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STEP's plan for understanding REBCO coated conductors in the Fusion Environment

1st International Workshop on Irradiation effects on high temperature superconductors (IREF23)

William Iliffe, Simon Chislett-McDonald, Fiona Harden, Kirk Adams, James Tufnail, Chris Grovenor, Susannah Speller, Aidan Reilly, Stuart Wimbush, Ezzat Nasr

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at IREF 23, November 15, 2023, Arona, Italy

Requirements for Current Carriers in Fusion Magnets (1)

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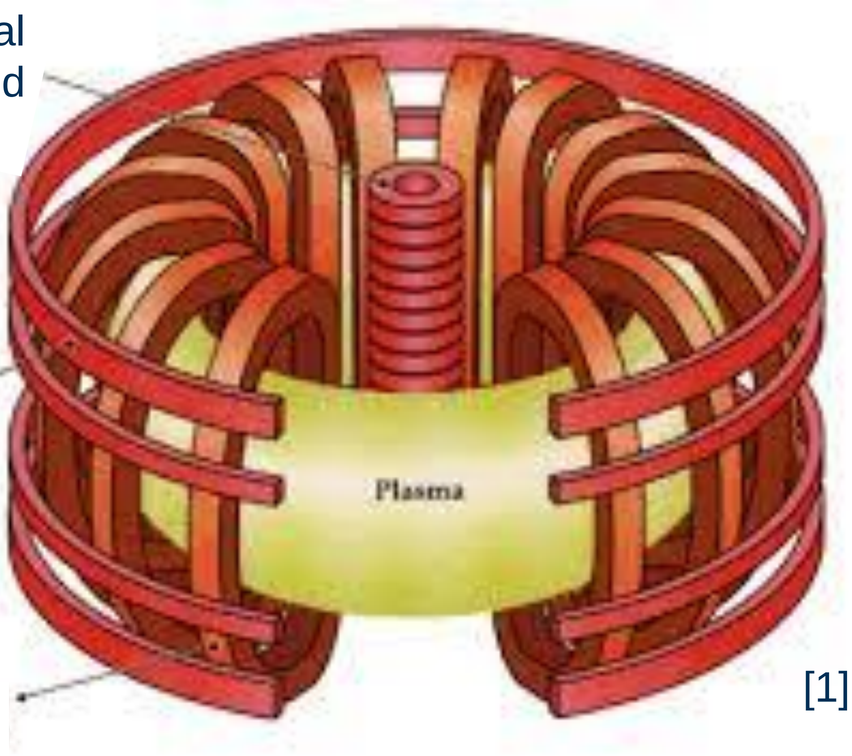
Anatomy of a Tokamak



Plasma Energy Confinement ∝ B^3
& Plasma Power Density ∝ B^4
But $B \propto I$ (Ampere's Law)
& space is limited in compact tokamaks
∴ **Need high current density (J)**

Given $P_\Omega \propto \sigma J^2$ (Ohm's Law)
To keep P_Ω as low as possible
(recirculating power),
➔ Conductor 'σ' needs to be
As low as possible
∴ **Need Superconductors**

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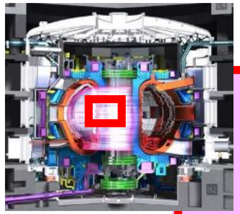
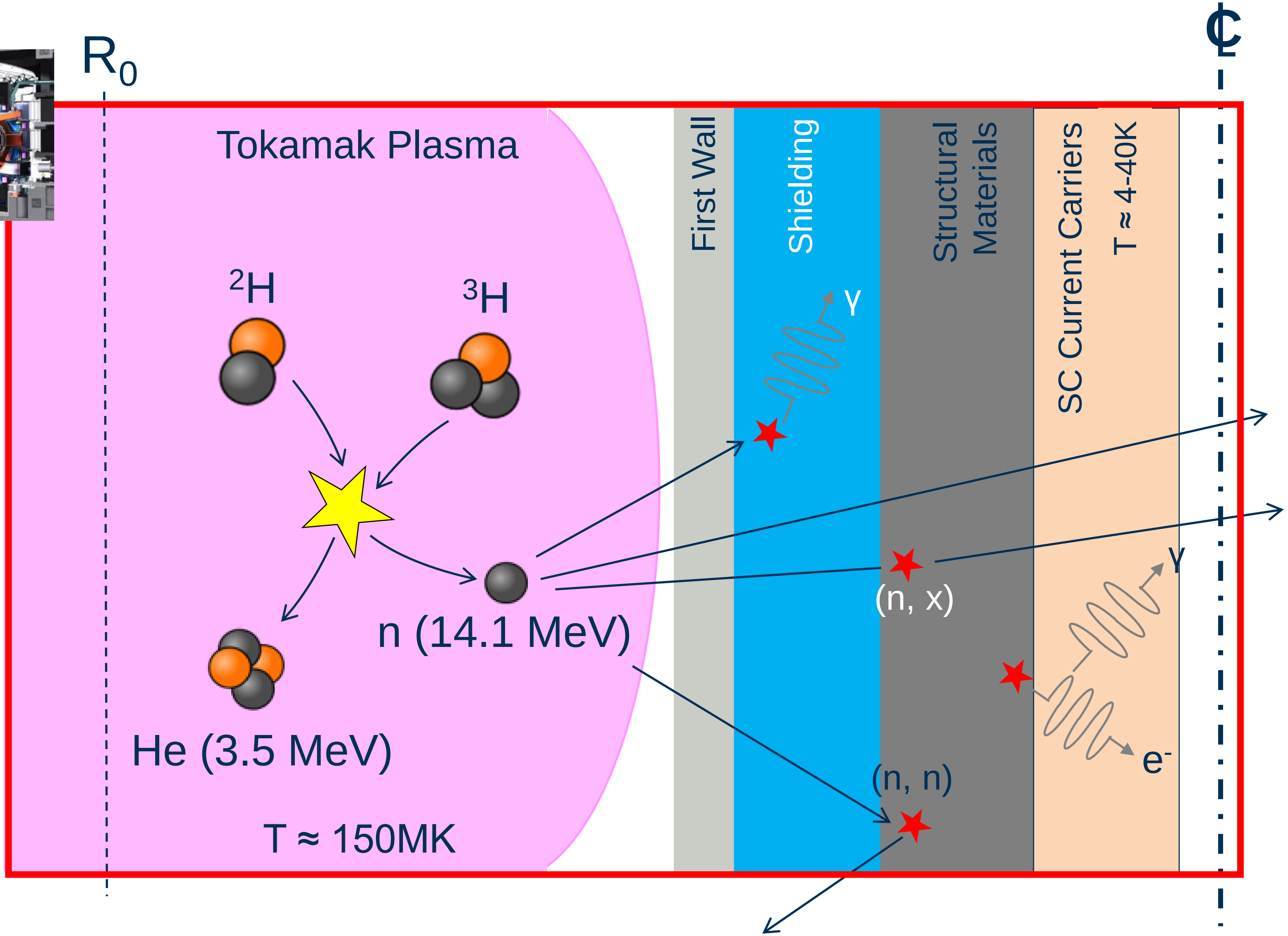
Requirements for Current Carriers in Fusion Magnets (2)





