J_c degradation in CCs for fusion magnets by small defects and its mitigation

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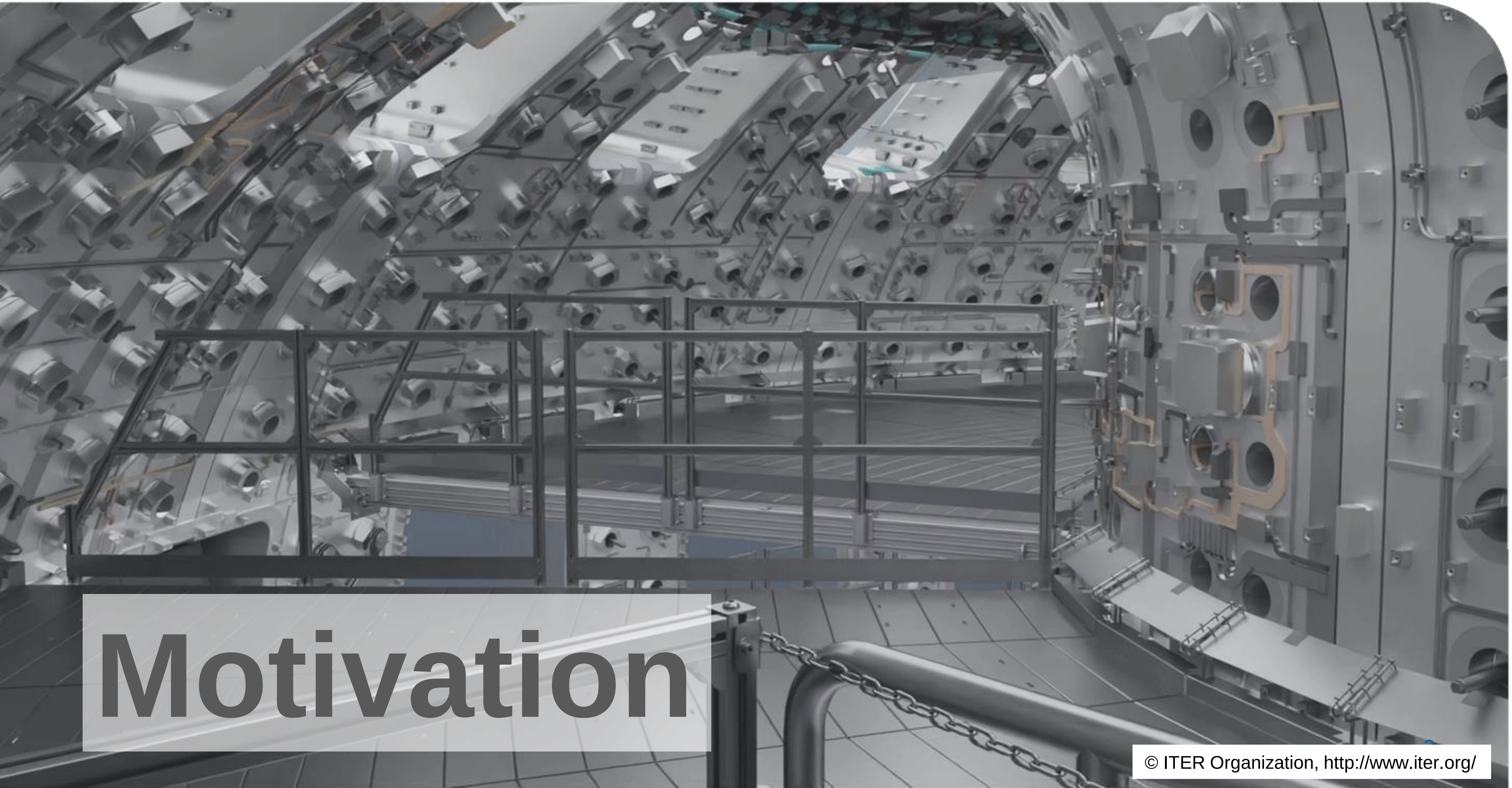

Motivation

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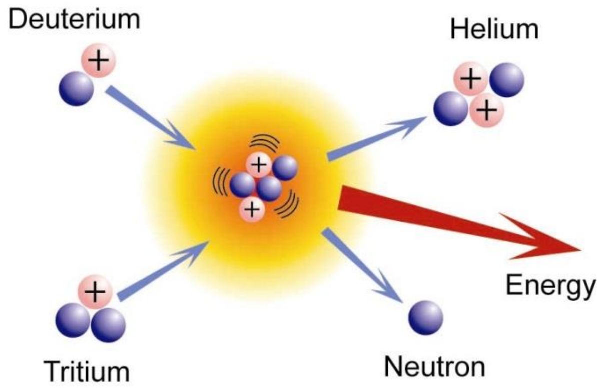
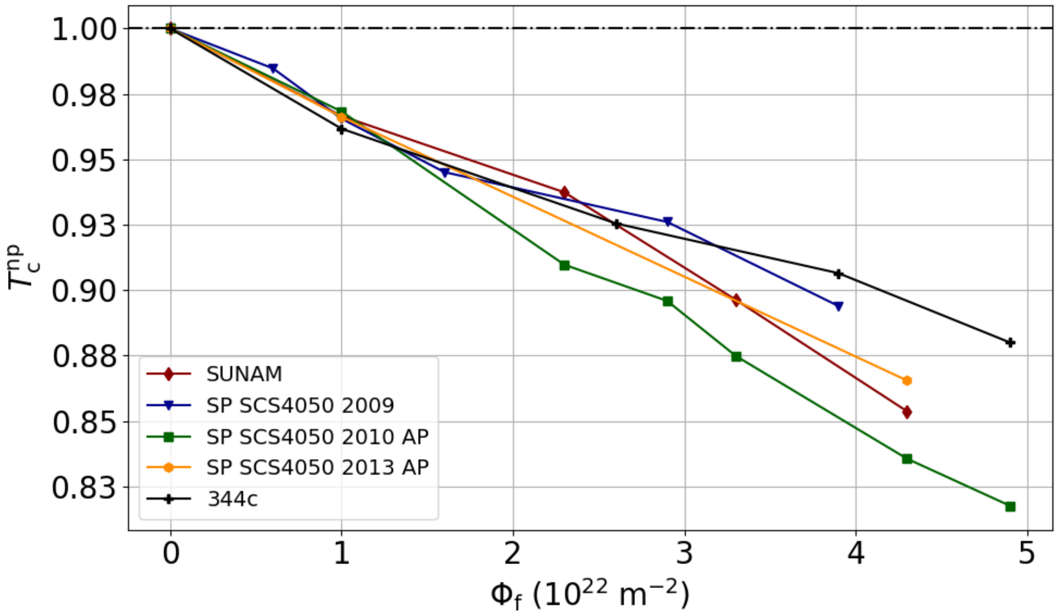
Motivation

Nuclear Fusion



Normalized transition temperature



Fast neutron fluence

small fraction of the fusion neutrons reach the magnets

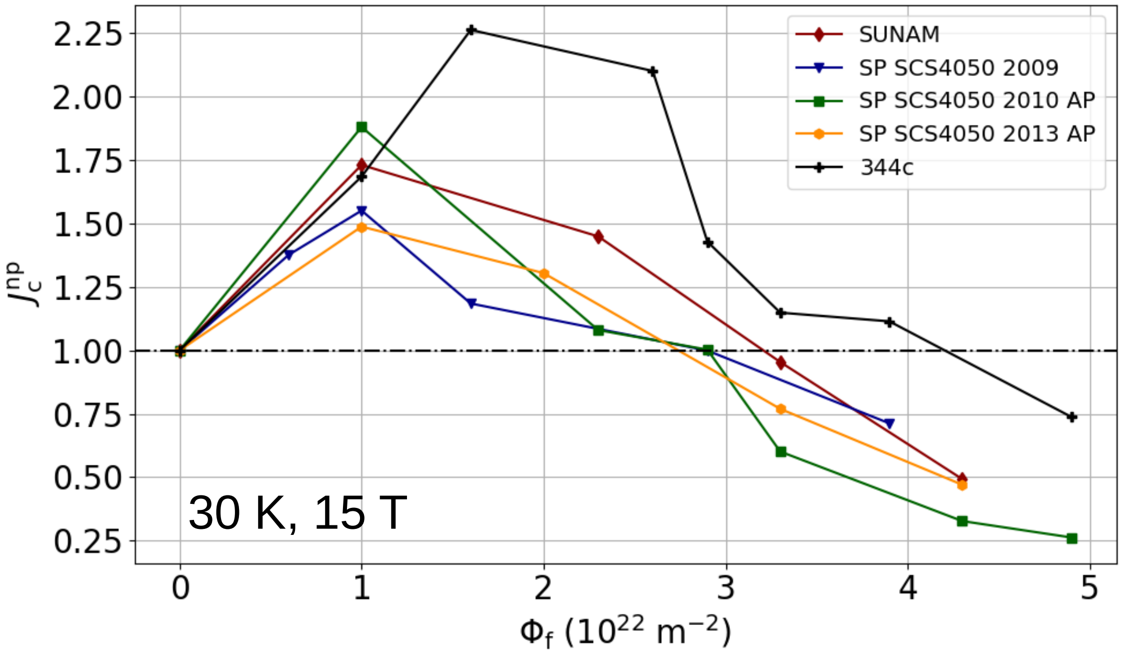
scattering is pair breaking in d-wave superconductors

