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The influence of small defects on the superconducting properties of REBCO based CCs

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Funded by the European Union

Outline

Motivation

- nuclear fusion
- role of defects of different size (point defects, collision cascades)

Experimental

- neutron irradiation
- introduced defects

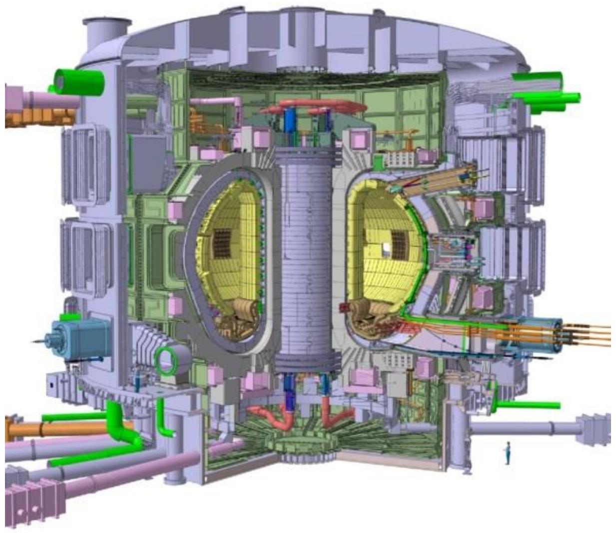
Results

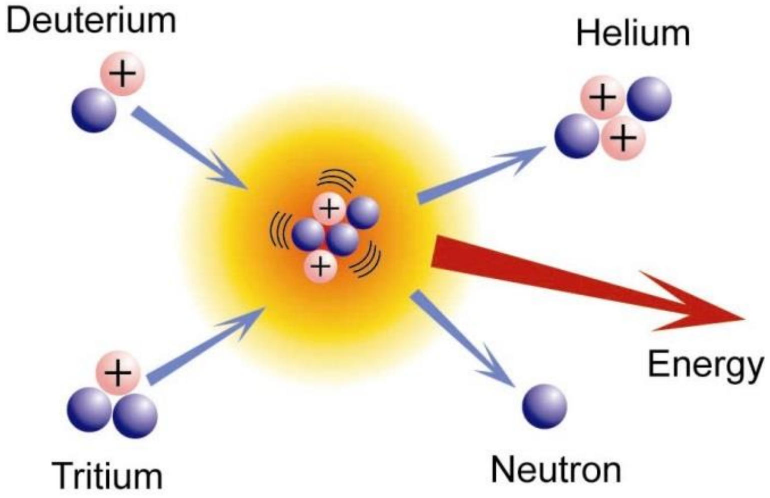
- decrease of T_c and superfluid density
- enhancement of vortex pinning

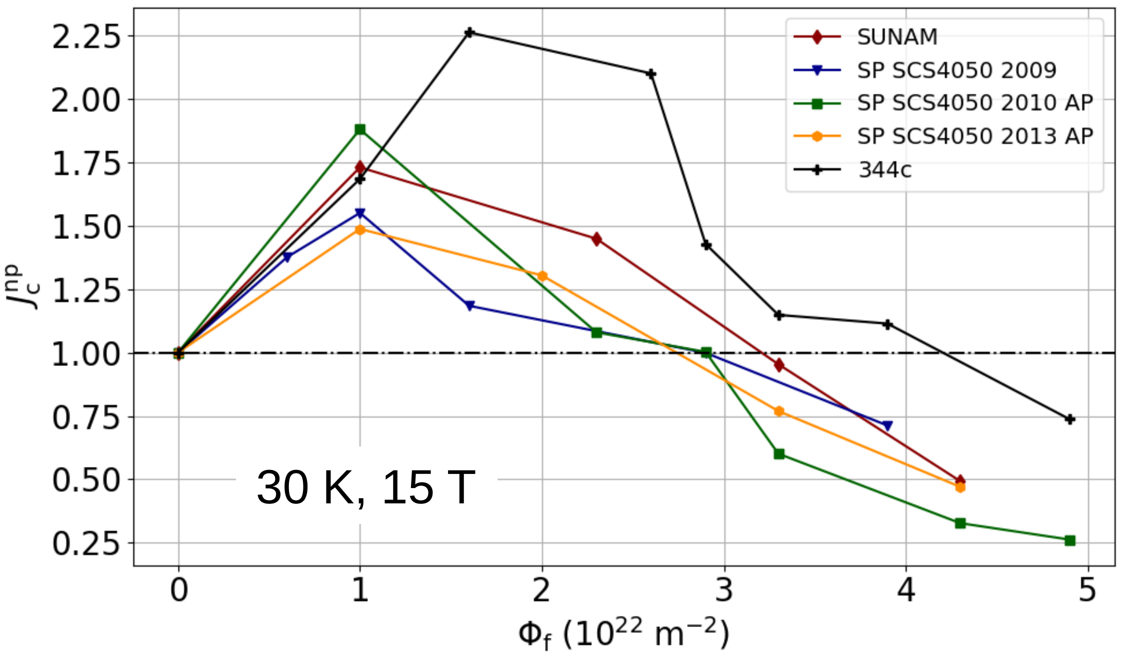
Conclusions

Motiviation

Nuclear Fusion







introduced defects

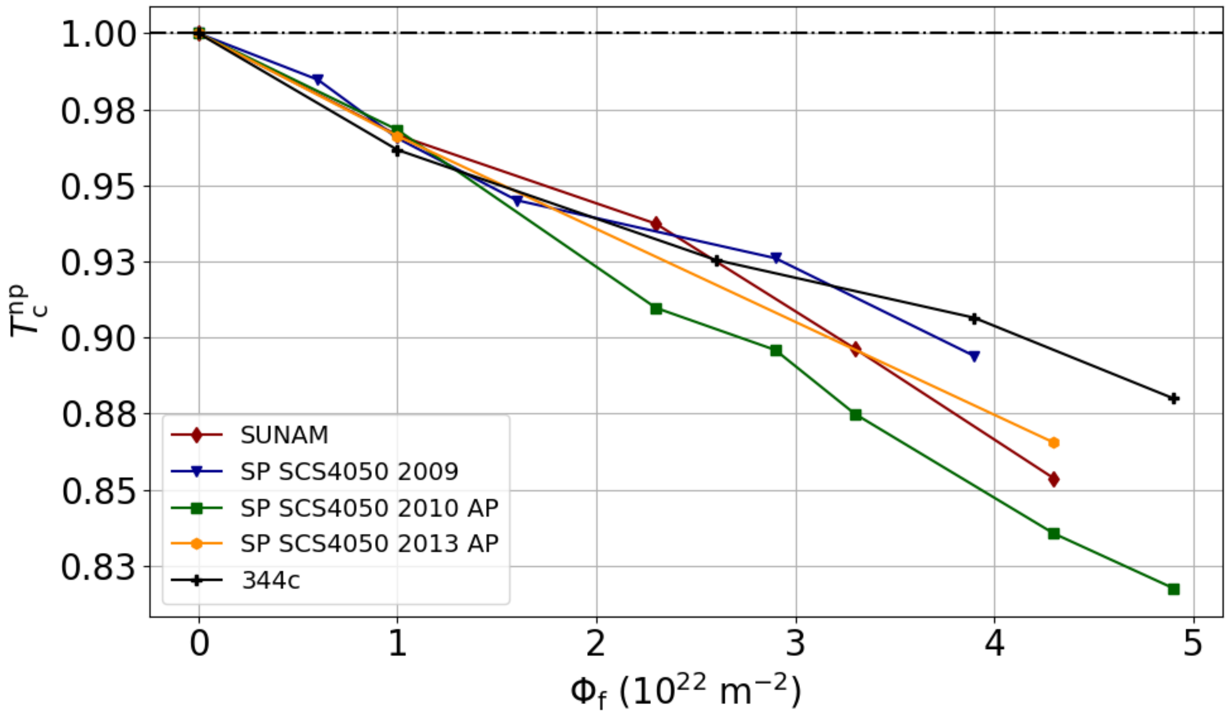
- enhance pinning
- increase scattering of charge carriers

A small fraction of the fusion neutrons reaches the superconducting magnets.