∴ **Magnet Superconductors must**:

- Run near continuously
- At their Rated Current
- In (High) Magnetic Fields
- Whilst subject to Lorentz Forces
- At as low as possible power
- And whilst being irradiated with
    - Fusion Spectrum Neutrons
    - And Gammas

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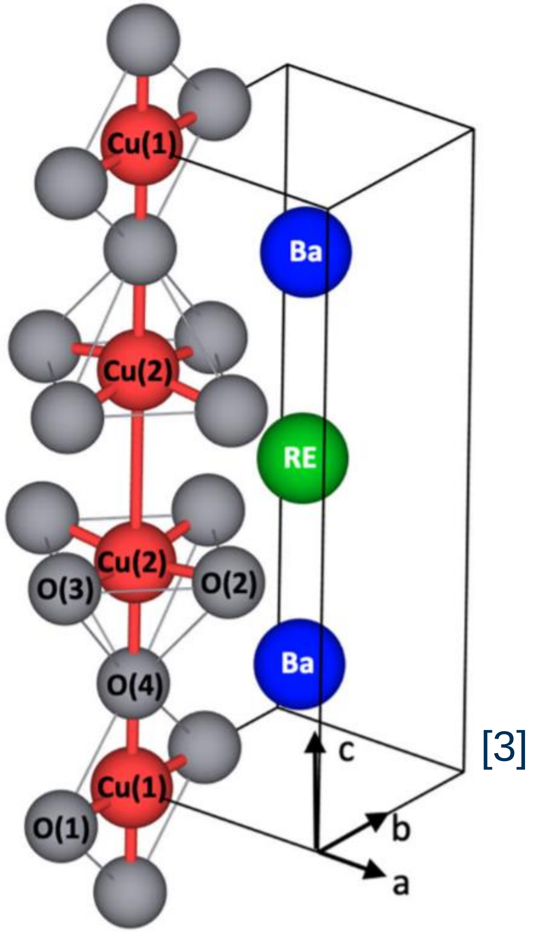
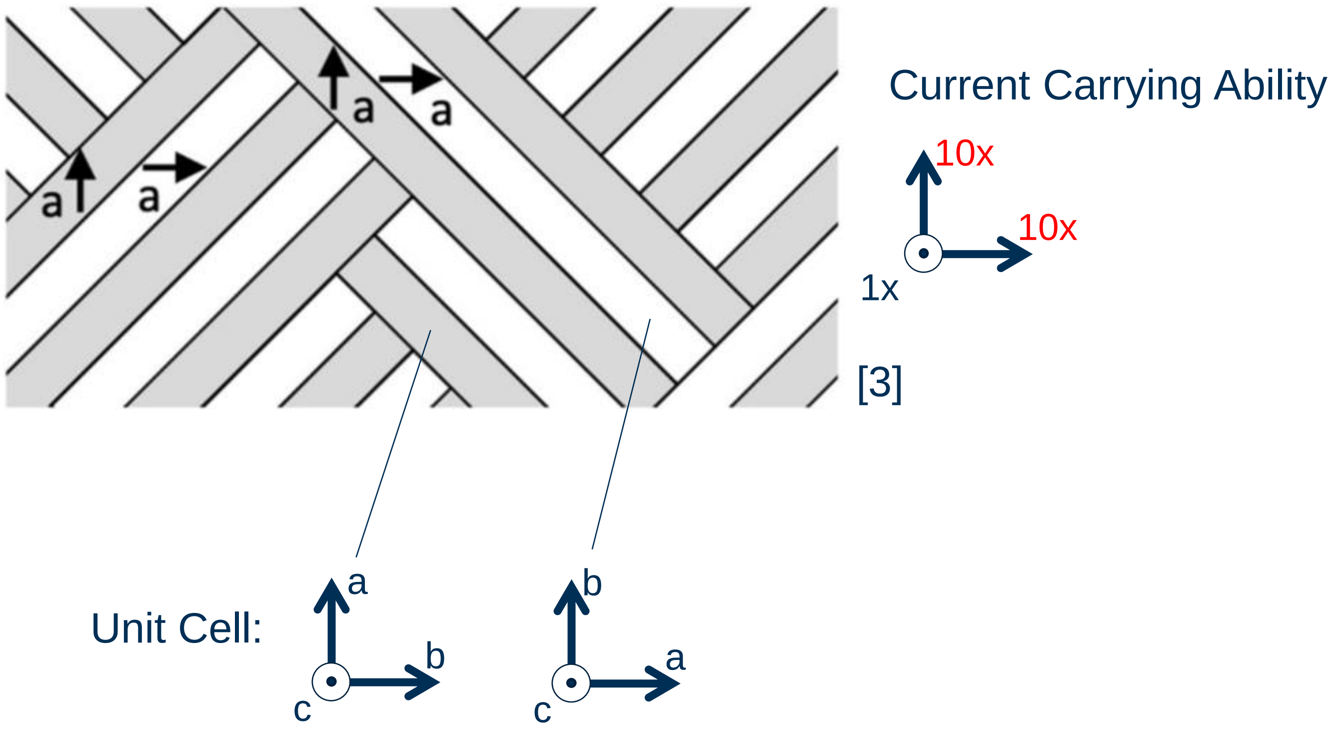
Anatomy of a REBCO Coated Conductor (1)

REBCO Unit Cell



Twin Structure in REBCO



REBCO is Orthorhombic
(ie. it's rectanguloid but lengths a ≠ b ≠ c)

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Anatomy of a REBCO Coated Conductor (2)