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

Motivation

introduced defects
- enhance pinning
- increase scattering of charge carriers

Normalized critical current



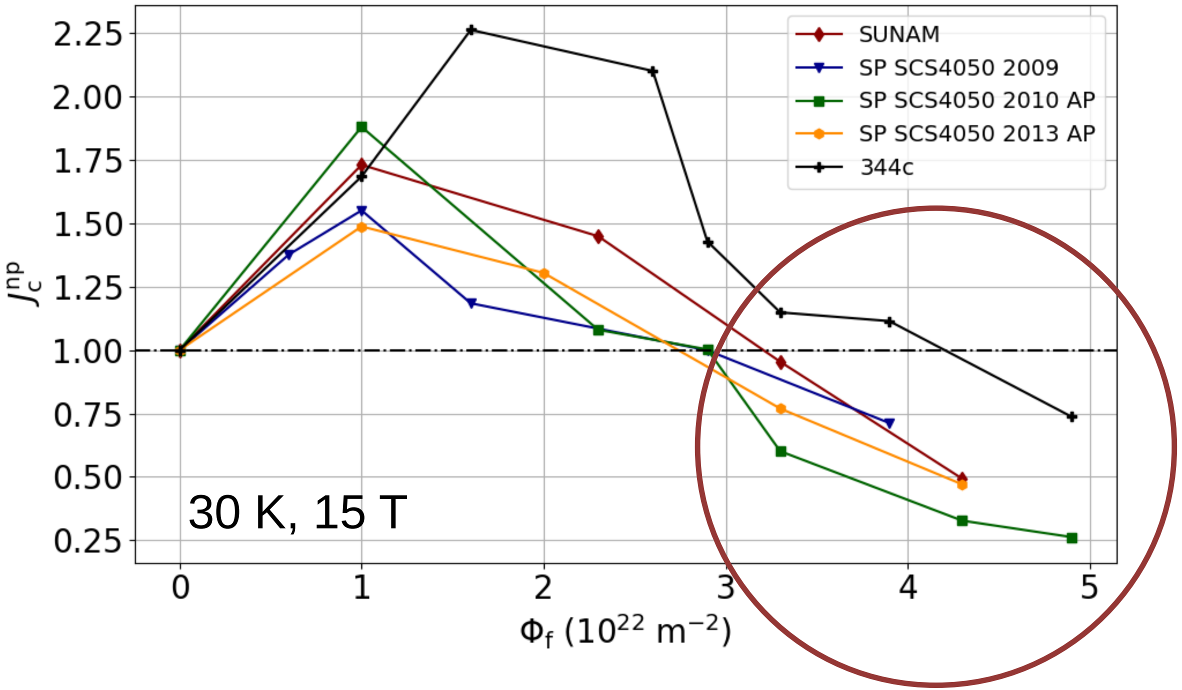
Fast neutron fluence

Motivation

introduced defects

- enhance pinning
- increase scattering of charge carriers

Normalized critical current



Fast neutron fluence

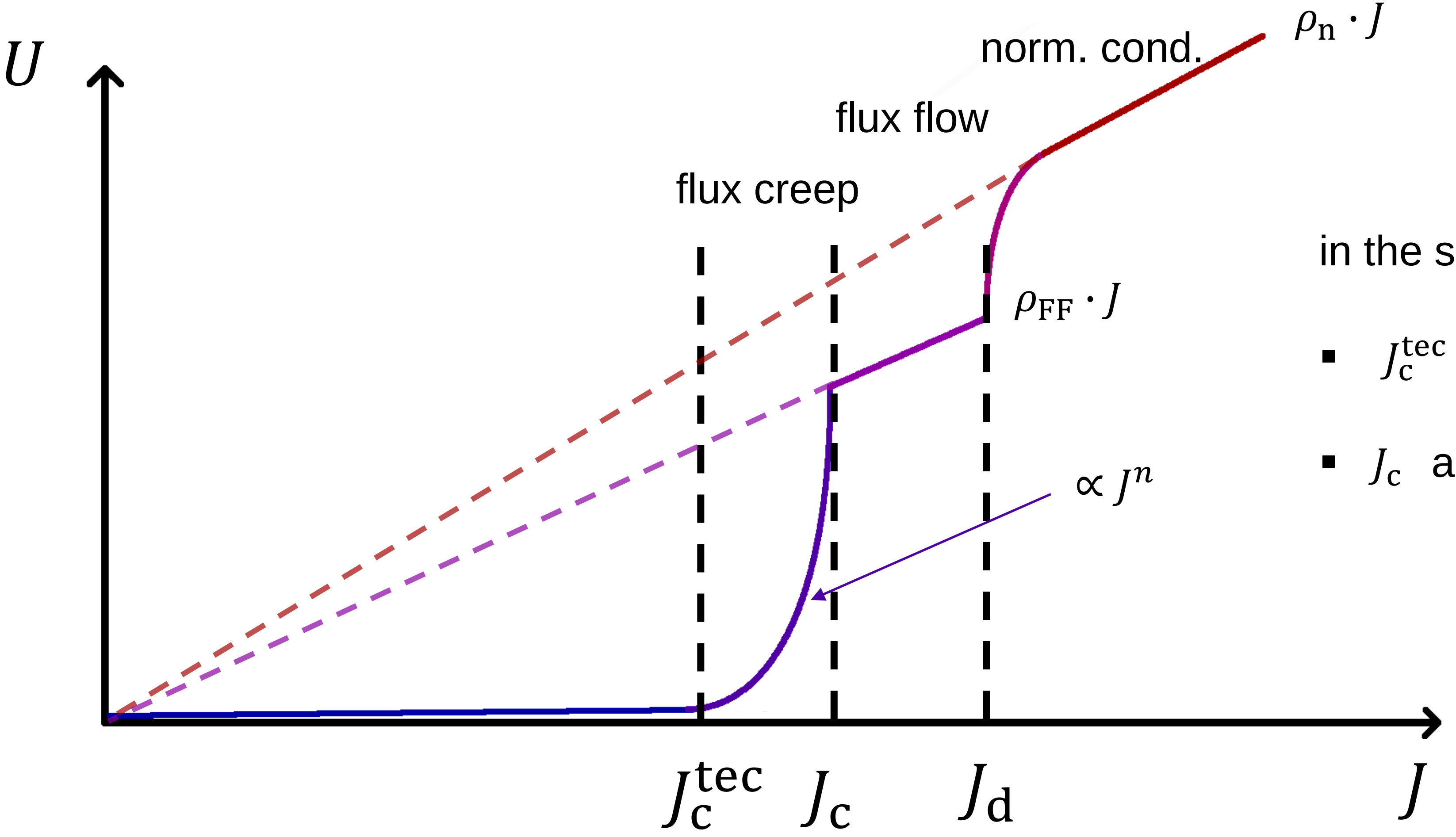
What drives the degradation?

How can we mitigate this?

Experimental

Transport current measurements

Concerning J_c

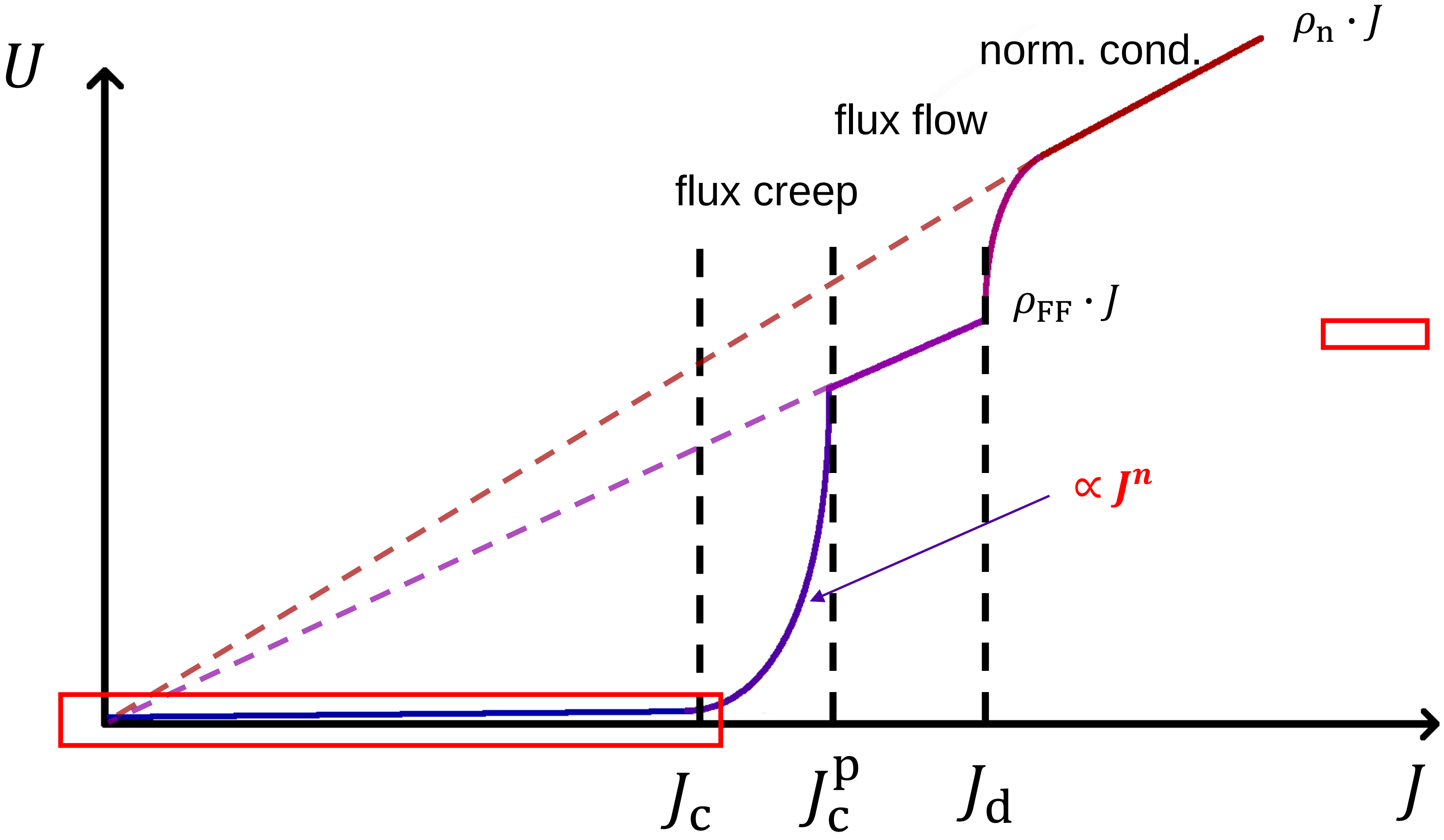


in the scope of this presentation:

