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Recent neutron irradiation experiments on HTS coated conductors and Nb$_3$Sn wires

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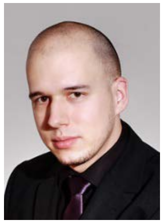
Outline

- Neutron Irradiation
  - TRIGA reactor
  - Neutron induced damage
- HTS coated conductor for fusion magnets
  - EUROFUSION
- Nb_3Sn for accelerator magnets
  - LHC Upgrade (collaboration with CERN)
- Comparison: Coated conductors and Nb_3Sn
- Conclusions

Acknowledgments


Rainer Prokopec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David Fischer


Harald Weber

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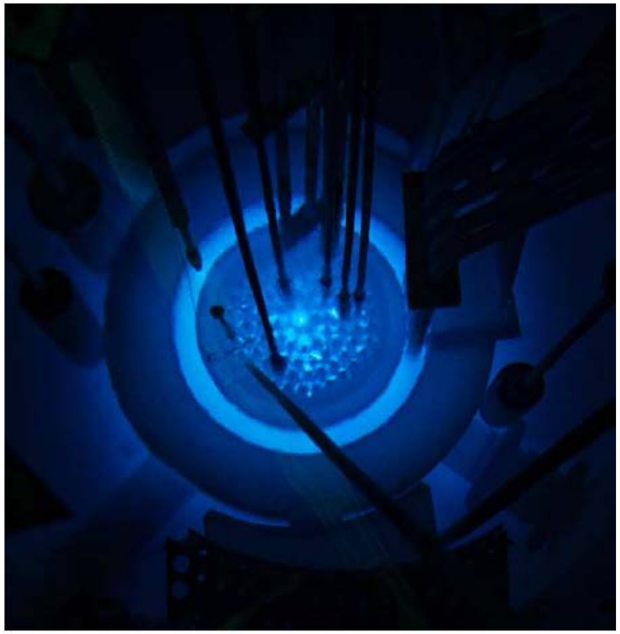
Samples provided by AMSC, SuperPower, SuNam
Funding: EFDA/EUROFUSION, CERN

NEUTRON IRRADIATION AND RESULTING DEFECT STRUCTURE

TRIGA MARK II Reactor

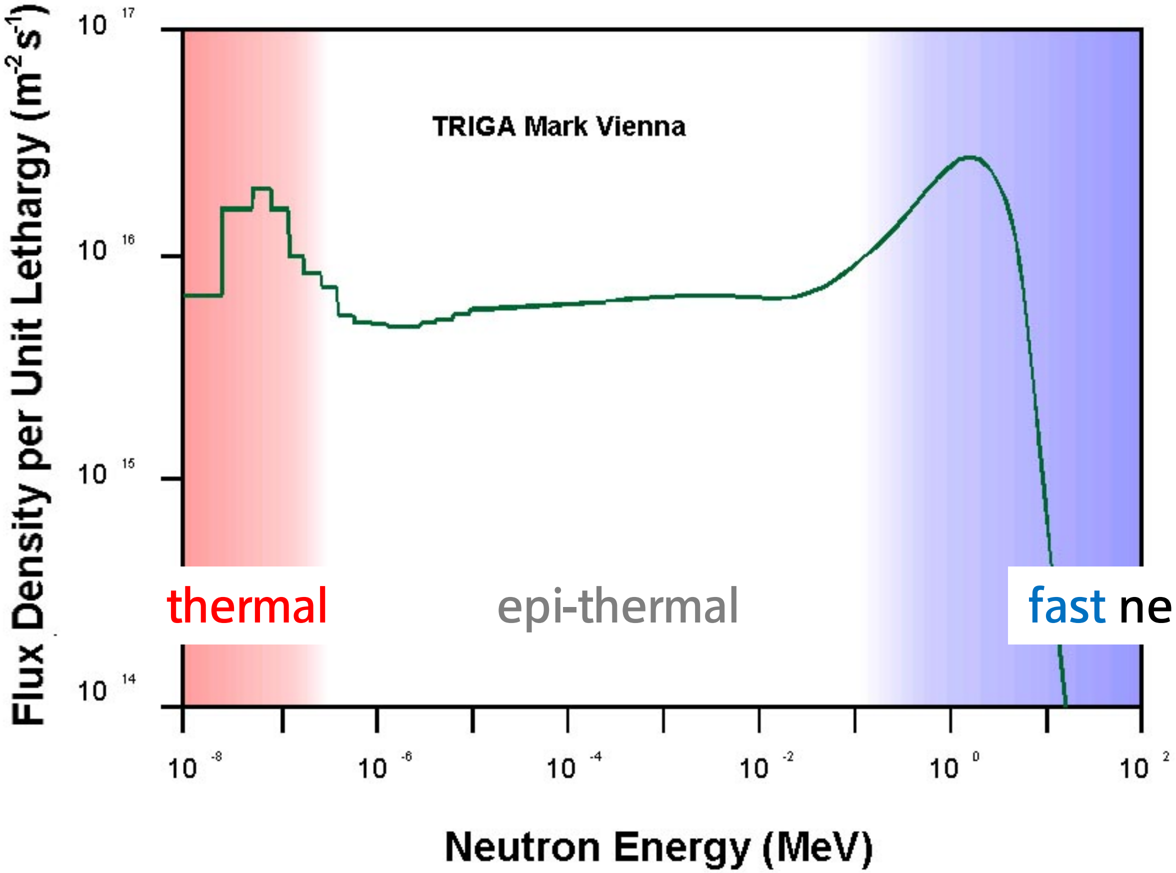
Neutron flux determination in 1985:
Thermal (<0.55 eV) / fast (>0.1 MeV) flux density: 6.1/7.6 × 10^{16} $m^{-2}s^{-1}$
γ - radiation: ~ 1MGy/h

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



Nickel monitor is used in each irradiation!

Neutron energy distribution

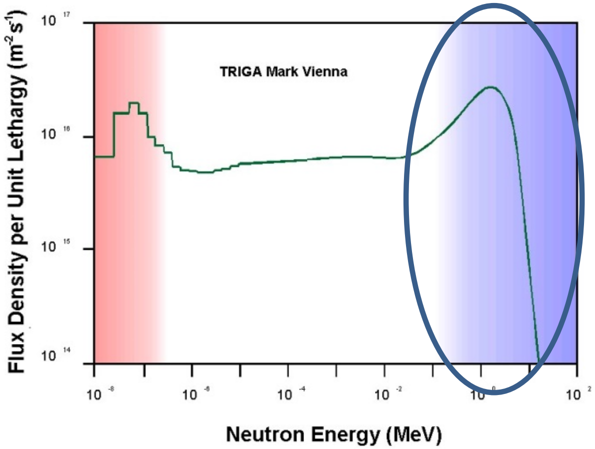


thermal

epi-thermal

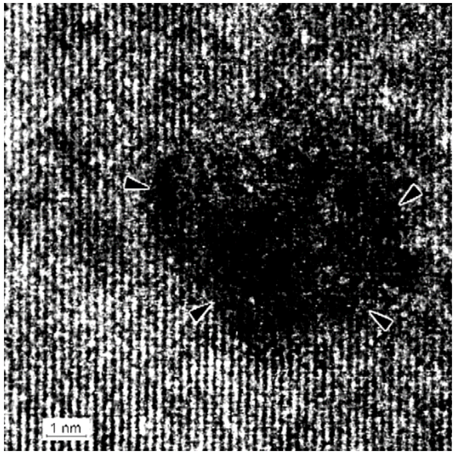
fast neutrons

Neutron Irradiation: Created Defects (Cuprates)



Direct collisions
(high energy (fast) neutrons E>0.1 MeV)

Largest defects: collision cascades
Ø ~ 5 nm
Density
$5\cdot10^{22}$ m^{-3} at a fluence of 10^{22} m^{-2}
(d_{av}~ 27 nm, B_{ϕ}~ 3 T)



Nb_3Sn

Clusters of point defects

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

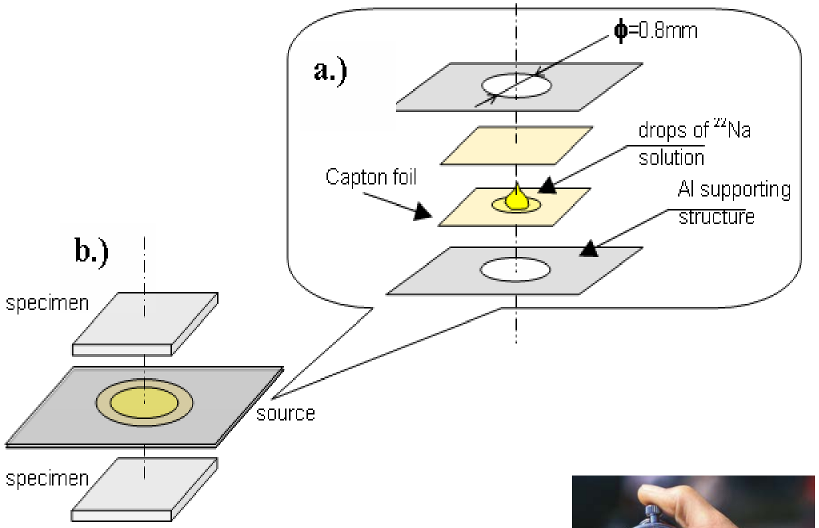


Table 1 Typical lifetime for bulk and defects [22–24]

	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

$$^{22}\mathrm{Na} \xrightarrow{2.6y} {}^{22}\mathrm{Ne}\ (+\overset{1274\ \mathrm{keV}}{\gamma}) + e^+, \qquad e^+ + e^- \rightarrow 2\overset{511\ \mathrm{keV}}{\gamma}$$