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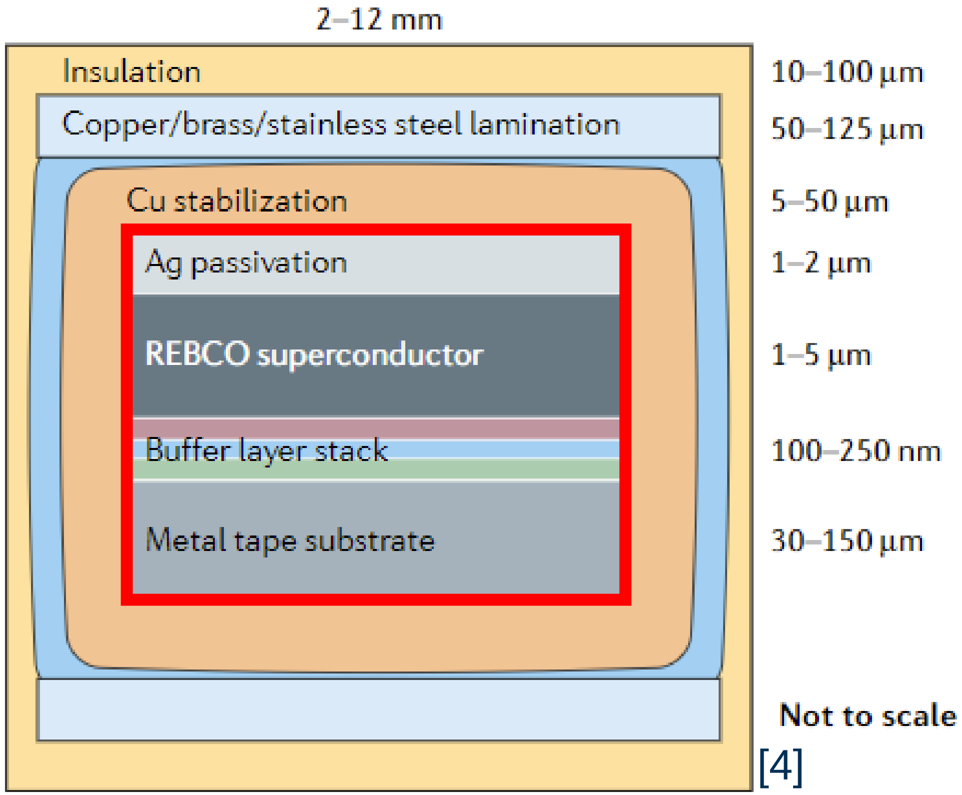
General Structure of a REBCO Coated Conductor



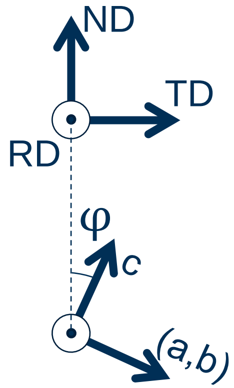
[4]

Essential Parts

REBCO Layer Texturing Definitions

Wire Axes:

REBCO Unit Cell Axes:



φ: angle between ND and c-axis

Twin Structure of REBCO leads to ‘Biaxial” Texturing in a REBCO CC

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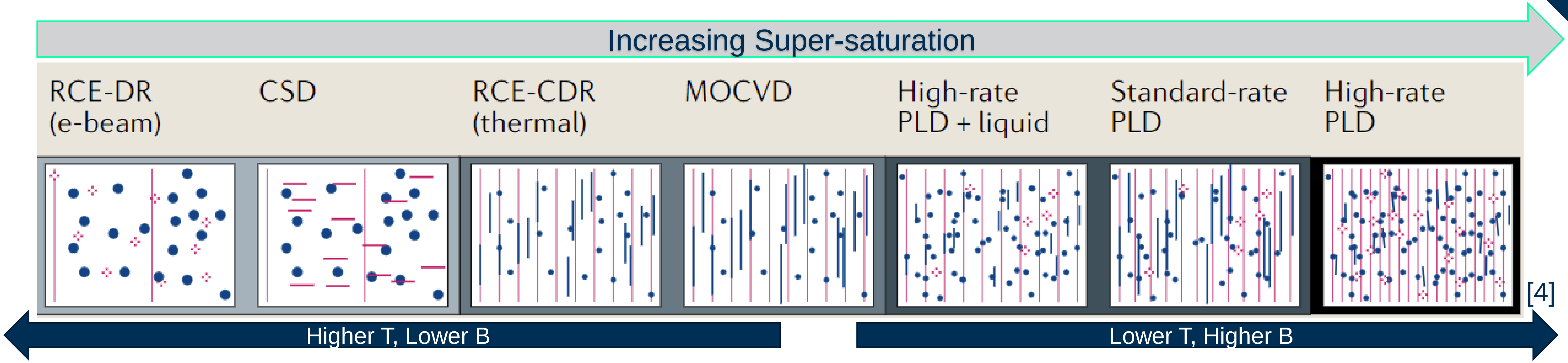
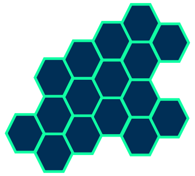
Anatomy of a REBCO Coated Conductor (4)

Resultant REBCO Defect Structures:



Big Grains



Small Grains

Super-saturation

"the concentration of REBCO chemical species above the equilibrium level [at the point the REBCO pre-cursor is deposited on the coated conductor]"

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Properties of REBCO CC (1)