- J_c^{tec} denoted as J_c
- J_c as J_c^p

Transport current measurements

Concerning J_c

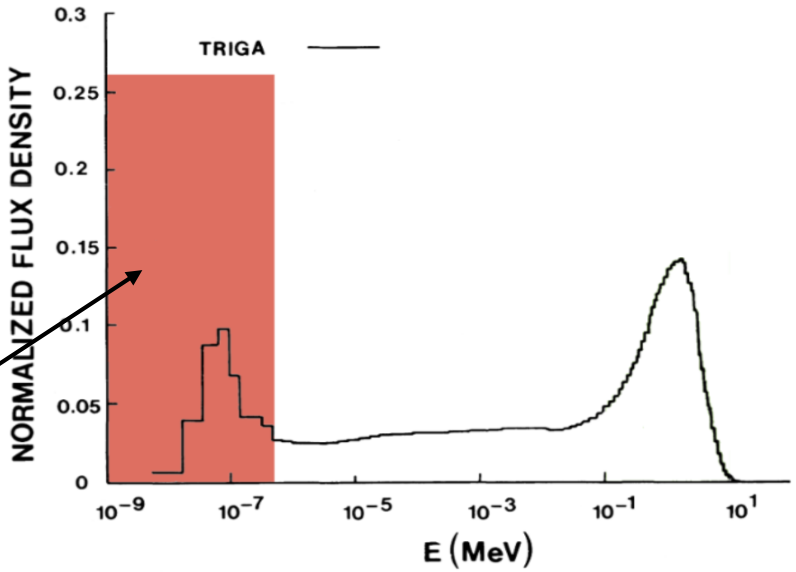


▭ typical transport current measurement

Neutron Irradiation

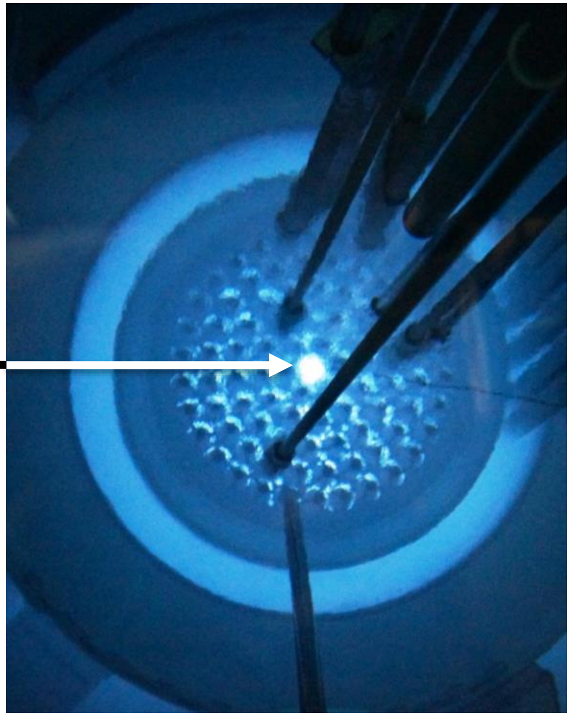
TRIGA MARK II at TU Wien

- 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



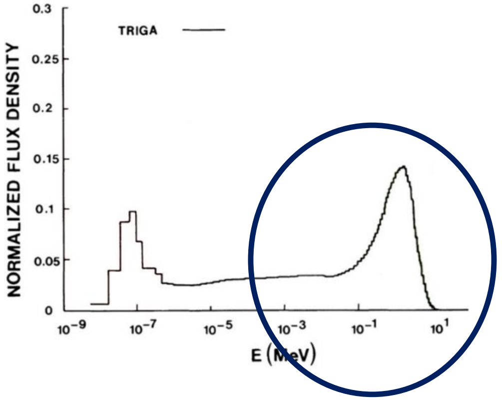
May be screened by cadmium foil

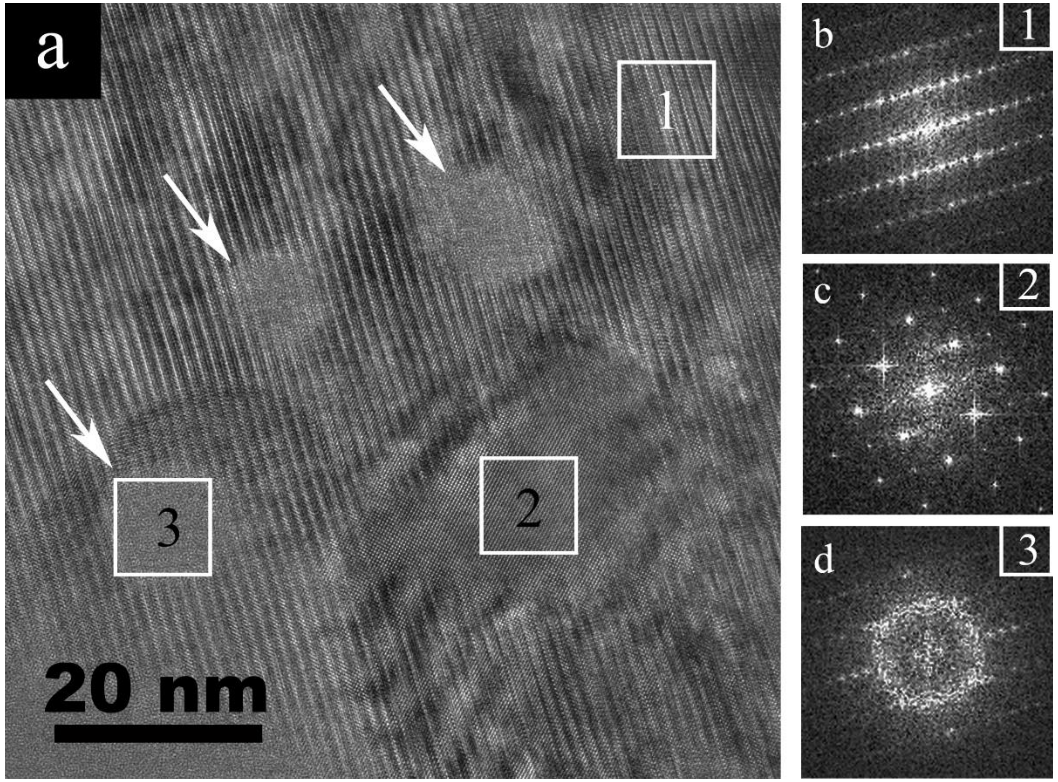
< 70 C at sample



TRIGA MARK II – experimental fission reactor

Volume defects





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,
See: *Analysing neutron radiation damage in YBa2Cu3O7–x high-temperature superconductor tapes,*
Department of Materials, University of Oxford, Oxford, UK

And the rest?

Neutron Irradiation

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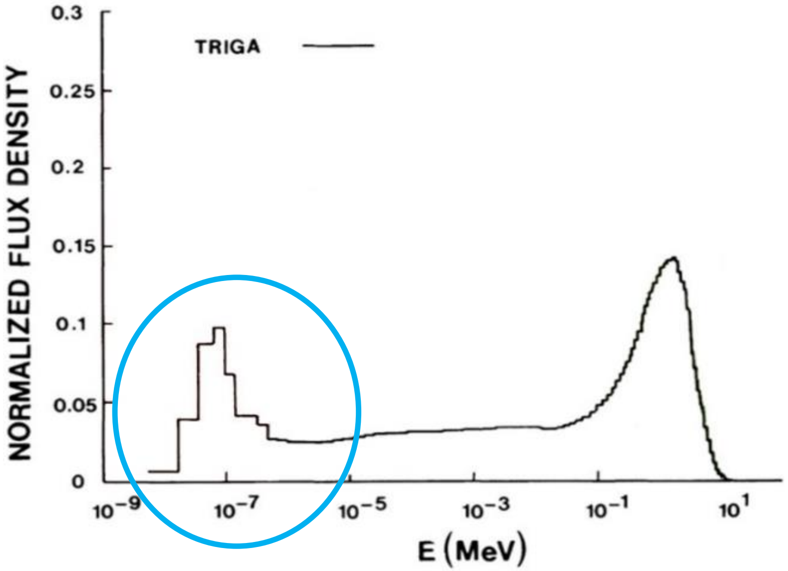
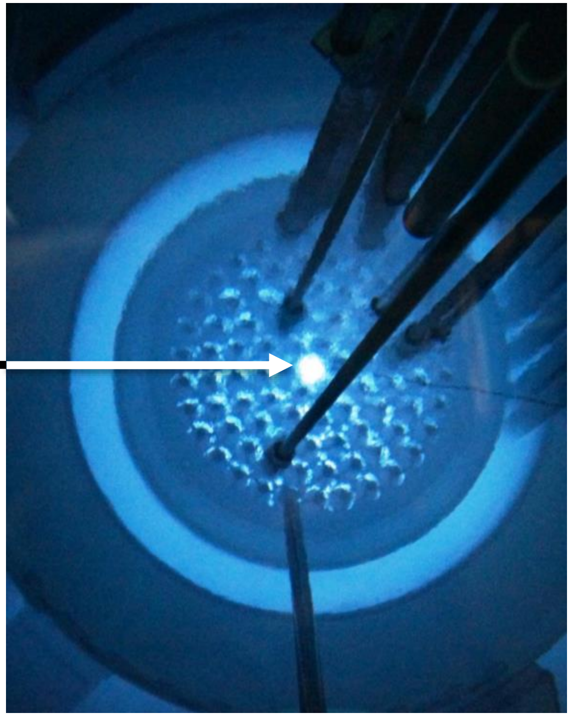
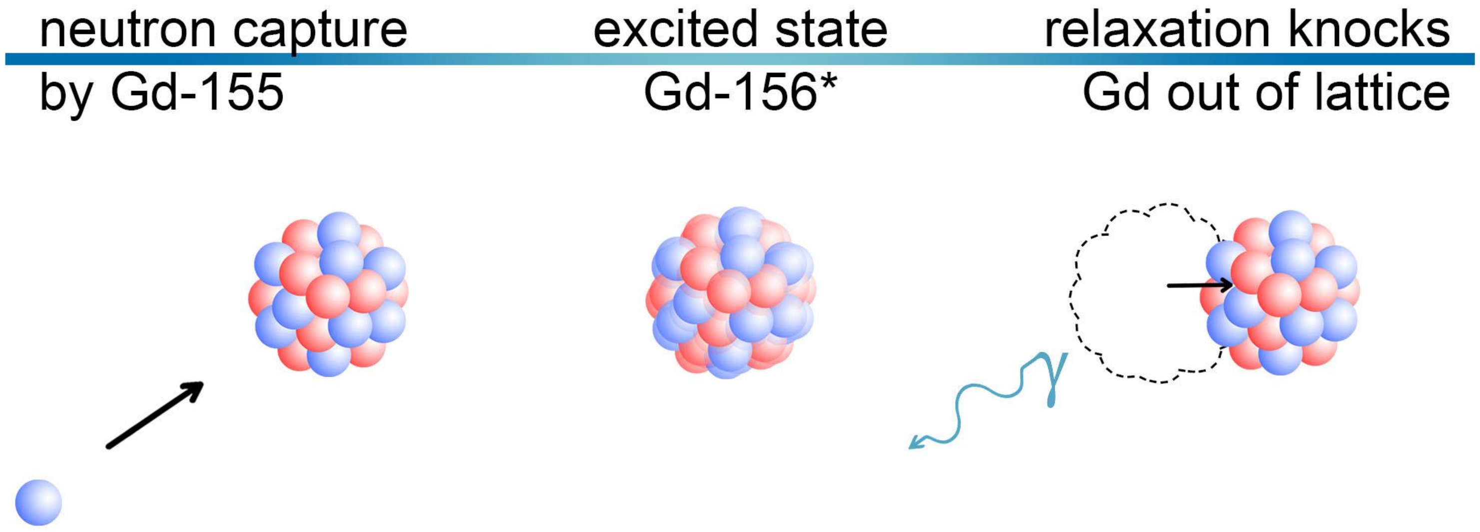


< 70 C at sample



TRIGA MARK II – experimental fission reactor

Point-like defects – Frenkel Pairs

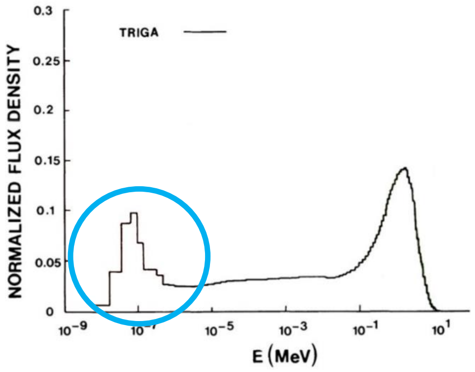


neutron capture by Gd-155

excited state Gd-156*

relaxation knocks Gd out of lattice

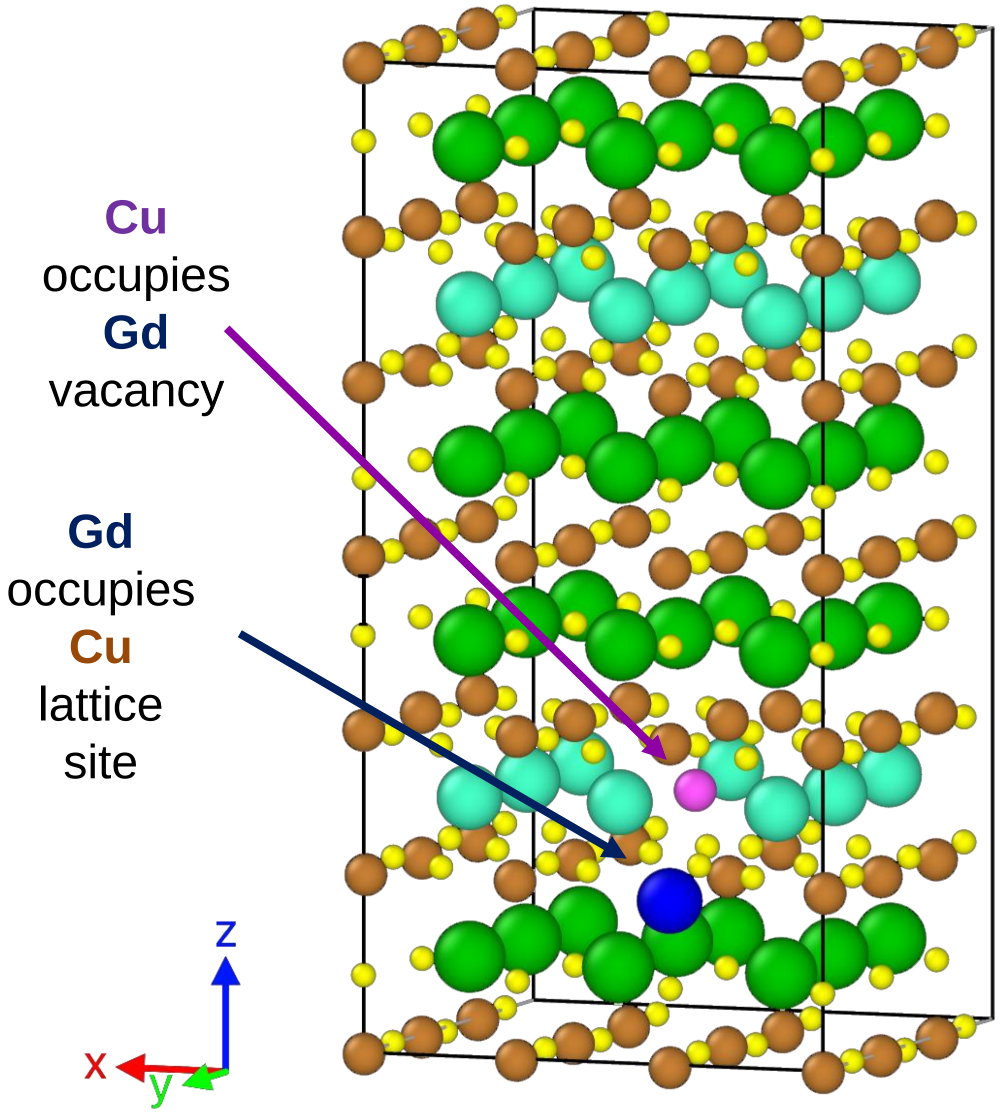
K.E. Sickafus et al., Phys. Rev. B **46** (1992) 11862