Motiviation

scattering is pair breaking in *d*-wave superconductors

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

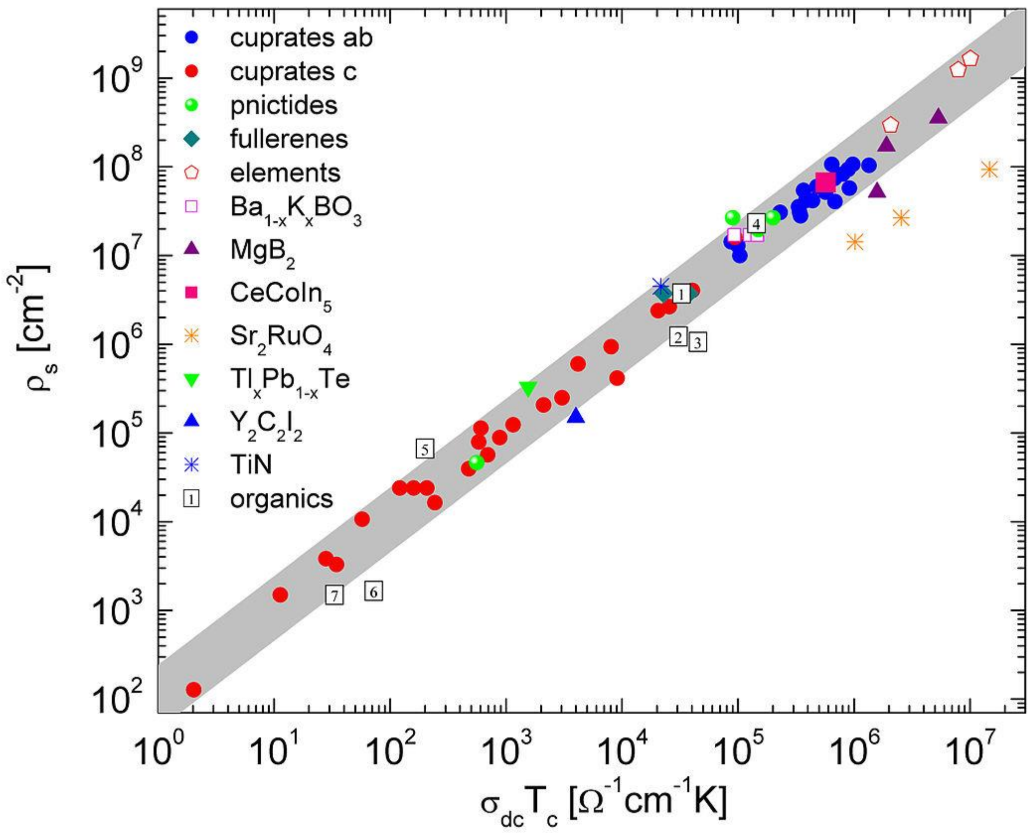


Normalized transition temperature

Fast neutron fluence

Motiviation

Homes' scaling law



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

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

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

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

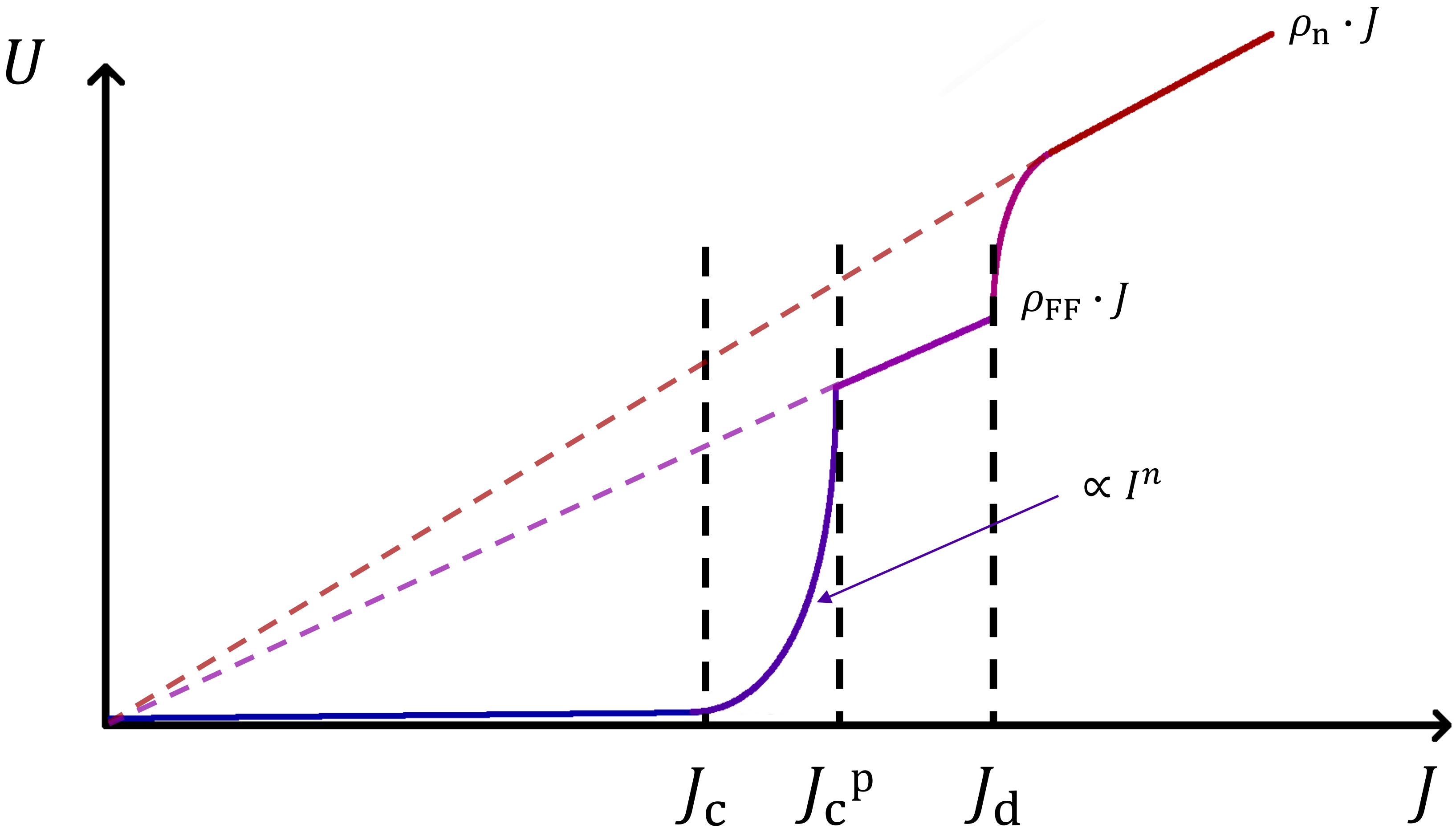
η ... pinning efficiency

j_c^p ... physical critical current

j_c should be proportional to the normal state resistivity

Motiviation

Homes’ scaling law



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

Motiviation

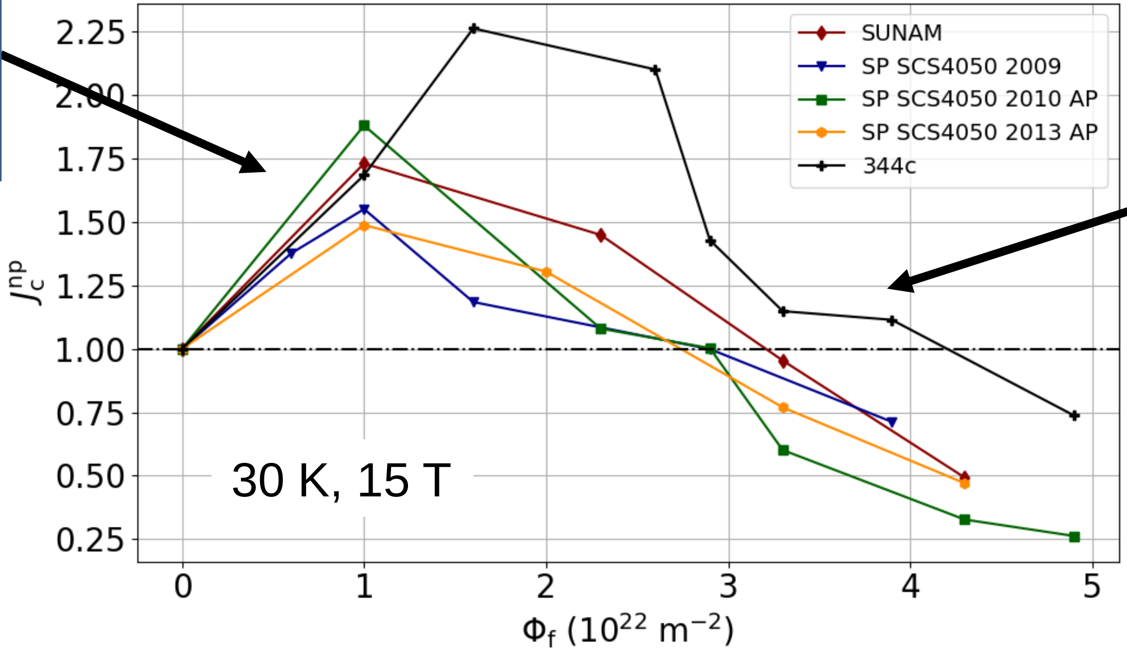
High scattering rate: high density of **small** defects.

Size of pinning centres should match the superconducting coherence length: **large** defects.

Large defects

⬇

Improved flux pinning



Small defects

⬇

Reduced superfluid density

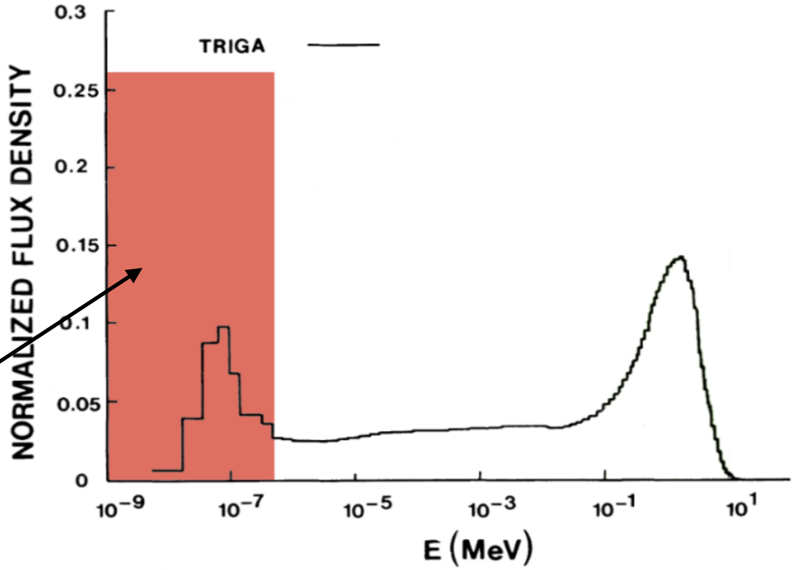
Oversimplified picture?