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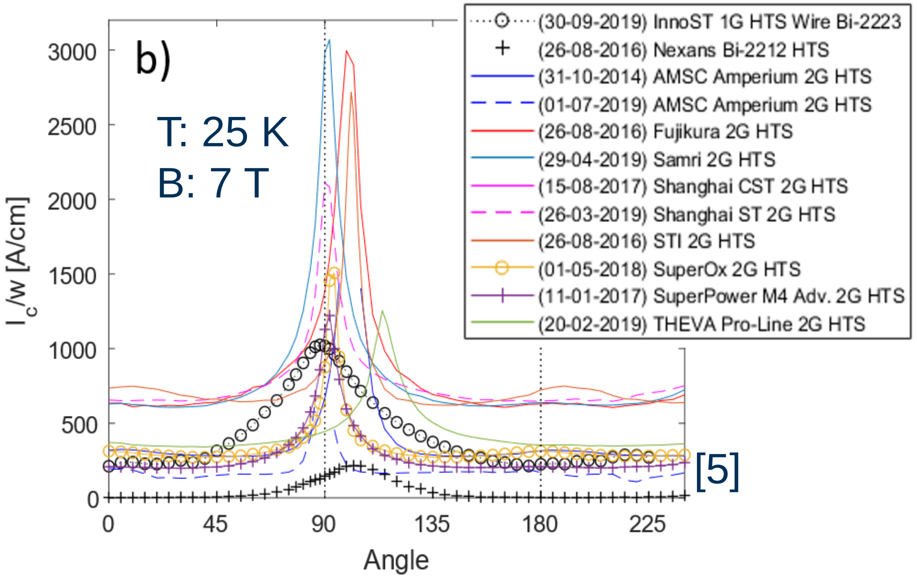
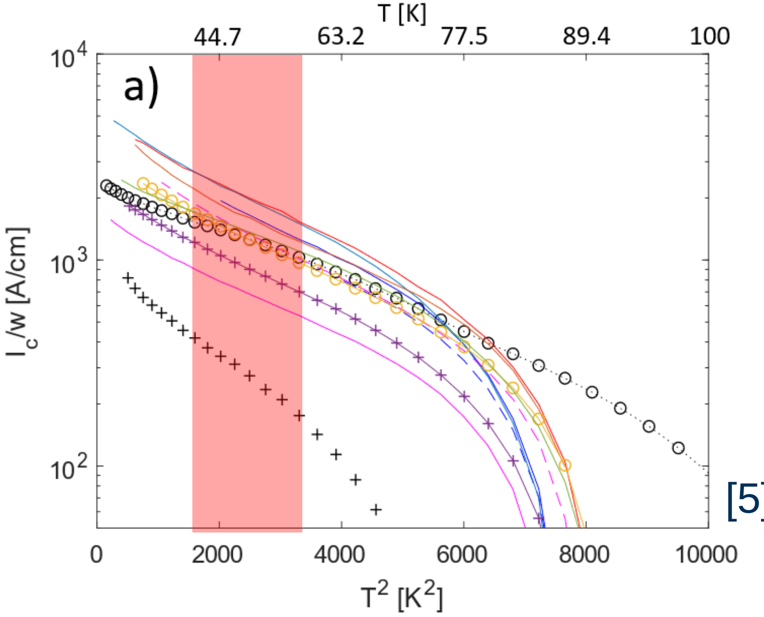
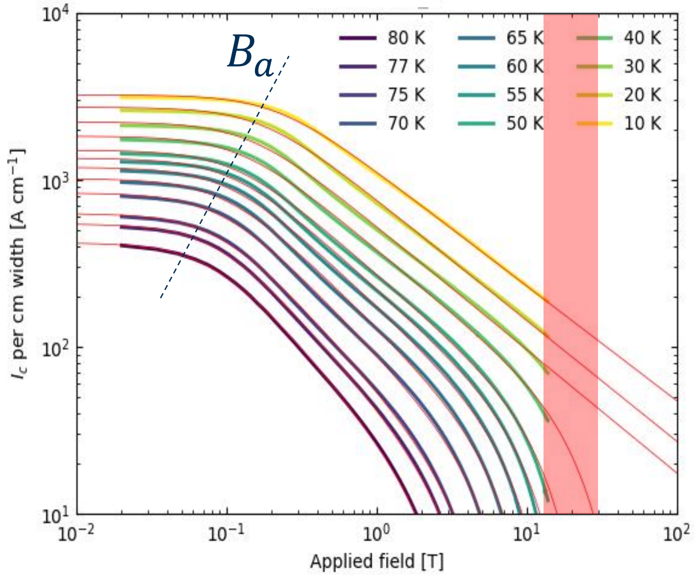
Current Carrying Capacity as a function of **Temperature**, **Field** and **Field Angle***



[5]



[5]



$$J_c(B,\theta) = J_c(\tilde{B})$$

$$\tilde{B} = B[\cos^2\theta + \gamma_m^{-2}\sin^2\theta]^{1/2}$$ [6]

$$J_c^{wk}(T) = J_c^{wk}(0)\exp\left\{-\frac{T}{T_0}\right\}$$

$$J_c^{str}(T) = J_c^{str}(0)\exp\left\{-3\left(\frac{T}{T^+}\right)^2\right\}$$ [7]

$$I_c^*(B) = I_{c0}(0)\left(1+\frac{B^2}{B_a^2}\right)^{-\alpha}\left(1+\frac{B^2}{B_\beta^2}\right)^{-\beta}$$ [8]

* With respect to CC Normal direction

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Properties of REBCO CC (2)

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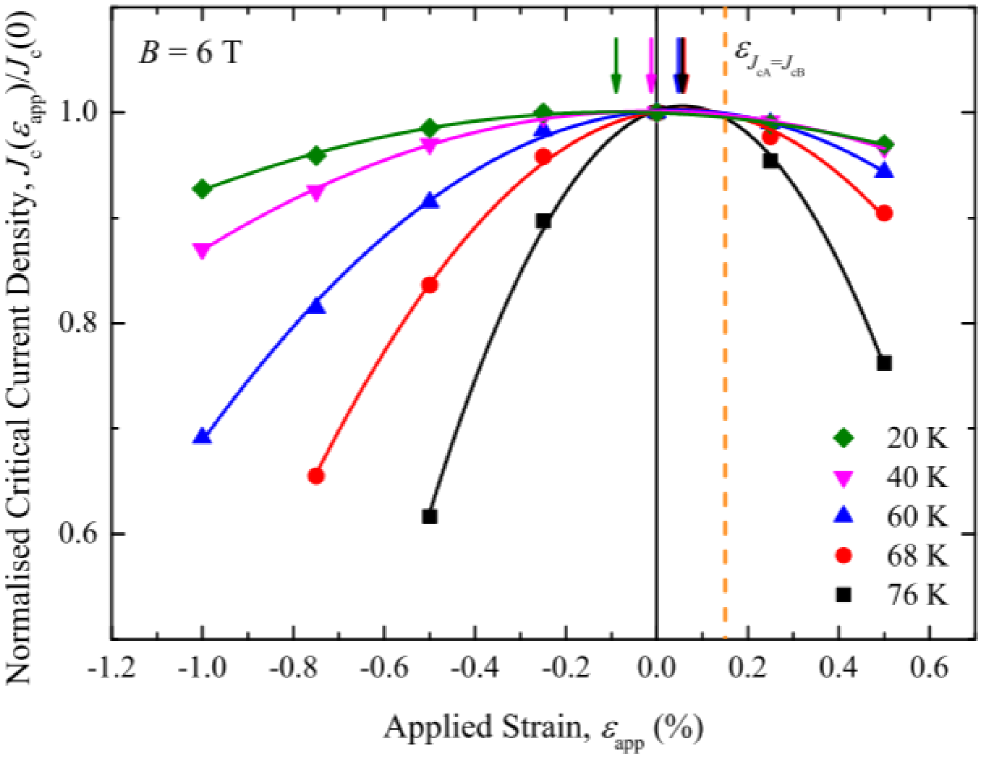
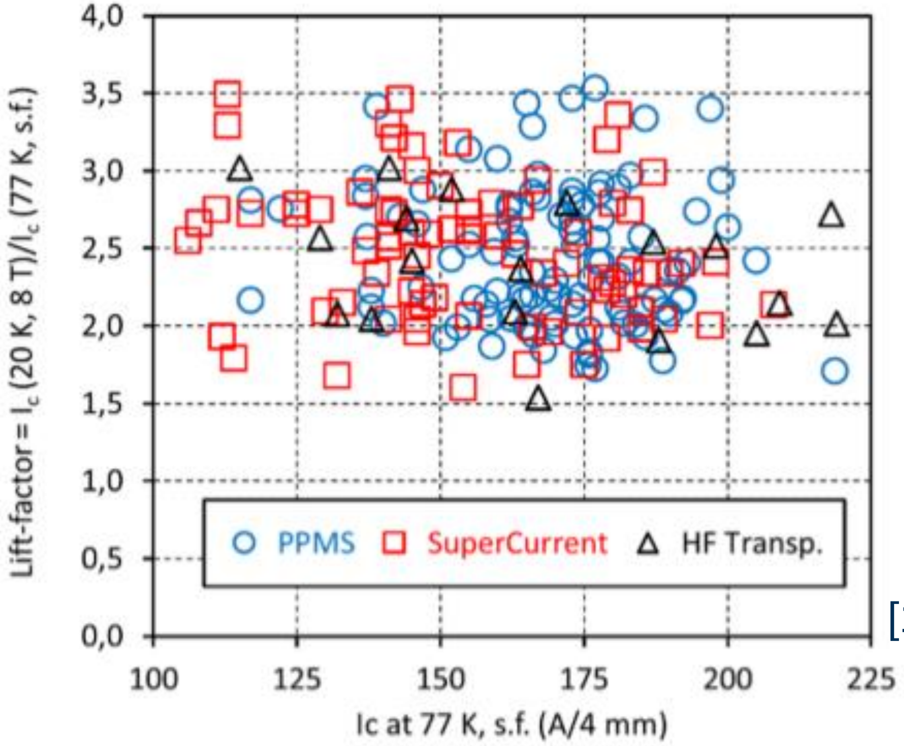
Current Carrying Capacity as a function of **Axial Strain** and **Consistency in Manufacture**.



