High fluence neutron irradiation of coated conductors

M. Eisterer
Atominstitut, Vienna University of Technology
Stadionallee 2, 1020 Vienna, Austria

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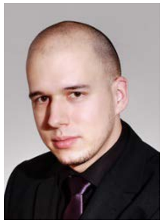
Outline

- Motivation: lifetime/design of fusion power plant/accelerator magnet
- Neutron induced damage
- Influence of radiation damage
  - Transition temperature
  - Critical currents
- Comparison: Coated conductors and Nb_3Sn
- Outlook

Acknowledgments


Rainer Prokopec


Thomas Baumgartner


David Fischer


Harald Weber

Former PhD students: Johann Emhofer, Michal Chudy
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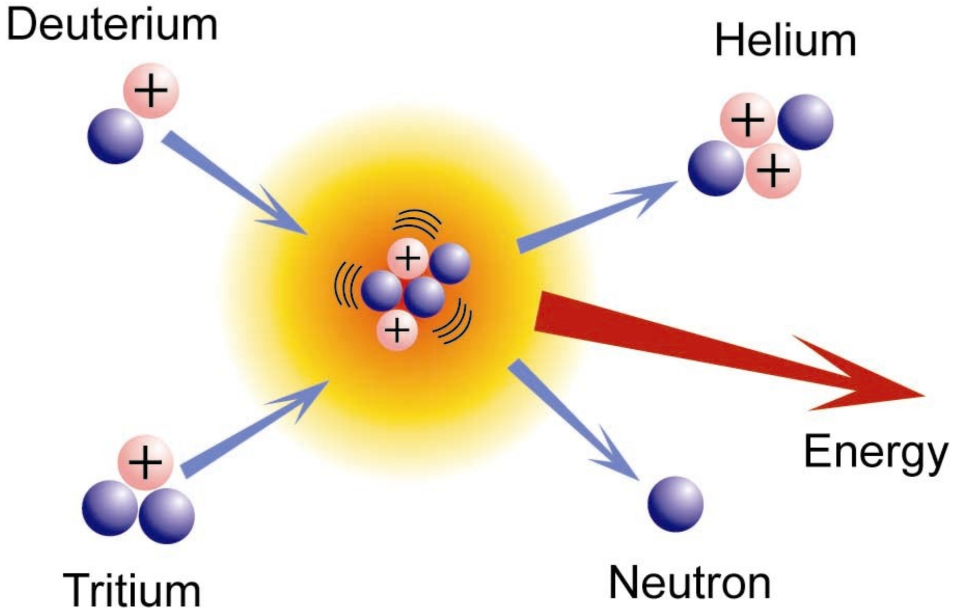
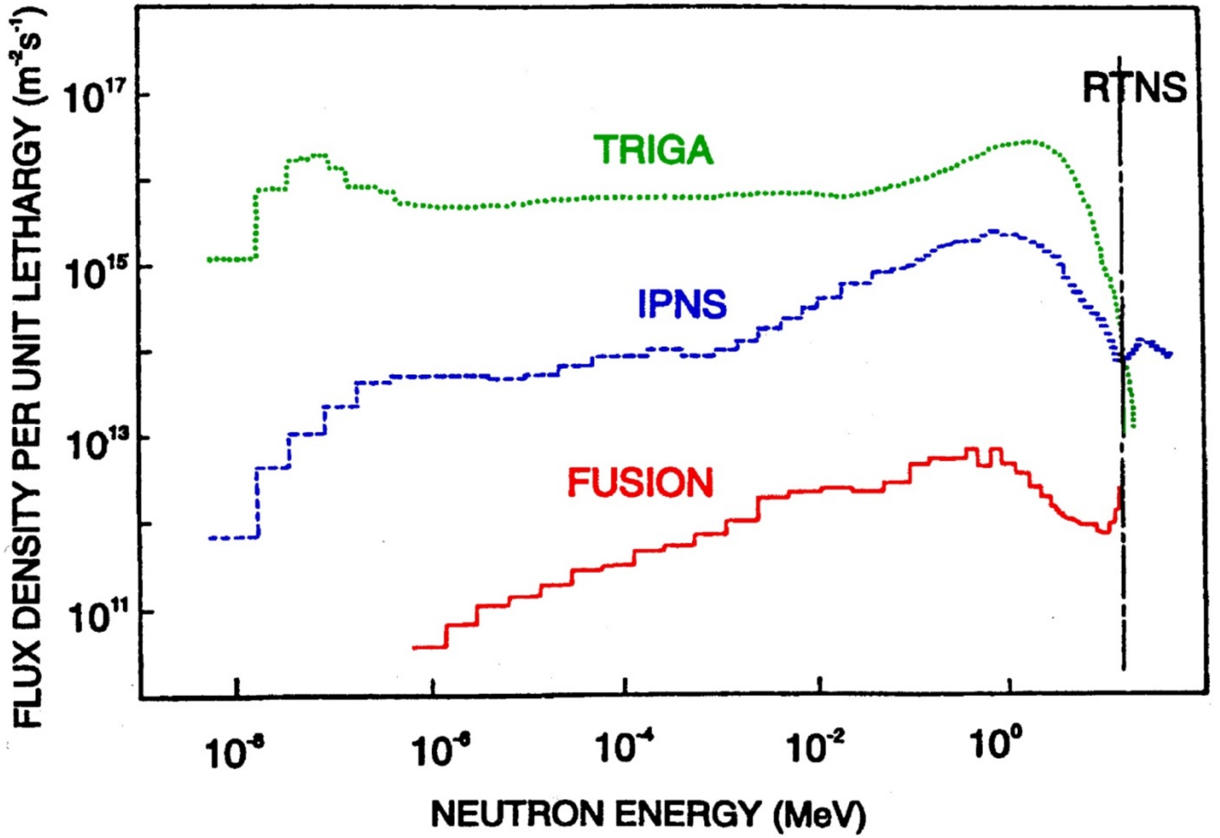
Nuclear Fusion



Production of 14 MeV neutrons – deposition of energy in the “first wall” → substantial material problems (~1 MW/m^2)!

At the magnet location: Attenuation by a factor of ~ 10^6. Scattering processes lead to a “thermalization” of the neutrons!

Neutron Energy Distribution



Motivation

The superconducting properties do degrade at high neutron fluences.

- Lifetime of the power plant/accellerator magnet
- Radiation shielding

Influence on the costs and competitiveness of nuclear fusion!

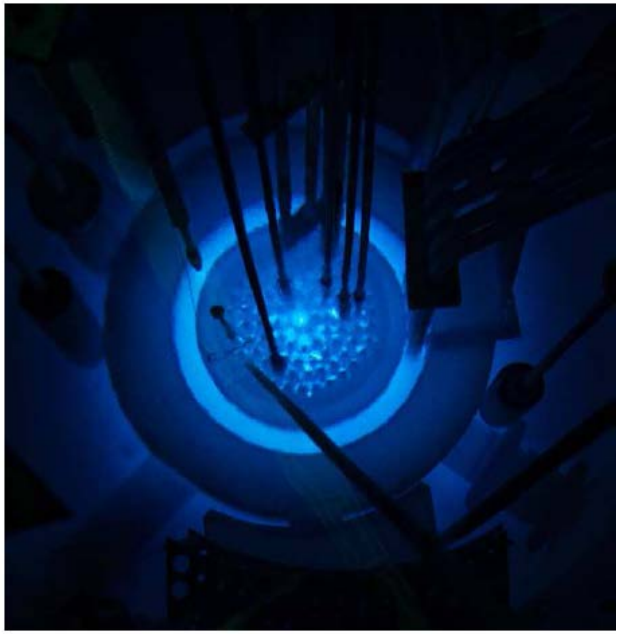
Which superconductor can withstand the highest radiation load?

NEUTRON IRRADIATION AND RESULTING DEFECT STRUCTURE

TRIGA MARK II Reactor

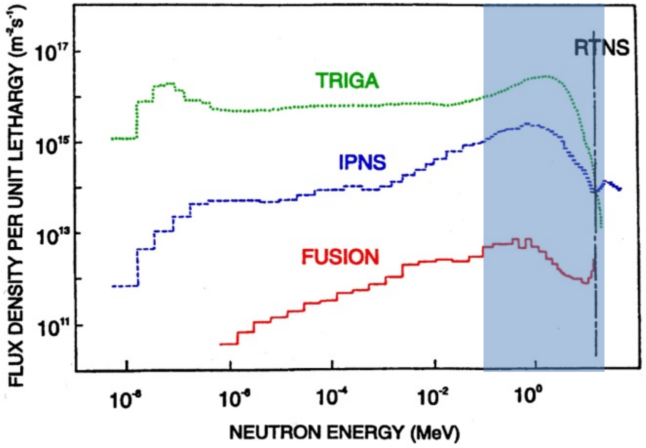
Neutron flux determination in 1985:
Thermal (<0.55 eV) / fast (>0.1 MeV) flux density: $6.1/7.6 \times 10^{16}\ m^{-2}s^{-1}$

Core renewed in 2012: fast neutron flux density of ~ $4.1 \times 10^{16}\ m^{-2}s^{-1}$



Nickel monitor is used in each irradiation!

