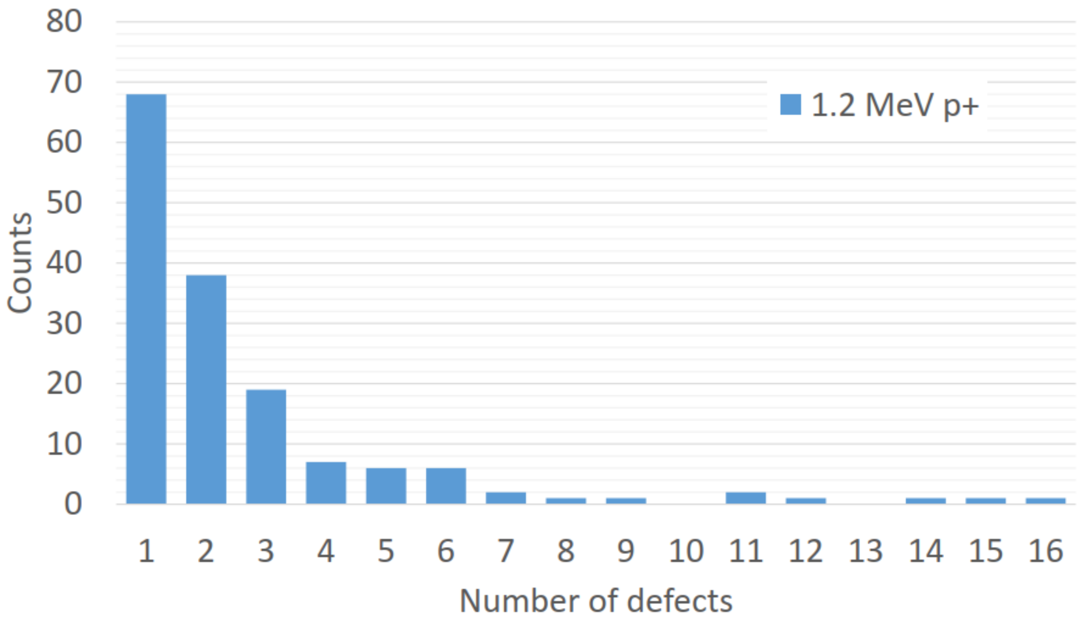


- Mainly point-like defects
- Small defects form clusters
- Up to 1 nm in size
- Slightly improves pinning behavior

1.2 MeV p^+ Irradiation

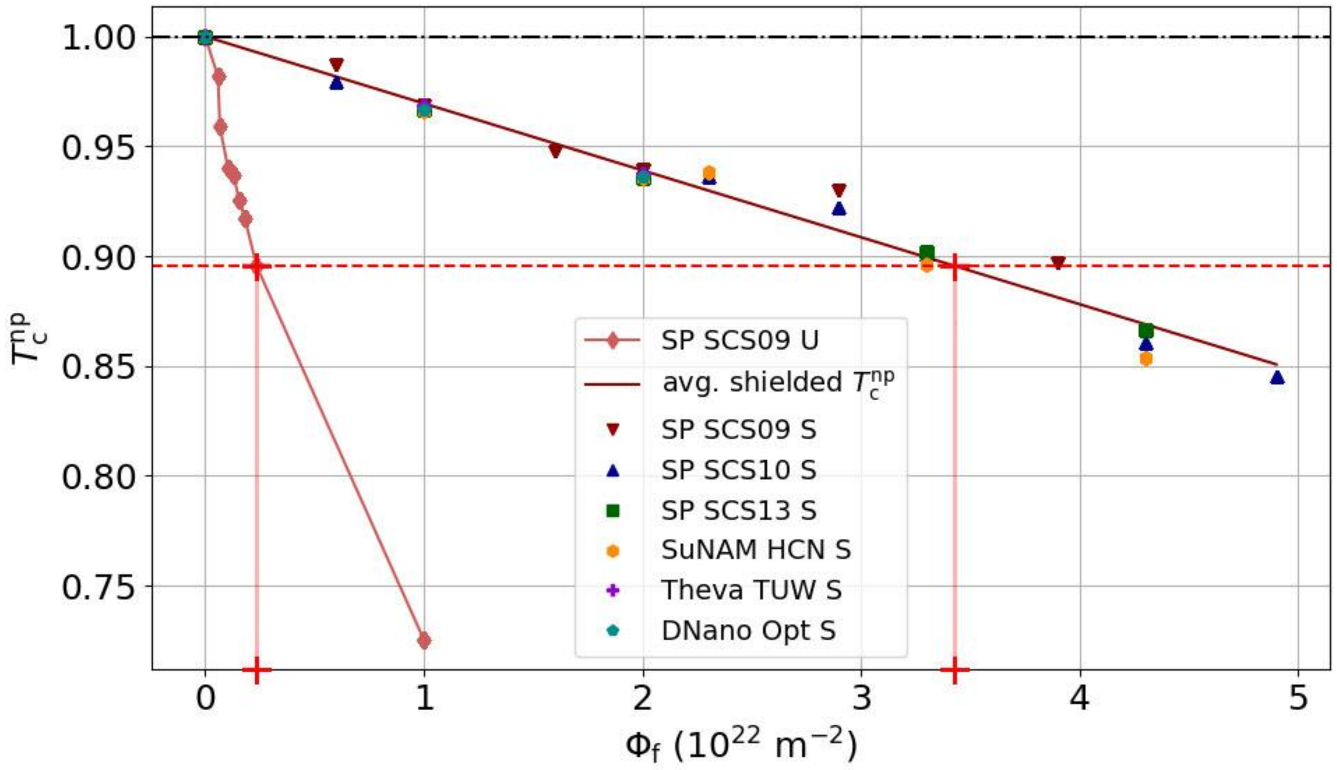


- SRIM/TRIM
- Most defects are oxygen displacements (low binding energy)
- Little is known about actual defects and recombination
- Large defects are possible but improbable
- Most defects are point-like or small clusters like with thermal neutrons

