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Neutron radiation effects on superconducting magnet materials

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Collaborations and Funding

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David Fischer MIT (proton irradiation)

Daniele Torsello, Francesco Laviano Politecnico di Torino
(radiation environment, damage calculations) WB5-4-INV, 11:15, Dec.5

Davide Gambino Linköping University (MD calculations) WB5-3-INV, 10:45, Dec.5

Ruben Hühne IFW Dresden (thin film preparation)

Christian Scheuerlein CERN (organic insulators)

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Funded by the
European Union

Outline

Nuclear fusion based on magnetic confinement

- Fusion neutrons
- Their journey to the magnets

Shrinking the reactor size

- Solving/generating problems

Radiation damage

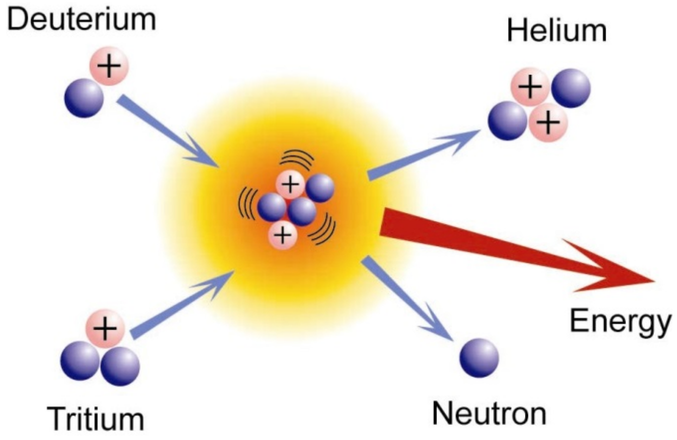
- Improved pinning by large defects
- Degradation of superconductivity due to small defects

Mitigation strategies

- Reliable prediction of the changes caused by neutron radiation
- Shielding/annealing

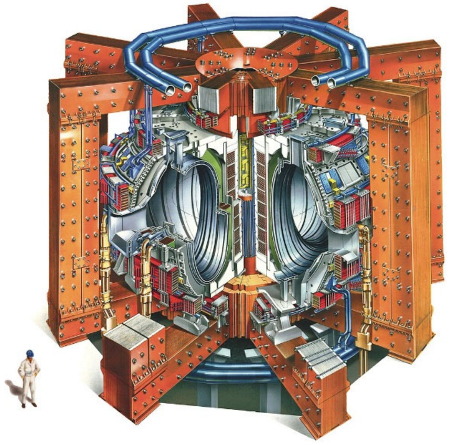
Conclusions

Nuclear Fusion



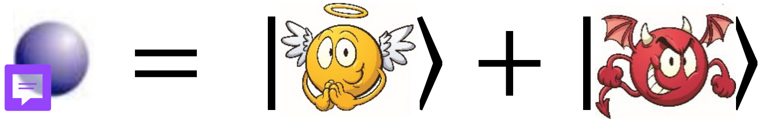
$D + T \rightarrow {}^{4}He\ (3.5\ MeV) + n\ (14.1\ MeV)$

@150 million °C



JET record
69 MJ, 5.2 s
Q<1

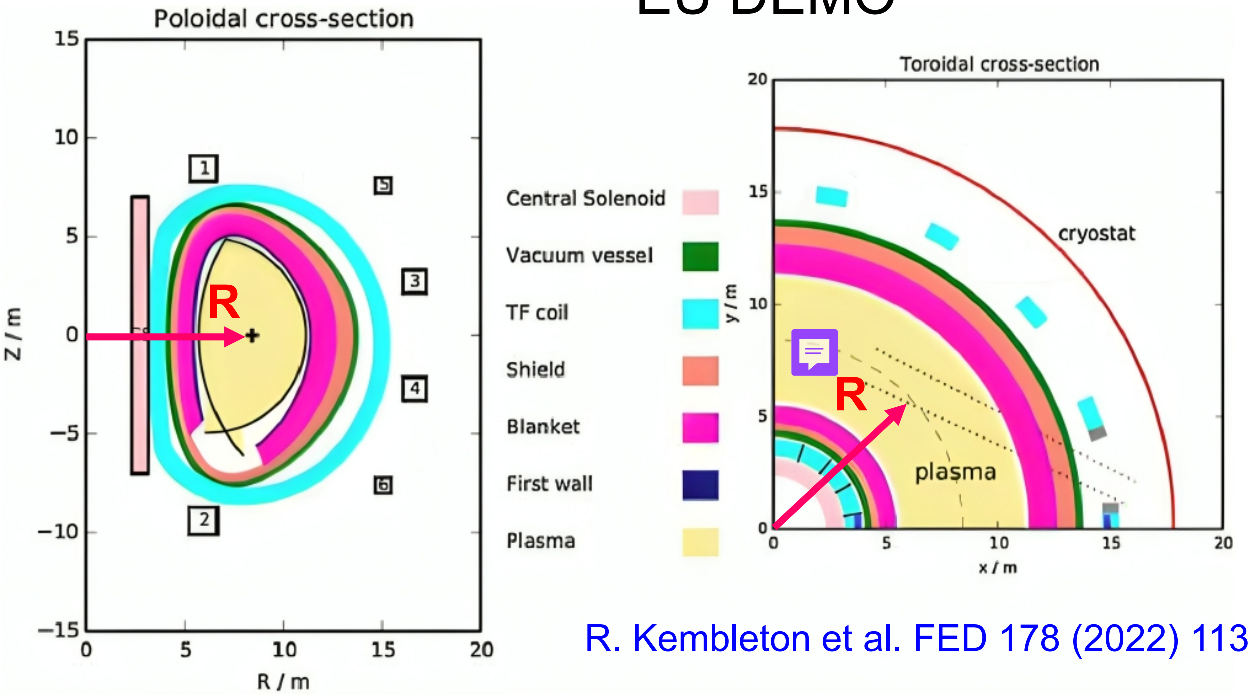
Fusion neutrons are needed for the fuel cycle but some of them harm reactor components.



www.euro-fusion.org/media-library/fusion-experiments

Conventional fusion reactor concepts

EU DEMO



R. Kembleton et al. FED 178 (2022) 113080

Use of Nb_3Sn:

- Low T_c (~18 K)

→ Acceptable heat load is small
→ Keep distance to the plasma

- Low H_{c2} (~25 T)

→ Limited achievable field
→ Restricts the power density ($\propto B^4$).

Advantages:

- Demonstrated technologies (ITER)
- Only few technological issues left
- No radiation issues for the superconductors

Disadvantages:

- Very expensive (commercial viability?)
  → Difficult to find funding
  → Slow progress
  (DEMO operation: second half of century)

High temperature superconductors have become available

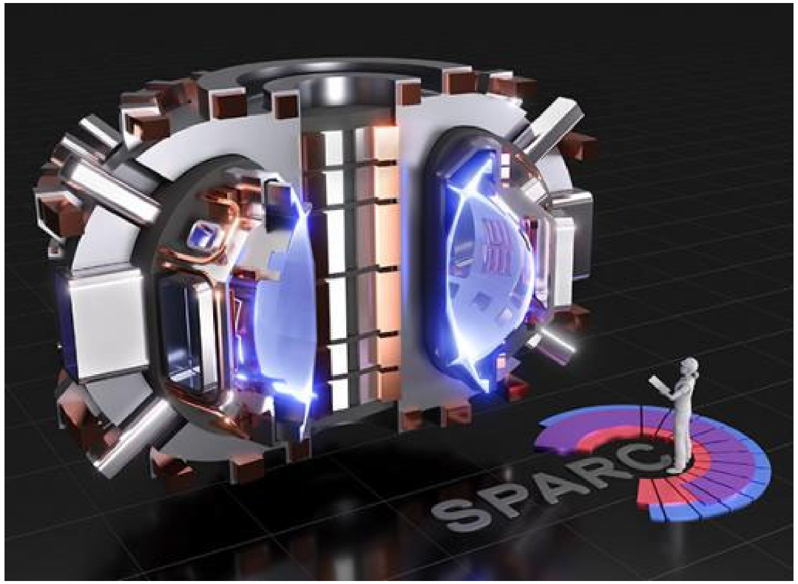
High temperature superconductors enable
higher operation fields (H_{c2}~150 T) and temperatures (T_c~90 K)!

- Fusion power density scales with fourth power of magnetic field, B^4.
  → Same power possible with smaller reactors
  → Higher heat load
- Compact reactors
  + Affordable
    → Private investments
    → Dozens of start-ups worldwide
    → Rapid development
  – Many open issues

At 1 GW_{th}:

1 GJ/17.6 MeV = $3.5 \cdot 10^{20}$ neutrons per second

Flux density through enclosing torus: $\approx \frac{2 \cdot 10^{19}}{R^2}$ $m^{-2}s^{-1}$

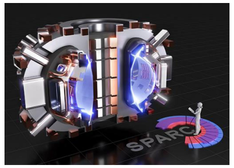


https://www.psfc.mit.edu/sparc

Size matters

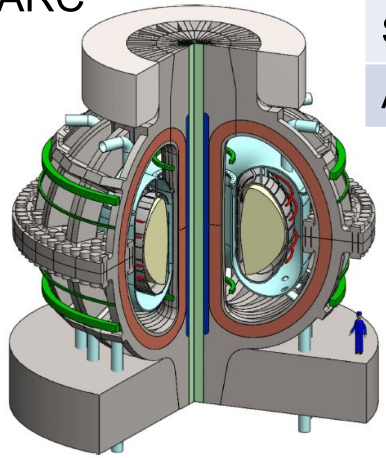
Reactor cost increases exponentially with size, heat and radiation load decrease for fixed power.

SPARC



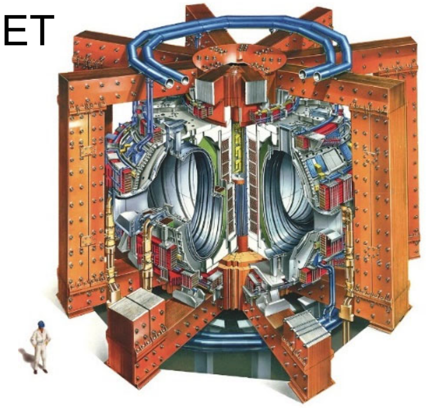
	R, major plasma radius (m)	Fusion power (GW)
JET	3	0.015
ITER	6.2	0.5
DEMO	9	2
SPARC	1.85	0.1
ARC	3.3	0.5

