IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Invited presentation 3-MO-FP4-011 given at EUCAS, 01 - 05 September 2019, Glasgow, UK.

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Neutron Irradiation: Introduced Defects and Effects on Various Superconductors

Michael Eisterer
Atominstitut, TU Wien

EUCAS 2019, Glasgow, September 4th

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Outline

- Motivation
- Neutron irradiation / defect structure
- Influence on critical temperature and current
- Pinning efficiency
- Influence of defect size and density
  - Cuprates, iron-based superconductors, Nb_3Sn, MgB_2

Acknowledgments

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- American Superconductor, SuNam (S. Moon), SuperOx, SuperPower;

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Motivation

- **Operation in radiation environments**
  - Nuclear fusion, particle accelerators
- **Flux pinning**
  - Benchmarking J_c of a material
  - Influence of a “tunable” defect structure
- **Understanding the mechanism of superconductivity**
  - Decrease of T_c with impurity scattering
  - Depairing current density

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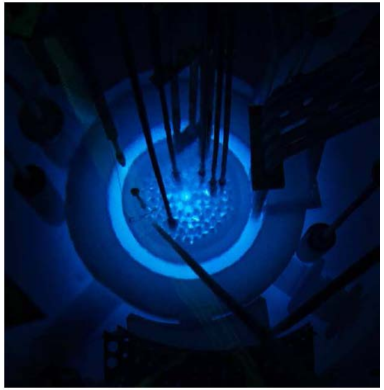
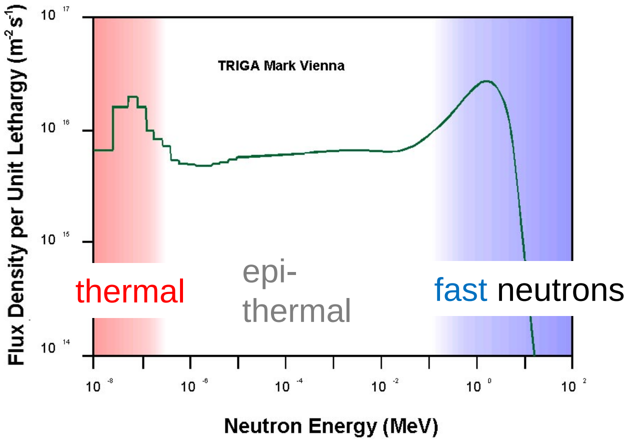
TRIGA MARK II Reactor (250 kW)

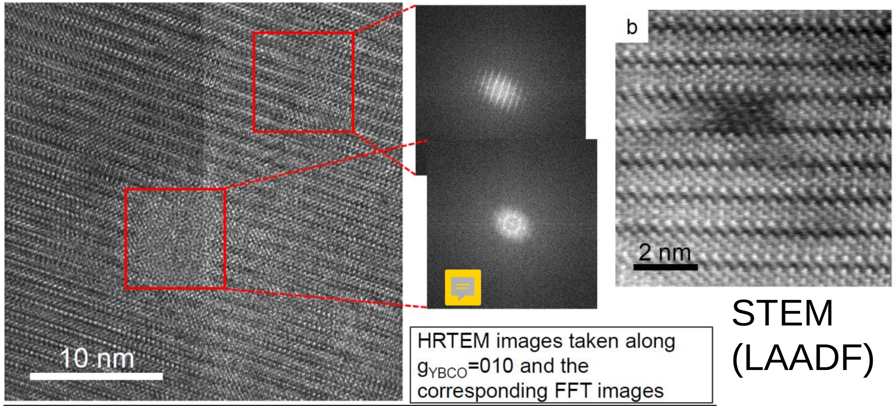
Neutron flux determination in 1985:
Thermal (<0.55 eV) / fast (>0.1 MeV) flux density: 6.1/7.6 × 10^{16} $m^{-2}s^{-1}$
Core renewed in 2012: fast neutron flux density of ~ 4.1× 10^{16} $m^{-2}s^{-1}$