Results

Influence of thermal neutrons - T_c

More on
Small Defects

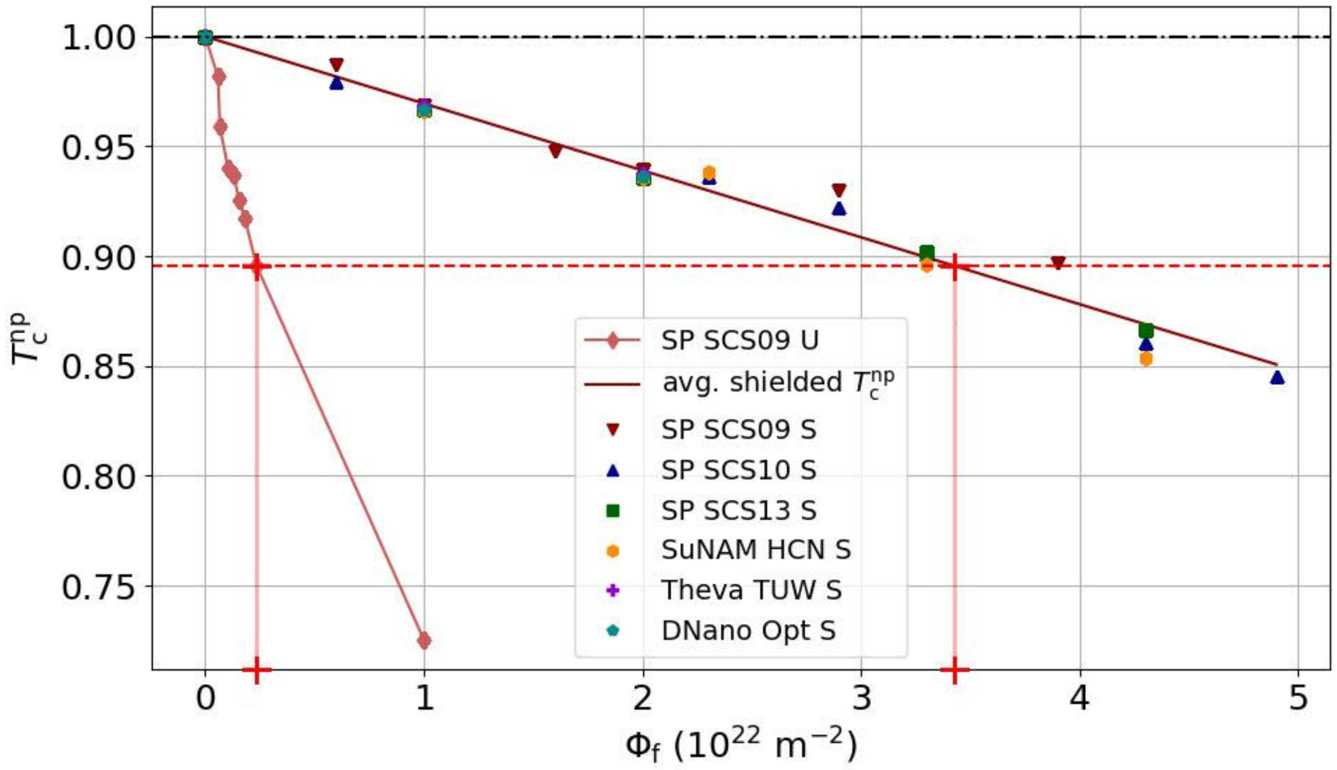


$$\frac{T_c}{T_c^0} = T_c^{\mathbf{np}}$$

np… normalized to pristine value

T_c degrades ~14 x faster due to Gd-point defects

Influence of thermal neutrons - T_c



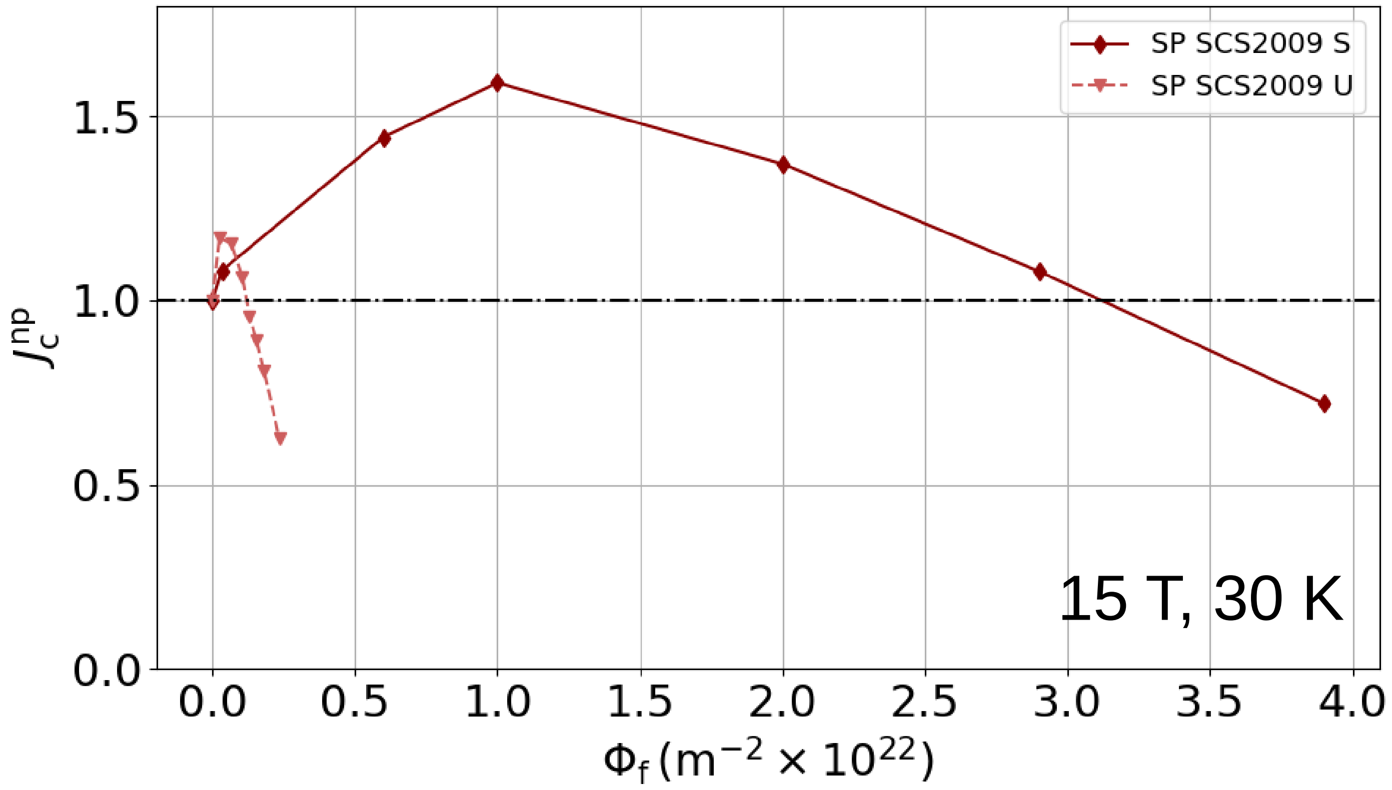
More on
Small Defects

$$\frac{T_c}{T_c^0} = T_c^{np}$$

np… normalized to pristine value

Fluence is not a good measure for the disorder!

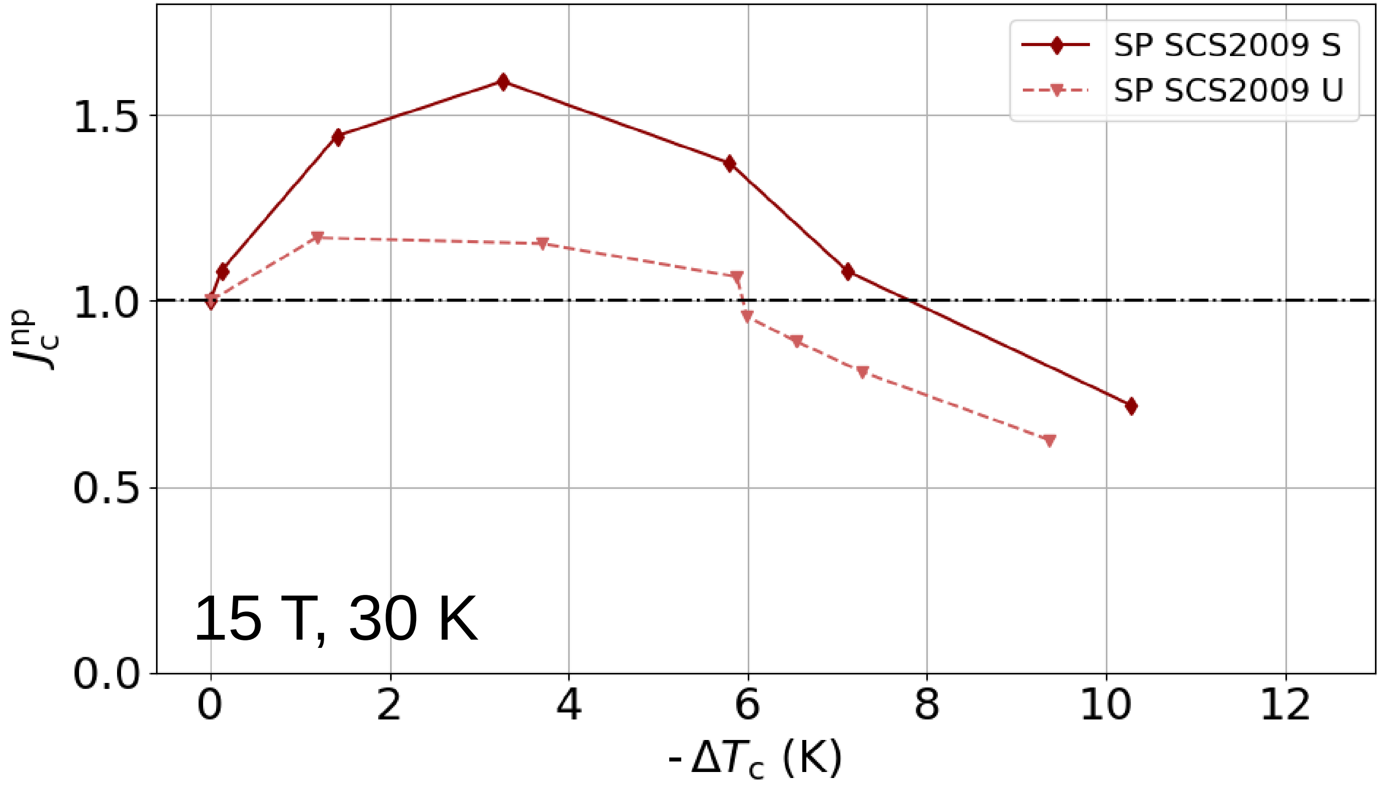
Influence of thermal neutrons - J_c



- maximum occurs at much lower neutron fluences
- J_c at maximum is smaller
- degradation is much faster

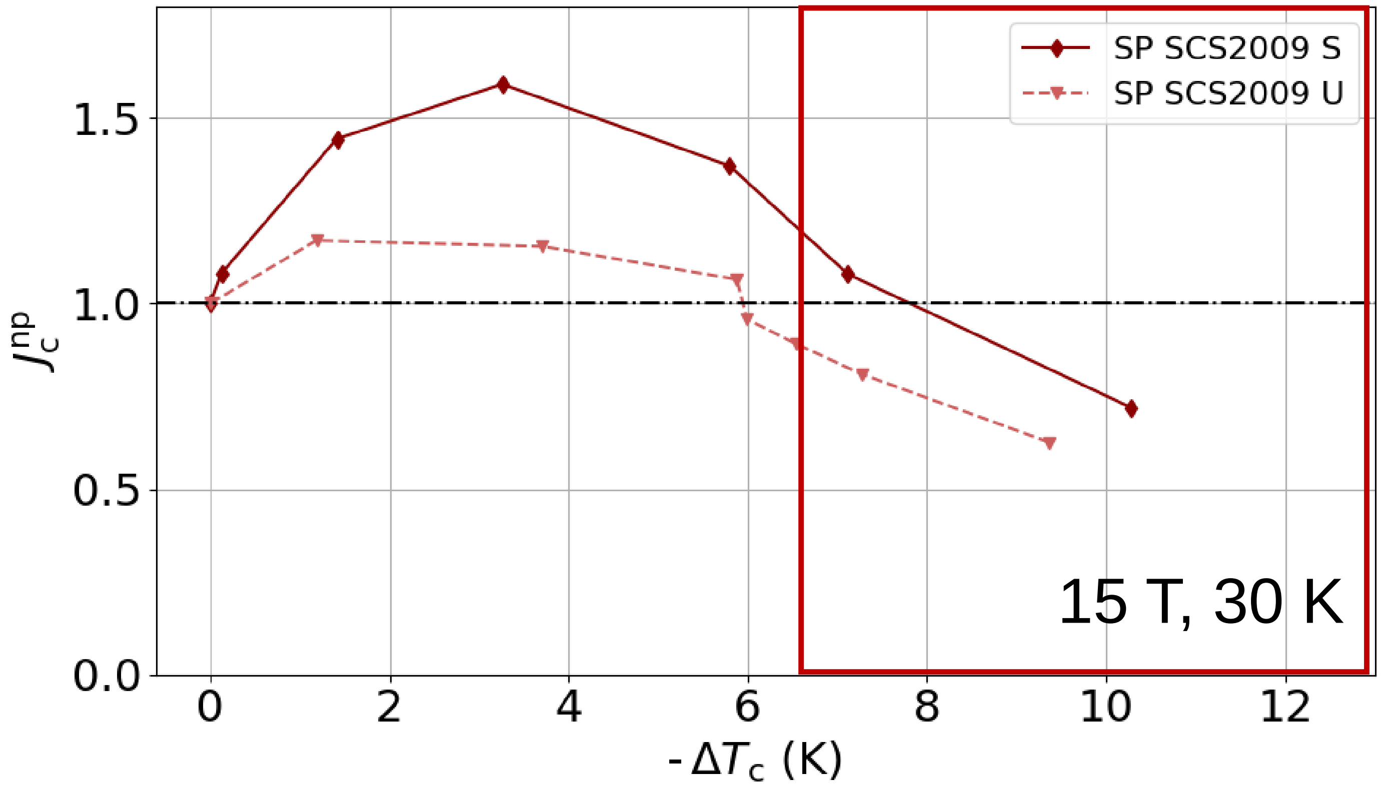
More on Small Defects

Influence of thermal neutrons - J_c



- J_c maximum shifted to lower T_c
- Degradation with similar slope
  - Accumulation of similar defects?
- T_c is efficient disorder parameter (decrease of superfluid density)