ARC

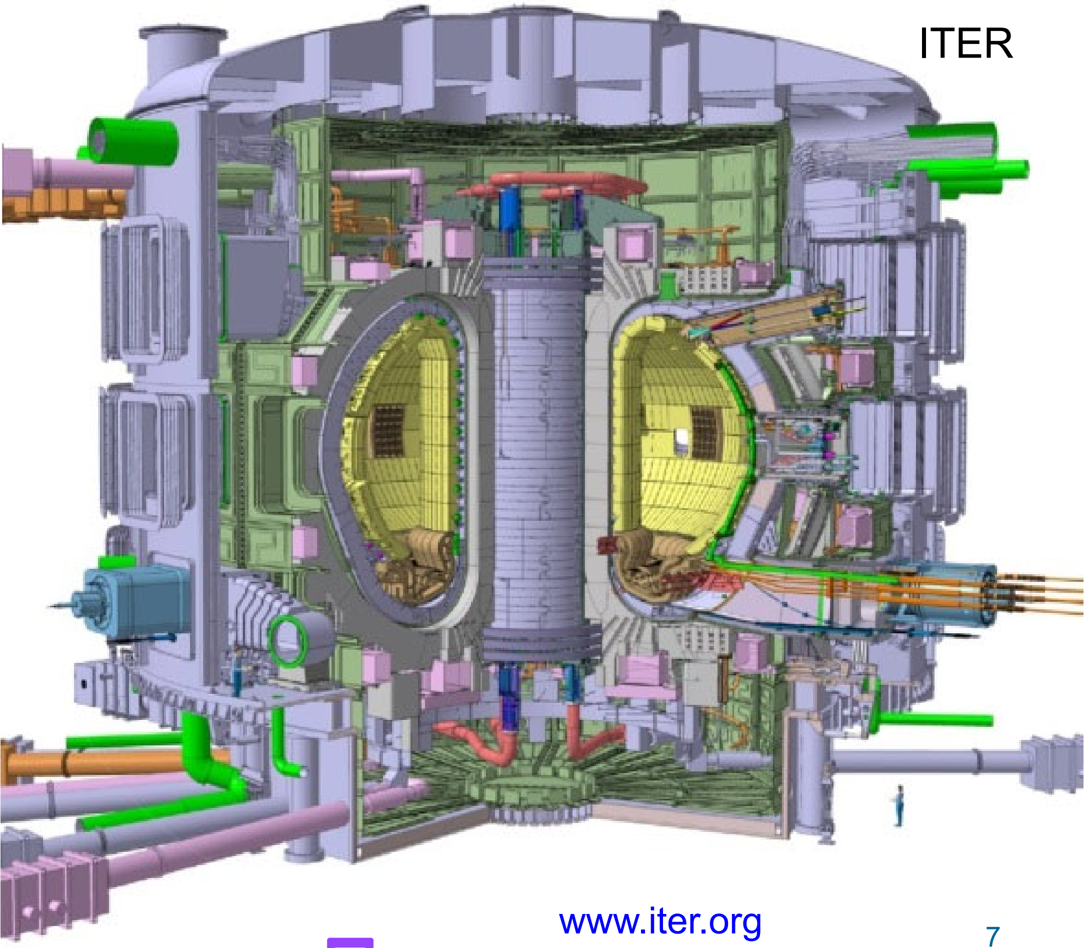


Sorbom et al.,
FED 100 (2015) 378

JET

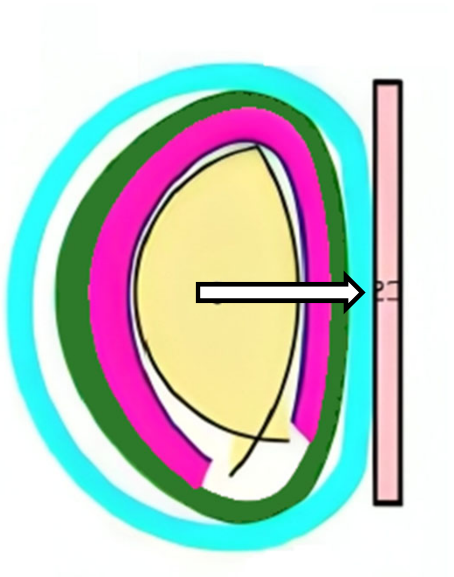


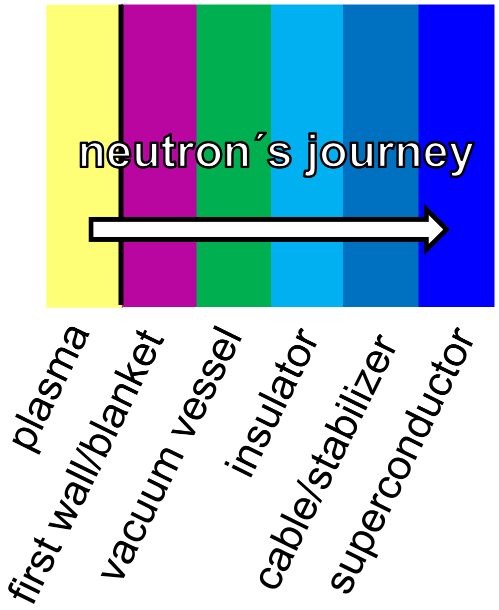
ITER



www.iter.org

A neutron’s journey to the magnet



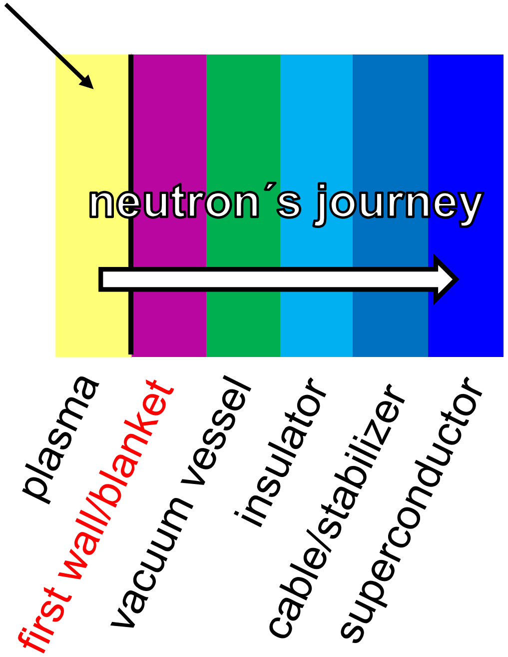


- Neutron flux density decreases with the distance from the plasma.
  - Geometric effect
  - Absorption
- Neutrons are moderated.
  → Mean energy decreases (elastic collisions).
  → Continuous energy distribution
- Secondary particles are generated.

Neutron flux density decreases from the first wall to the magnets by many orders of magnitude, depending on the reactor design.

Blanket

D + T → ^{4}He (3.5 MeV) + n (14.1 MeV)



- Heat production (steam turbine)
- Tritium breeding (blanket):
  ^{6}Li + n → ^{4}He + T + 4.8 MeV

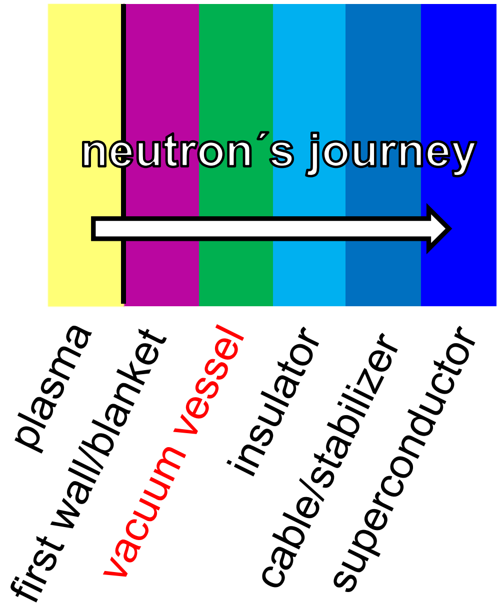
- Neutron multiplier:
  - ^{9}Be + n → 2^{4}He + 2n
  - ^{208}Pb + n → ^{207}Pb + 2n

Most neutrons are absorbed in the blanket.

Vacuum vessel/magnet casing/structural material

- Neutrons are moderated (energy becomes lower).
- Neutrons are absorbed.
- Nuclear reactions
  - Production of secondary particles (e.g. nickel)
    - Neutrons
    - Protons
    - Electrons
    - α-Particles

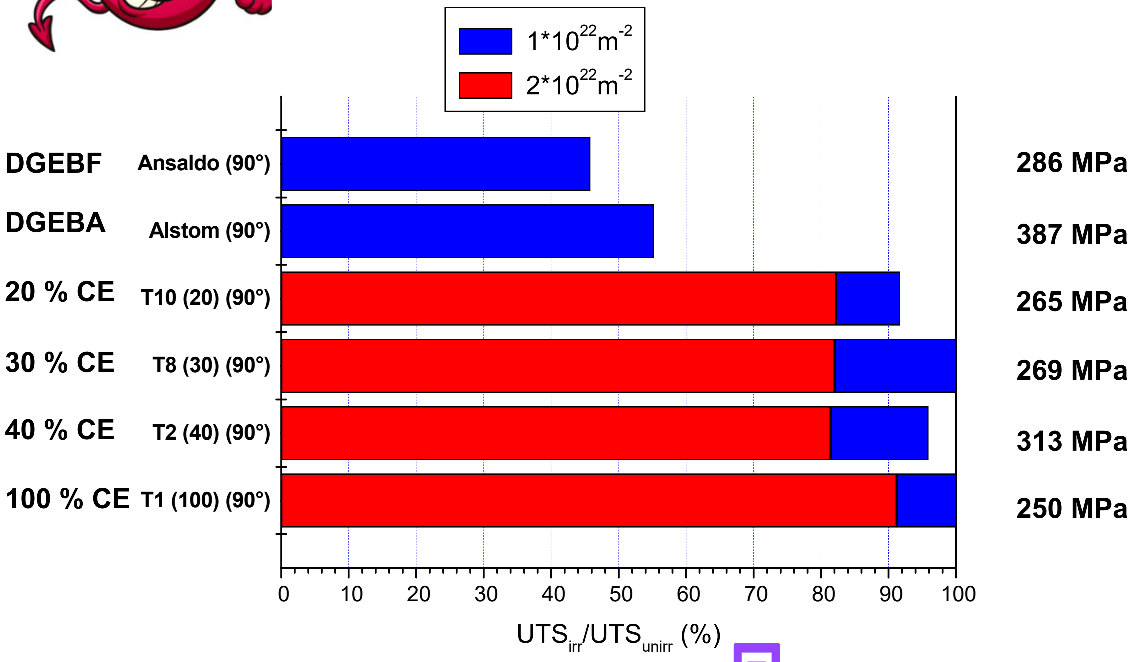
  → Complex radiation field



Radiation tolerant materials (no problem for their properties)

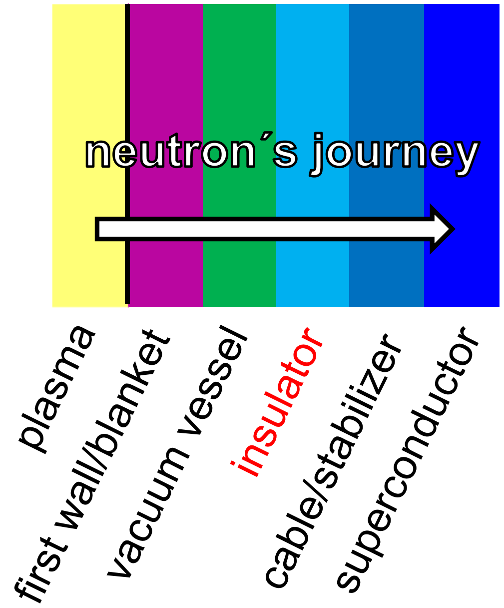
Insulators

- Ceramic insulators are robust against radiation.
- Organic materials
  - Degradation of mechanical properties
  - Gas production/swelling



Similar radiation tolerance as coated conductors.

R. Prokopec et al., AIP Conf. Proc. **986** (2008) 182



Ultimate tensile strength (UTS)

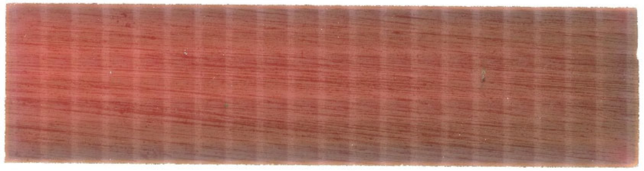
- Fast degradation of epoxy resins
- Good radiation hardness of cyanate esters (CE)
- Sufficient radiation hardness of epoxy – CE blends

Organic insulators

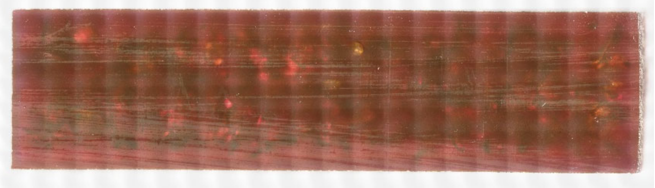
- Degradation of mechanical properties
- Gas production/swelling

0 MGy

1 MGy



3 MGy

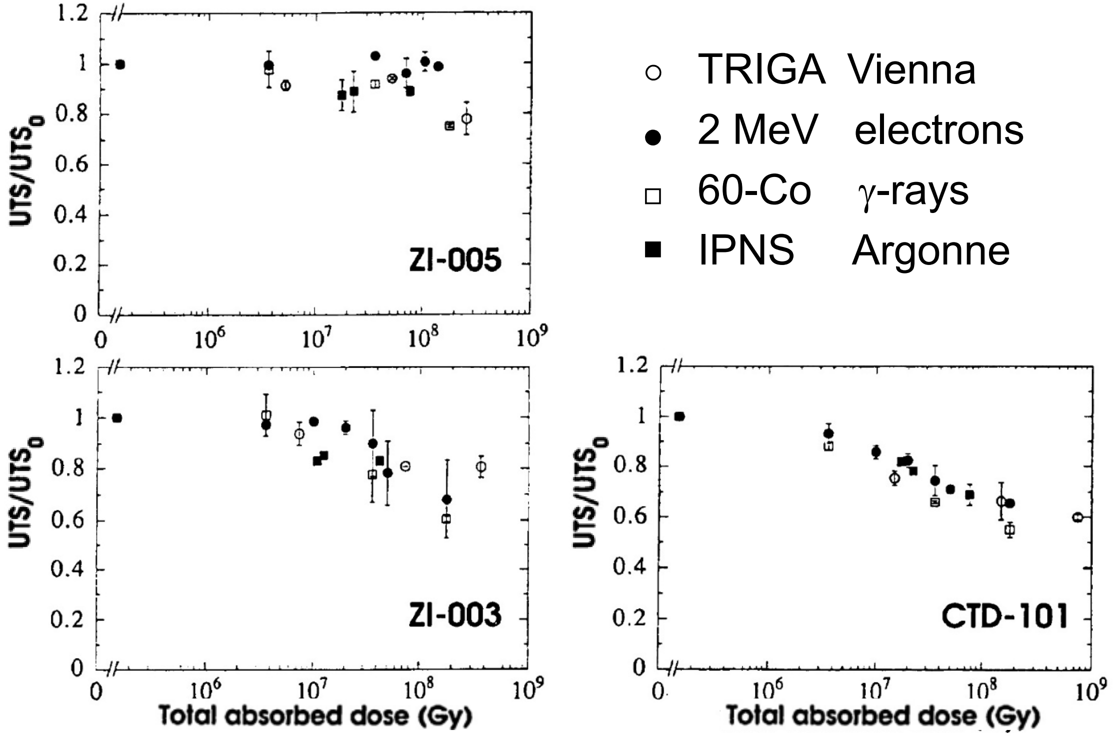


10 MGy

Gas production: 3-12 mm^3/mg
Swelling (thickness): < 11%

Insulators: absorbed dose

Tests at 77 K, irradiation at ~340 K (minor influence)



○ TRIGA Vienna
● 2 MeV electrons
□ 60-Co γ-rays
■ IPNS Argonne

Ionizing radiation breaks chemical bonds.