Defect structure YBCO: small defects

Positron annihilation lifetime spectroscopy (PALS): Cu-O di-vacancies

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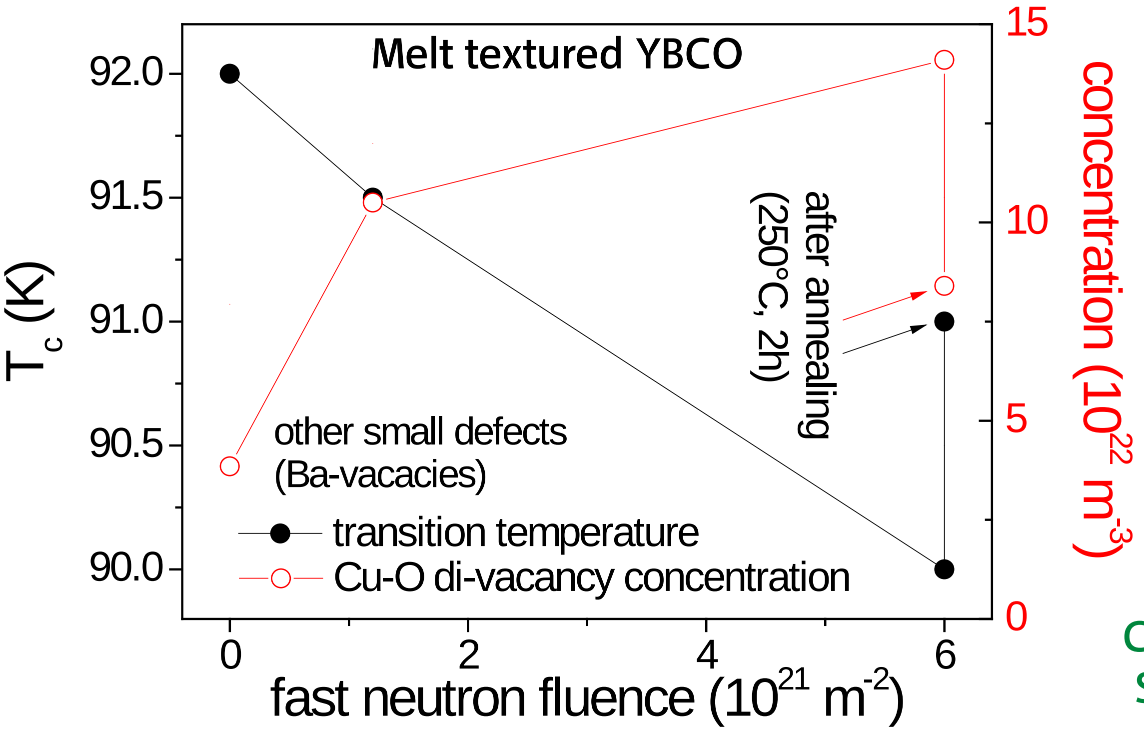
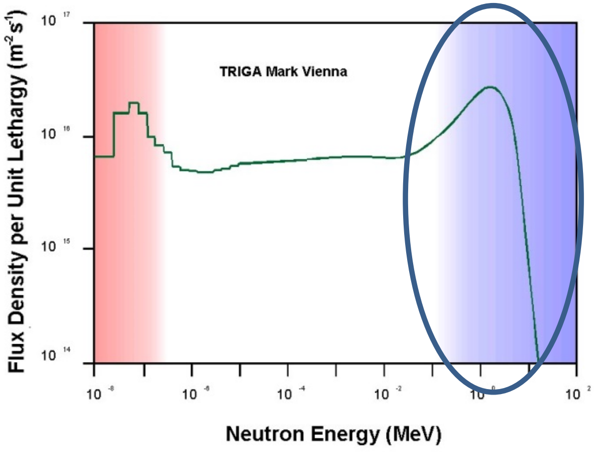




Chudý et al.,
SUST 25 (2012) 075017

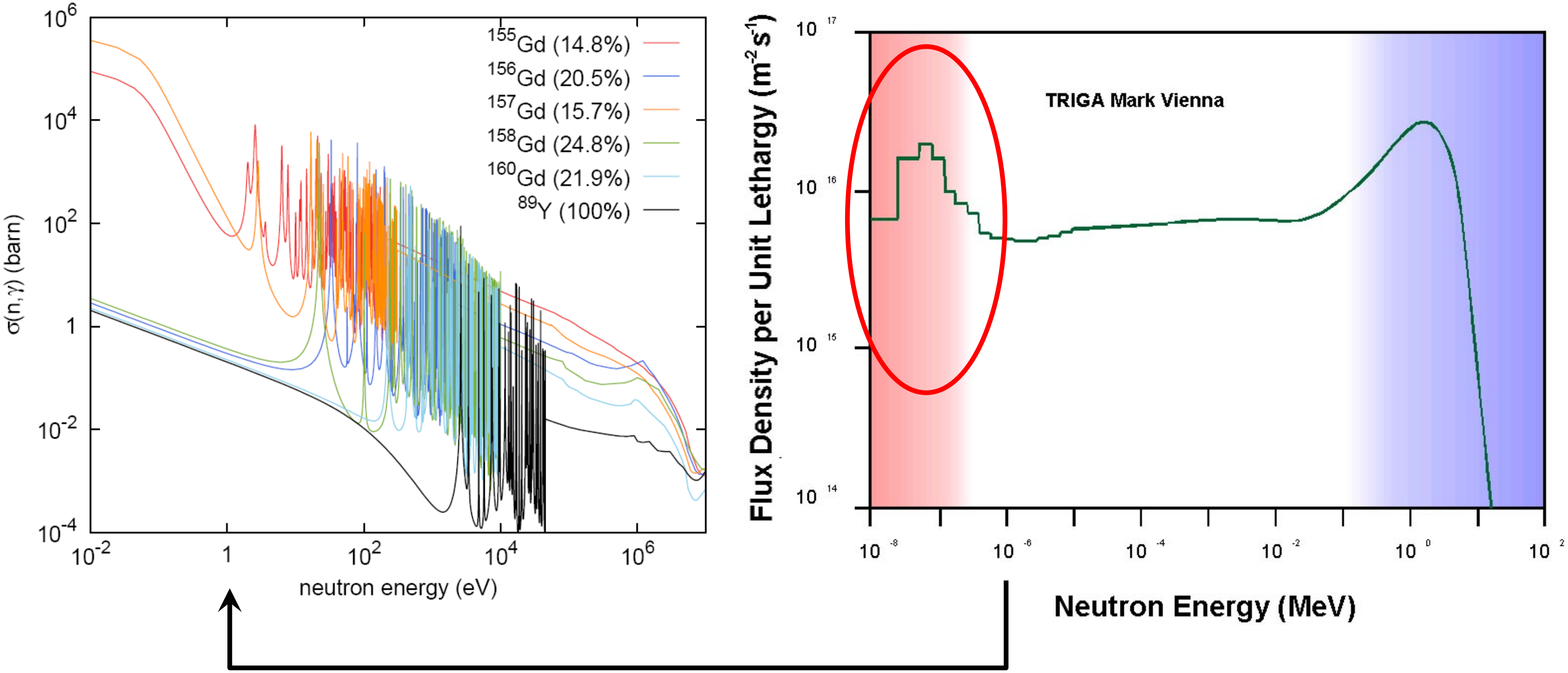
Cu-O di-vacancy concentration: highly non-linear with fluence!

Neutron Irradiation: Created Defects

Neutron capture reactions (low energy neutrons)

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

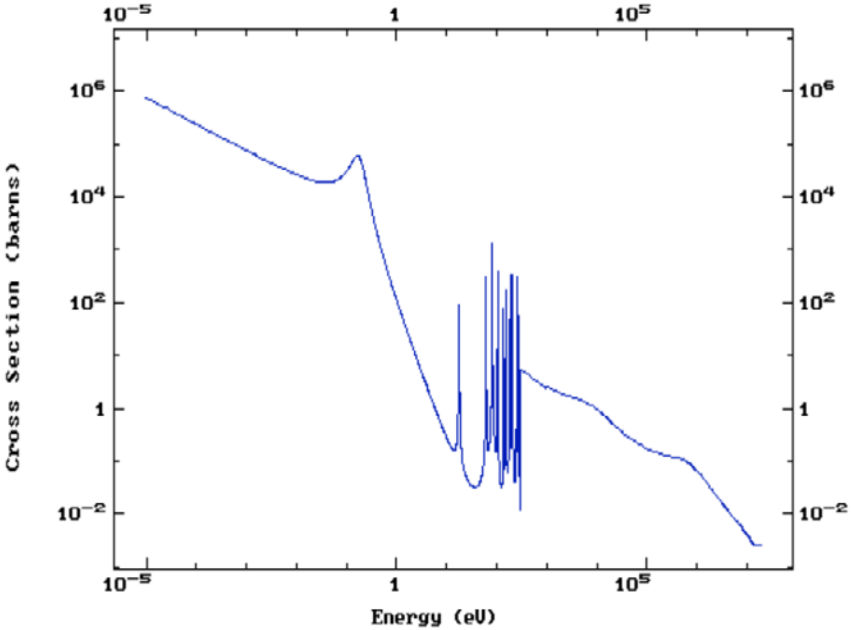
Recoil energy: ~ 30 eV → single displaced atom