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

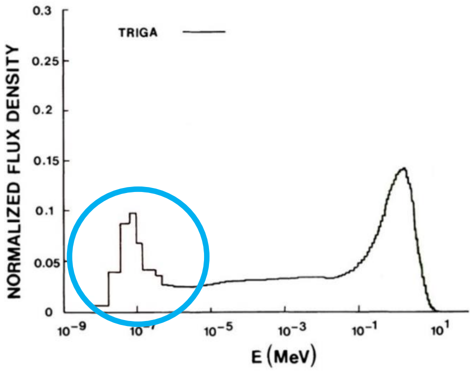
- very high defect densities achievable
- add to fast neutron induced defects

Point-like defects – Frenkel Pairs



Cu occupies **Gd** vacancy

Gd occupies **Cu** lattice site



- picture shows one of the potential defects
- distortion in the **Oxygen** lattice very localized
- very stable distortions of the lattice

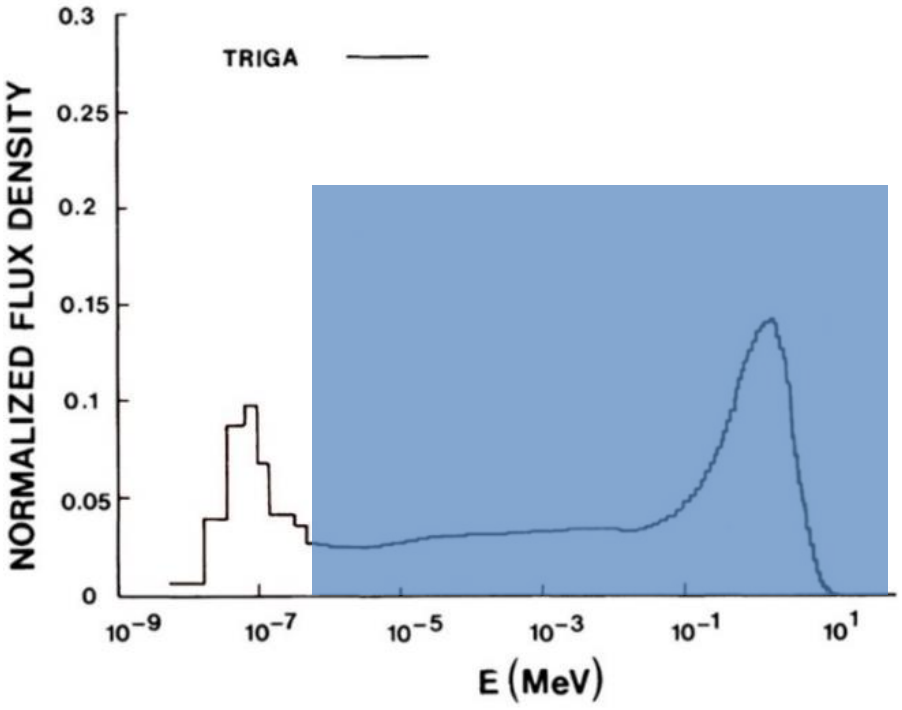
*data acquired by MDS using YBCO potential

Two samples – two colours

Sample Type:
SuperPower 2009 no APCs

Sample size:
27 x 4 mm

Material:
GdBCO



—	irradiated with Cd shielding	**shielded**	**E > 0.55 eV**
	irradiated without Cd shielding	**unshielded**	**full fission spectrum**

Two samples – two colours

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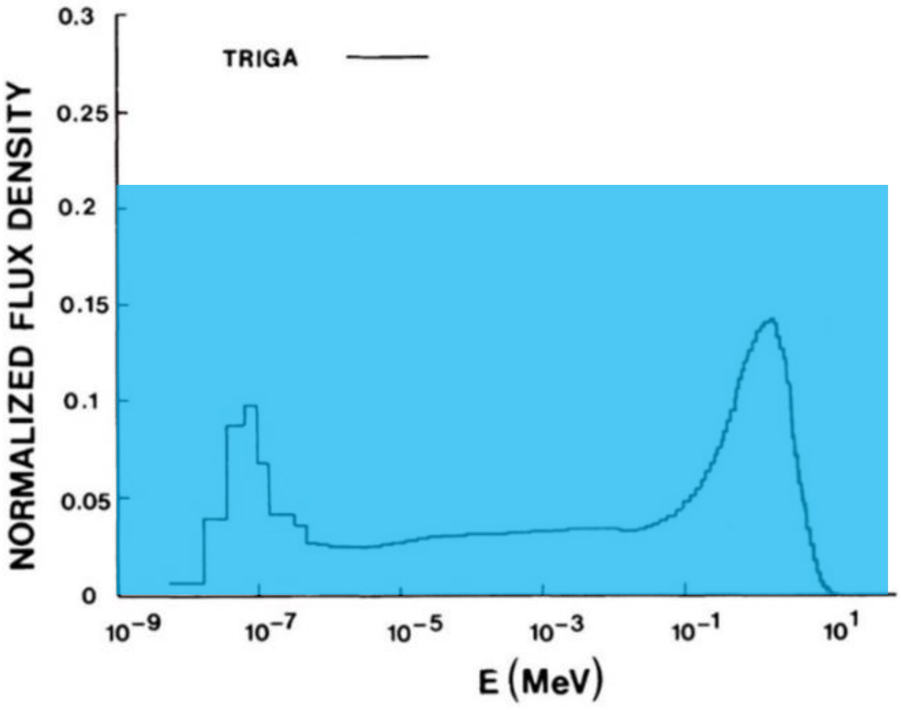
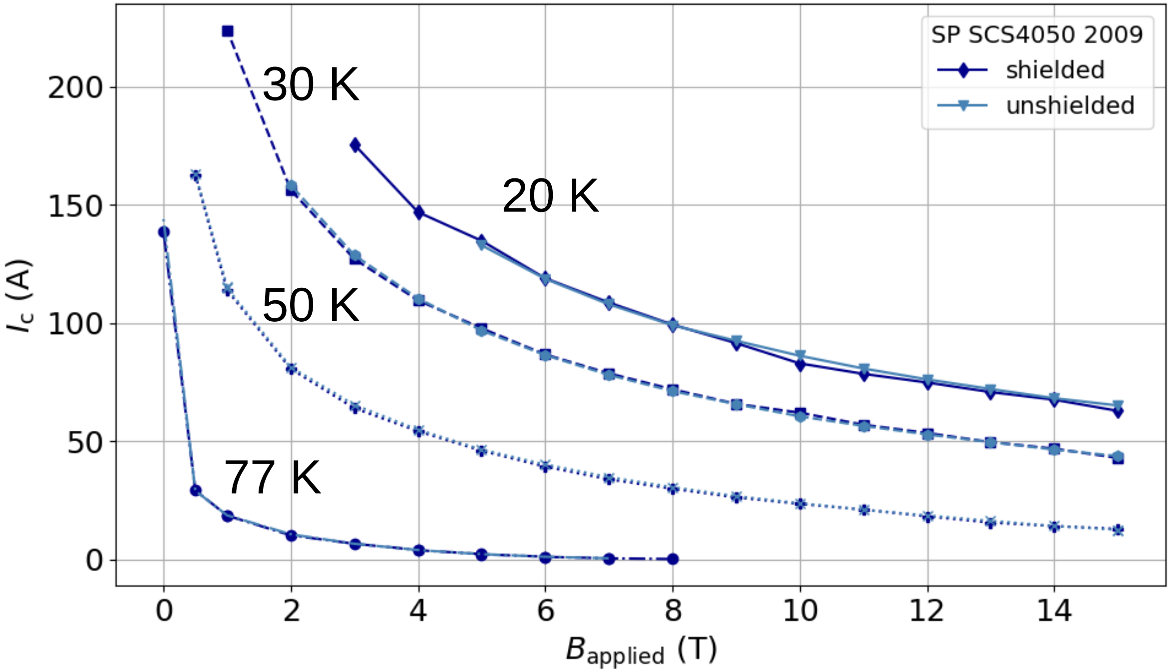


▬	irradiated with Cd shielding	**shielded**	**E > 0.55 eV**
▬	irradiated without Cd shielding	**unshielded**	**full fission spectrum**

Two nearly identical samples

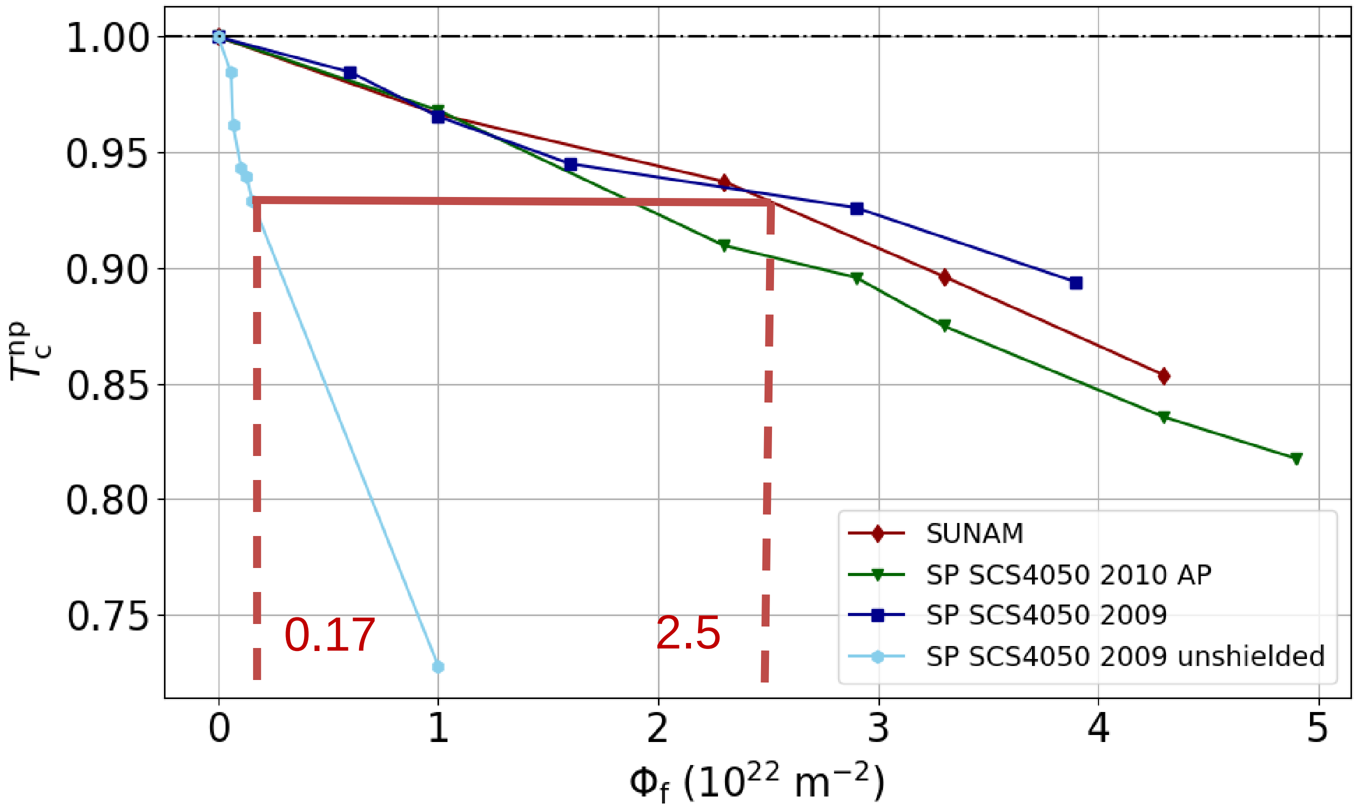
pristine I_c



- practically identical $I_c(B,T)$ behavior
- same pristine T_c = 93 K
- sample homogeneity checked by hall scans at self-field & 77 K