Neutron Irradiation: Created Defects (Cuprates)



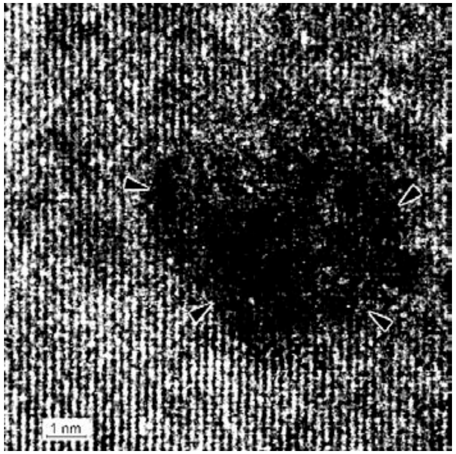
Direct collisions
(high energy neutrons E>0.1 MeV)

Defect cascades

Ø ~ 5 nm

Density

$5 \cdot 10^{22}$ m^{-3} at a fluence of 10^{22} m^{-2}
(d_{av}~ 27 nm, B_ϕ~ 3 T)
$2.5 \cdot 10^{23}$ m^{-3} at a fluence of $5 \cdot 10^{22}$ m^{-2}
(d_{av}~ 16 nm, B_ϕ~ 8 T)



Defect structure YBCO: small defects

Positron annihilation lifetime spectroscopy (PALS)
Slovak University of Technology: Cu-O di-vacancies

Veterníková et al., J. Fusion Energy 31 (2012) 89

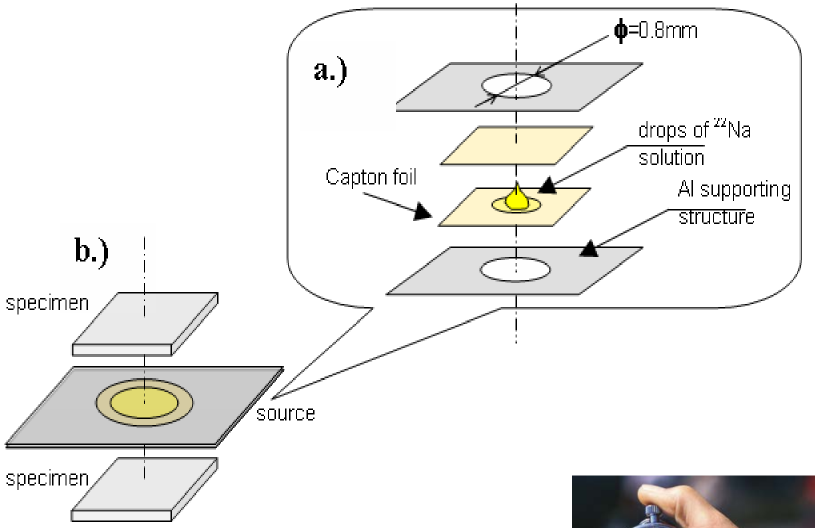


Table 1 Typical lifetime for bulk and defects [22–24]

	Lifetime (ps)	Binding energy (eV)
$YBa_2Cu_3O_7$ [22]	159	–
$YBa_2Cu_3O_7$ [23]	190	
O vacancy	~170	~0.2
O vacancy cluster (2–4 vacancies)	181–190	0.1–0.2
Cu (1) vacancy	207	1.1
Cu (2) vacancy	182	0.7
Y vacancy	206	2.7
Ba vacancy	263	3.5
Cu (1)–O (1) di-vacancy	236	1.5

1274 keV

511 keV

$$^{22}\mathrm{Na} \xrightarrow{2.6y} {}^{22}\mathrm{Ne}\ (+\gamma)\ +e^+, \qquad e^+ + e^- \rightarrow 2\gamma$$

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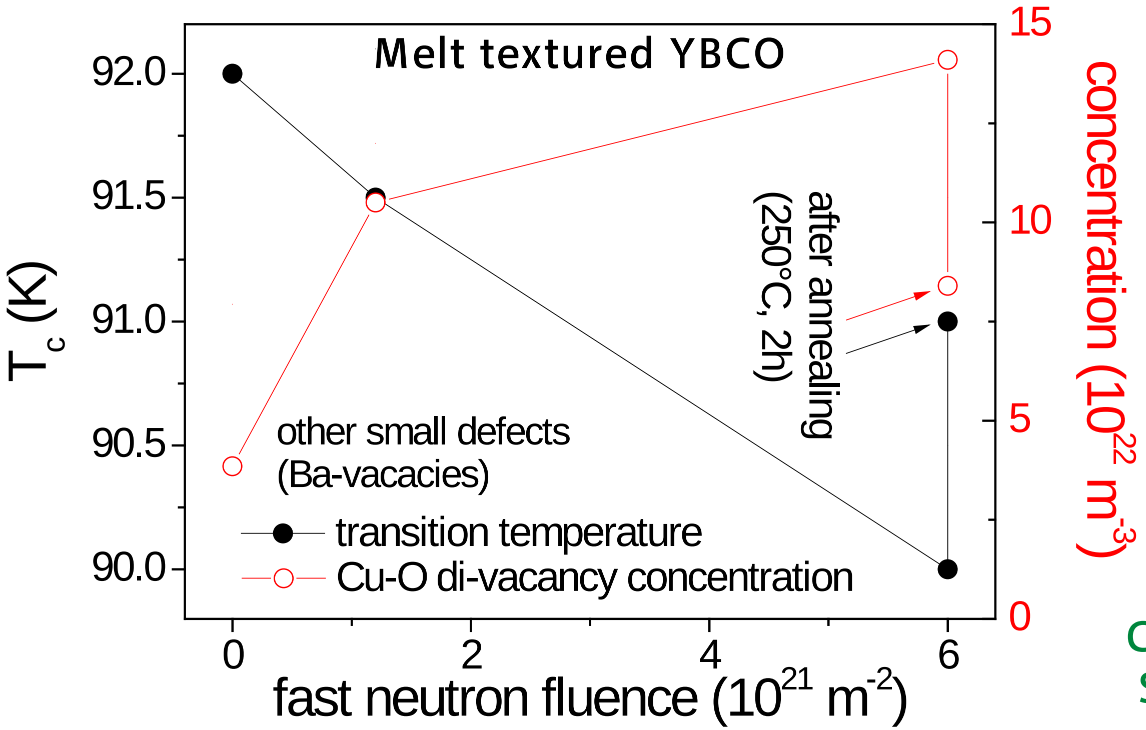
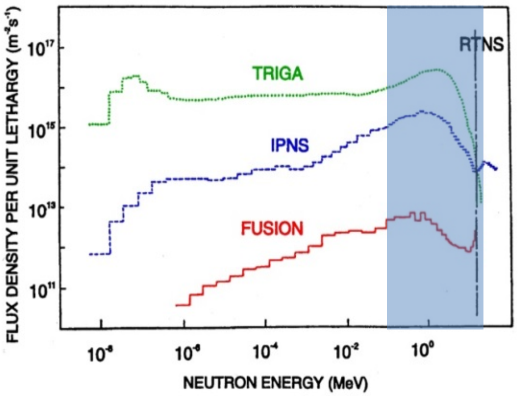




Chudý et al.,
SUST 25 (2012) 075017

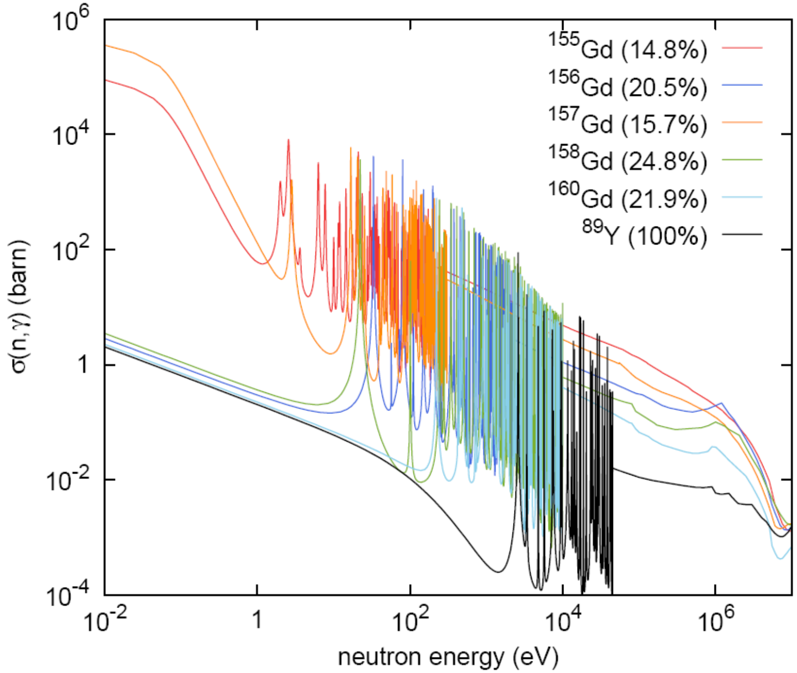
Cu-O di-vacancy concentration: highly non-linear with fluence!