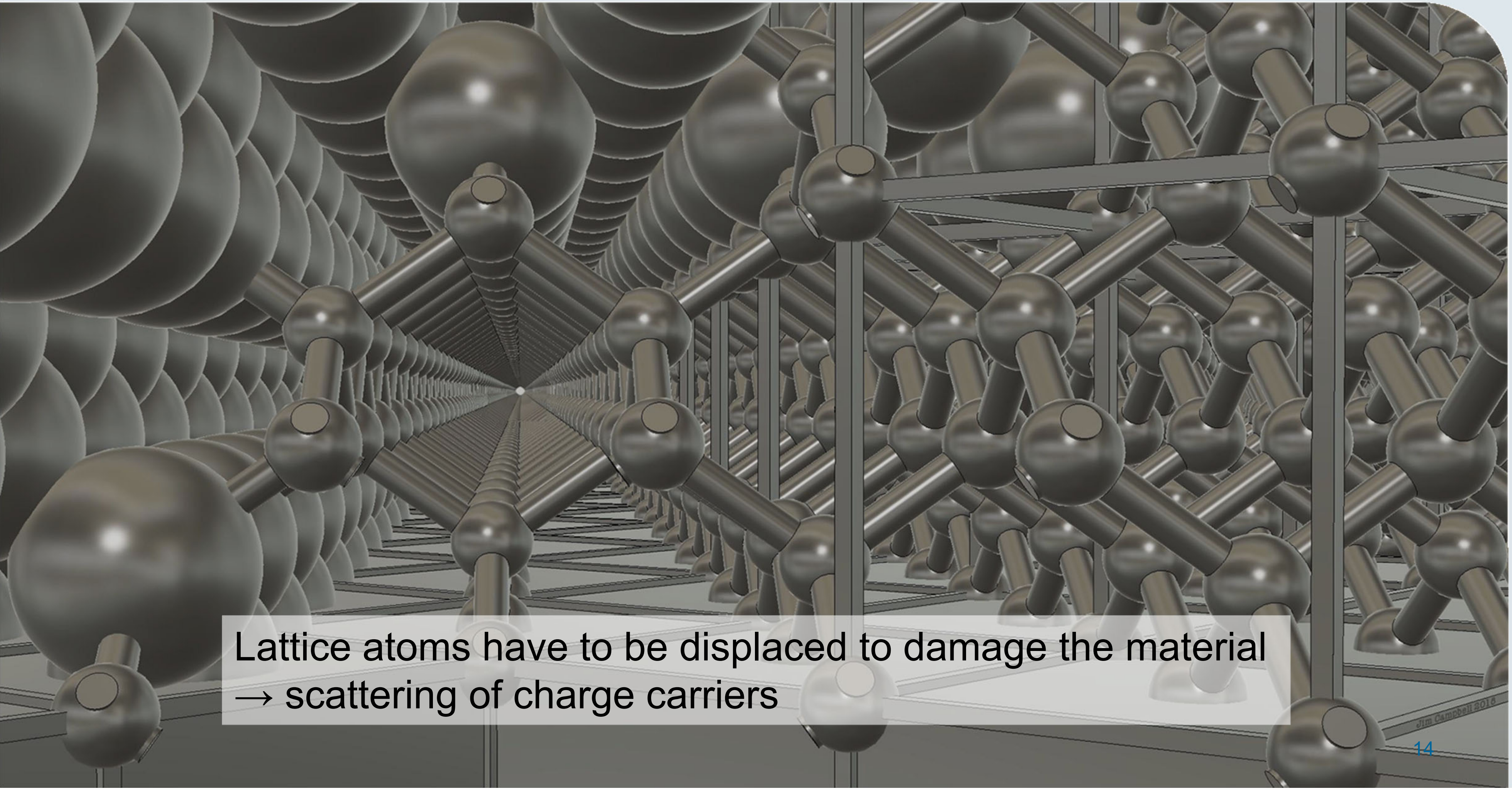
⬇

Deposited energy (dose: J/kg) changes chemistry.

K. Humer et al., *Cryogencis* **35** (1995) 871

Scaling all data to the absorbed dose works well!

Crystalline Materials

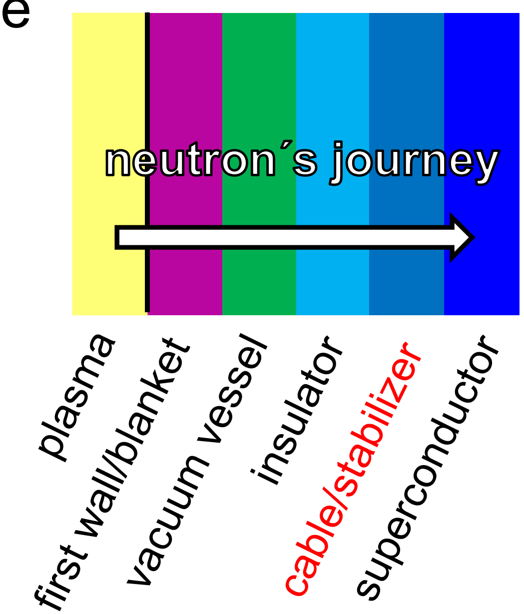


Lattice atoms have to be displaced to damage the material
→ scattering of charge carriers

Cable/stabilizer

Any defect breaks translational symmetry of the crystal lattice
→ scattering of charge carriers

- Decrease in mean free time τ
- Increase in scattering rate τ^{-1}
- Decrease in mean free path $l = v_\mathrm{F}\tau$
- Increase in normal state resistivity $\rho_\mathrm{n} = \frac{m_e v_\mathrm{F}}{n e^2 l}$



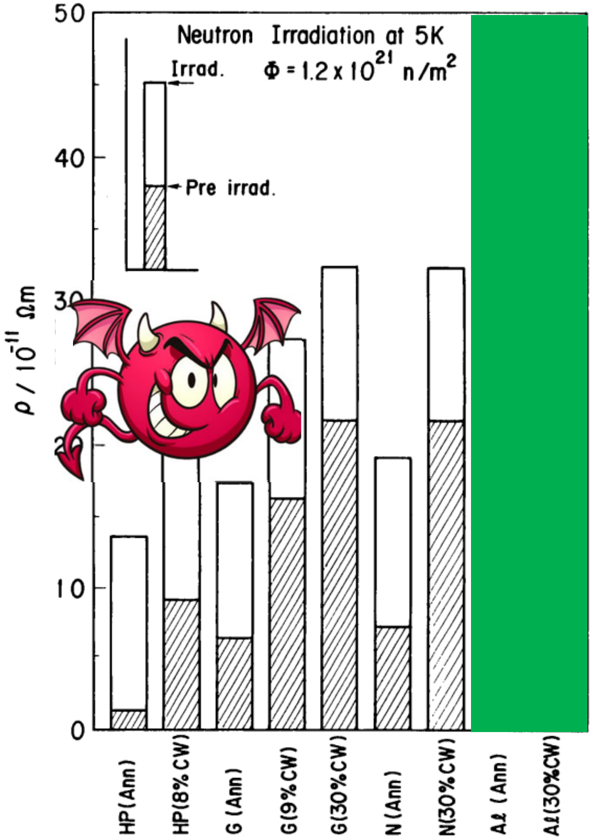
v_F… Fermi velocity
m_e… mass of charge carriers
n… density of charge carriers
e… elementary charge

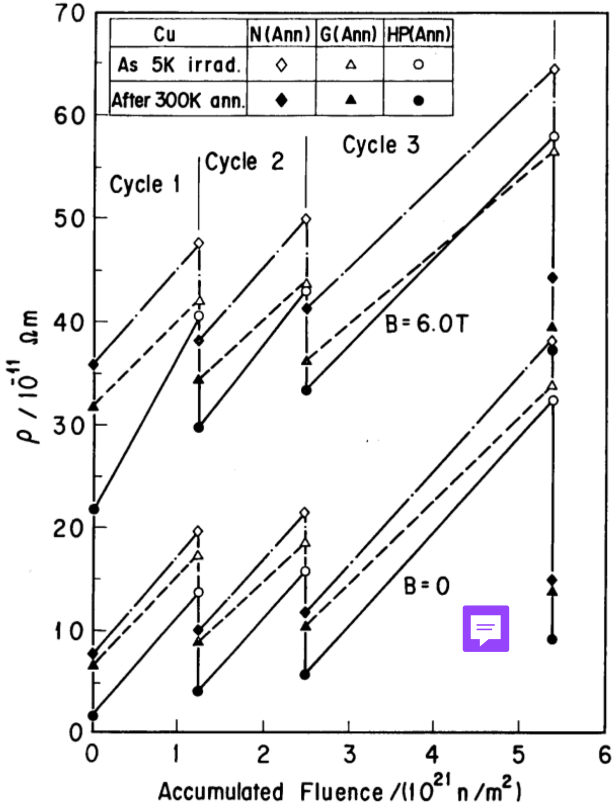
Problem for magnet stability?

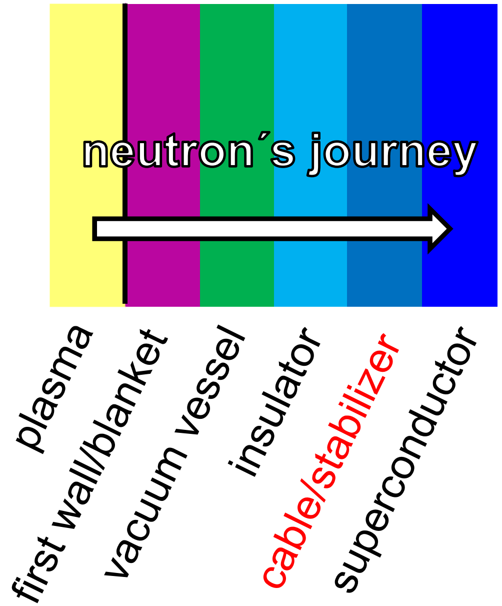
IEEE CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 58, Feb. 2025.
Presentation given at ISS 2024, Kanazawa, Japan, Dec. 3-5, 2024.

Cable/stabilizer

Resistivity (@4.2 K) change in copper after n-irradiation (@5 K)





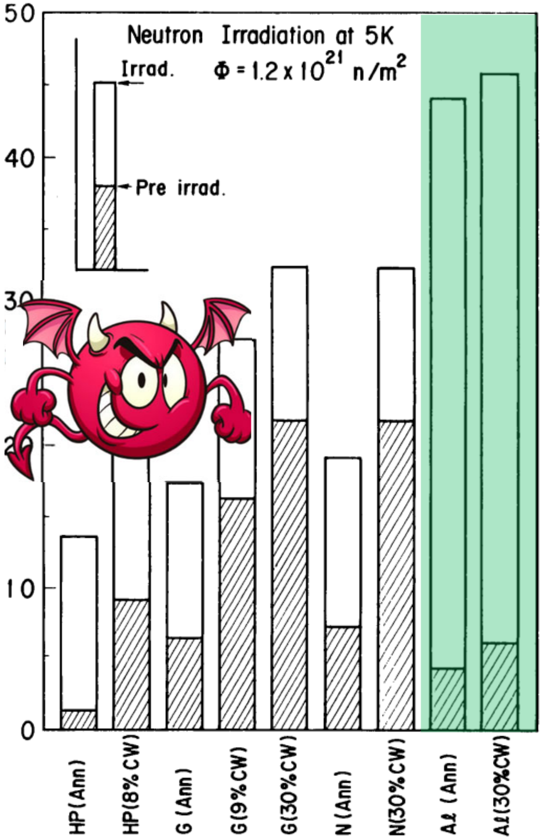


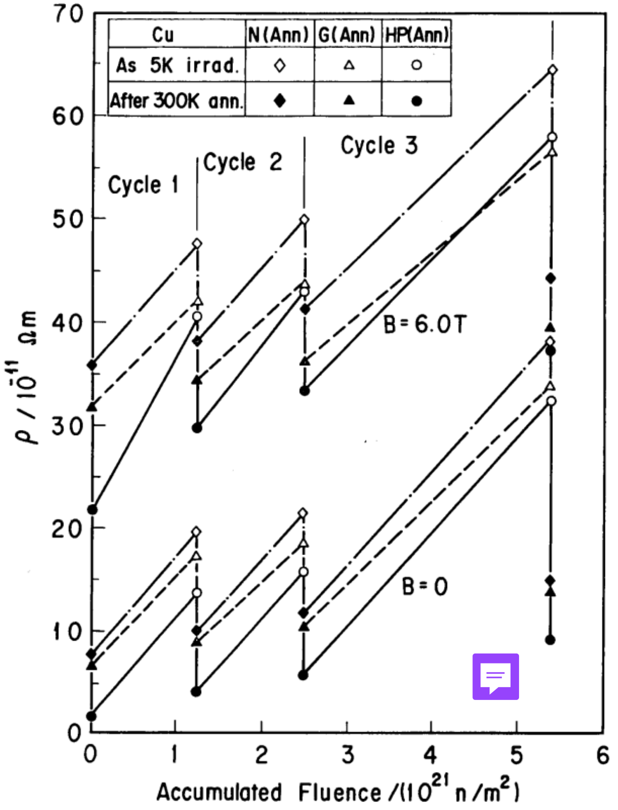
- Δρ is nearly independent of initial resistivity.