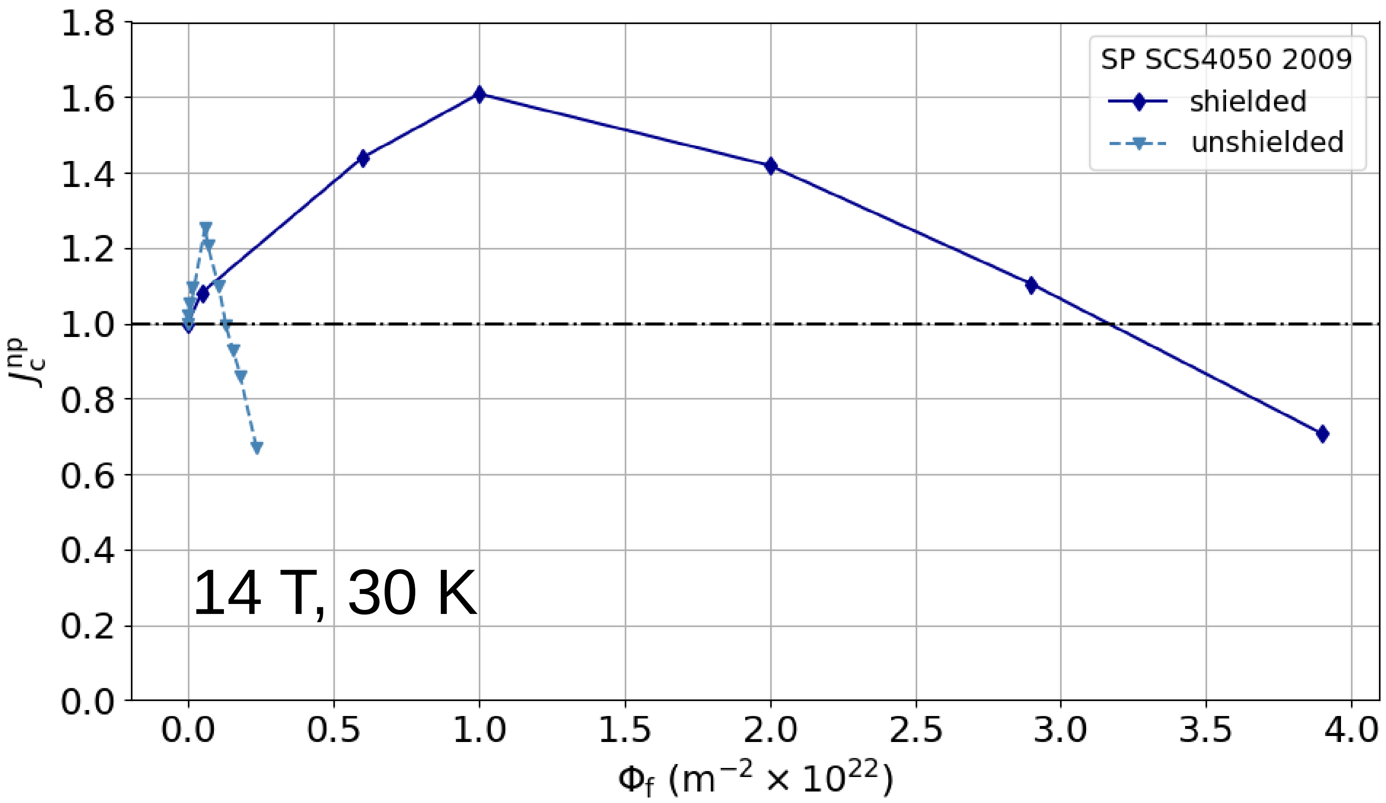
Results

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 steeper

Influence of defect size

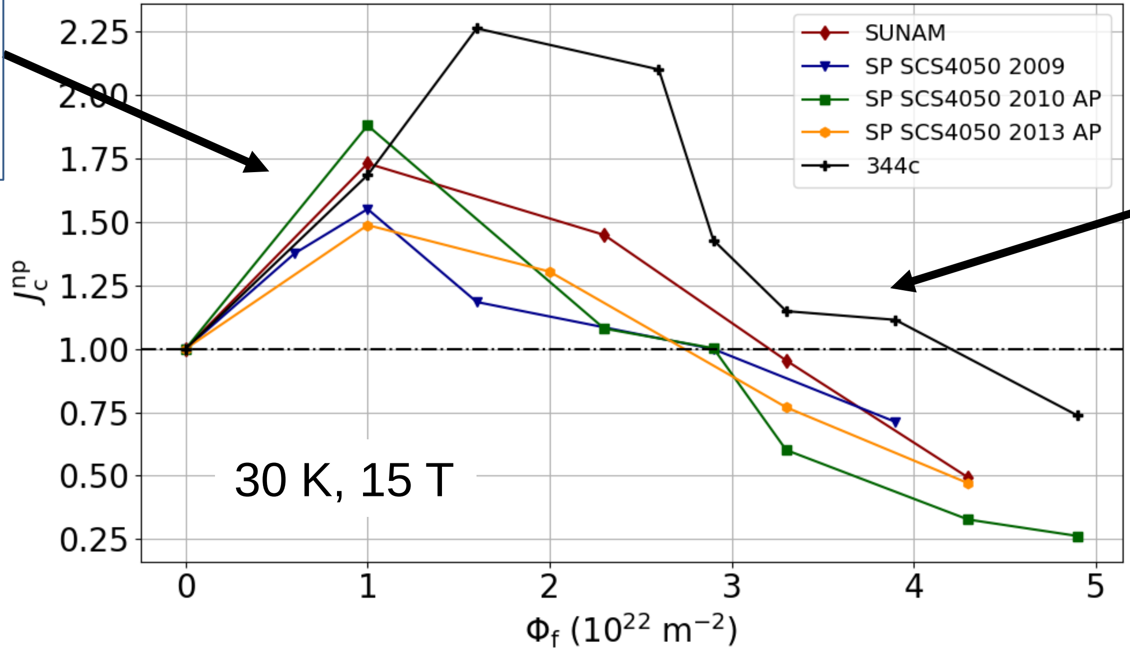
high scattering rate - high density of **small** defects

size of pinning centers match the superconducting coherence length: **large** defects

large defects

⬇

improved flux pinning



small defects

⬇

reduced superfluid density

Perfect world!

Influence of defect size

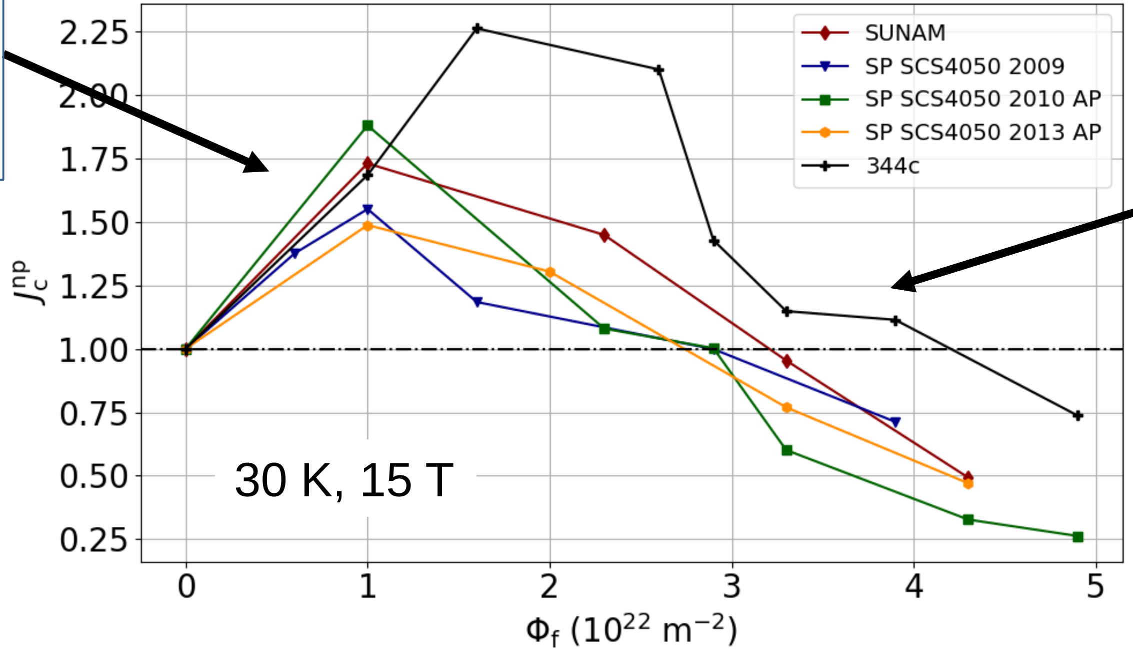
high scattering rate - high density of **small** defects

size of pinning centers match the superconducting coherence length: **large** defects

large defects

⬇

improved flux pinning



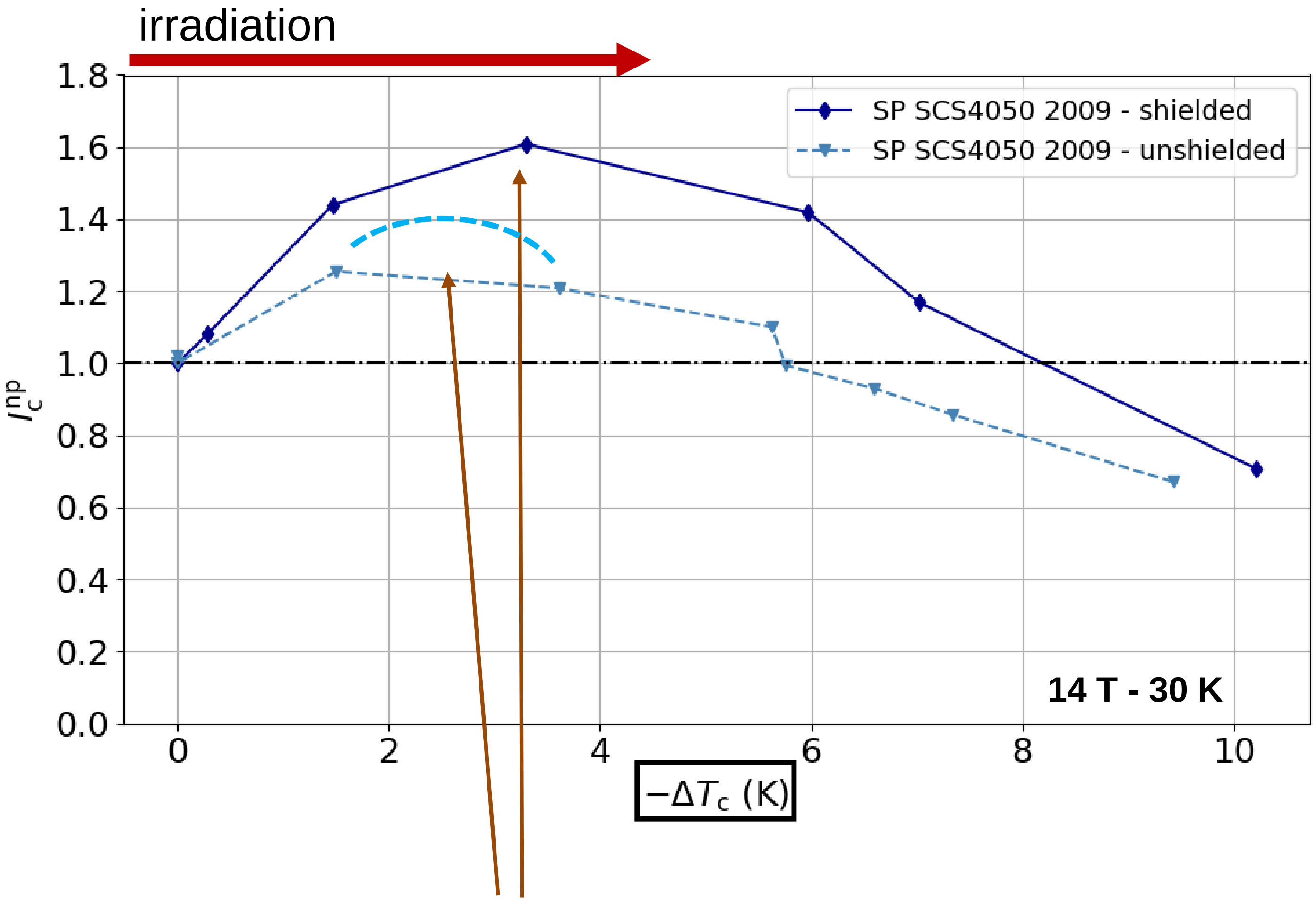
small defects

⬇

reduced superfluid density

Oversimplified picture?

