Radiation effects in superconductors

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Outline

- Change of superconducting properties after fast neutron irradiation
  - T_c, J_c, anisotropy, strain sensitivity, flux creep
- Degradation due to scattering
  - Reduction of superfluid density
- Neutron fluence versus dpa
- Can we mitigate the performance degradation?
  - Defect annealing

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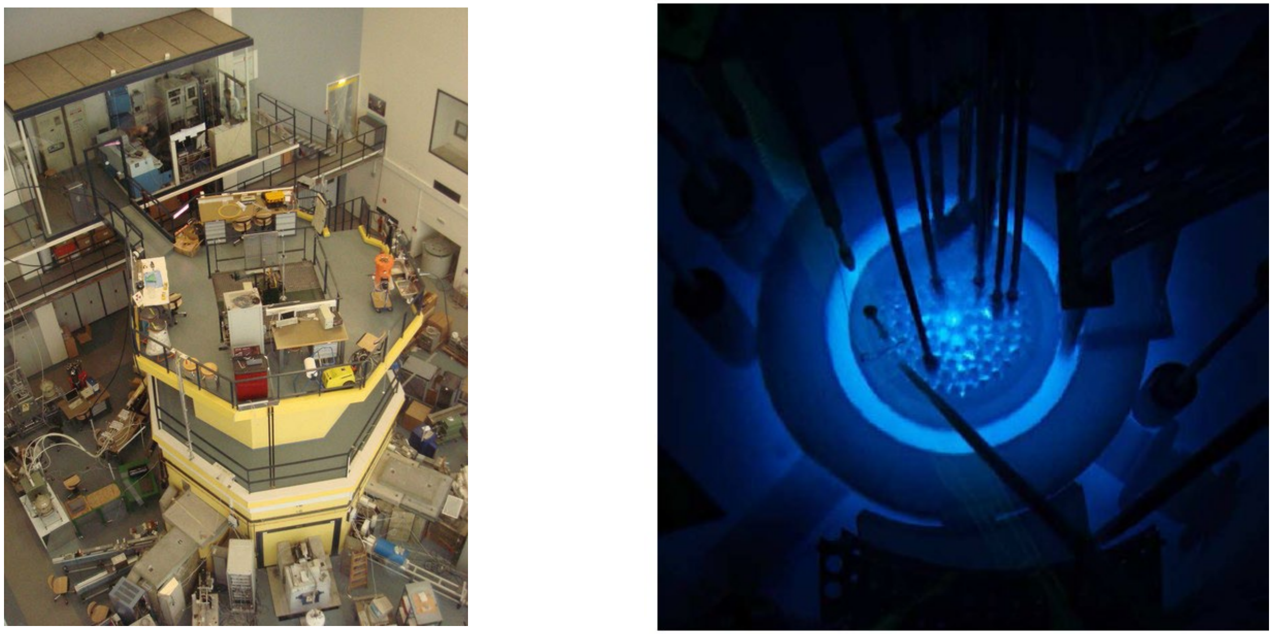
Experimental

TRIGA-MARK II REACTOR DEFECT STRUCTURE

TRIGA MARK-II reactor

Neutron flux density (**1985**): 2.1 × 10^{17} $m^{-2}s^{-1}$

- Thermal (<0.55 eV) neutron flux density: 6.1 × 10^{16} $m^{-2}s^{-1}$
- Fast (>0.1 MeV) neutron flux density: 7.6 × 10^{16} $m^{-2}s^{-1}$
- About 60 % after core renewal in 2012

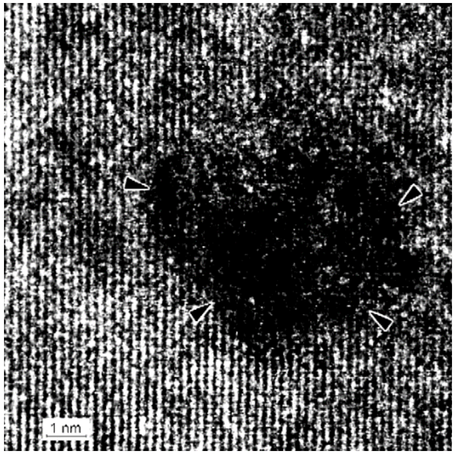


Created defects

Fast neutron fluence: 10^{22} m^{-3}

Direct collisions (high energy neutrons)

- Defect cascades
  Ø ~ 5 nm, density: $5\cdot10^{22}$ m^{-3} (d_{av}~ 27 nm)
- Smaller defects
  Single displaced atoms, clusters of point defects….