Resulting defect structure

Gd/Y-123



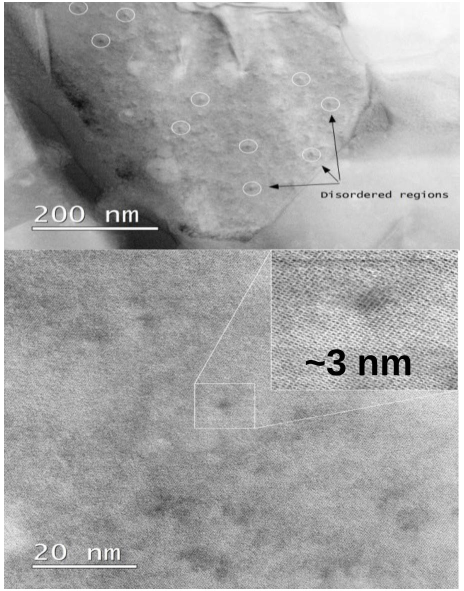
HRTEM images taken along g_{YBCO}=010 and the corresponding FFT images

STEM (LAADF)

Courtesy of Yatir Linden (Univ. of Oxford)

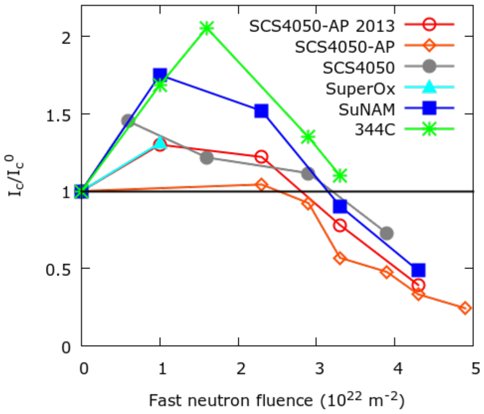
Spherical collision cascades + smaller defects

Nb_3Sn

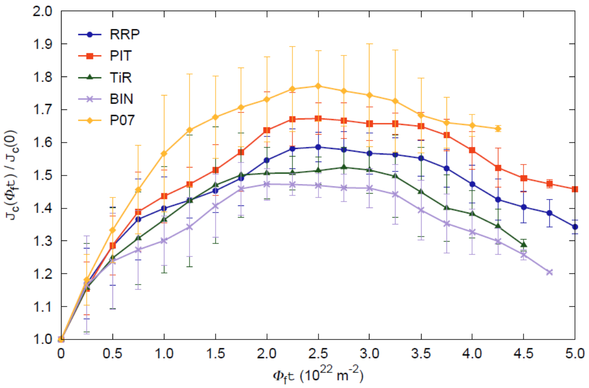


Defect density (irradiation time)

Coated conductors (30 K, 15 T)



Nb_3Sn wires (4.2 K, 6 T)



Increase due to the introduced pinning centers, degradation because of ?

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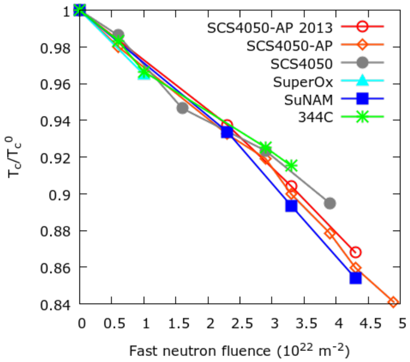
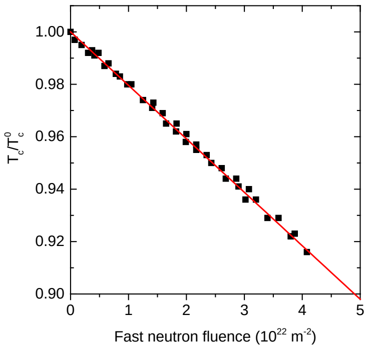
Reasons for J_c degradation

Coated conductors



Nb_3Sn wire (RRP)



- Decrease of T_c (E_c, f_p, J_d)
- Reduced superconducting volume (~10^{-2} dpa)
- **????**

No obvious reasons for the J_c degradation were found in the microstructure (TEM).

