Impact of neutron induced ex-situ defects on the properties of CCs and their thermal stability

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IREF 2023

Collaborations and Funding

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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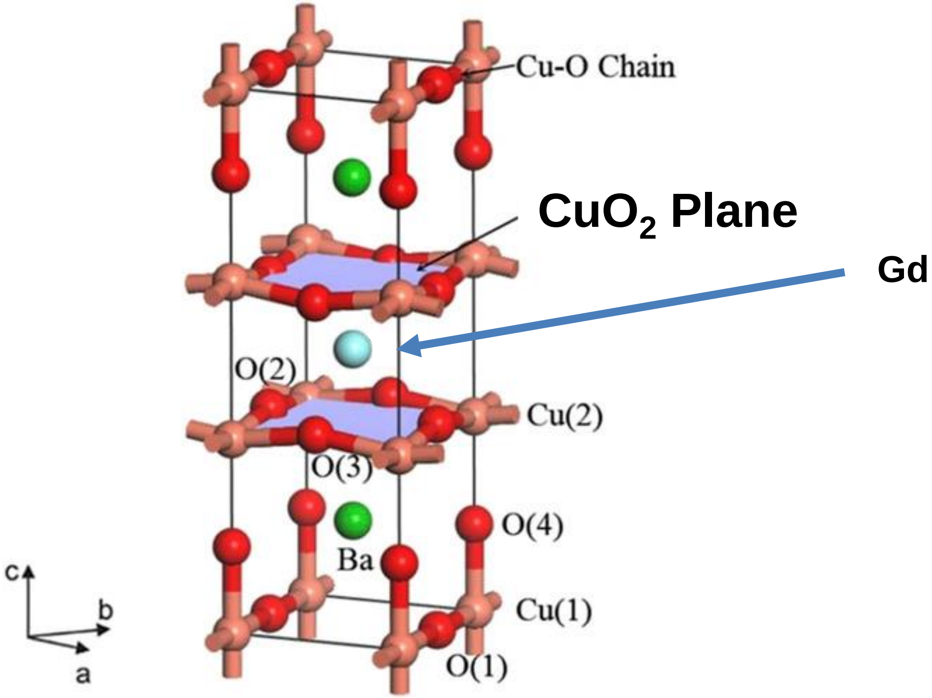
Motivation



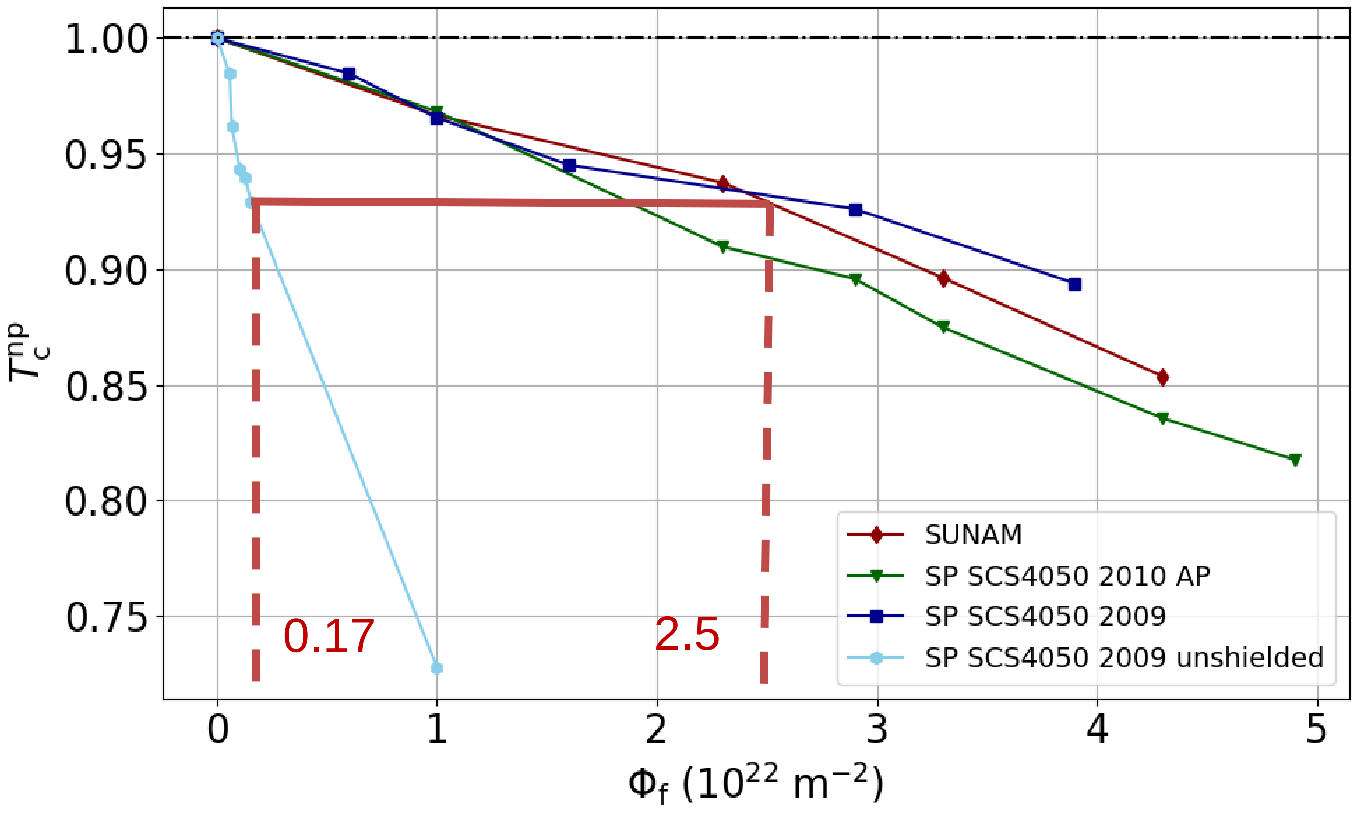
P. Gao et al., AIP Advances **7** (2017) 035215

- position enables introduction of many defects close to the planes
- defects are small in comparison to coll. cascades
- defects may be modelled with MDS

Motivation

Irradiation influences performance

Change in critical temperature



Outline

Background

- what values do we actually determine J_c, n - value, T_c
- how does irradiation influence those parameters

Methods

- neutron irradiation techniques
- Gd – neutron capture process
- introduced defects – molecular dynamics simulations (MDS & DFT)

Results

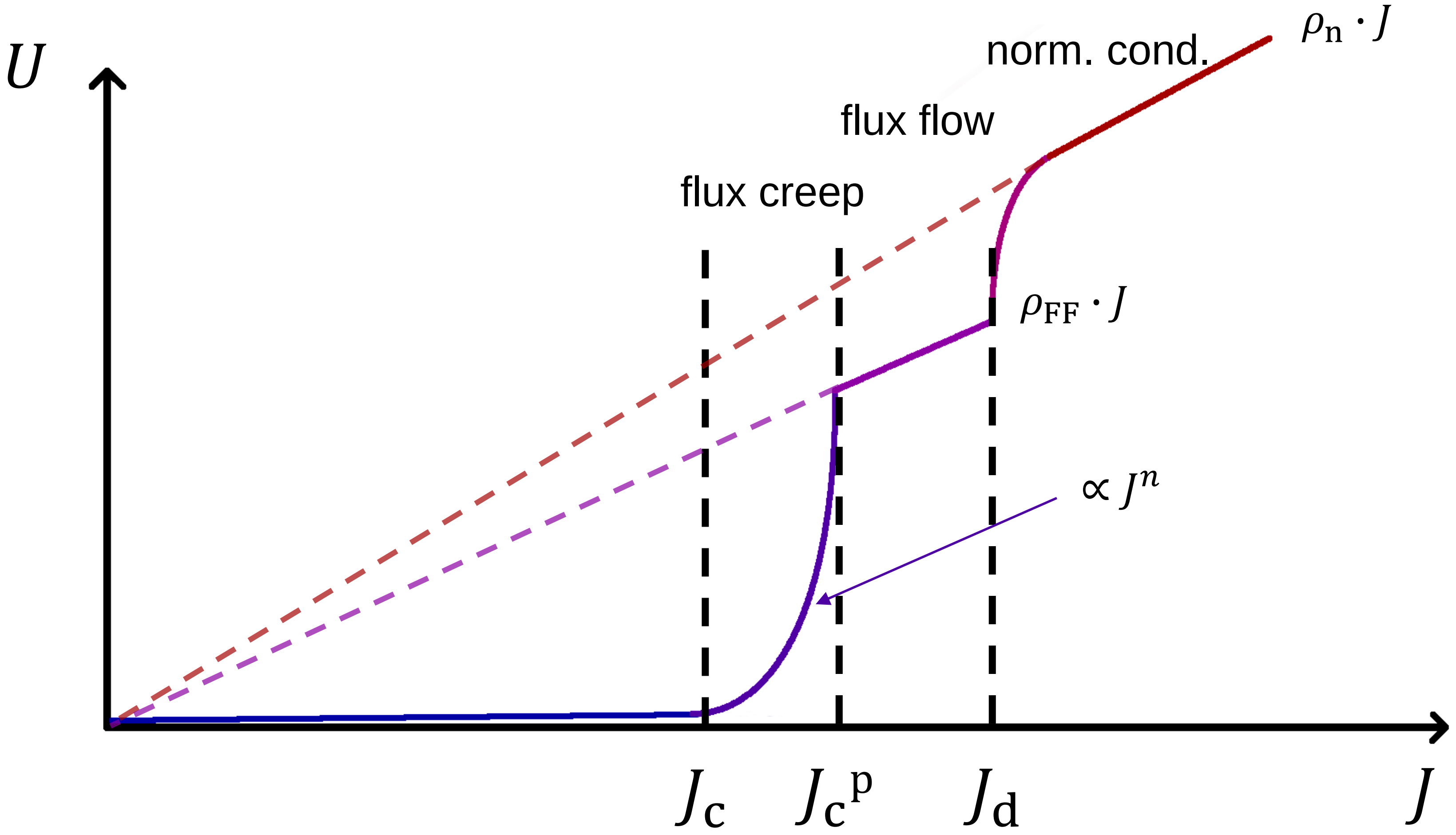
- decrease of T_c and superfluid density
- degradation of the irreversibility line
- Recovery of T_c by annealing

Conclusions

Background

Background - $\boldsymbol{J_c}$

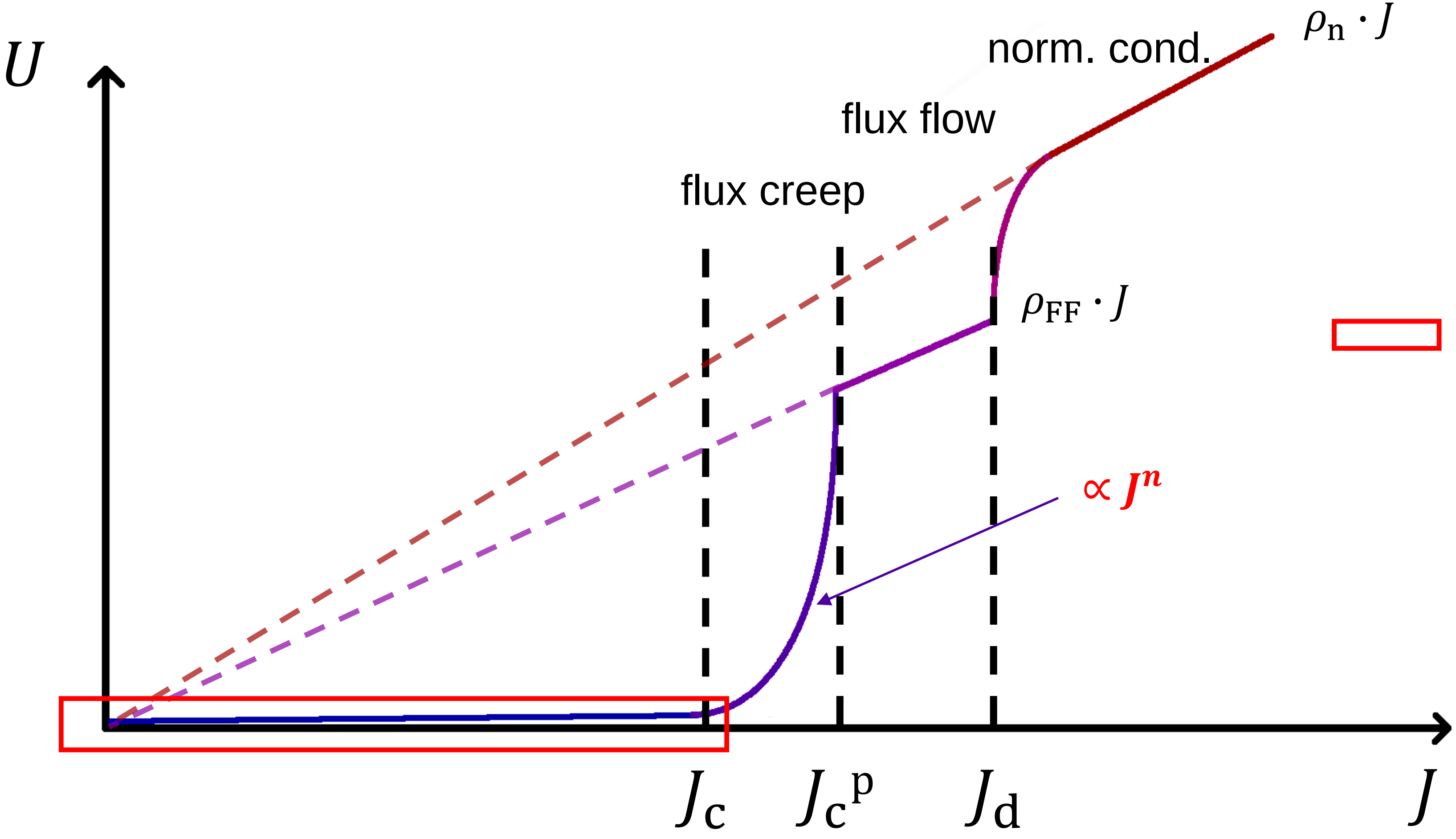
Concerning $\boldsymbol{J_c}$



$$\boxed{J_c^p = \eta\, \mathrm{J_d}}$$

Background - J_c

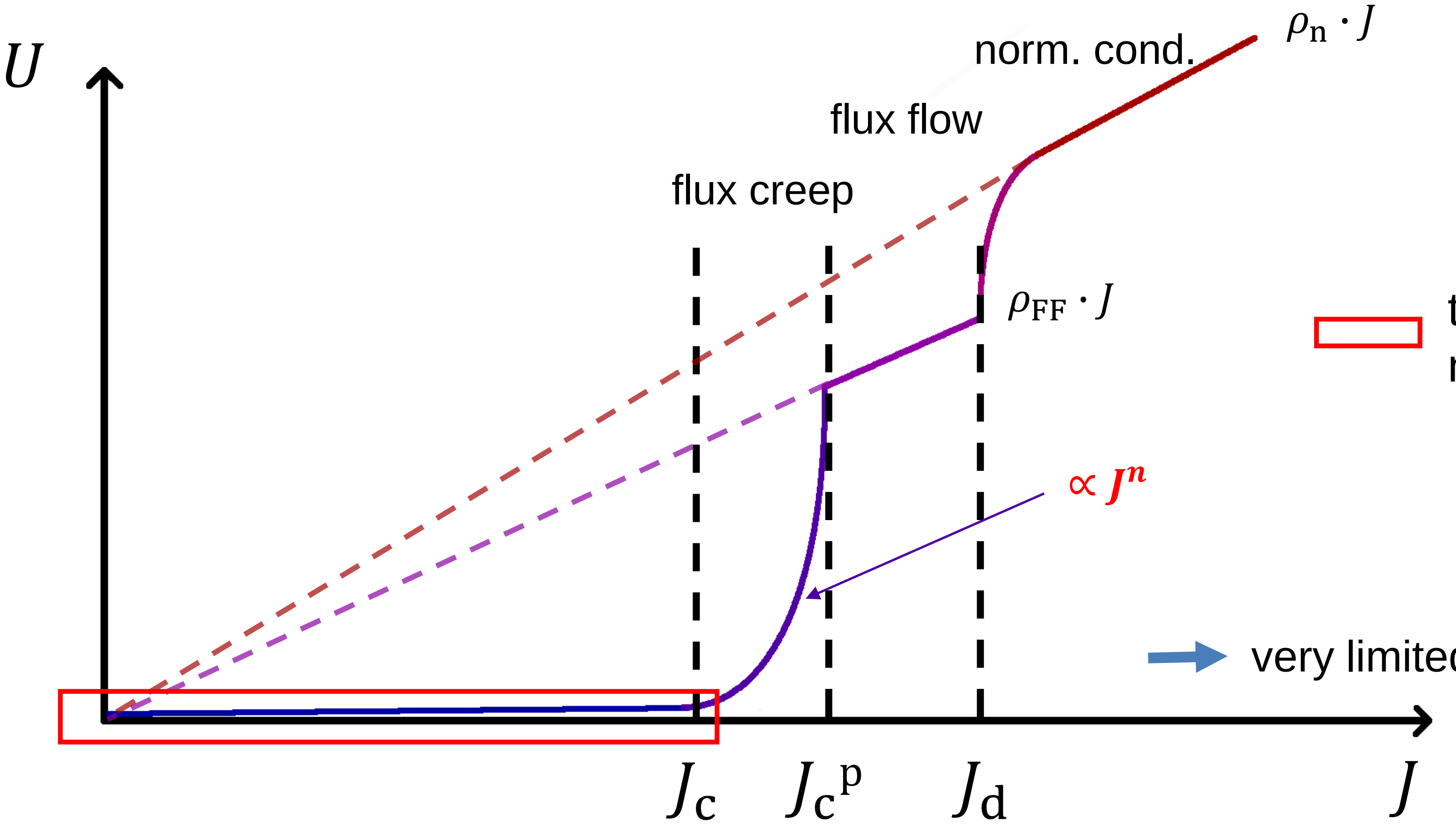
Concerning J_c



▭ typical transport current measurement

Background - J_c

Concerning J_c



▭ typical transport current measurement

→ very limited view of the bigger picture

Theory

$$E_{\mathrm{c}} = \frac{1}{\lambda^2 \xi^2} = \frac{1}{\lambda^2} H_{\mathrm{c2}}$$

$$n = \frac{U_0}{k_B T} \qquad \frac{1}{\lambda^2} = \rho_s$$

$$U_0 \propto E_c$$

$$E_{\mathrm{c}} = \rho_s \frac{1}{\xi_0 l}$$

$$J_d \propto \frac{H_c}{\lambda} \propto \frac{1}{\lambda^2 \xi} \propto \sigma_{dc} T_c \propto \eta^{-1} J_c^p$$

ρ_{s} ... superfluid density

$\sigma_{\mathrm{dc}} = \rho_{\mathrm{dc}}^{-1}$... normal state conductivity

ξ_0 ... clean limit coherence length

l ... mean free path

E_c ... condensation energy

U_0 ... pinning energy

η ... pinning efficience

Theory

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What’s important here?

$$E_c = \rho_s \frac{1}{\xi_0 l}$$

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$$\frac{1}{\lambda^2} = \rho_s \qquad U_0 \propto E_c$$