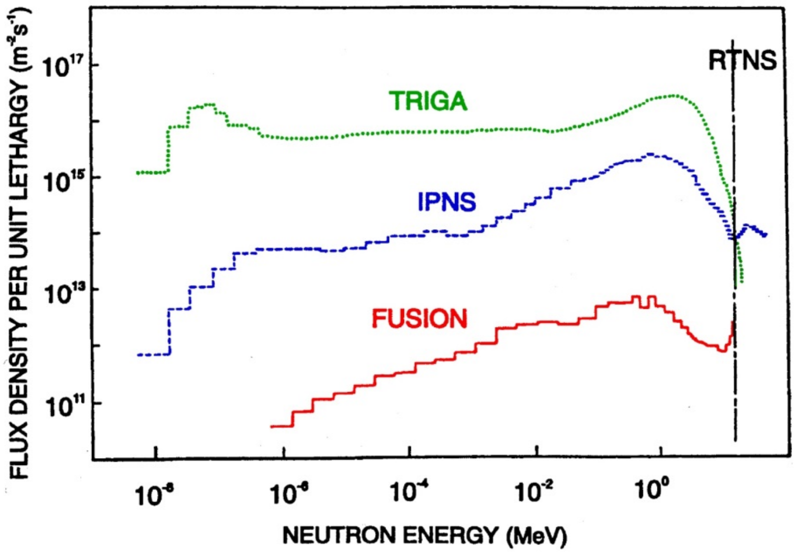
Neutron Irradiation: Created Defects

Neutron capture reactions (low energy neutrons)

$^{157}\mathrm{Gd} + \mathrm{n} \rightarrow {}^{158}\mathrm{Gd} + \gamma$ ($\sigma \sim 2\mathrm{x}10^5$ b)

Recoil energy: ~ 30 eV → single displaced atom

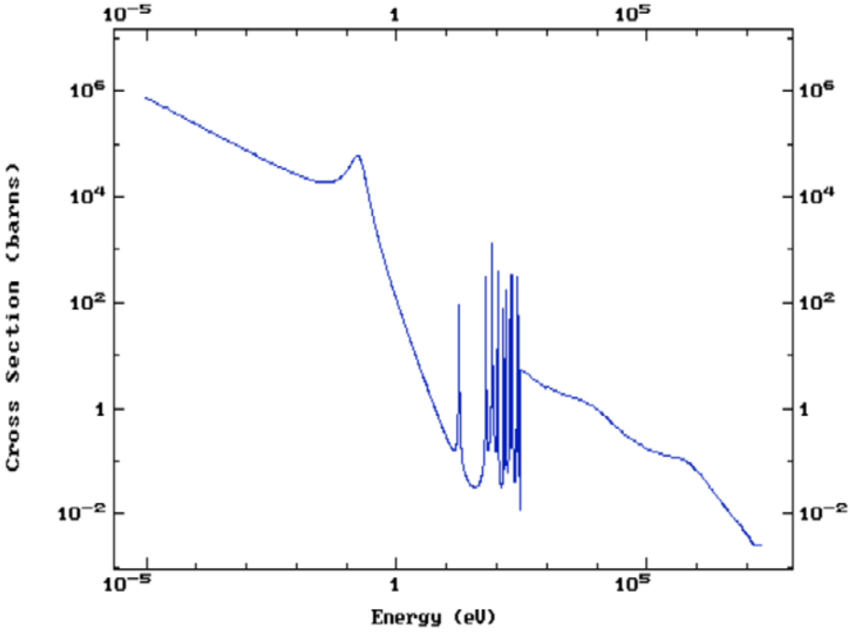


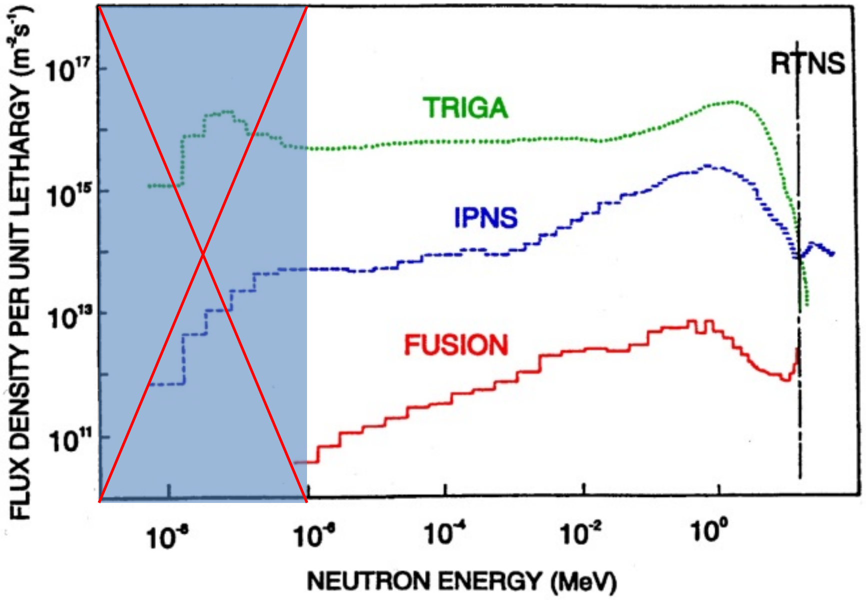


Shielding of thermal neutrons

Irradiation inside Cd-foil: Removes the low energy neutrons (E<0.55 eV)
Better simulation of a fusion spectrum