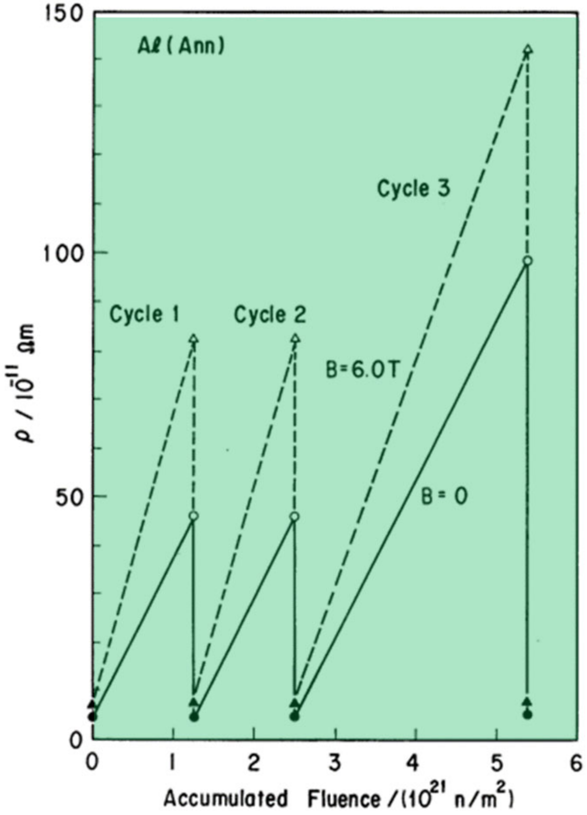
K. Nakata et al., JNM **135** (1985) 32

Cable/stabilizer

Resistivity (@4.2 K) change in copper and aluminum after n-irradiation (@5 K)



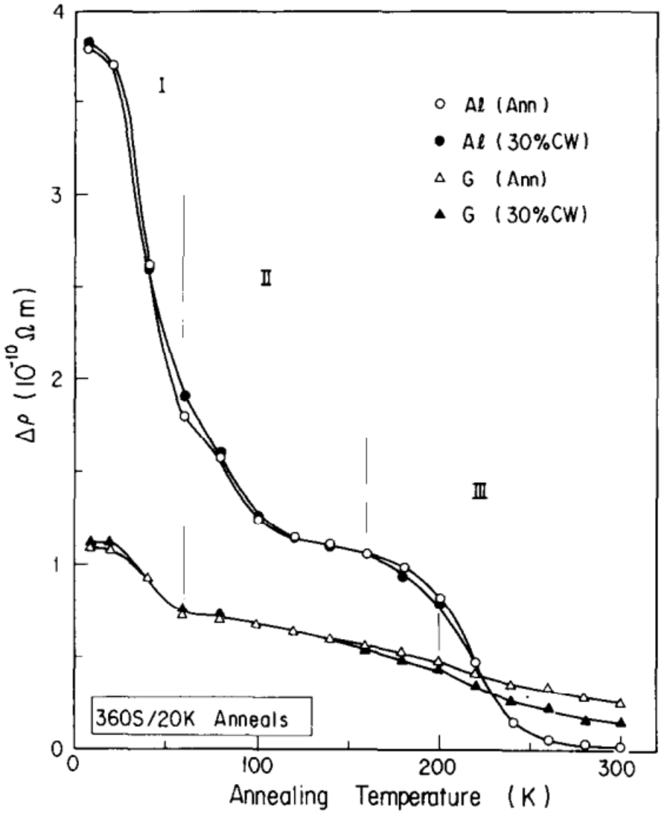


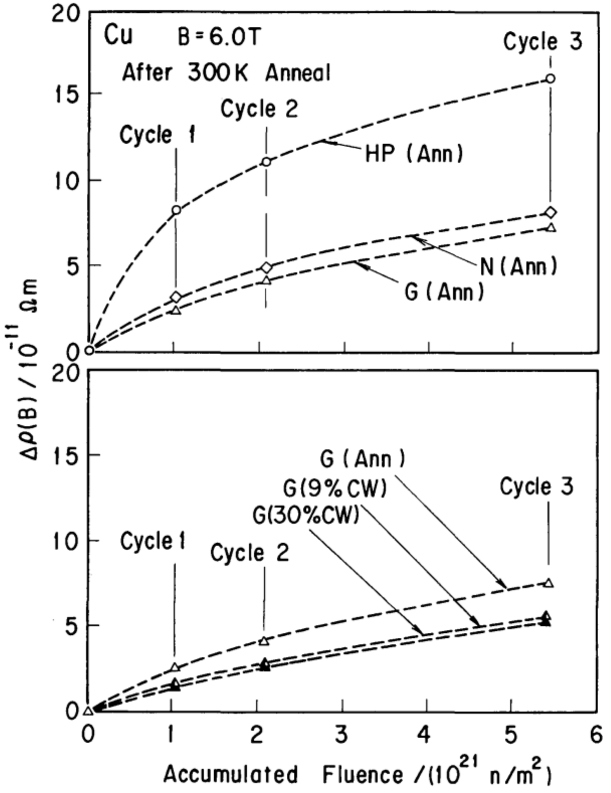


- $\Delta\rho$ is much larger in aluminum.

K. Nakata et al., JNM **135** (1985) 32

Cable/stabilizer



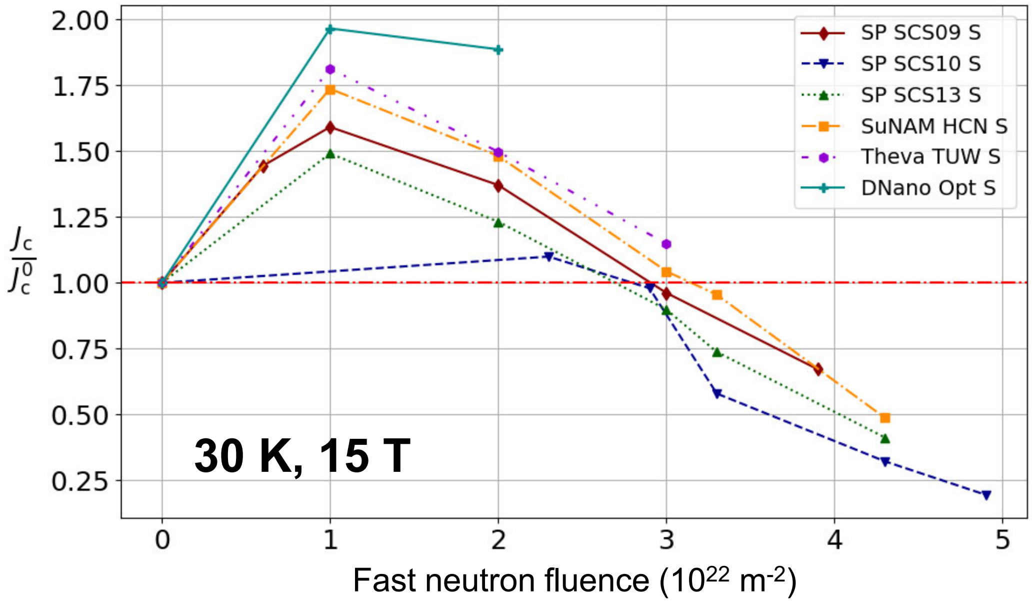


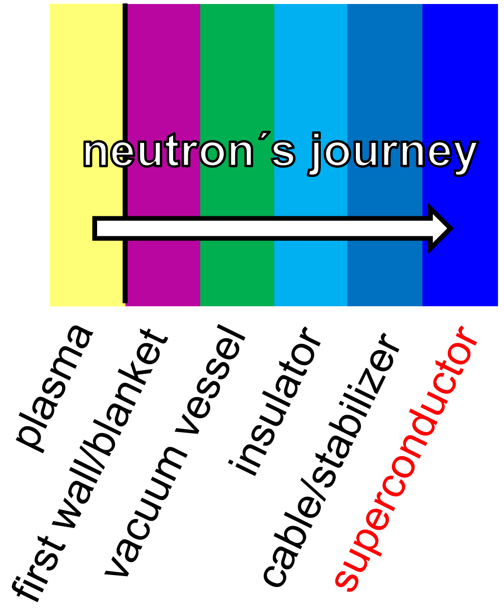
- Resistivity of aluminum fully recovers after a thermal cycle to room temperature.
- Thermal annealing of radiation induced defects starts below 50 K.
- Retained $\Delta\rho$ depends on purity (top) and mechanical treatment (bottom) of copper.

K. Nakata et al., JNM **135** (1985) 32

See also a recent review: J.M. John et al., arXiv:2308.03794

Superconductor (*RE*$Ba_2Cu_3O_{7-\delta}$)



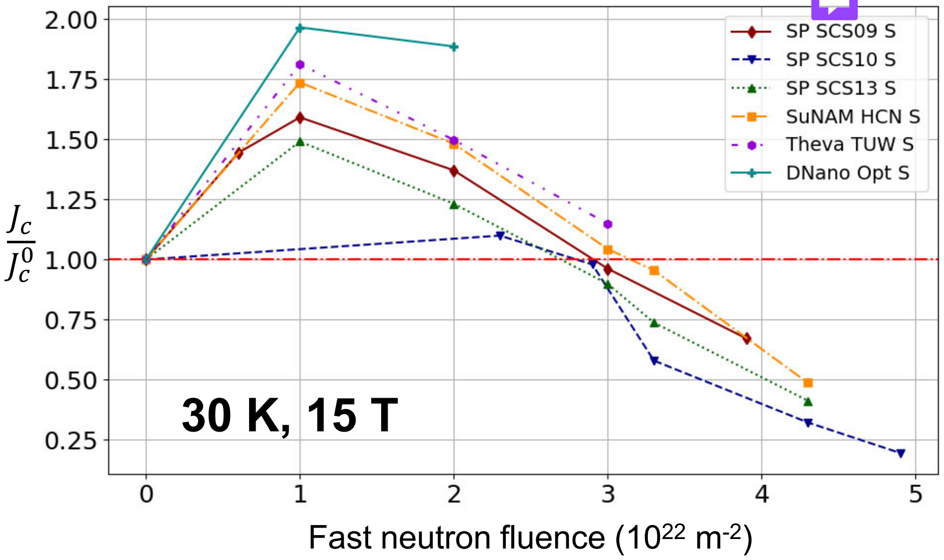


R. Unterrainer et al., SuST **37** (2024) 105008

- J_c first increases (pinning) then decreases with neutron fluence.
- **Degradation starts at a fast neuron fluence of about $3\cdot10^{22}$ m^{-2}!**
  ($1.5\cdot10^{22}$ m^{-2} for low temperature irradiation?)

