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Radiation effects on HTS: improved pinning vs. pair breaking

Michael Eisterer

Atominstitut, TU Wien, Vienna, Austria

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Collaborations and Funding

Raphael Unterrainer, Alexander Bodenseher

David Fischer MIT (proton irradiation)

Daniele Torsello, Francesco Laviano Politecnico di Torino (radiation environment, damage calculations)

Davide Gambino Linköping University (MD calculations)

Ruben Hühne IFW Dresden (thin film preparation)

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Outline

Motivation

- This talk
- RADSUM 2025

Developing a workflow

- Predicting the change of the critical current under particle radiation

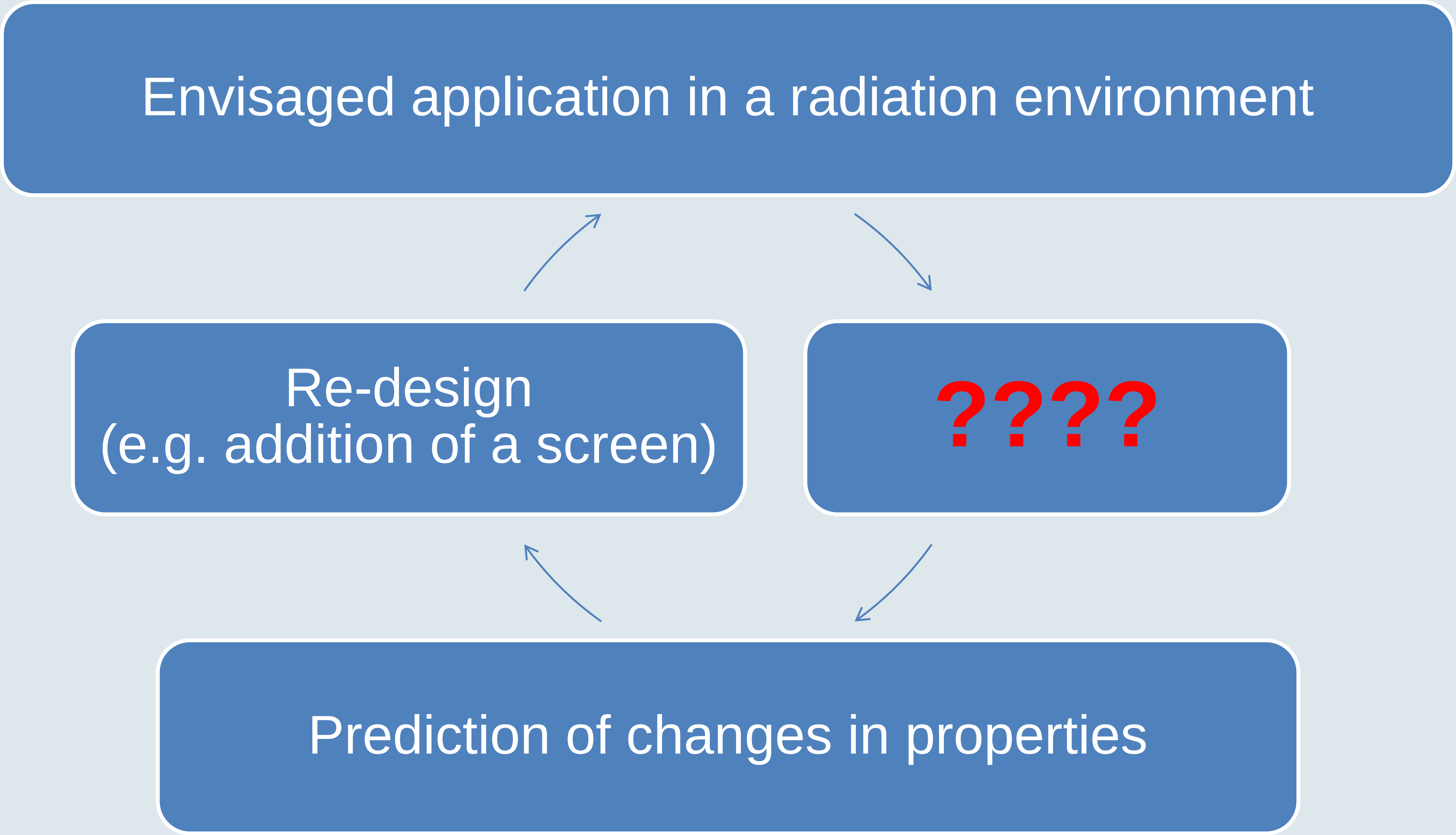
Enhanced pinning versus decreased superfluid density

- Favorable increase in flux pinning („large defects“)
- Harmful suppression of superfluid density („small defects“)
  - ➢ Effect of scattering in conventional s-wave superconductors
  - ➢ Pair breaking in cuprates
- Separation of the two contributions
  - Pinning efficiency

Conclusions

Developping a workflow

Motivation



Envisaged application in a radiation environment

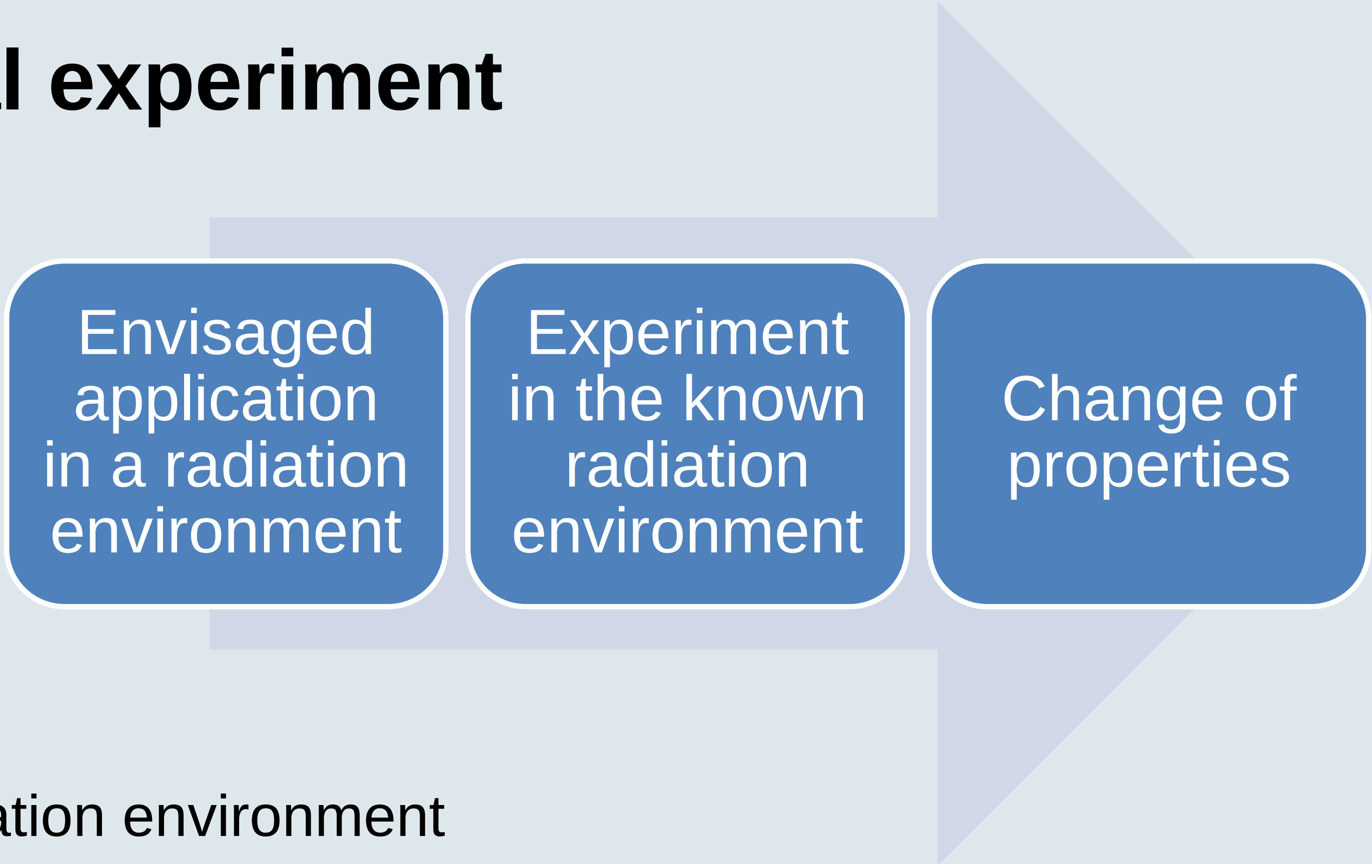
????