Cadmium



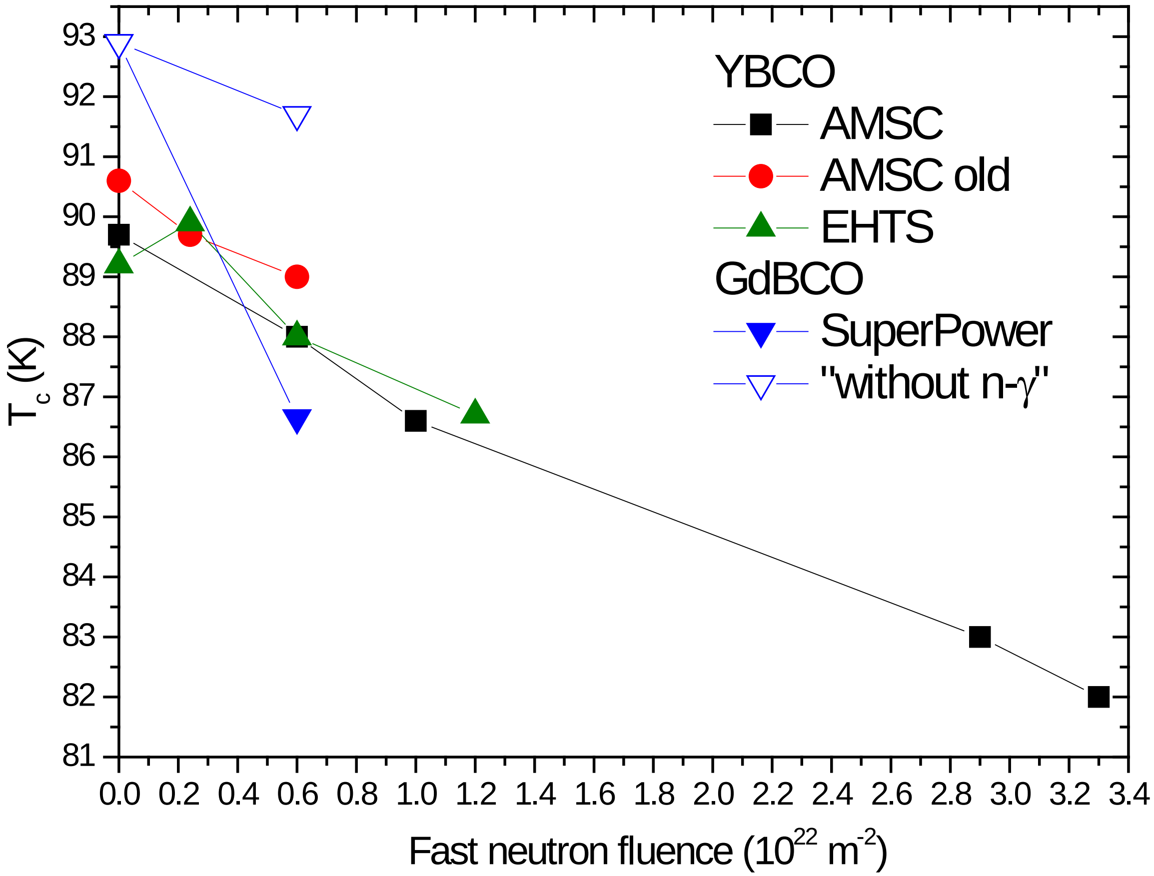


Samples

- **AMSC 344C Amperium (ASC-40)**
  - **RABiTS template**
  - ***RE*****BCO by MOD Y:Dy:Ba:Cu=1:0.5:2:3 (1.2 μm)**
  - **Brass laminated**
- SuperPower SCS4050/SCS4050-AP
  - Hastelloy MgO-IBAD Template
  - GdBCO by MOD (1 μm)
  - BZO nano-particles (SCS4050-AP)
- SuNam
  - SS MgO-IBAD Template
  - GdBCO by RCE-DR (1.35 μm)

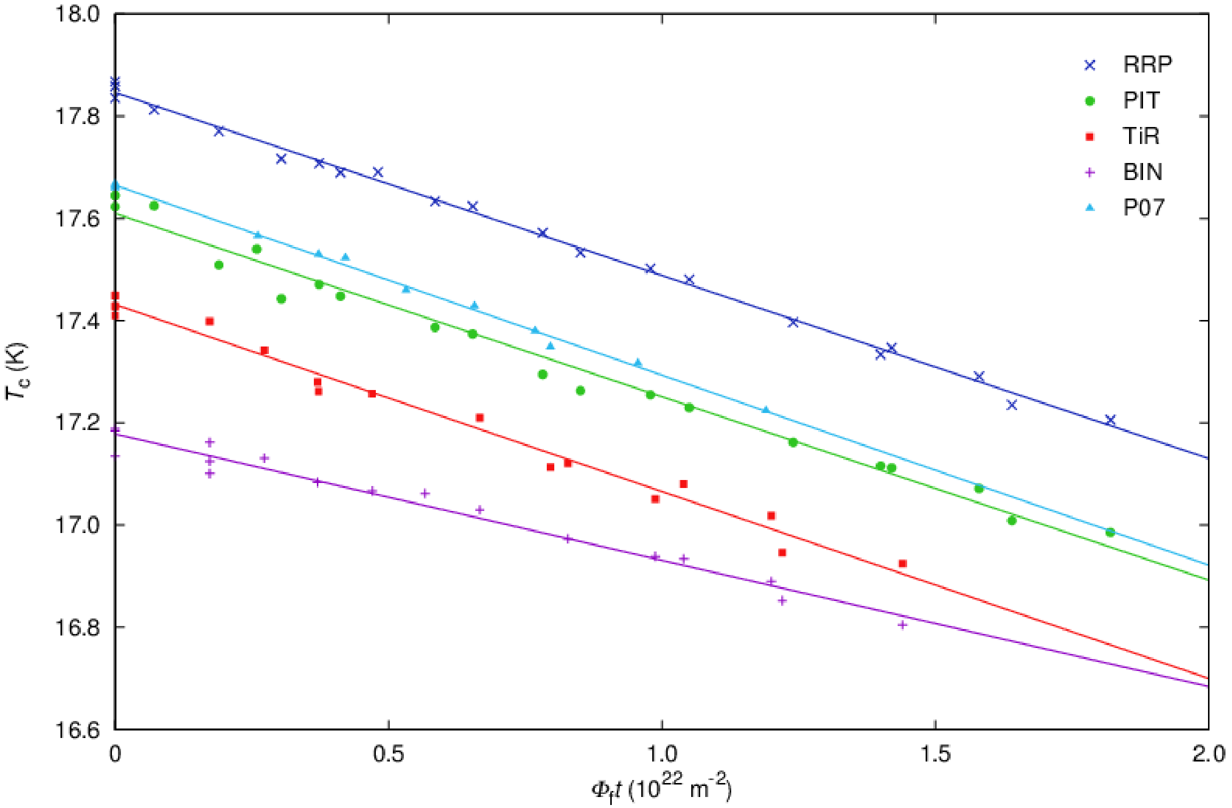
CHANGES OF SUPERCONDUCTING PROPERTIES

Decrease in Transition Temperature



Decrease in T_c: ~2.5 K at a fluence of 10^{22} m^{-2} (2.7%)

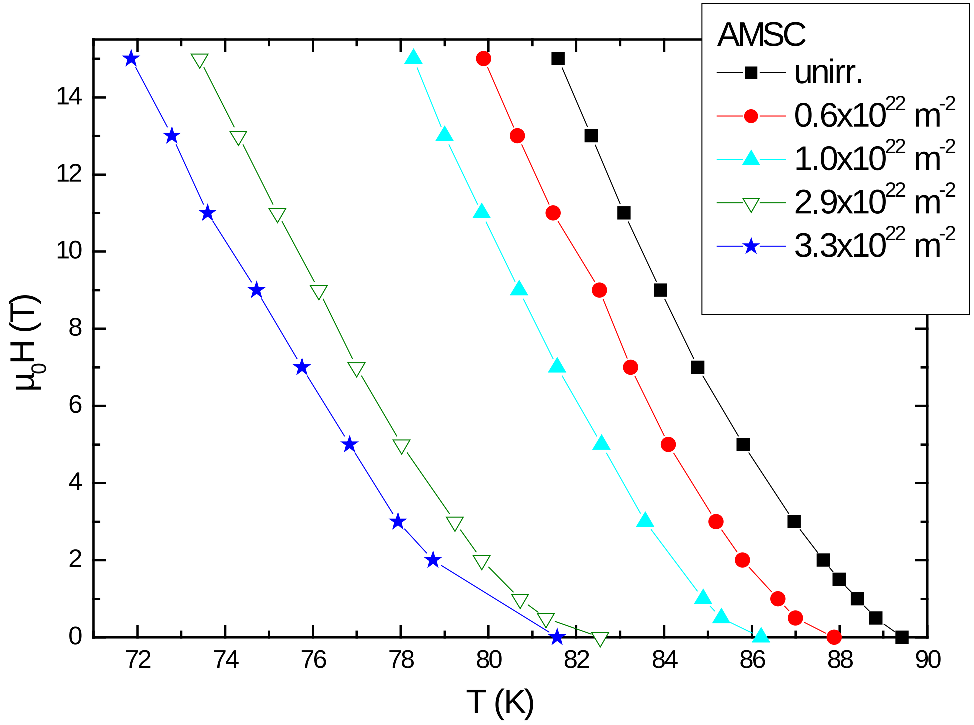
Decrease in Transition Temperature: Nb_3Sn



Decrease in T_c: ~0.35 K at a fluence of 10^{22} m^{-2} (2%)