Very simplified

$$n = \frac{U_0}{k_B T} \qquad E_c = \frac{1}{\lambda^2 \xi^2}$$

$$\boldsymbol{\rho_s \propto T_c \propto E_c \propto n \propto J_d \propto J_c^p \, \eta^{-1}}$$

$$J_d \propto \frac{H_c}{\lambda} \propto \frac{1}{\lambda^2 \xi} \propto \sigma_{dc} T_c \propto \eta^{-1} J_c^p$$

ρ_s ... superfluid density

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ξ_0 ... clean limit coherence length

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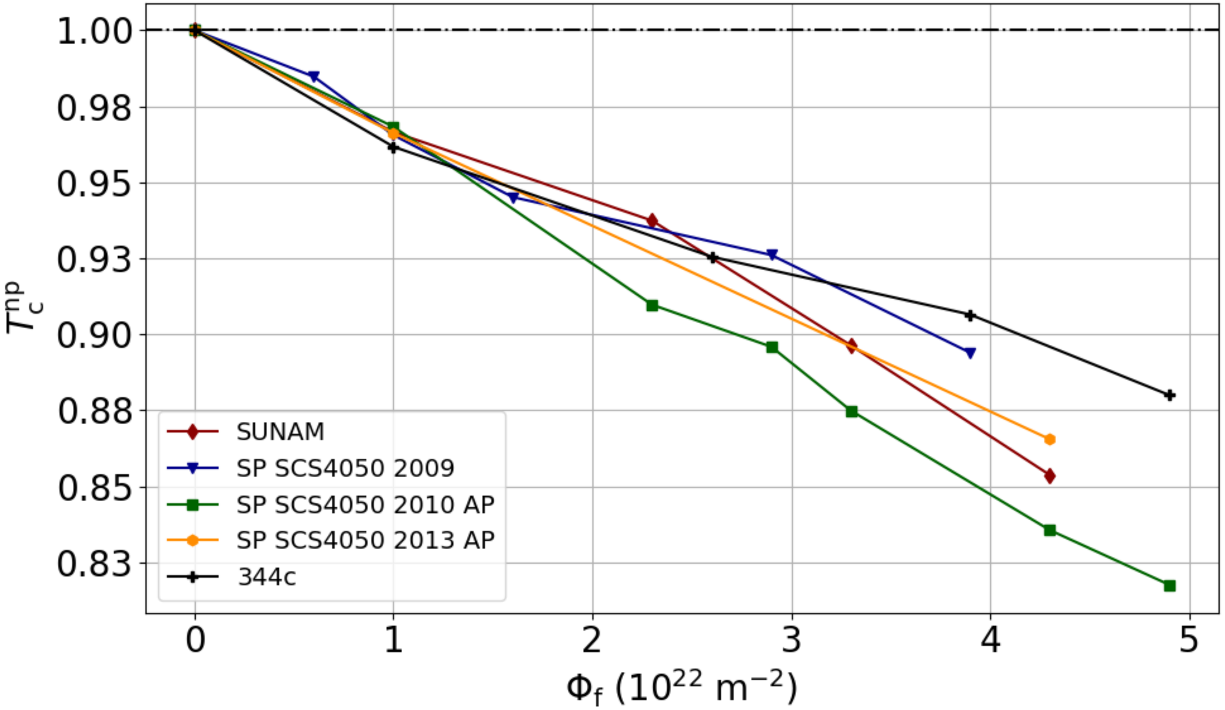
Background - T_c degradation

scattering is pair breaking in *d*-wave superconductors

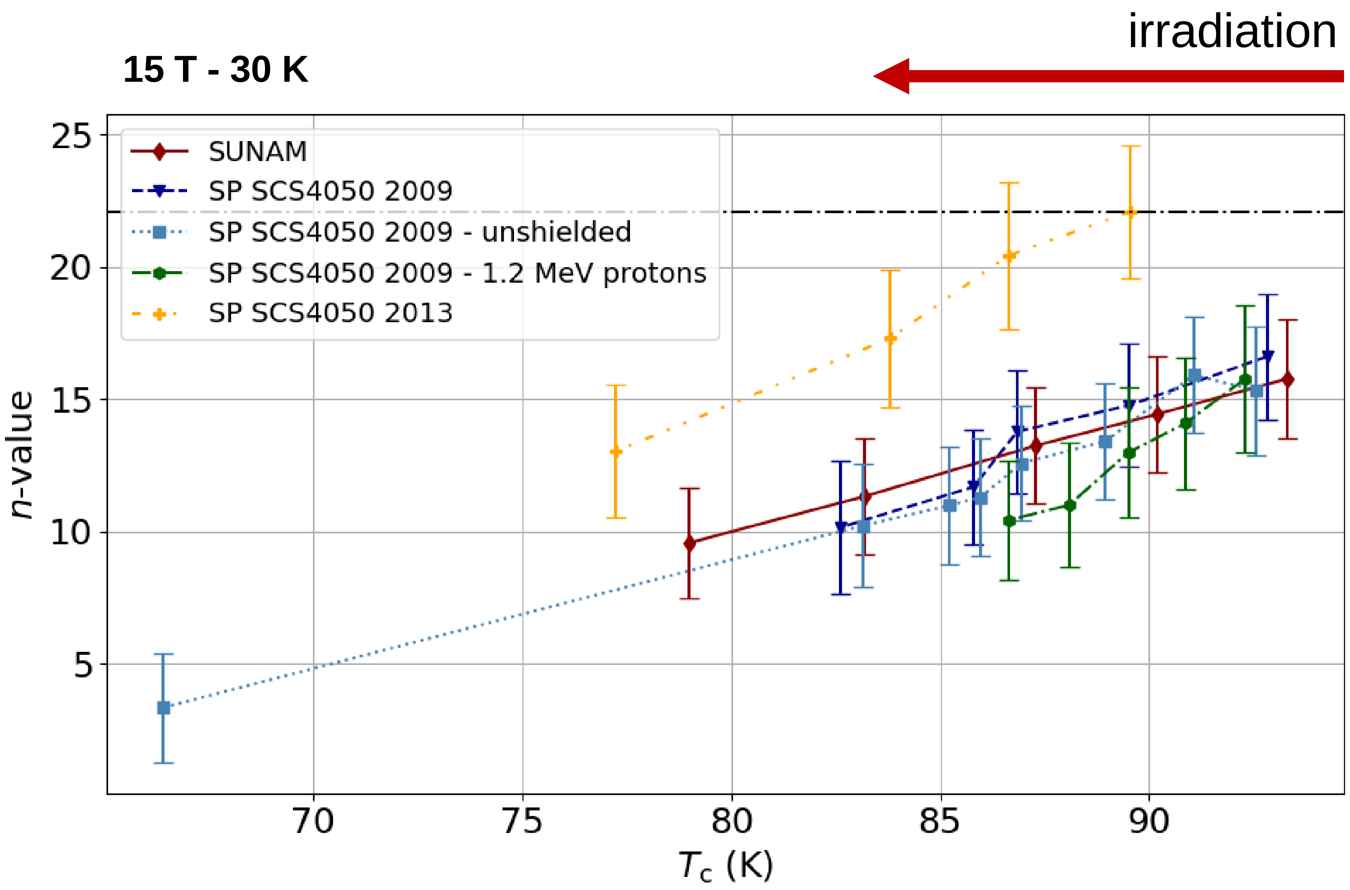
- decrease of transition temperature, $\boldsymbol{T_c}$
- decrease of superfluid density, $\boldsymbol{\rho_s}$

Normalized transition temperature



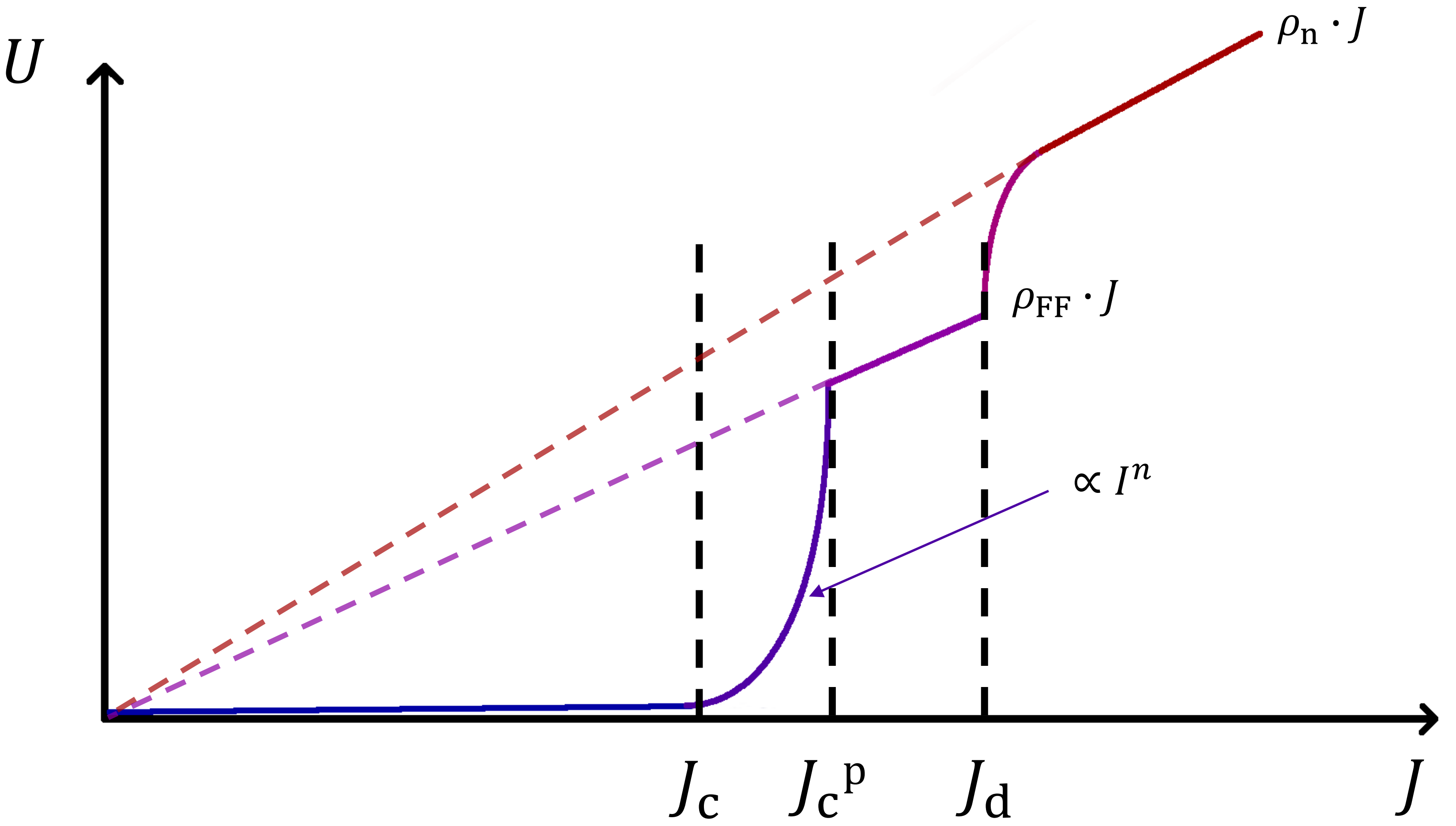
Fast neutron fluence

Background – *n*-value degradation



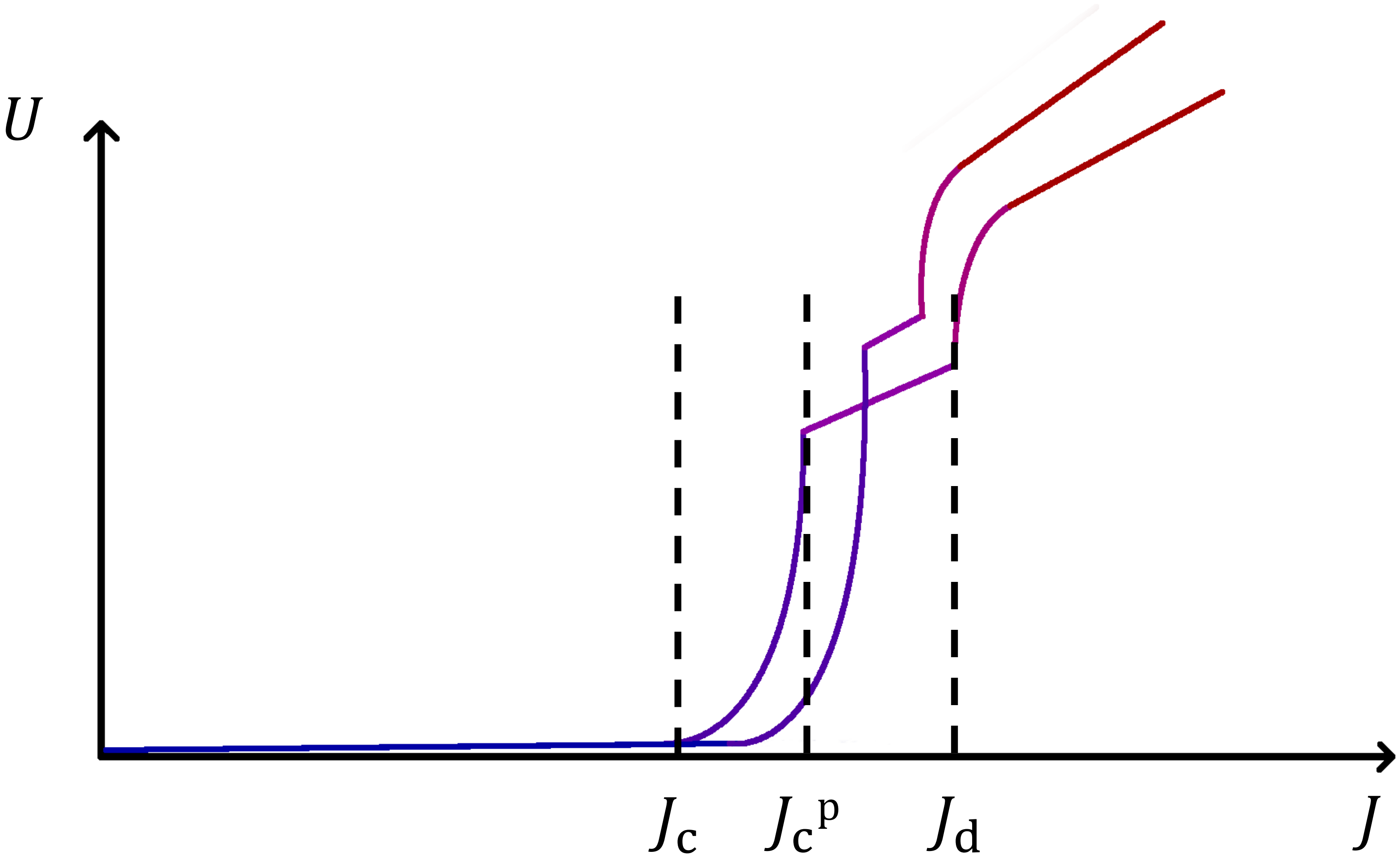
- *n* – value degrades linearly with T_c
- degradation of condensation energy reduces T_c, I_c and *n*
- *n* degrades with the same slope for completely different defect landscapes