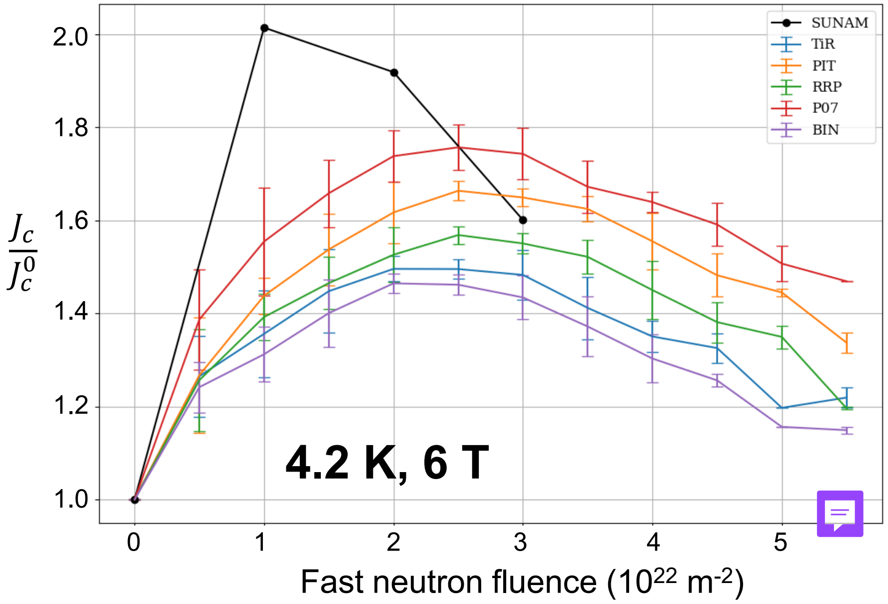
Superconductor

RE**BCO**
(transport measurements)



R. Unterrainer et al., SuST **37** (2024) 105008

Nb_3Sn wires
(magnetization measurements)

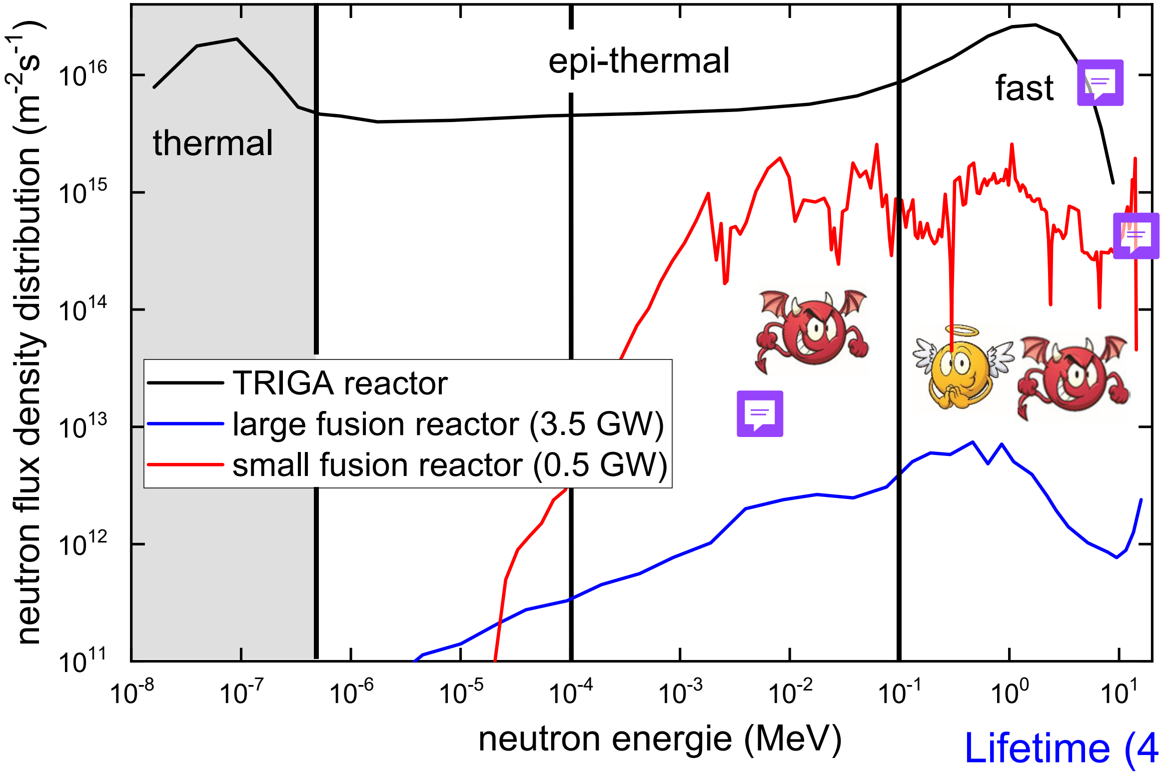


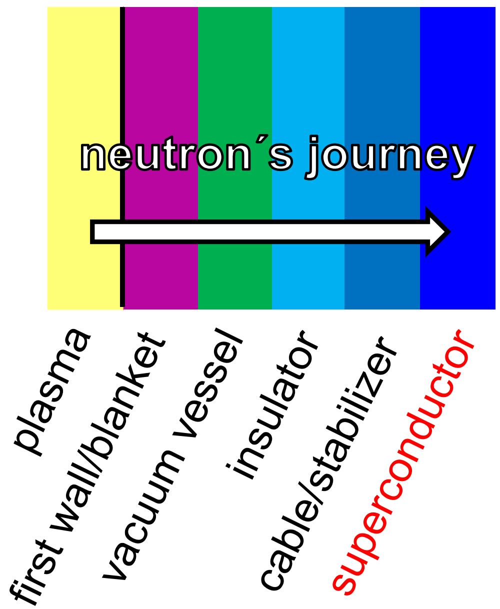
Baumgartner et al., Sci. Rep. **5** (2015) 10236
(M. Asiyaban, unpublished, 2024)

Significantly higher radiation tolerance of Nb_3Sn

Neutron energy distribution

Most of the neutrons reaching the magnets have lost part of their energy (moderation).





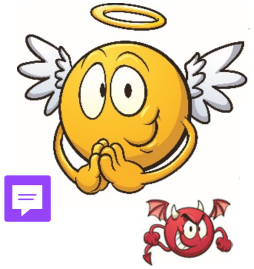
Lifetime (40 ys) fluence (>0.1 MeV): 2· 10^{21} m^{-2}

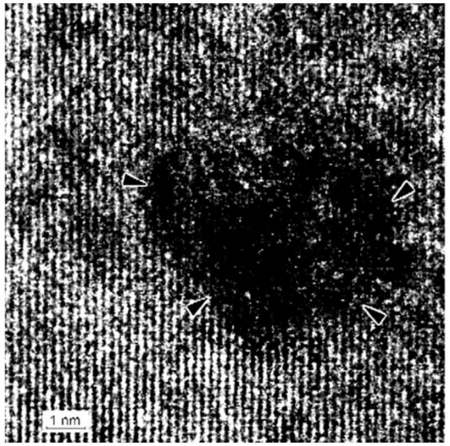
F. Ledda et al., IEEE TAS 34 (2024) 4206105
D. Torsello et al., WB5-4-INV, 11:15, Dec.5

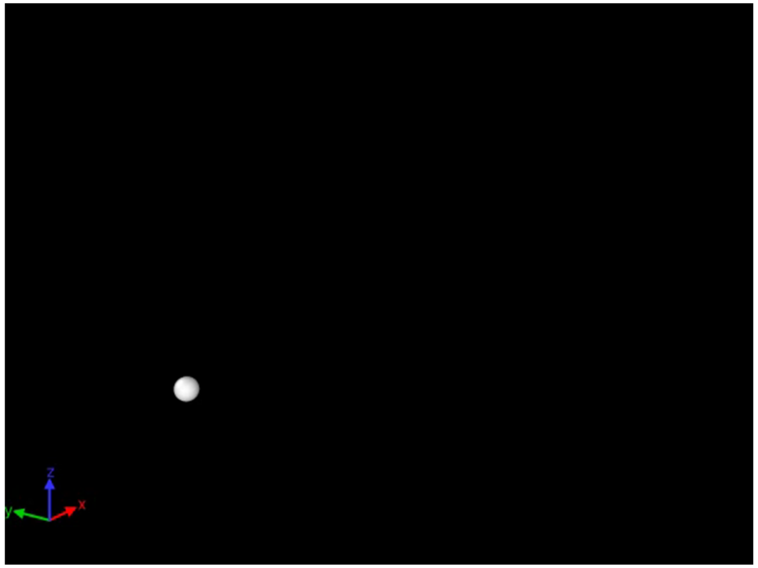
Baker et al., STARFIRE — A Commercial Tokamak Fusion Power Plant Study, ANL/FPP-80-1 (1980).

Introduced defects

- Fast neutrons (E_n>0.1 MeV): collision cascades





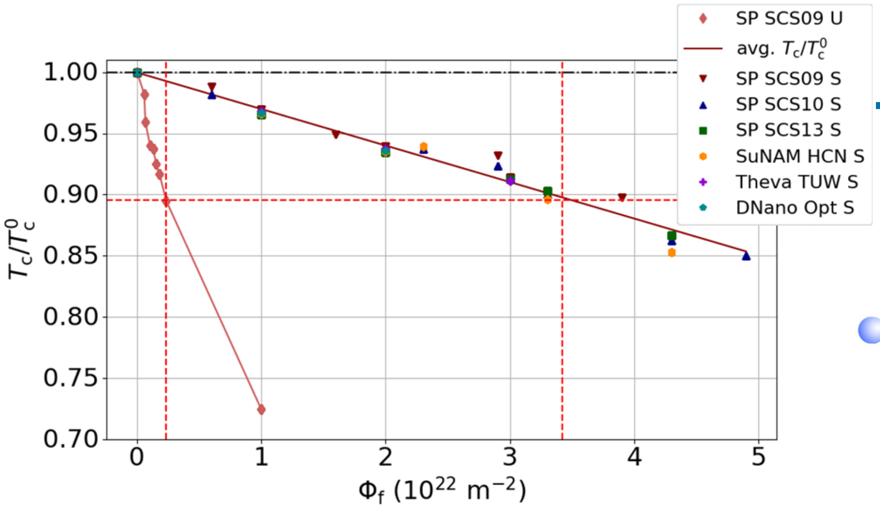


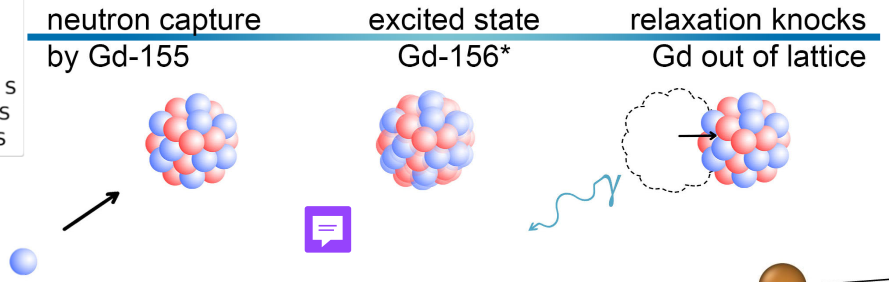
D. Torsello et al., SuST **36** (2023) 014003
D. Gambino et al., WB5-4-INV, 10:45, Dec.5

- ~ 0.1 keV < E_n < 0.1 MeV: single displaced atoms: vacancies, interstitials, Frenkel pairs (mainly oxygen).

Introduced defects

- Nuclear reactions: resonance energy, low energy (thermal) neutrons, e.g.