Prediction of changes in properties

Re-design
(e.g. addition of a screen)

Motivation

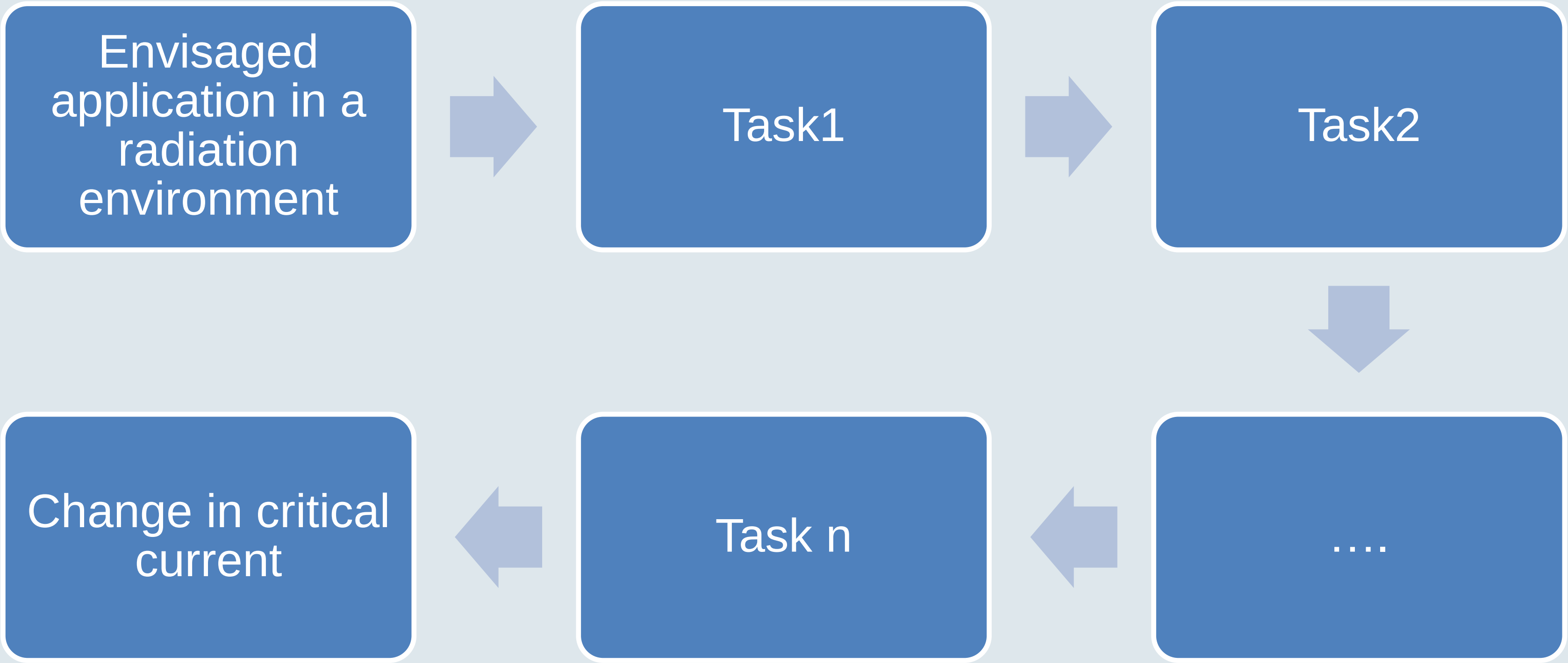
????: Ideal experiment



Real world: radiation environment

- not known exactly
- not available for experiments
  - → Modelling
  - → Benchmarking experiments: verifying models, providing input parameters

Workflow



- Splitting into tasks
- Developing interfaces
- Defining benchmarking experiments

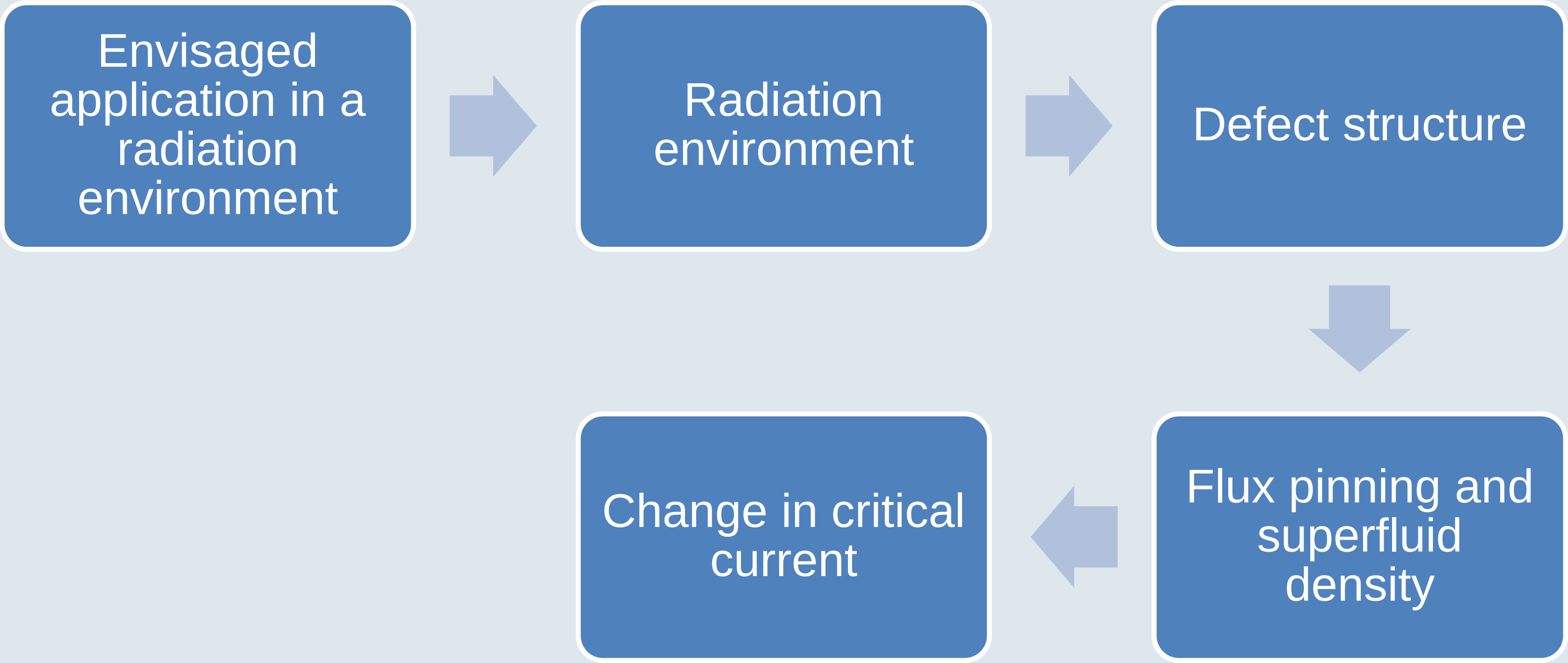
Interfaces

- Task i has to provide an input for Task i+1
  - Parameter
  - Distribution function
  - …..
- Task i+1 has to accept this input

Example : Proton irradiation as a proxy for neutron irradiation

- Expects target proton fluence as input, but neutron fluence is specified.
  → Possible interface: displacements per atom (dpa).
- Output: e.g. change in T_c but next task expects scattering rate
  → Possible interface: Relationship between T_c and τ^{-1}.