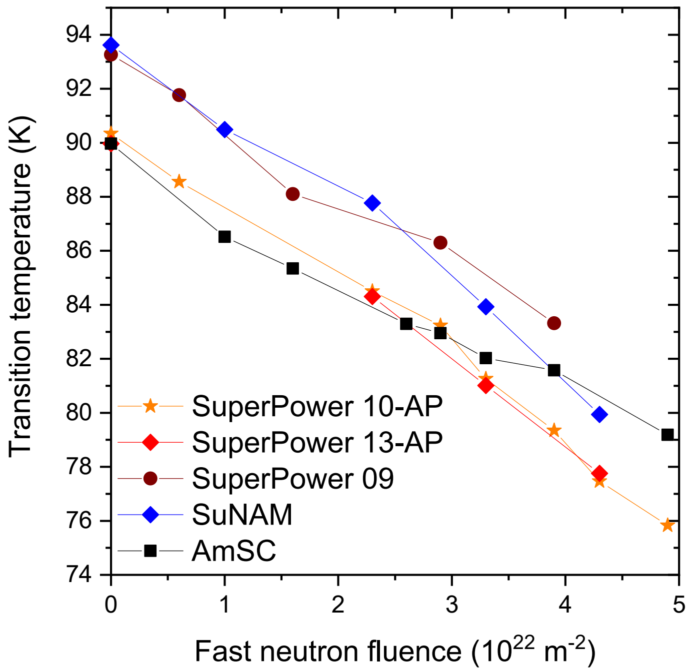


Change of superconducting parameters

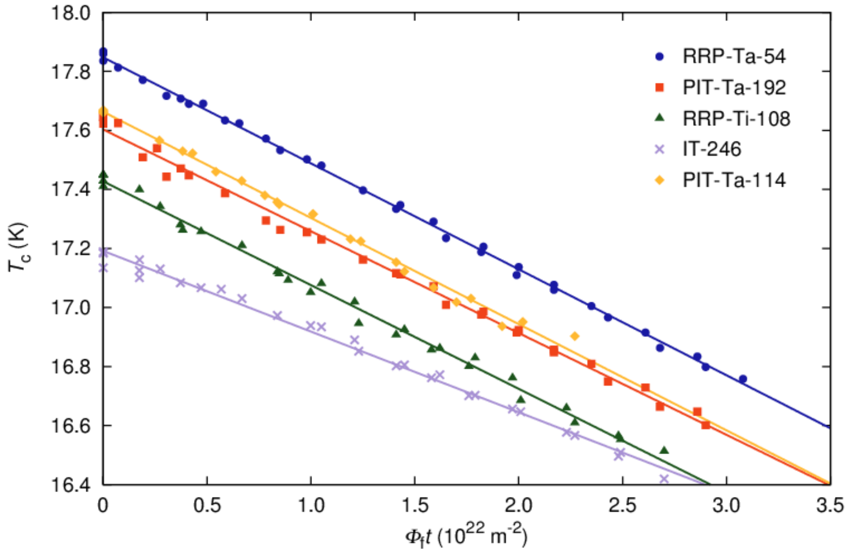
CRITICAL TEMPERATURE CRITICAL CURRENT

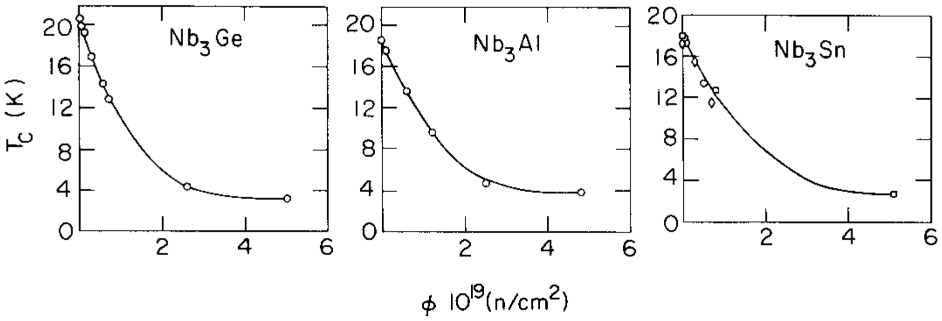
Decrease of transition temperature

Coated conductors



Nb_3Sn

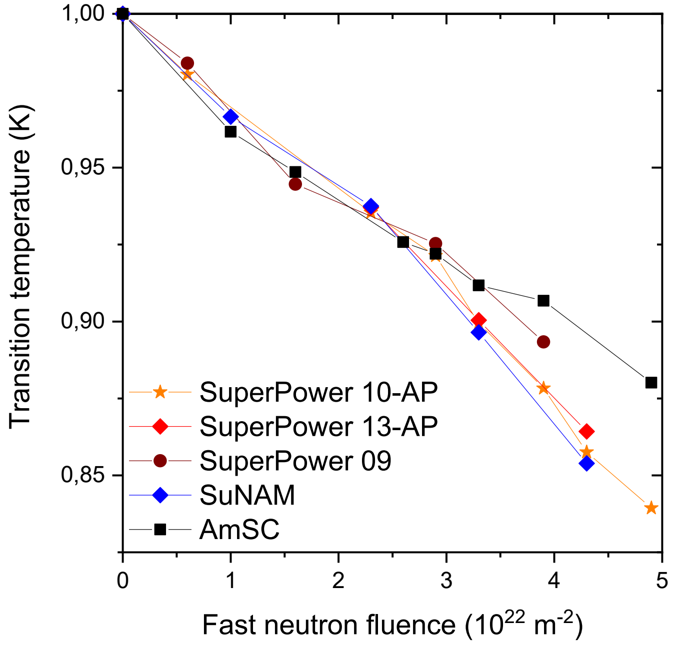




maximum fluence around 7-10·10^{23} m^{-2} (E>0.1 MeV)

Decrease of transition temperature

Coated conductors



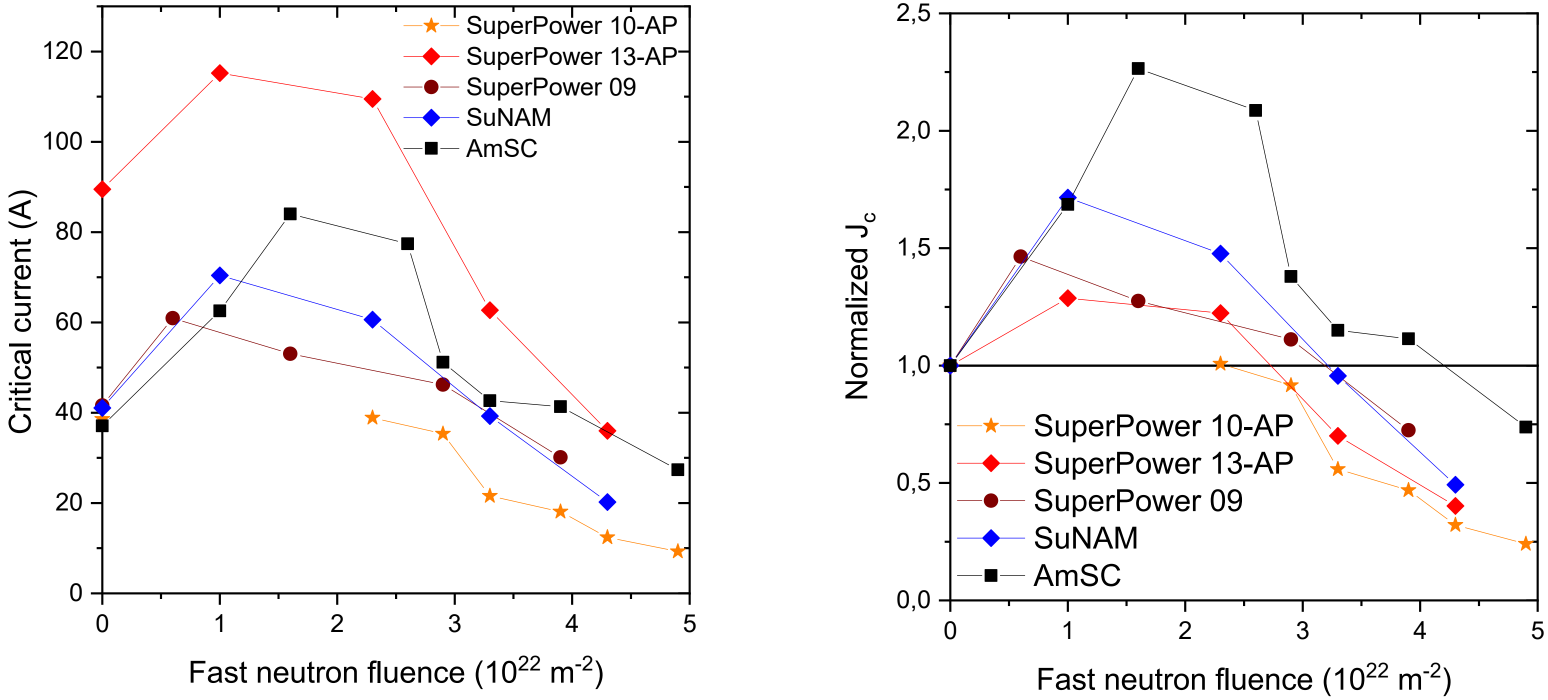
Decrease at a fast fluence of 10^{22} m^{-2}:

- NbTi: ~ 0.015 K
- A-15: ~ 0.3 K
- Cuprates: ~ 2.5 - 3 K
- MgB_2: ~ 4 K (n,α)!

- Conventional superconductors
  - No change of T_c due to non-magnetic scattering expected.
  - Secondary effects: smearing of DOS, anisotropic energy gap, phonon hardening, interband scattering.
- Cuprates
  - Non-magnetic scattering is pair breaking.

Change of critical current

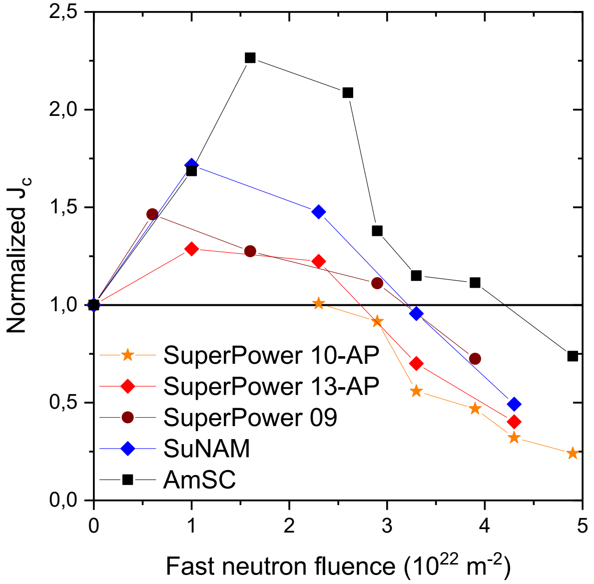
Coated conductors (30 K, 15 T)
(Transport, 1 µV/cm)



Not unique to coated conductors

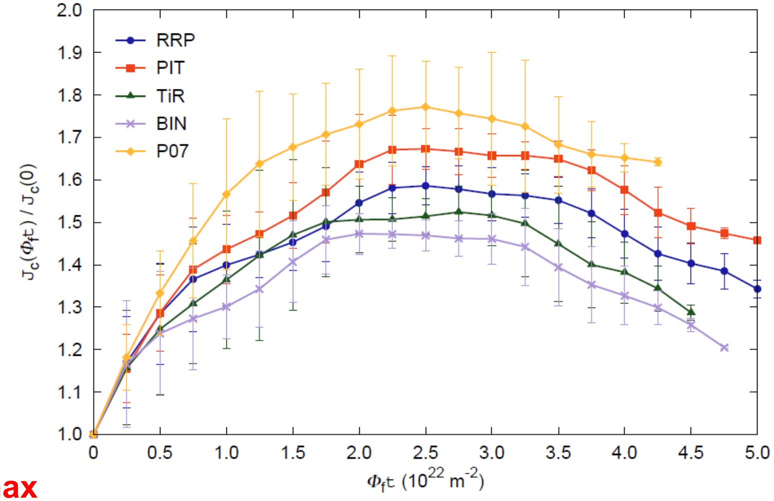
Coated conductors (30 K, 15 T)
(Transport, 1 µV/cm)

Nb$_3$Sn wires (4.2 K, 6 T)
(Magnetization)



< 50 % of I_{c0}

< 25 % of $I_{c,max}$



$$J_c = \eta J_d$$

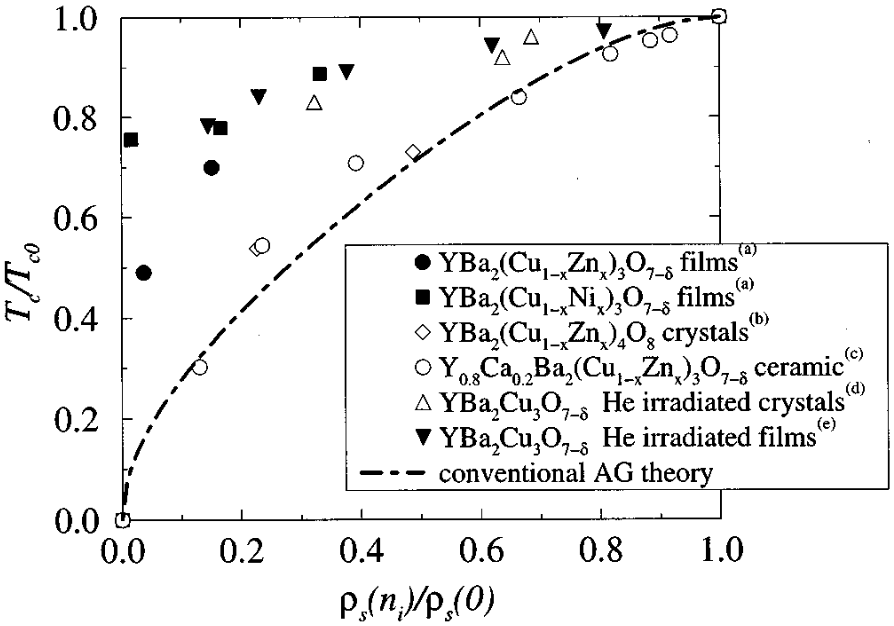
Initial increase due to the introduced pinning centers (η).