Influence of radiation on the I-V curve



$$\boxed{J_c^p = \eta \, J_d}$$

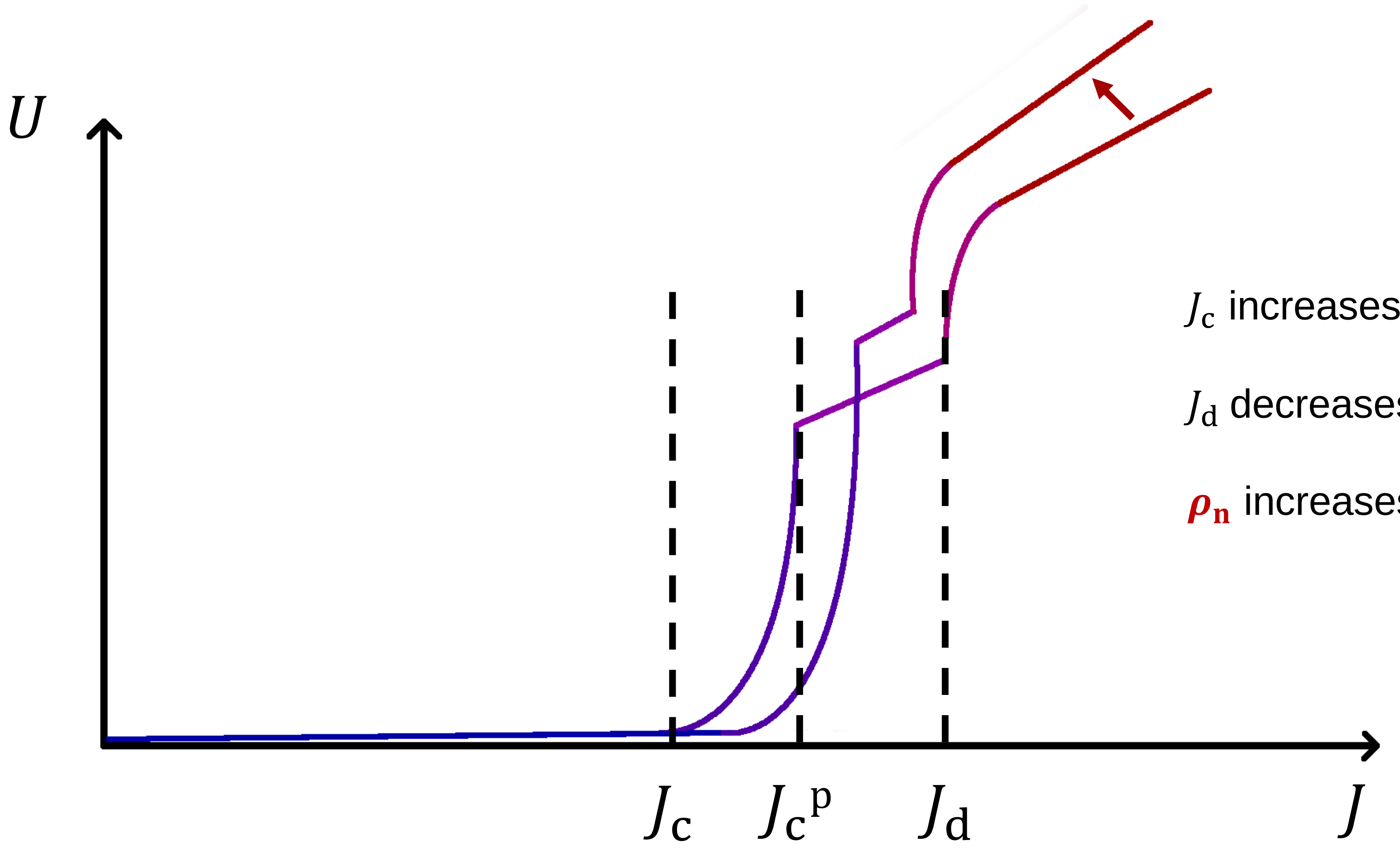
Influence of radiation on the I-V curve



$$\boxed{J_c^p = \eta \, \mathrm{J_d}}$$

*drawing assumes constant n

Influence of radiation on the I-V curve



$$\boxed{J_{\mathrm{c}}^{\mathrm{p}} = \eta\, \mathrm{J_d}}$$

J_{c} increases with J_c^p

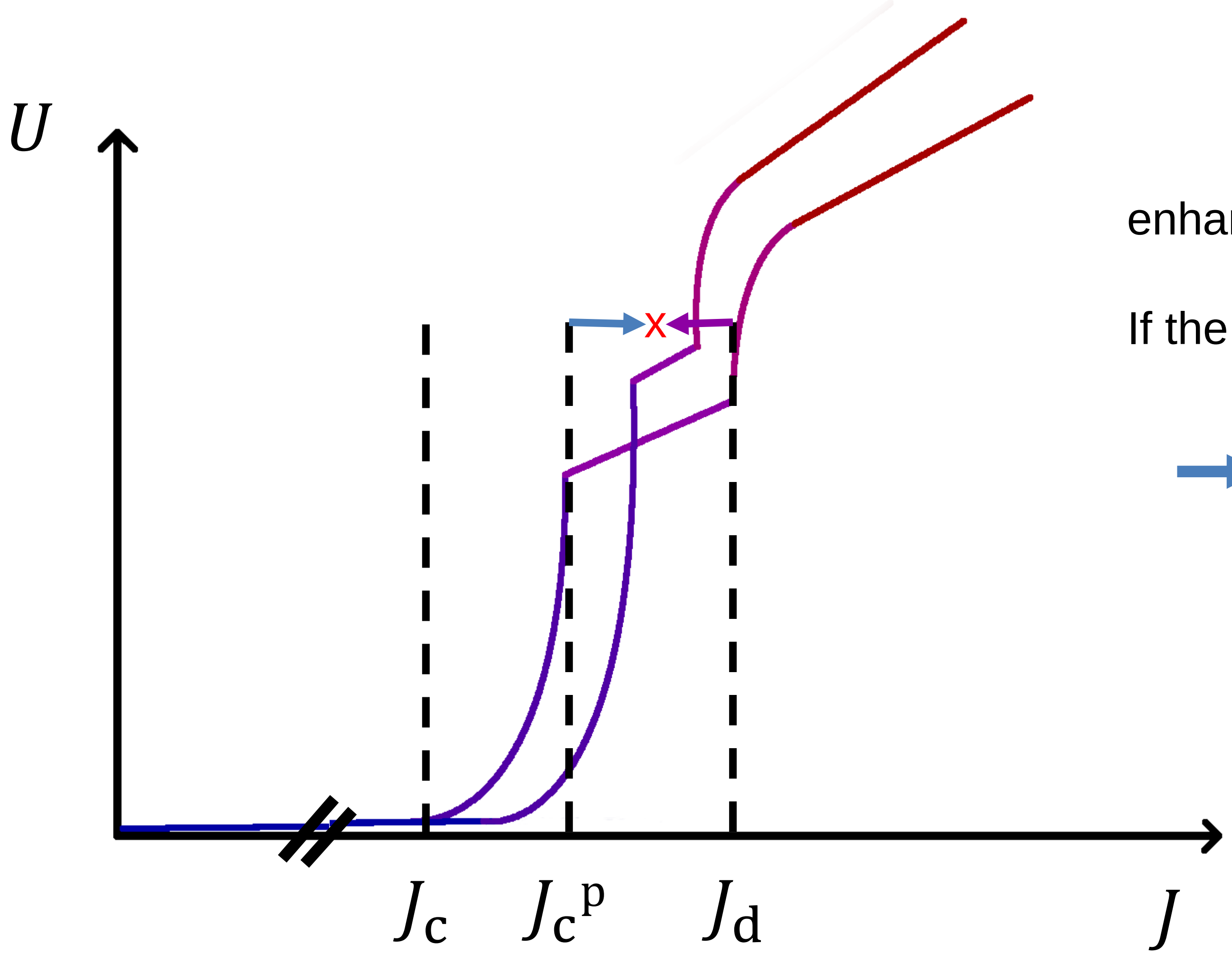
J_{d} decreases

$\boldsymbol{\rho}_{\mathbf{n}}$ increases

$\boldsymbol{\eta}$ has to increase

*drawing assumes constant n

Influence of radiation on the I-V curve



*drawing assumes constant n

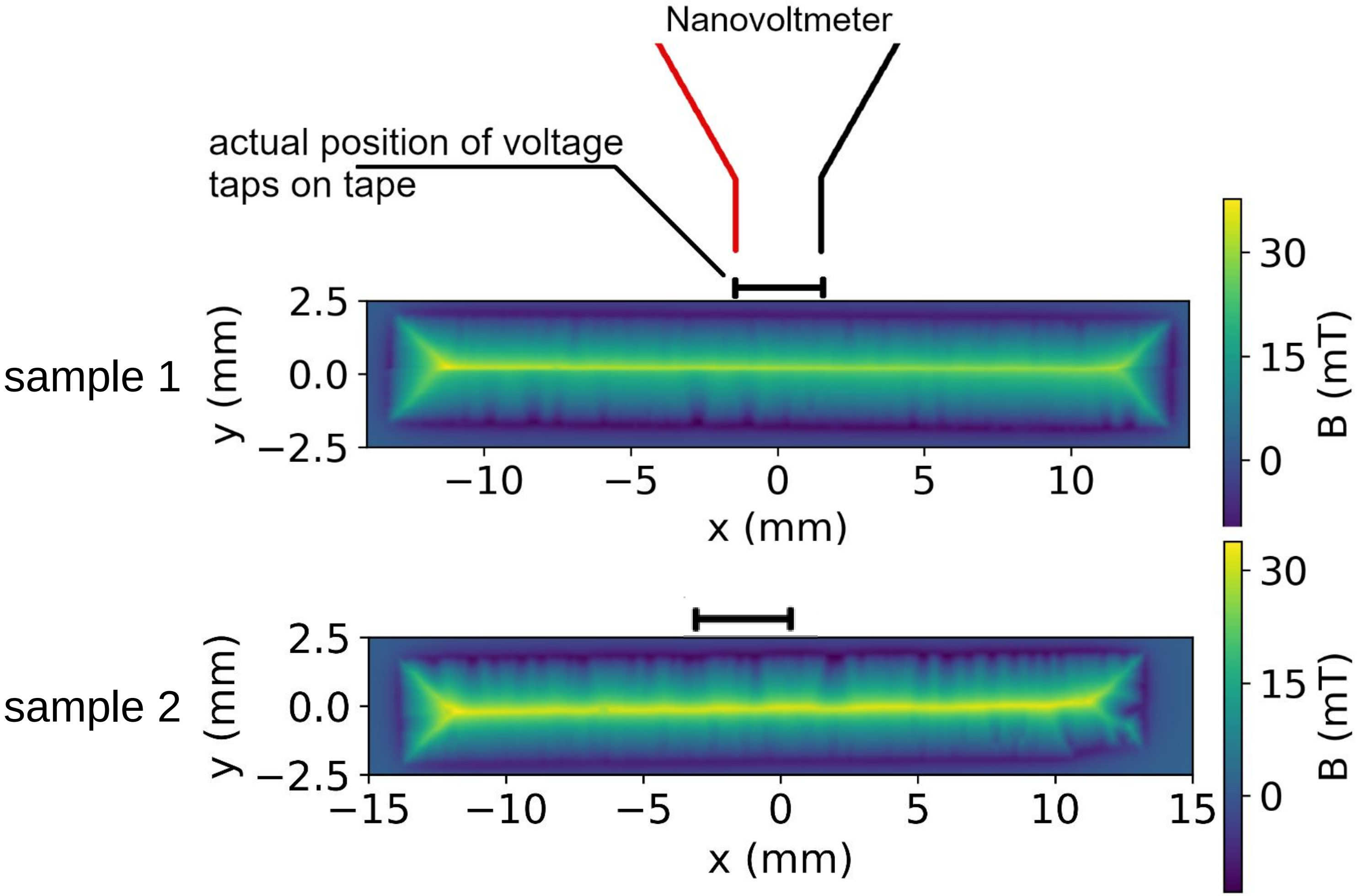
enhancing of η can increase J_c only so much

If the degradation of J_d is too high – J_c decreases

→ degradation driven by superfluid density and reduction of pinning energy

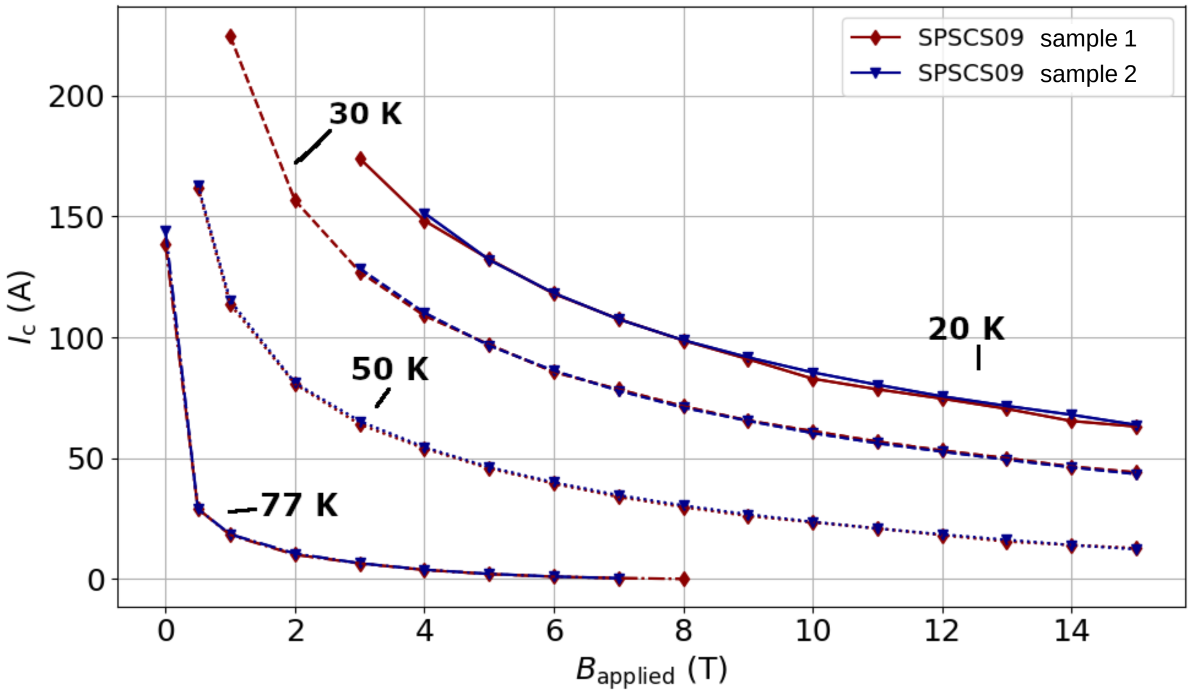
Methods

Two nearly identical samples



- SuperPower 2009 no APC
- sample consistency checked by hall scans
- profile at self-field & 77 K
- voltage taps in low defect areas

Two nearly identical samples



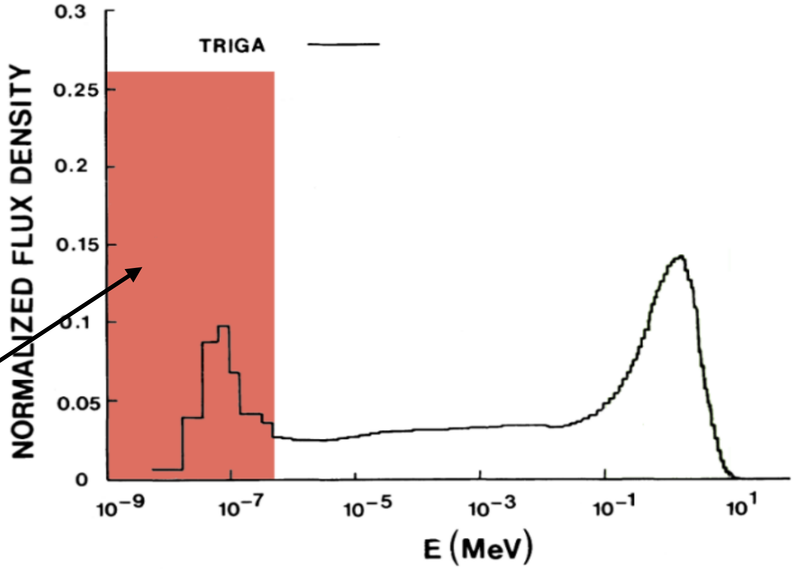
- two nearly identical pristine samples
- Gd-123 tape from SuperPower (2009) no APCs

- irradiated with and without Cd-screen
- difference: number of displaced Gd-atoms

Neutron irradiation – sample 1

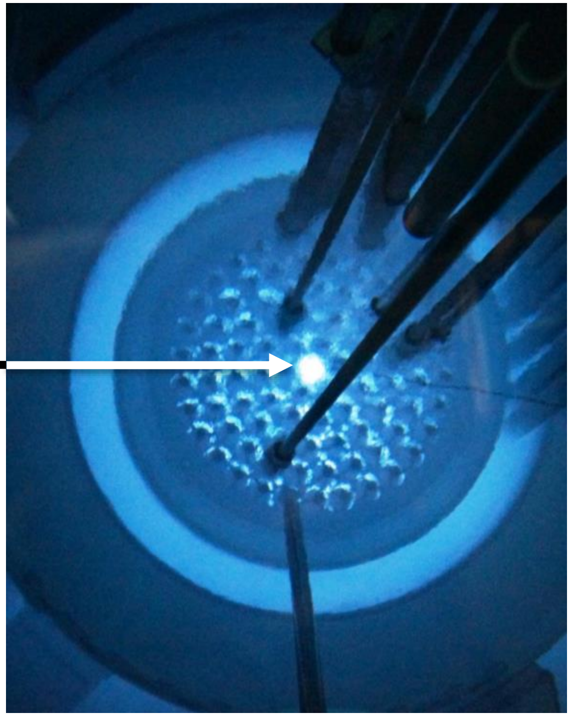
TRIGA MARK II at TU Wien

- 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



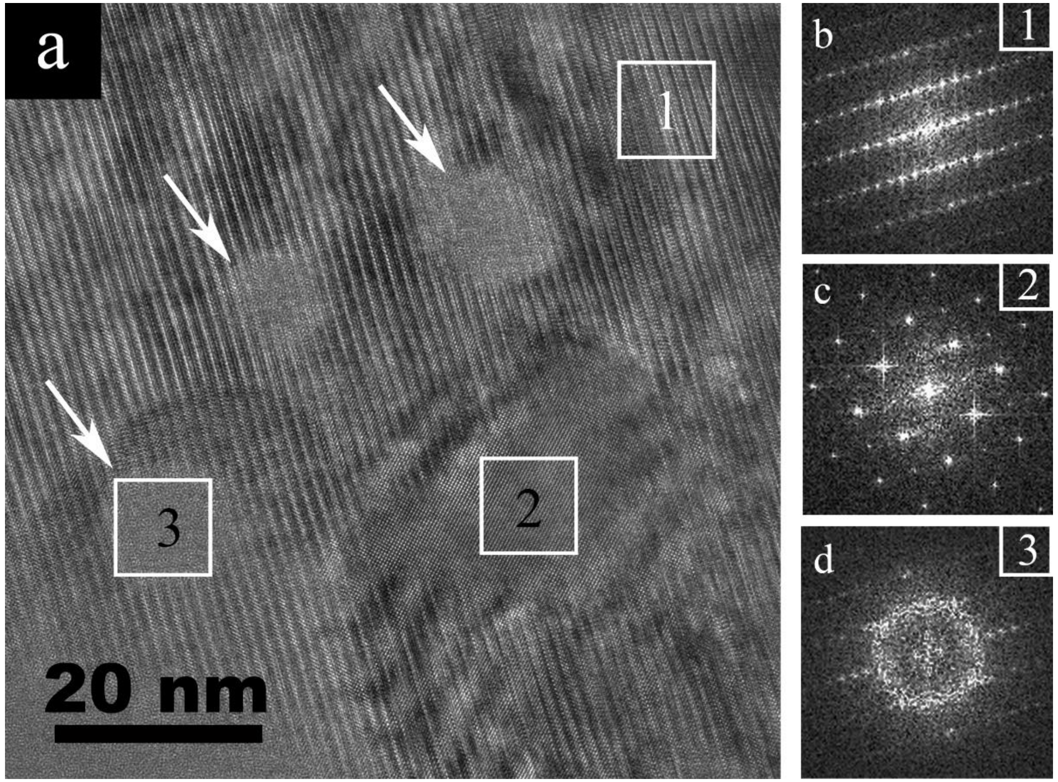
can be screened by cadmium foil

< 70 C at sample

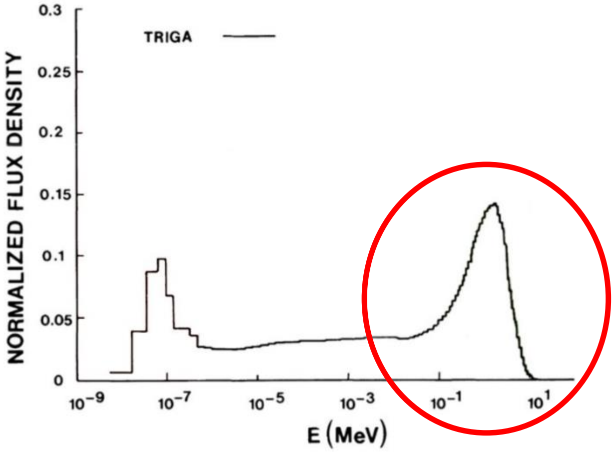


TRIGA MARK II – experimental fission reactor

Defect structure



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

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

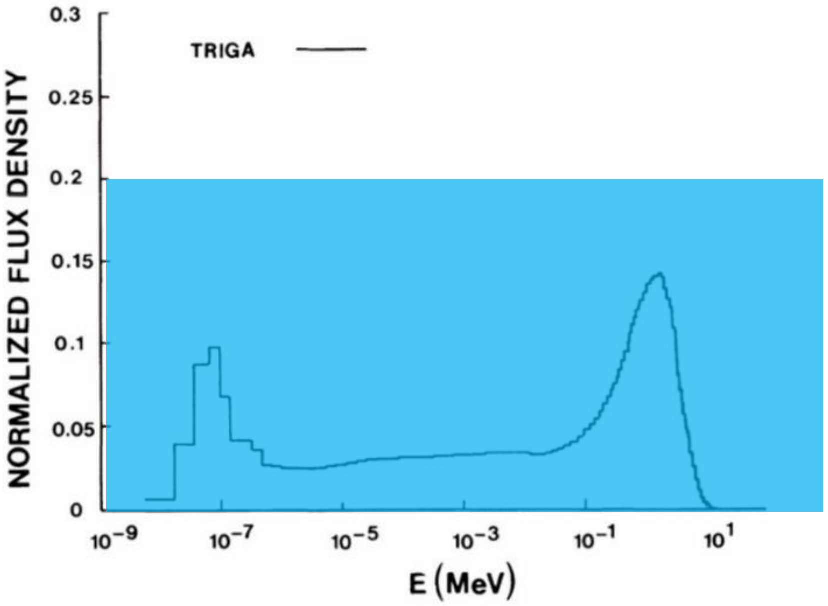
Only large defects visible in TEM

[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

Neutron irradiation – sample 2

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



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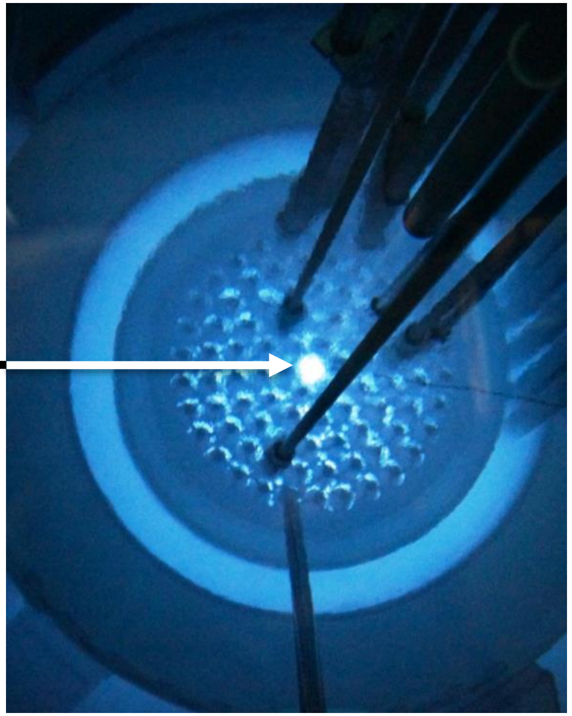