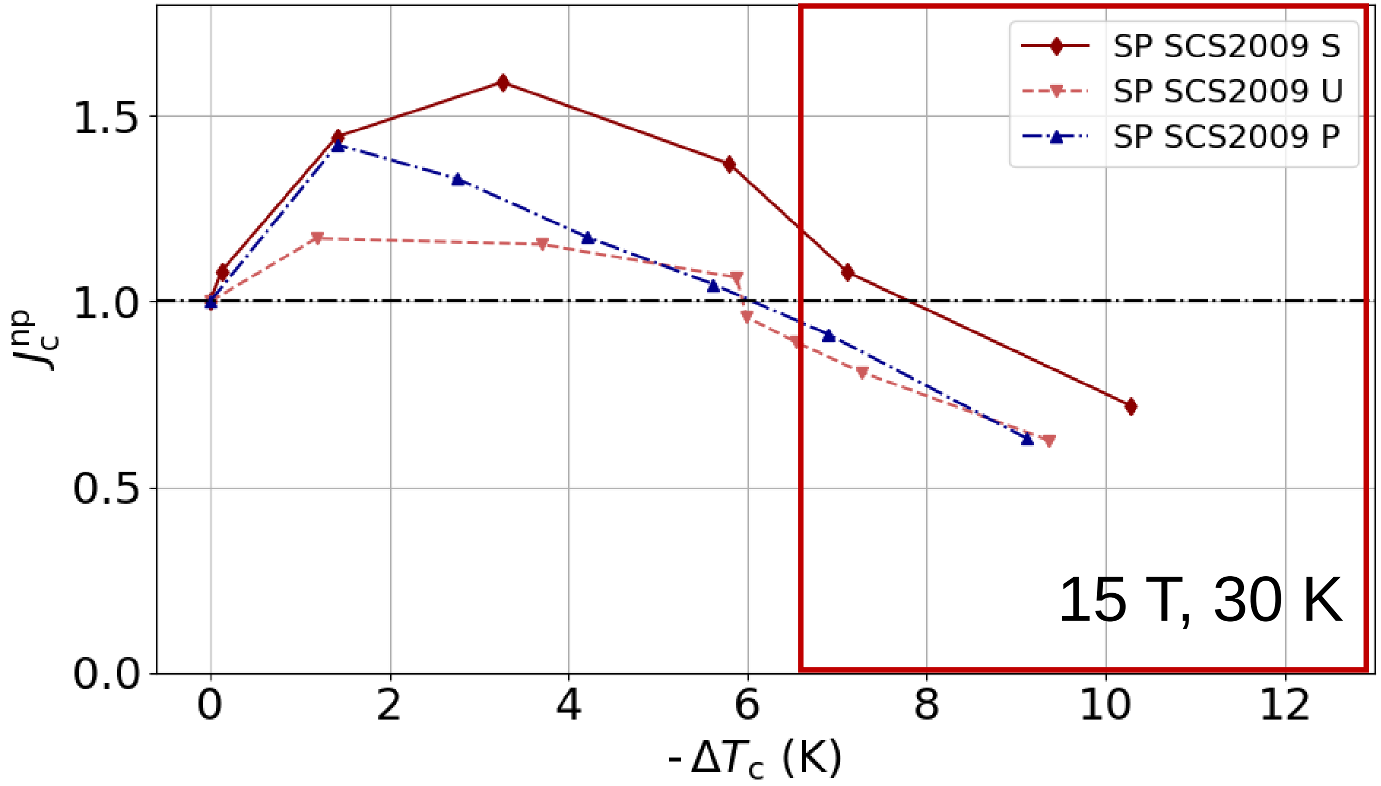
Influence of thermal neutrons - J_c



- Different defect densities
- Parallel degrading branch
- Specific defects origin of degradation?
- Accumulation in all irradiation techniques?

Focus on degrading branch

Influence of thermal neutrons - J_c



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- Parallel degrading branch
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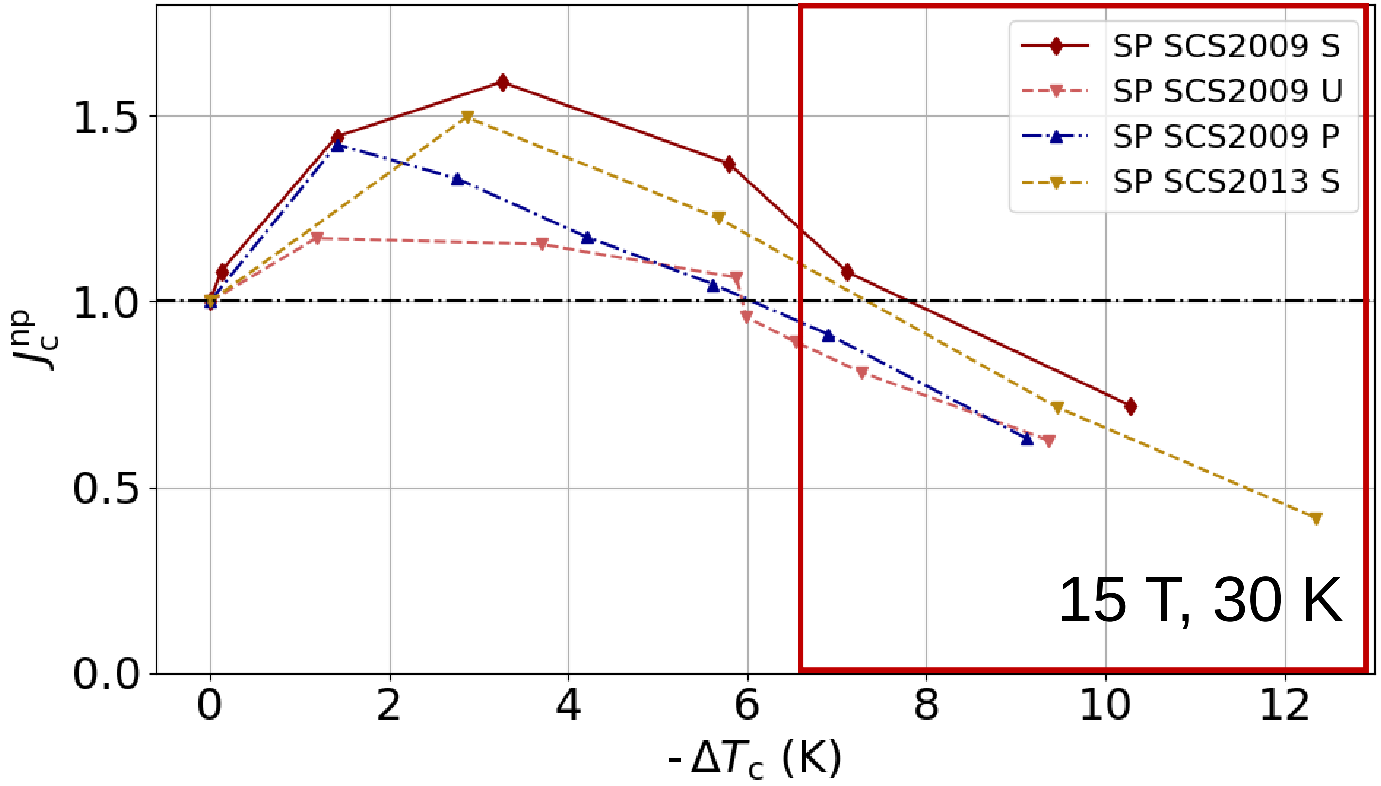
- Accumulation in all irradiation techniques?

Sample irradiated with 1.2 MeV proton at room temperature

Influence of thermal neutrons - J_c

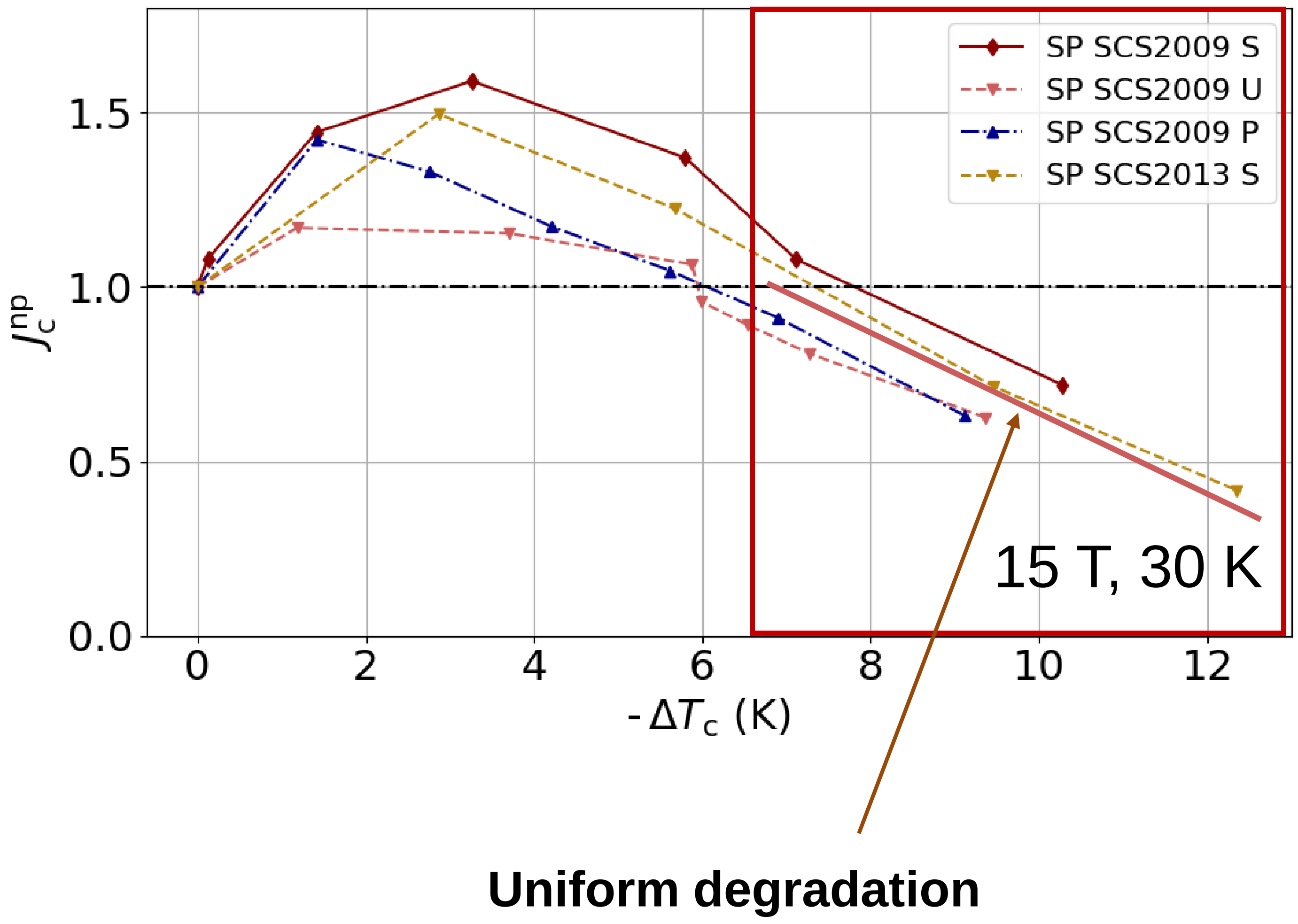


- Different defect densities
- Parallel degrading branch
- Specific defects origin of degradation?
- Accumulation in all irradiation techniques?