Decrease due to reduction of superfluid density, ρ_s. ($J_d = \frac{\phi_0}{3\mu_0\sqrt{3}\pi\lambda^2\xi} = \frac{\rho_s}{\xi}$)

Decrease of superfluid density

Energy of vortex core per meter (possible gain for vortex pinning):

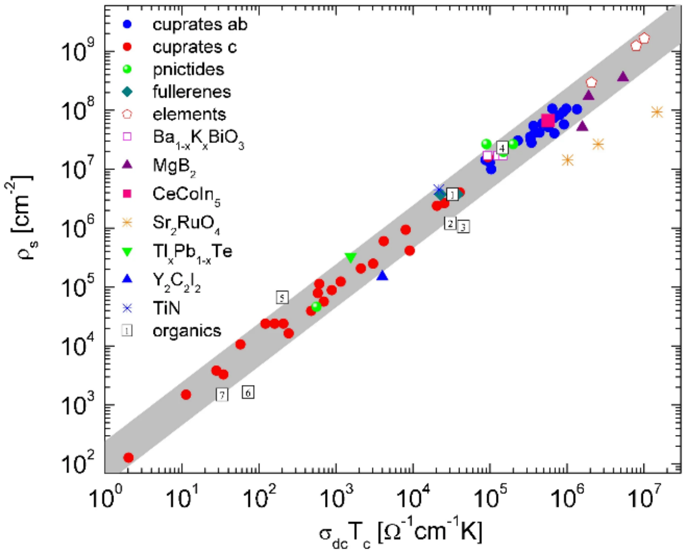
$E_{\text{core}} = \frac{\phi_0^2}{16\mu_0\pi\lambda^2} \propto \frac{1}{\lambda^2} \propto \rho_s$…superfluid density



M. Franz et al. PRB 56 (1997) 7882

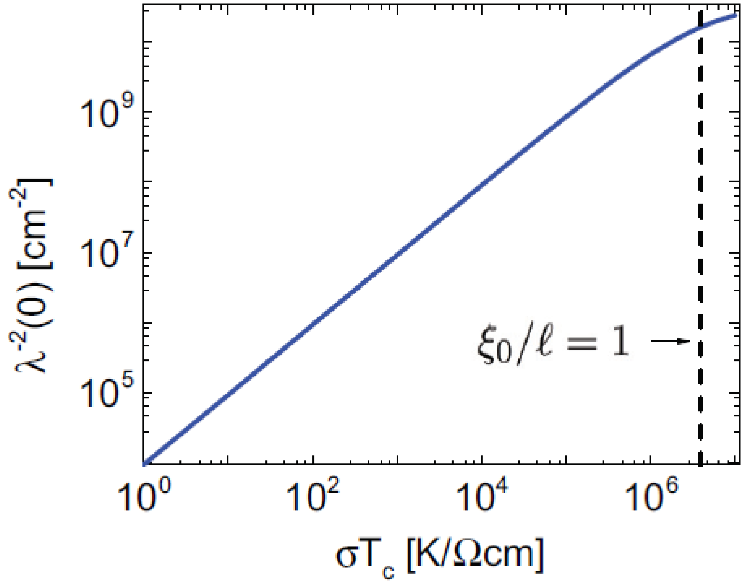
Homes Law

Experimental



S.V. Dordevic SR 3 (2013) 1713

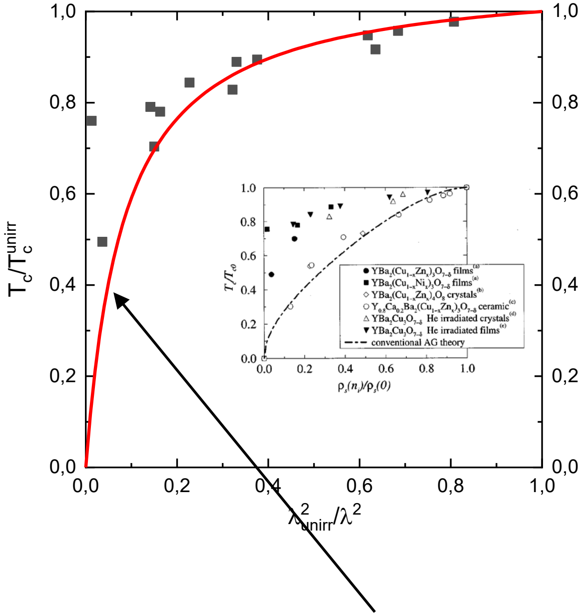
Theoretical (BCS)



V.G. Kogan PRB 87 (2013) 220507 (R)

$$\frac{1}{\lambda^2} \propto \rho_s \propto \frac{T_c}{\rho_n}$$

Homes Law



$$\frac{1}{\lambda^2} \propto \rho_s \propto \frac{T_c}{\rho_n} \qquad \rho_n = \rho_0 + \alpha\phi$$

$$T_c = T_{c0} - \beta\phi$$

$$\Longrightarrow \frac{\lambda_0^2}{\lambda^2} = \frac{T_c}{T_{c0}\left(1 + \boxed{\frac{\alpha}{\rho_0\beta}}(1 - T_c/T_{c0})\right)}$$