Draft Workflow



- Defining tasks
- Defining benchmarking experiments
- Defining interfaces
  - This talk: Flux pinning and superfluid density

Task 1: Radiation environment

- Input: Primary radiation source.
- Output: flux of particles with their energy distributions (including secondary particles)
- Numerical methods (yesterday).
- Experiments: not needed/possible?

On track (?)

Task 2: Defect structure

- Input: flux of particles with their energy distributions
- Output (?):
  - Scattering rate
  - Size and density of pinning efficient defects
- Numerical methods:
  - Damage (dpa) calculations
  - Molecular dynamic simulations
- Experiments: Benchmarking particles/energy
  - XRD
  - TEM
  - XANES
  - ….

Interface or additional task needed?

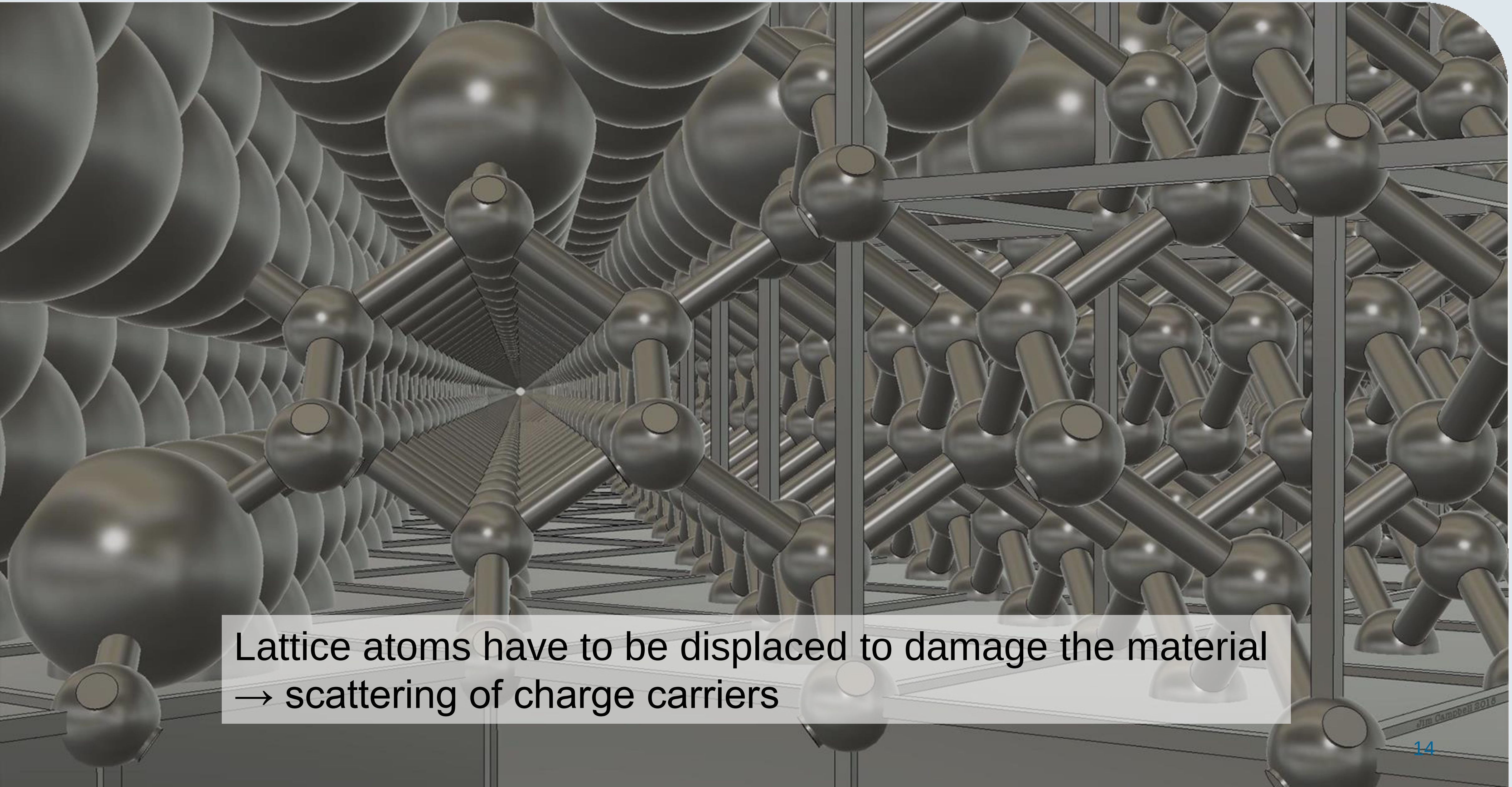
Task 3: flux pinning and superfluid density

- Input (?):
  - Scattering rate
  - Size and density of pinning efficient defects
- Output: Critical current density
- Numerical methods:
  - Time dependent Ginzburg Landau theory (pinning)
- Relation between scattering rate and superfluid density.
- Experiments: Benchmarking particles/energy
  - Scattering rate
    - Normal state resistivity
    - Hall resistivity
    - Transition temperature
  - Critical current

Modelling changes in I_c

Scattering

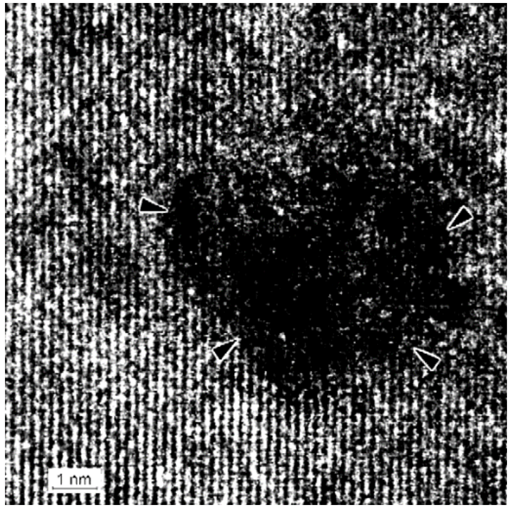
Ideal Crystal

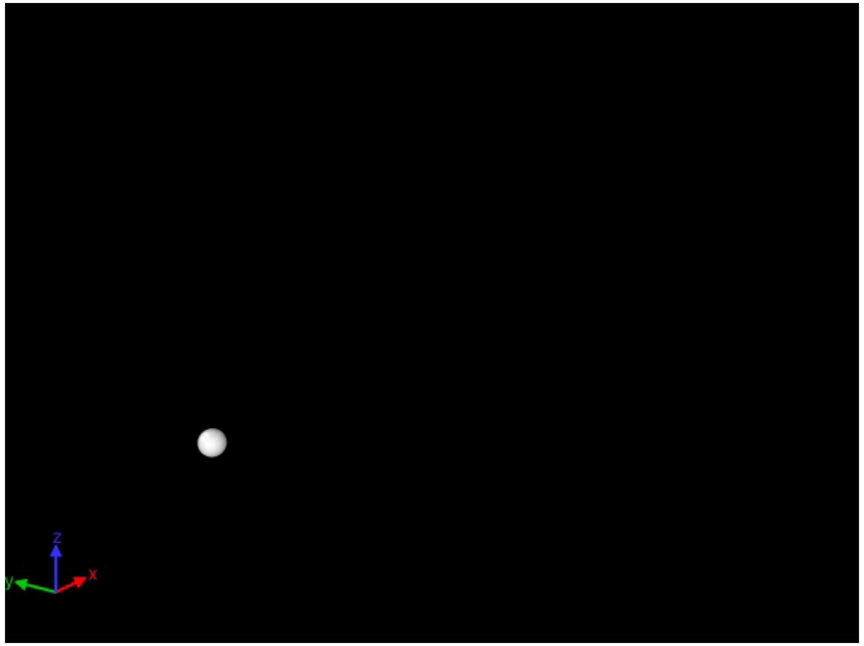


Lattice atoms have to be displaced to damage the material
→ scattering of charge carriers