Sample irradiated with 1.2 MeV proton at room temperature

Shielded sample with APCs

Influence of thermal neutrons - J_c

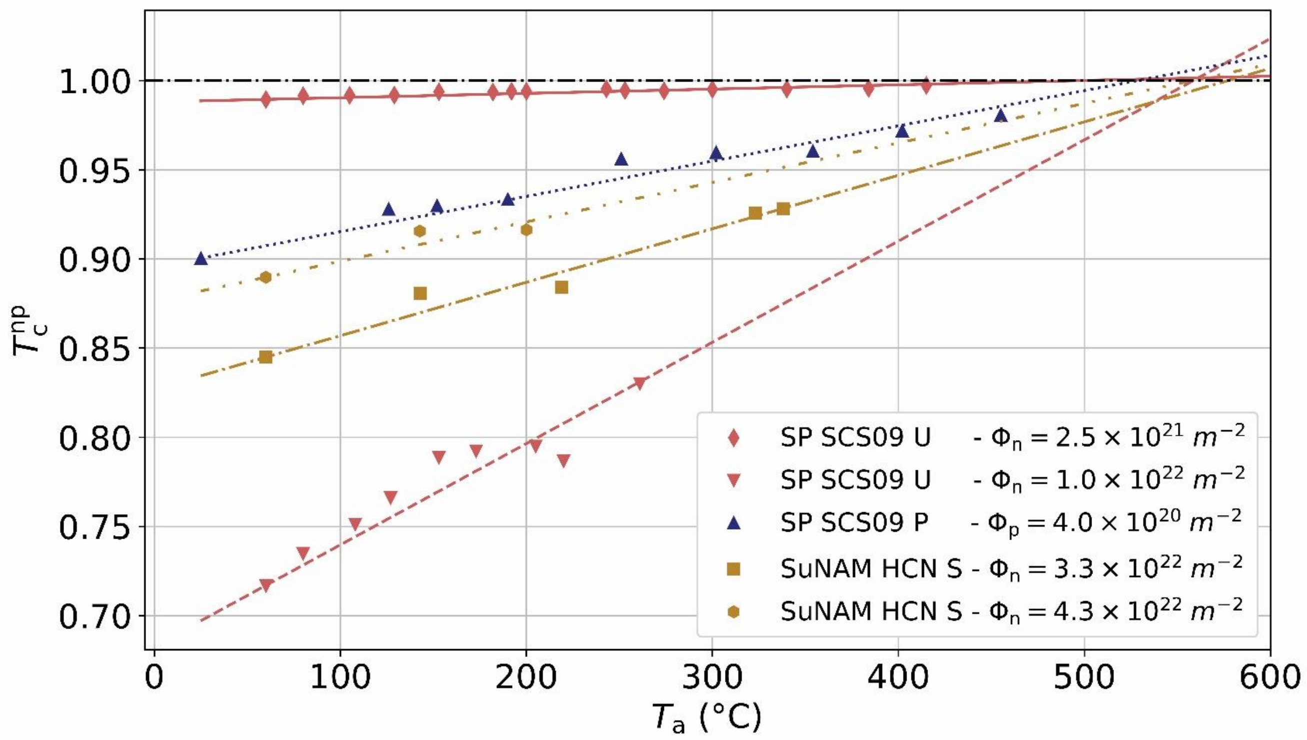


- Different defect densities
- Parallel degrading branch
- Specific defects origin of degradation?
- Accumulation in all irradiation techniques?

Thermal stability of small vs large defects

More on
Defect Annealing

annealing



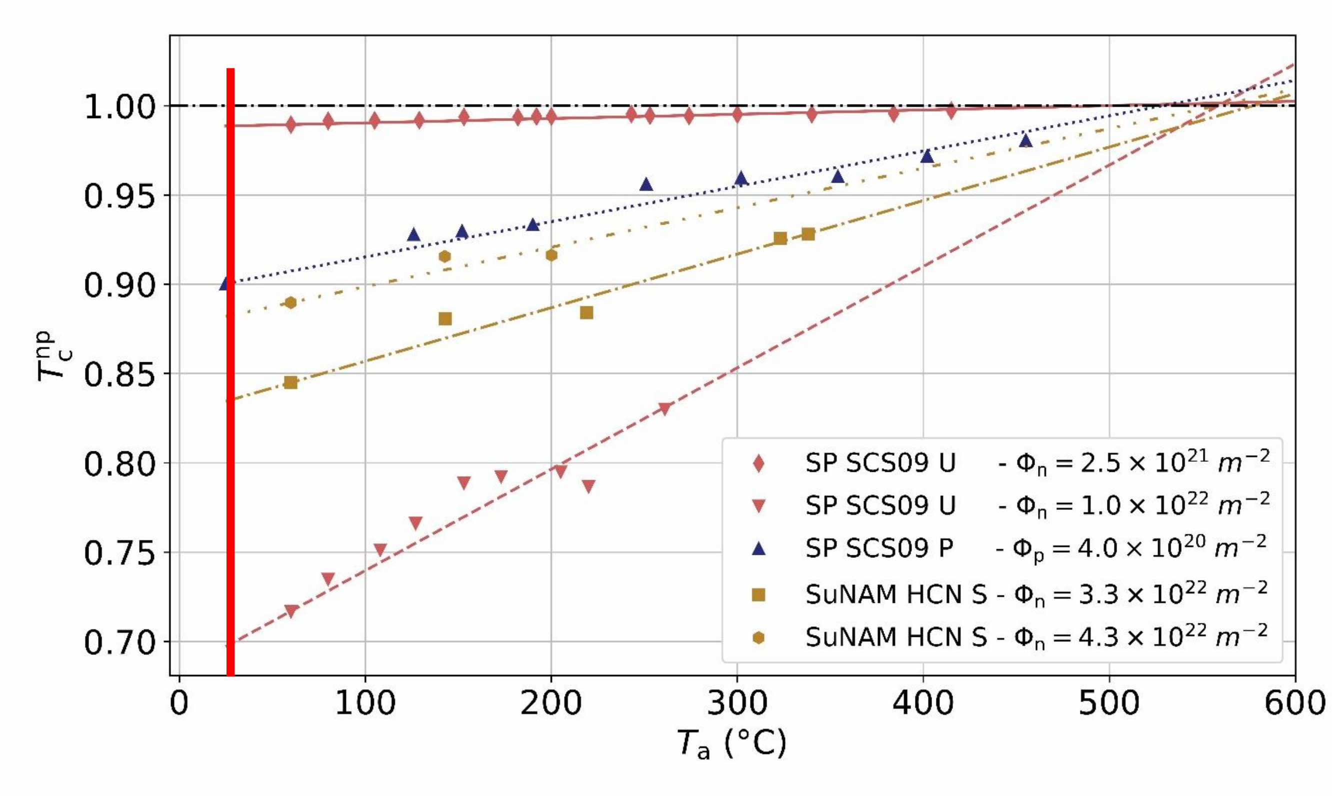
- T_c regenerates "linearly" with T_a
- All neutron and proton irradiated samples anneal to same point
- Annealing defects have same/similar distribution and activation barrier
- n_{therm}, n_{fast} & p^+ irradiated samples

Samples annealed in pure O_2 atmosphere at 1 atm

Thermal stability of small vs large defects

More on
Defect Annealing

annealing



Normalizing $\Delta T_c(T_a)$ to $\Delta T_c(T_a = 25\ °C)$

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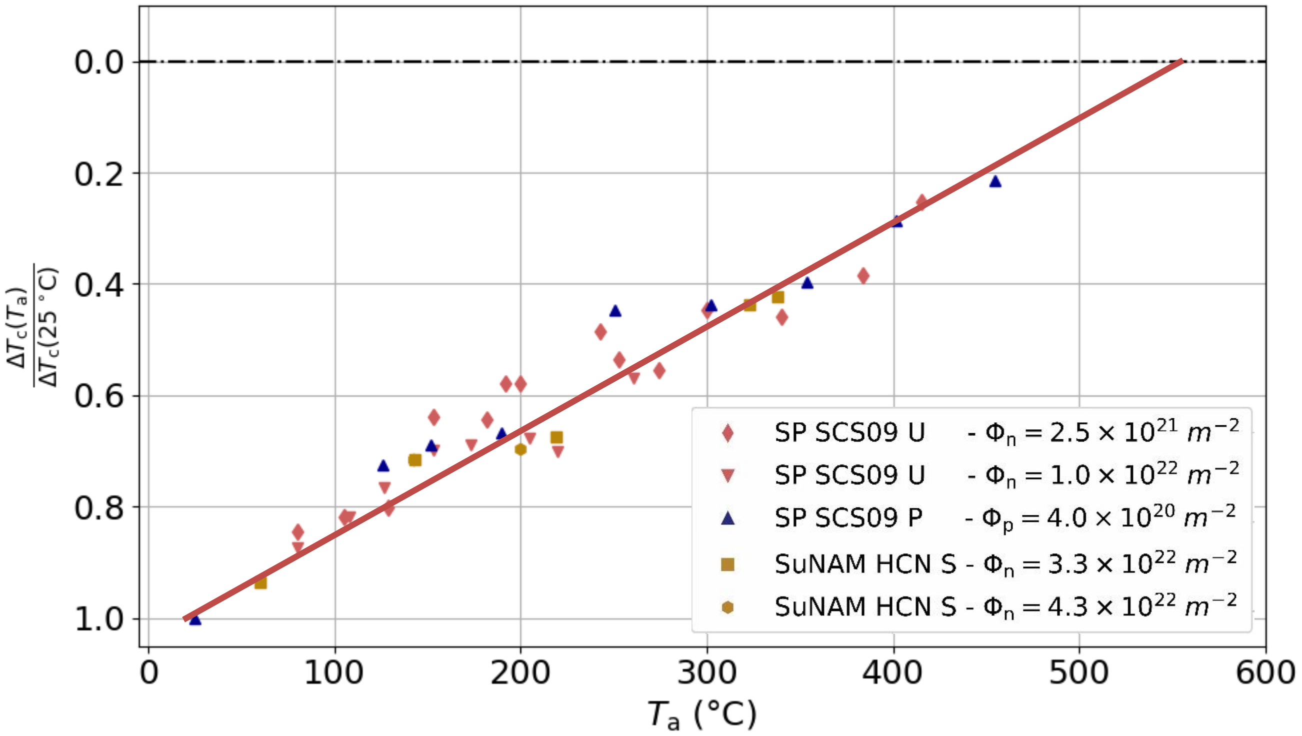
Thermal stability of small vs large defects