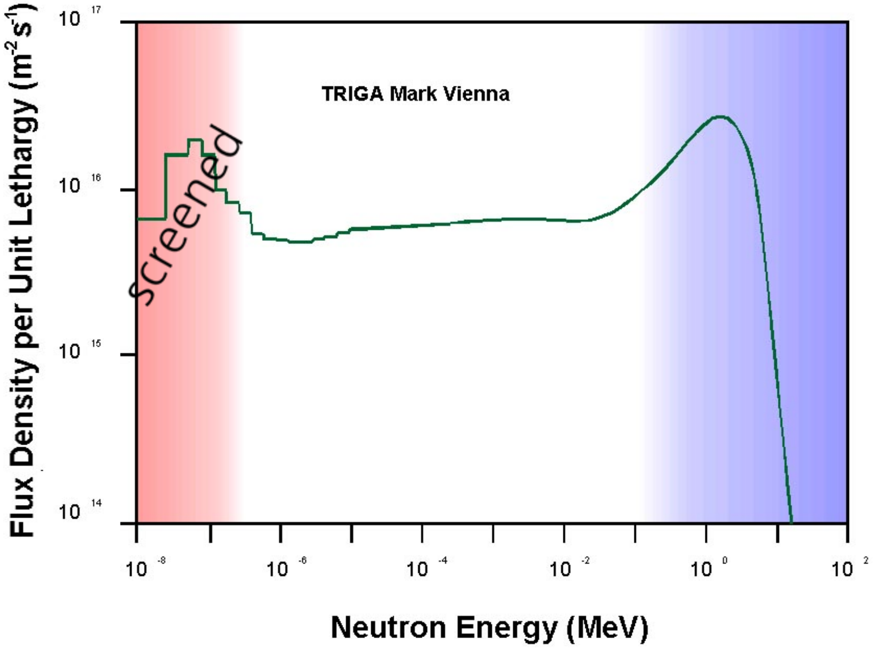


Shielding of thermal neutrons

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

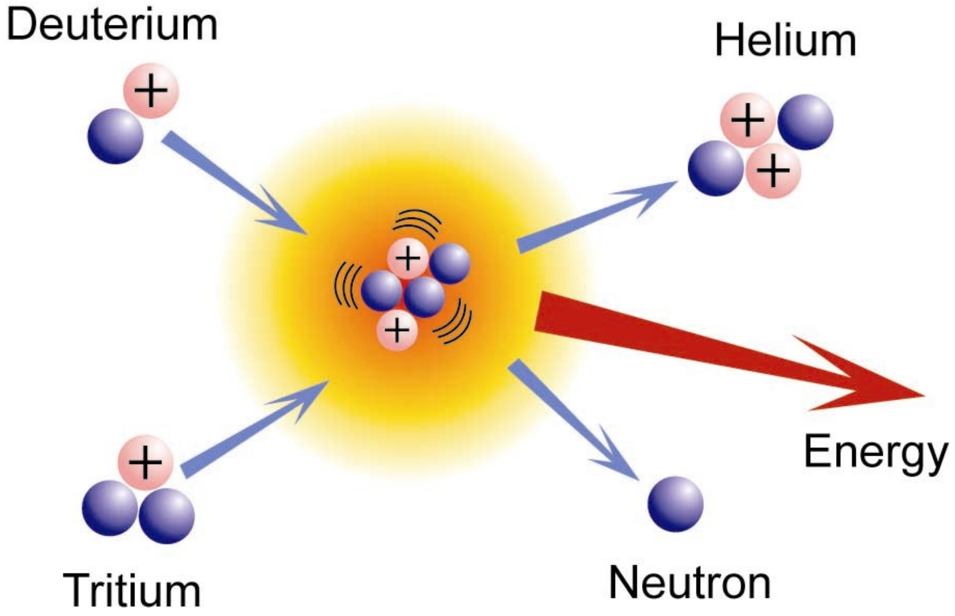
Cadmium





HTS COATED CONDUCTORS FOR FUSION MAGNETS

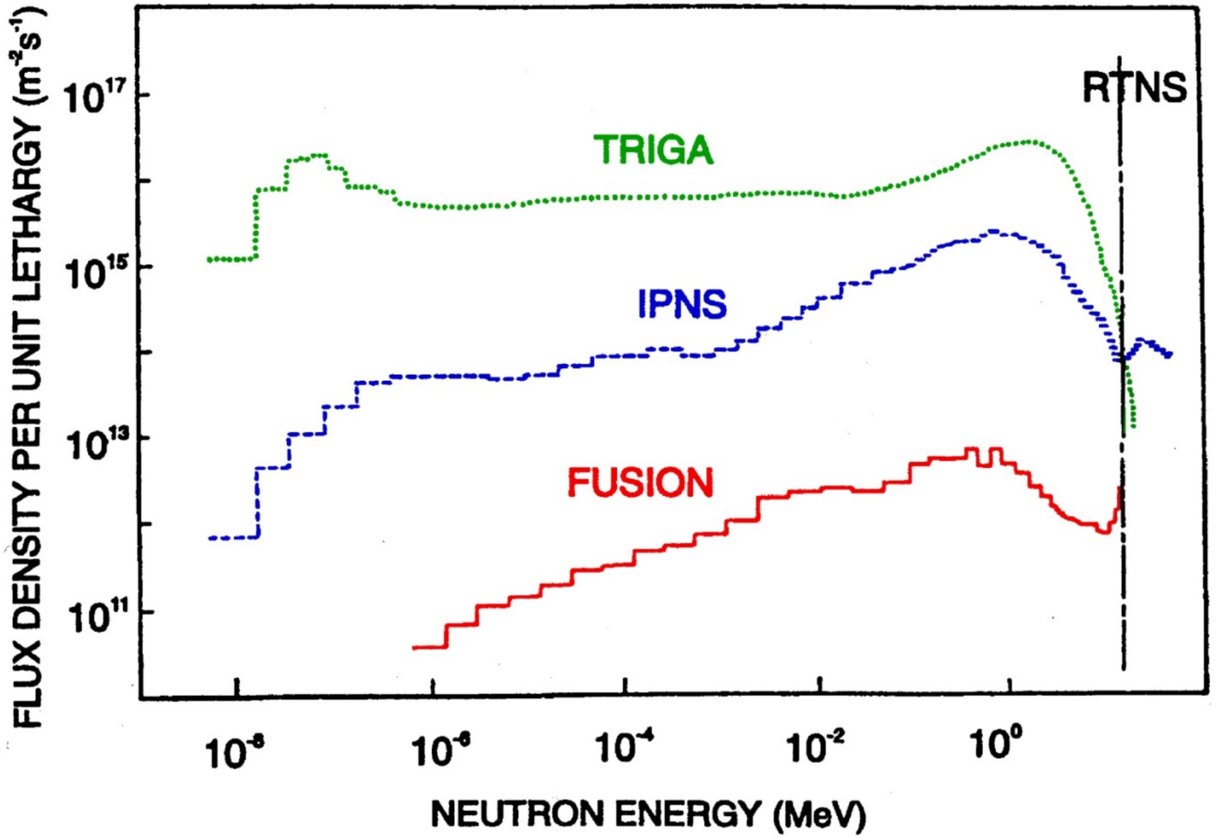
Nuclear Fusion



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!

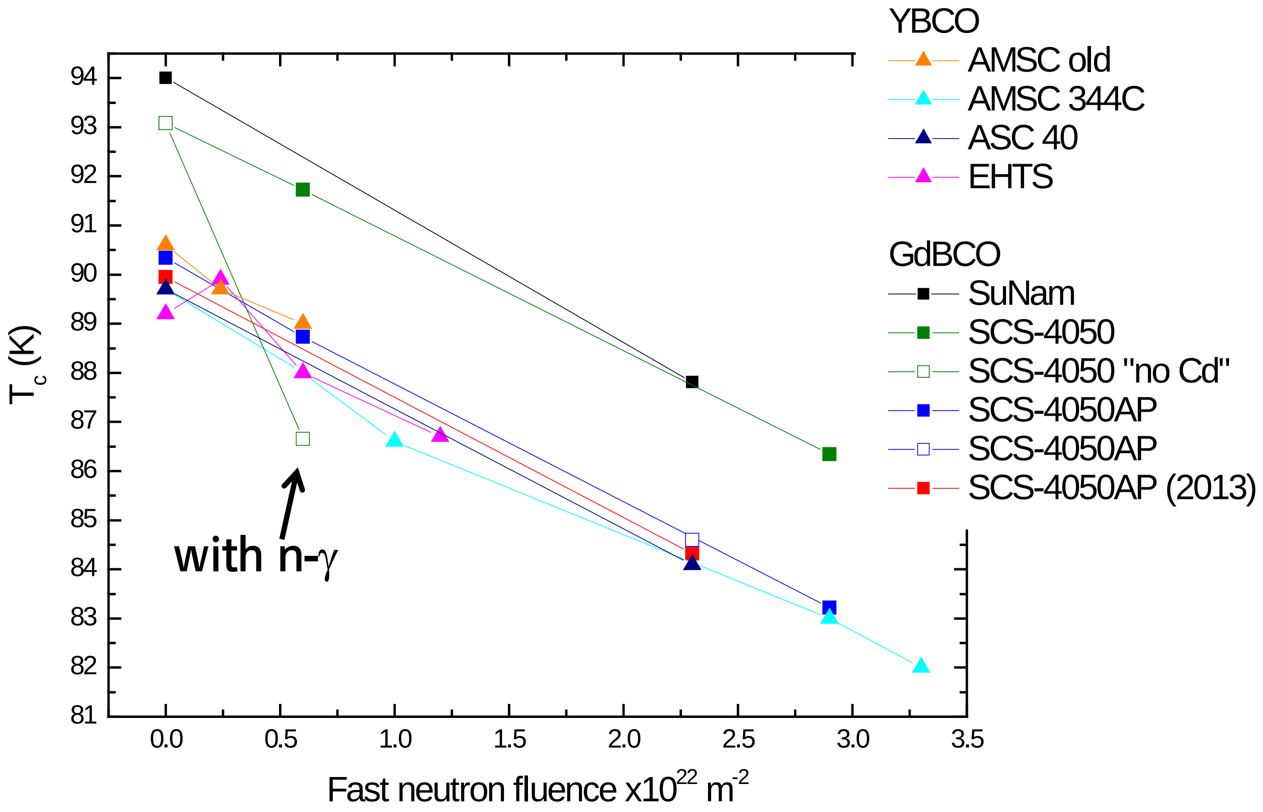
Neutron Energy Distribution



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)