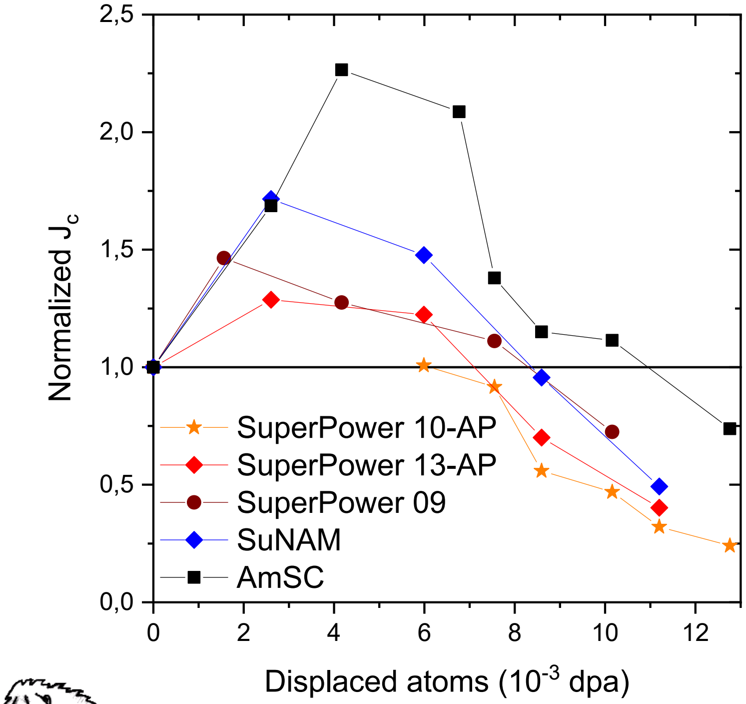
$\frac{\alpha}{\rho_0\beta} = 12$ from experimental values for α, ρ_0, and β.

Quantifying Disorder

DPA (DISPLACEMENTS PER ATOM)

Neutron fluence - dpa

Coated conductors (30 K, 15 T)
(Transport, 1 µV/cm)



Damage calculations (MARS):

Fast neutron fluence of 10^{22} m^{-2}:

$1.1 – 4\cdot10^{-3}$ dpa (avg: **$2.6\cdot10^{-3}$** dpa)

Nikolai Mokhov, RESMM 2017

Degradation at around 8(2.5 – 15) $\cdot10^{-3}$ dpa at 30 K and high magnetic fields.

Radiation tolerance generally increases at lower temperatures.

Is dpa a suitable measure?

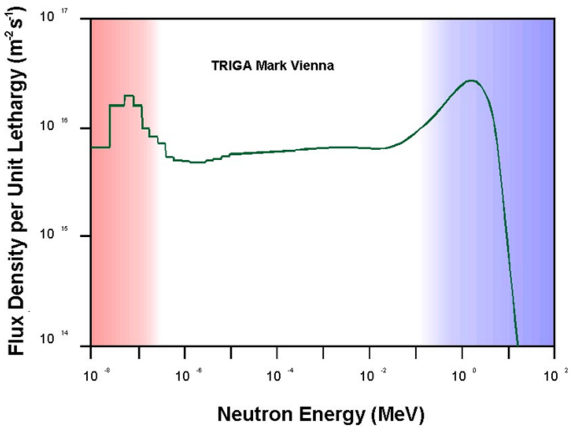
Tapes with Gd-123: low energy neutrons: nuclear reactions:

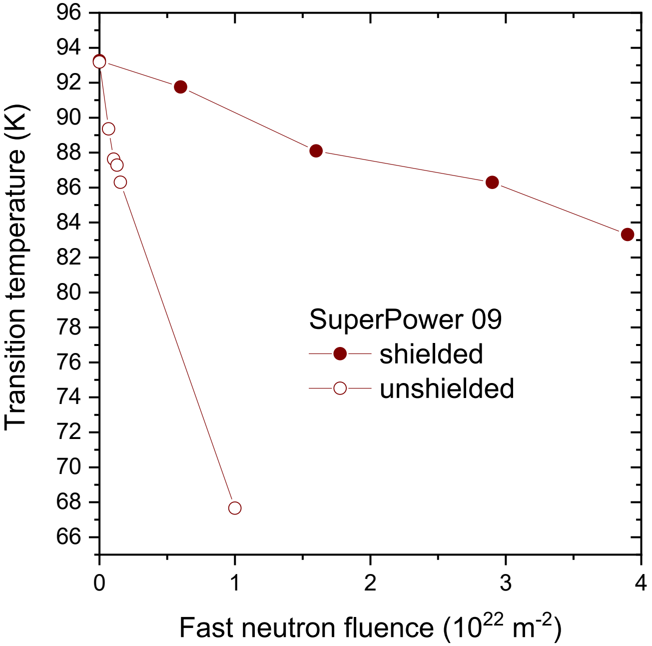
n-γ: $0.8\cdot10^{22}\ \mathrm{m}^{-2} \cdot 61$ kbarn $\cdot\ 0.145$ (Gd-155) $\cdot\ 1/13 = 0{,}55 \cdot 10^{-3}$ dpa

n-γ: $0.8\cdot10^{22}\ \mathrm{m}^{-2} \cdot 254$ kbarn $\cdot\ 0.157$ (Gd-157) $\cdot\ 1/13 = 2.45 \cdot 10^{-3}$ dpa

Total: $\mathbf{3\cdot10^{-3}}$ dpa / MARS: $0.4\text{-}0.7 \cdot 10^{-3}$ dpa

Add to the $2.6\cdot10^{-3}$ dpa (at $10^{22}\ \mathrm{m}^{-2}$) from fast neutrons