Introduced defects

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





D. Torsello et al., SuST **36** (2023) 014003

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

Normal state resistivity

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

Superconductors: Ginzburg-Landau theory

Thermodynamic behavior is determined by three parameters:

- Transition temperature, T_c.
- Magnetic penetration depth, λ.
- Superconducting coherence length, ξ.

Other parameters can be calculated:

- Condensation energy density: $E_\mathrm{c} = \frac{\phi_0^2}{16\pi^2\mu_0\lambda^2\xi^2}$.
- Upper critical field: $B_{c2} = \frac{\phi_0}{2\pi\xi^2} = \sqrt{2}\kappa B_c$.
- Lower critical field: $B_{c1} = \frac{\phi_0}{4\pi\lambda^2}\ln(\frac{\lambda}{\xi} + 0.5)$.

Relation to basic material properties:

- Magnetic penetration depth: $\lambda = \sqrt{\frac{m_e}{\mu_0 n_\mathrm{s} e^2}}$.

  $\rightarrow$ Superfluid density $n_\mathrm{s} \propto \frac{m_e}{\lambda^2}$.
- BCS Coherence length $\xi_0 = \frac{\hbar v_\mathrm{F}}{\pi\Delta} = 0.18\,\frac{\hbar v_\mathrm{F}}{k_B T_\mathrm{c}}$

Scattering in conventional (d-wave) superconductors

(Non-magnetic) Scattering is not pair breaking in isotropic conventional superconductors.

→ Transition temperature does not change.

→ Condensation energy: $E_c = \frac{\phi_0^2}{16\pi^2\mu_0\lambda^2\xi^2}$ and B_c do not change.

- Gorkov-Goodman relations: $\kappa = \frac{\lambda}{\xi} = \kappa_0 + 2.37 \cdot 10^6\sqrt{\gamma_n}\rho_0 = \kappa_0\left(1 + \frac{\xi_0}{l}\right)$

→ Upper critical field increases: $B_{c2} = B_{c2}^{\rho_0\to 0} + 2.37 \cdot 10^6\sqrt{\gamma_n}\rho_0 = B_{c2}^{\rho_0\to 0}\left(1 + \frac{\xi_0}{l}\right)$

→ Superconducting coherence length decreases: $\xi = \frac{\xi_0}{\sqrt{1+\frac{\xi_0}{l}}}$ $\left(\approx \sqrt{\xi_0 l}\right)$

- Isotropic conventional superconductors

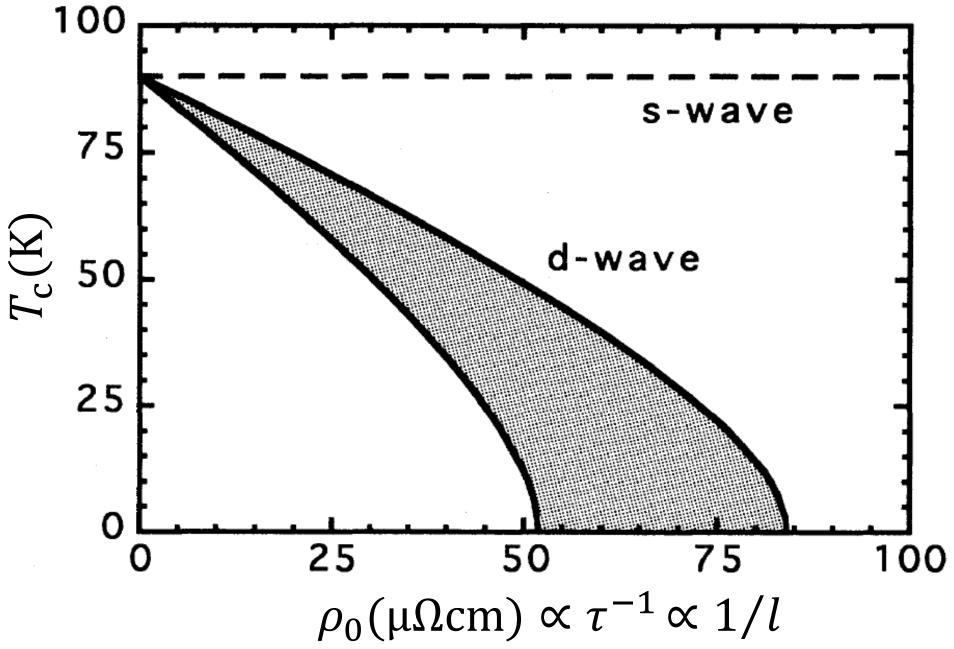
→ Magnetic penetration depth increases: $\lambda = \sqrt{\frac{m_e}{\mu_0 n_s e^2}} = \lambda_\mathrm{L}\sqrt{1 + \frac{\xi_0}{l}}$

→ Superfluid density $n_s \propto \frac{1}{\lambda^2}$ is reduced.

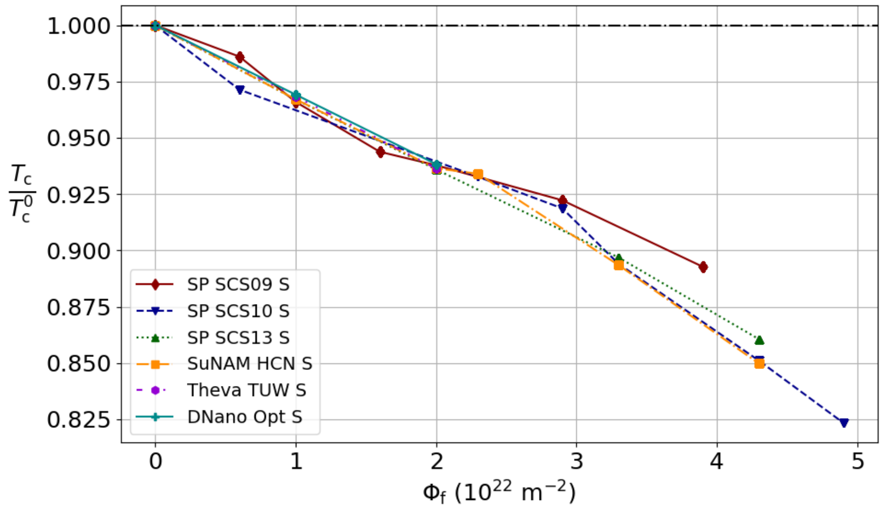
→ Pair breaking current density, $J_\mathrm{d} = \frac{\phi_0}{3\sqrt{3}\mu_0\pi\lambda^2\xi}$, decreases.