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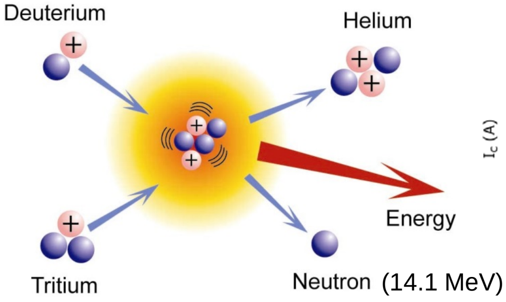
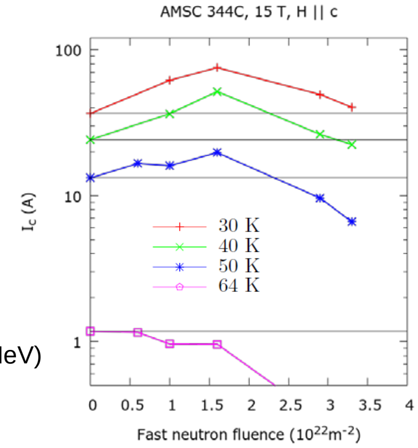
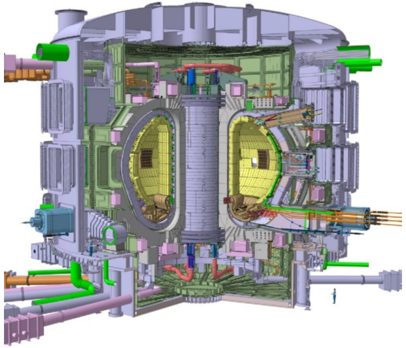
Nuclear Fusion



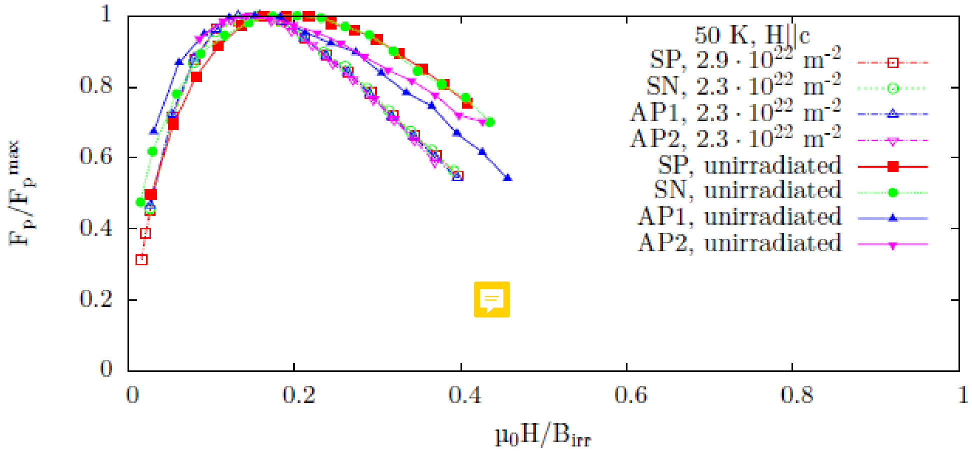




- Coated conductors are more tolerant against neutron irradiation at lower operation temperature
- A large density of APCs harms the radiation robustness.

FLUX PINNING

Dominance of radiation induced defects



The (normalized) volume pinning force curves collapse to a universal behavior after neutron irradiation.