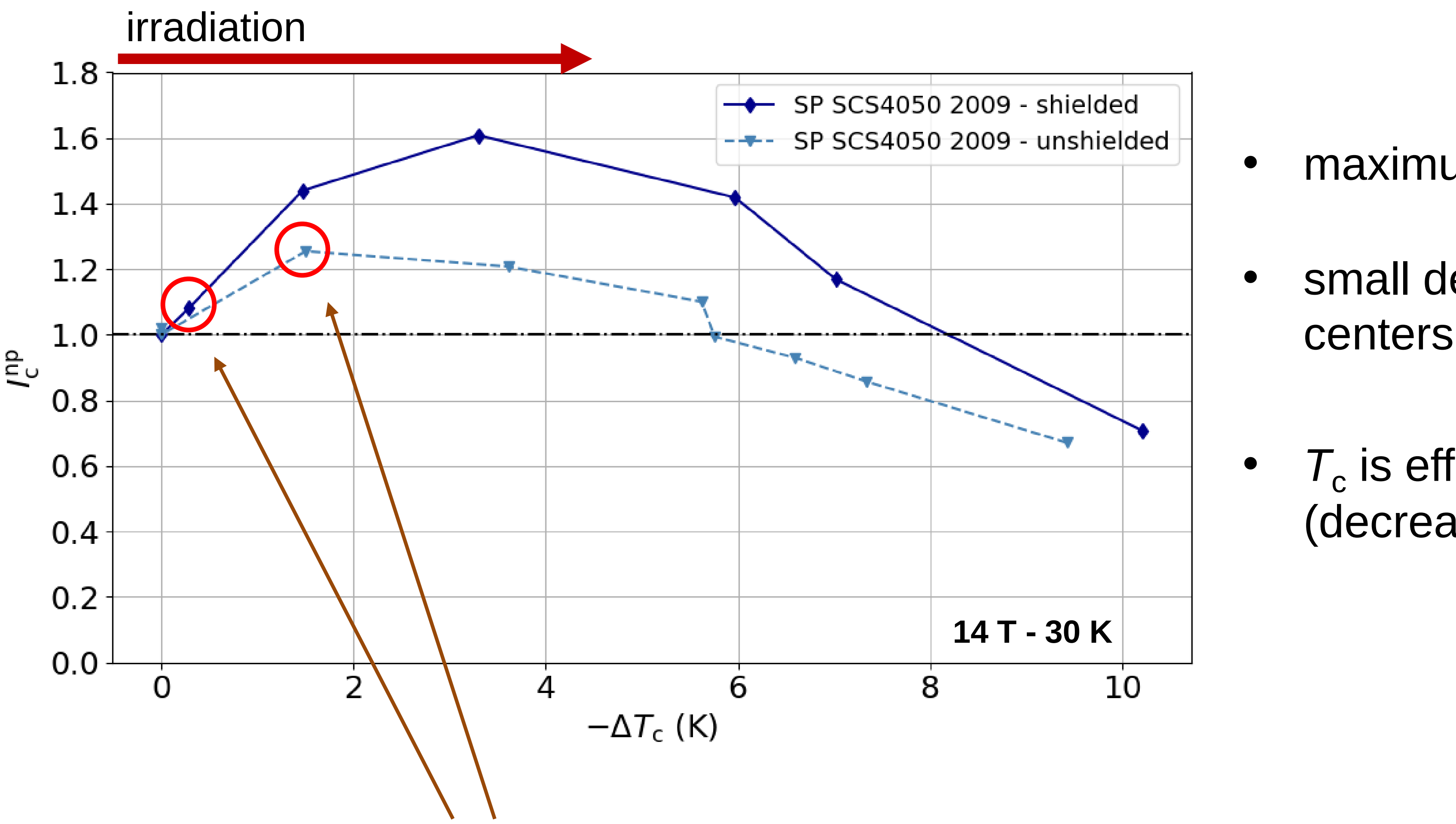
Influence of thermal neutrons: J_c



- maximum occurs at similar T_c
- small defects are efficient pinning centers < 40 K!
- T_c is efficient disorder parameter (decrease of superfluid density)

Does J_c increase due to large fast neutron induced defects?

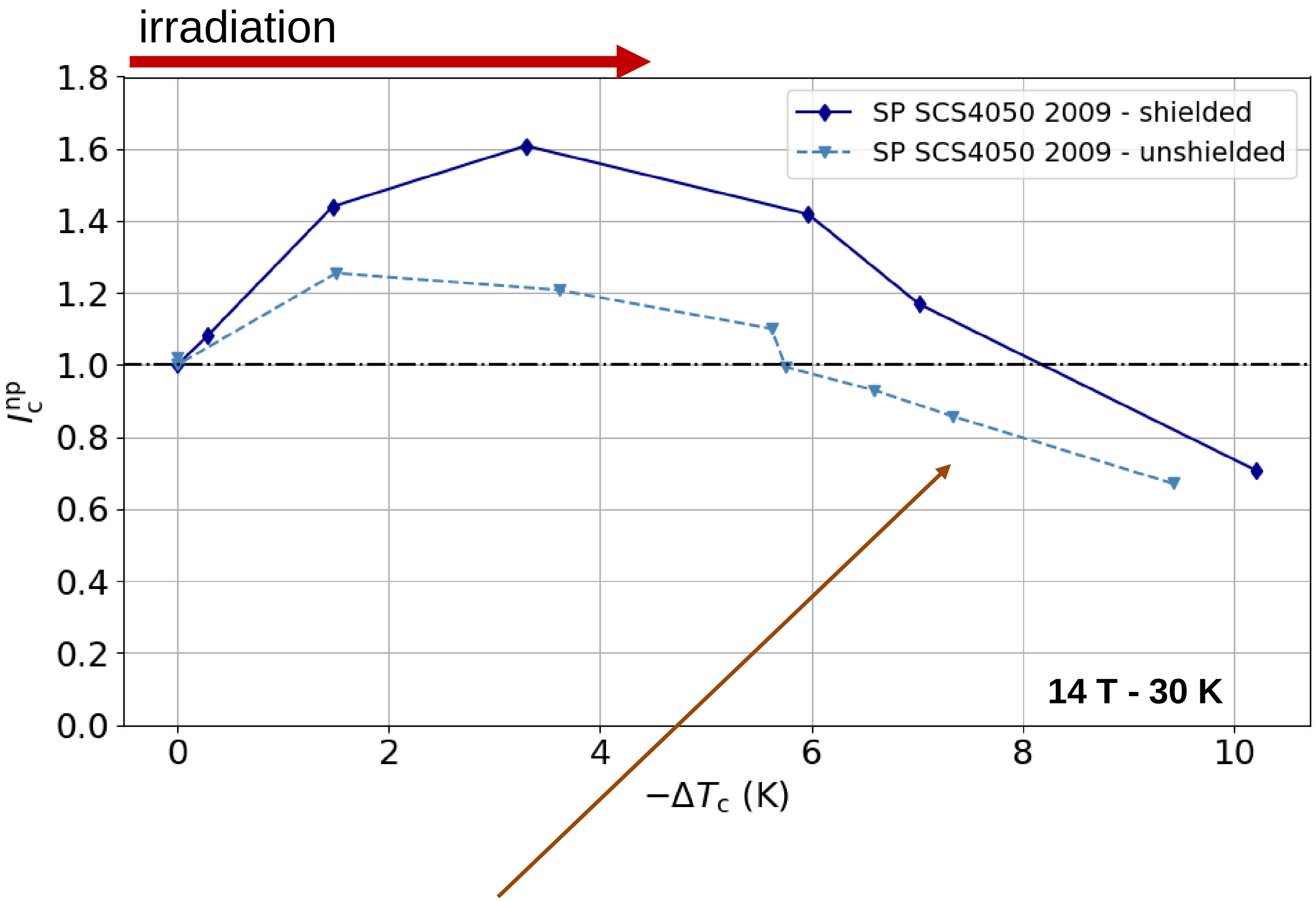
Influence of thermal neutrons: J_c



- maximum occurs at similar T_c
- small defects are efficient pinning centers < 40 K!
- T_c is efficient disorder parameter (decrease of superfluid density)

Both samples have same density of large cascades

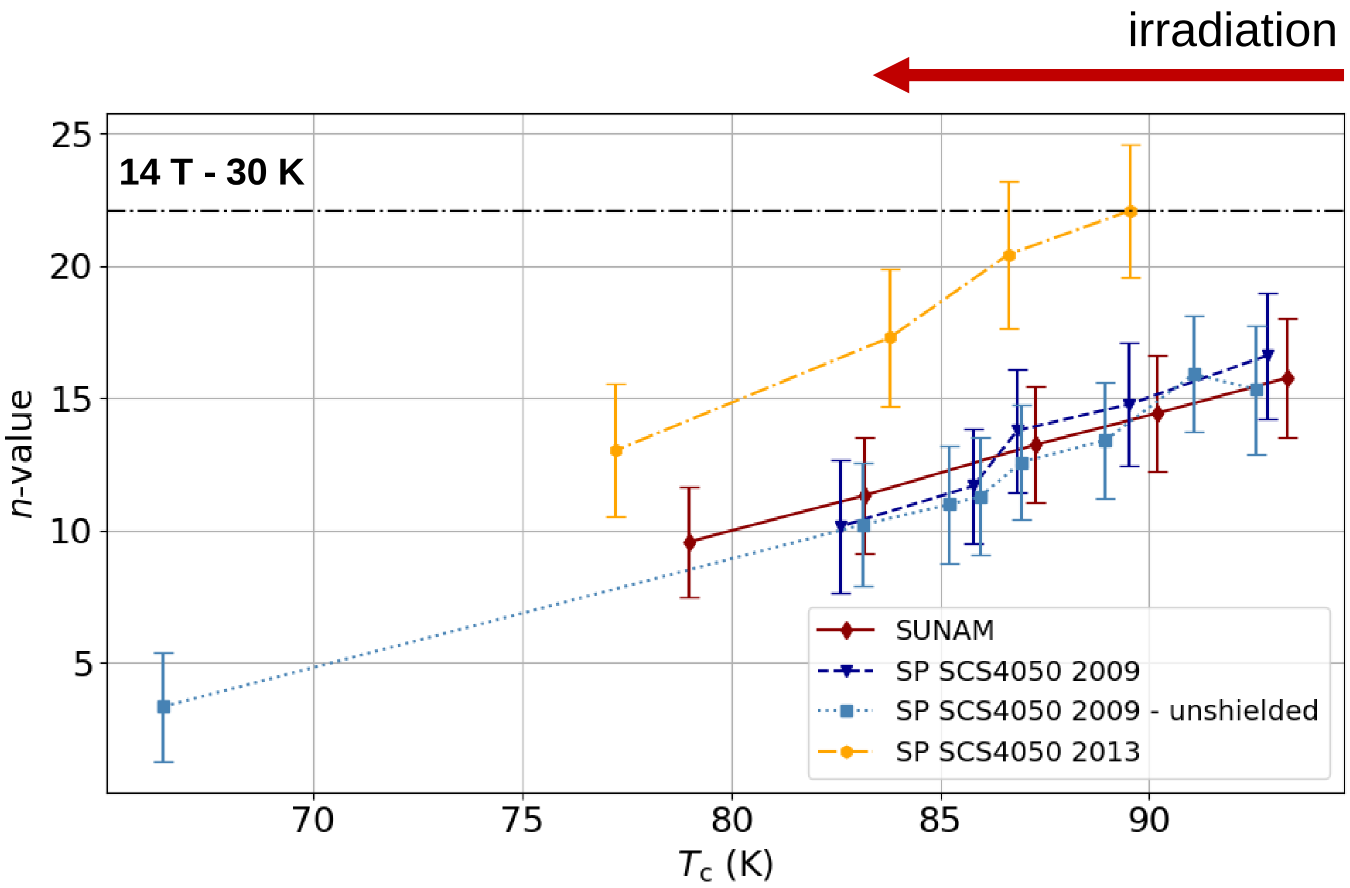
Influence of thermal neutrons: J_c



- extremely different defect size distribution
- almost equivalent slope in degrading branch
- same slope in proton irradiated samples!