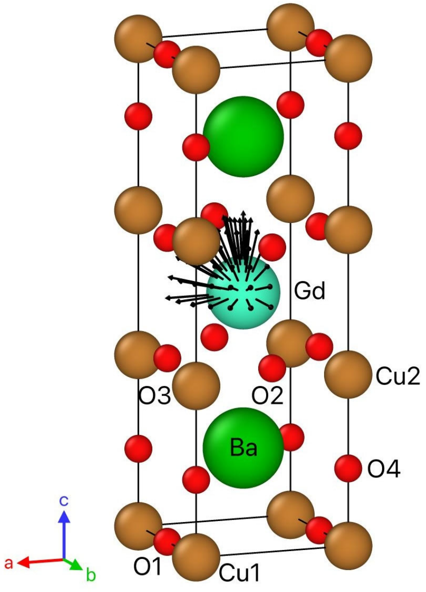




neutron capture by Gd-155

excited state Gd-156*

relaxation knocks Gd out of lattice



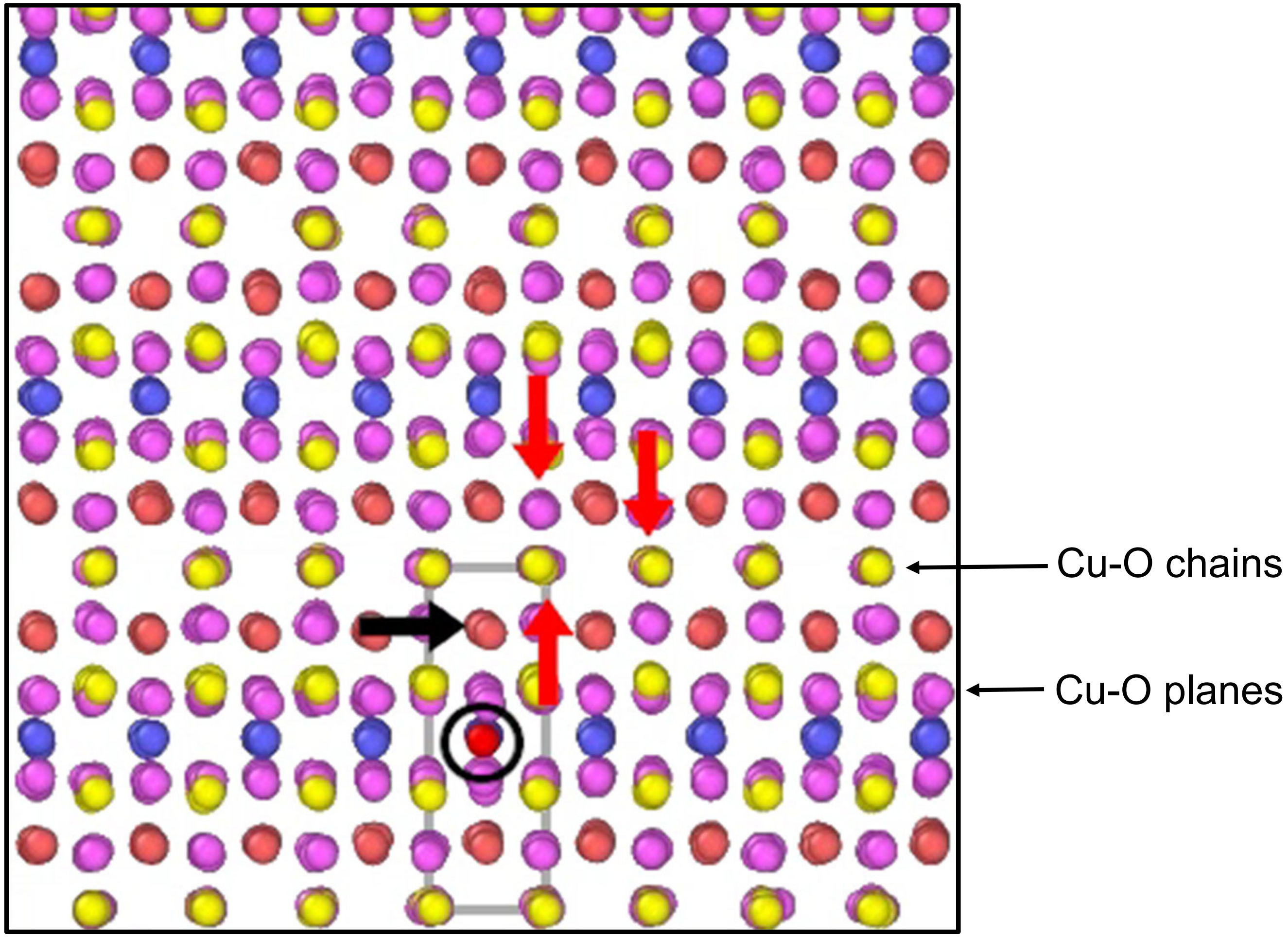
- Particular harmful defects
- Known Primary Knock-on Atom (PKA)
- Known momentum of the PKA

  → Ideal for Molecular Dynamic (MD) simulations

R. Unterrainer et al., SuST **37** (2024) 105008

Molecular dynamics simulation

- ● Primary knock-on atom (PKA)
- ● Gadolinium
- ● Barium
- ● Copper
- ● Oxygen

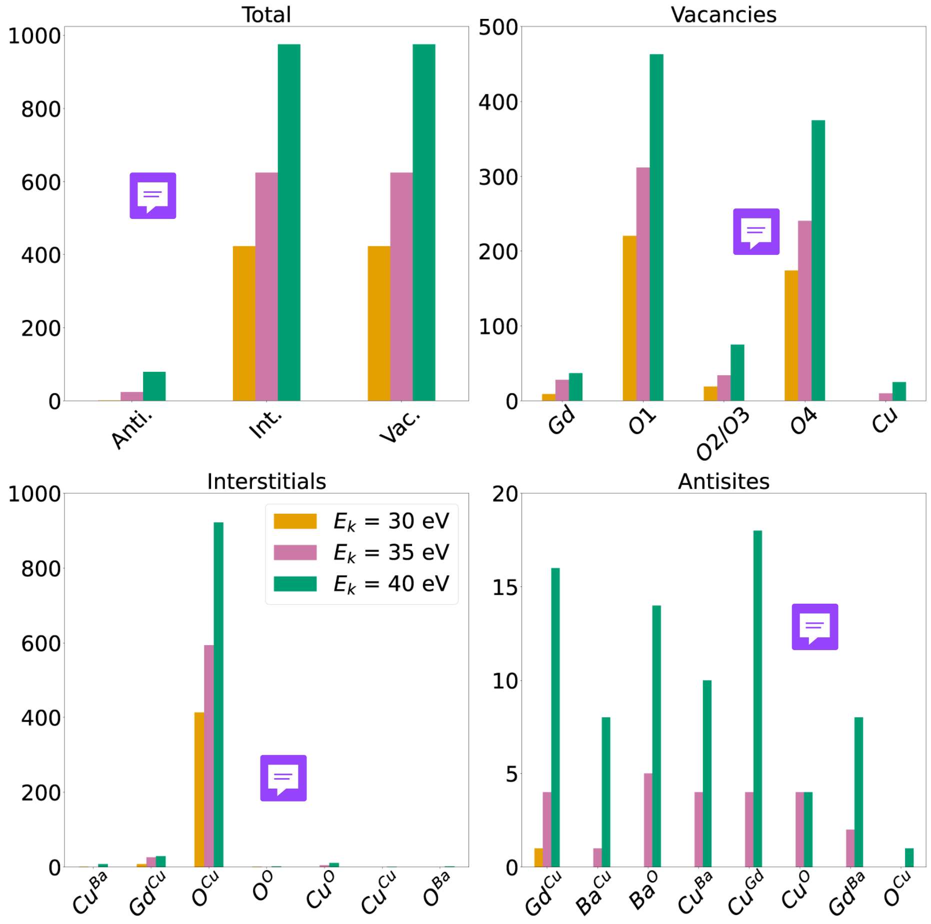


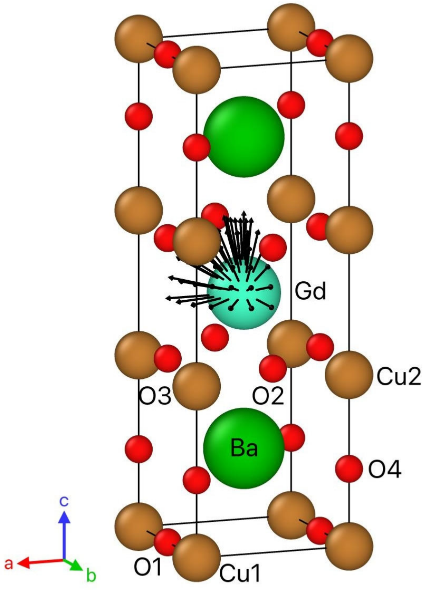
R. Unterrainer et al.,
SuST **37** (2024) 105008

D. Gambino et al.,
WB5-3-INV, 10:45, Dec.5

Introduced defects

Defects created in
430 MD simulation runs





R. Unterrainer et al.,
SuST **37** (2024) 105008

D. Gambino et al.,
WB5-3-INV, 10:45, Dec.5

Enhanced scattering (conventional sc)

- Decrease in mean free time τ
- Increase in scattering rate τ^{-1}
- Decrease in mean free path $l = v_\mathrm{F}\tau$
- Increase in normal state resistivity $\rho_\mathrm{n} = \frac{m_e v_\mathrm{F}}{ne^2 l}$
- Superconducting coherence length decreases: $\xi = \frac{\xi_0}{\sqrt{1+\frac{\xi_0}{l}}}$ $\left(\approx \sqrt{\xi_0 l}\right)$
- Isotropic conventional superconductors
  - Condensation energy: $E_\mathrm{c} = \frac{\phi_0^2}{16\pi^2\mu_0\lambda^2\xi^2}$ = const.

    → Magnetic penetration depth increases: $\lambda = \sqrt{\frac{m_e}{\mu_0 n_s e^2}} = \lambda_\mathrm{L}\sqrt{1+\frac{\xi_0}{l}}$

    ↔ Superfluid density $n_\mathrm{s} \propto \frac{1}{\lambda^2}$ is reduced.
  - Pair breaking current density, $J_\mathrm{d} = \frac{\phi_0}{3\sqrt{3}\mu_0\pi\lambda^2\xi}$, decreases.

IEEE CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 58, Feb. 2025.
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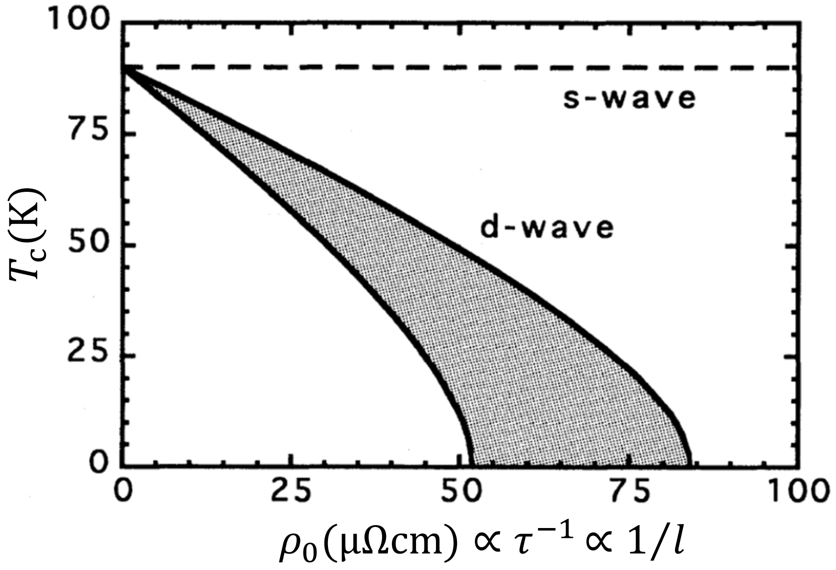
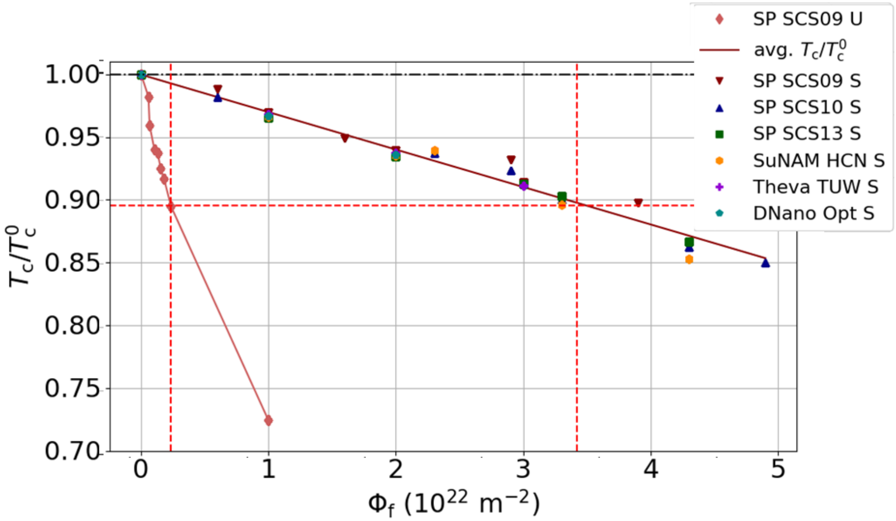
Pair breaking

- Scattering is pair breaking in cuprates.
- T_c degrades with increasing resistivity.



R. J. Radtke et al., PRB **48** (1993) 653



R. Unterrainer et al., SuST **37** (2024) 105008

Fluence is an unsuitable parameter.

- T_c degrades ~13-15 x faster due to low energy neutrons.
- Disorder parameter, D: decrease of T_c $(D = T_c^0 - T_c)$
- $D \propto \tau^{-1}$

Enhanced scattering (cuprates)

- BCS coherence length: $\xi_0 = \frac{\hbar v_\mathrm{F}}{\pi\Delta} = 0.15\,\frac{\hbar v_\mathrm{F}}{k_B T_\mathrm{c}}$ (d-wave) increases.
- Change (increase?) of coherence length: $\xi = \frac{\xi_0}{\sqrt{1+\frac{\xi_0}{l}}}$.
- Magnetic penetration depth increases: $\lambda = \sqrt{\frac{m_e}{\mu_0 n_s e^2}} = \lambda_\mathrm{L}\sqrt{1+\frac{\xi_0}{l}}$.