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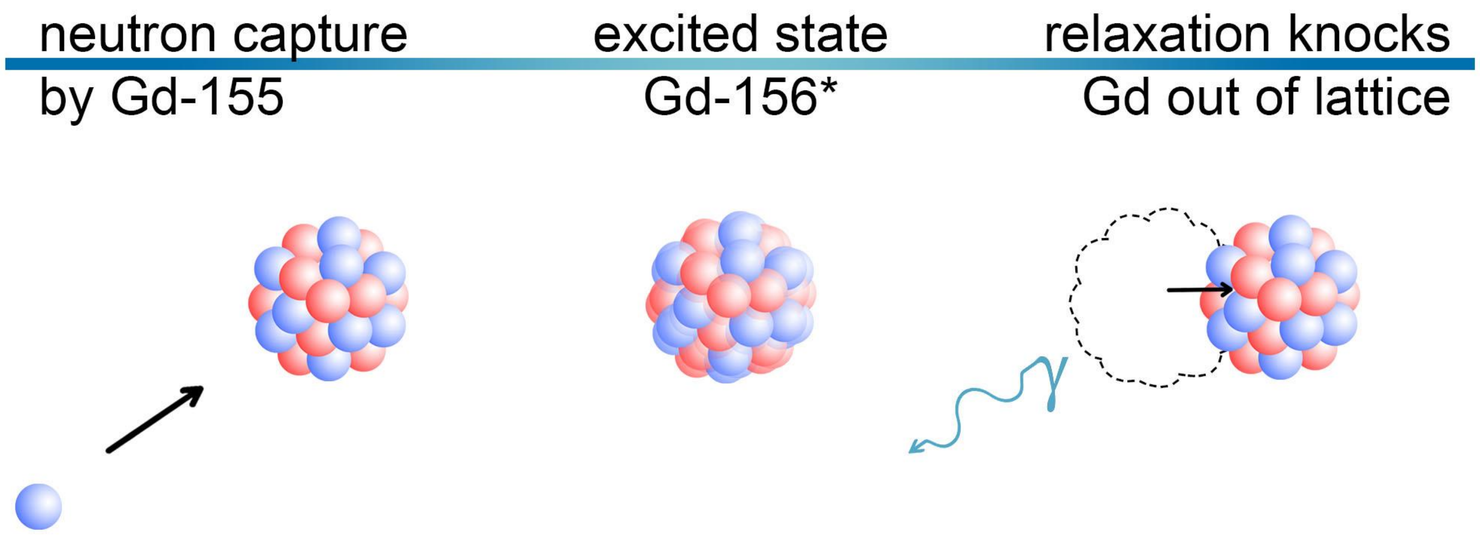
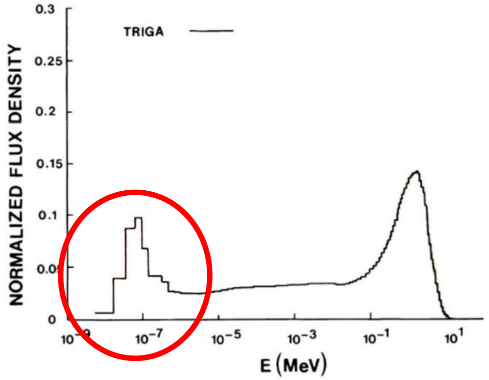


neutron capture by Gd-155

excited state Gd-156*

relaxation knocks Gd out of lattice



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

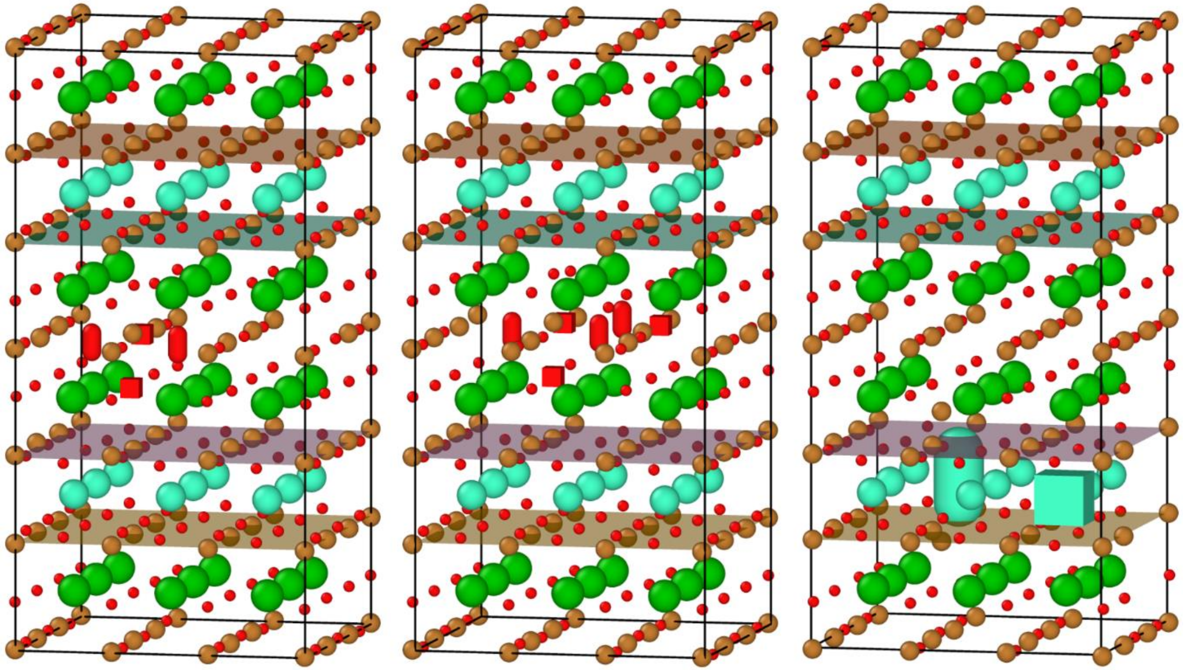
- thermal neutrons excite Gd ➡ emission of gamma displaces the nucleus

- very high defect densities achievable
- add to fast neutron induced defects

Defect structure

What defects do we introduce?

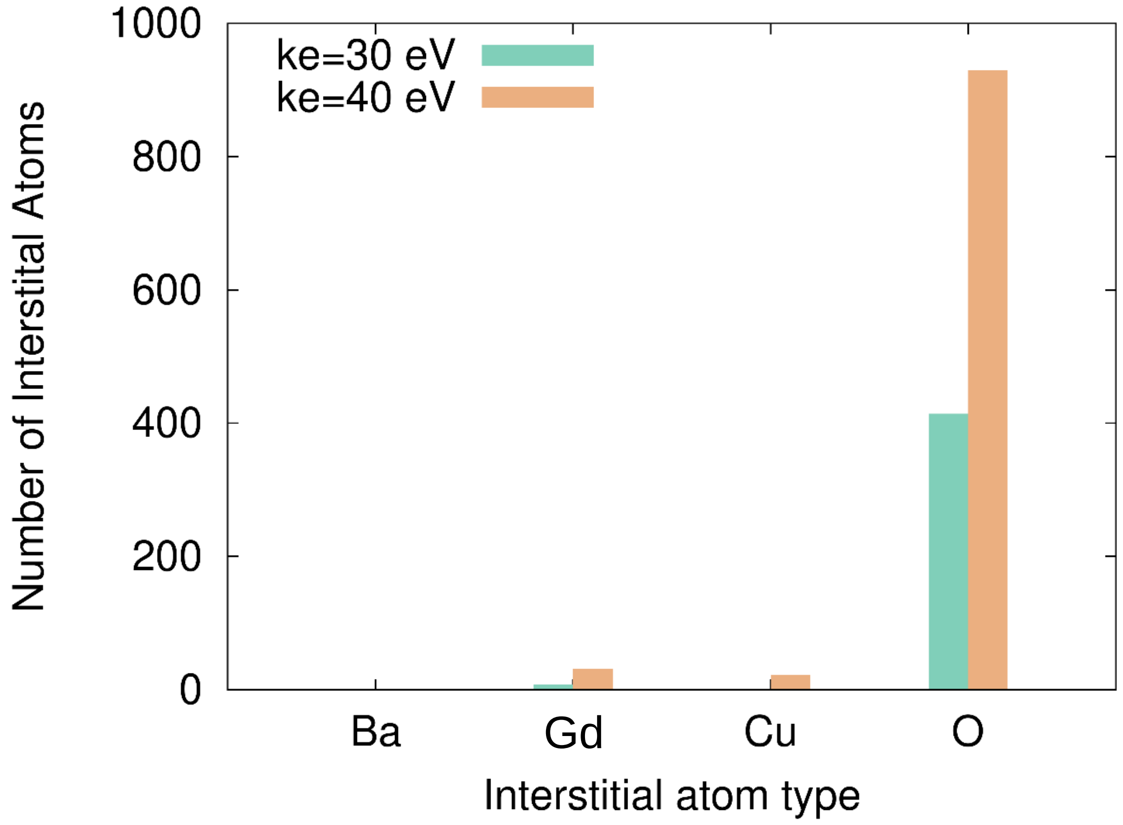
MD simulations



- different defects originating from Gd PKA (primary knock on atom)
- calculate expected defect distribution
- calculate DOS close to the Fermi-energy
  → estimate influence on superconducting properties

MD… molecular dynamics
DFT… density-functional theory

MD simulations



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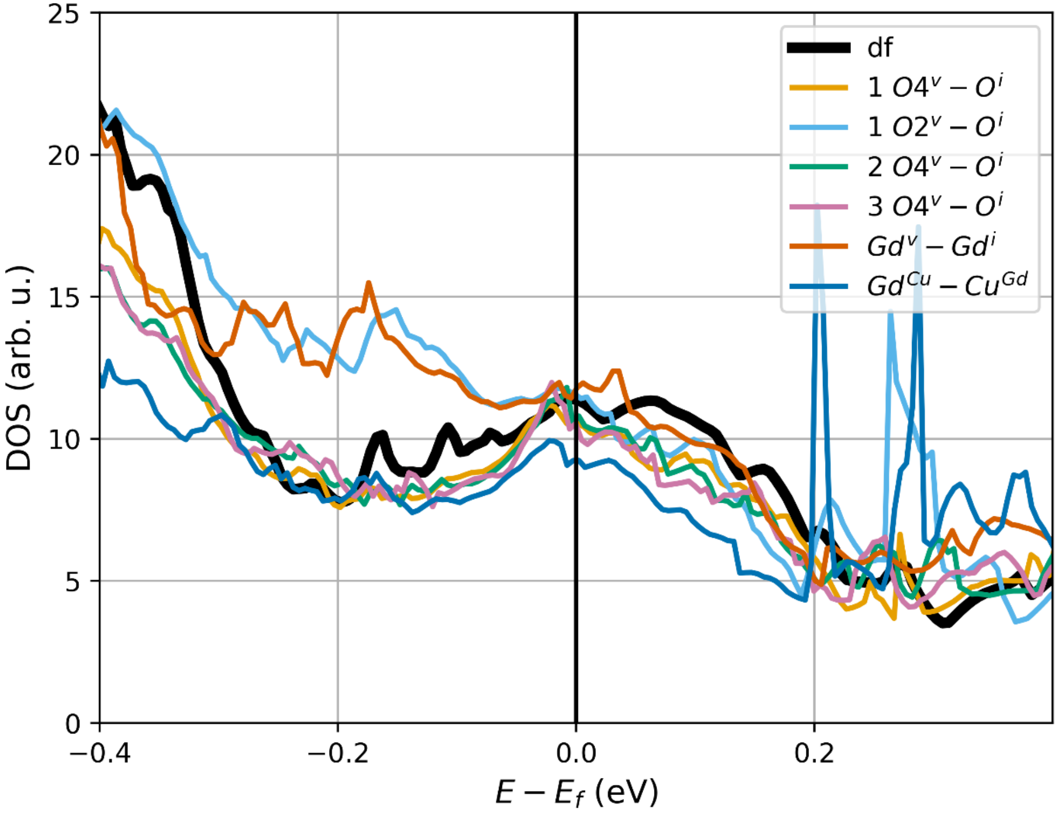
DFT calculations



- different defects originating from Gd PKA (primary knock on atom)
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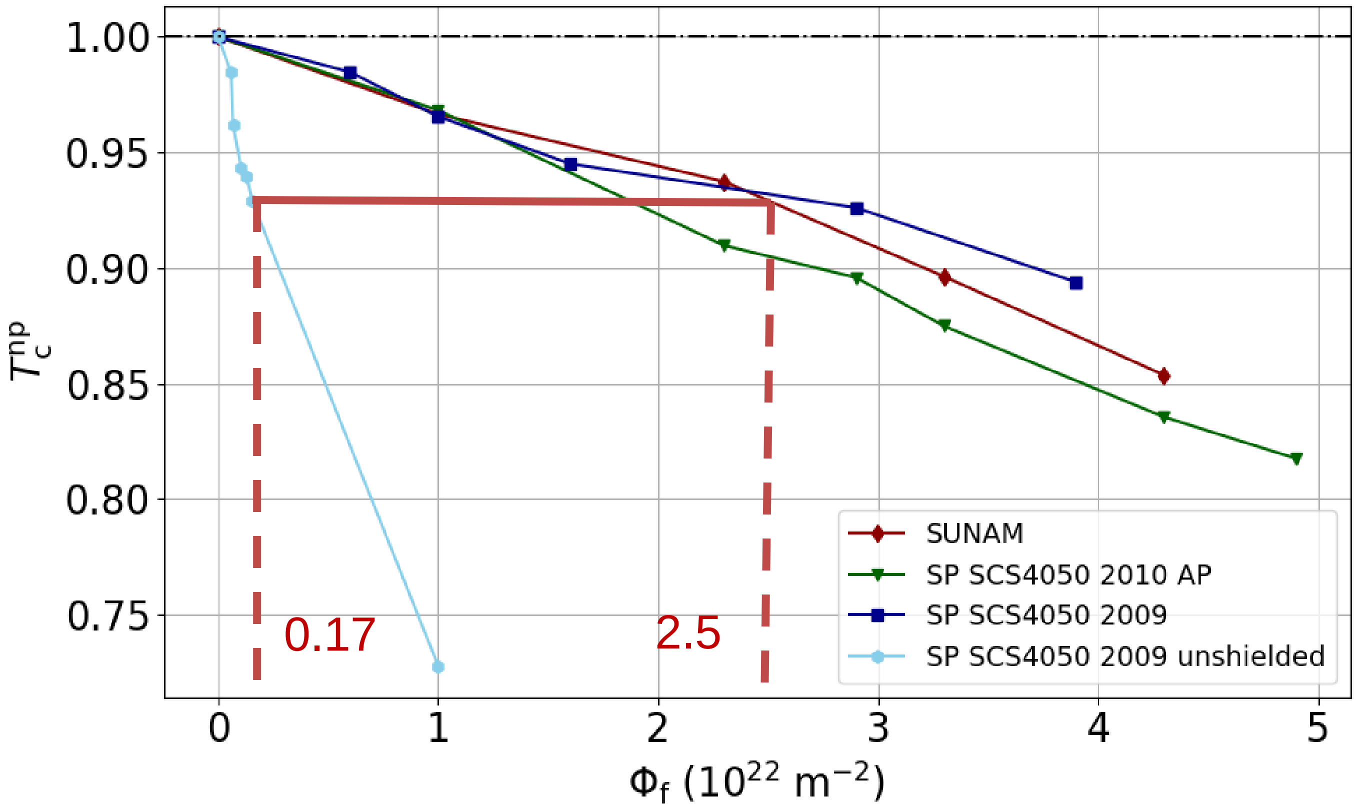
* consistency of DFT calculation confirmed with exp. data Cu substitution by Fe, Zn & Ni