Experimental

Neutron Irradiation

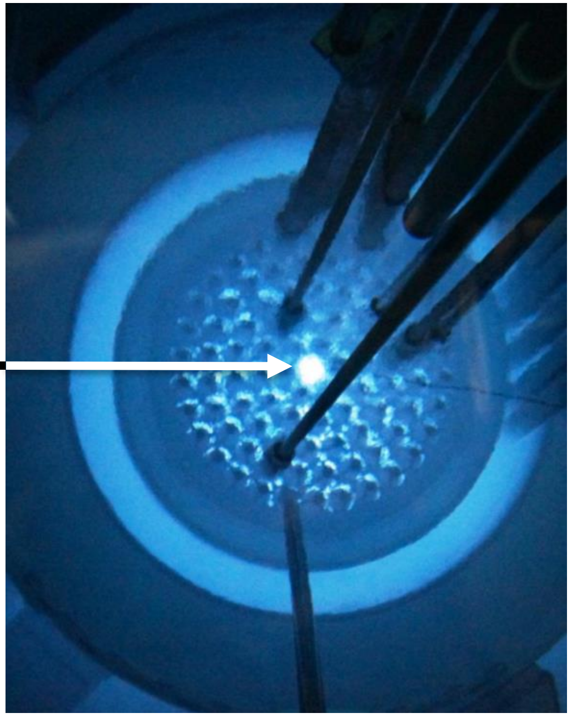
TRIGA MARK II at TU Wien

- 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



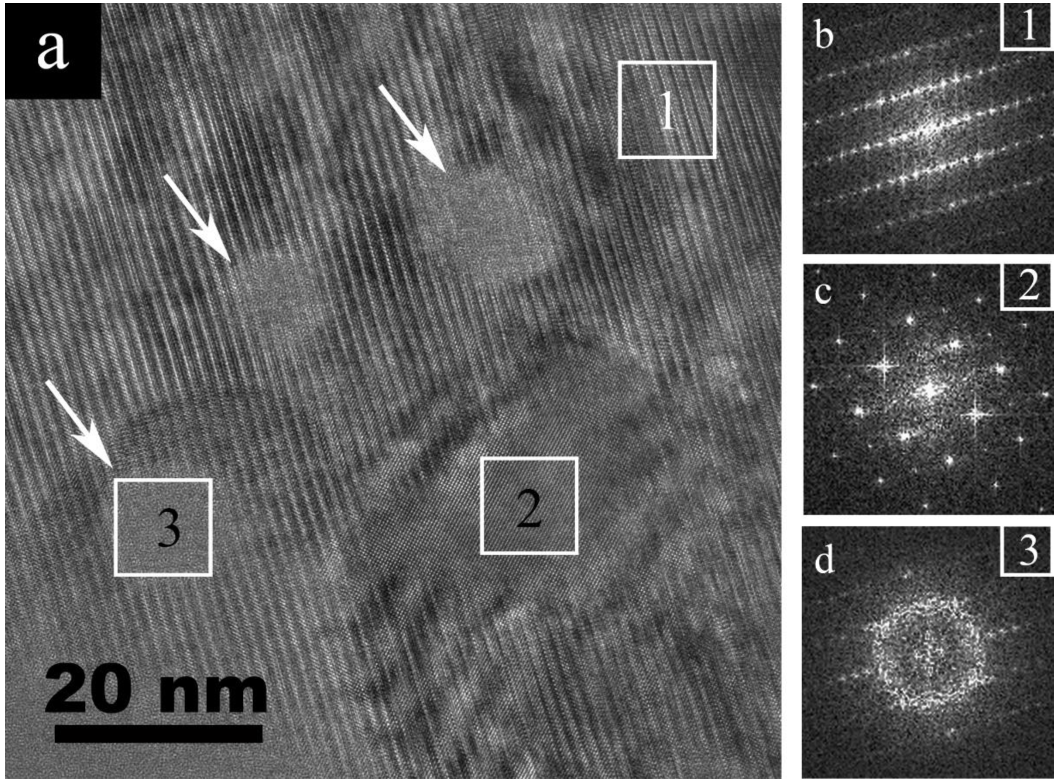
Can be screened by cadmium foil

> 70 C at sample



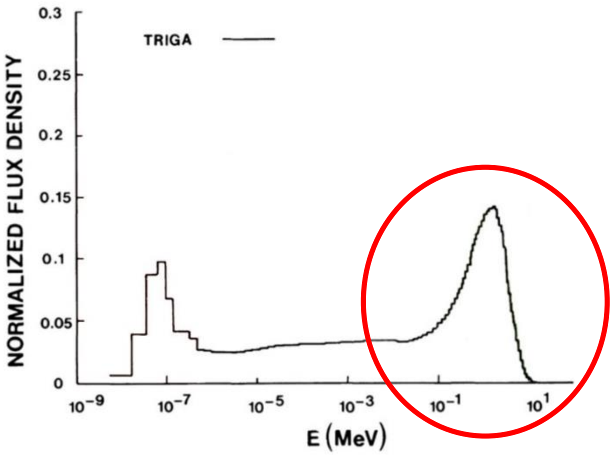
TRIGA MARK II – experimental fission reactor

Defect structure



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

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

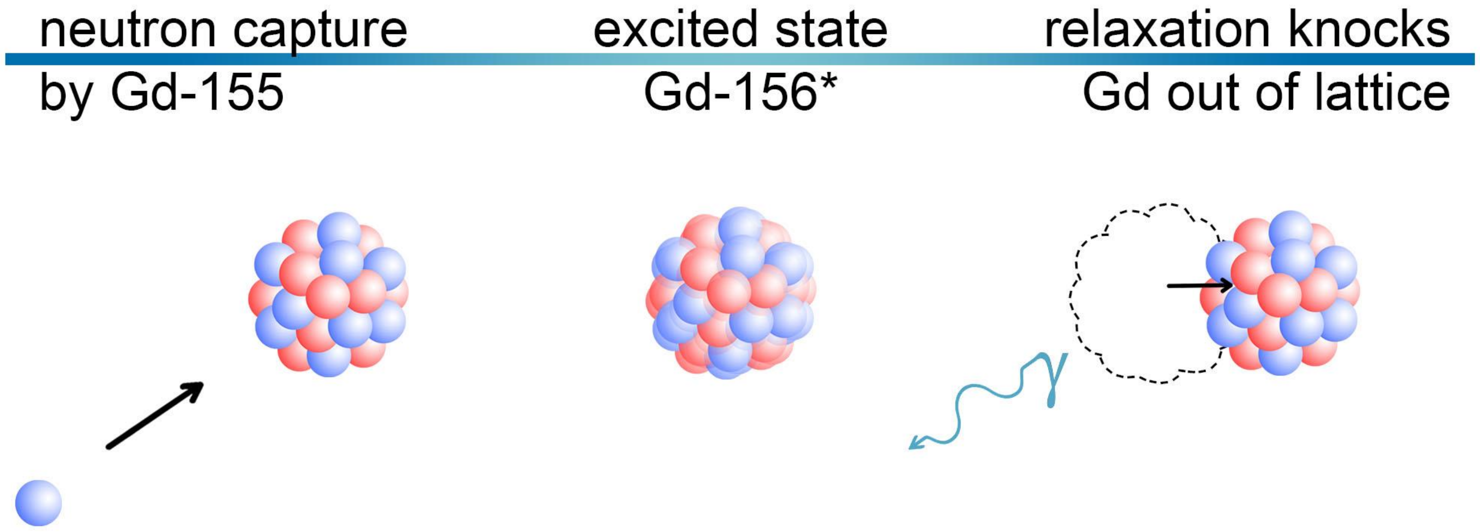


Defect size	≤ 10 nm
Mean	~ 4 nm
ξ^0_{ab}	~ 1.4 nm
ξ^{77}_{ab}	~ 3 nm

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

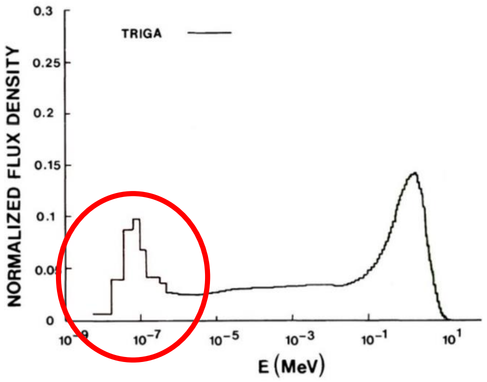
Defect structure



neutron capture by Gd-155

excited state Gd-156*

relaxation knocks Gd out of lattice

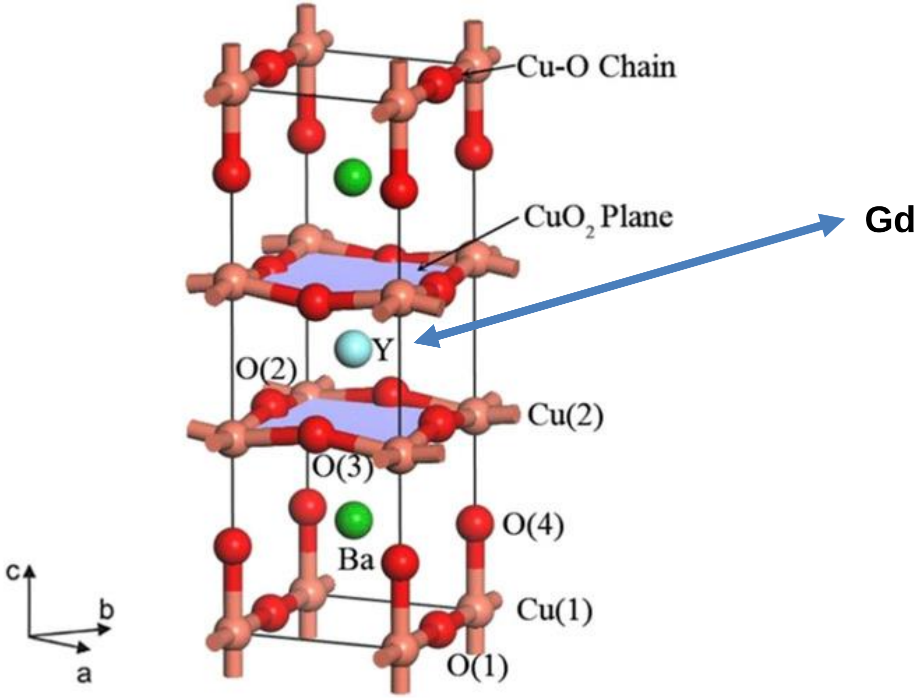


K.E. Sickafus et al., Phys. Rev. B **46** (1992) 11862

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

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

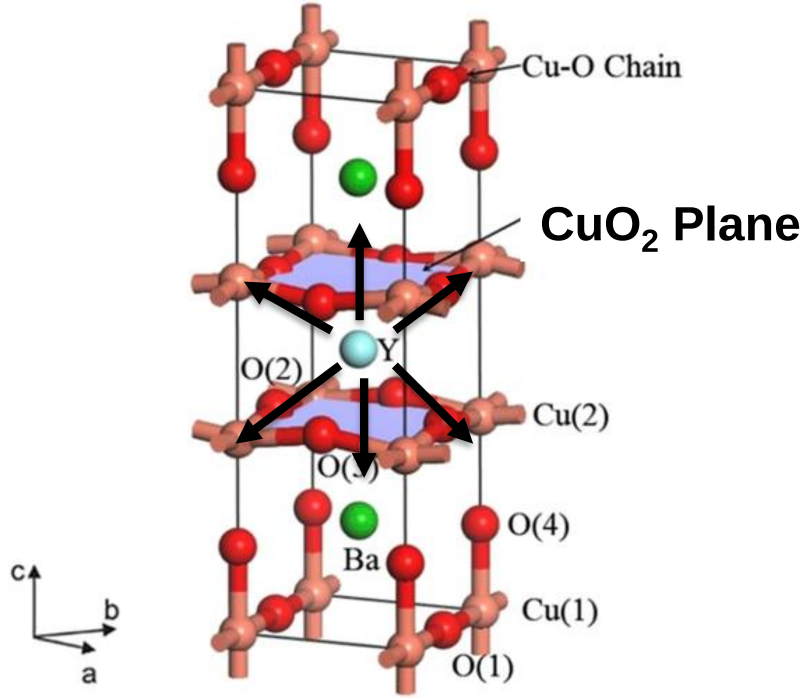
Defect structure



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

How do these defects influence the superconducting properties?

Defect structure



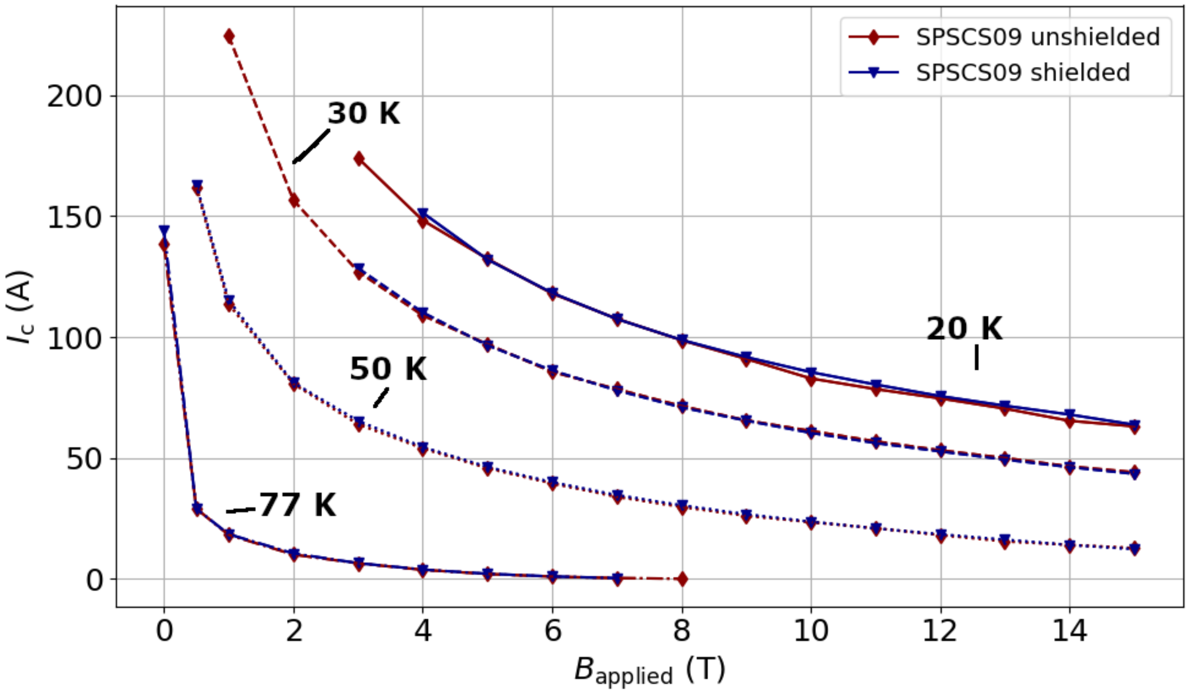
P. Gao et al., AIP Advances **7** (2017) 035215

How do these defects influence the superconducting properties?