Pair breaking in cuprates

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



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

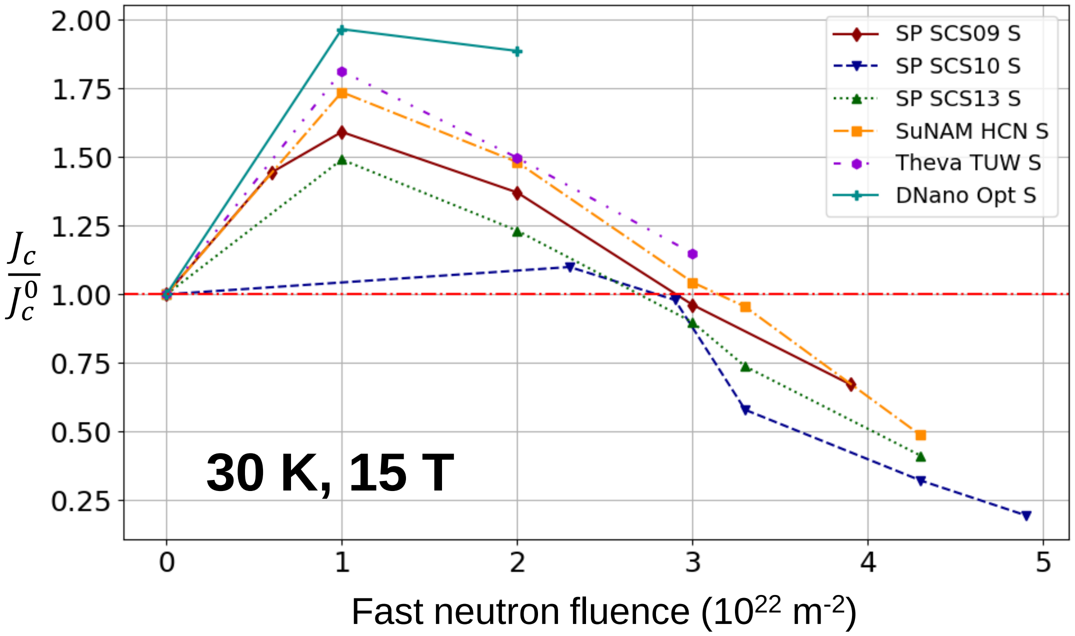


R. Unterrainer et al., SuST **37** (2024) 105008

- Resistivity not easily accessible in coated conductors
- Disorder parameter, D: decrease of T_c $(D = T_\mathrm{c}^0 - T_\mathrm{c})$
- $D \propto \tau^{-1}$
- $D \propto \phi$ (different slope for different particles)

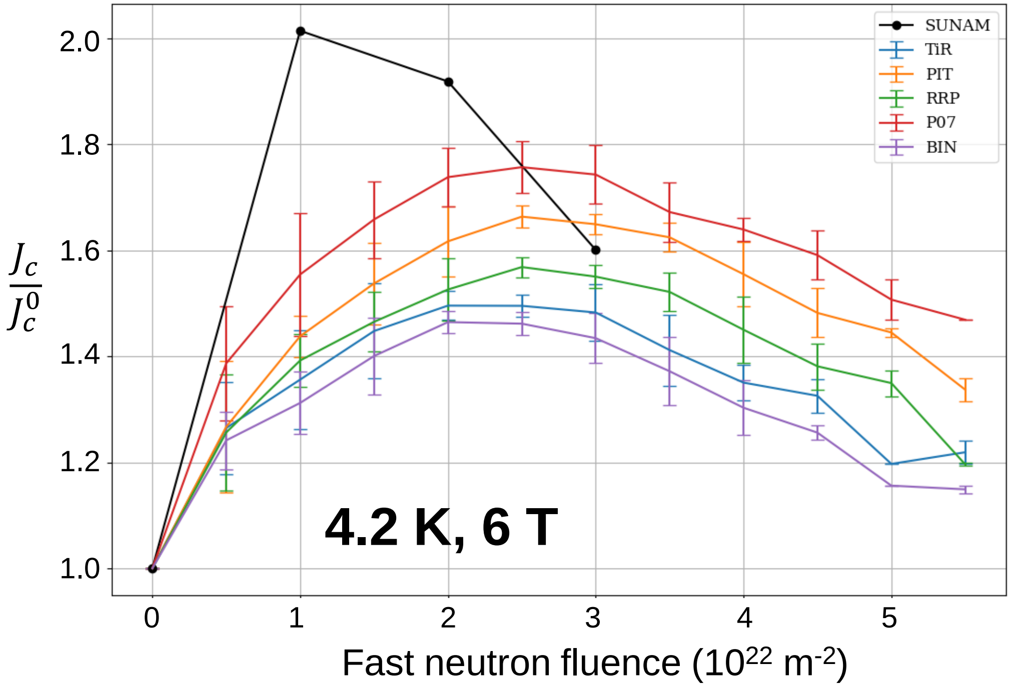
Change in critical current density

_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

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 stronger: $\lambda = \sqrt{\frac{m_e}{\mu_0 n_s e^2}} = \lambda_\mathrm{L}\sqrt{1+\frac{\xi_0}{l}}$.

→ Superfluid density $n_\mathrm{s} \propto \frac{1}{\lambda^2}$ is stronger 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): $J_\mathrm{d}(D) = \frac{\phi_0}{3\sqrt{3}\mu_0\pi\lambda_\mathrm{L}^2\xi_0(D)\sqrt{1+\frac{\xi_0(D)}{l(D)}}}$

Change in superfluid density (Homes's Law)

$\lambda = \lambda_L\sqrt{\frac{\xi_0}{l}}$ with the BCS relation $\xi_0 = 0.18\frac{\hbar v_f}{k_B T_c}$, $\rho_n = \frac{m_e v_f}{n e^2 l}$ and $\lambda_L = \sqrt{\frac{m_e}{\mu_0 n e^2}}$

$$\frac{1}{\lambda^2-\lambda_L^2} = \frac{\mu_0 k_B}{0.18\hbar}\frac{T_c}{\rho_n} = \frac{1}{\lambda^2} \quad \frac{\mu_0 k_B}{0.18\hbar} = 9.14\cdot 10^5\ \Omega\mathrm{m}^{-1}\mathrm{K}^{-1}$$

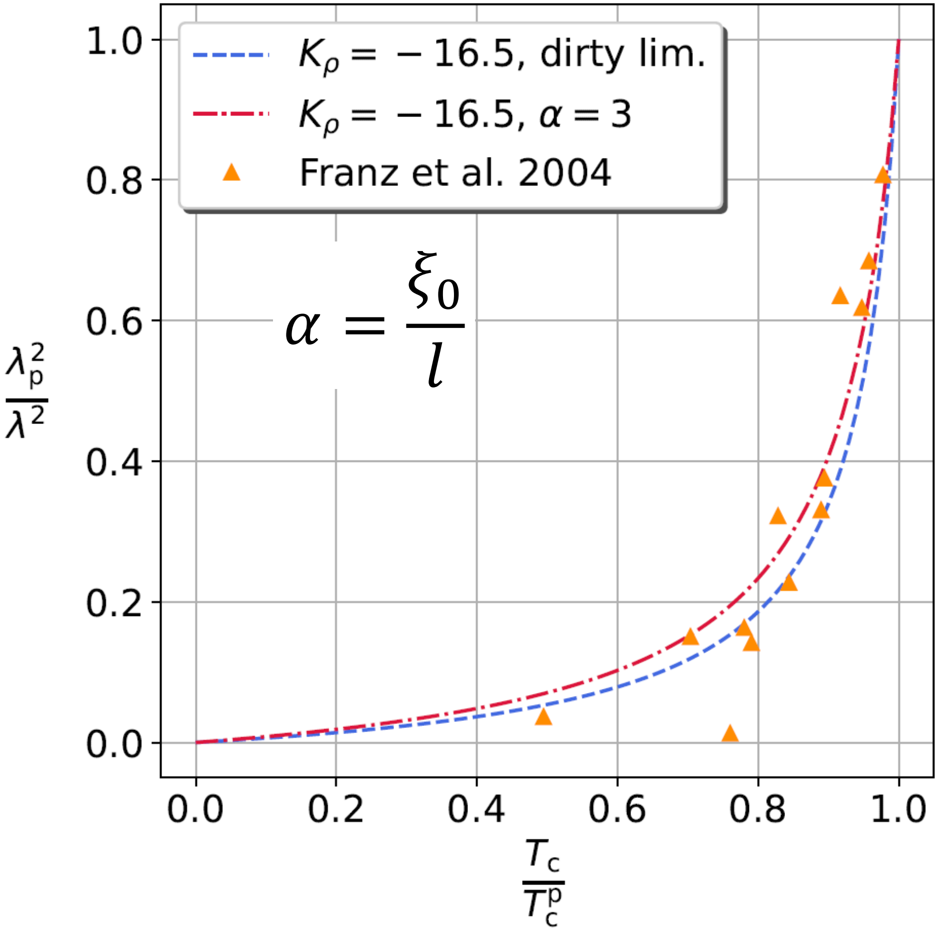
Our experimental data:

$$T_c = \boldsymbol{T_c^{unirr}} - \boldsymbol{\beta}\phi,\ \rho = \boldsymbol{\rho_{unirr}} + \boldsymbol{\alpha}\phi$$

$$K_\rho = -\frac{\alpha T_c^{unirr}}{\beta\rho_{unirr}} = \frac{T_c^{unirr}}{\rho_{unirr}}\frac{\partial\rho}{\partial T_c}$$

Experimental data from literature:

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



$$\alpha = \frac{\xi_0}{l}$$

Suitable prediction of the change in superfluid density!

Summary scattering

Any defect decreases the mean free path of the charge carrier, l.

- Normal conductors
    - Increase in normal state resistivity $\rho_\mathrm{n} = \frac{m_e v_\mathrm{F}}{n e^2 l}$
- Conventional superconductors
    - Decrease of coherence length: $\xi = \frac{\xi_0}{\sqrt{1+\frac{\xi_0}{l}}} \approx \sqrt{\xi_0 l}$
    - Increase of magnetic penetration depth: $\lambda = \lambda_\mathrm{L}\sqrt{1+\frac{\xi_0}{l}}$

  → Decrease of superfluid density $\propto \frac{1}{\lambda^2}$.

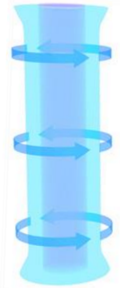
- **Most efficient**: large number of small defects (dpa!).
- Cuprate superconductors: scattering is pair breaking!
    - Decrease of T_c and E_c.
    - Stronger reduction of superfluid density.
    - Relevant parameter: τ^{-1} (→ ρ_n, T_c)

Modelling changes in I_c

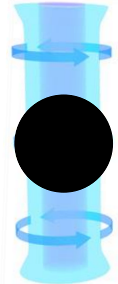
Flux pinning

Flux pinning

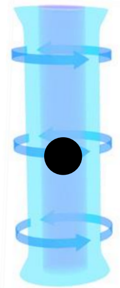
- Condensation energy density: $E_{\mathrm{c}} = \frac{\phi_0^2}{16\pi^2\mu_0\lambda^2\xi^2}$



- Energy of vortex core per meter: $E_{\mathrm{core}} = E_{\mathrm{c}}\,\pi\xi^2 = \frac{\phi_0^2}{16\pi\mu_0\lambda^2}$



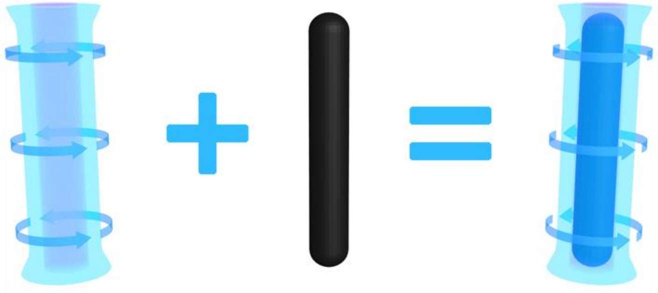
1. Normal conducting/insulating defects (ΔT_c-pinning)
    a. Large defects: $r_D > \xi$: $E_{pin} \cong E_{\mathrm{c}}\,\pi\xi^2 2r_D = \frac{\phi_0^2 r_D}{8\pi\mu_0\lambda^2}$
    b. Small defects: $r_D < \xi$: $E_{pin} = E_{\mathrm{c}}\,\frac{4\pi r_D^3}{3} = \frac{\phi_0^2 r_D^3}{12\pi\mu_0\lambda^2\xi^2}$

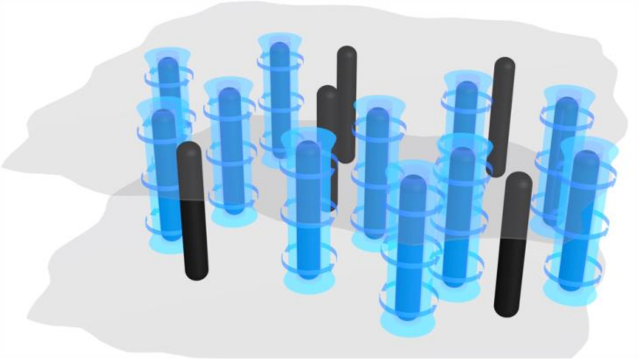


2. Tiny defects, no suppression of E_{c} (Δl-pinning): vortex core shrinks

- Critical state: $F_p = F_L = |J_c \times B\,|$, force balance.
- $f_{pin} = \frac{E_{\mathrm{pin}}}{\xi}$

Pinning efficiency





- Thermodynamic limit: depairing current density

$$J_\mathrm{d} = \frac{\phi_0}{3\pi\sqrt{3}\mu_0\lambda^2\xi}$$

- Energy of vortex core per meter: $E_\mathrm{core} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2}$

$$f_p^\mathrm{max} = \frac{E_\mathrm{core}}{\xi} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2\xi}$$

- Critical state: $F_p = F_L = |J_c \times B\,|$
- Highest possible pinning force per vortex and unit length: cylindrical defect with $r_D \geq \xi$
- Force balance for one vortex ($B \perp J_c$): $f_L = f_p$

$$f_L = \iint F_L \mathrm{d}A = \iint J_c \times B \mathrm{d}A = J_c\phi_0 \leq f_p^\mathrm{max} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2\xi}$$

- $J_c^{max} = \frac{f_p^{max}}{\phi_0} = \frac{\phi_0}{16\pi\mu_0\lambda^2\xi} = \frac{3\sqrt{3}}{16}J_d \approx 0.32 J_d$
- $\eta_\mathrm{pin} = \frac{J_c}{J_d}$ ... pinning efficiency
- $\eta_\mathrm{pin,max} \approx 32\%$
- Large defects $r_D \geq \xi$ needed for a large η_pin (although any defect can contribute to pinning)