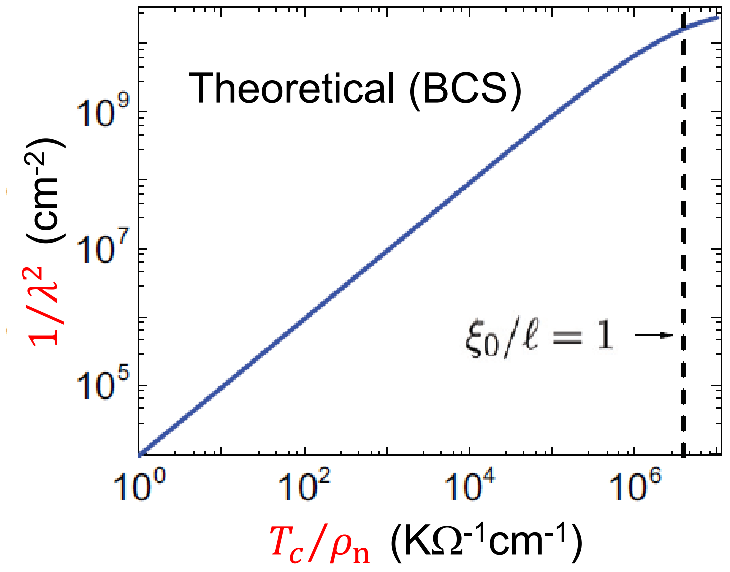
↔ Superfluid density $n_\mathrm{s} \propto \frac{1}{\lambda^2}$ is reduced.

→ Pair breaking current density, $J_\mathrm{d} = \frac{\phi_0}{3\sqrt{3}\mu_0\pi\lambda^2\xi}$, decreases.

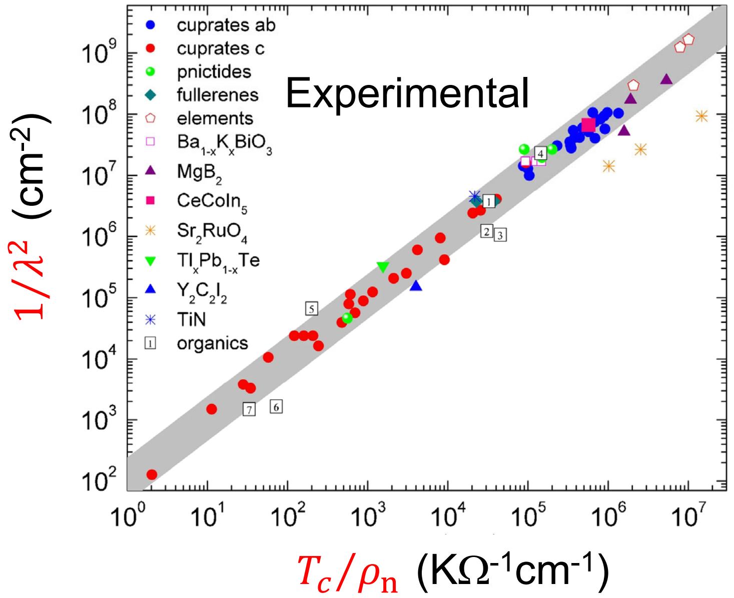
Decrease of depairing current density with D (T_c): $J_\mathrm{d}(D) = \frac{\phi_0}{3\sqrt{3}\mu_0\pi\lambda_\mathrm{L}^2\xi_0(D)\sqrt{1+\frac{\xi_0(D)}{l(D)}}}$

By product: Homes’ Law (dirty limit)

$$\frac{1}{\lambda^2-\lambda_{\mathrm{L}}^2}=\frac{\mu_0 k_{\mathrm{B}}}{0.18\hbar}\,\frac{T_c}{\rho_{\mathrm{n}}}\approx\frac{1}{\lambda^2}\ \text{(dirty limit)}\qquad \frac{\mu_0 k_{\mathrm{B}}}{0.18\hbar}=9.14\cdot 10^5\ \Omega\mathrm{m}^{-1}\mathrm{K}^{-1}$$



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



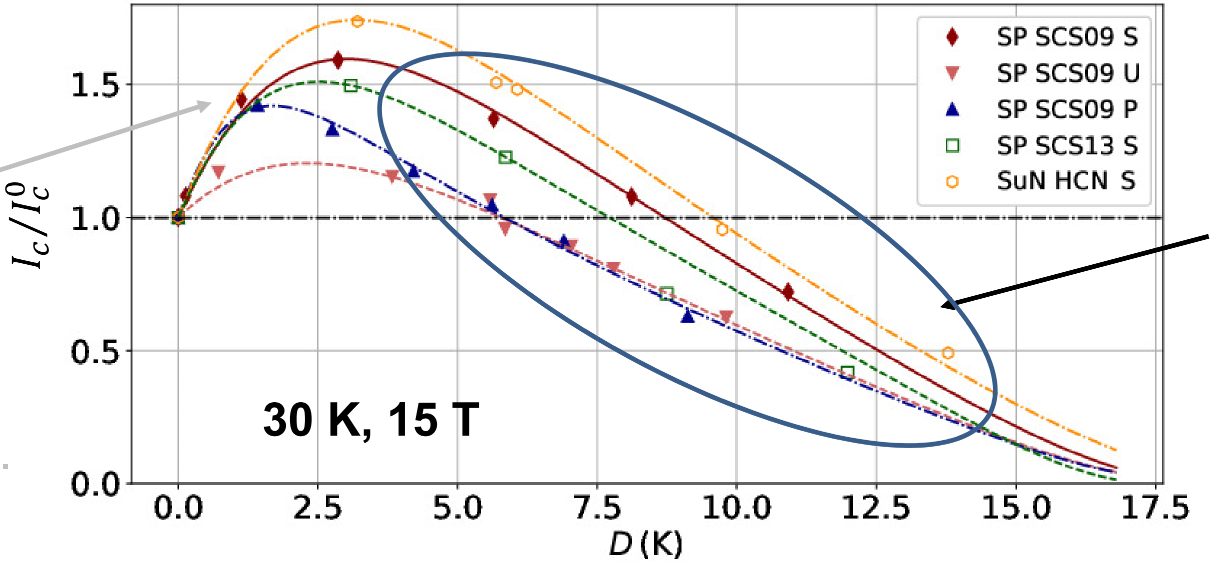
S.V. Dordevic SR 3 (2013) 1713

Universal degradation

$$J_\mathrm{c} = \eta_\mathrm{pin} J_\mathrm{d}(\mathrm{D})$$

Pinning efficiency η_pin increases

Difficult to predict, because of mixed pinning landscape.



J_d decreases

Predictable by changes in T_c and ρ_n.

M. Eisterer et al., arXiv:2409.01376v1

Very similar degradation behavior:

- Same tape (SP SCS09) different irradiation techniques
  - Fast and thermal neutrons (U)
  - Fast neutrons (S)
  - 1.2 MeV protons (P)
- Different tapes (S): SP SCS09, SuN HCN, SP SCS13 (artificial pinning centers)

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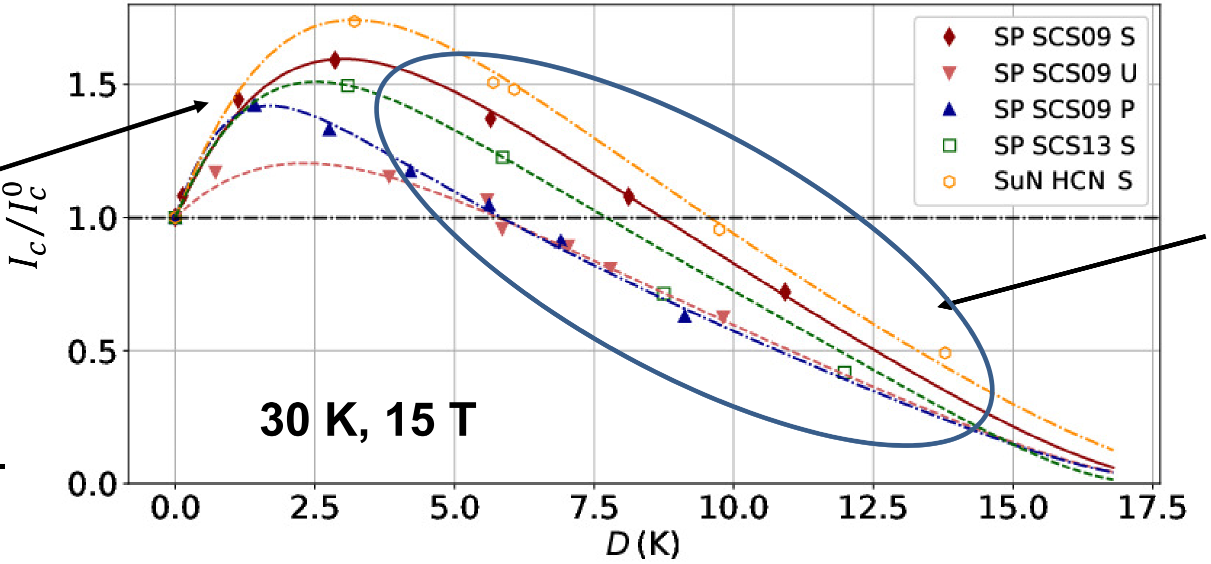

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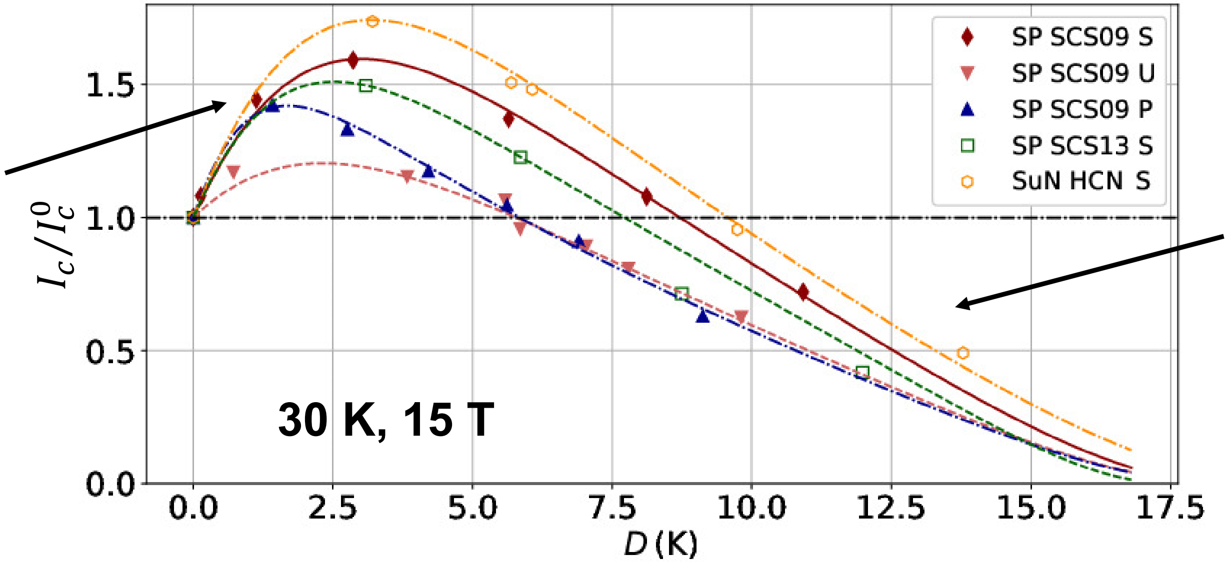
Change of critical current

$$J_\mathrm{c} = \eta_\mathrm{pin} J_\mathrm{d}(D)$$

Pinning efficiency η_pin increases

Mainly caused by large defects



J_d decreases

Resulting from scattering (small defects)

Separation of contributions from enhanced pinning and scattering: $J_\mathrm{c} \propto \eta_\mathrm{pin} J_\mathrm{d}$

$$\frac{I_\mathrm{c}}{I_c^0} = \frac{\eta_\mathrm{pin}}{\eta_\mathrm{pin}^0}\frac{J_\mathrm{d}}{J_\mathrm{d}^0}\frac{A_\mathrm{creep}}{A_\mathrm{creep}^0} =: \frac{\eta_\mathrm{pin}}{\eta_\mathrm{pin}^0} F_\mathrm{D}(D)$$