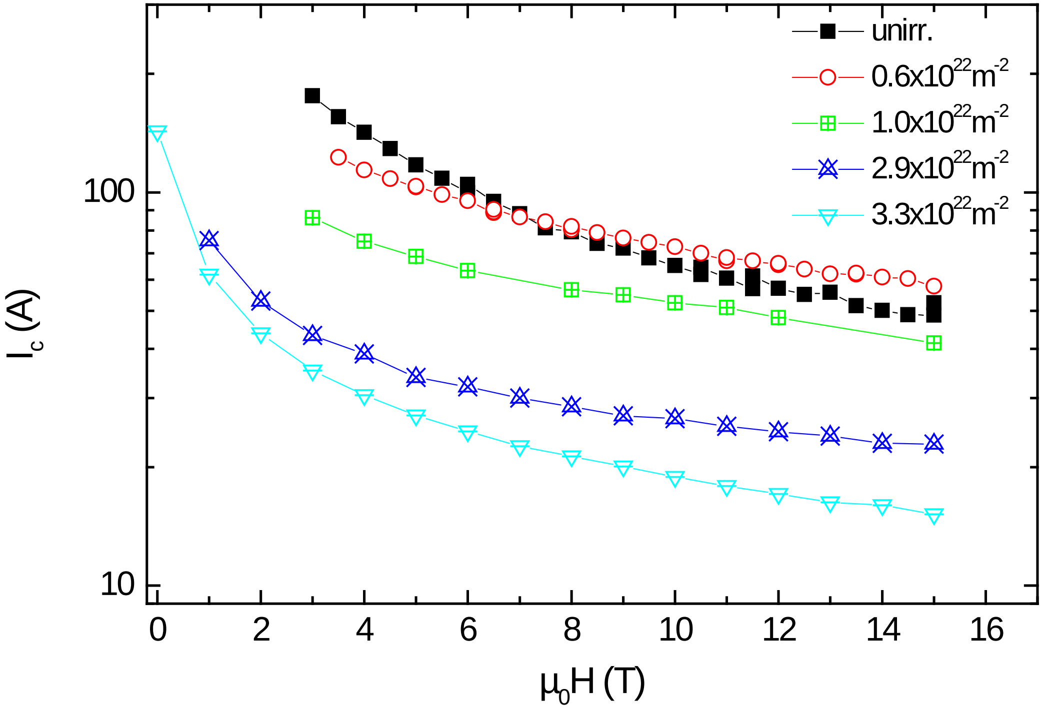
Decrease in Transition Temperature



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

Critical currents of 344C (AMSC old)

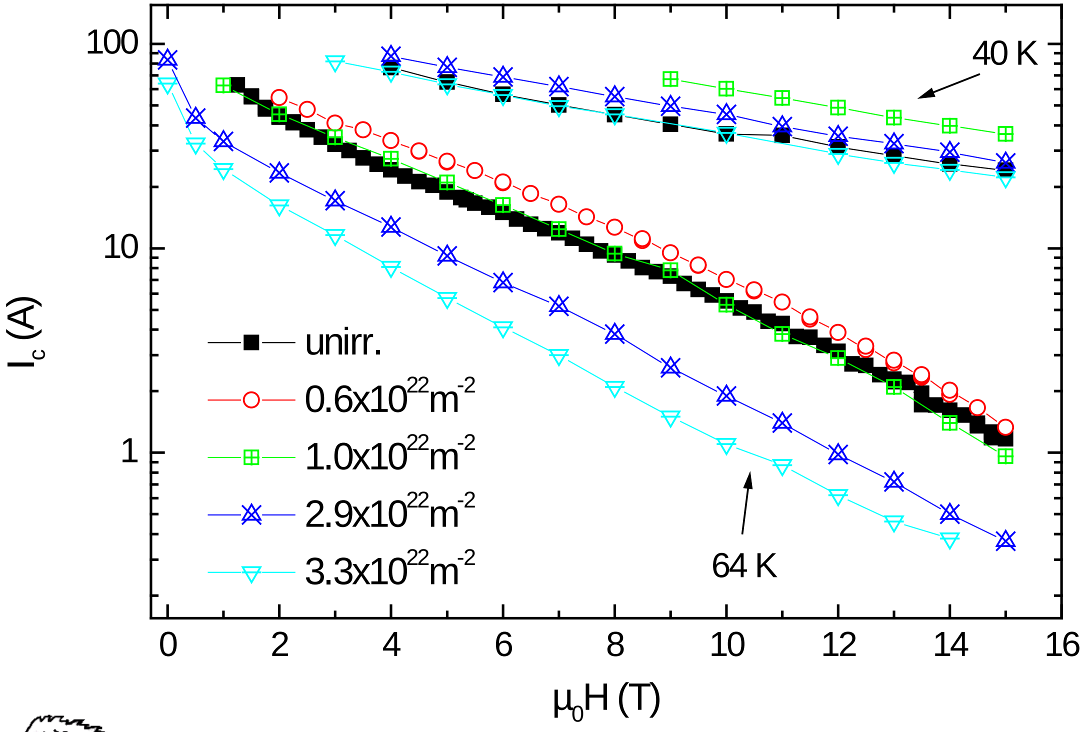
H||ab @ 50 K



- Small I_c enhancement at high fields after irradiation to $0.6 \cdot 10^{22}$ m^{-2}
- Strong I_c reduction at higher fluences

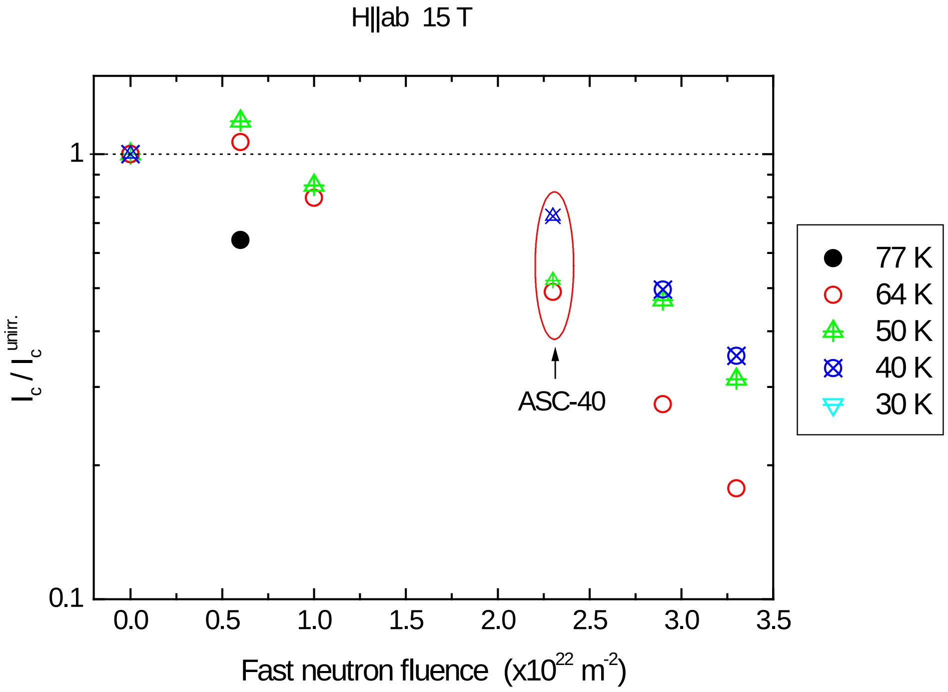
Critical currents of 344C

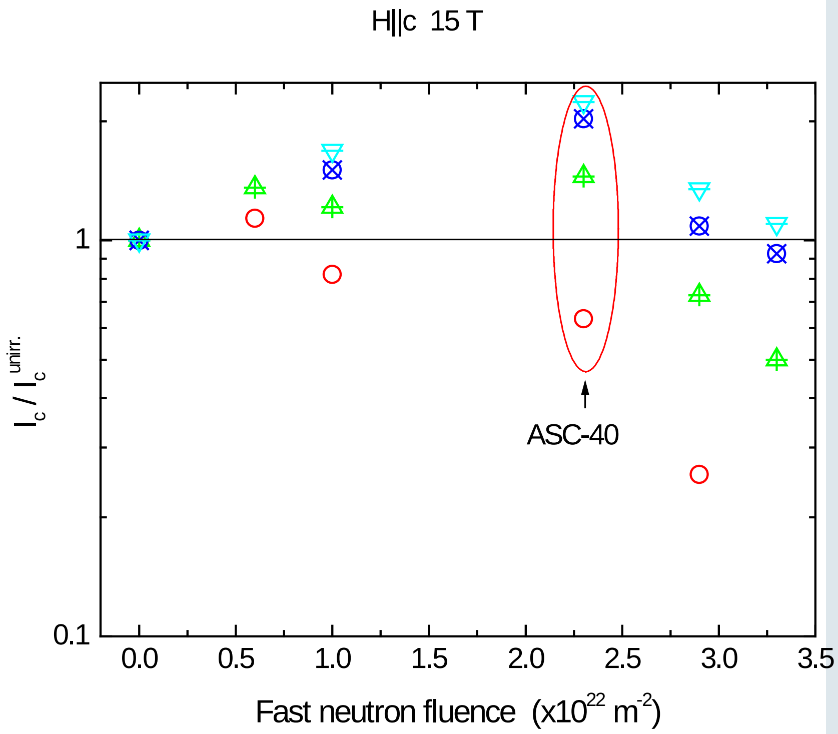
H||c @ 64 K and 40 K



- Temperature dependent I_c enhancement
- Degradation starts after irradiation to $1.0 \cdot 10^{22}$ m^{-2} at 64 K and after $2.9 \cdot 10^{22}$ m^{-2} at 40 K.