Modelling changes in I_c

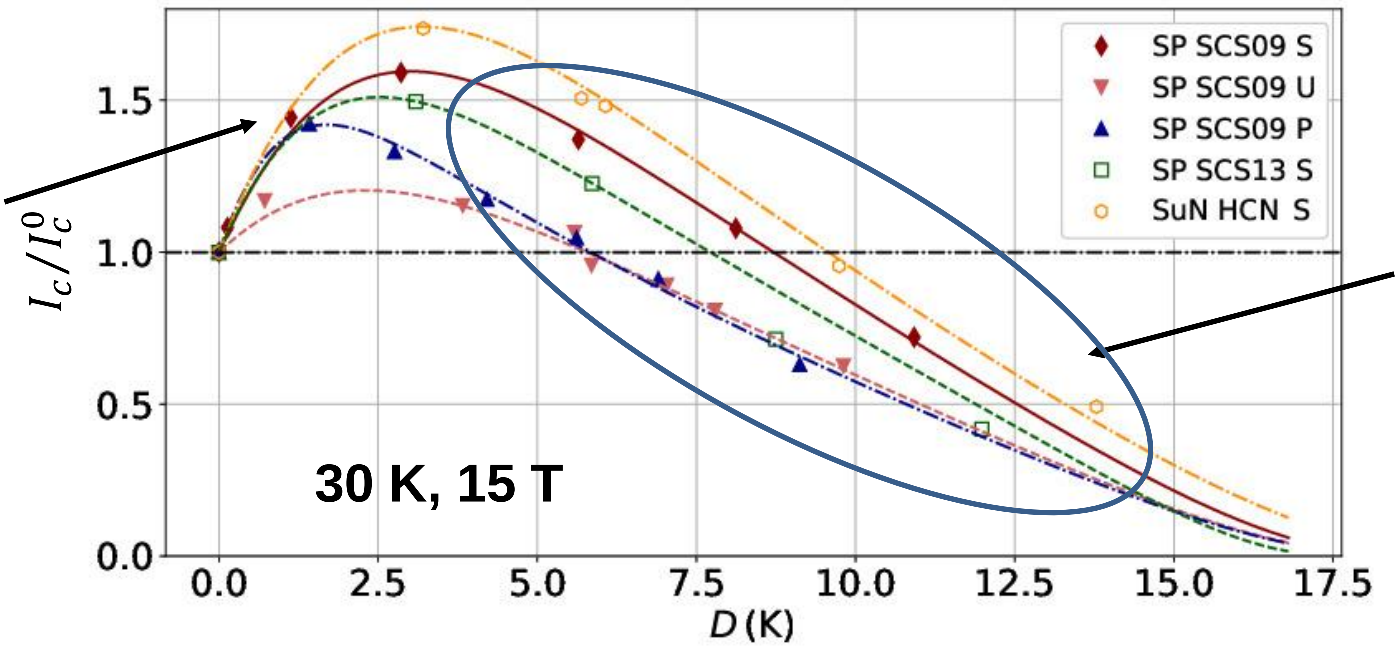
Resulting changes

Universal degradation

$$J_c = \eta_{\text{pin}} J_d(D)$$

Pinning efficiency η_{pin} increases

Large defects?
Good dpa?



J_d decreases

Predictable from changes in T_c and ρ_n.

Small defects?
Bad dpa?

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)

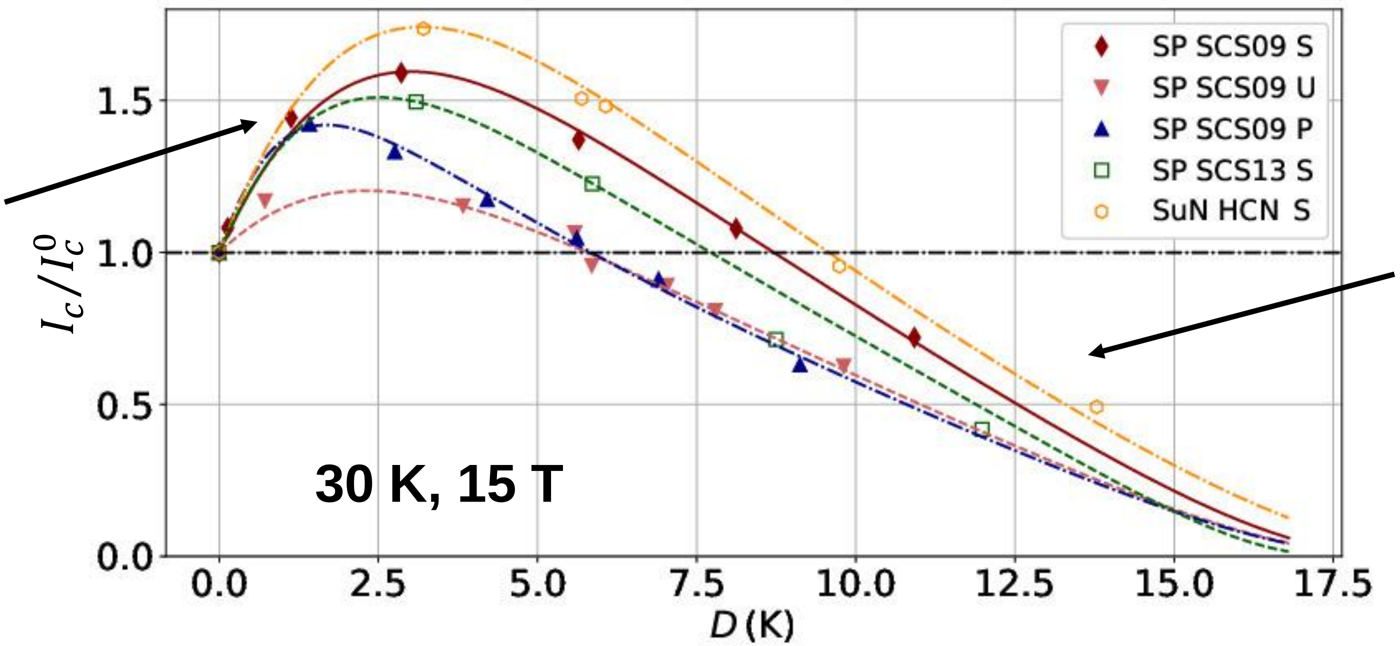
M. Eisterer et al., arXiv:2409.01376v1

Change of critical current

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

Pinning efficiency η_pin increases

Mainly caused by large defects



J_d decreases

Resulting from scattering (small defects)

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

F_D…degradation function

M. Eisterer et al., arXiv:2409.01376v1

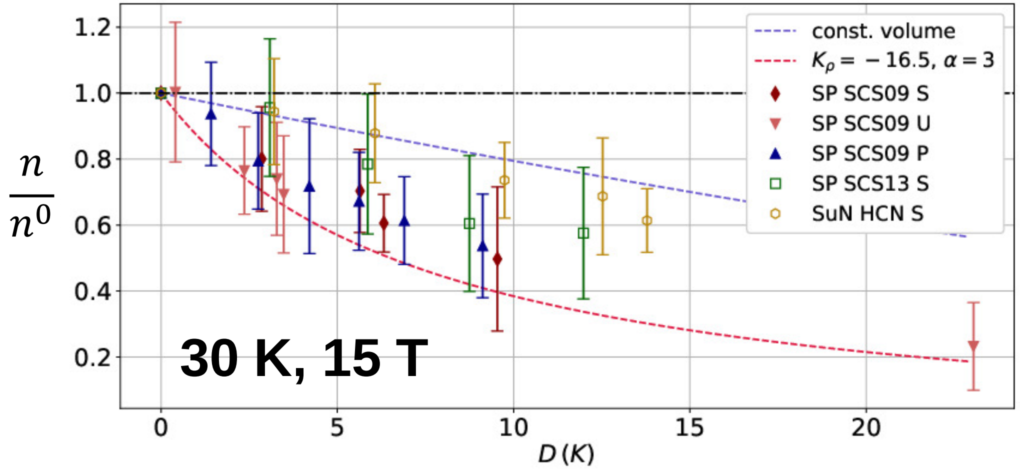
$$F_\mathrm{D} = \sqrt{\frac{(\alpha_\mathrm{p}+1)t_c^3}{\alpha_\mathrm{p}\left(1-K_\rho(1-t_\mathrm{c})\right)+t_\mathrm{c}}}\left(\frac{E_\mathrm{crit}}{\sqrt{\phi_0 B \nu_0}}\right)^{\frac{1}{n}-\frac{1}{n_\mathrm{p}}}$$