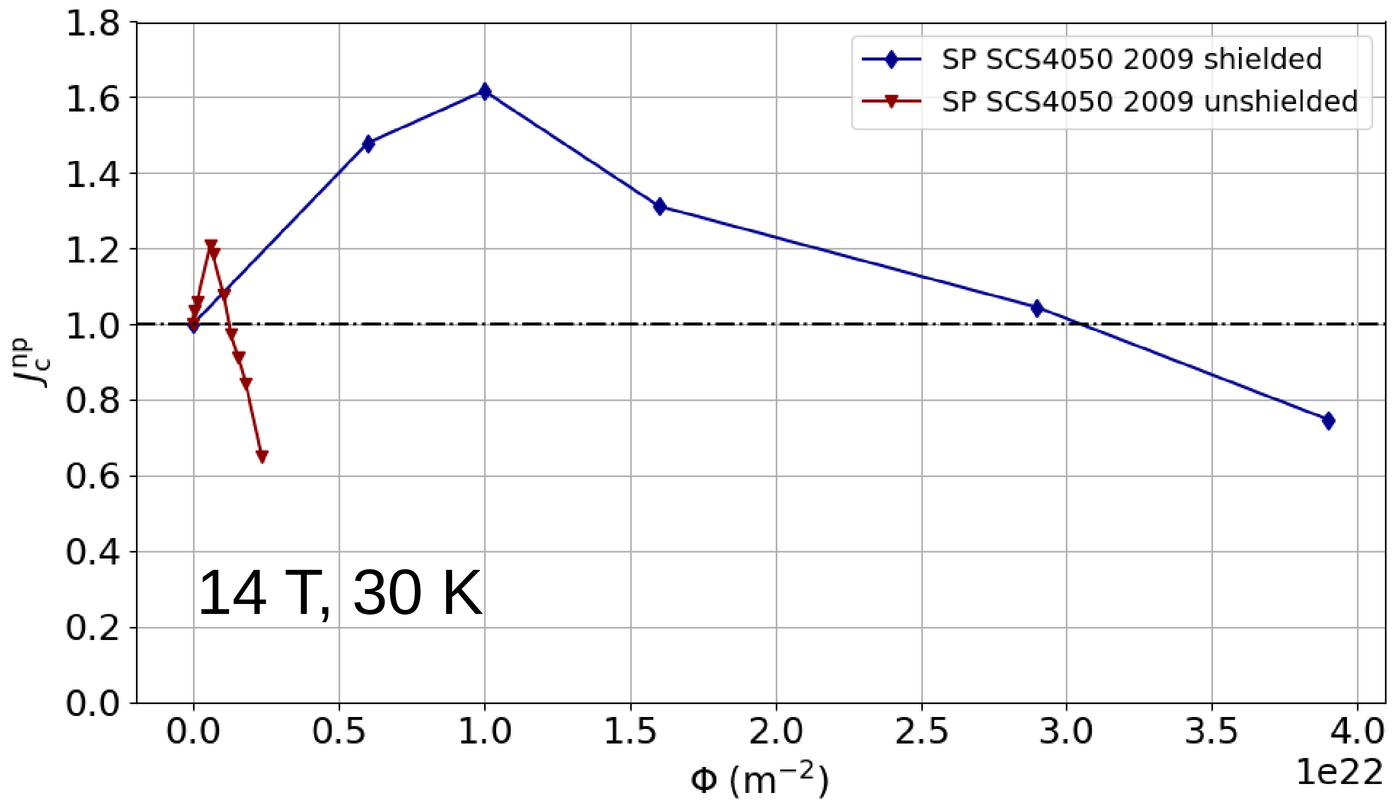
Results

Influence of thermal neutrons - T_c



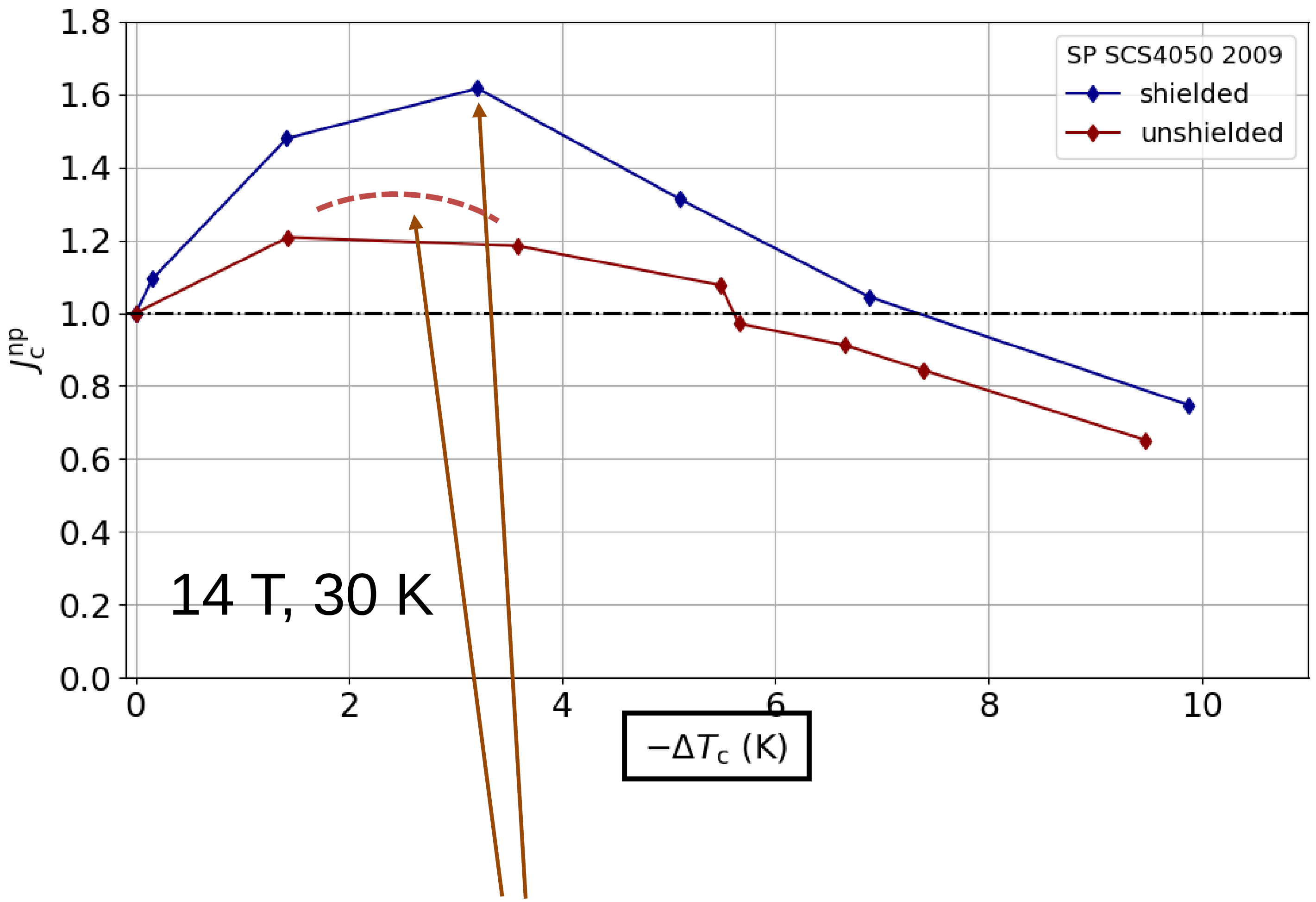
T_c degrades ~13-15 x faster due to Gd-point defects

Influence of thermal neutrons - J_c



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

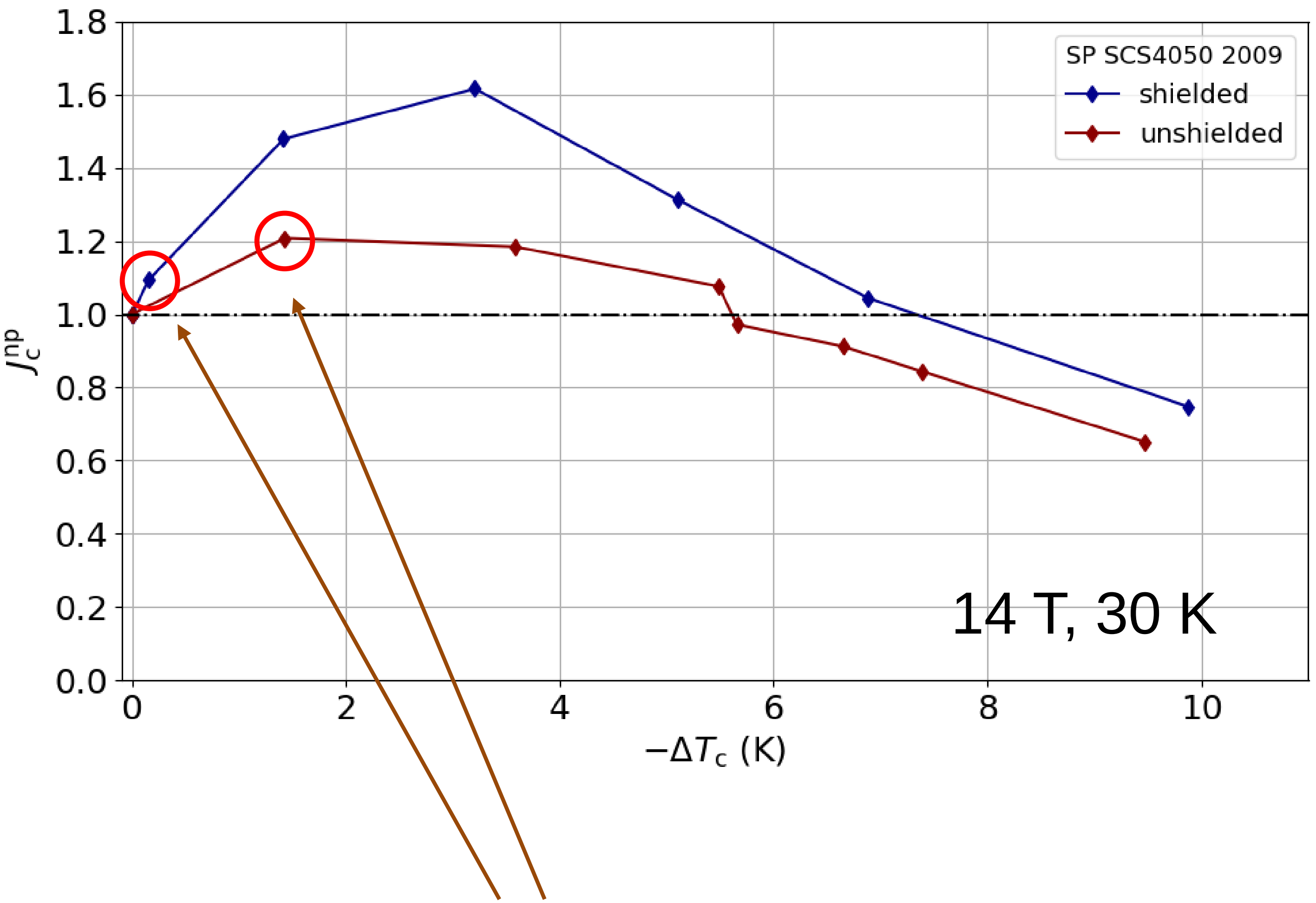
Influence of thermal neutrons - J_c



- maximum occurs at similar T_c
- degradation with similar slope
- T_c is efficient disorder parameter (decrease of superfluid density)

Does J_c increase due to large fast neutron induced defects?

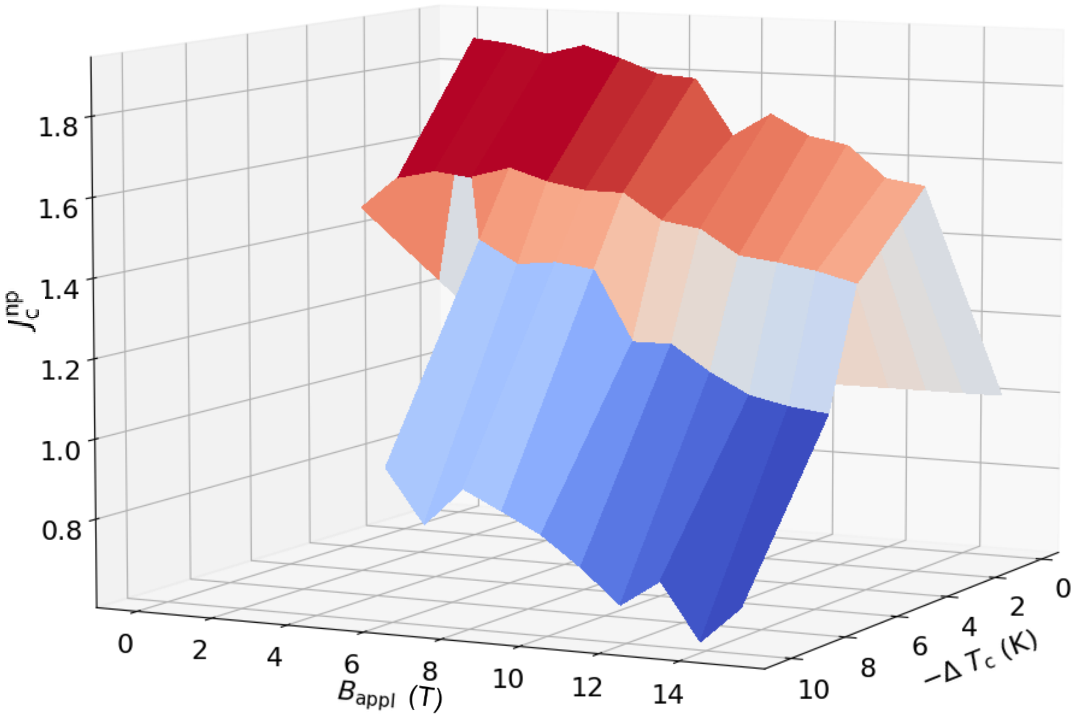
Influence of thermal neutrons - J_c

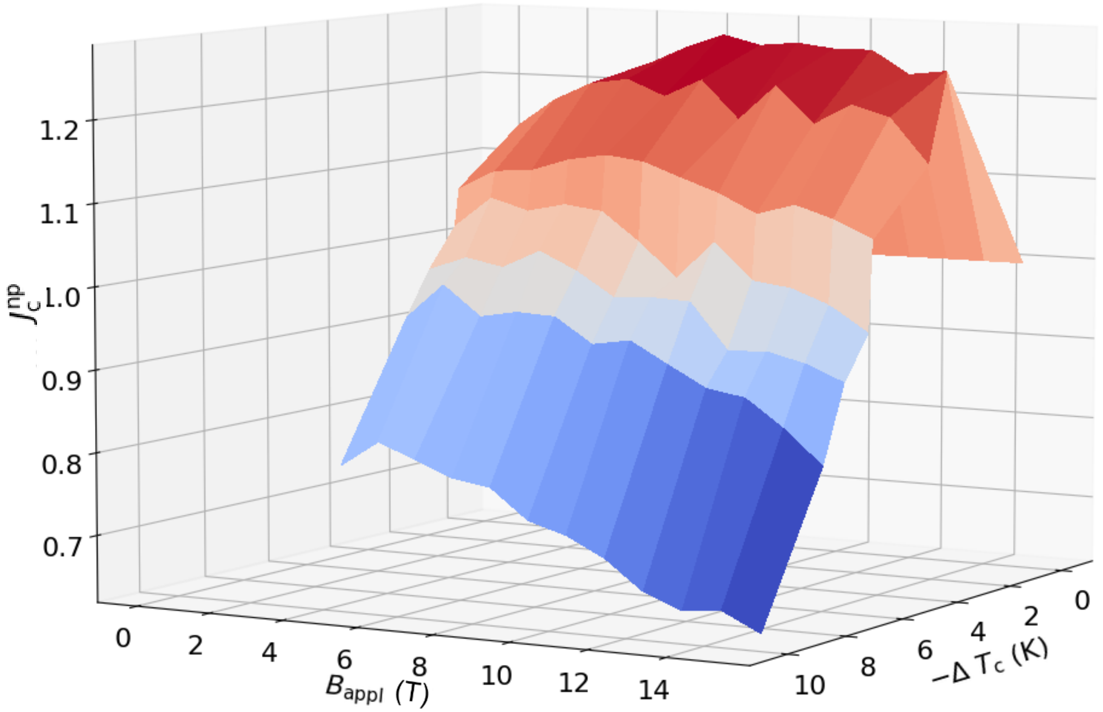


- maximum occurs at similar T_c
- degradation with similar slope
- T_c is efficient disorder parameter (decrease of superfluid density)