Normalized Critical Currents



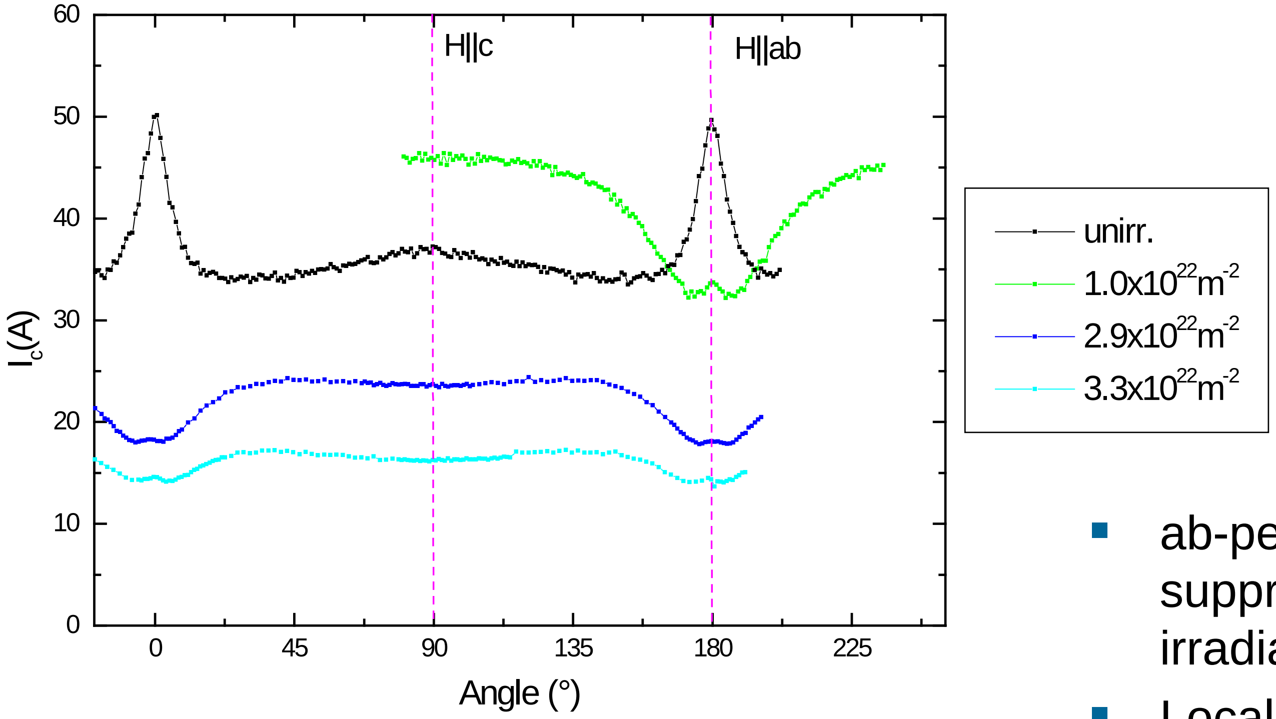


Maximum at low fluence.

Maximum at around $2.3 \cdot 10^{22}$ m^{-2}.
Lower temperatures: Slower degradation.

I_c-Anisotropy

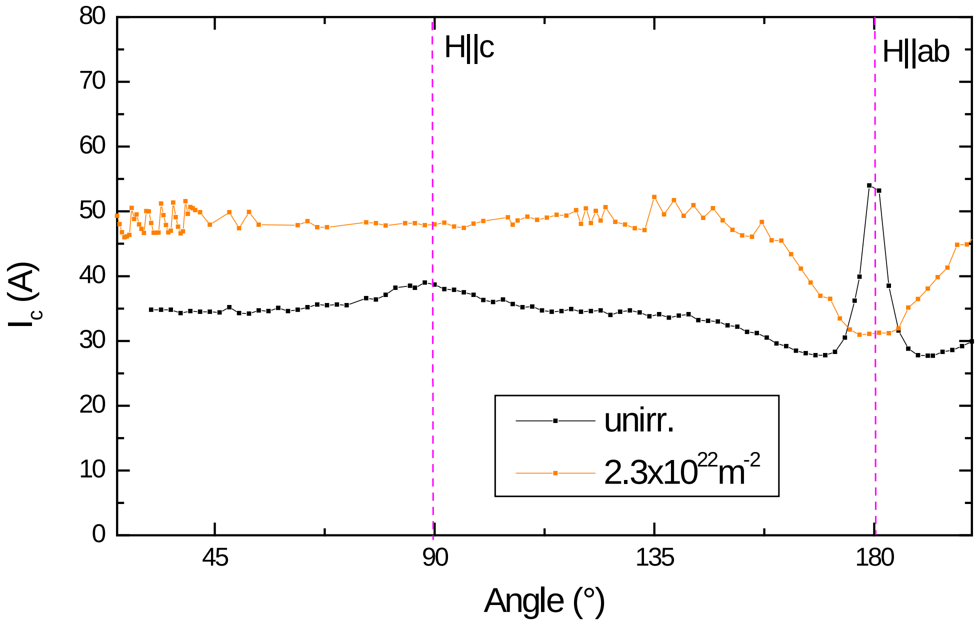
344C @ 64 K / 2 T



- ab-peak heavily suppressed after first irradiation step
- Local minimums are found close to main field orientations

I_c-Anisotropy

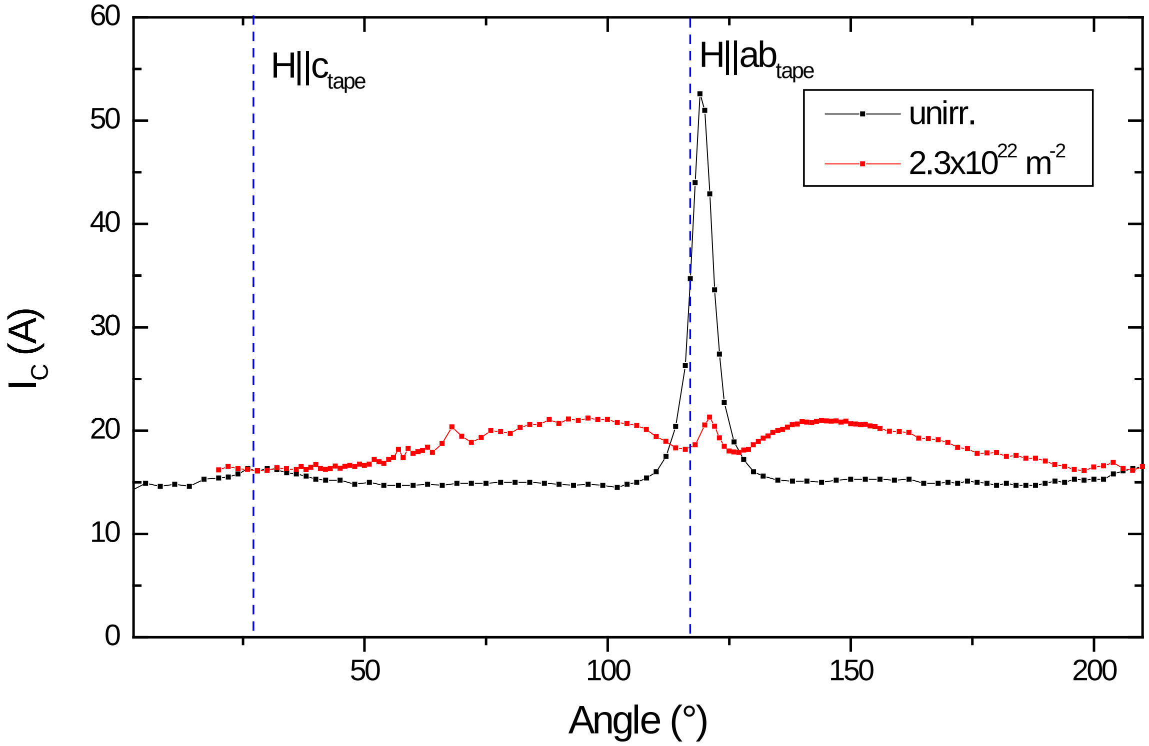
ASC-40 @ 60 K / 5 T



- ab-peak heavily suppressed after irradiation
- Peaks in pristine tape turns into minimums after irradiation