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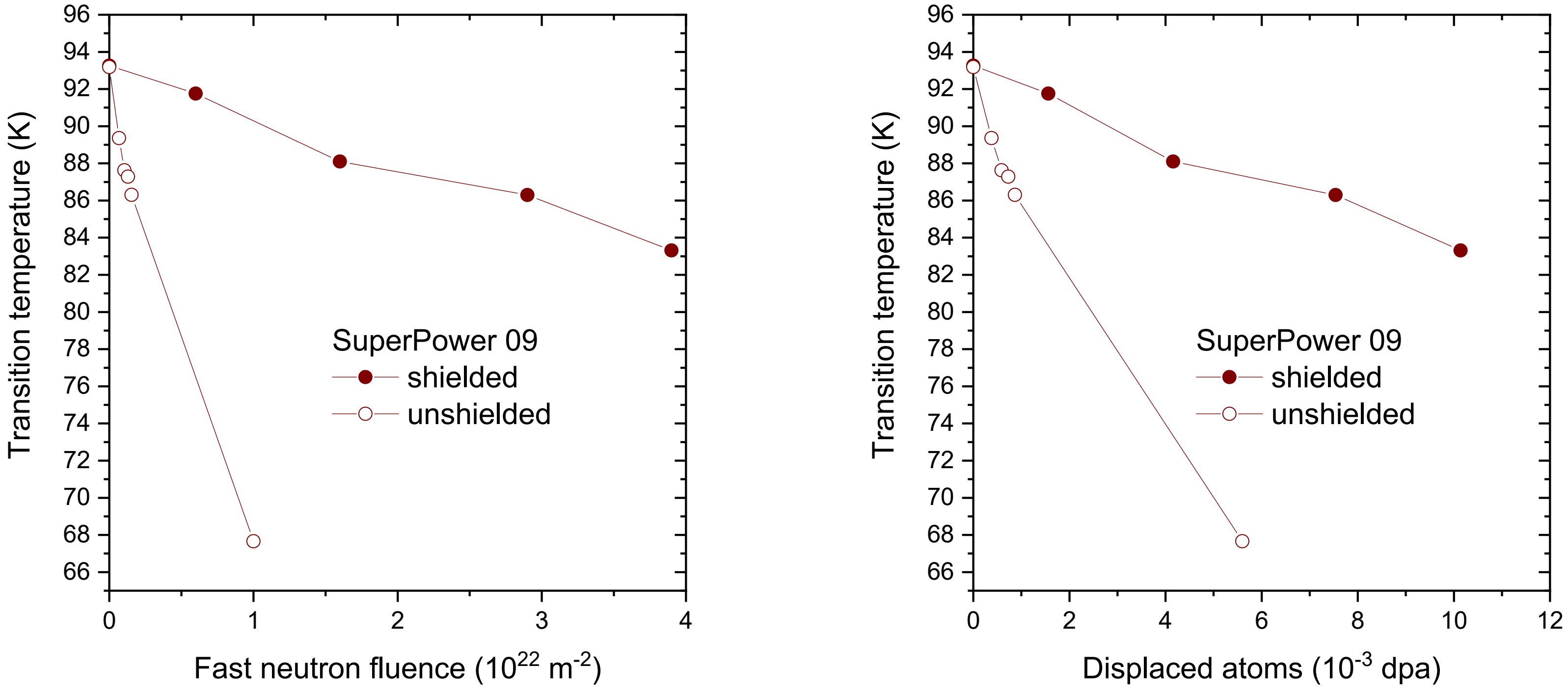
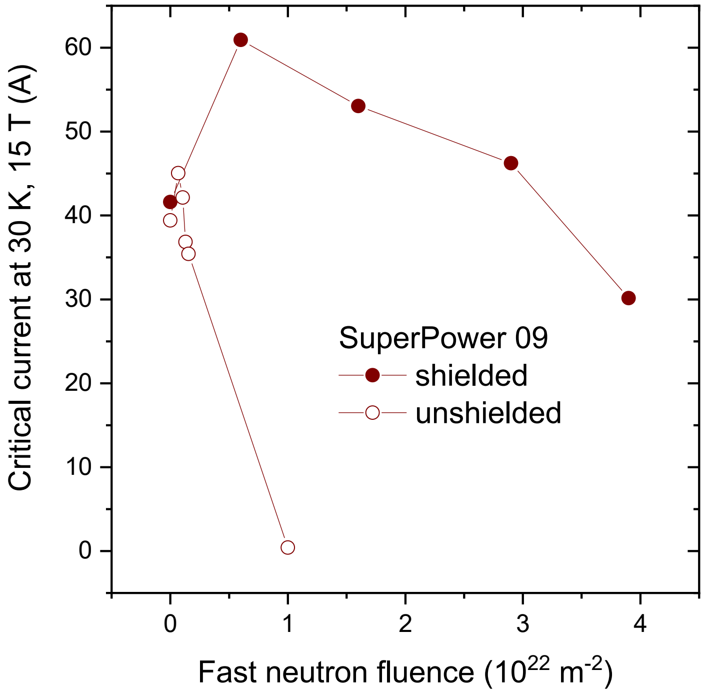
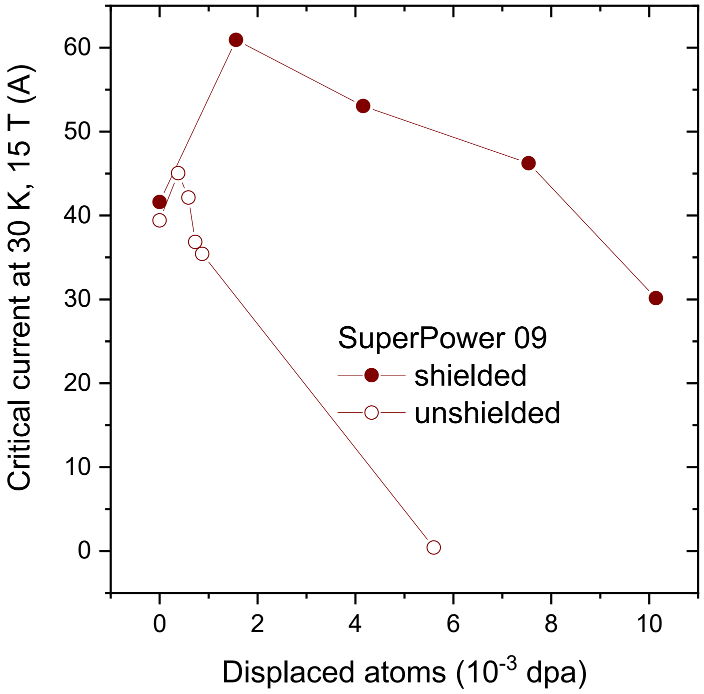


No, “point dpa“ is much worse!

Is dpa a suitable measure?