Most likely distorting the CuO_2 Planes!

→ Daniele Torsello, Davide Gambino & Francesco Laviano

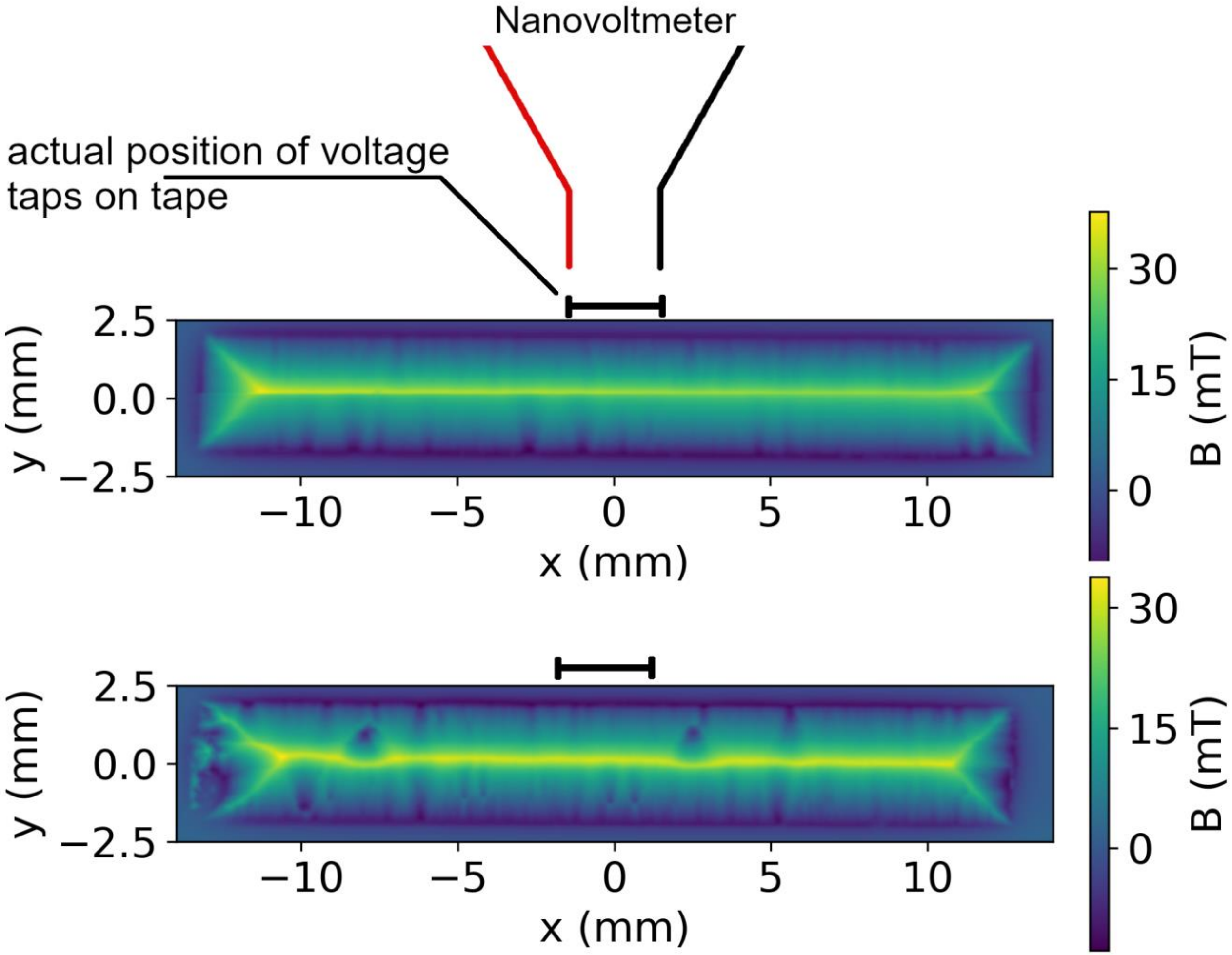
Two nearly identical samples



- 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

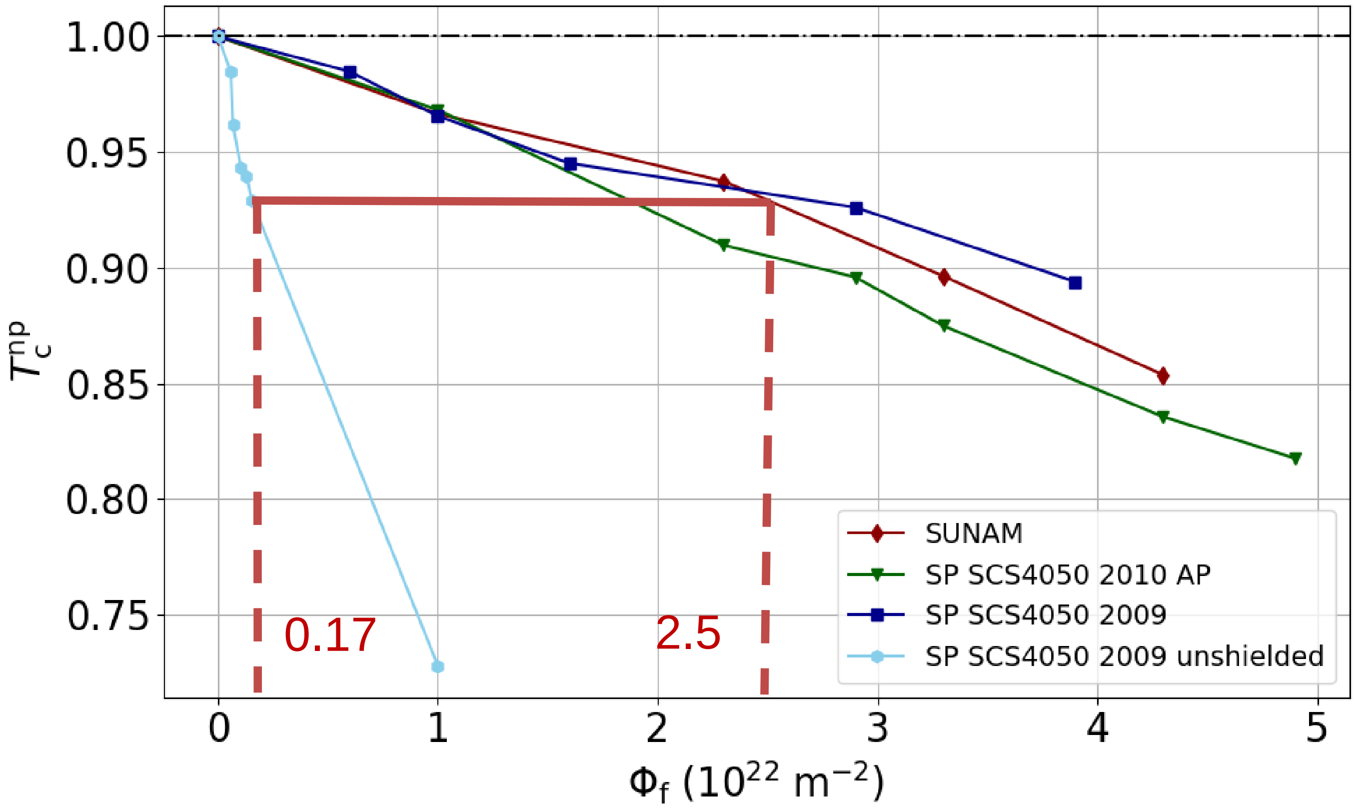
Two nearly identical samples



- sample consistency checked by hall scans
- profile at selfield & 77 K
- voltage taps in low defect areas
- slight differences in signal due to probe – sample distance