More on
Defect Annealing

annealing



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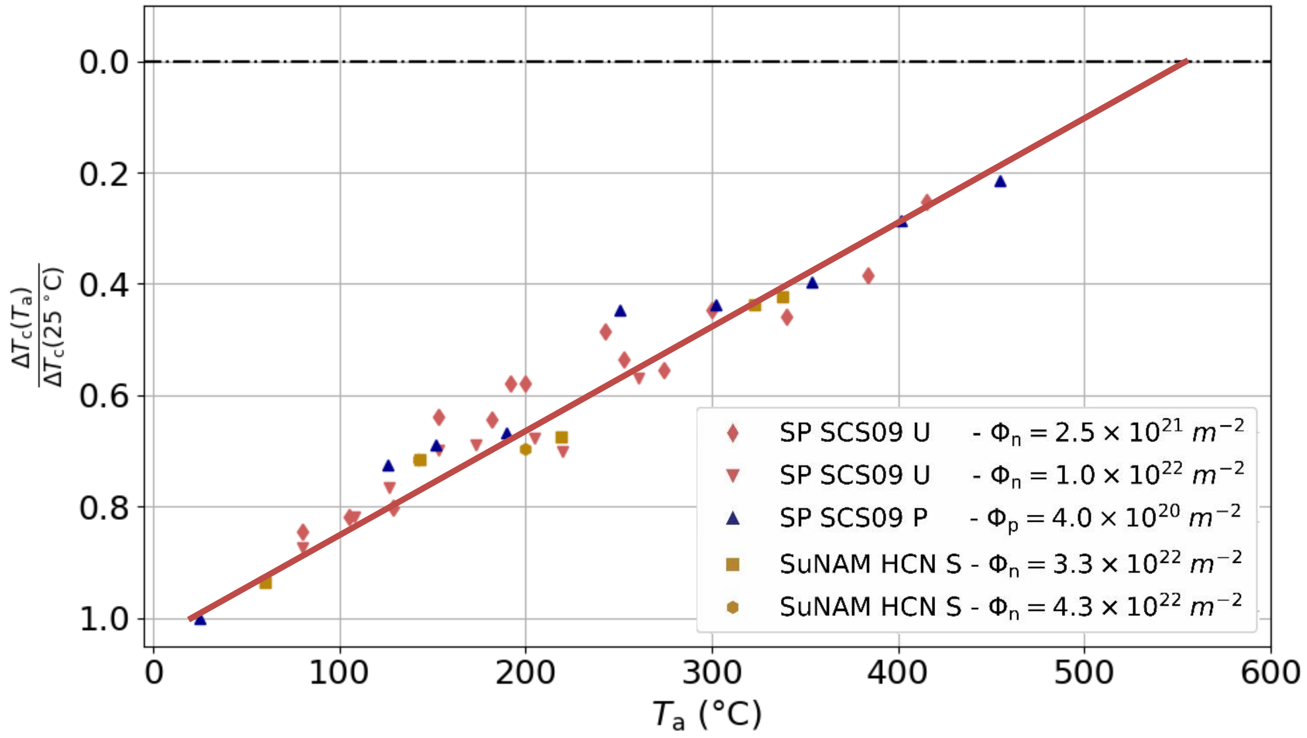
Thermal stability of small vs large defects

More on
Defect Annealing

annealing

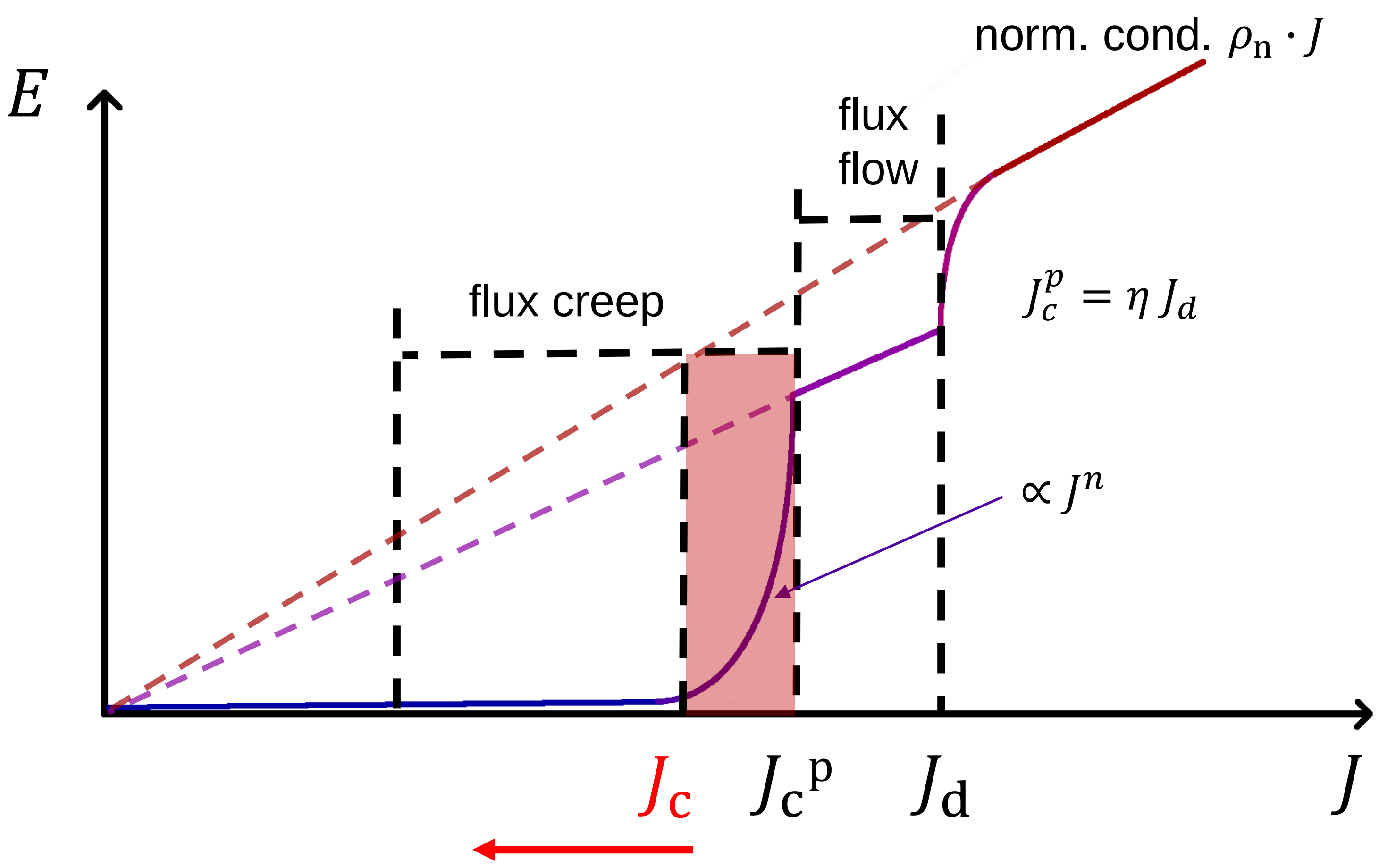


Normalizing $\Delta T_c(T_a)$ to $\Delta T_c(T_a = 25\ °C)$

- Large defects were shown to be stable up to at least 350 °C
- The same defects which are annealed occur in comparable densities in all samples