Change in Irreversibility Field

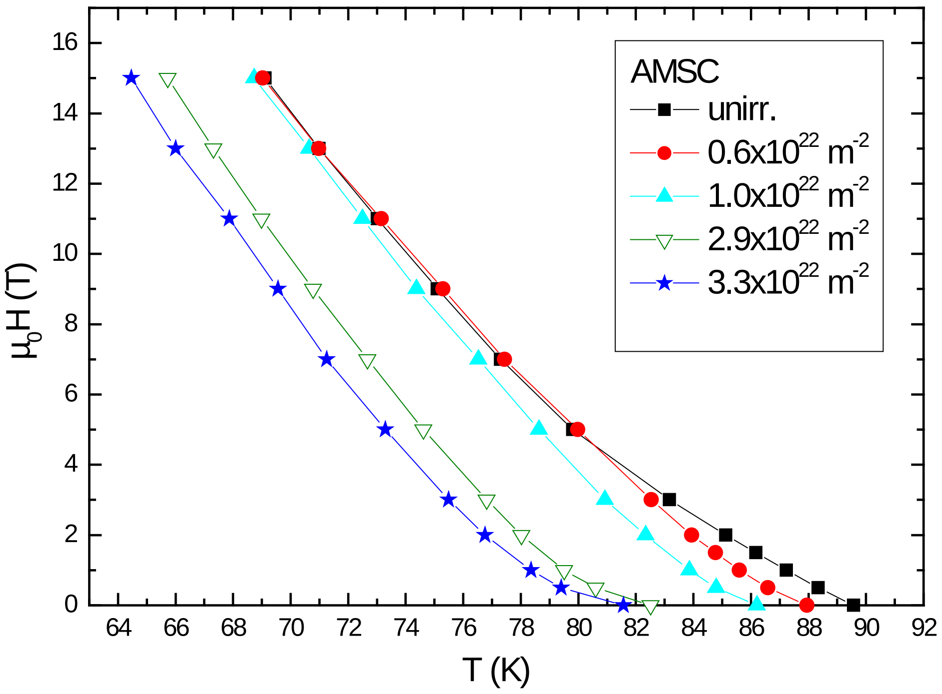
H||ab



B_{irr} shifts with T_c to lower temperatures

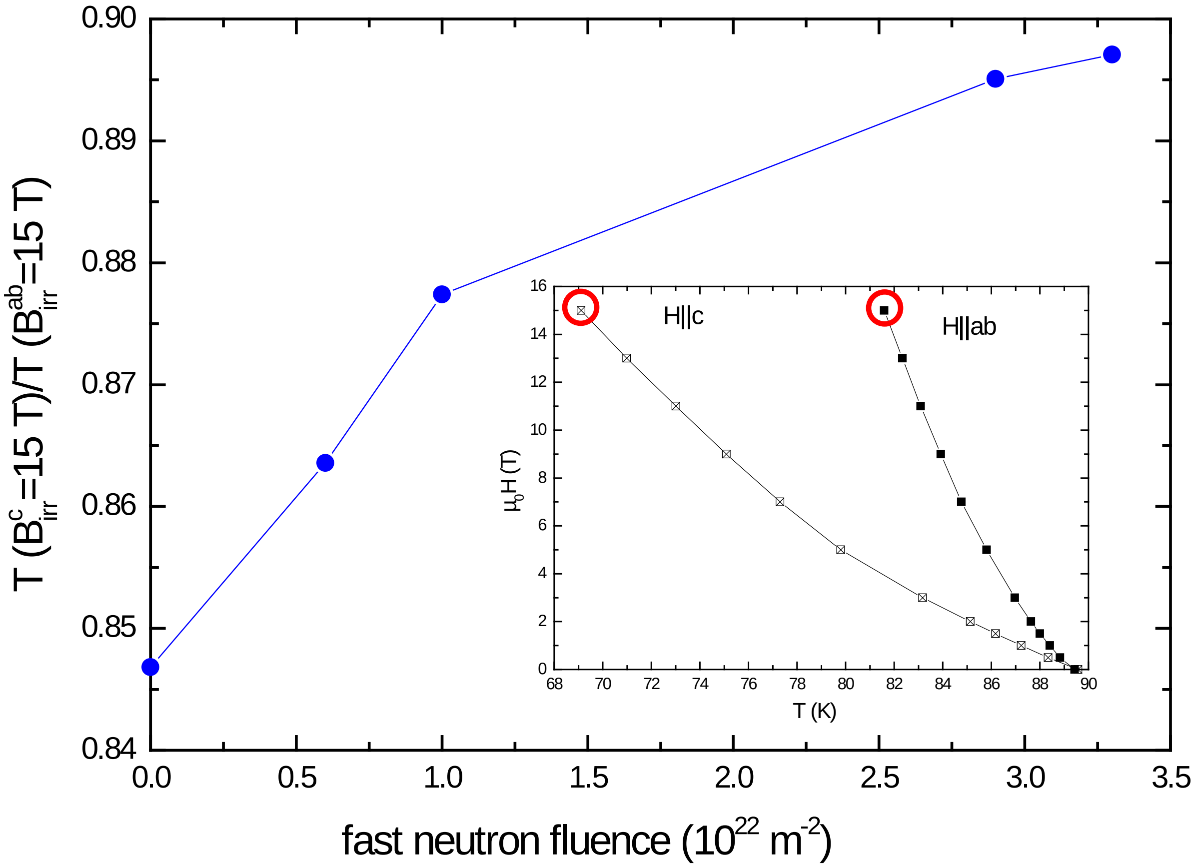
Change in Irreversibility Field

H||c



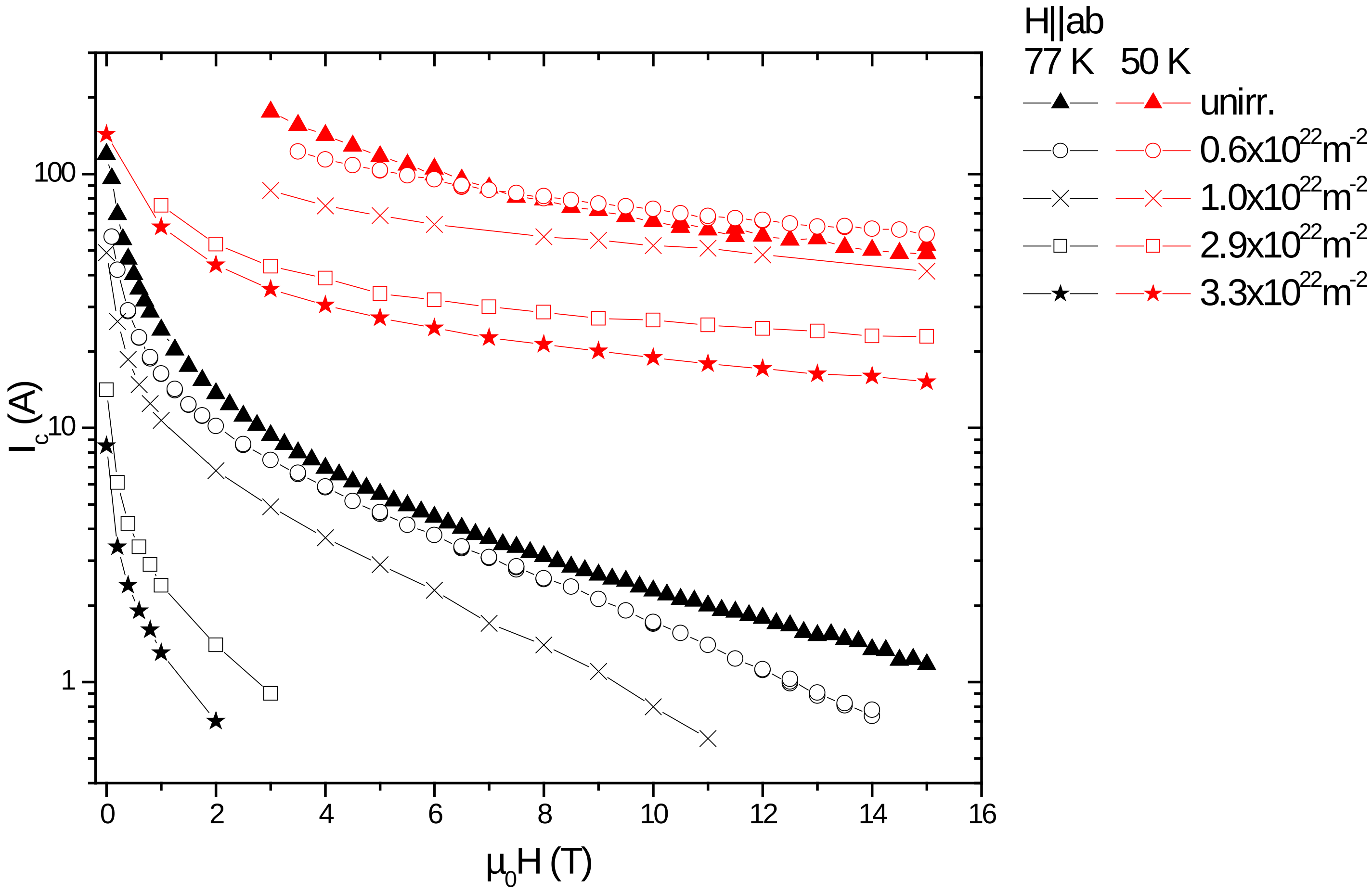
B_{irr} shifts to lower temperatures, but the slope increases.