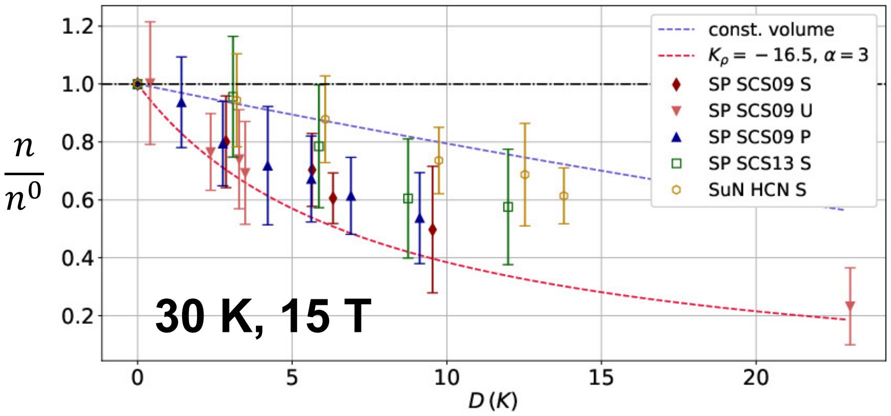
F_D…degradation function

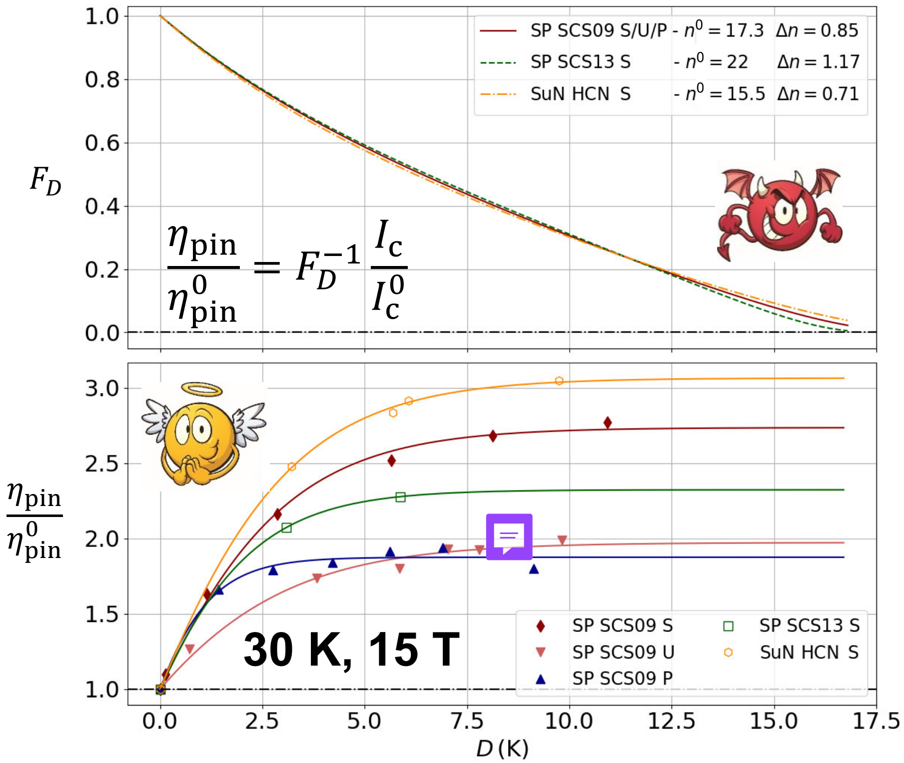
M. Eisterer et al., arXiv:2409.01376v1

Degradation function - pinning contribution

Parameters in F_{D}

- $\alpha_{\mathrm{p}} = \frac{\xi_0^0}{l^0}$ (fixed to 3, weak influence)
- $K_\rho = \frac{T_c^0}{\rho_n^0}\frac{\partial \rho_{\mathrm{n}}}{\partial T_{\mathrm{c}}} \approx -16.5$
  (experimental value, thin film)
- n-value, $U \propto I^n$
  linear fit to the experimental values
  (sample dependent)

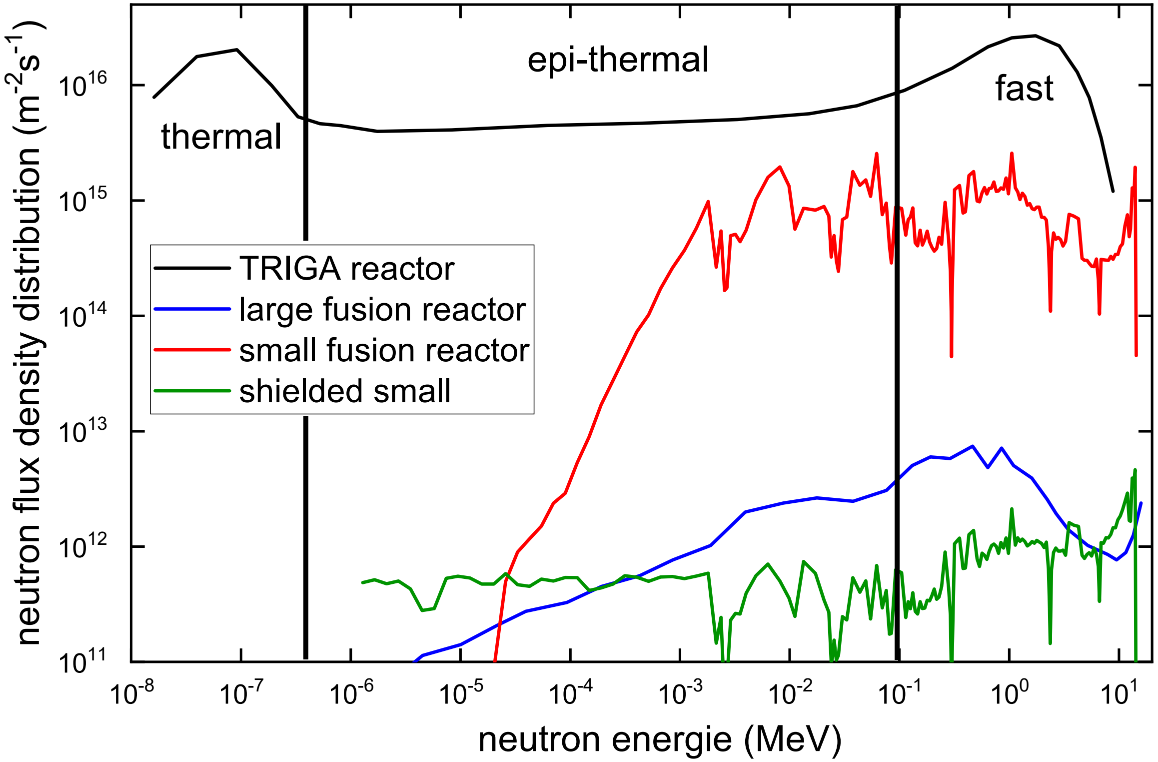




- Strong increase near $D = 0$.
- Saturation at large D.

M. Eisterer et al., arXiv:2409.01376v1

Mitigation strategies: shielding

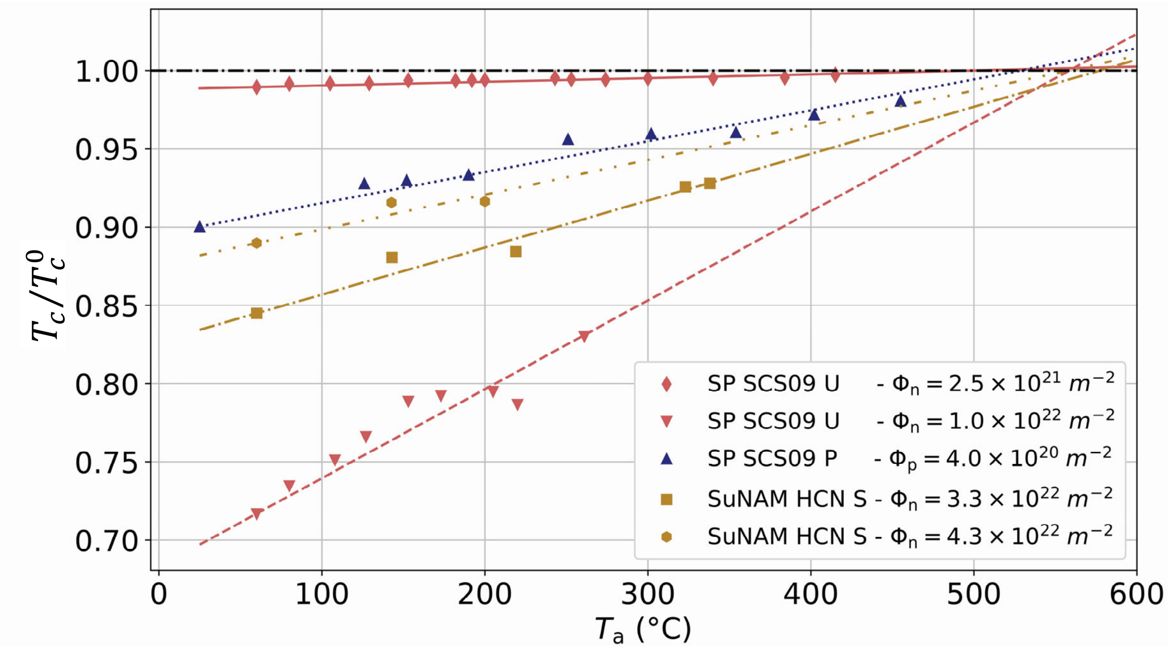


50 cm thick ZrH_2 layer as a shield.

Shielding is an obvious solution, however, it makes the reactor larger and more expensive.

F. Ledda et al., IEEE TAS 34 (2024) 4206105
D. Torsello et al., WB5-4-INV, 11:15, Dec.5

Mitigation strategies: annealing

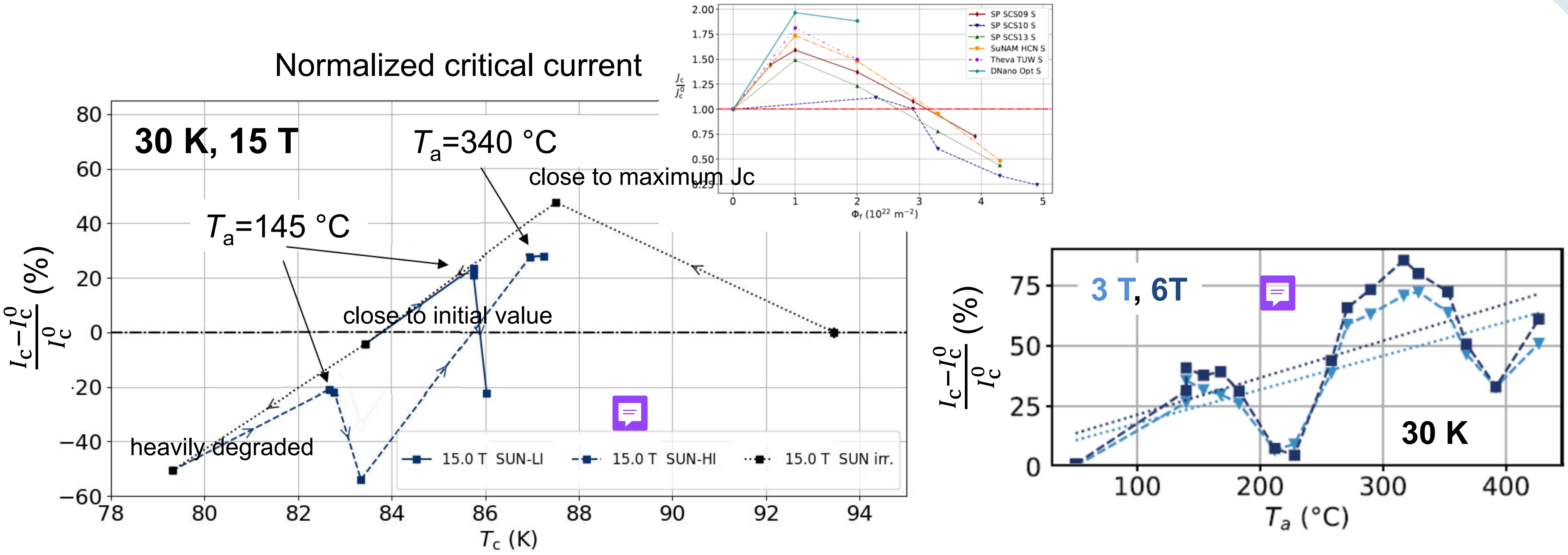

Normalized transition temperature

Loss of oxygen has to be avoided!

R. Unterrainer et al., SuST 35 (2022) 04LT01

- Annealing starts at cryogenic temperatures (protons).
- Partial recovery during maintenance breaks.
- Linear behavior up to high annealing temperatures.

Mitigation strategies: annealing


Normalized critical current

30 K, 15 T

T_a=340 °C

close to maximum Jc

T_a=145 °C

close to initial value

heavily degraded

3 T, 6T

30 K

- Recovery is non-monotonous, although with a linear trend.
- Degraded samples was recovered above its initial value.
- Optimum annealing protocol to be derived.

R. Unterrainer et al., SuST 35 (2022) 04LT01

Conclusions

- Radiation is an issue for compact fusion reactors.
  - Degradation of insulator, stabilizer, and superconductor.
- Pair breaking by scattering decreases T_c of cuprate superconductors linearly with neutron fluence (defect density).
  - T_c is an efficient disorder parameter.
  - Indicating a decrease in superfluid density.
- Decrease of J_c at high defect density is driven by the decrease of superfluid density.
  - Successful modelling.
- Efficient scattering centers (defects) have to be identified and their production rate as a function of the neutron energy for a reliable prediction of the maximum lifetime fluence of the magnet.