Modelling

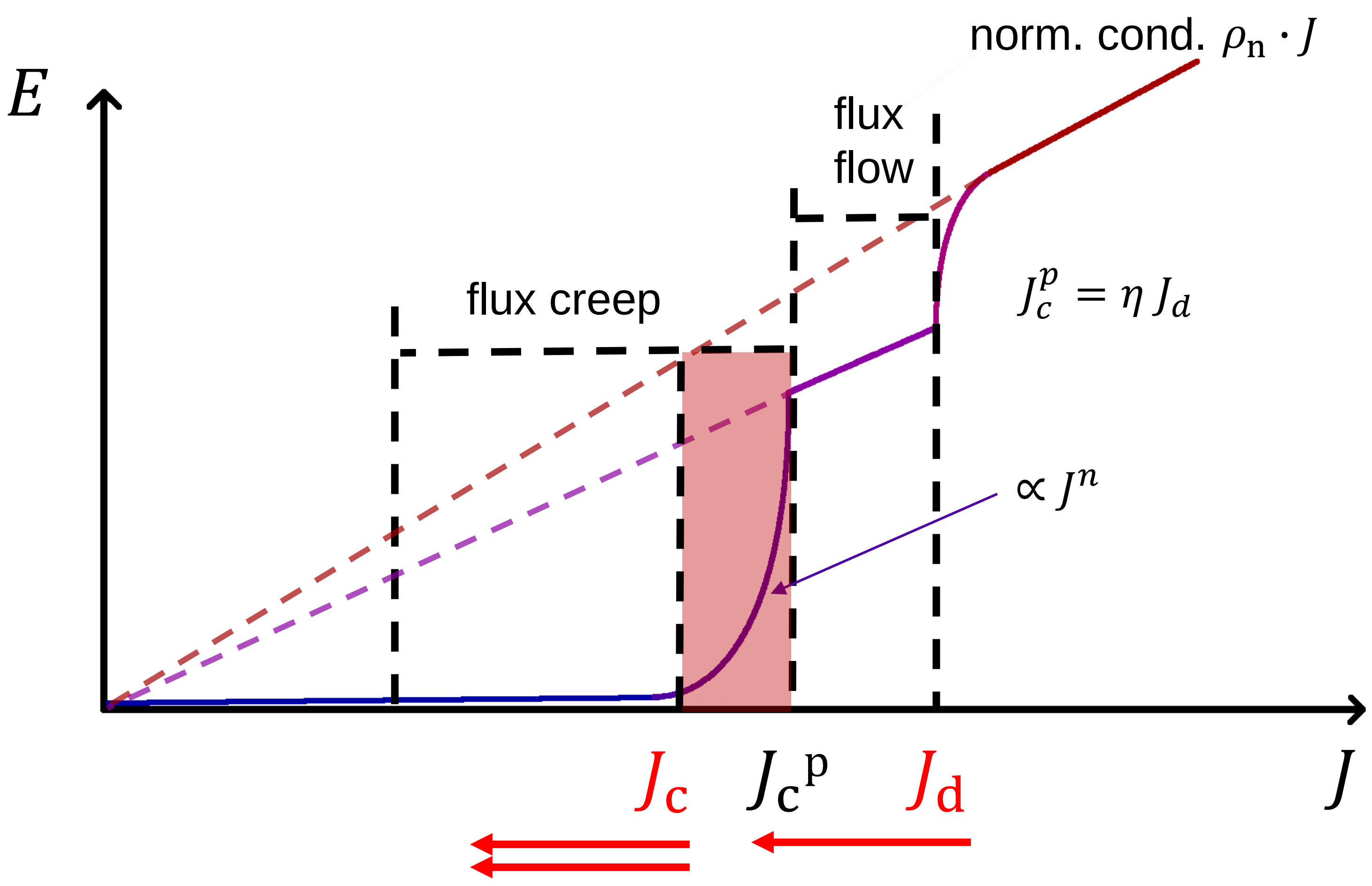
Modelling



Degrading

- *n*-value decreases
- T_c decreases
- Normal state resistivity ρ_n increases

Modelling



Degrading

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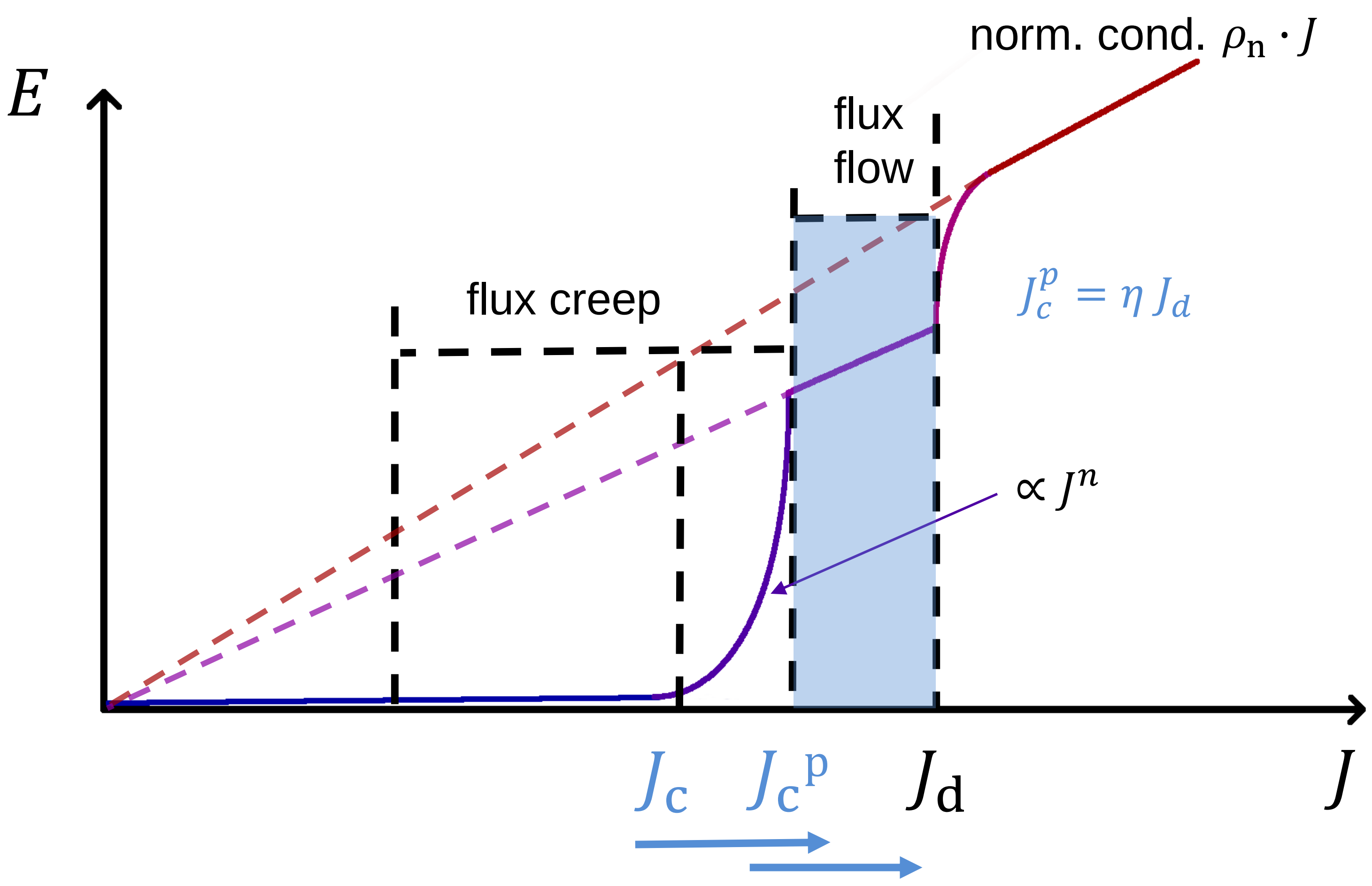
Modelling