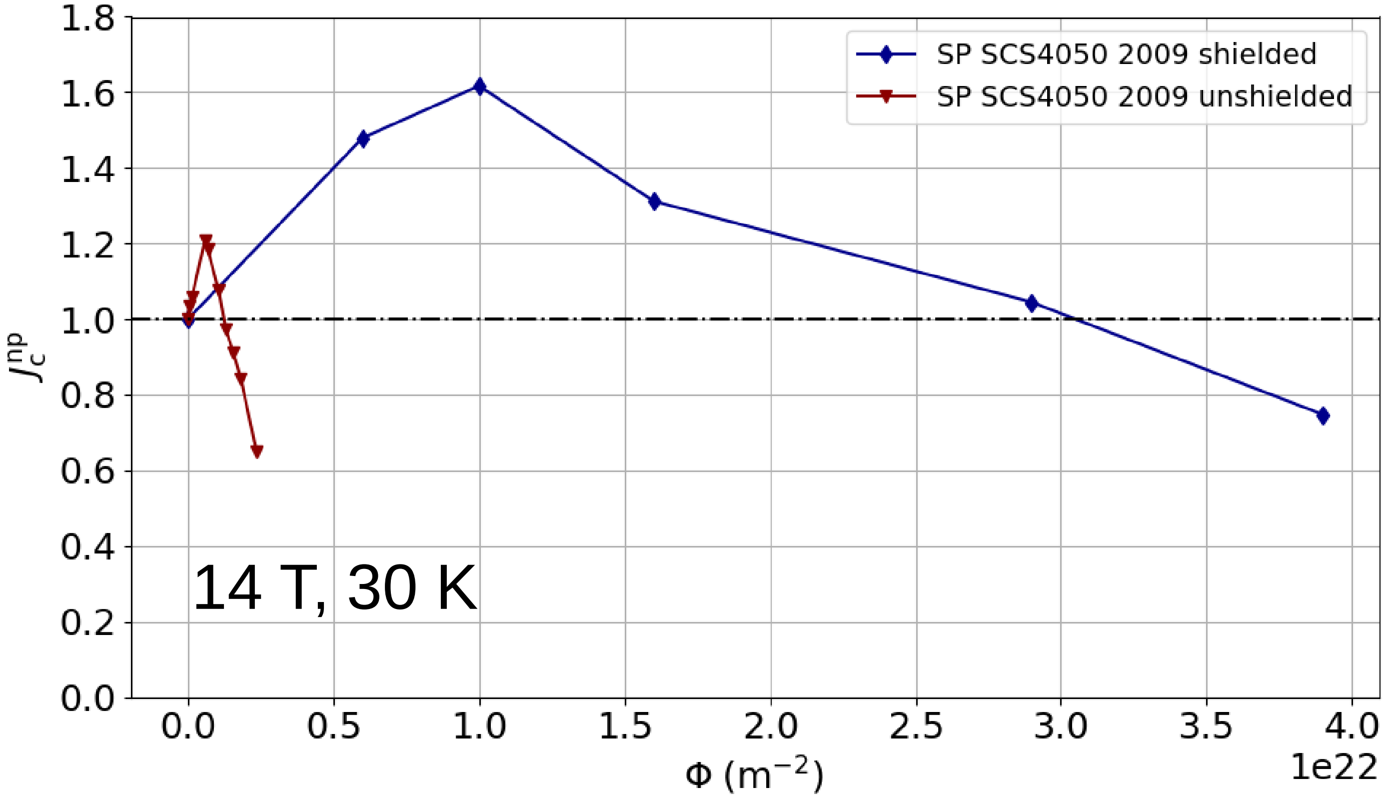
Results

Influence of thermal neutrons: T_c



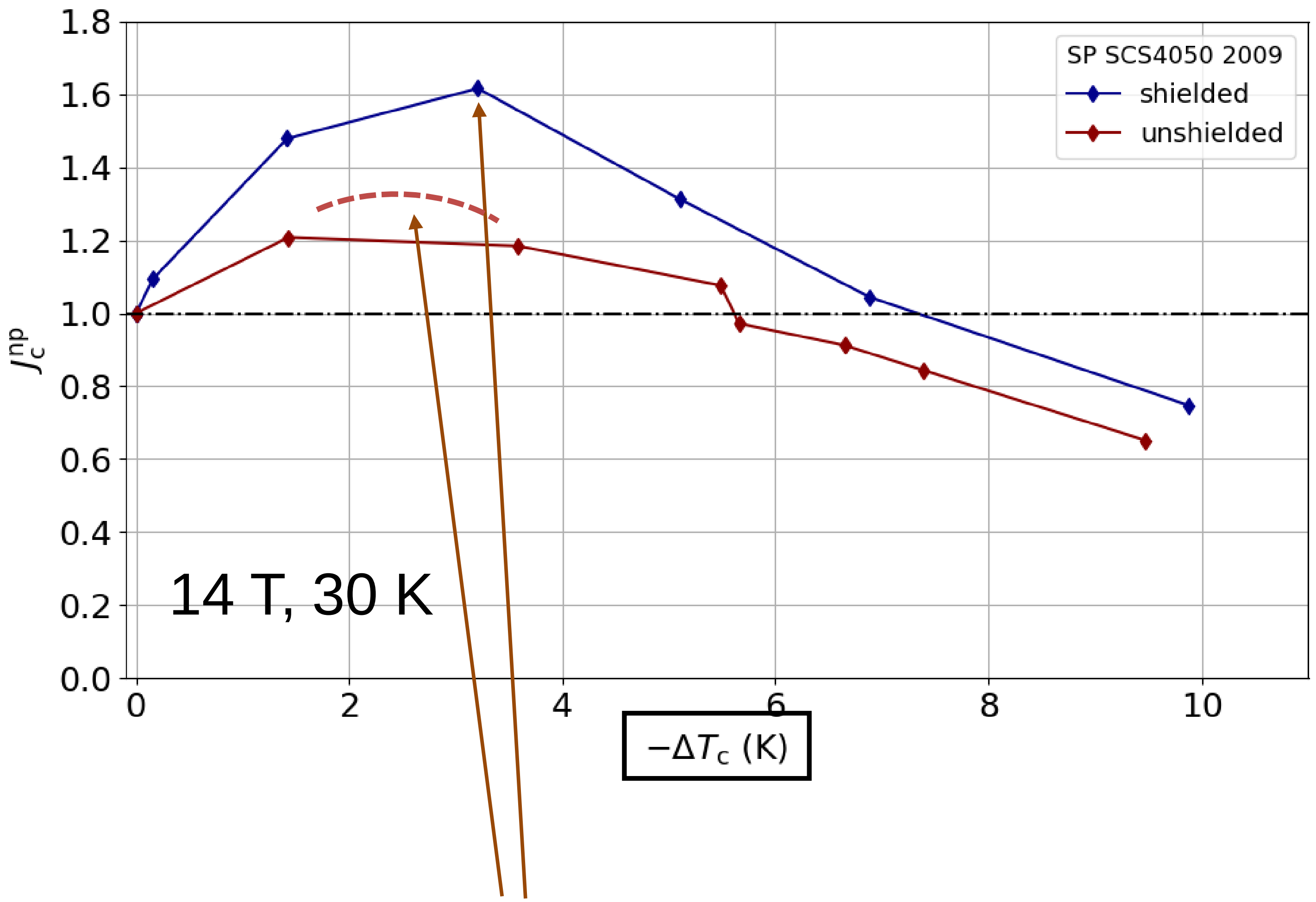
T_c degrades ~13-15 x faster due to Gd-point defects

Influence of thermal neutrons: J_c



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

Influence of thermal neutrons: J_c

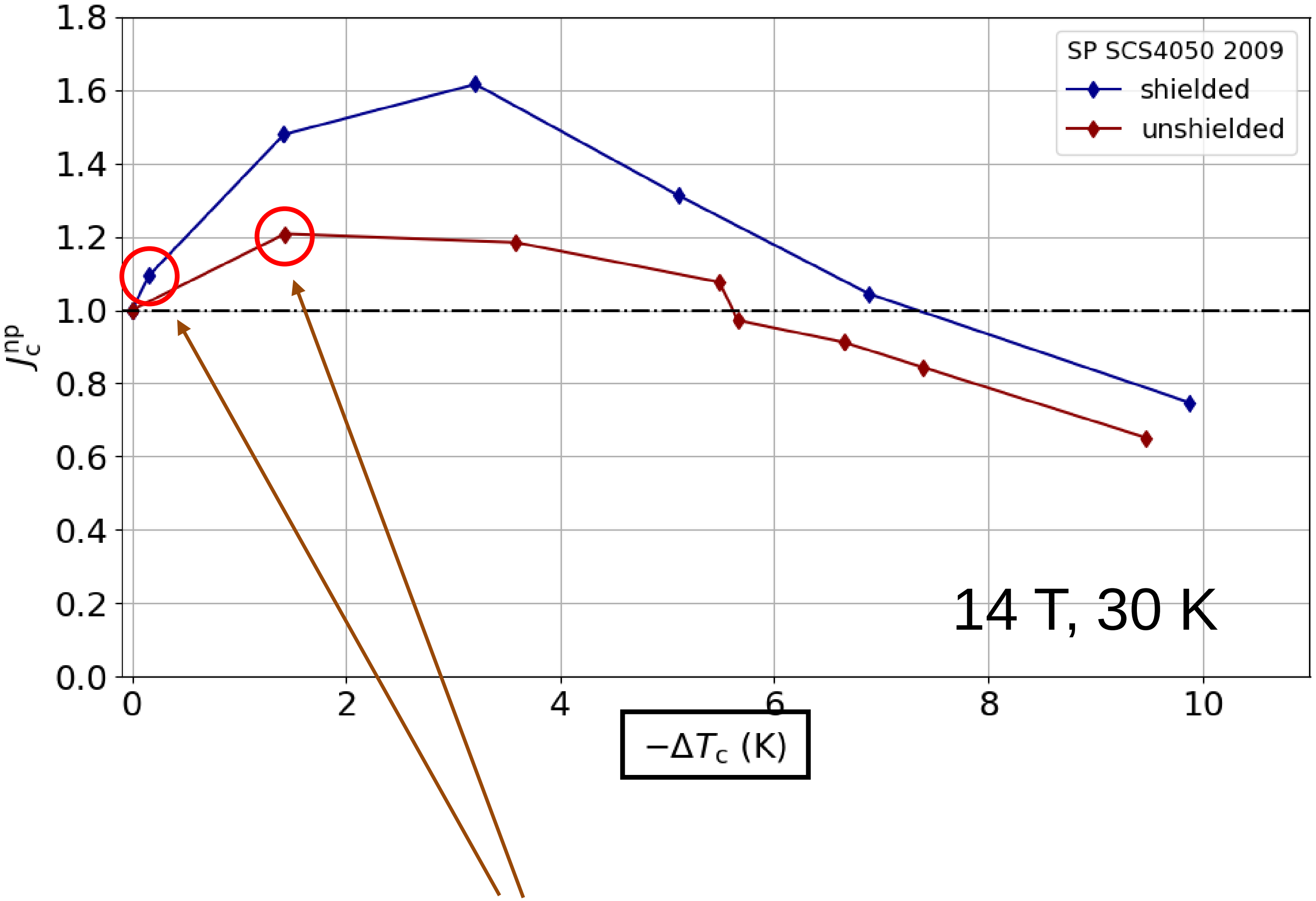


14 T, 30 K

- 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?