Where does the degradation come from?

Annealing

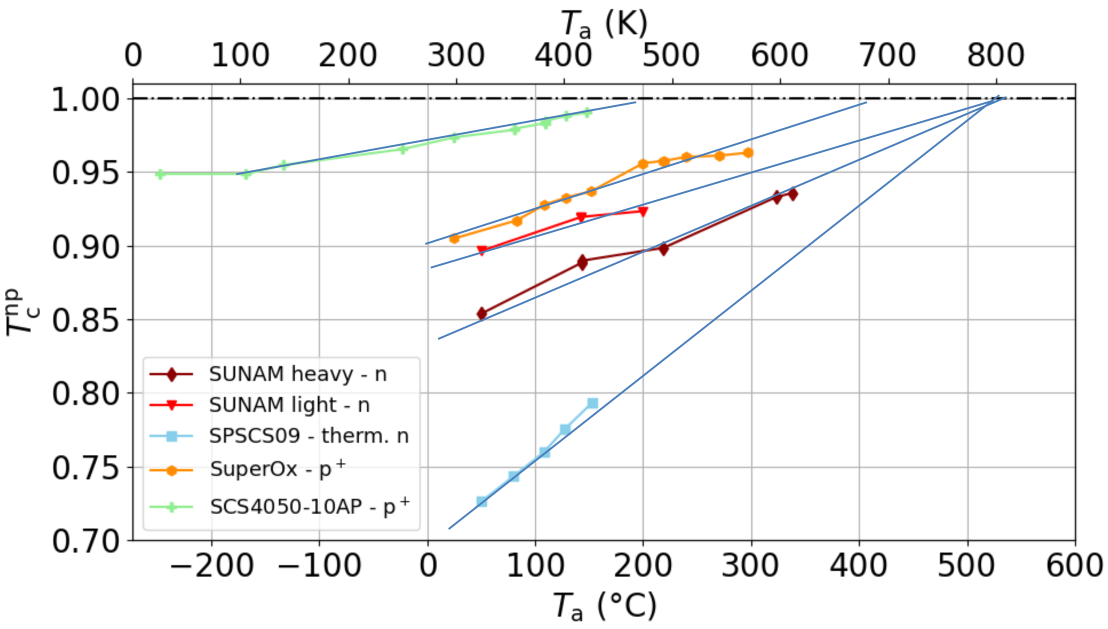


- n – value degrades linearly with T_c
- no change in slope between **shielded** and **unshielded** sample
- sample with higher starting n exhibits steeper slope
- degradation of condensation energy reduces T_c, I_c and n

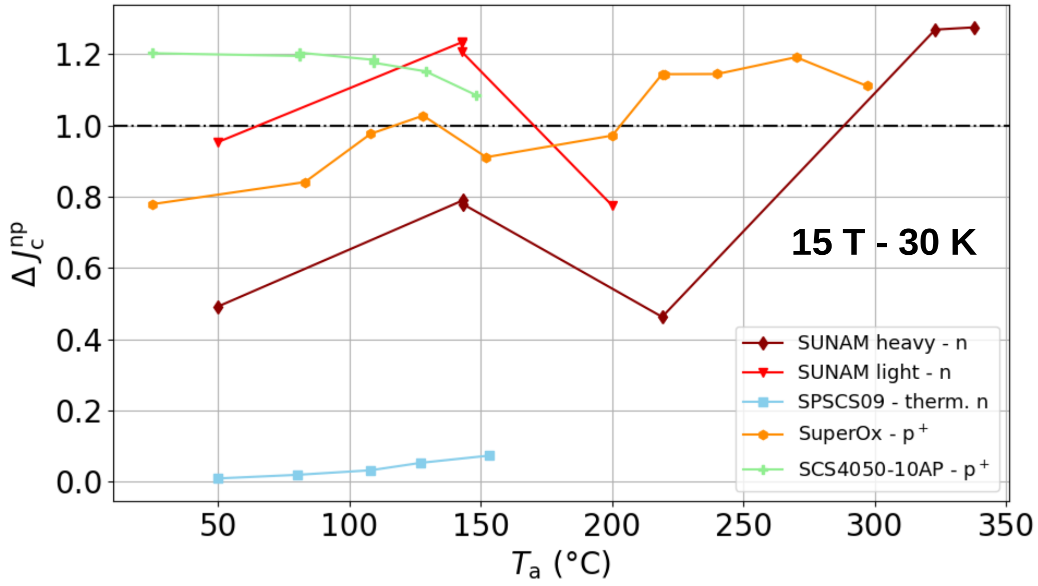
$\boldsymbol{n \propto T_c \propto J_c^p \propto \sigma_s}$ … superfluid density

Annealing

annealing

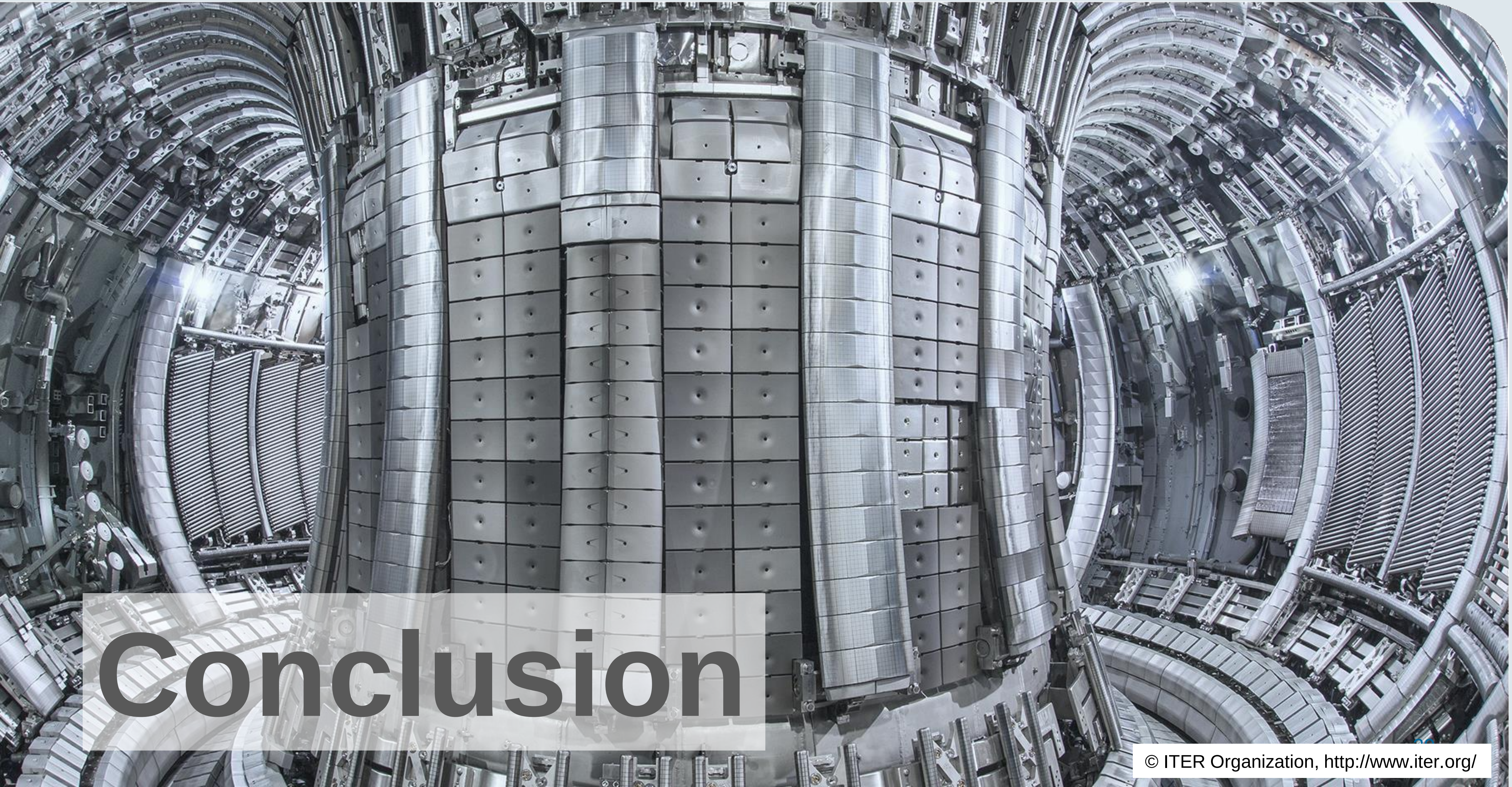


annealing



- T_c regenerates linearly with T_a
- even at cryogenic temperatures after reaching onset (p$^+$ irradiation)

- J_c regenerates non monotonic
- J_c only regenerates if maximum has been exceeded



Conclusion

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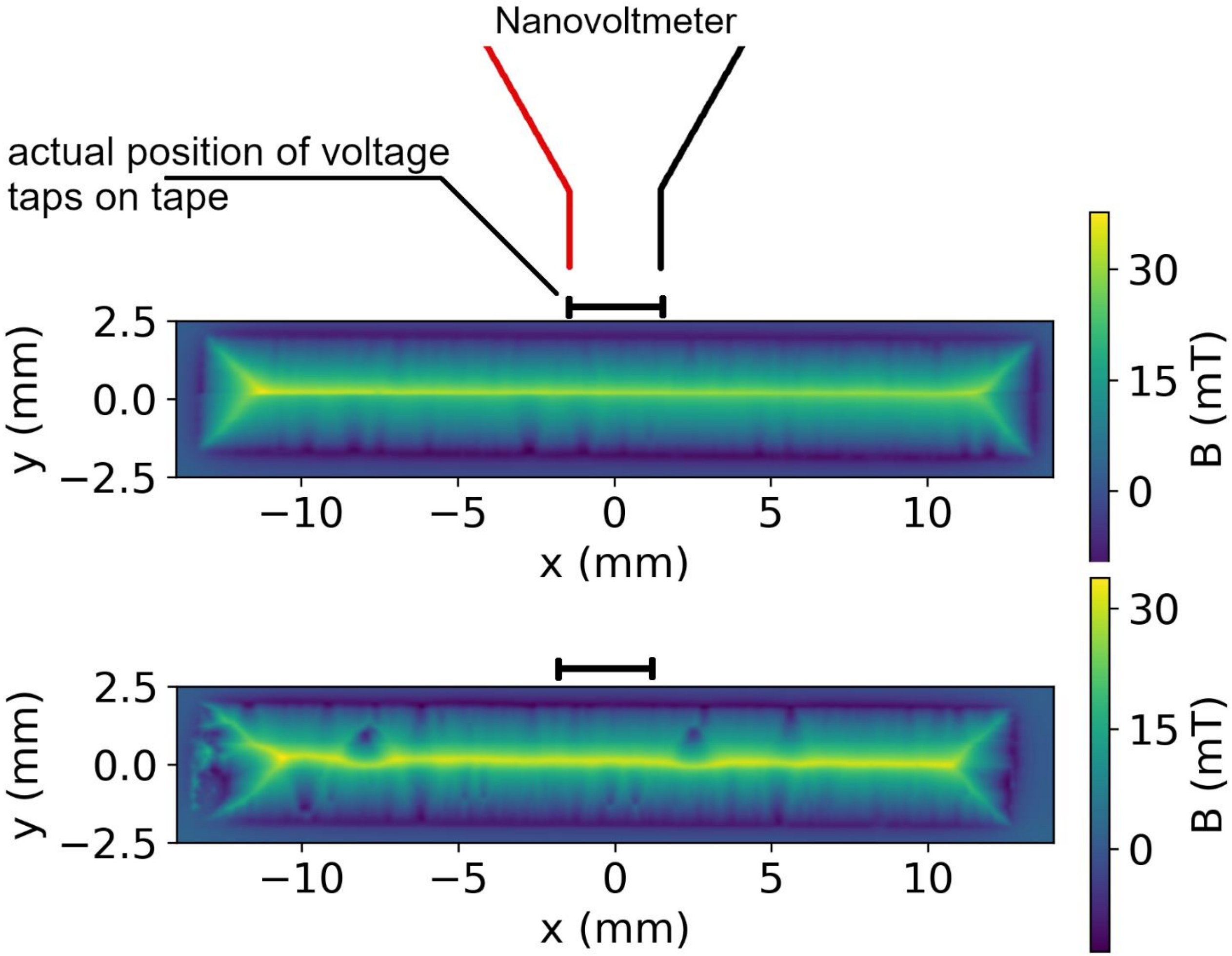
Conclusions

- Pair breaking by scattering decreases T_c linearly with neutron fluence (defect density).
- Point-like disorder / strain field enhances pinning at low temperatures (< 40 K) and high magnetic fields.
- Decrease of J_c at high defect density driven by the decrease of condensation energy.
- Defects, which are responsible for degradation of J_c are stable at elevated temperatures and don’t anneal easier.
- Annealing can be an effective way to increase lifetime of magnets but is no simple “cure-all”.