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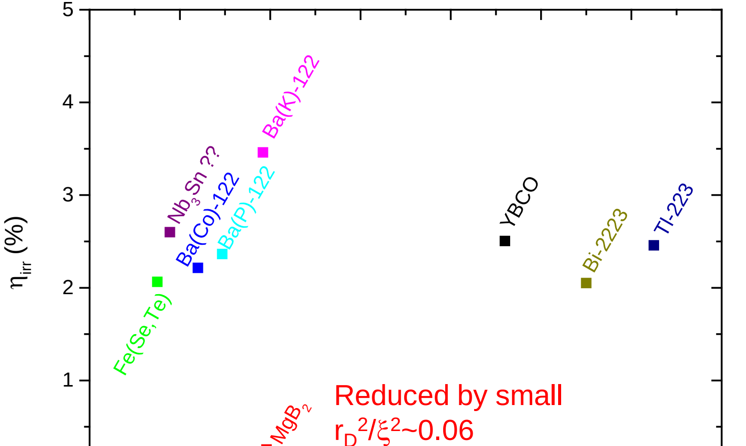
Pinning efficiency

Self-field J_c at low temperatures (single crystals)
Fluence ~ $4x10^{21}$ m^{-2}



$$J_d = \frac{\varphi_0}{3\sqrt{3}\pi\mu_0\lambda}$$

Definition of pinning effi

$$J_c =: \eta J_d$$

η_{irr} is about 2-3% (η_{opt}

Similar defect structu
to a similar pinning e
(benchmarking)

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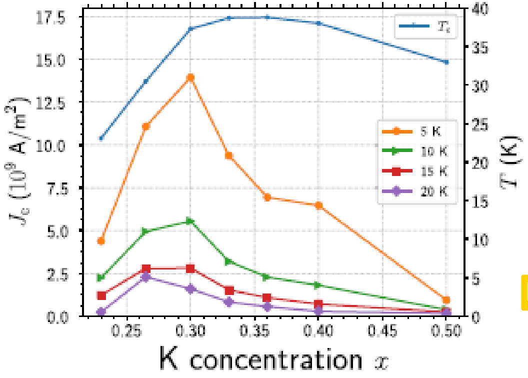
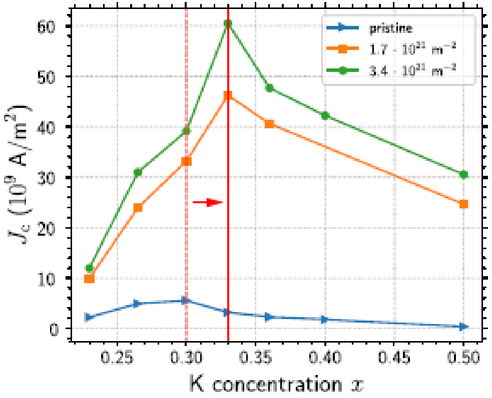
Behavior of J_d

$K_xBa_{1-x}Fe_2As_2$



irradiation



D. Kagerbauer et al., SUST 32 (2019) 094004

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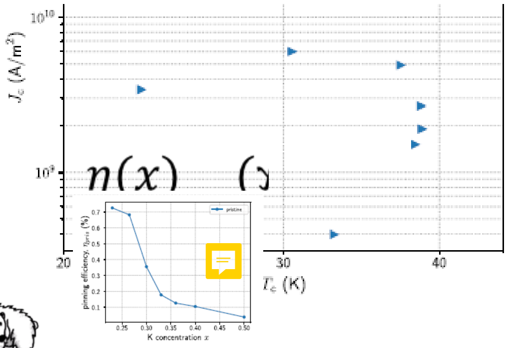
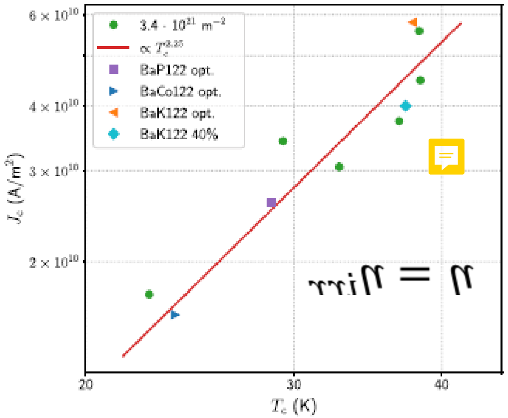
Behavior of J_d