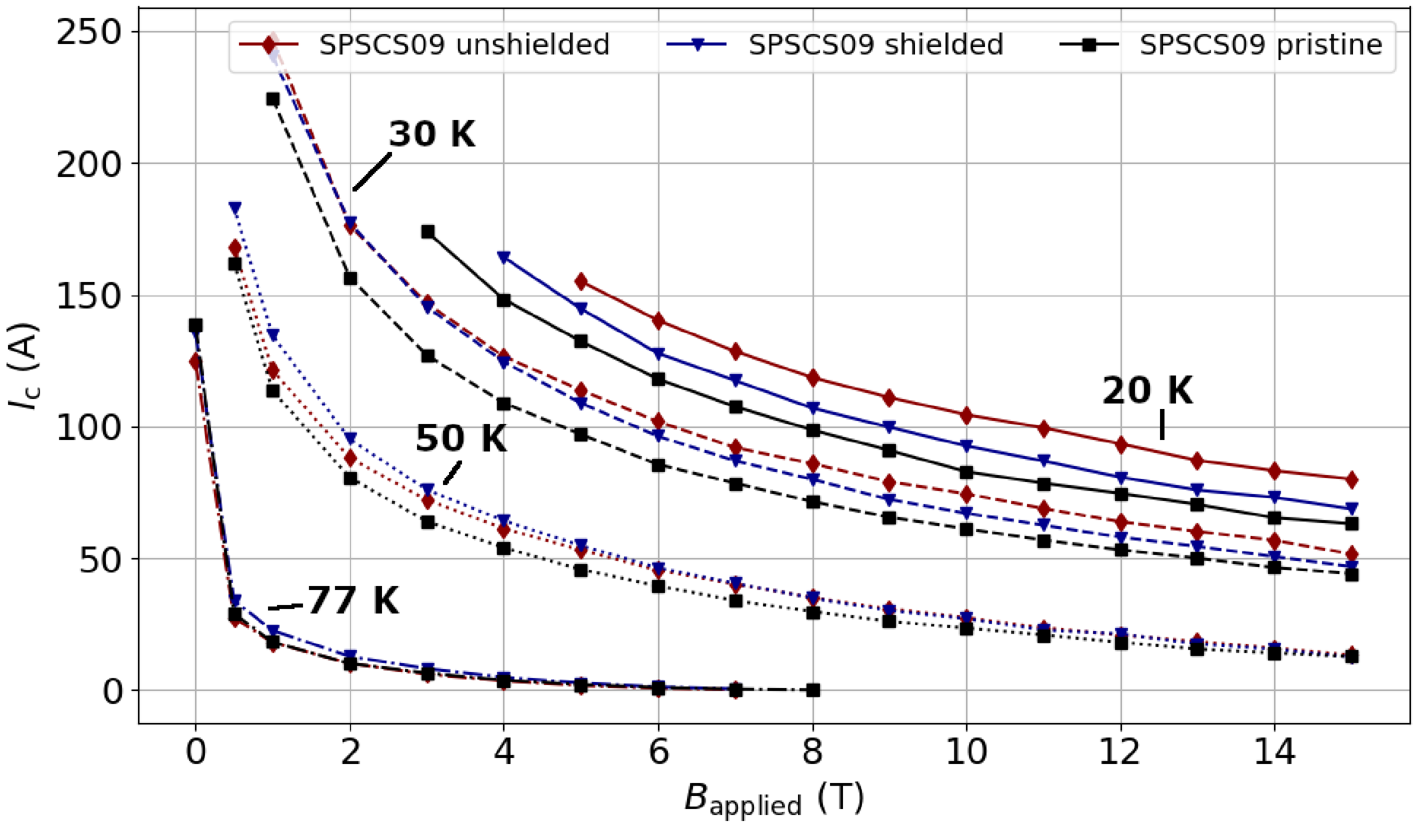
Influence of thermal neutrons: J_c



- 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 Gd point defects: J_c



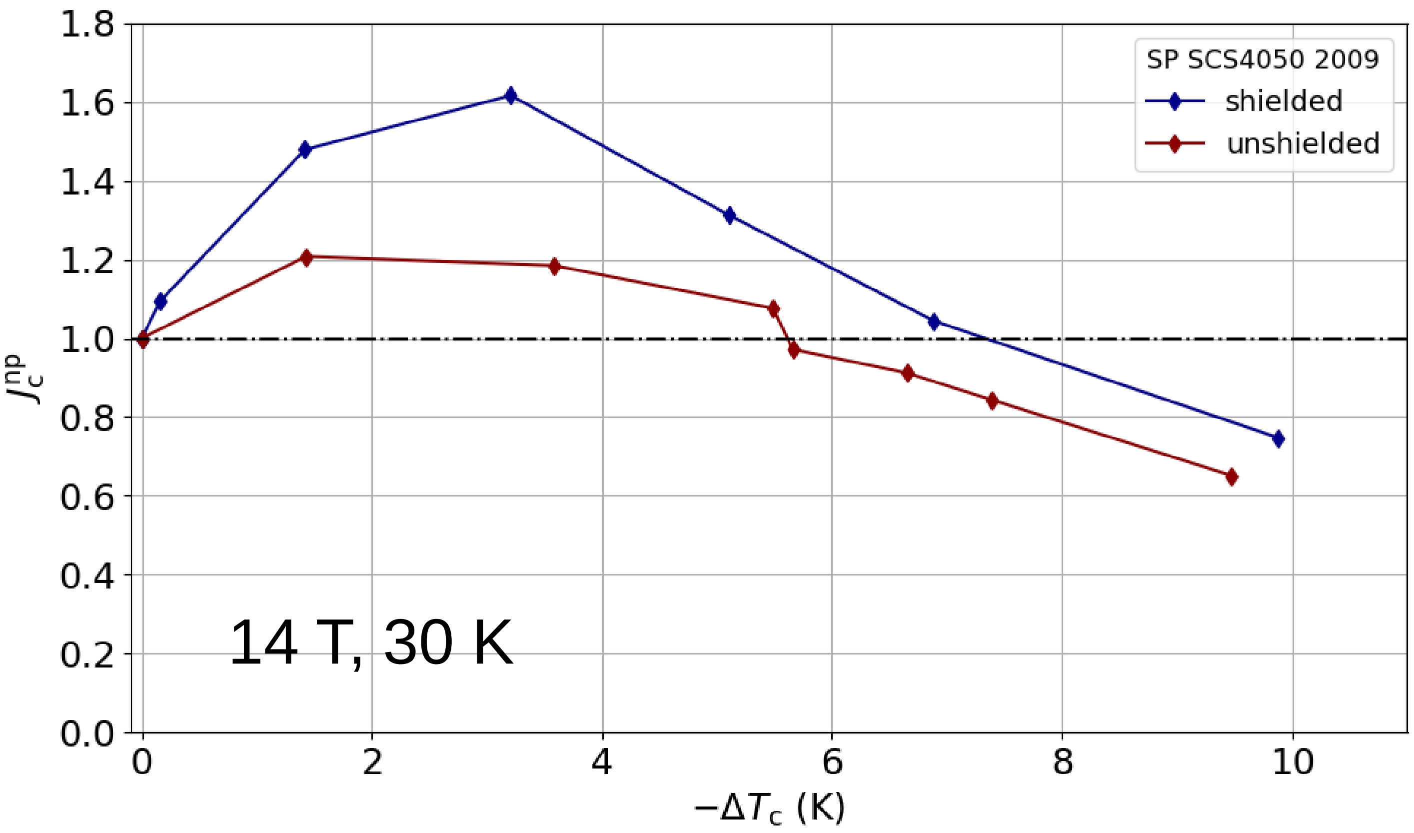
irradiated to similar fluence

unshielded sample:

- smaller T_c
- similar density of large defects
- larger J_c at low temperatures and high fields
- lower J_c at low fields (crossover)

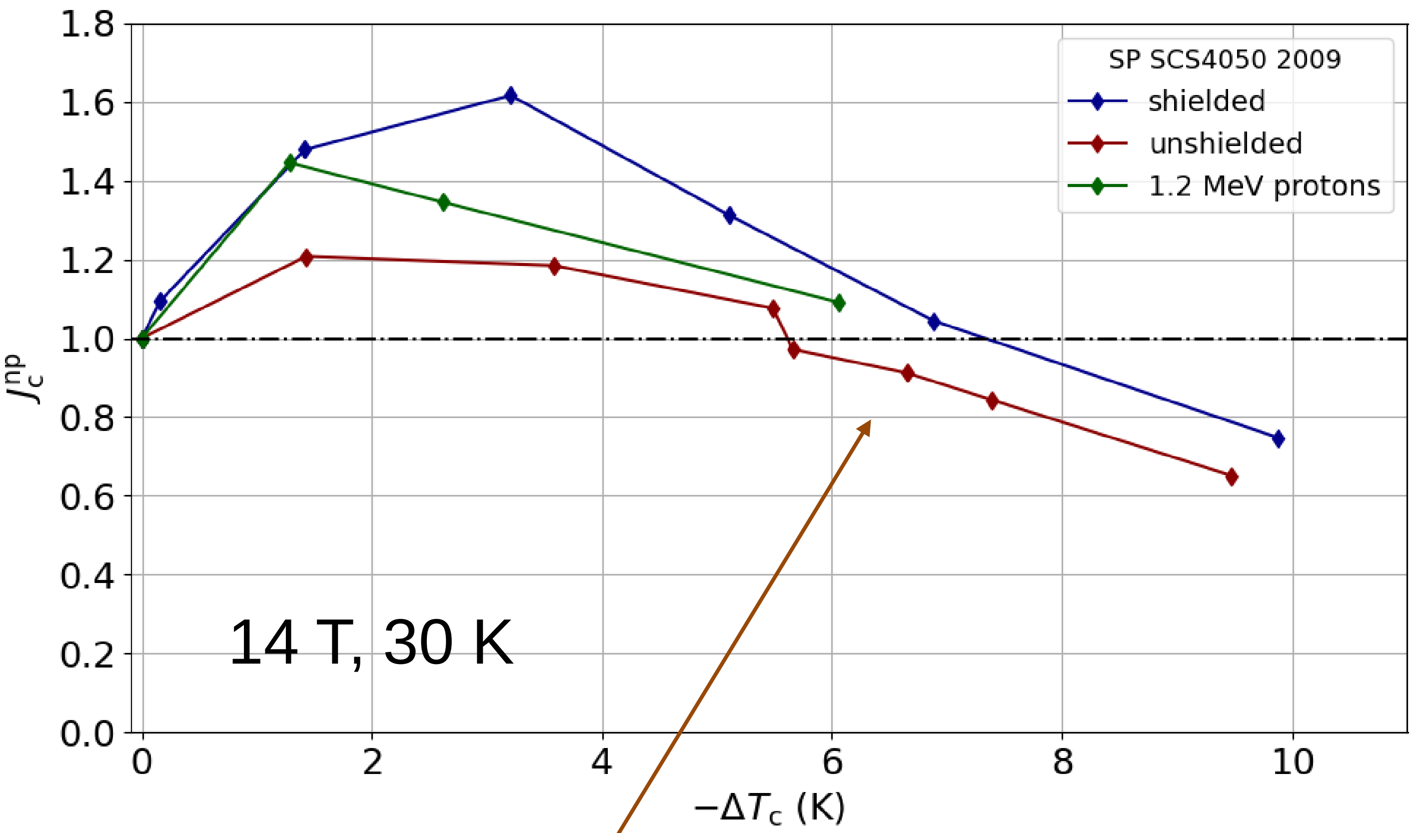
Displaced Gd atoms lead to efficient pinning below about 30 K!

Influence of thermal neutrons: J_c



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

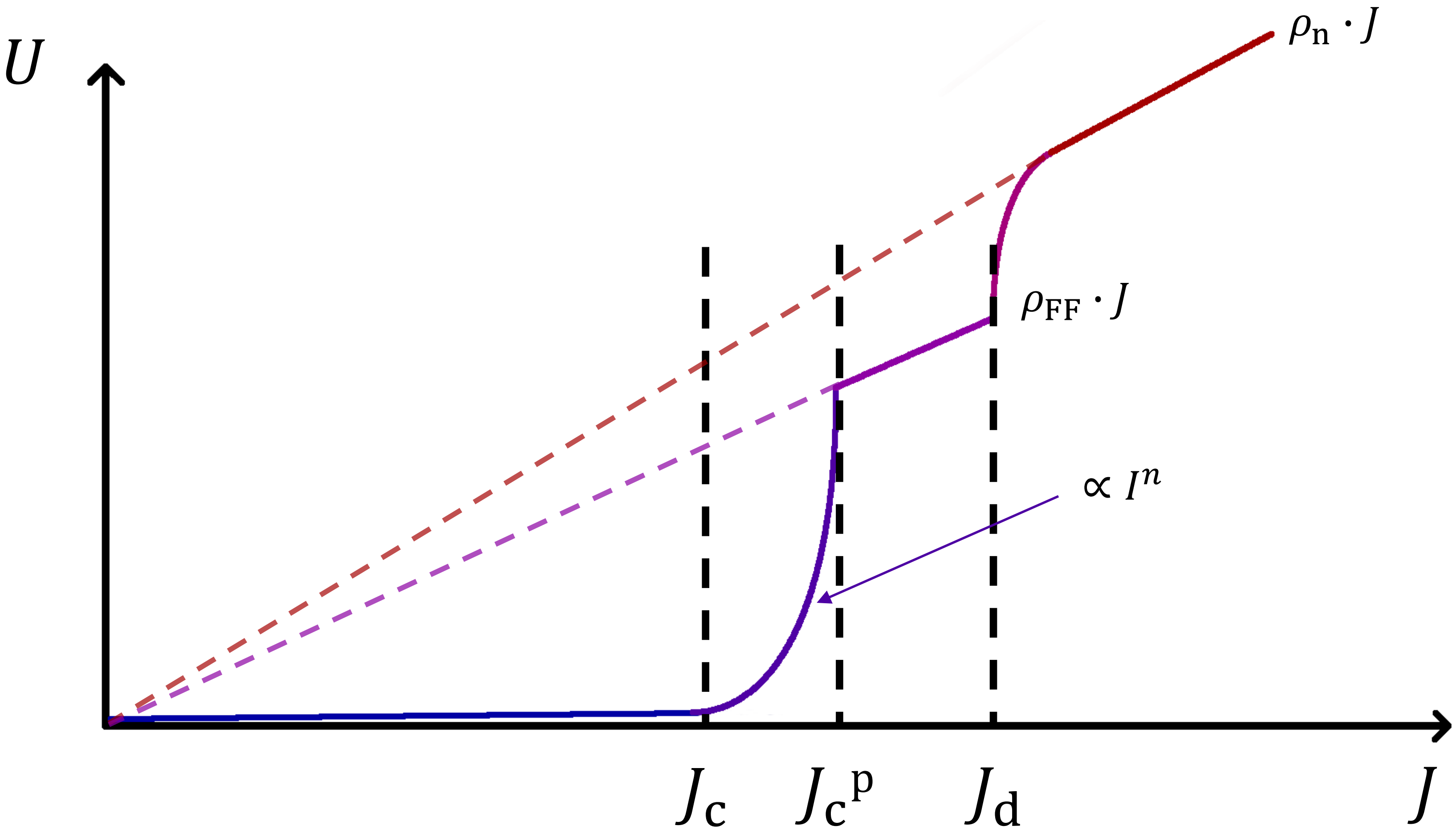
Influence of thermal neutrons: J_c



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

Why does J_c decrease so uniformally?