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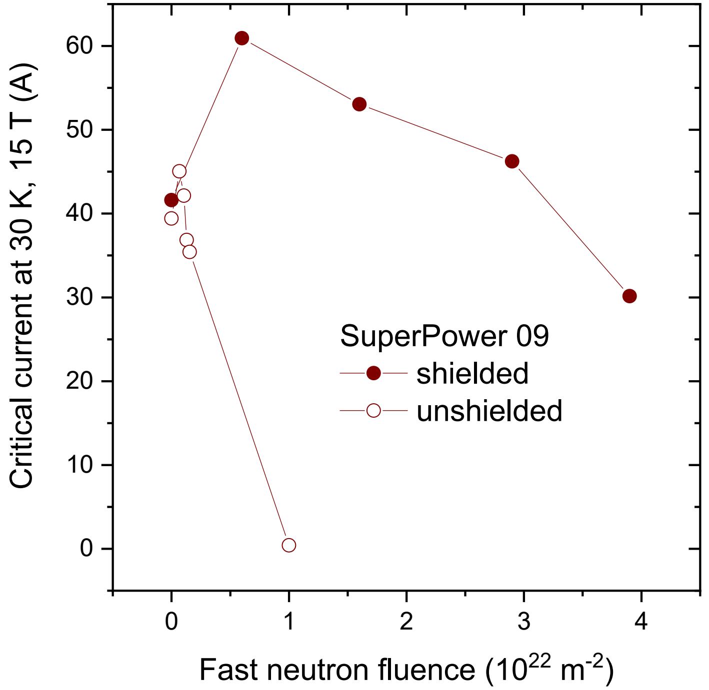
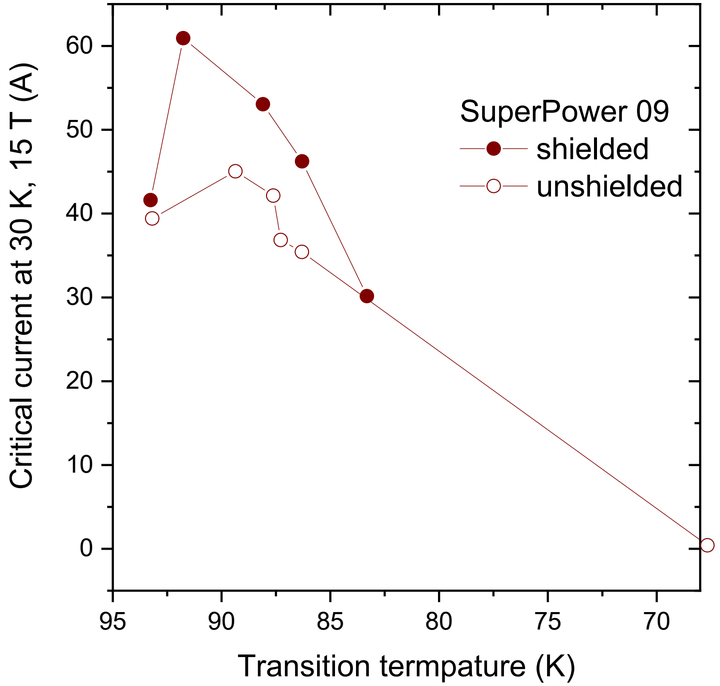
Is dpa a suitable measure?



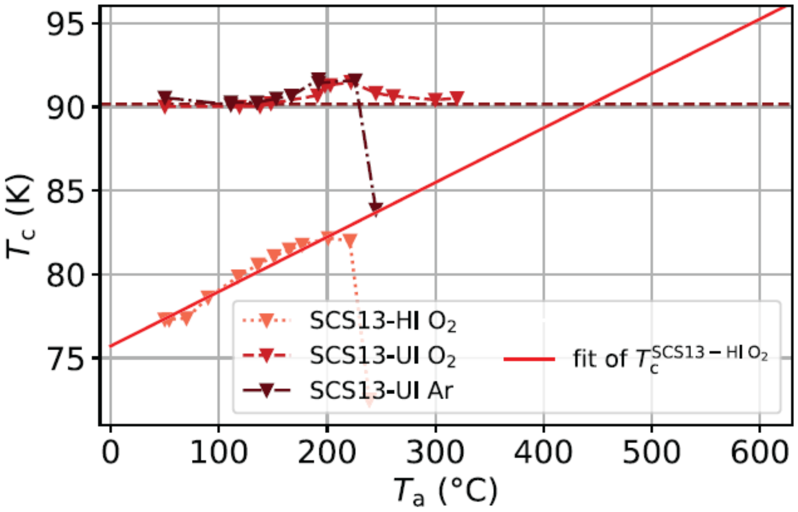


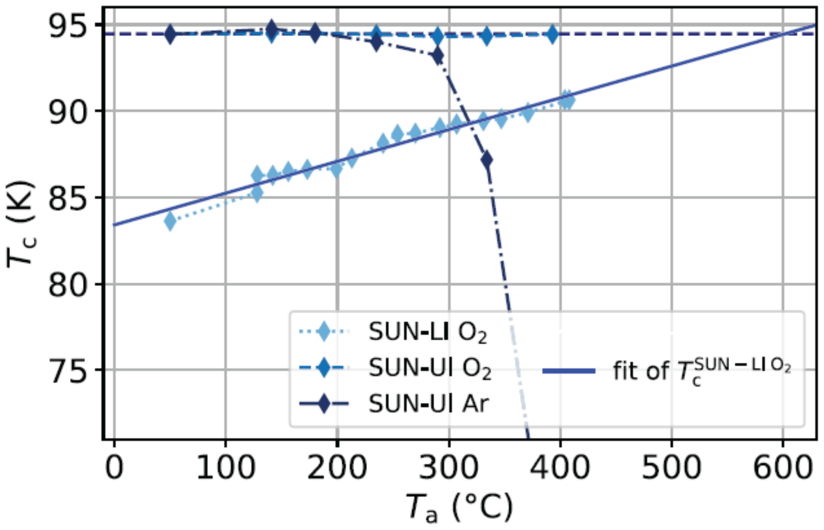
- T_c is a much better parameter for the degradation.
- Scattering is responsible for the degradation of T_c and J_c.
- Prediciton of scattering rate?
- Change of pinning!

What can we do?