[9]



[10]

$$J_c(\varepsilon_{app}) = J_c(0)\left[1 + \beta(\varepsilon_{app} - \varepsilon_{peak})^2\right]$$

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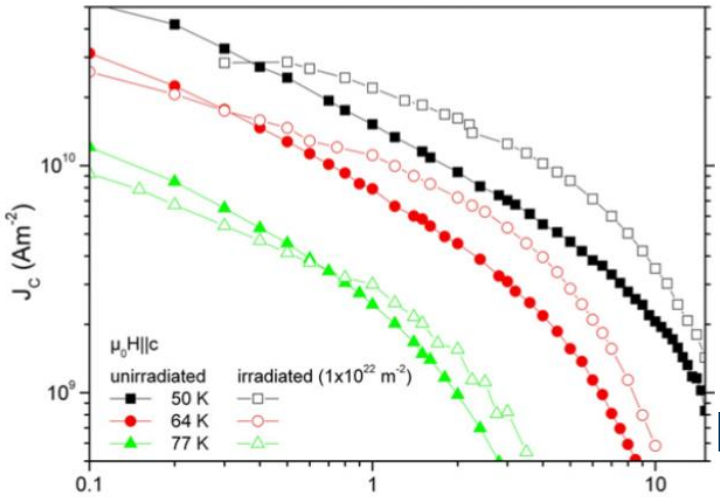
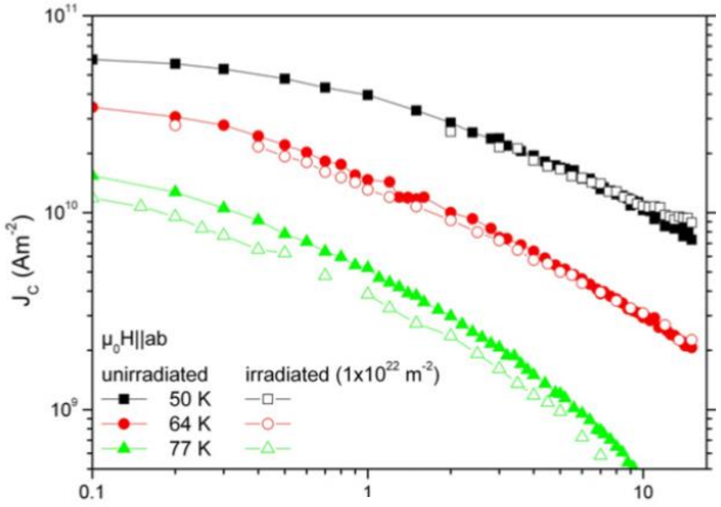
Neutron Irradiation Experiments on REBCO (1)



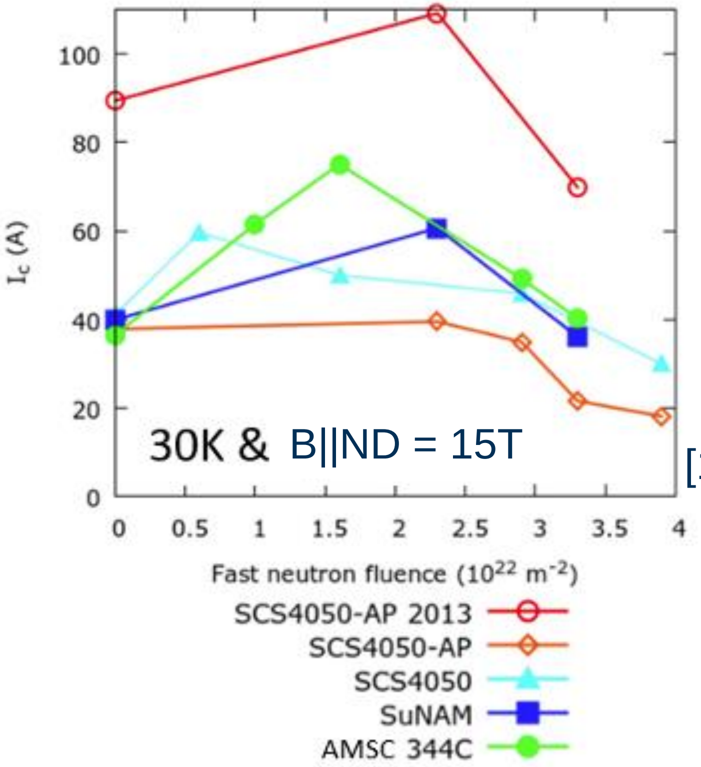
[11]

B||ND [T]