Influence of radiation on the I-V curve

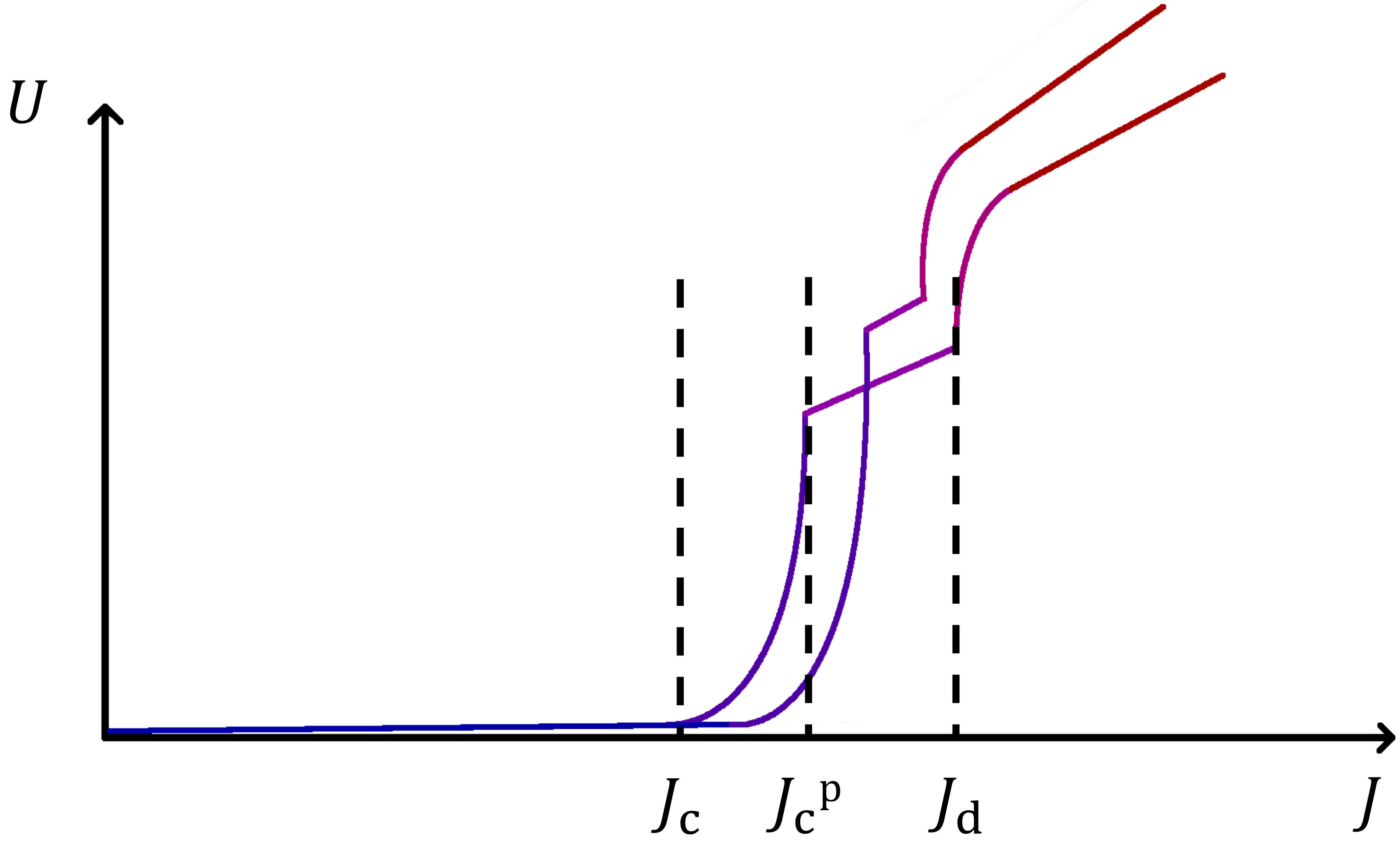


$$\boxed{j_c^p = \eta \, j_d}$$

Influence of radiation on the I-V curve

assumption: n … almost constant

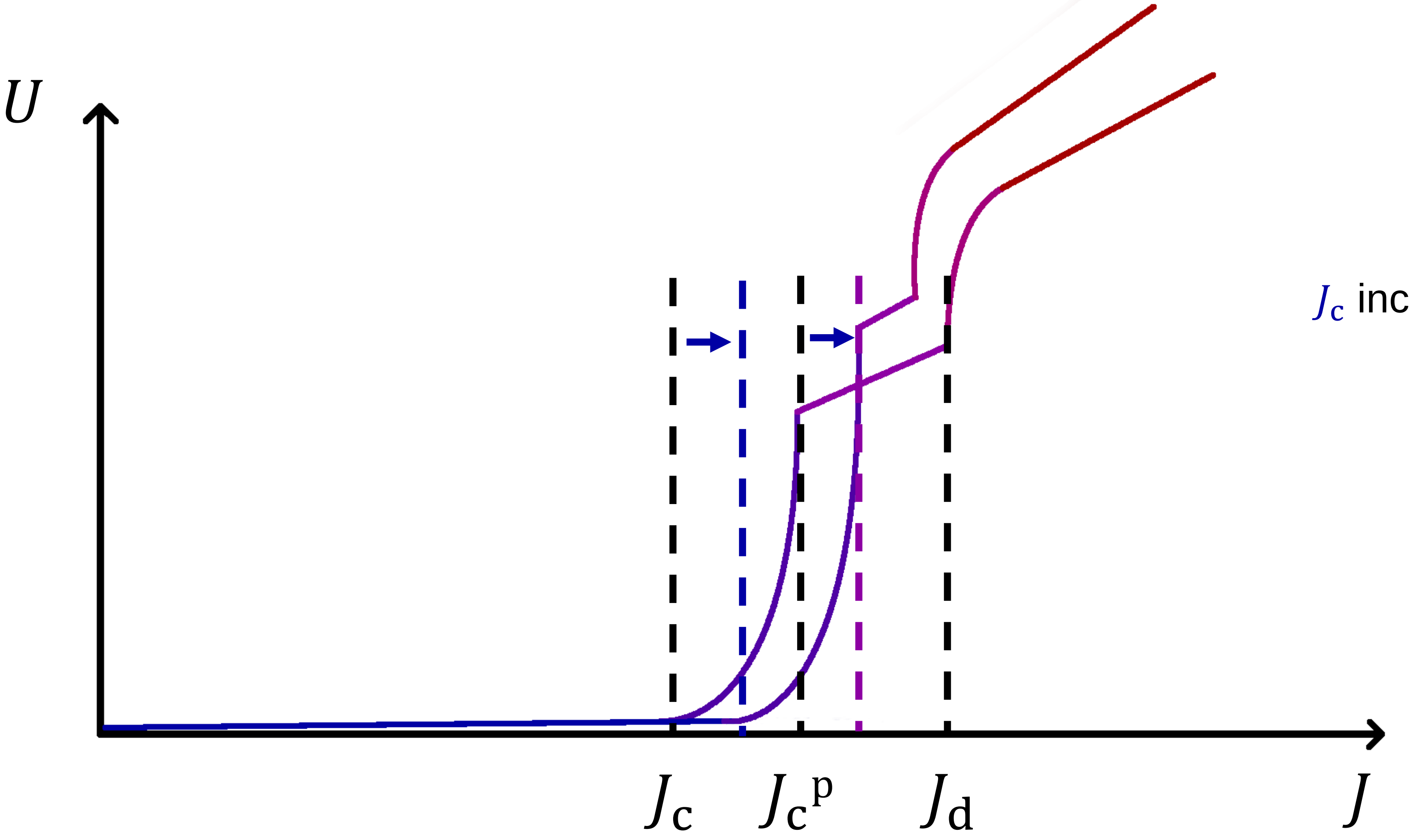
$$\boxed{j_c^p = \eta \, j_d}$$



Influence of radiation on the I-V curve

assumption: n … almost constant

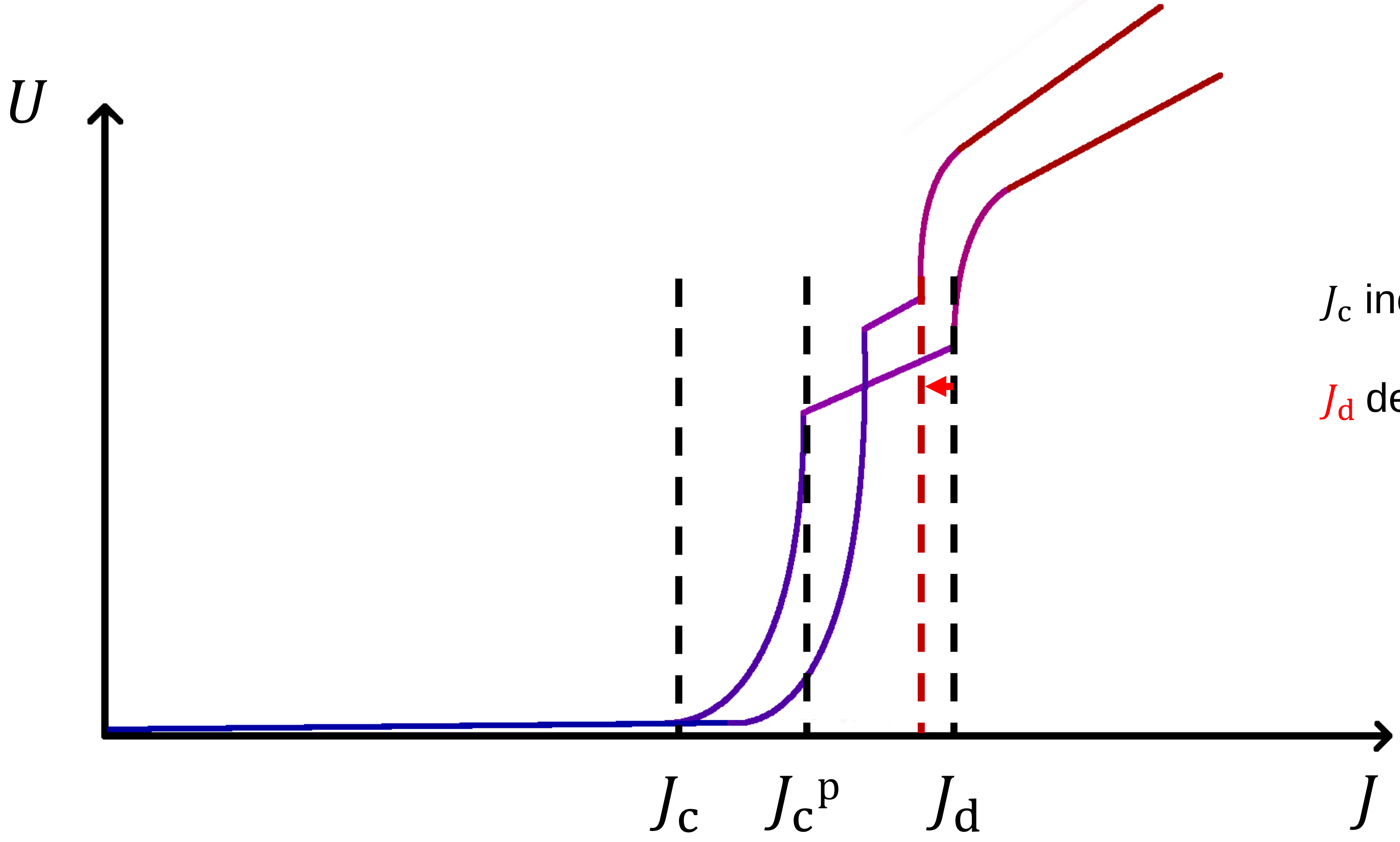
$$\boxed{j_{\mathrm{c}}^{\mathrm{p}} = \eta\, j_{\mathrm{d}}}$$



J_{c} increases with J_c^p

Influence of radiation on the I-V curve

assumption: n … almost constant



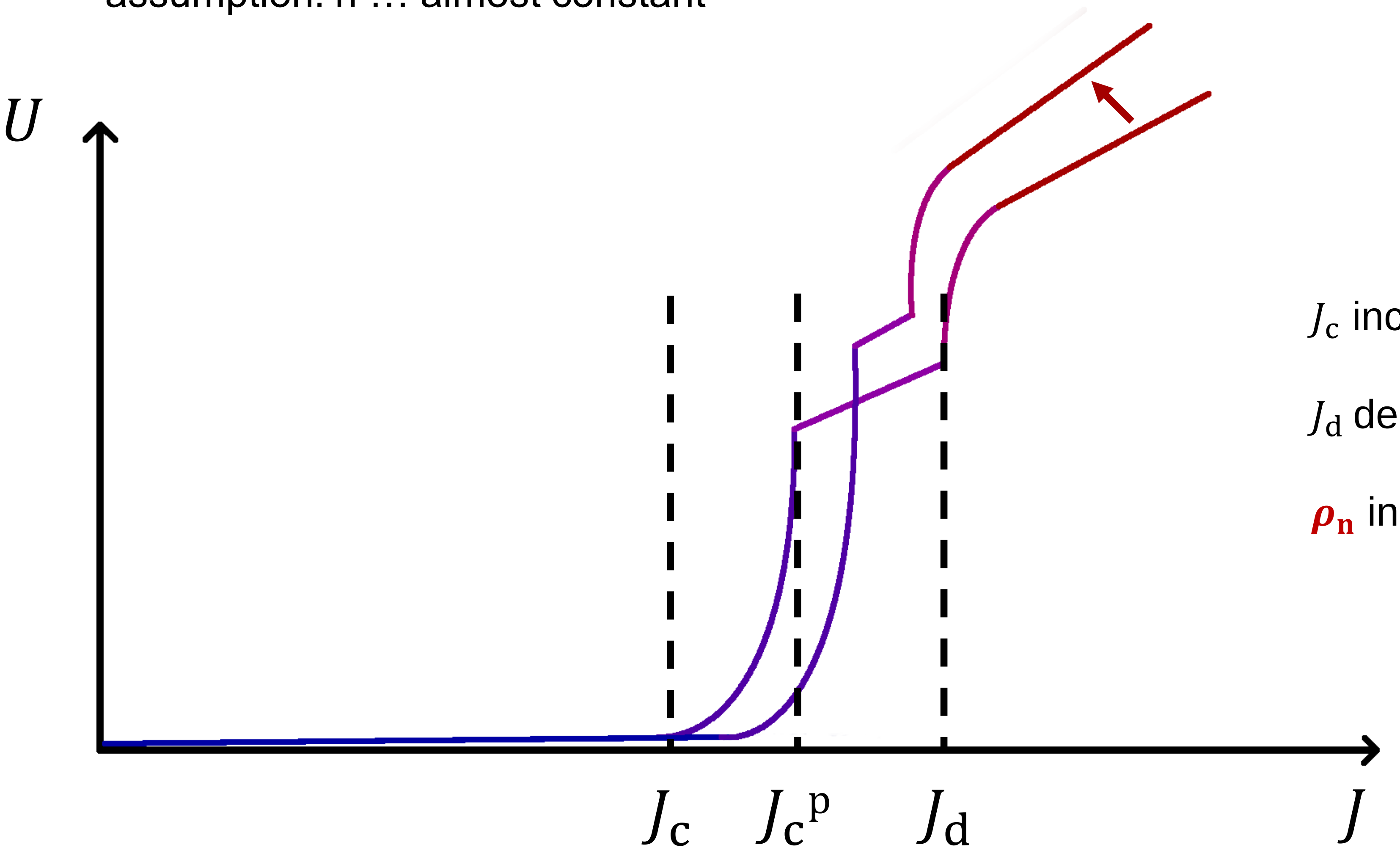
$$j_c^p = \eta \, j_d$$

J_c increases with J_c^p

J_d decreases

Influence of radiation on the I-V curve

assumption: n … almost constant

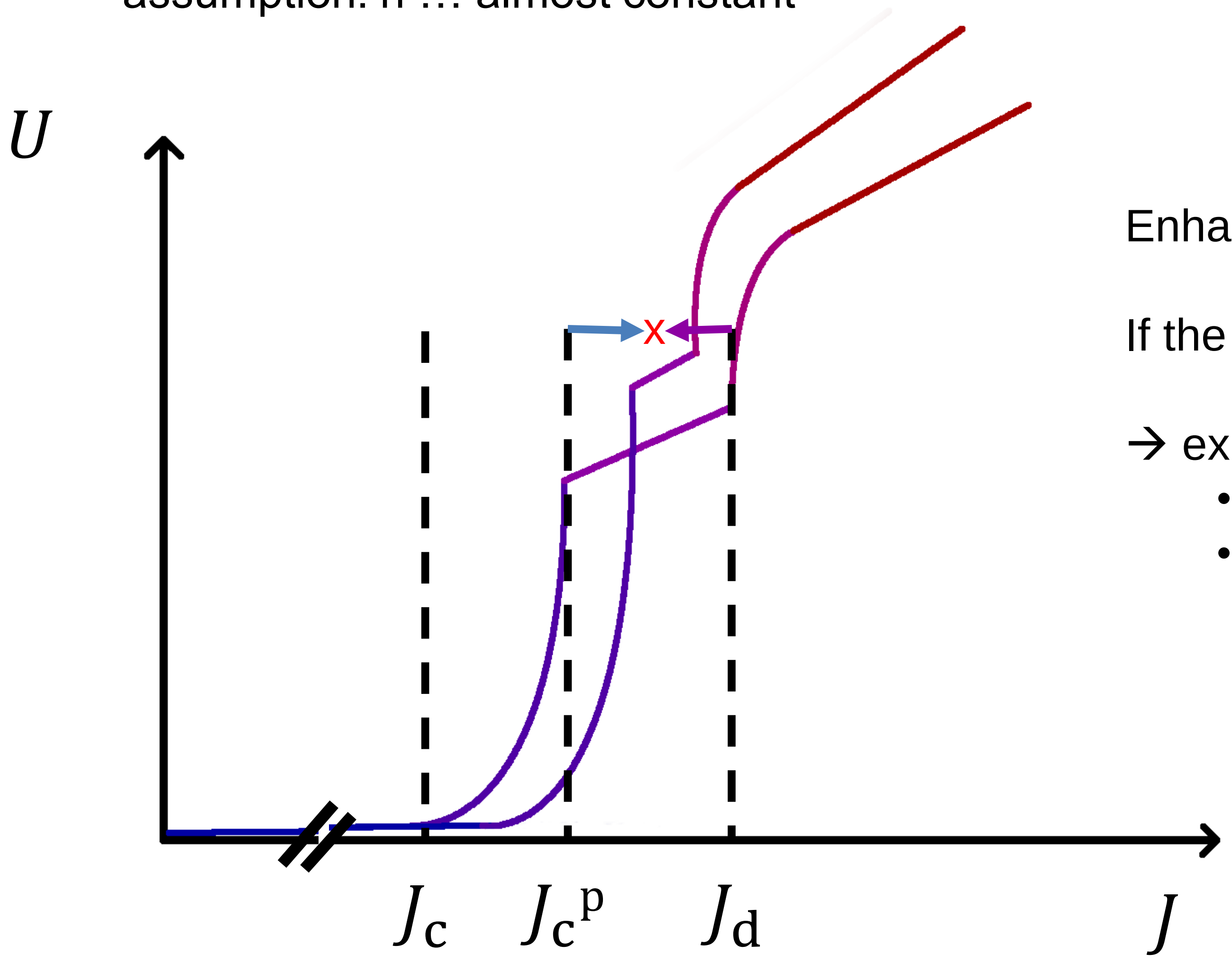


$$\boxed{j_\mathrm{c}^\mathrm{p} = \eta\, j_\mathrm{d}}$$

$$\left.\begin{array}{l} J_\mathrm{c} \text{ increases with } J_c^p \\ J_\mathrm{d} \text{ decreases} \\ \boldsymbol{\rho}_\mathbf{n} \text{ increases} \end{array}\right] \boldsymbol{\eta} \text{ increases}$$

Influence of radiation on the I-V curve

assumption: n … almost constant



Enhancing of η can increase J_c only so much

If the degradation of J_d is too high – J_c decreases

→ explains (?) uniformity

- in maximum position
- and slope of degrading branch

Conclusions

- pair breaking by scattering decreases T_c linearly with neutron fluence (defect density).
  - T_c is an efficient disorder parameter.
  - Indicating a decrease in superfluid density.
  - linear decrease of J_c at high fluences?

- decrease of J_c at high defect density

  driven by the decrease of superfluid density

- point-like disorder as displaced Gd-atoms enhances pinning at low temperatures (< ~30 K) and high magnetic fields

- competition between enhanced pinning and reduced superfluid density

Discussion

- irradiation studies. What is important?
  - understanding the degradation mechanism
  - correlation with introduced defects
  - irradiation experiments with other particles?
  - mitigation strategy
    - radiation robust conductors?
    - annealing
    - shielding (expensive)
    - new materials?

  - irradiation at cryogenic temperatures