Anisotropy of B_{irr}



Critical Currents: AMSC (YBCO)

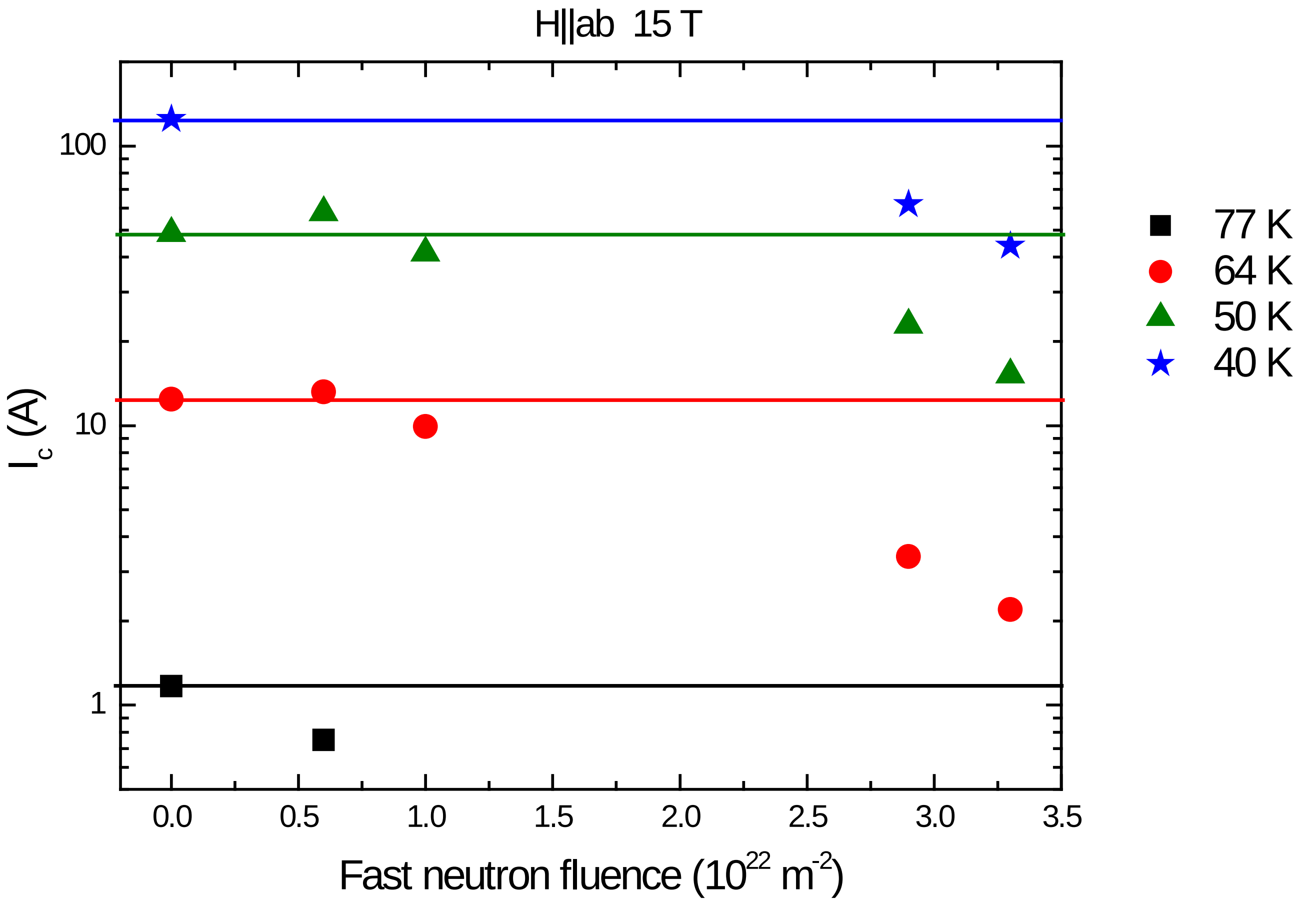
H||ab



Degradation of the critical current for H||ab.

Critical Currents: AMSC (YBCO)

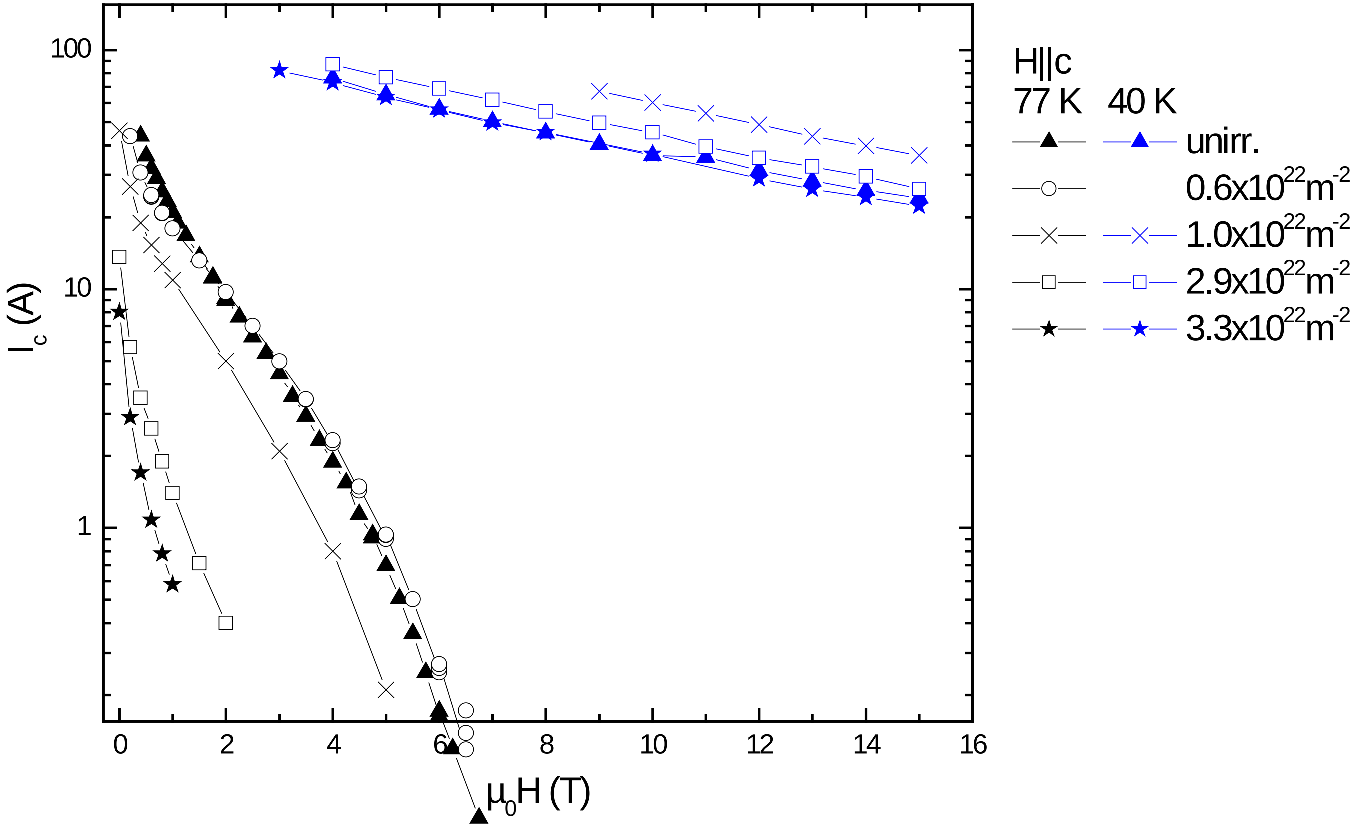
H||ab



Degradation of the critical current for H||ab.

Critical Currents: AMSC (YBCO)