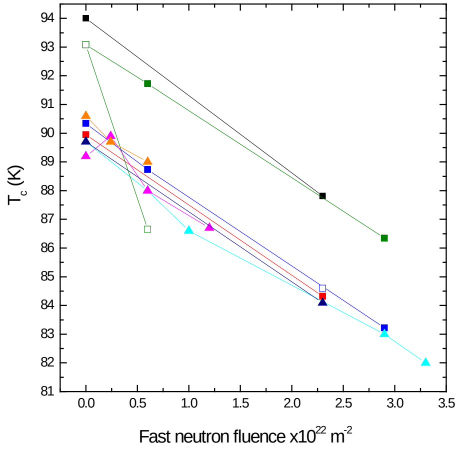
I_c-Anisotropy

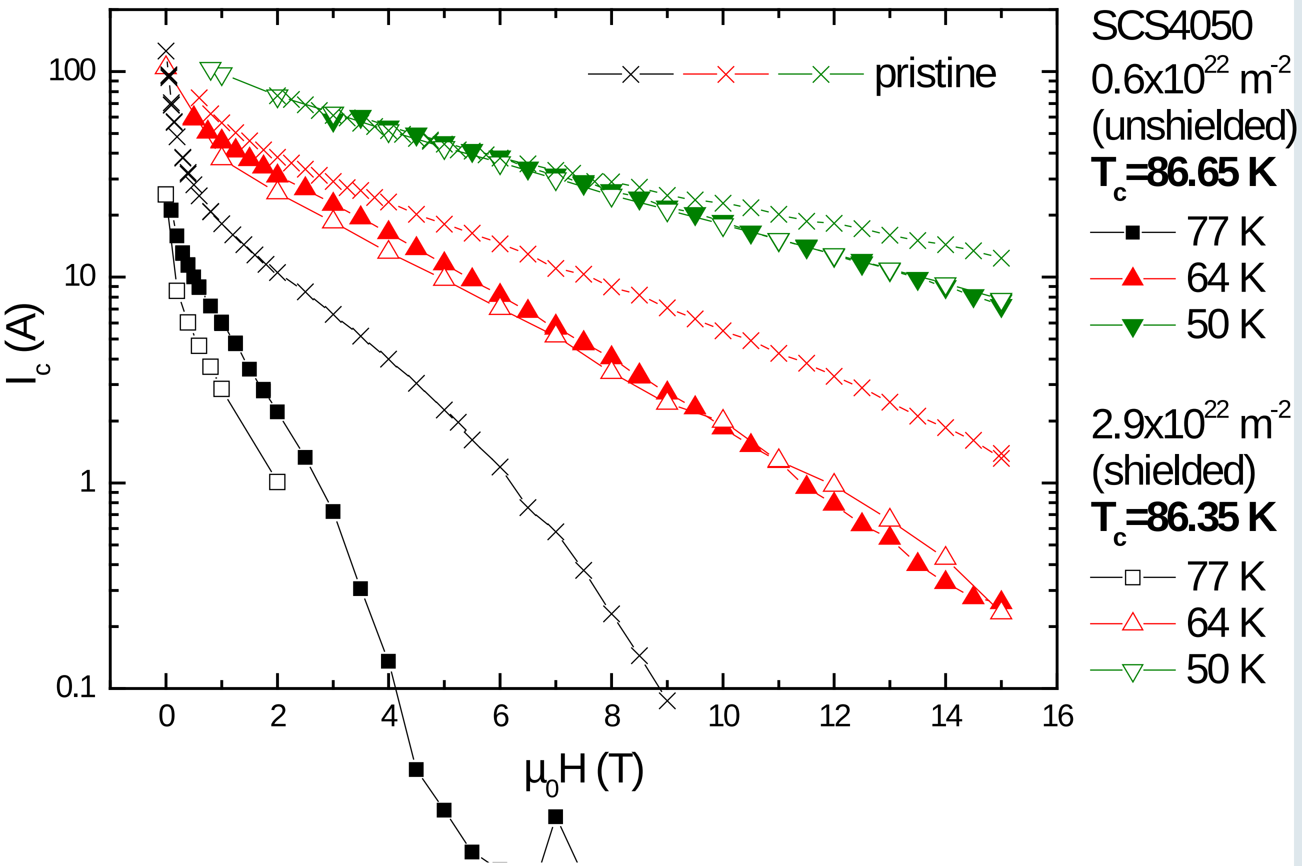
SuNam @ 5 T / 64 K



WHICH DEFECTS ARE RESPONSIBLE FOR FLUX PINNING/DEGRADATION?

Large vs. small defects





Density of collision cascades differ by a factor of about 5!

Displaced atoms

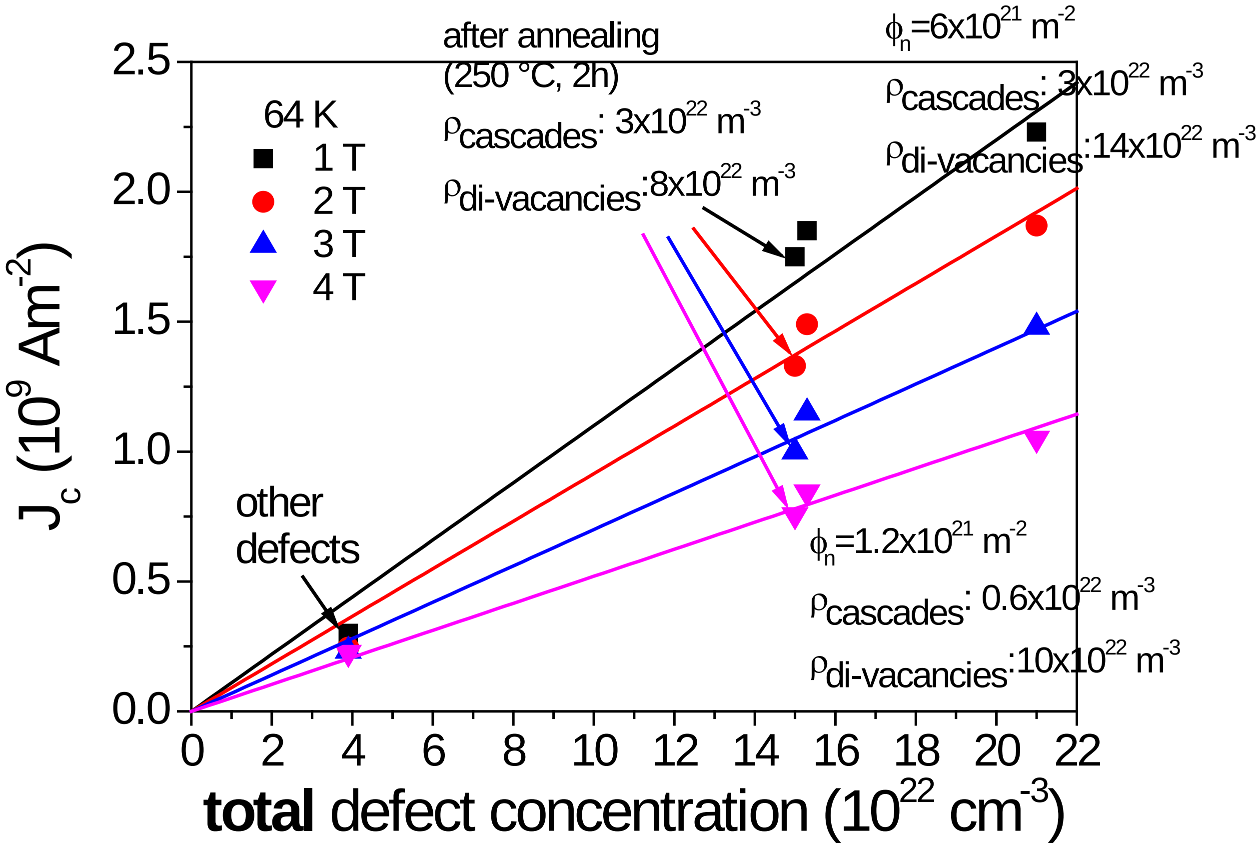
1) Without Cd-screen (fast/thermal neutron fluence: $6/5 \cdot 10^{21}$ m^{-2})

n-γ: $5 \cdot 10^{21}$ m^{-2} · 61 kbarn · 0.145 (Gd-155) · 1/13 = $3 \cdot 10^{-4}$ dpa
n-γ: $5 \cdot 10^{21}$ m^{-2} · 254 kbarn · 0.157 (Gd-157) · 1/13 = $1.5 \cdot 10^{-3}$ dpa
Cacscades: $3 \cdot 10^{22}$ m^{-3} · 500 / $2.7 \cdot 10^{28}$ m^{-3} = $5.5 \cdot 10^{-4}$ dpa
Total: $2.3 \cdot 10^{-3}$ dpa

2) With Cd-screen (fast neutron fluence: $2.9 \cdot 10^{22}$ m^{-2})

Cacscades: $1.45 \cdot 10^{23}$ m^{-3} · 500 / $2.7 \cdot 10^{28}$ m^{-3} = **$2.6 \cdot 10^{-3}$ dpa**

Large vs. small defects (melt textured YBCO)

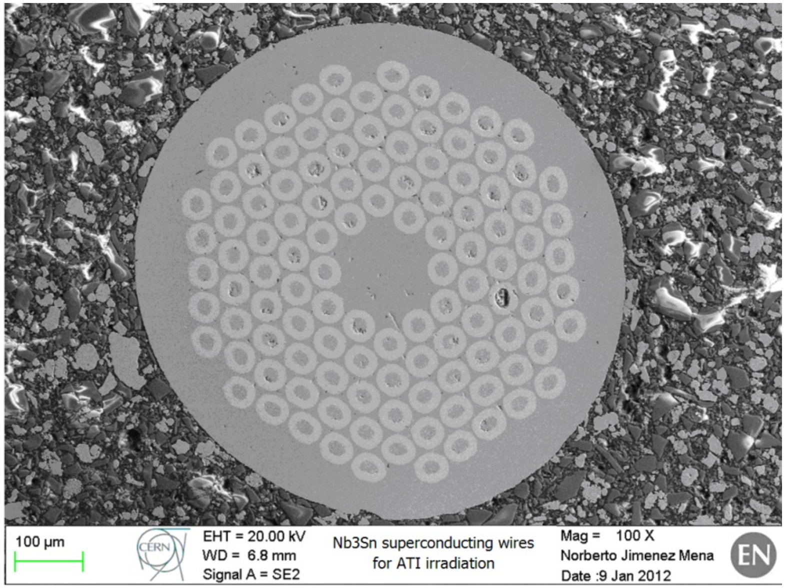


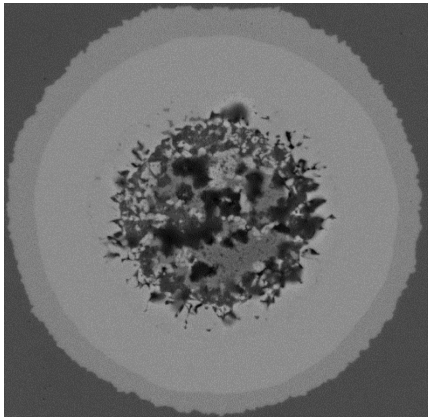
Linear scaling with total (cascades+di-vacancies+original) defect density!
Different "stable dpa" similar J_c.