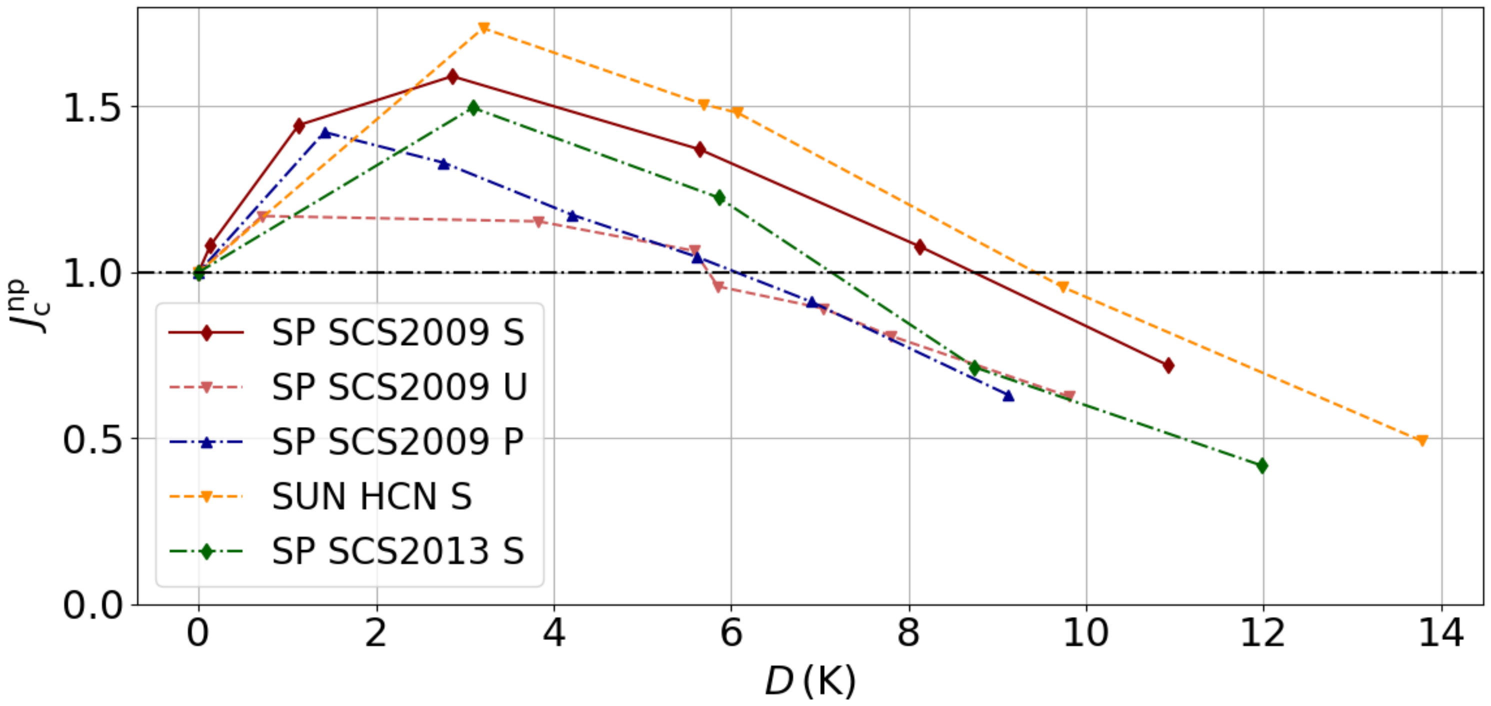
Degrading

- *n*-value decreases
- T_c decreases
- Normal state resistivity ρ_n increases

Enhancing

- η – pinning efficiency

Modelling



Disorder parameter

$$1\,D \propto -\Delta T_c$$

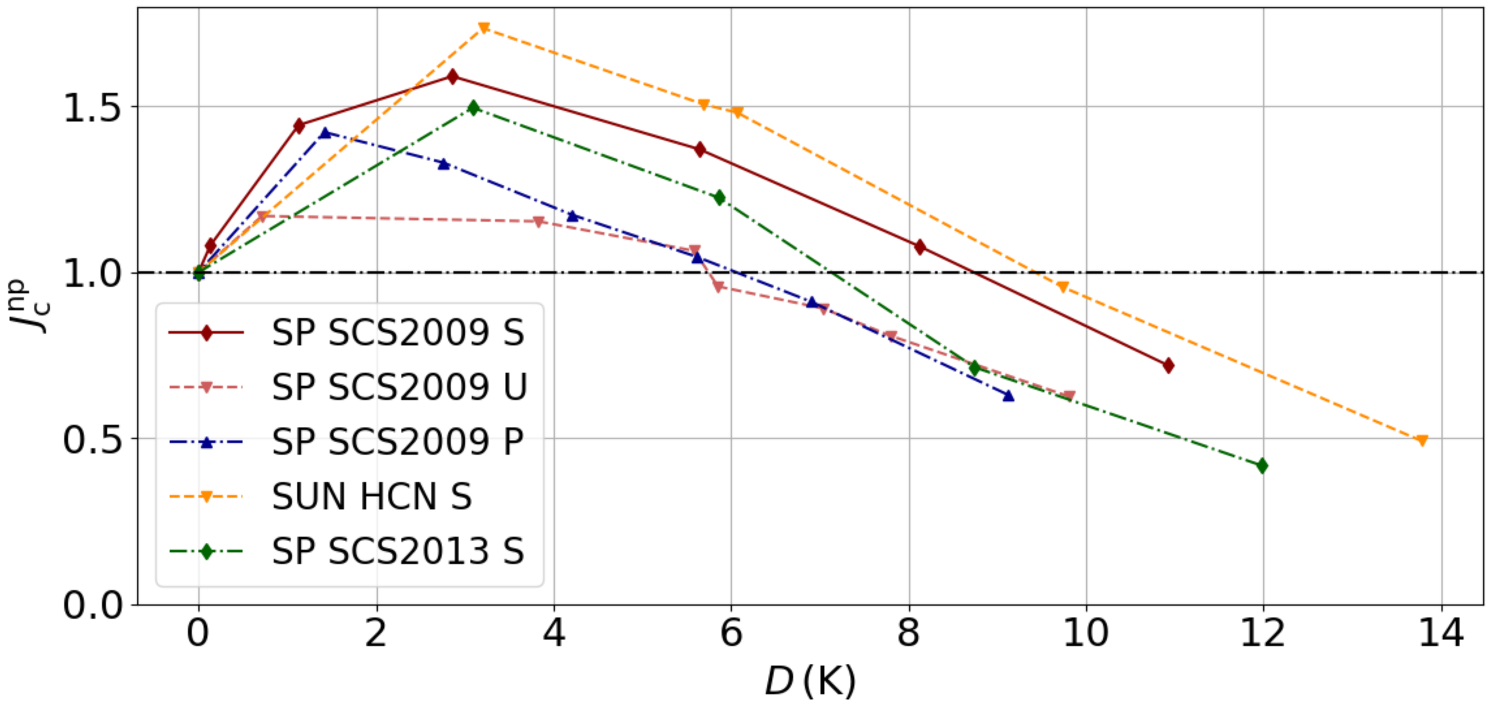
measure for scattering

Φ_f Fast neutron fluence shielded

$\Phi_f^{\text{therm, Gd}}$ Fast neutron fluence unshielded

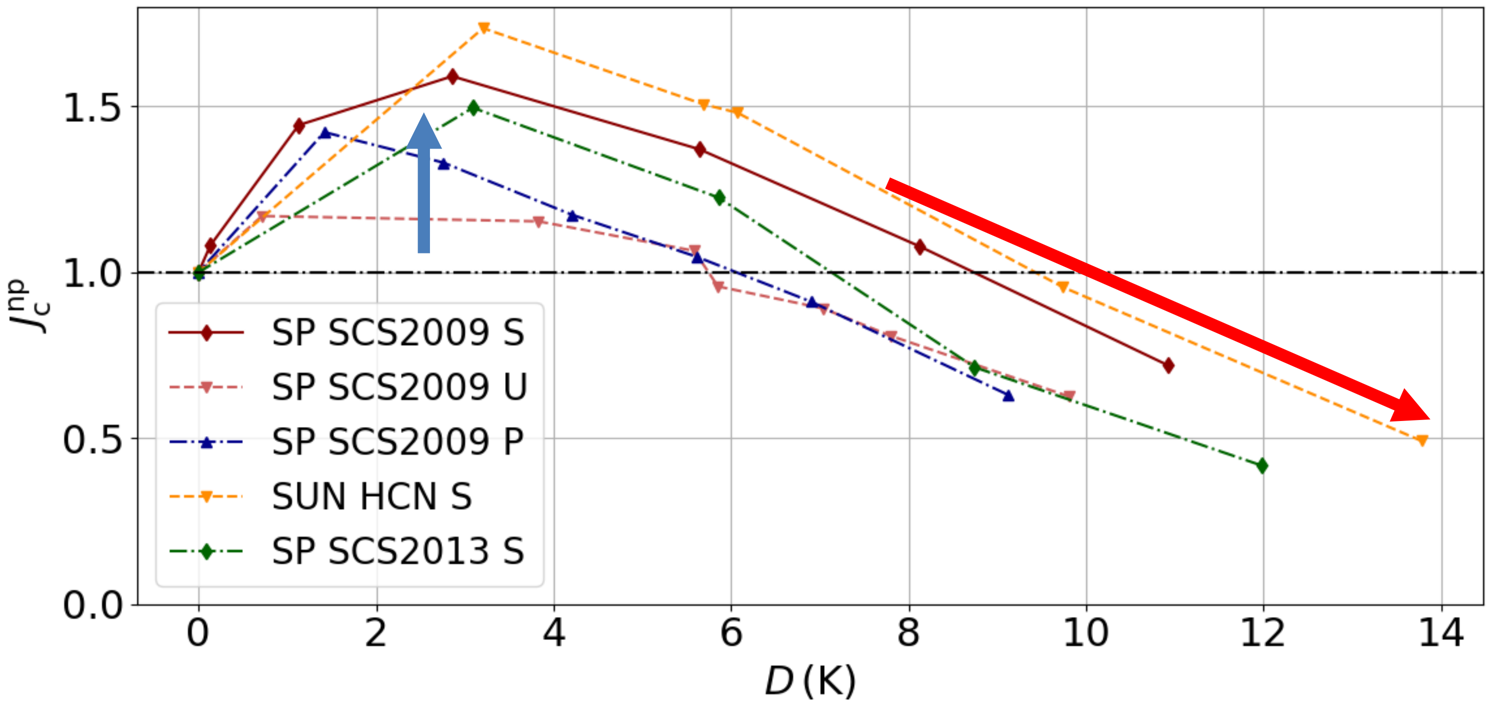
Φ_p Proton Fluence

Modelling



$$J_c^{np} = \frac{J_c^{irr}}{J_c^{0}} = \left(\frac{E_c}{\nu_0\sqrt{\Phi_0^B\, B}}\right)^{\frac{1}{n_{irr}}-\frac{1}{n^0}} \left(\frac{T_c^{irr}}{T_c^0}\right)^{\frac{3}{2}} \left(\frac{\rho_n^0}{\rho_0^{irr}}\right)^{\frac{1}{2}} \quad \frac{\eta_{max}}{\eta^0} \tanh\left(\frac{D}{D_{\eta_{max}}}(\pi - A) + A\right)$$

Modelling



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Degrading - F_D

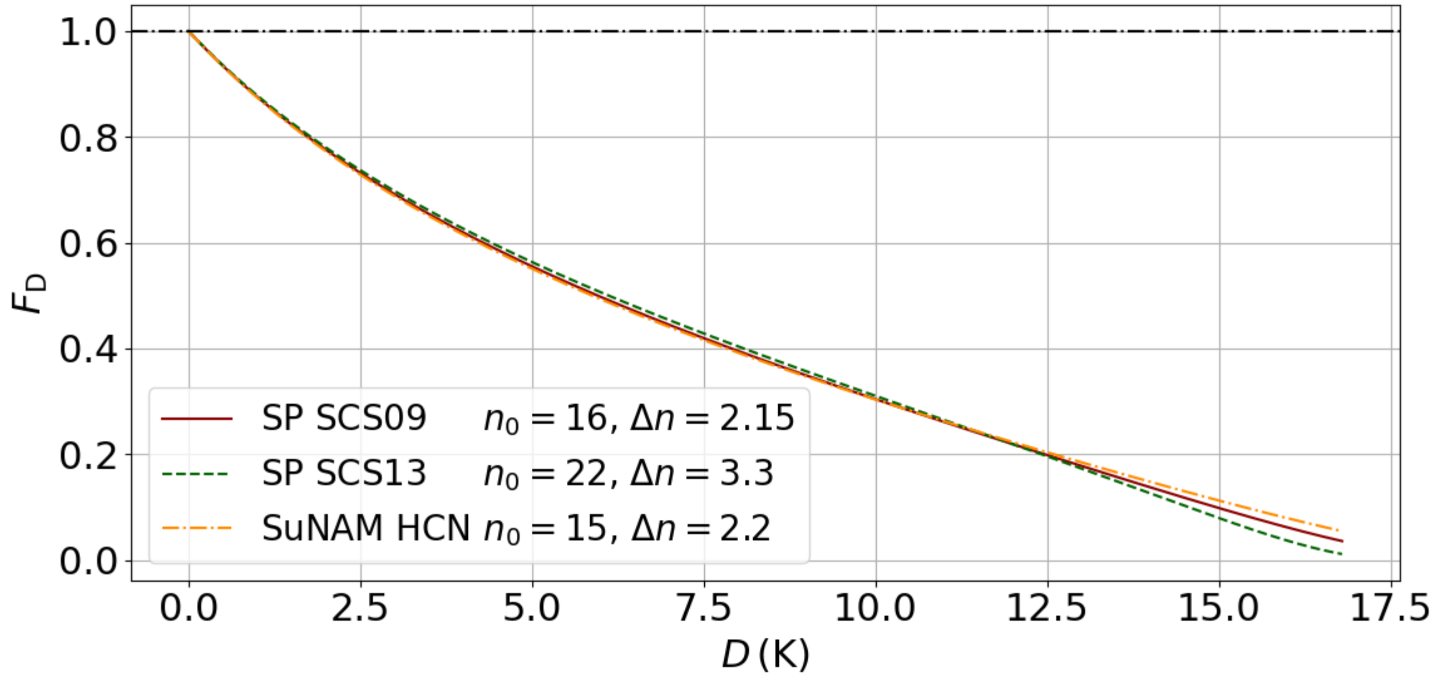
Enhancing - η

Modelling - Degradation

Derived using only BCS, GL and Drudes' model

$$J_c^{np} = \frac{J_c^{irr}}{J_c^0} = \left(\frac{E_c}{\nu_0\sqrt{\Phi_0^B\, B}}\right)^{\frac{1}{n_{irr}}-\frac{1}{n^0}} \left(\frac{T_c^{irr}}{T_c^0}\right)^{\frac{3}{2}} \left(\frac{\rho_n^0}{\rho_0^{irr}}\right)^{\frac{1}{2}} \quad \frac{\eta_{max}}{\eta^0} \tanh\left(\frac{D}{D_{\eta_{max}}}(\pi - A) + A\right)$$

Degradation Model



Norm. state resistivity $\rho_n = 48\ \mu\Omega\ cm$

attempt frequency $\nu_0 = 2.5 \times 10^7$ Hz

el. field criterion $E_c = 1\ \mu V\ cm$

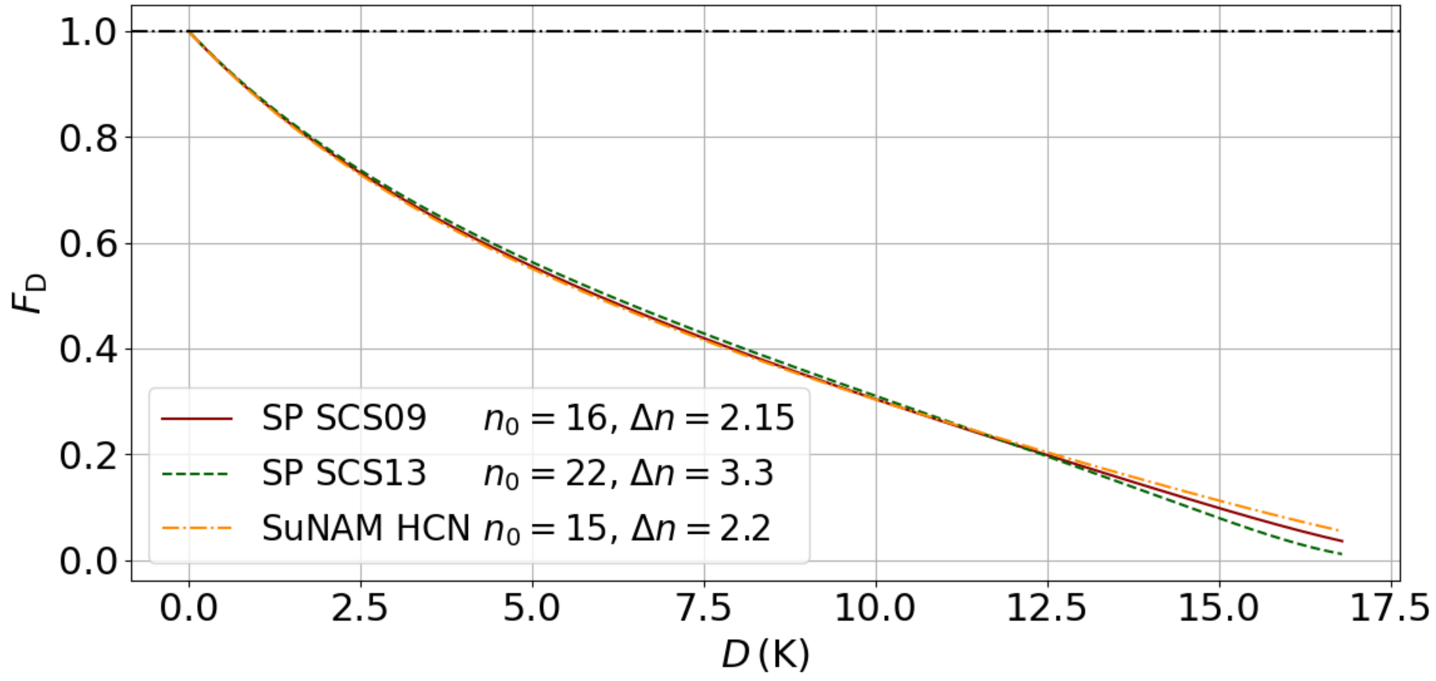
- Universal behavior
- All parameters fairly easy accessible
- Curve hard to measure directly due to pinning