$K_xBa_{1-x}Fe_2As_2$



$$J_c(1T, \frac{T}{T_c} = 0.3)$$

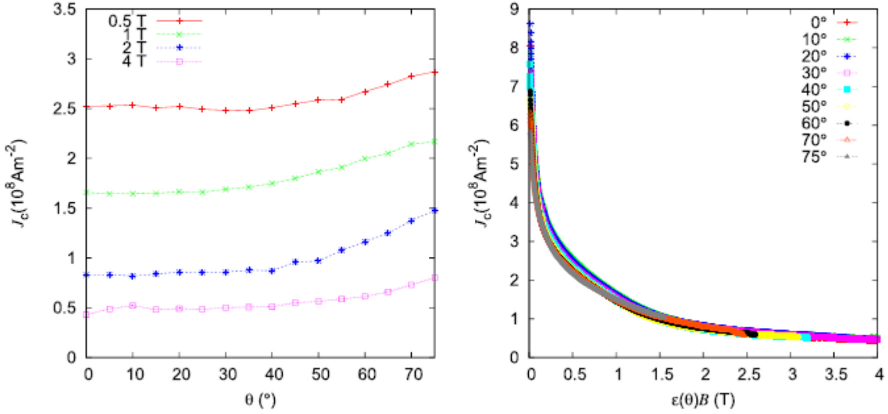
irradiation



$$J_d \propto T_c^{2.25}$$

D. Kagerbauer et al., SUST 32 (2019) 094004

Angular dependence of J_c



- $Ba_{0.6}K_{0.4}Fe_2As$
- Weak pinning
- Electronic anisotropy (γ~2.2)
- “Usual”scaling behavior

V. Mishev et al., SUST 28 (2015) 102001

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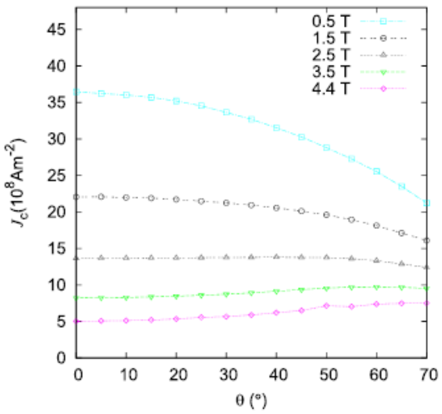
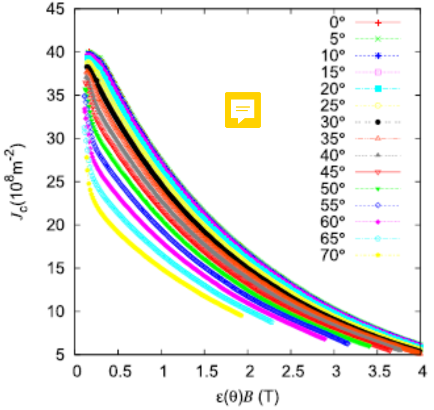
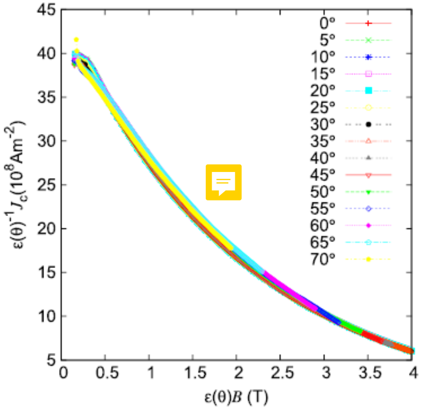
Angular dependence of J_c