NB$_3$SN FOR ACCELERATOR MAGNETS

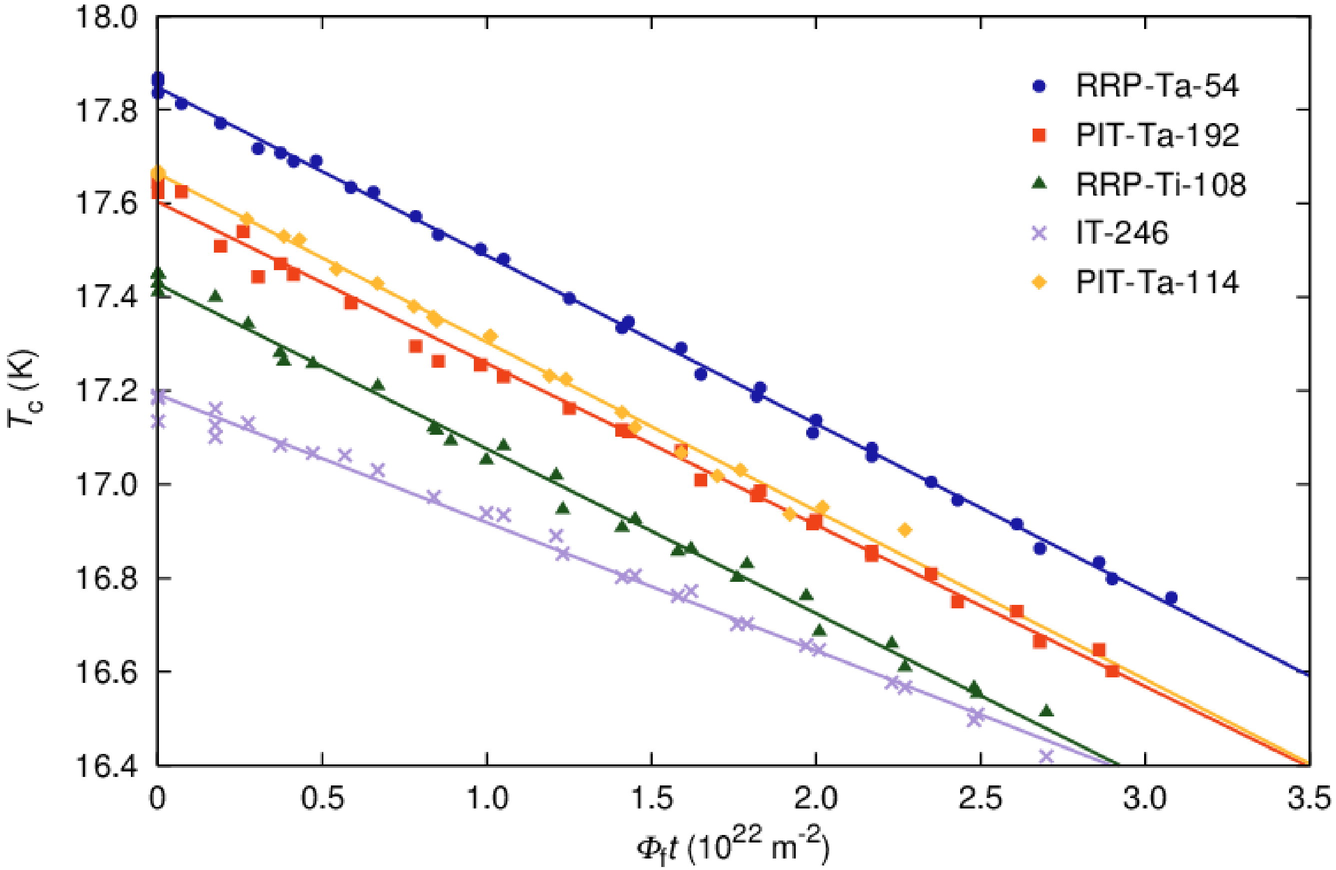
5 types of state-of-the-art Nb_3Sn wires

- Ta-alloyed RRP (restack-rod process), 54 sub-elements
- Ti-alloyed RRP, 108 sub-elements
- Binary IT (internal tin), 246 sub-elements
- Ta-alloyed PIT (powder-in-tube), 192 sub-elements
- Ta-alloyed PIT, 114 sub-elements





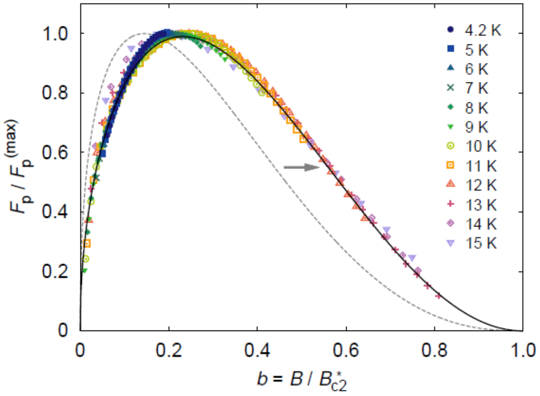
Decrease in Transition Temperature: Nb_3Sn

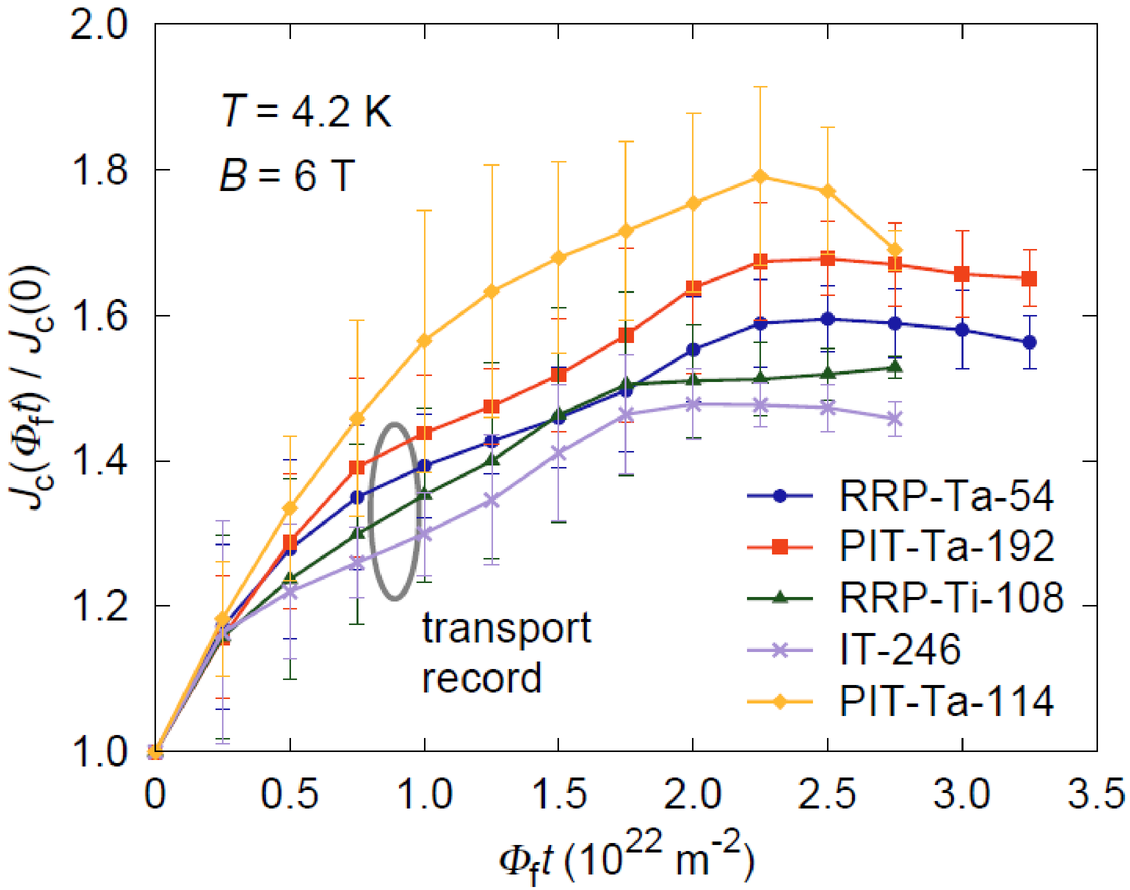


Decrease in T_c: ~0.35 K at a fluence of 10^{22} m^{-2} (2%)

Critical Current: Nb_3Sn

Volume pinning force

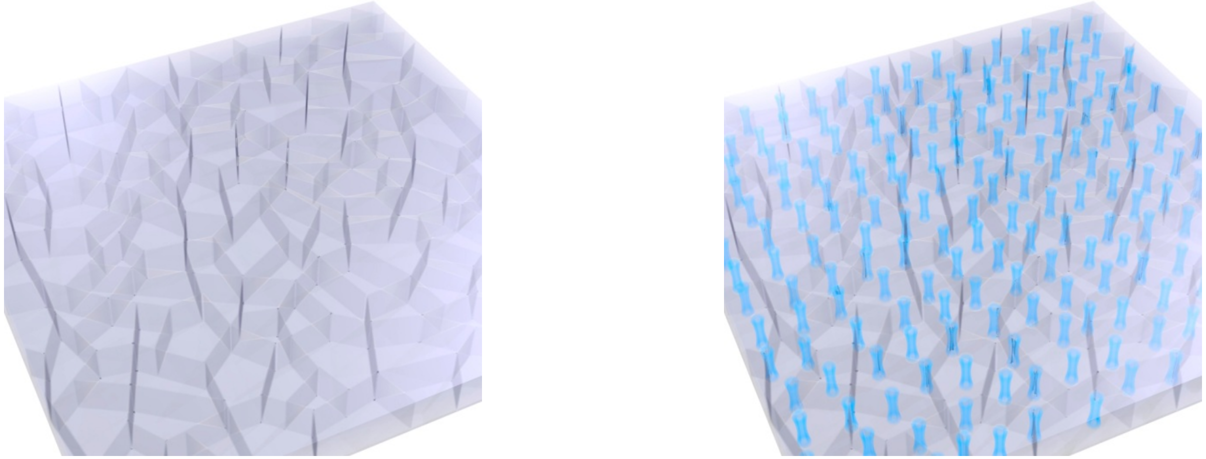




Maximum of J_c at a fluence of about $2.5 \cdot 10^{22}$ m^{-2}

Pinning Mechanism

- Possible contributions of other pinning mechanisms[1] were investigated to explain the observed shift in the pinning function
- $f(b) = \alpha b^{p_1}(1-b)^{q_1} + \beta b^{p_2}(1-b)^{q_2}$
- p_1 and q_1 correspond to the unirradiated state, $\alpha + \beta = 1$
- Shift can be explained with a point-pinning contribution[2] ($p_2 = 1$, $q_2 = 2$) which increases with fluence