Both samples have same density of large cascades

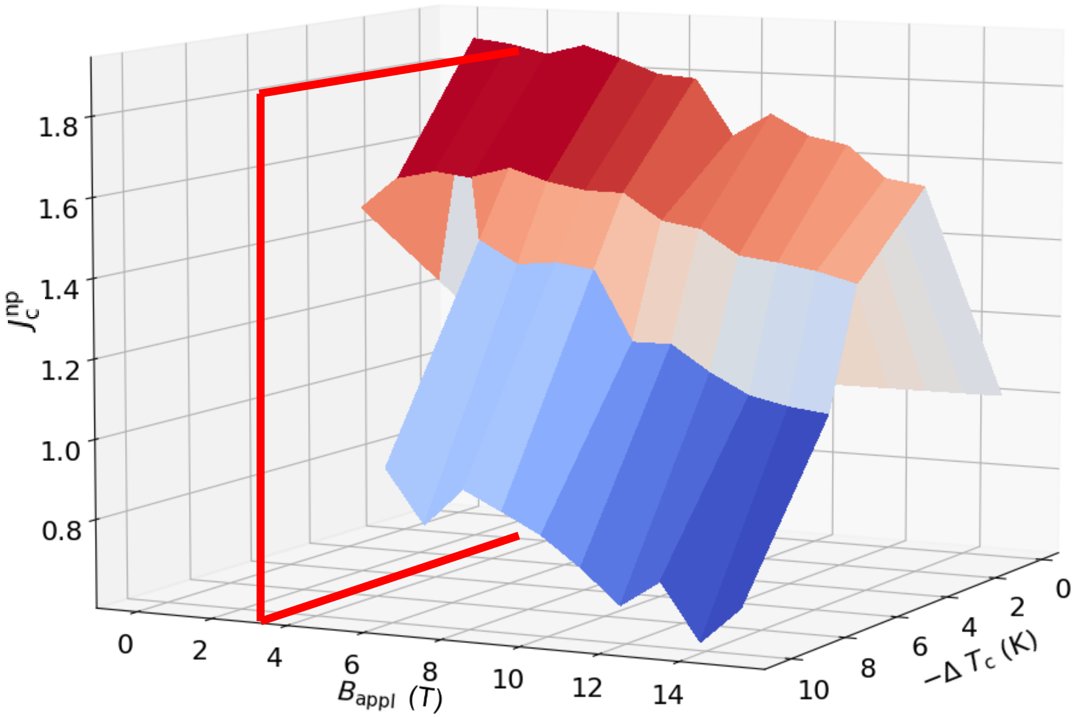
Influence of point defects vs cascades


shielded sample


unshielded sample

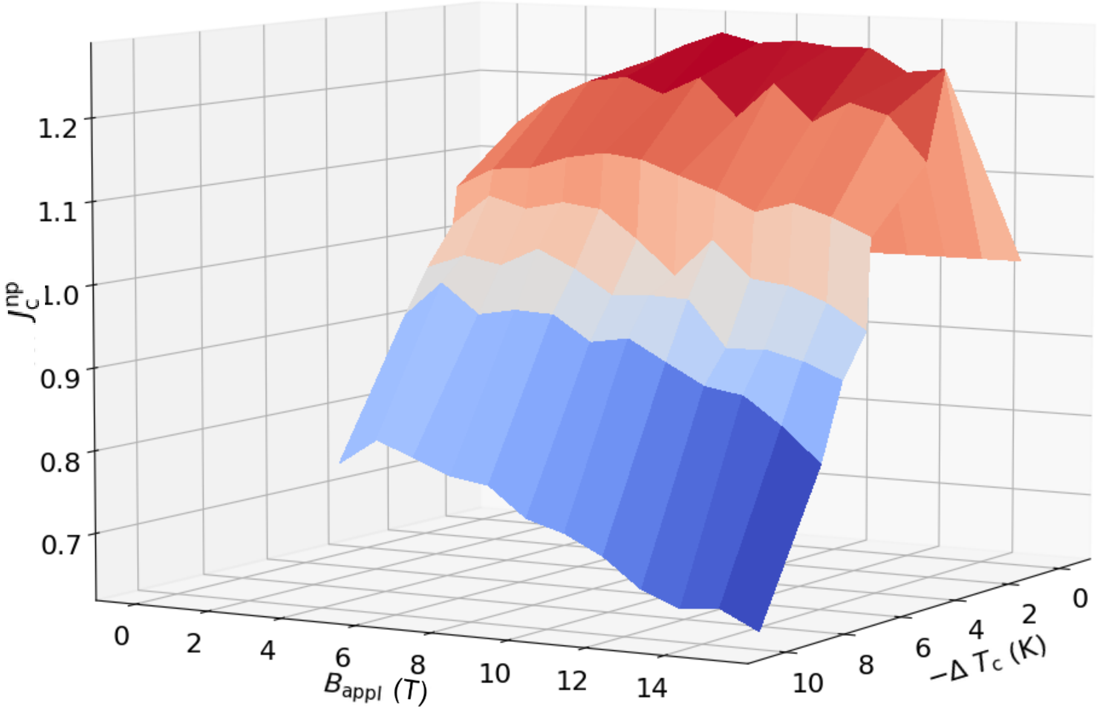
Influence of point defects vs cascades

shielded sample



- shielded peak is at lower fields at “matching” field

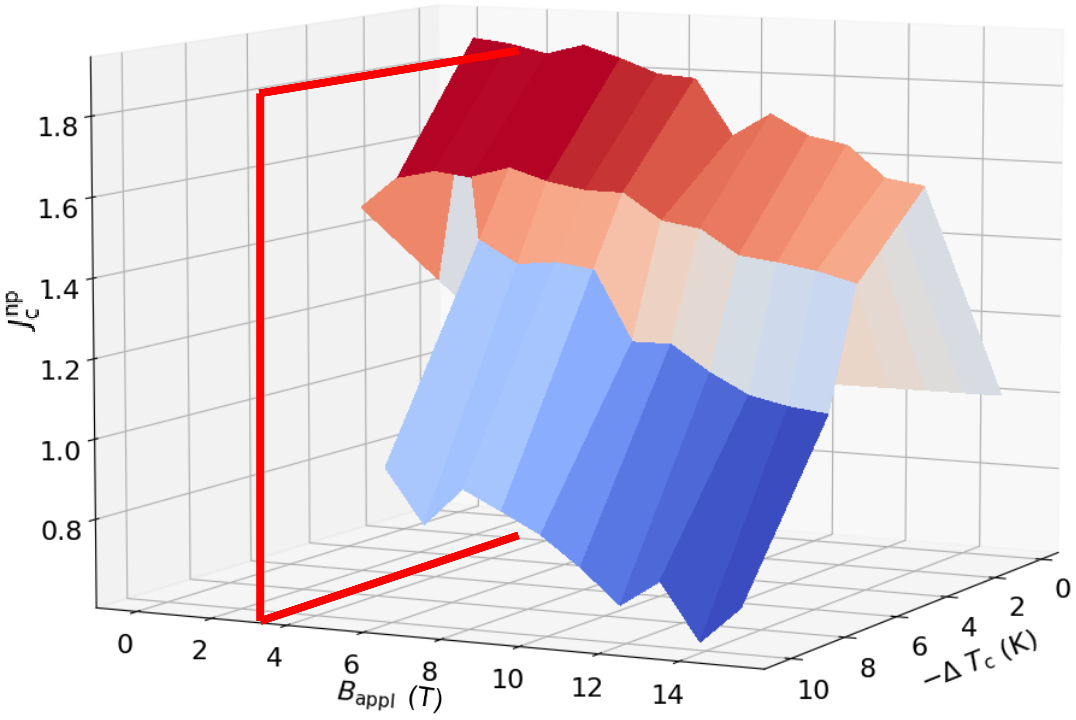
unshielded sample



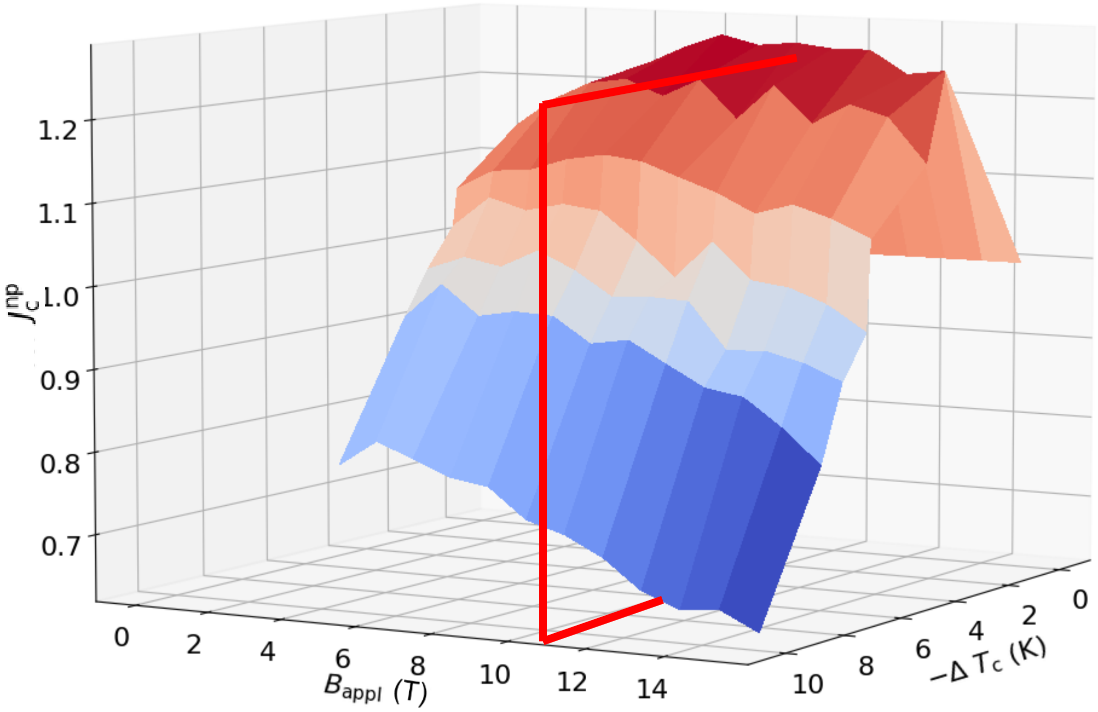
- unshielded peak is broad and at higher fields

Influence of point defects vs cascades

shielded sample



unshielded sample



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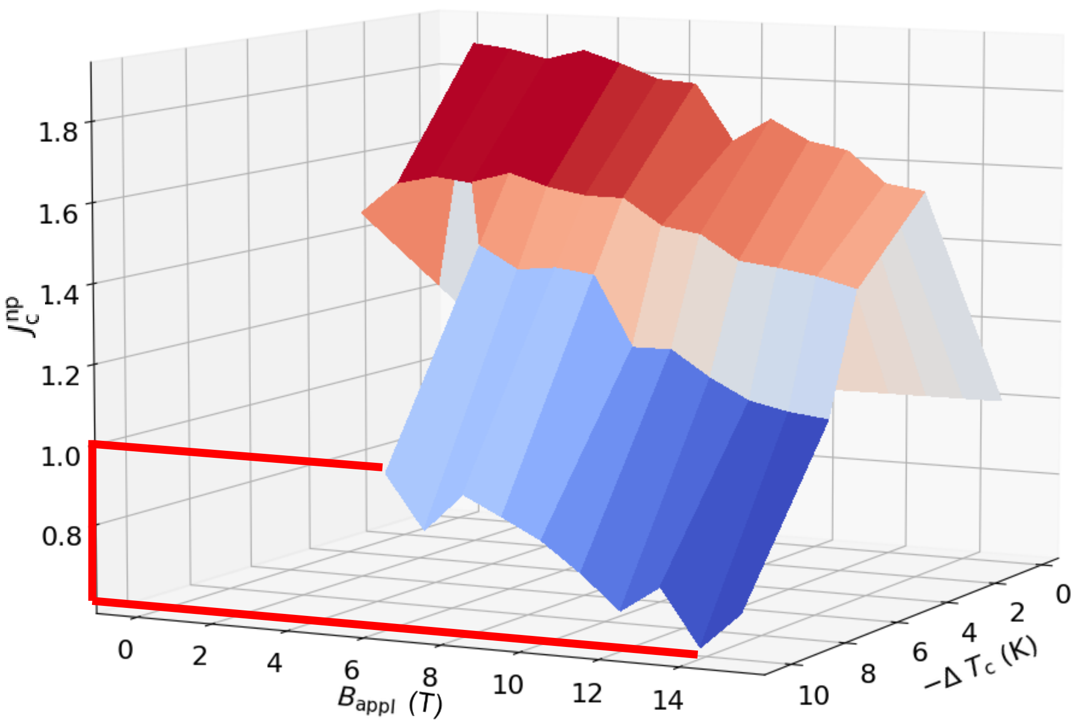
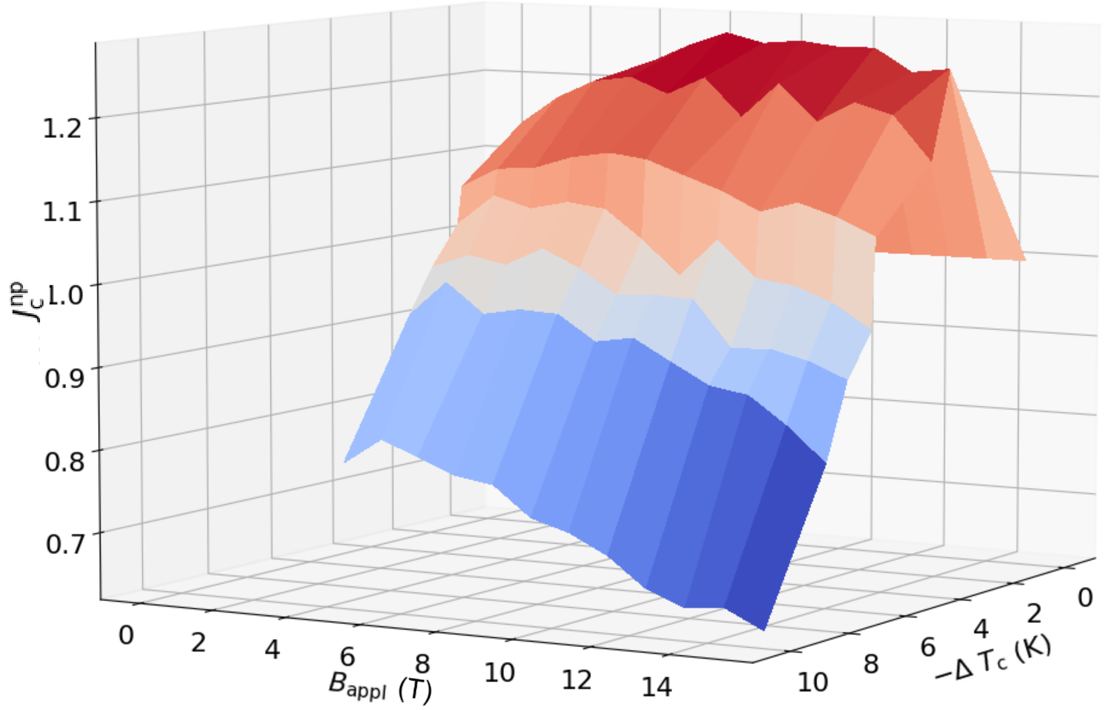
Influence of point defects vs cascades



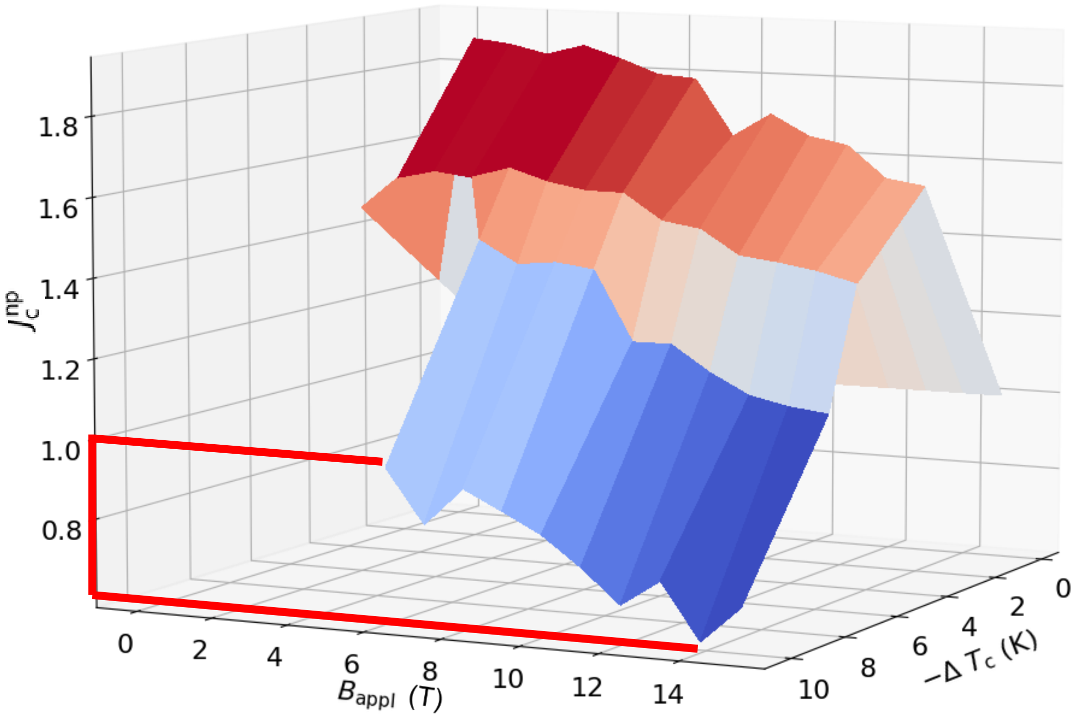


- more degradation at higher fields
- secondary defects?

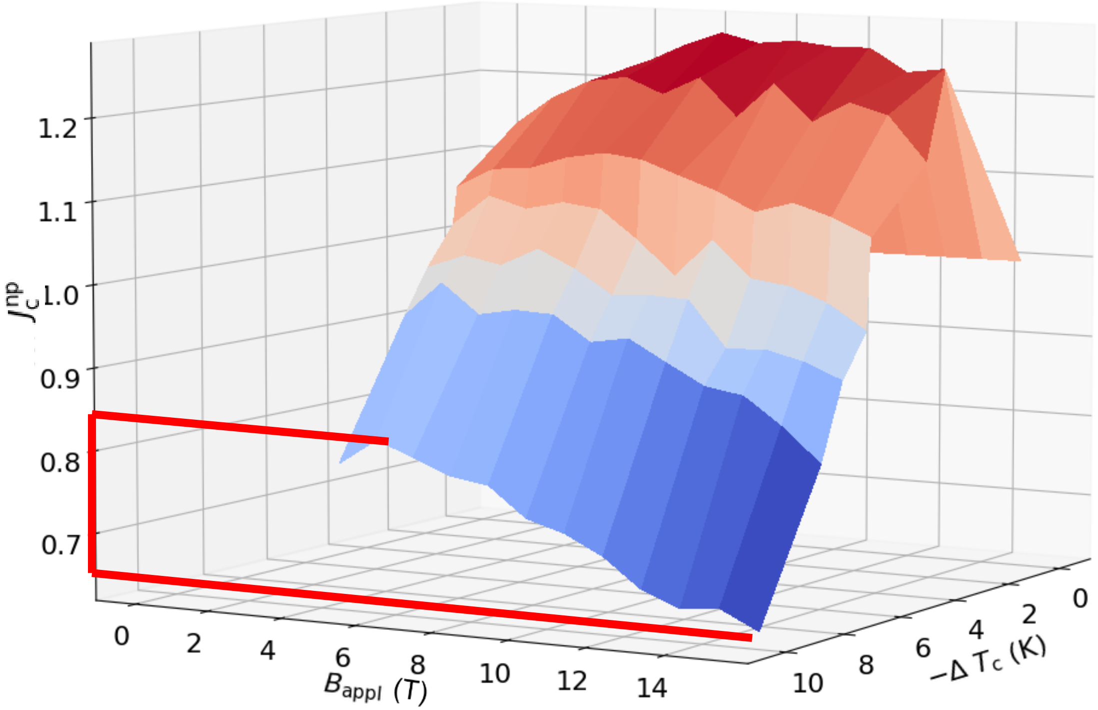
- degrading effect more homogeneous less field dependent

Influence of point defects vs cascades

shielded sample



unshielded sample



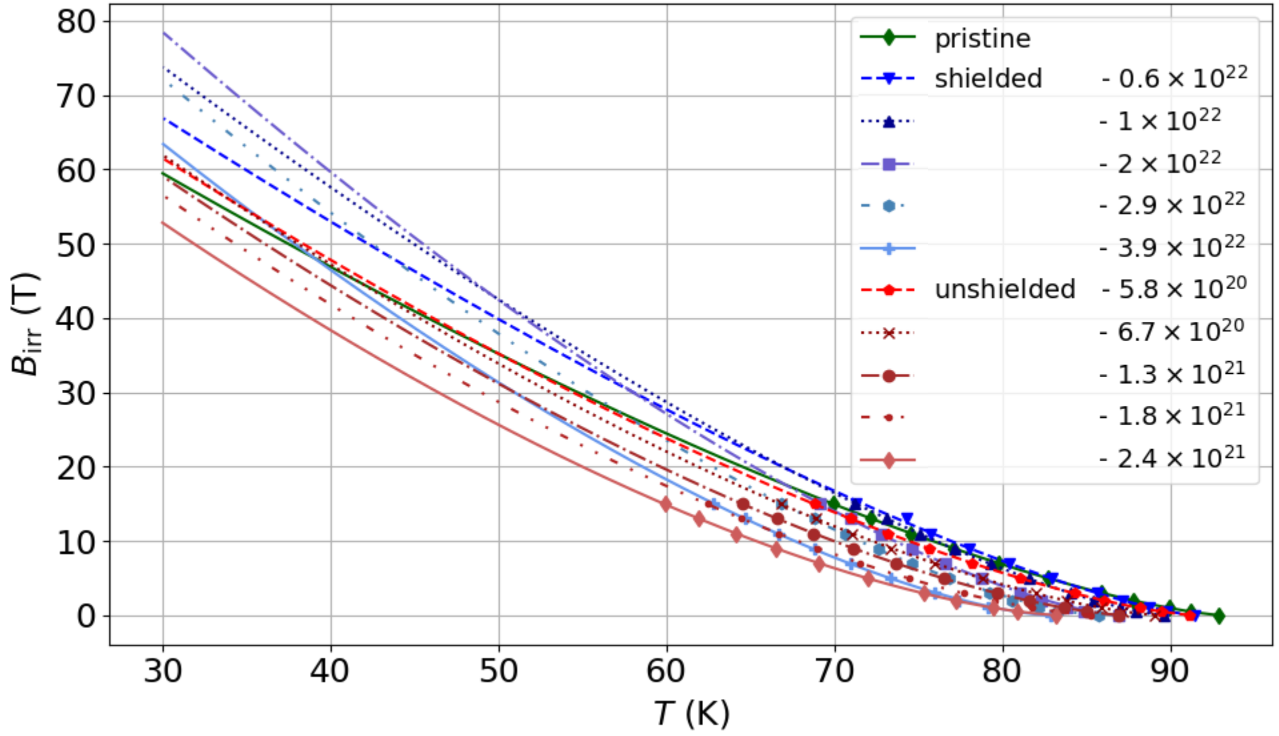
- more degradation at higher fields
- secondary defects?

- degrading effect more homogeneous less field dependent

Homogeneous degradation

What’s leading to this almost equivalent degradation?