Modelling - Degradation

Derived using only BCS, GL and Drudes' model

$$J_c^{np} = \frac{J_c^{irr}}{J_c^0} = \left(\frac{E_c}{\nu_0\sqrt{\Phi_0^B\,B}}\right)^{\frac{1}{n_{irr}}-\frac{1}{n^0}} \left(\frac{T_c^{irr}}{T_c^0}\right)^{\frac{3}{2}} \left(\frac{\boldsymbol{\rho}_{\mathbf{n}}^{\mathbf{0}}}{\boldsymbol{\rho}_{\mathbf{0}}^{\mathbf{irr}}}\right)^{\frac{1}{2}} \quad \frac{\eta_{max}}{\eta^0}\tanh\left(\frac{D}{D_{\eta_{max}}}(\pi - A) + A\right)$$

Degradation Model



Norm. state resistivity $\rho_n = 48\ \mu\Omega\ cm$

- Influences degradation
- measured on YBCO thin film on MgO

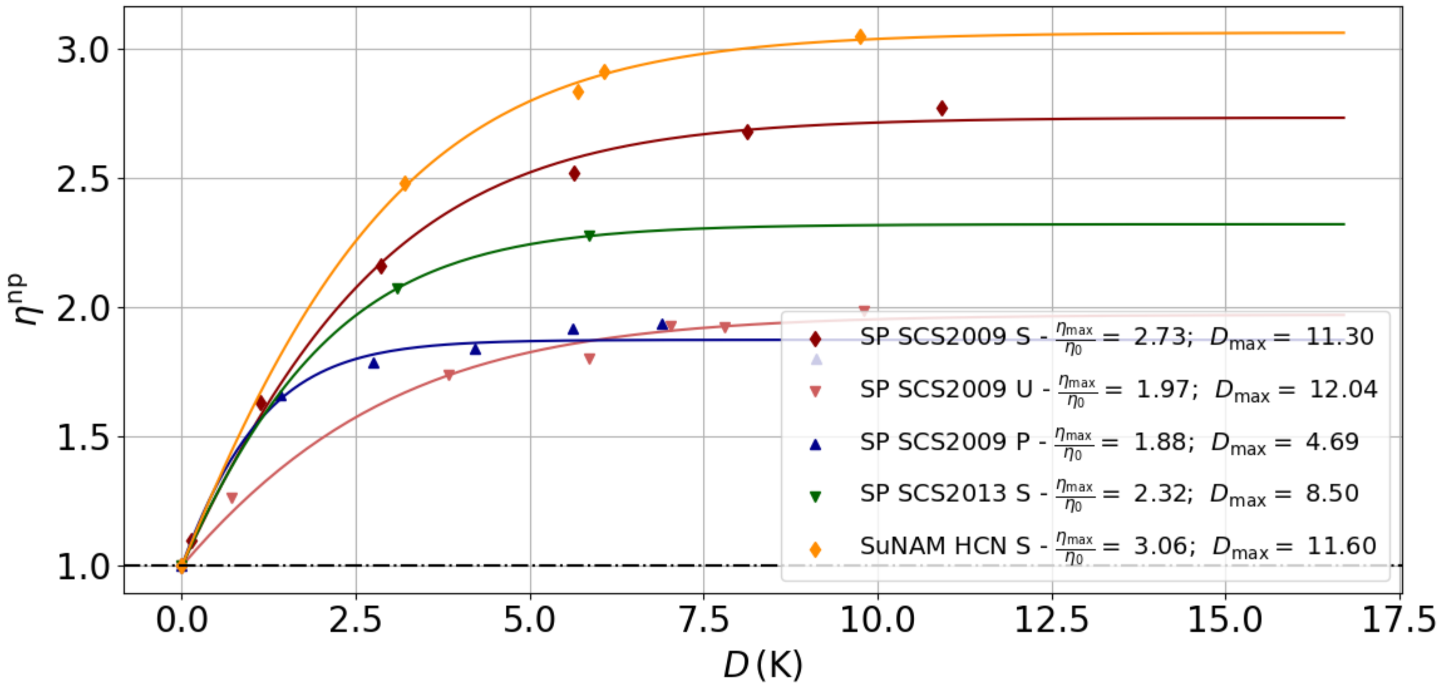
Talk - Alexander Bodeseher
4MOr2B-02 – right now, right here

Modelling - Enhancement

$$J_c^{np} = \frac{J_c^{irr}}{J_c^0} = \left(\frac{E_c}{\nu_0\sqrt{\Phi_0^B\, B}}\right)^{\frac{1}{n_{irr}}-\frac{1}{n^0}} \left(\frac{T_c^{irr}}{T_c^0}\right)^{\frac{3}{2}} \left(\frac{\rho_n^0}{\rho_0^{irr}}\right)^{\frac{1}{2}} \quad \frac{\eta_{max}}{\eta^0}\tanh\left(\frac{D}{D_{\eta_{max}}}(\pi - A) + A\right)$$

Degradation Model

$$A = \tanh^{-1}\frac{\eta^0}{\eta_{max}}$$

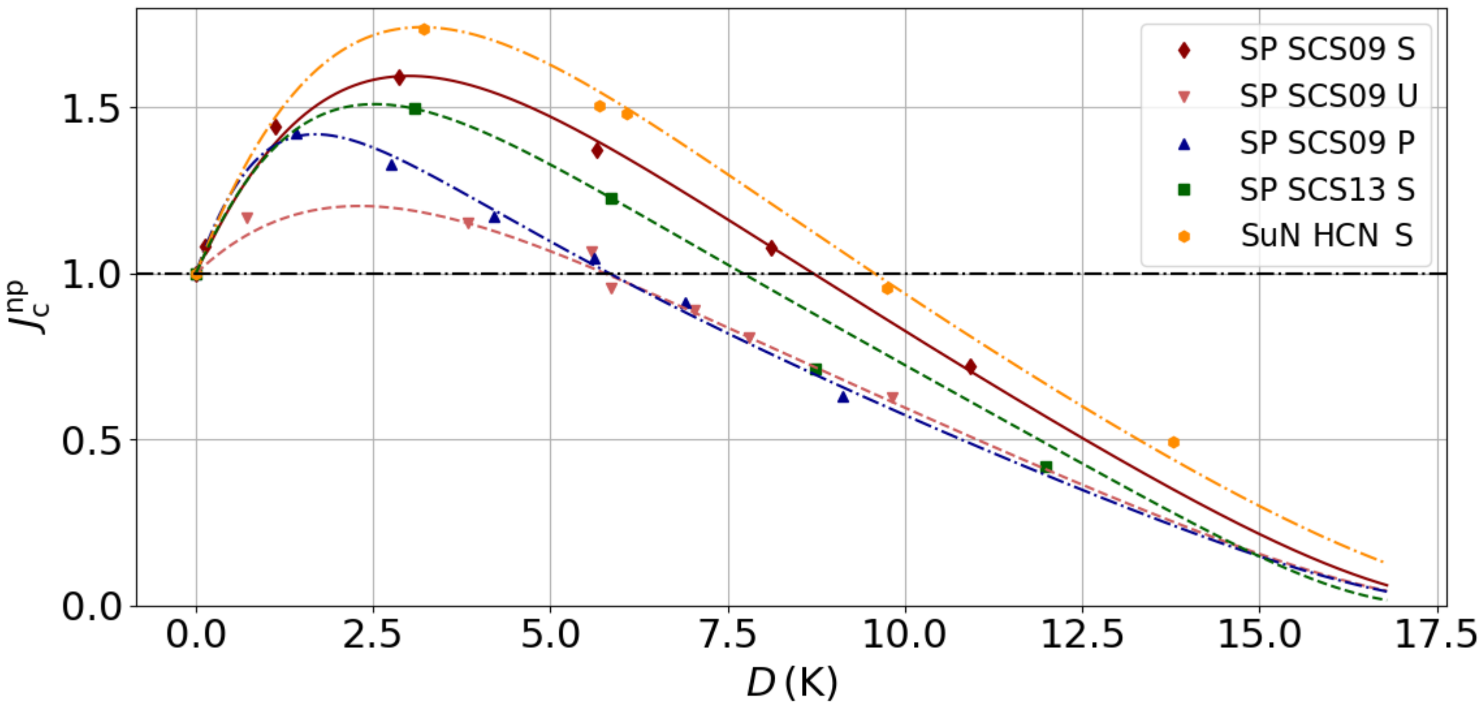


- tanh was chosen for the good correspondence to the data
- Pinning efficiency can not increase indefinitely physical limit ~ 0.3
- At low defect densities linear behavior was observed

Modelling

Degradation Model

$$J_{\mathrm{c}}^{\mathrm{np}} = \frac{J_{\mathrm{c}}^{\mathrm{irr}}}{J_{\mathrm{c}}^{0}} = \left(\frac{E_{\mathrm{c}}}{\nu_0\sqrt{\Phi_0^B\ B}}\right)^{\frac{1}{n_{\mathrm{irr}}}-\frac{1}{n^0}} \left(\frac{T_{\mathrm{c}}^{\mathrm{irr}}}{T_{\mathrm{c}}^{0}}\right)^{\frac{3}{2}} \left(\frac{\rho_{\mathrm{n}}^{0}}{\rho_0^{\mathrm{irr}}}\right)^{\frac{1}{2}} \quad \frac{\eta_{\max}}{\eta^0} \tanh\left(\frac{D}{D_{\eta_{\max}}}(\pi - A) + A\right)$$



Conclusion

Degradation Model

$$J_c^{np} = \frac{J_c^{irr}}{J_c^0} = \left(\frac{E_c}{\nu_0\sqrt{\Phi_0^B\ B}}\right)^{\frac{1}{n_{irr}}-\frac{1}{n^0}} \left(\frac{T_c^{irr}}{T_c^0}\right)^{\frac{3}{2}} \left(\frac{\rho_n^0}{\rho_0^{irr}}\right)^{\frac{1}{2}} \quad \frac{\eta_{max}}{\eta^0} \tanh\left(\frac{D}{D_{\eta_{max}}}(\pi - A) + A\right)$$

$$A = \tanh^{-1}\frac{\eta^0}{\eta_{max}}$$

Degradation is universal and mainly **driven by the loss of superfluid density**
But: Influence of **pinning term shapes the curve**

Relevant Parameters:

For the degradation: $\boldsymbol{n^0}$, Δn^0, T_c^0, T_c^{irr}
Degradation of these parameters linear as function of fluence in area of interest

For the enhancement: $\frac{\eta_{max}}{\eta^0}$ and $D_{\eta_{max}}$
Fit parameters which define the interaction of the radiation environment with the existing pinning landscape