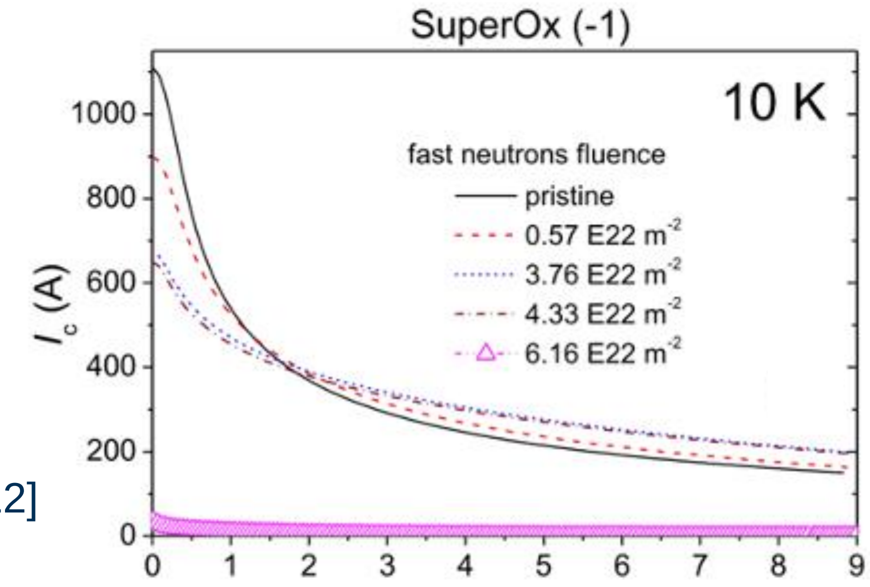


[11]

B||(RD,TD) [T]



[12]



[13]

B||ND [T]

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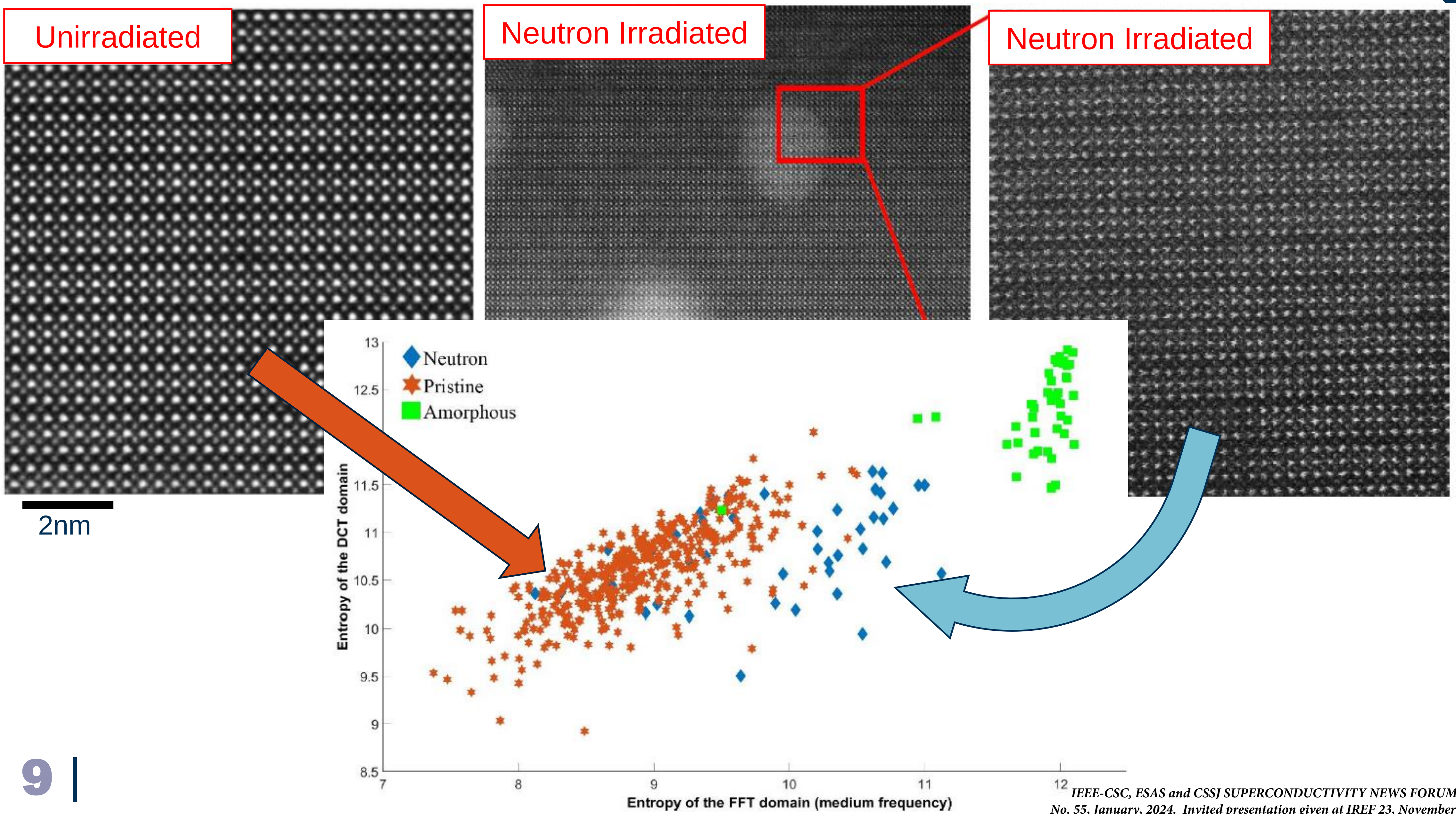
Neutron Irradiation Experiments on REBCO (2)



[14]

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STEP HTS Irradiation Test plan

IREF Presentation by Chris Grovenor

IREF Presentation by Simon Chislett-MacDonald

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Current Knowledge

- Literature Search
- Conference Attendance
- Supplier Engagement
- Initial Tape Properties Survey
- REBCO in STEP

In-situ, flux

- Cold In-situ Ion Irradiation Exp.
- Cold In-situ Gamma Irradiation Exp.
- REBCO as a neutron-Bolometer Exp.