Change of the irreversibility line



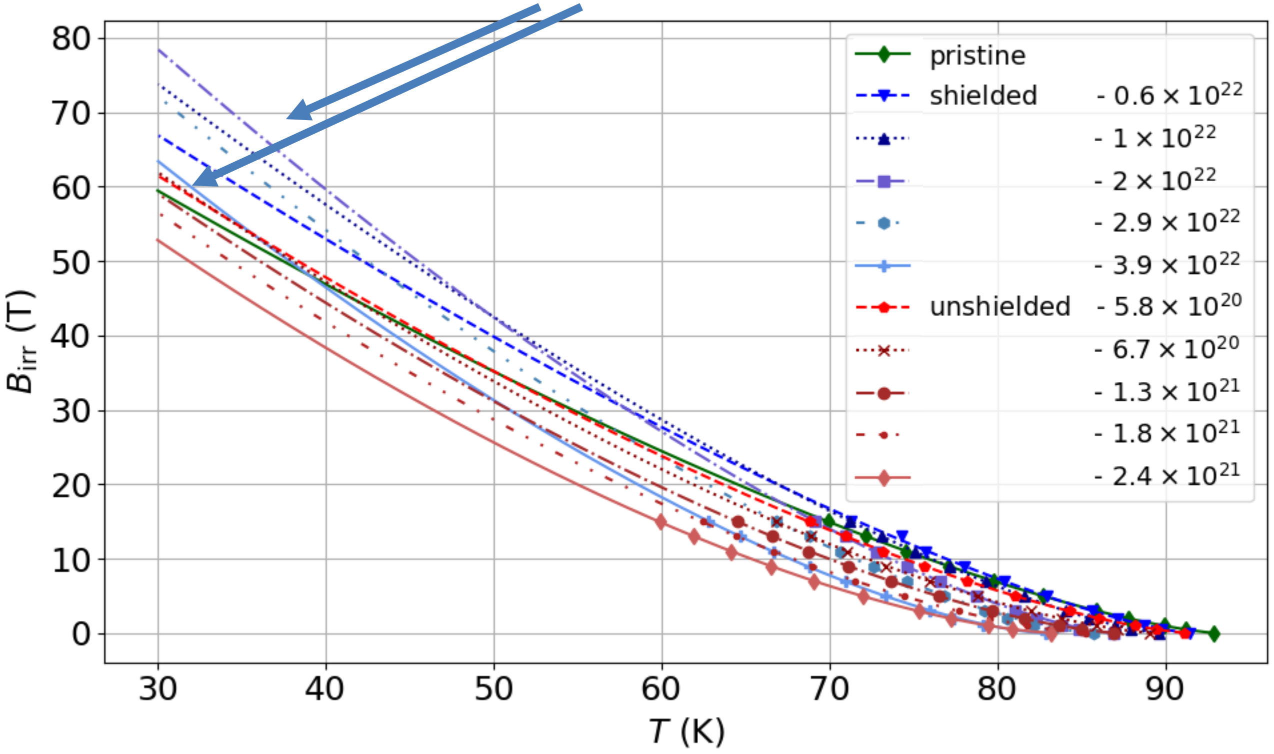
Can’t we just blame the irreversibility field?

$$B_{\mathrm{irr}}(\mathrm{T}) = \boldsymbol{B_{irr}}(\mathbf{0}) \times \left(1-\frac{T}{T_{\mathrm{c}}}\right)^{\boldsymbol{n}}$$

applied fit function

bold – fit parameters

Change of the irreversibility line



max B_{irr} at max J_c (experimental)

Can we trust this interpolation?

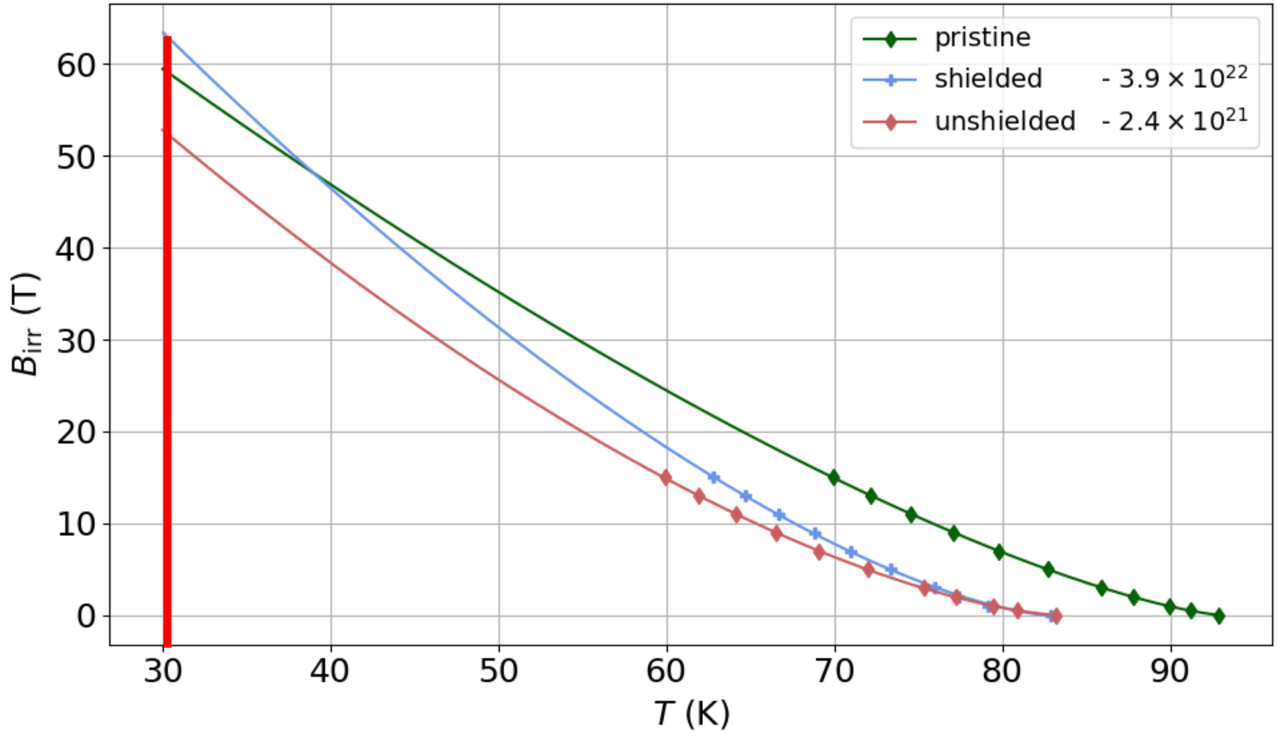
fit is extrapolated quite far
however trend is probably valid

$$B_{\mathrm{irr}}(\mathrm{T}) = \boldsymbol{B_{irr}(0)} \times \left(1 - \frac{T}{T_c}\right)^{\boldsymbol{n}}$$

applied fit function

bold – fit parameters

Change of the irreversibility line



- in shielded sample B_{irr} at 30 K is still at or above pristine value
- in unshielded sample B_{irr} is degraded to ~ 80% of pristine value

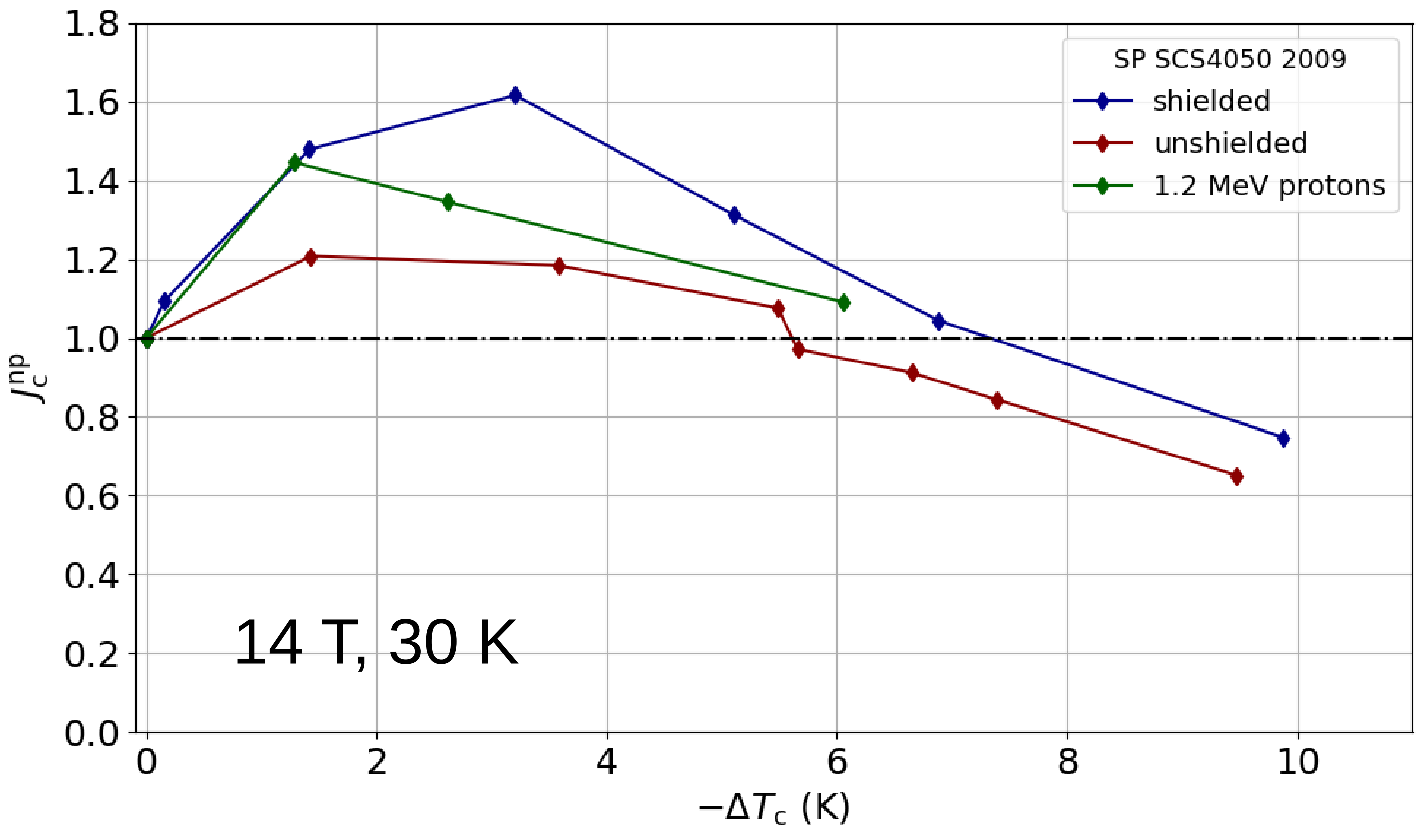
→ B_{irr} behaves completely different in both samples

degradation of J_c at 15 T and 30 K is the same ~ 70% of pristine value

Homogeneous degradation

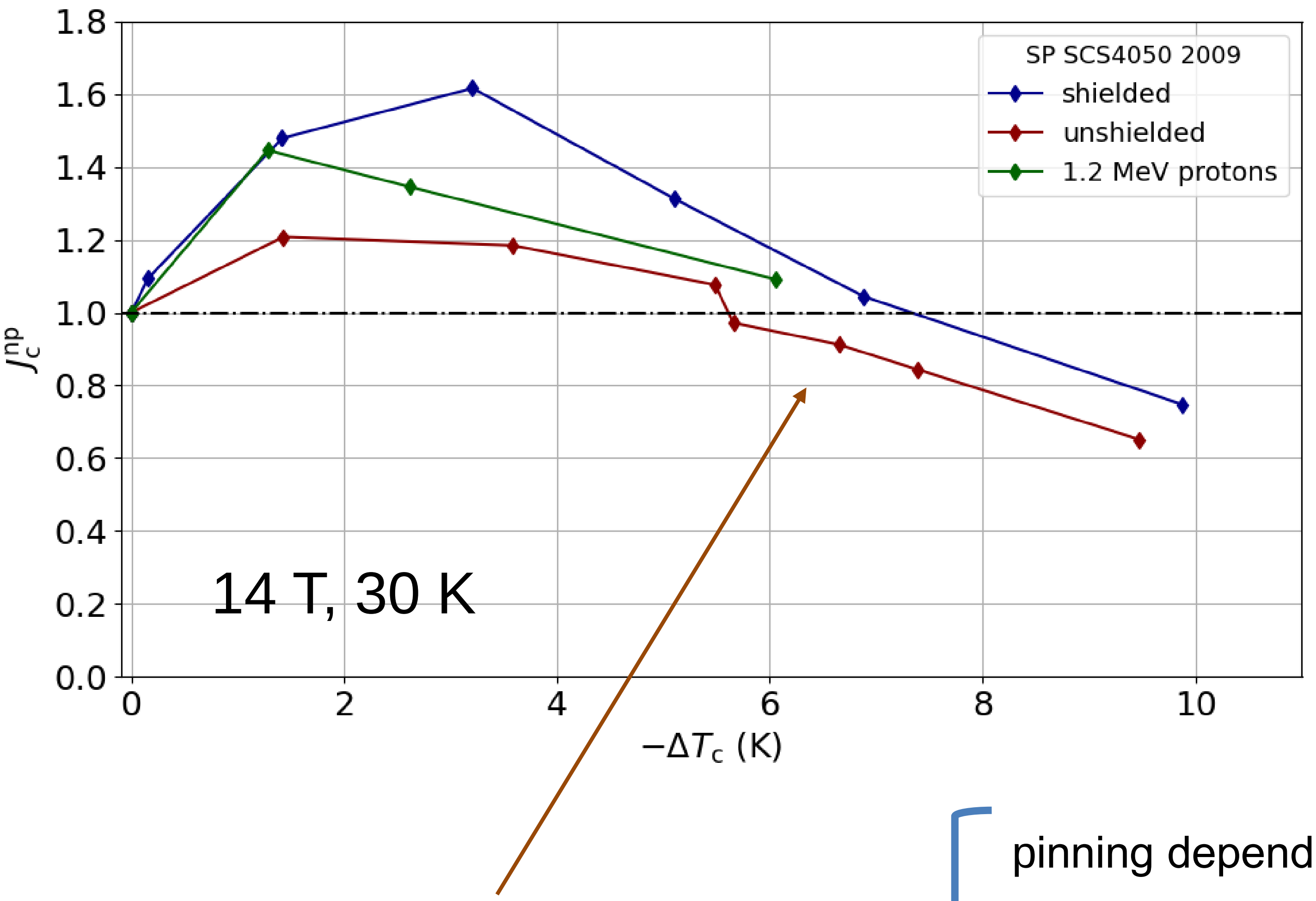
How can we (try to) explain it then?

Homogeneous degradation



- extremely different defect size distribution
- almost equivalent slope in degrading branch
- ~~uniformly only for neutron induced defects?~~

Homogeneous degradation



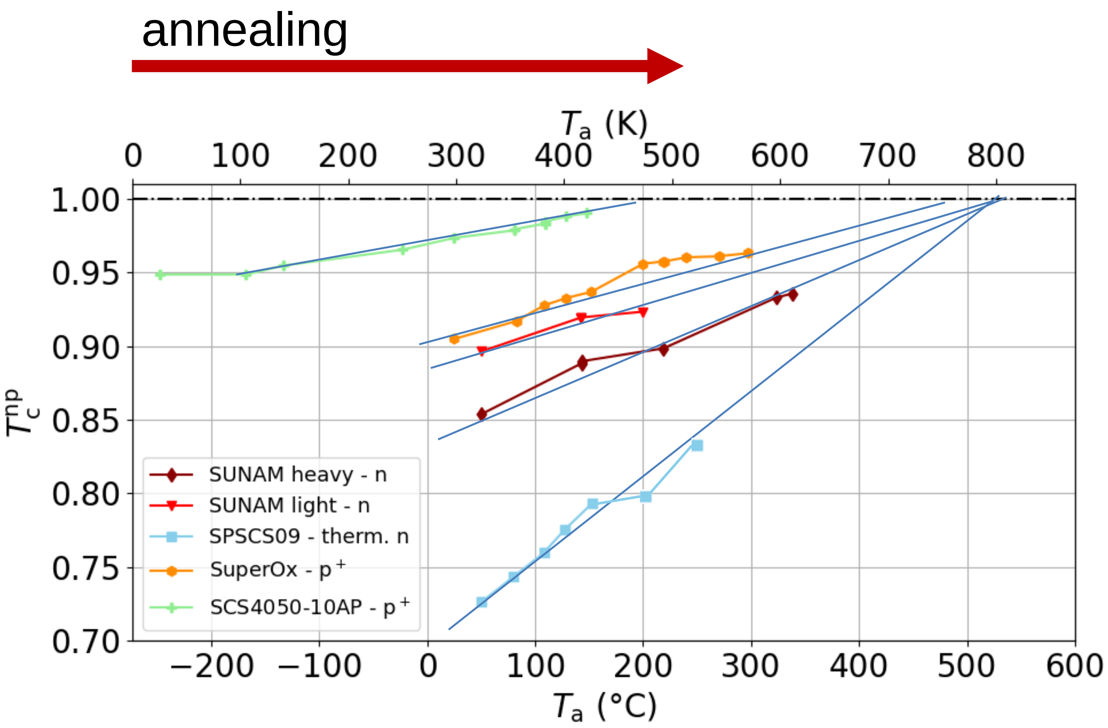
- extremely different defect size distribution
- almost equivalent slope in degrading branch
- ~~uniformly only for neutron induced defects?~~

J_c decreases uniformal

pinning depends on the defect (size, orientation…)

for the superfluid density **defect seems to be defect**

Thermal stability of small vs large defects



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

Conclusions

Simulation results:

- from MDS - dominant defect species are O_2 vacancies.
- Gd antisites are 500:1 less probable, however calculation of DOS indicates strong suppression at E_F

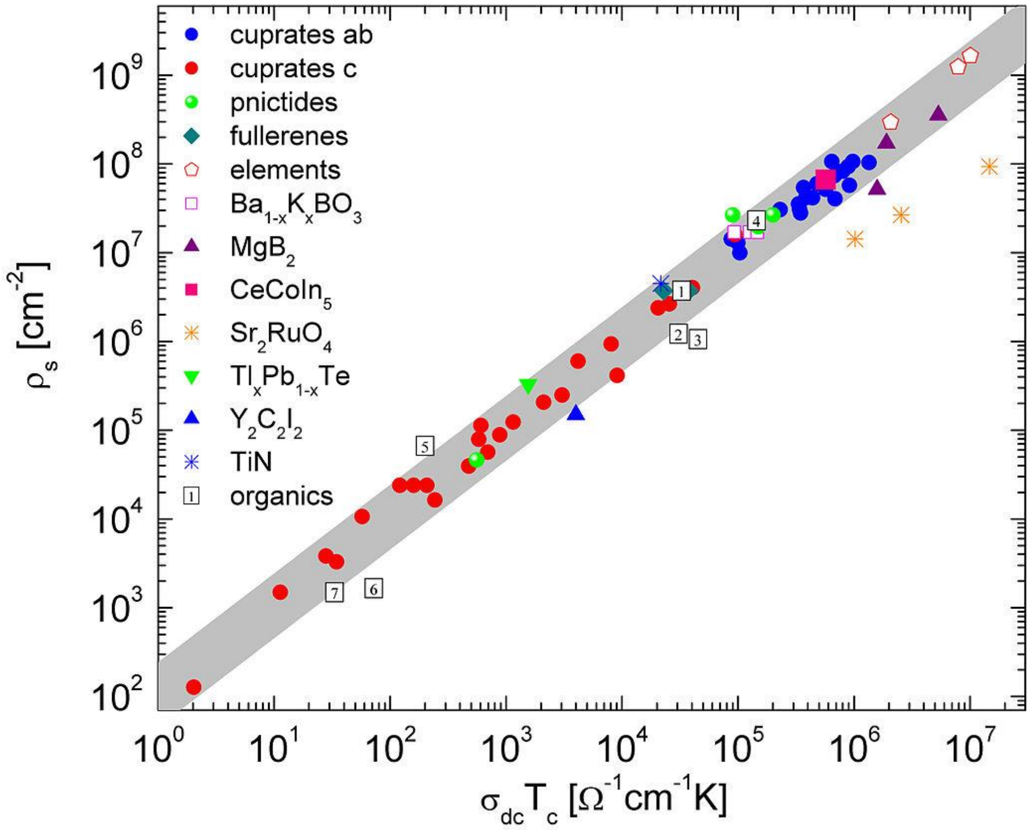
Experimental results:

- small defects contribute to pinning at large fields and low temperatures
- position of maximum in J_c is dependent on defect density
  independent of irradiation technique (p^+, n_{therm}, n_{fast})
- suppression of J_c at high fluences and fields almost equivalent (n_{therm} vs n_{fast})
- annealing indicates that degradation comes from same defect class

Seems to confirm that O_2 interstitials are the driving force in the degradation

Motiviation

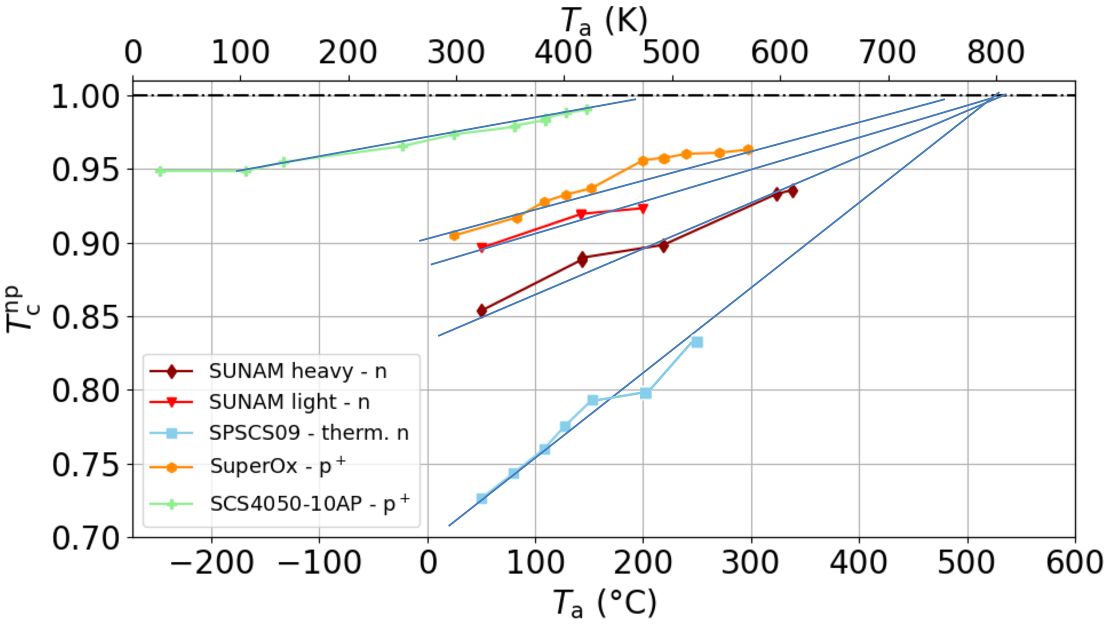
Homes’ scaling law



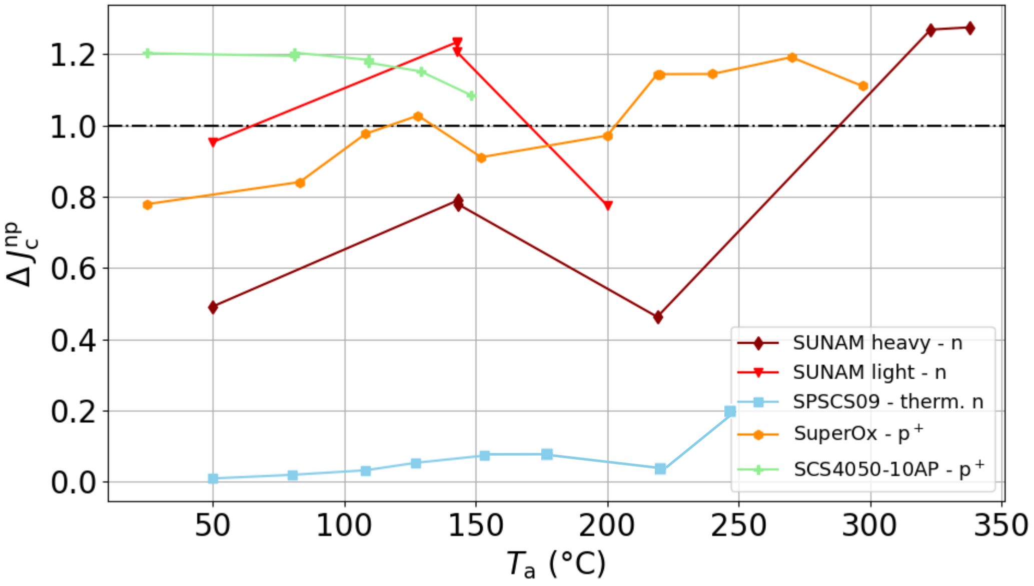
- though logarithmic, the superfluid density scales with σ_{dc} and T_{c}
- many orders of magnitude
- many different materials

Thermal stability of small vs large defects

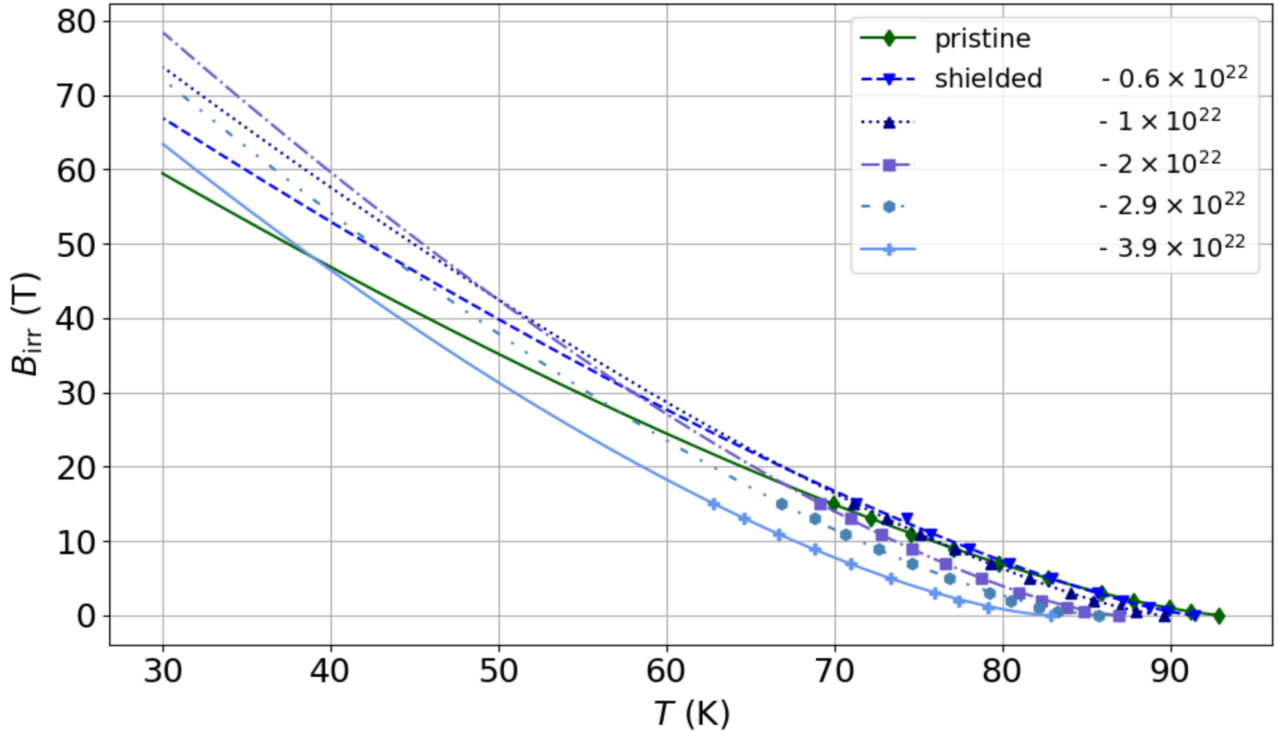
annealing



annealing



Change of the irreversibility line



$$B_{\mathrm{irr}}(\mathrm{T}) = \boldsymbol{B_{irr}}(\mathbf{0}) \times \left(1 - \frac{T}{T_{\mathrm{c}}}\right)^{\boldsymbol{n}}$$ applied fit function

bold – fit parameters

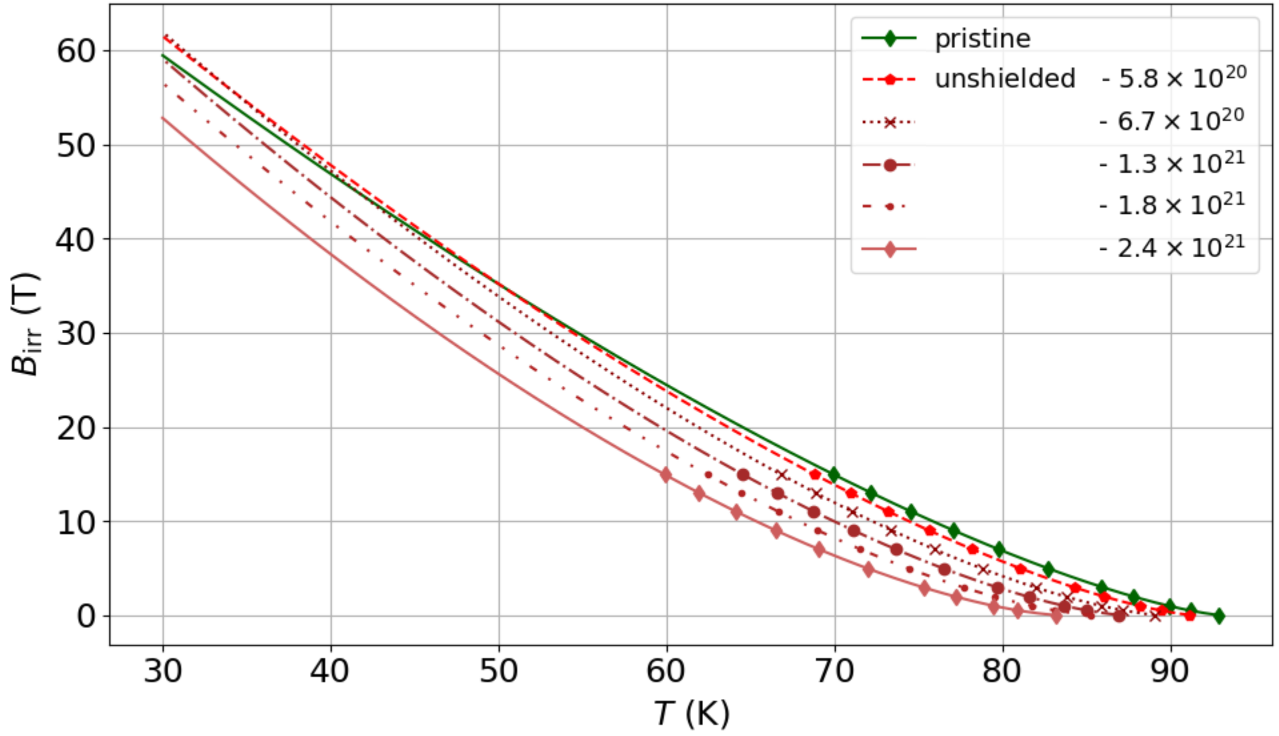
shielded tape

- irreversibility line changes slope
  - at low fluences → increases
  - at high fluences → decreases

unshielded tape

- irreversibility line keeps slope

Change of the irreversibility line



shielded tape

- irreversibility line changes slope
  - at low fluences ➔ increases
  - at high fluences ➔ decreases

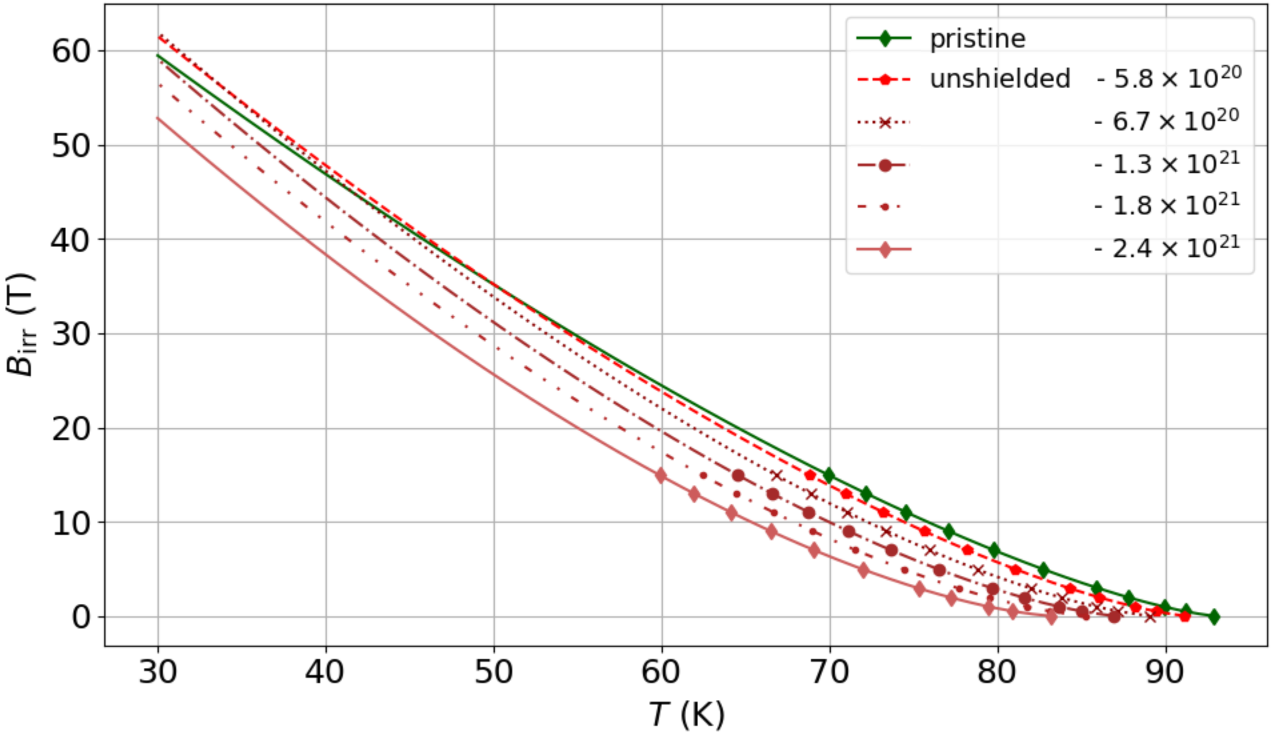
unshielded tape

- irreversibility line keeps slope

$$B_{\mathrm{irr}}(\mathrm{T}) = \boldsymbol{B_{irr}}(\mathbf{0}) \times \left(1 - \frac{T}{T_{\mathrm{c}}}\right)^{\boldsymbol{n}}$$ applied fit function

bold – fit parameters

Change of the irreversibility line

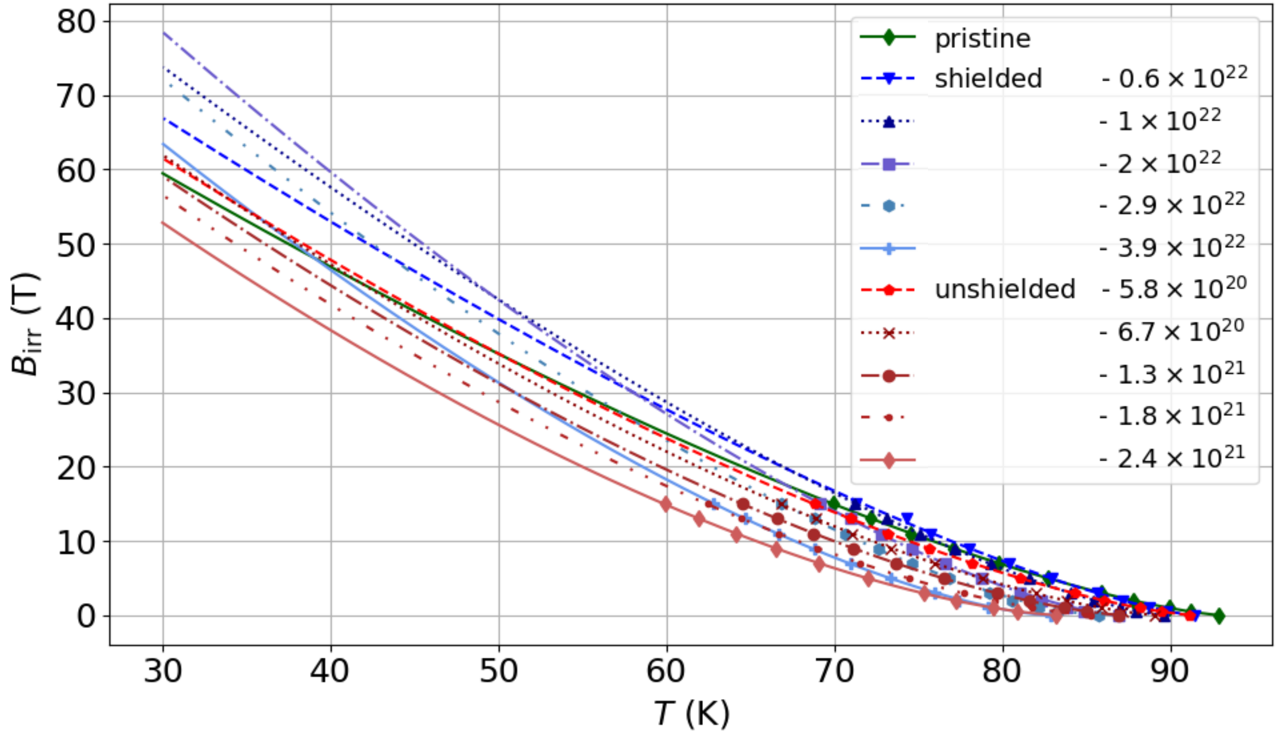


Does the degradation of B_{irr} explain the low J_c *at 30 K?*

$$B_{\mathrm{irr}}(\mathrm{T}) = \boldsymbol{B_{irr}}(\mathbf{0}) \times \left(1 - \frac{T}{T_{\mathrm{c}}}\right)^{\boldsymbol{n}}$$ applied fit function

bold – fit parameters

Change of the irreversibility line



Can’t we just blame the irreversibility field?

No.

$$B_{\mathrm{irr}}(\mathrm{T}) = \boldsymbol{B_{irr}}(\mathbf{0}) \times \left(1 - \frac{T}{T_{\mathrm{c}}}\right)^{\boldsymbol{n}}$$ applied fit function

bold – fit parameters

Motiviation

Homes’ scaling law

$$\boxed{\rho_\mathrm{s} \propto \sigma_\mathrm{dc} T_\mathrm{c}}$$

ρ_s ... superfluid density

$\sigma_\mathrm{dc} = \rho_\mathrm{dc}{}^{-1}$ ... normal state conductivity

$$j_\mathrm{d} \propto \frac{H_\mathrm{c}}{\lambda} \propto \frac{1}{\lambda^2 \xi} \propto \frac{\rho_\mathrm{s}}{\xi}$$

$$\boxed{j_\mathrm{c}^\mathrm{p} = \eta \, j_\mathrm{d}}$$

η ... pinning efficiency

j_c^p ... physical critical current

***j*$_\mathrm{c}$** should be proportional to the normal state resistivity