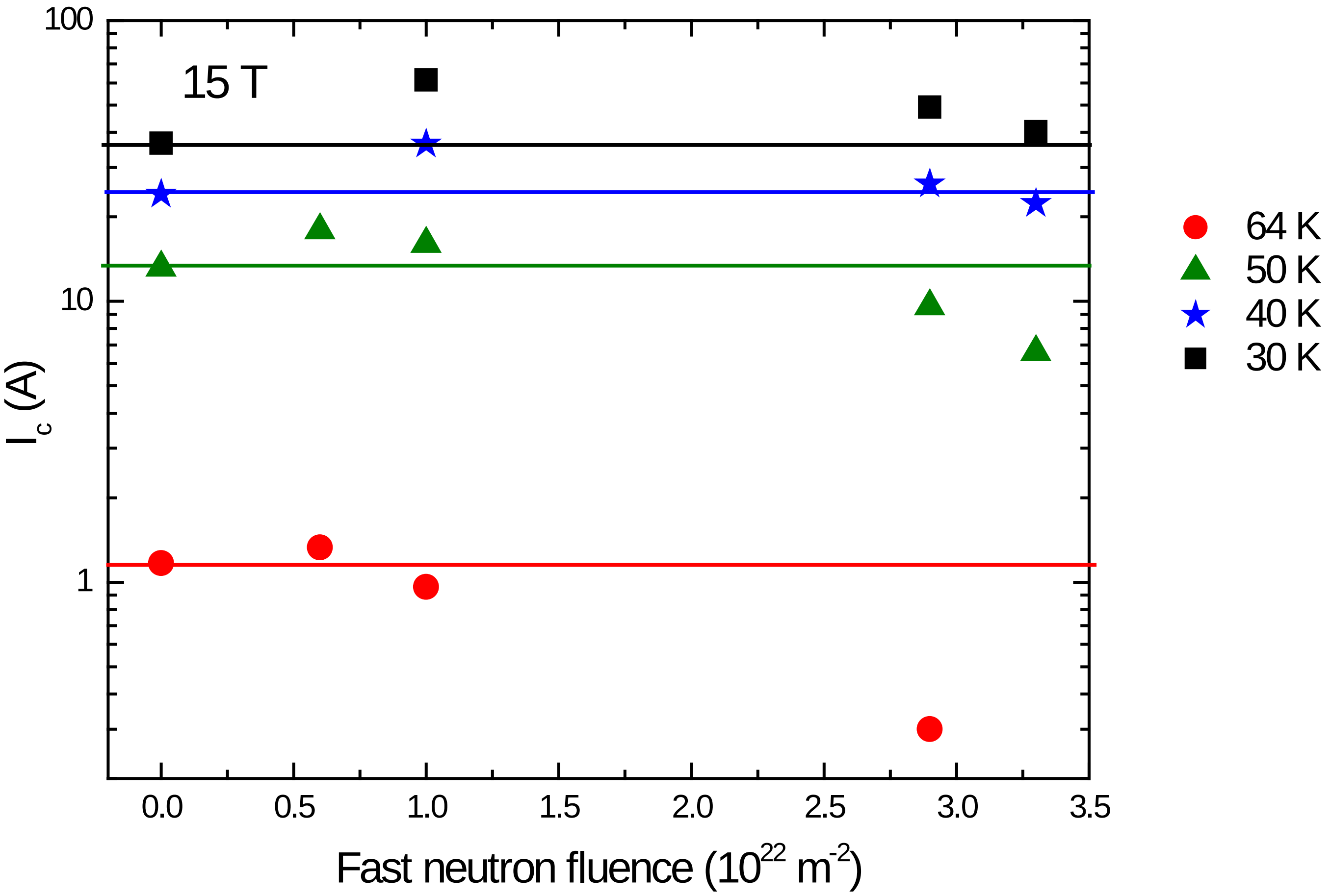
H||c



Degradation of the critical current starts at higher fluences for H||c.

Critical Currents: AMSC (YBCO)

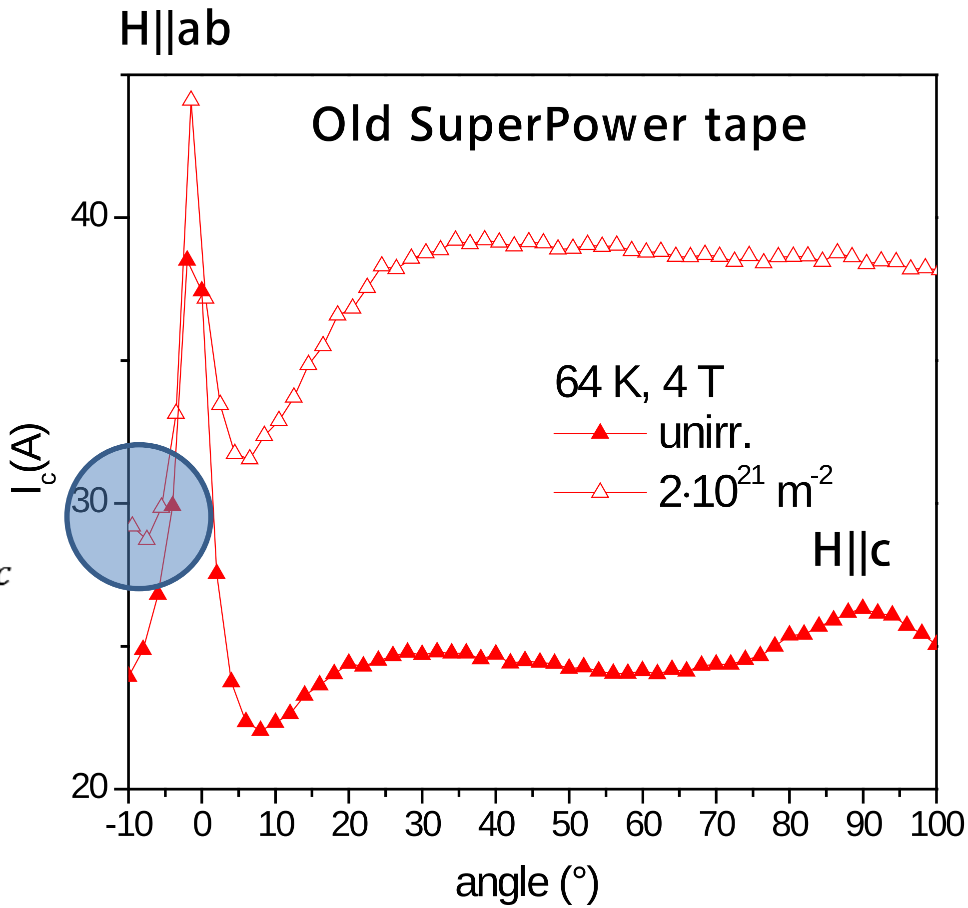
H||c



The critical currents at low temperatures and high fields are still (3.3×10^{22} m^{-2}) above the original values.

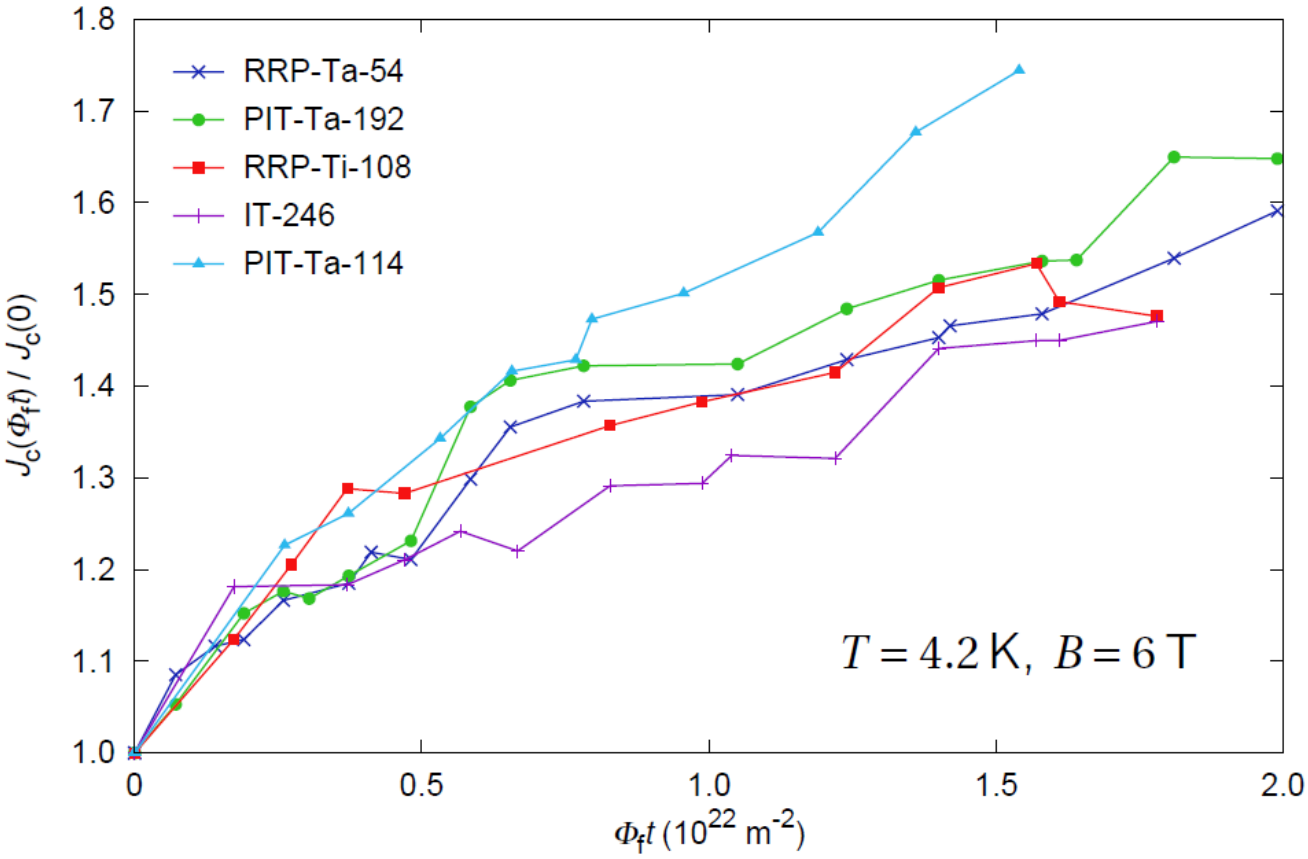
Angular dependence of I_c

Important: $\min_\theta I_c$
Degradation?