[1] D. Dew-Hughes: *Phil. Mag.* **30**, 293–305, 1974

[2] T. Baumgartner et al.: *Supercond. Sci. Technol.* **27**, 015005, 2014

Point Pinning

- Possible contributions of other pinning mechanisms[1] were investigated to explain the observed shift in the pinning function
- $f(b) = \alpha b^{p_1}(1-b)^{q_1} + \beta b^{p_2}(1-b)^{q_2}$
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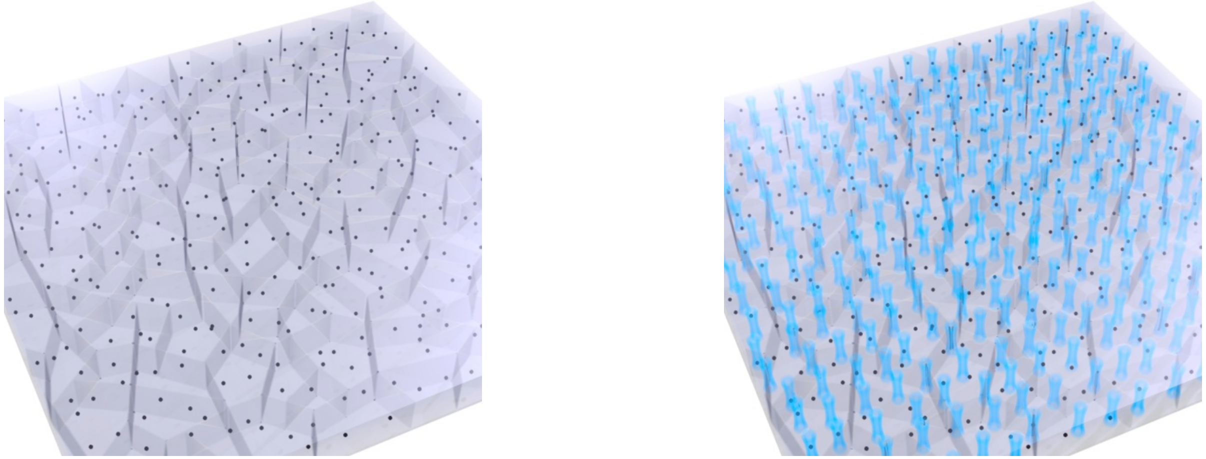

[1] D. Dew-Hughes: *Phil. Mag.* **30**, 293–305, 1974

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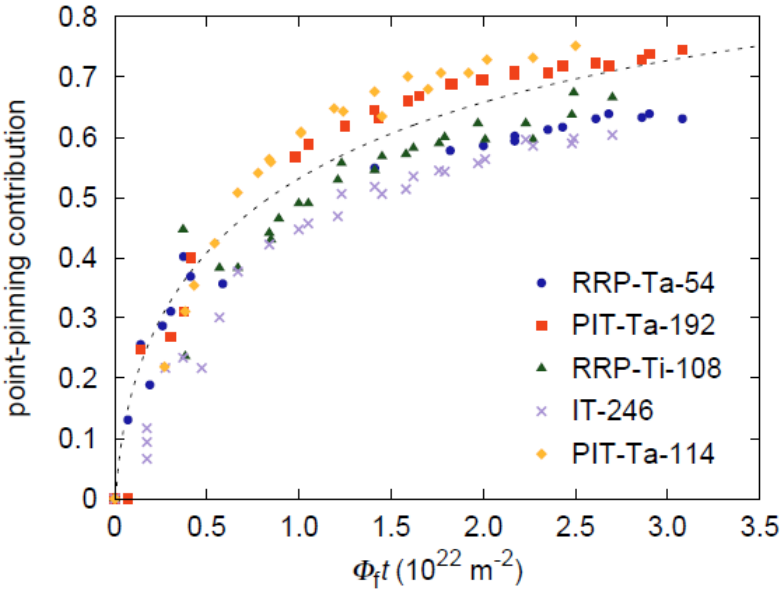
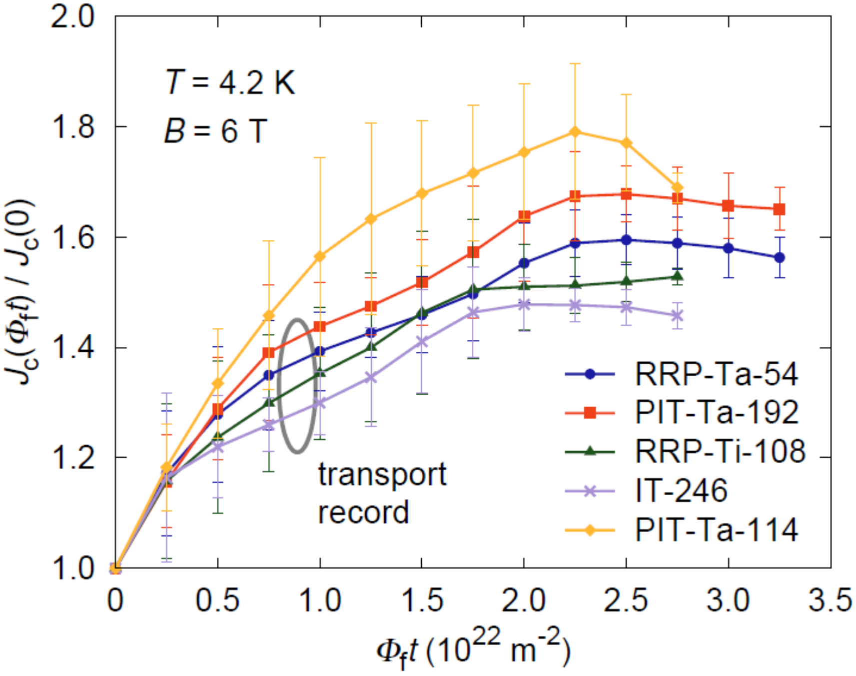
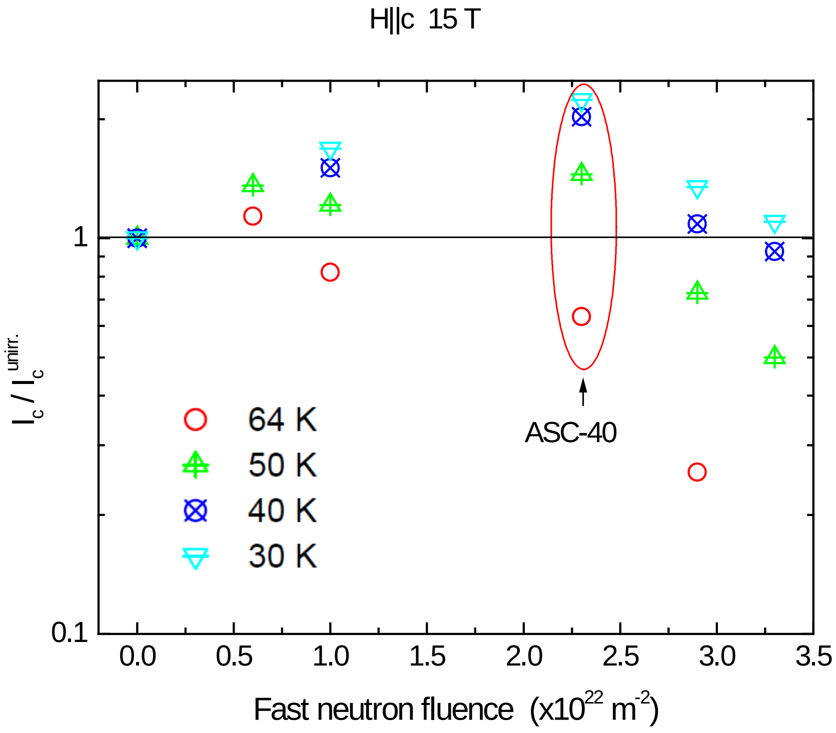
Point Pinning



- Point-pinning contribution was evaluated as a function of fast neutron fluence for all examined wires
- Same trend for all wire types
- Steep increase at low fluences, followed by saturation behavior

Critical Currents: Comparison YBCO – Nb_3Sn





Which compound is more robust against radiaton?

Conclusions

- The defect structure relevant for the change of J_c following neutron irradiation has to be identified and related to the damage mechanism in order to make reliable predictions of the conductor life-time in accelerator magnets.
  - Microstructural investigations
  - Comparison of different irradiation experiments
  - Modelling of stable defects
  - Annealing?
- The radiation resistance decreases at higher temperatures. Restriction to low temperatures (LH_2?).
- Similar radiation hardness for coated conductors and Nb_3Sn at low temperatures.