Magnet Institute

Ex-situ, fluence

- Filter O ion Irradiation Experiments
- N-irradiation Exp. at HF-ADNF Bham
- Cold Ion Irradiation Experiments

ISIS-STEP Strain Experiment

High fluence Cryo-irradiation of REBCO superconductors experiment

REBCO Coupons in STEP

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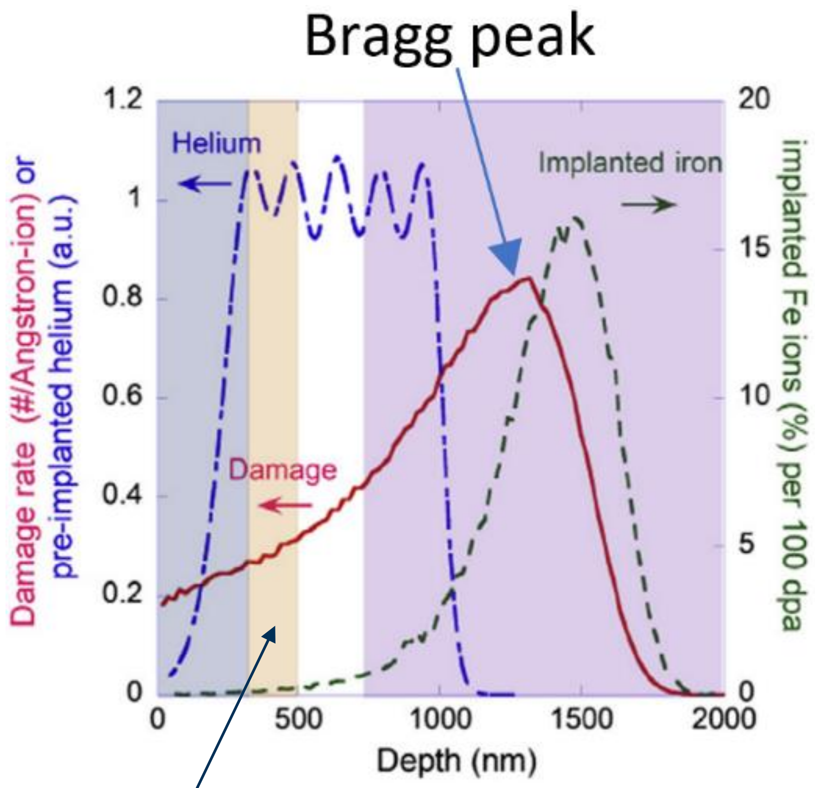
Filtered Ion Irradiation Experiment

Q. How to emulate neutron irradiation damage with ions?

Advice of G. S. Was *et al.*, "Emulation of reactor irradiation damage using ion beams" *Scr. Mater.*, vol. 88, pp. 33–36, 2014

- Use self-ions, where possible.
- To create **lattice damage**, ensure volume of interest has:
  - as-small-as-possible variation in the damage level
  - as-low-as-possible ion implantation concentration per bombarding ion over the volume of interest.
- To create the required **impurity concentration**:
  - ion energy(ies) needs to be minimised to avoid lattice damage but
  - still sufficient to push impurity ions to the desired location.



[15]

Fe – 9%C

Volume considered to have "neutron-like" damage

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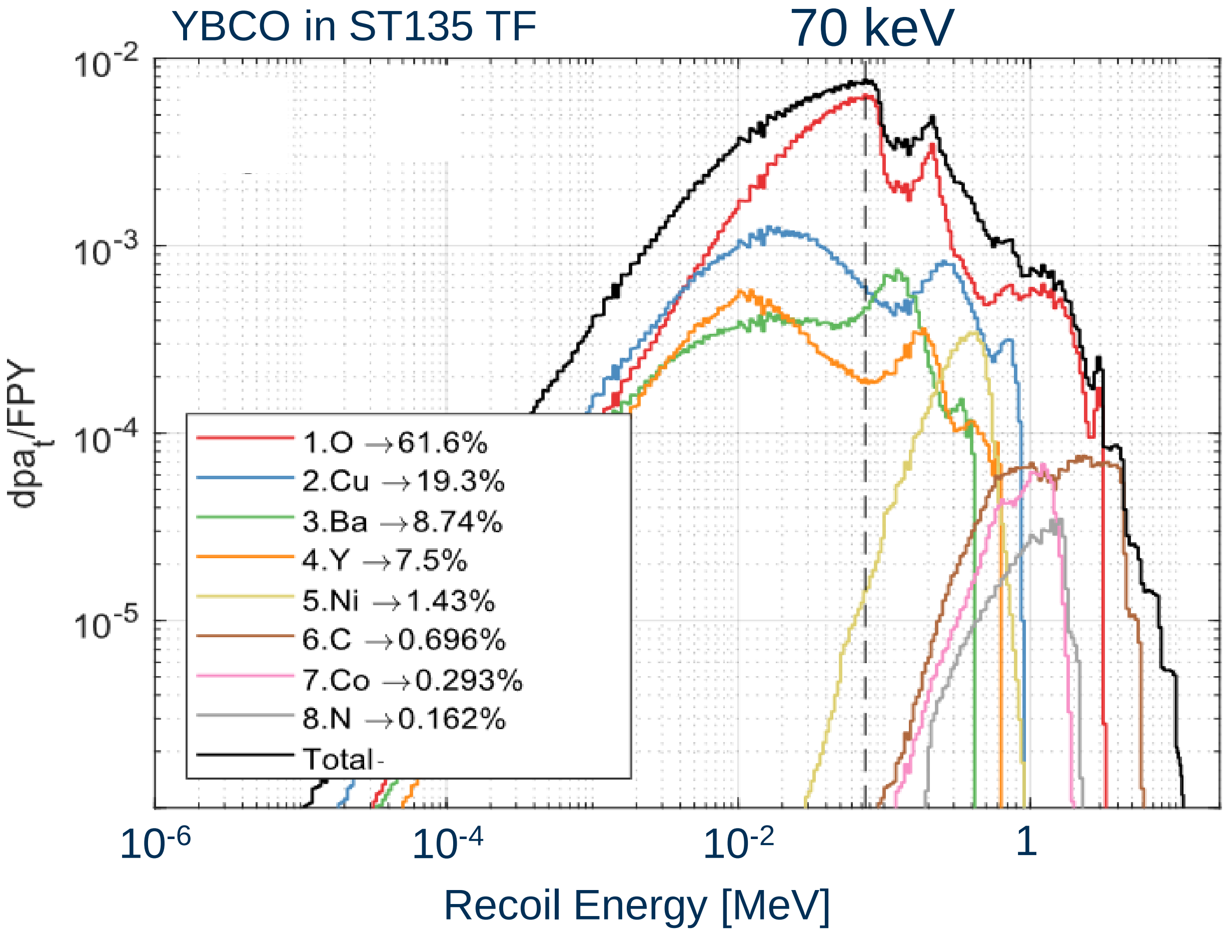
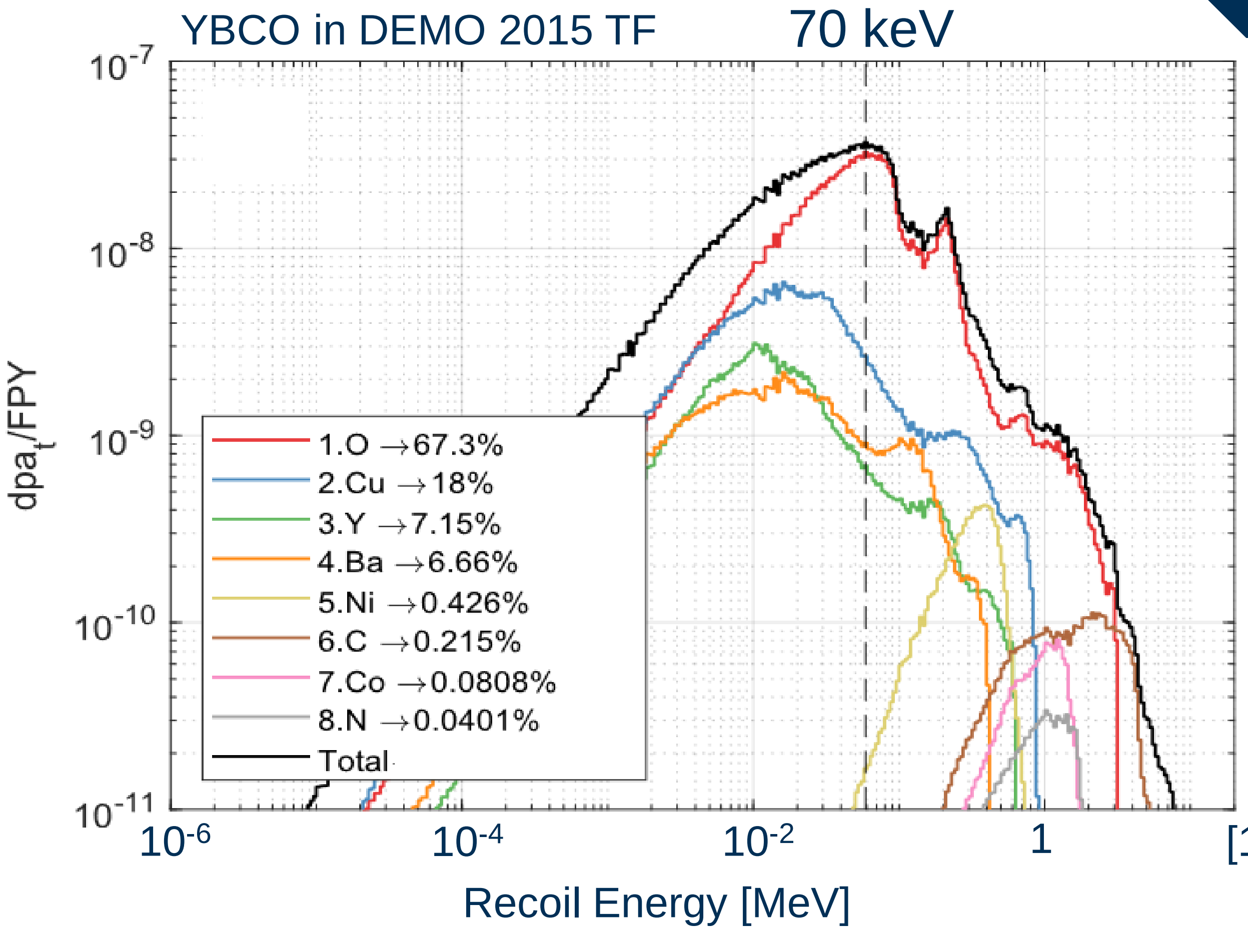
What do Fusion Neutrons do to REBCO?