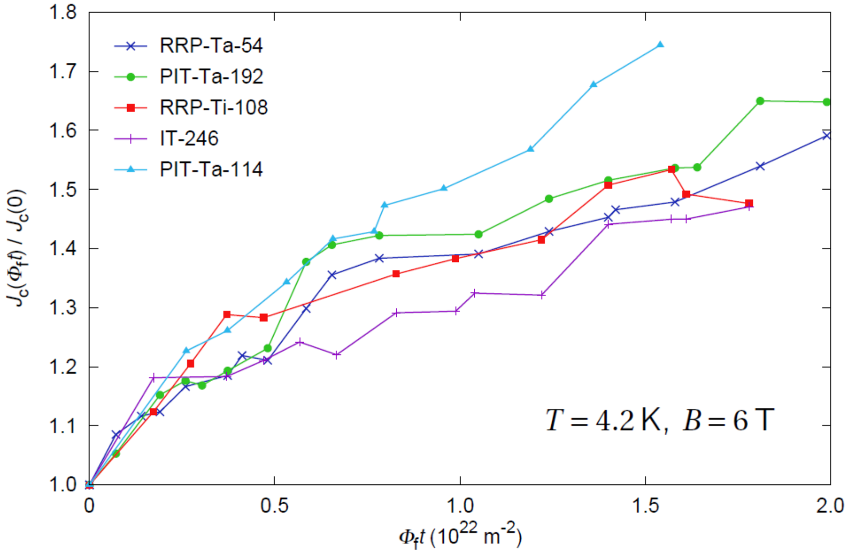


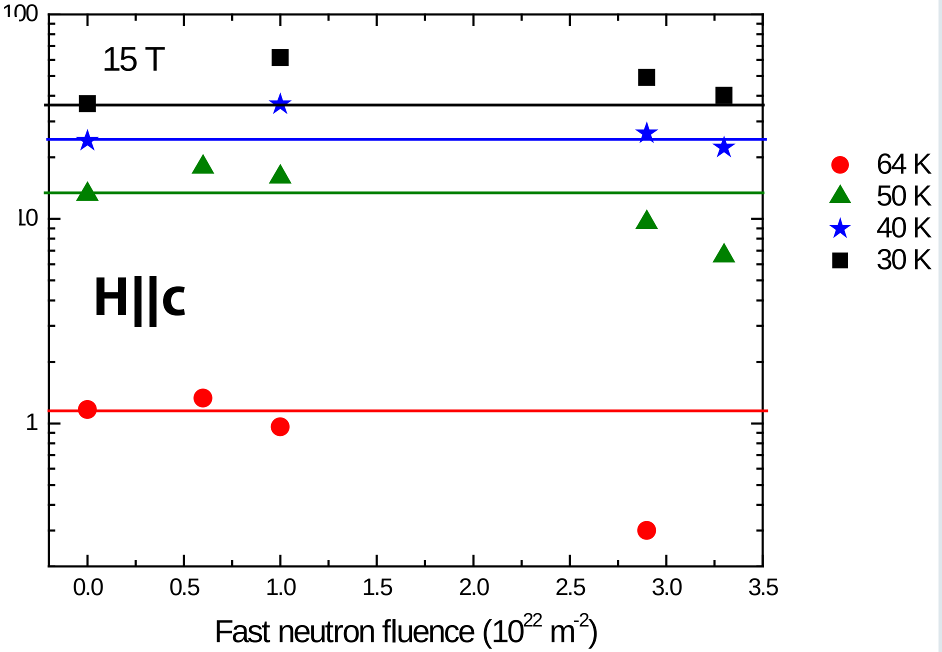
Minimum I_c is not always at H||c.
Angle-resolved measurements are desirable.

Critical Current: Nb_3Sn



Critical Currents: Comparison YBCO – Nb_3Sn

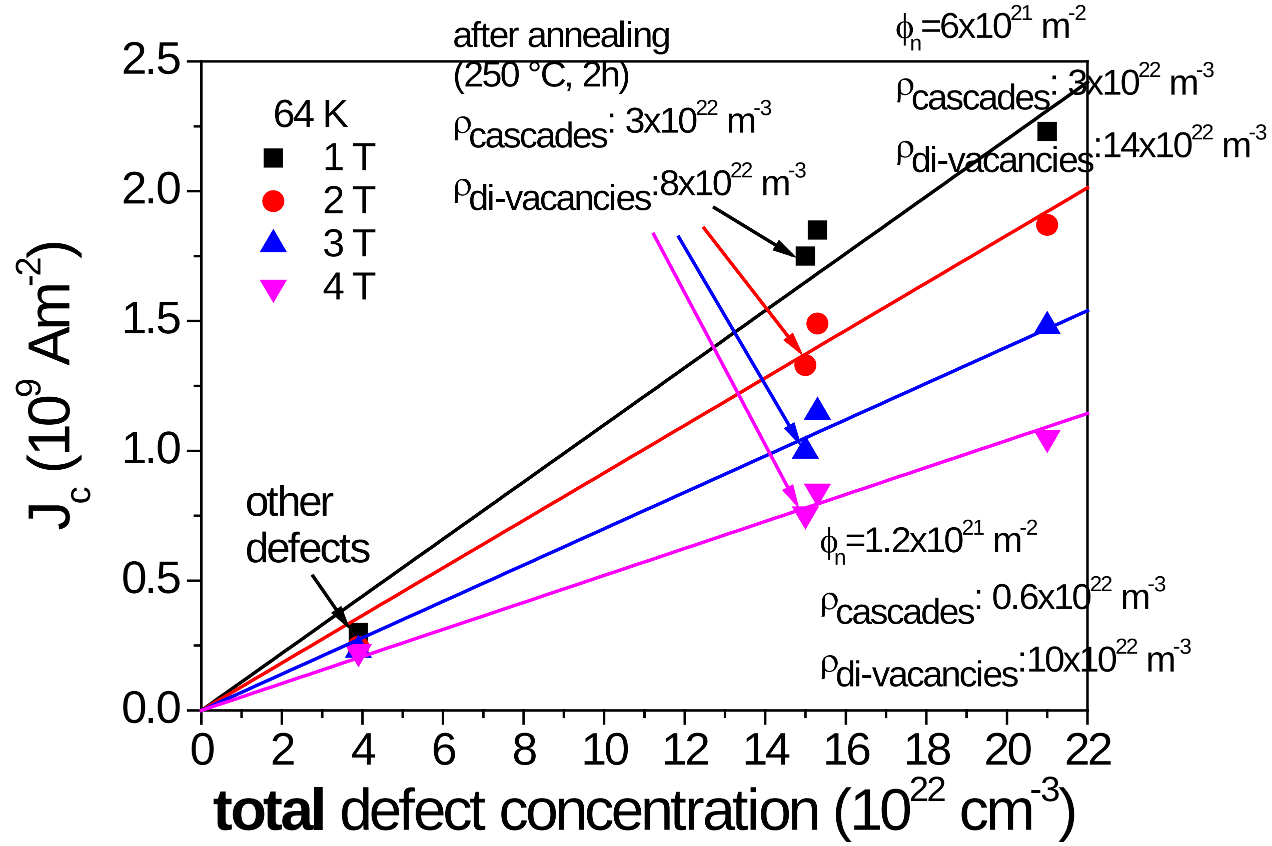




Which compound is more robust against irradiaton?

WHICH DEFECTS ARE RESPONSIBLE FOR FLUX PINNING?

Large vs. small defects (melt textured YBCO)



Linear scaling with total (cascades+di-vacancies) defect density!
Annealing possible?

Conclusions

- It is currently not clear if Nb_3Sn or *RE*BCO is more robust against neutron irradiation at low temperatures.
- The radiation resistance decreases at higher temperatures. Restriction to low temperatures (LH_2?).
- I_c degrades in coated condutctors at rather low fluences for H||ab. The tape becomes less anisotropic.

Outlook

- Characterization of irradiated tapes from AMSC, SuNam and Superpower (2.3/2.9/3.2x10^{22} m^{-2})
- Irradiation until properties severely degrade
  - Coated conductors
  - Nb$_3$Sn wires
- Thermal annealing