- $BaFe_{1.88}Co_{0.12}As_2$
- Pinning by **“large” isotropic** defects

- Electronic anisotropy (γ~2.2)
- Scaling of field **and** J_c

V. Mishev et al., SUST 28 (2015) 102001

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Defect density

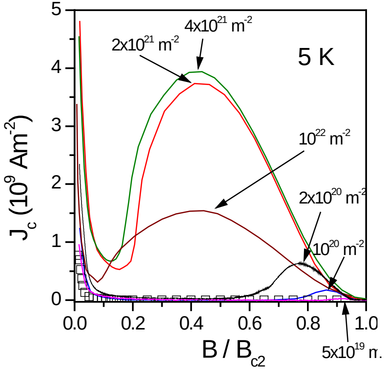
FLUX PINNING

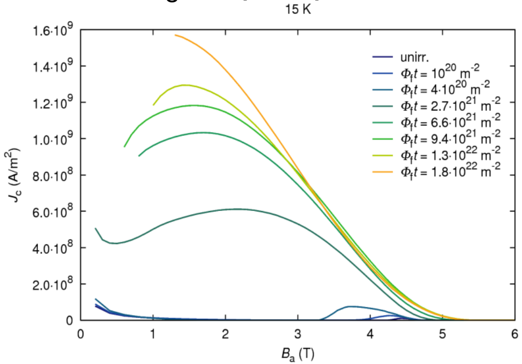
Defect density: low density limit

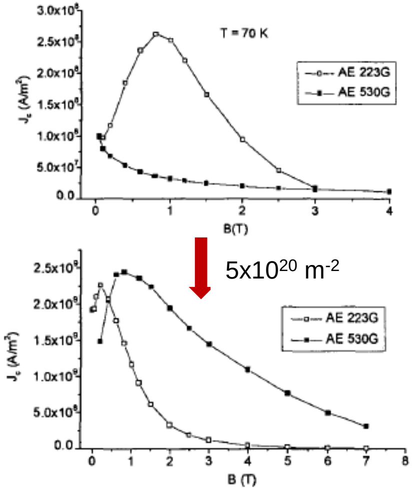
YBCO (sc)

MgB_2 (sc)

Nb_3Sn (bulk)







Zehetmayer et al.,
PRB 69 (2004) 054510

Baumgartner et al.,
unpublished

Köhler et al., Physica C
341-348 (2000) 1467

Fishtail effect occurs, order-disorder transition shifts to lower field with increasing defect density.

e.g. Mikitik and Brandt, PRB 69 (2004) 054510

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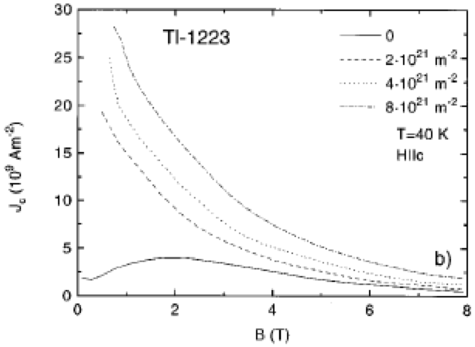
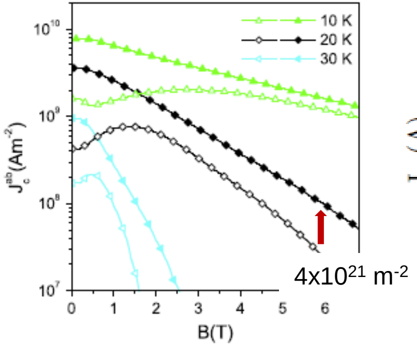
Defect density: optimum to high density limit



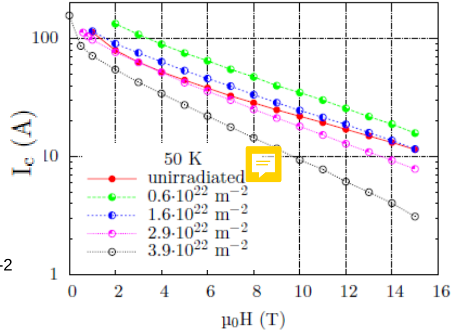
Brandstätter et al.,
PRB 55 (1997) 11693

$NdFeAsO_{0.65}F_{0.35}$



Eisterer et al.,
SUST 27 (2014) 044009

REBCO coated conductor



D. X. Fischer, PhD thesis,
TU Wien (2019)

Fishtail disappears, monotonous field dependence of J_c.