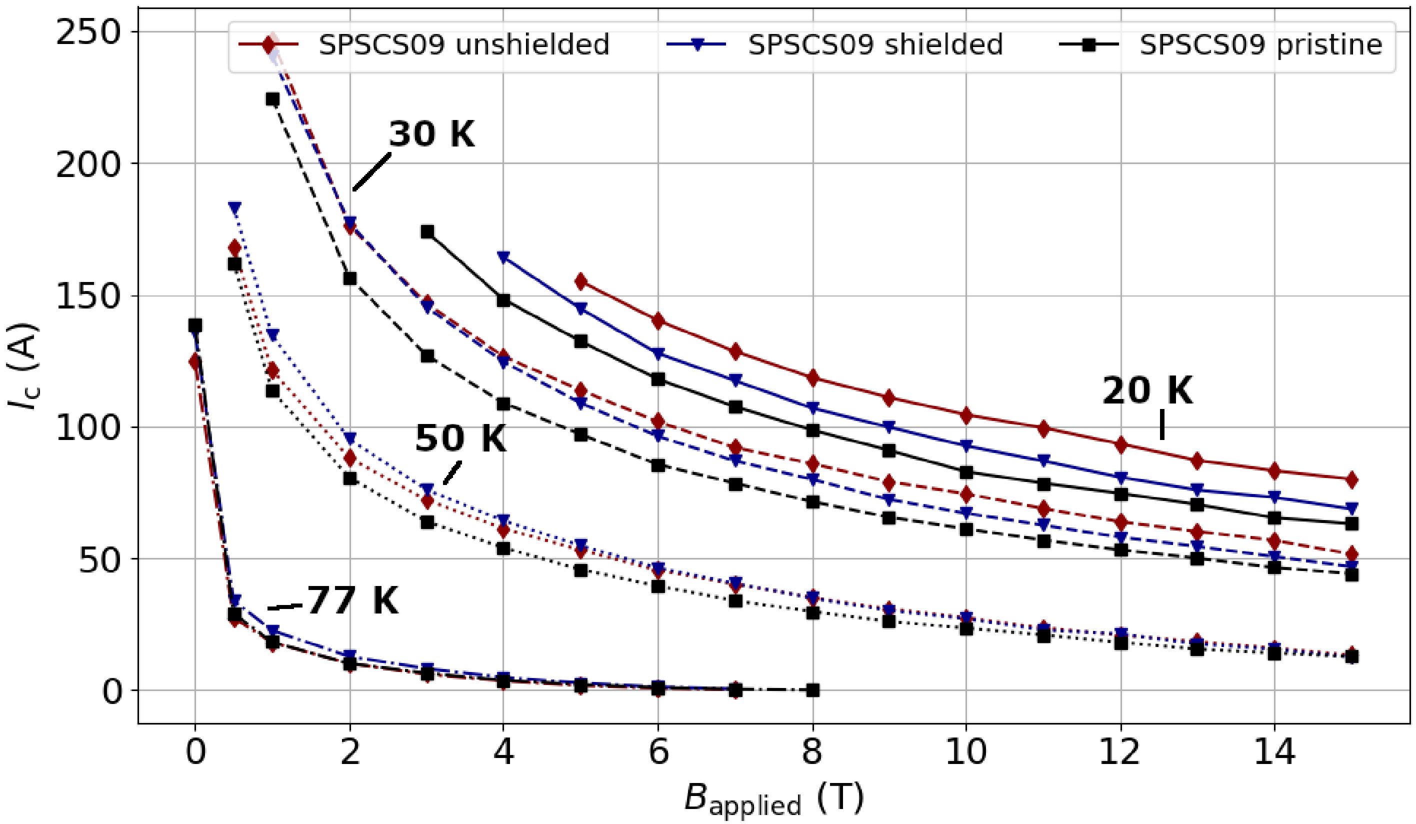
Appendix

Two nearly identical samples



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

Influence of Gd point defects: J_c



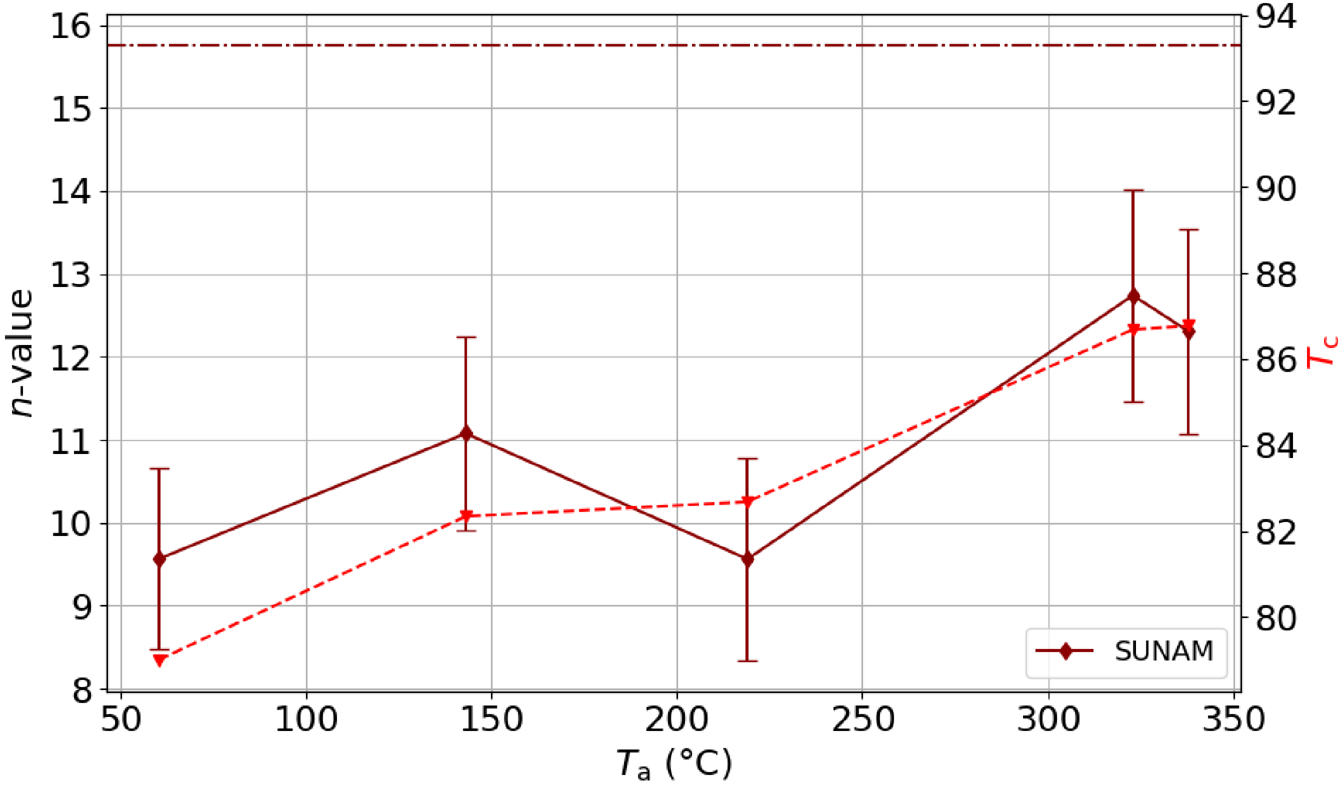
irradiated to similar fluence

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!

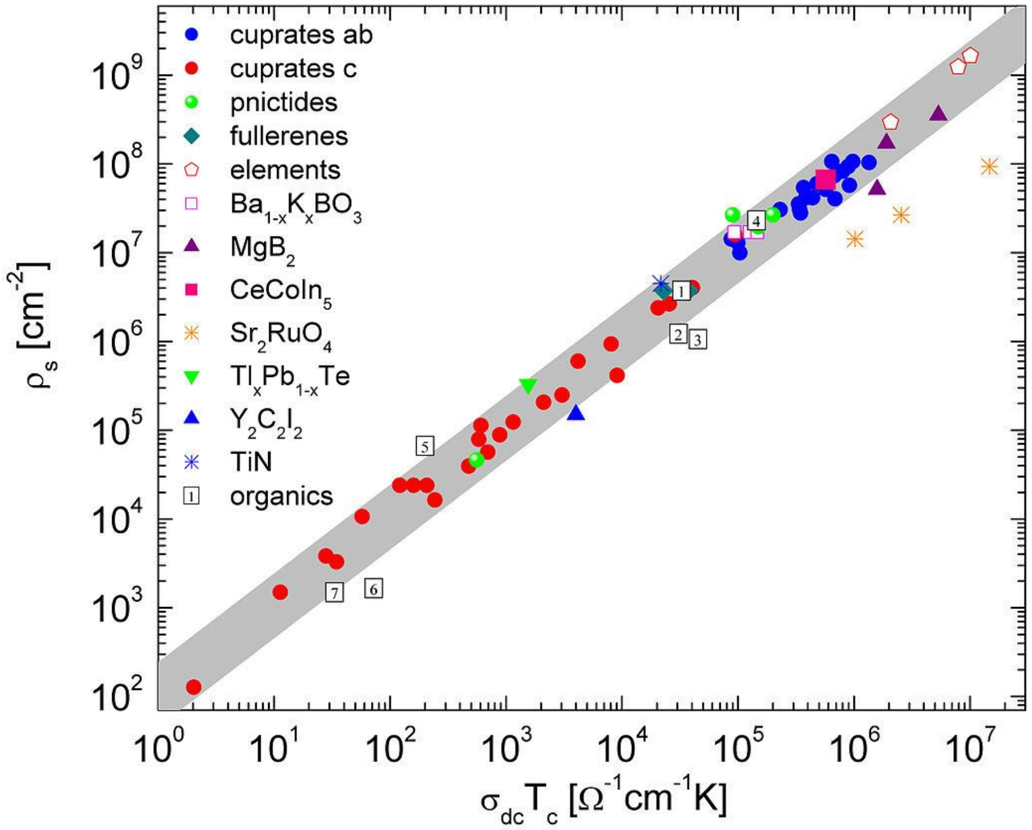
Annealing



- E_c increases ~linearly with T_a
- J_c^p increases monotonically with E_c

- n-value however does not and leads to non monotonic J_c annealing

Homes’ scaling law



- though logarithmic, the superfluid density scales with σ_{dc} and T_{c}

- many orders of magnitude

- many different materials

Theory

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

$$\frac{1}{\lambda^2} = \rho_s \qquad \xi = \sqrt{\xi_0 l}$$

$$\xi_0 \propto k_b T_{\mathrm{c}} \qquad \rho_{\mathrm{DC}} \propto \frac{1}{l}$$

$$E_{\mathrm{c}} = \rho_s \frac{1}{\xi_0 l} \propto \rho_s \rho_{DC} T_c$$

ρ_{s} ... superfluid density

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

ξ_0 ... clean limit coherence length

l ... mean free path

$$H_{c_2} \propto \rho_{DC}\, T_c$$

Theory

$$n \propto U_0$$

$$U_0 \propto E_c$$

$$E_\mathrm{c} = \rho_s \frac{1}{\xi_0 l} \propto \rho_s \rho_{DC} T_c \propto n$$

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