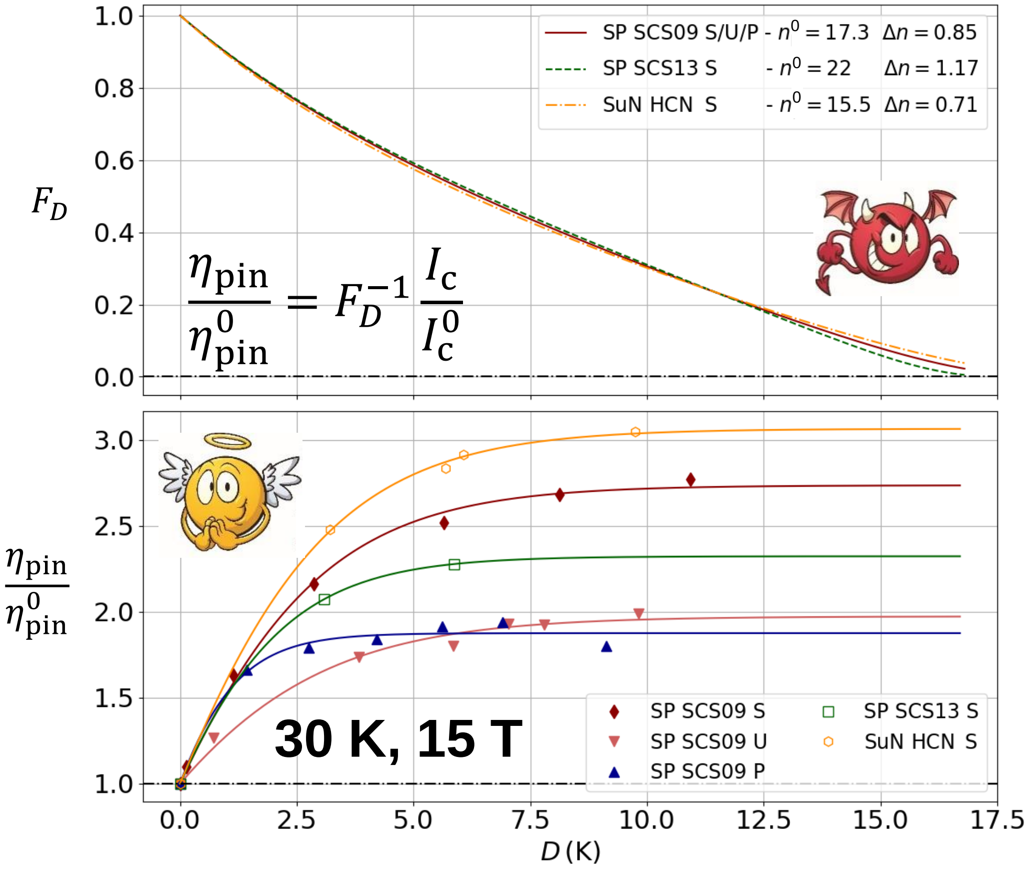
$$t_\mathrm{c} = \frac{T_\mathrm{c}}{T_\mathrm{c,p}} \qquad \alpha_\mathrm{p} = \frac{\xi_\mathrm{0,p}}{l_\mathrm{p}}$$

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)





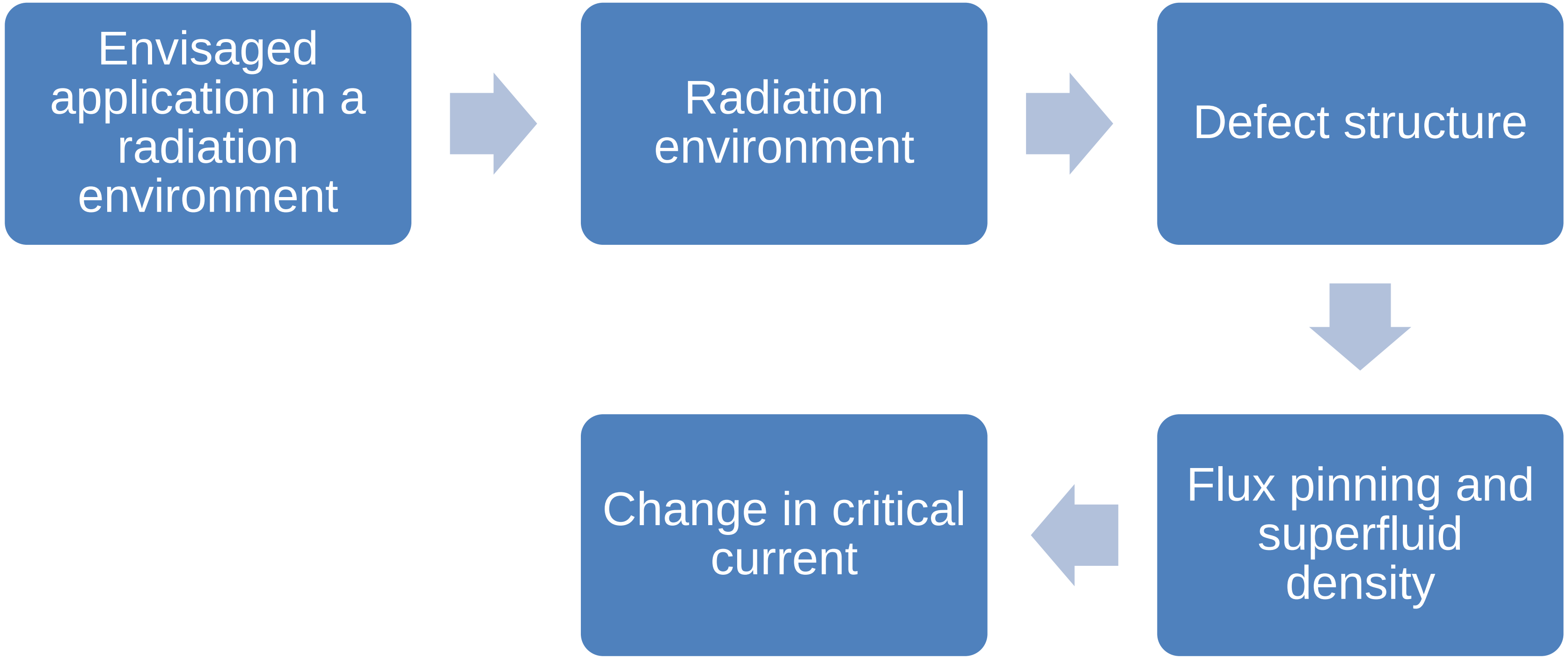
- Strong increase near $D = 0$.
- Saturation at large D.
- $\eta_\mathrm{pin,max}$ enough for decreasing branch.

M. Eisterer et al., arXiv:2409.01376v1

Conclusions

- Separating the positive and negative effects of radiation on superconductors paves the way for a reliable prediction of their behavior in radiation environments.
  - Harmful scattering (pair breaking in cuprates)
    - T_c is an efficient disorder parameter.
    - Indicating a decrease in superfluid density.
    - Decrease of J_c is driven by the decrease of superfluid density.
    - Enhanced flux creep
    - **Scattering rate** as the **input parameter**.
- Increase of pinning mainly by large defects. (**Size and density as input**)
  - Change of pinning may be predicted by TDGL, and or by a few benchmarking experiments for estimating $\eta_{\text{pin,max}}$.

Draft Workflow



Envisaged application in a radiation environment

Radiation environment

Defect structure

Flux pinning and superfluid density

Change in critical current

- What do you need as an input? ($I_{c,p}, n_p, \tau^{-1}$, not dpa)
- What can you offer as the output? ($I_c \frac{\eta_{\mathrm{pin}}^0}{\eta_{\mathrm{pin}}}$)