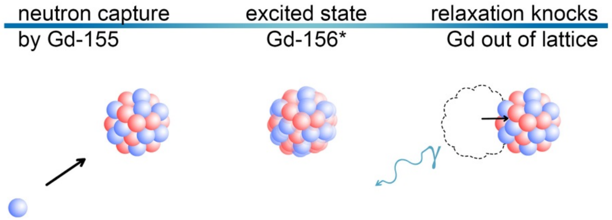
Defect size

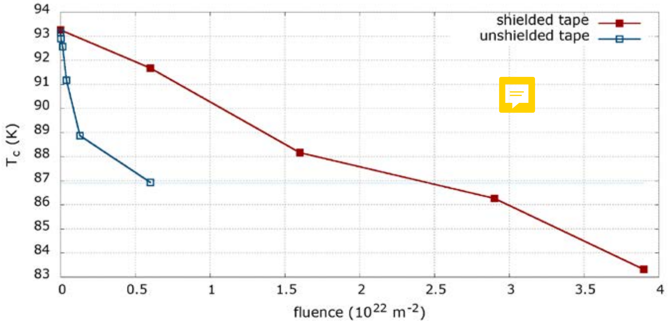
FLUX PINNING

Defect size: single displaced atoms

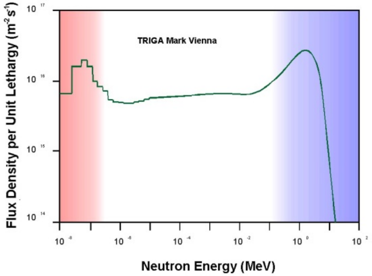
Gd-123 tapes:

^{157}Gd + n → ^{158}Gd + γ (σ ~ 2x10^5 b)
Recoil energy: ~ 30 eV
→ single displaced atom





Low energy neutrons can be shielded by Cd.



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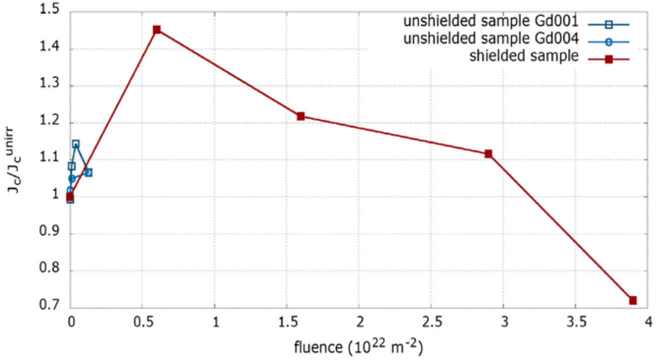
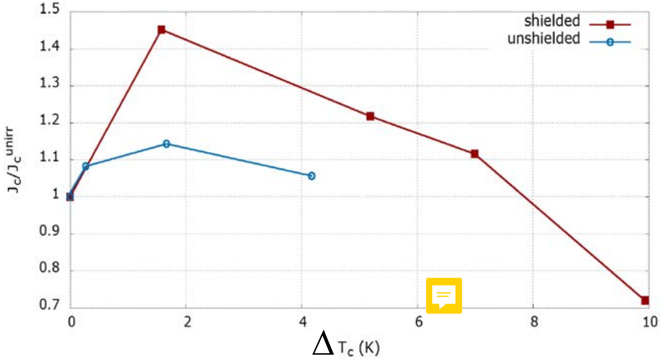
Defect size: single displaced atoms

30 K

Fluence dependence of J_c



J_c as function of T_c reduction



Small defects pin much weaker than collision cascades.

Conclusions

Neutron irradiation of superconducting materials offers the possibility to

- test the material for use in radiation environments (e.g fusion and accelerator magnets)
- benchmark the achievable currents
- investigate flux pinning (influence of anisotropy, defect size and density)
- learn about the intrinsic properties of the material (superconducting pairing symmetry, thermodynamic properties, e.g. J_d)