ANNEALING

Recovery of transition temperature





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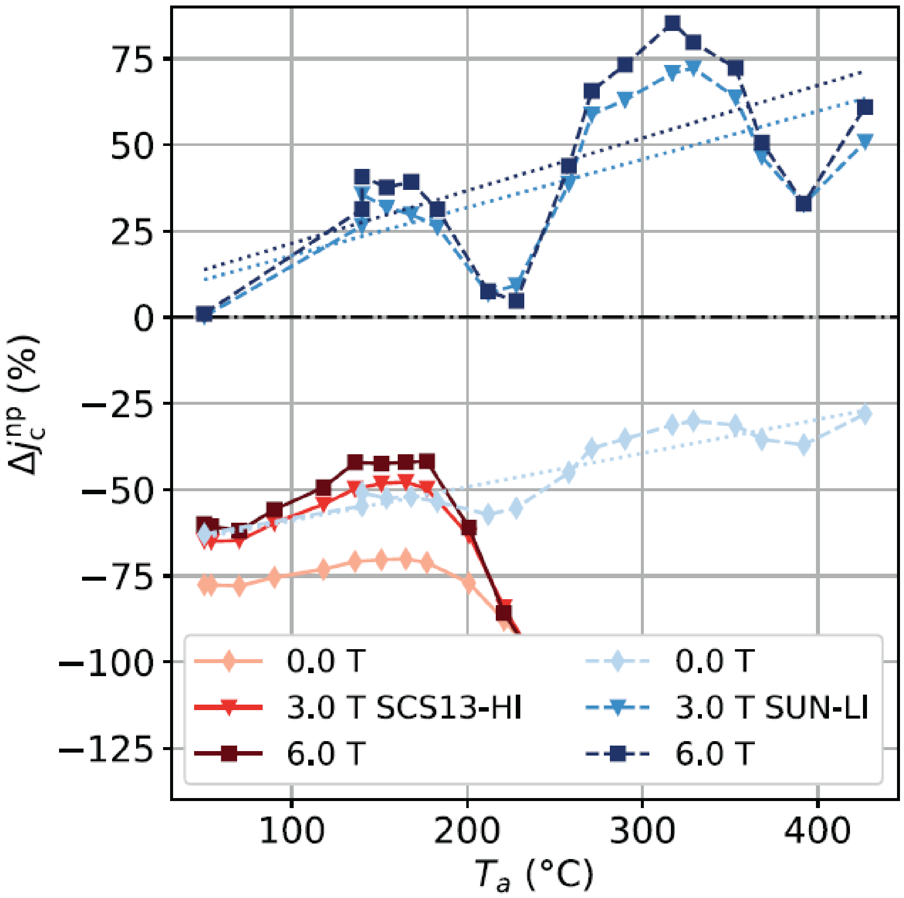
- Linear increase of T_c with annealing temperature. (Wide distribution of activation energies?)
- Loss of oxygen above ~220 °C.

Recovery of critical current



- Linear trend with superimposed minima and maxima.
- Recovery of superfluid density.
- Loss of pinning centers.

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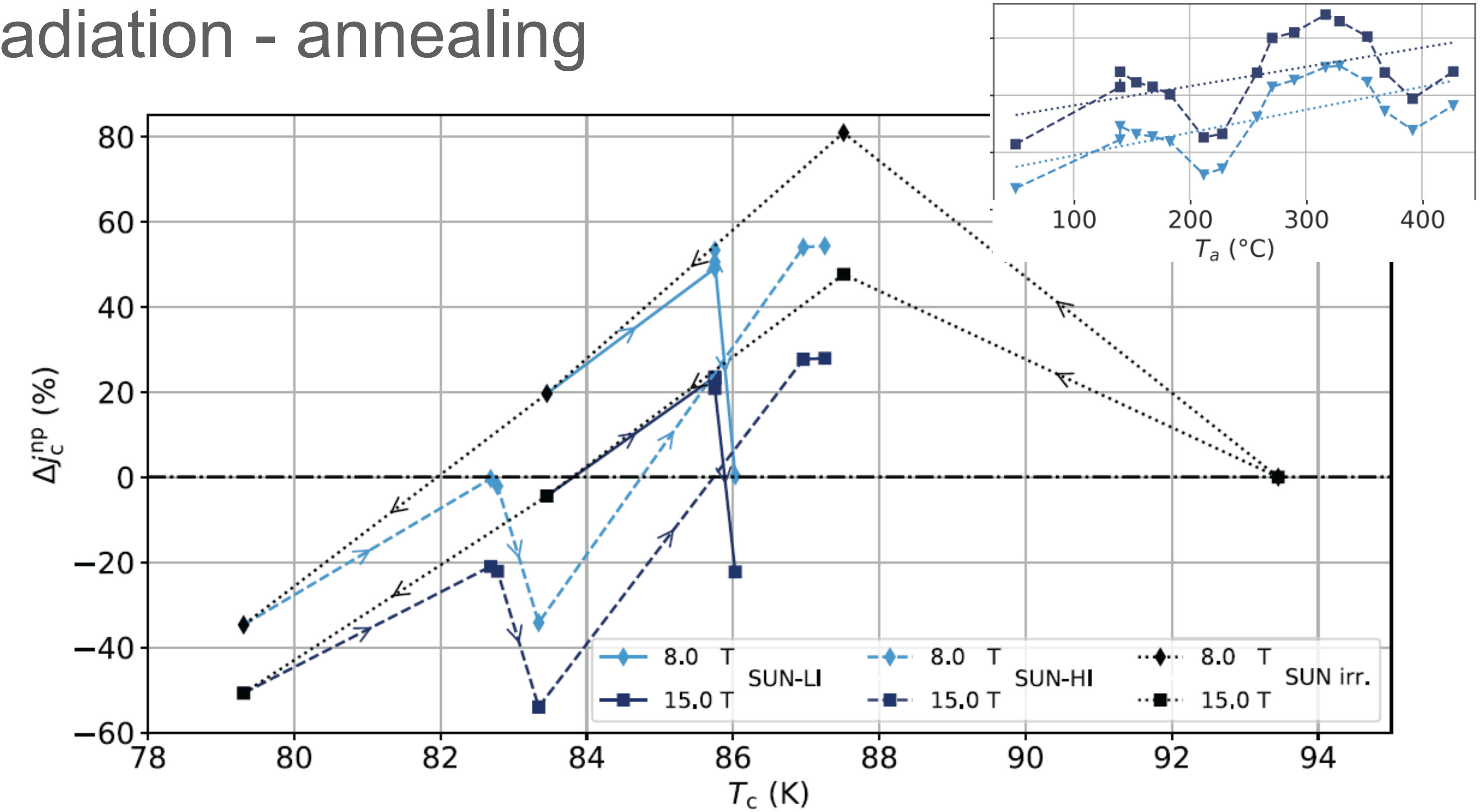
Irradiation - annealing



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Recovery of T_c (superfluid density?) leads to similar critical currents at the same T_c if the annealing is done at a favorable temperature.

Conclusions

- The critical current degrades at high neutron fluences due to a decrease of the superfluid density (enhanced scattering).
- Scattering rate seems a suitable parameter for the degradation.
- An optimized annealing strategy is promising for significantly enhancing the highest possible lifetime fluence.

Thank you for your attention!