Q. What do fusion spectrum neutrons do to YBCO?



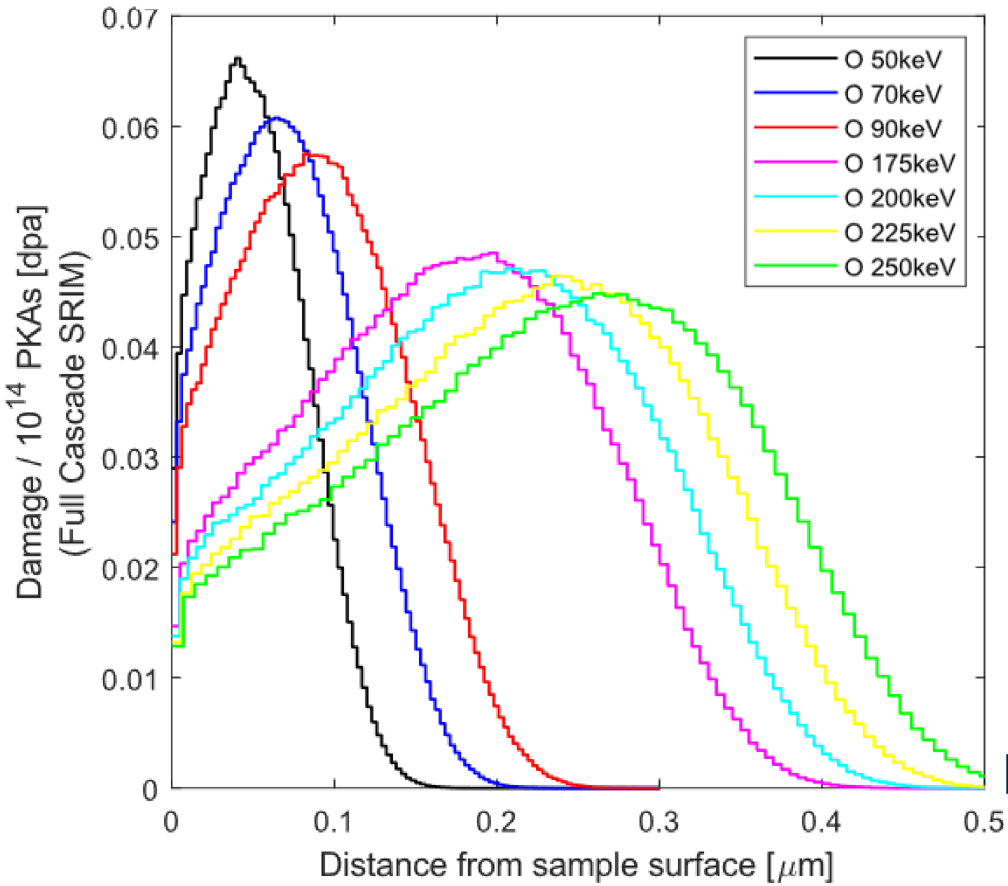


[16]

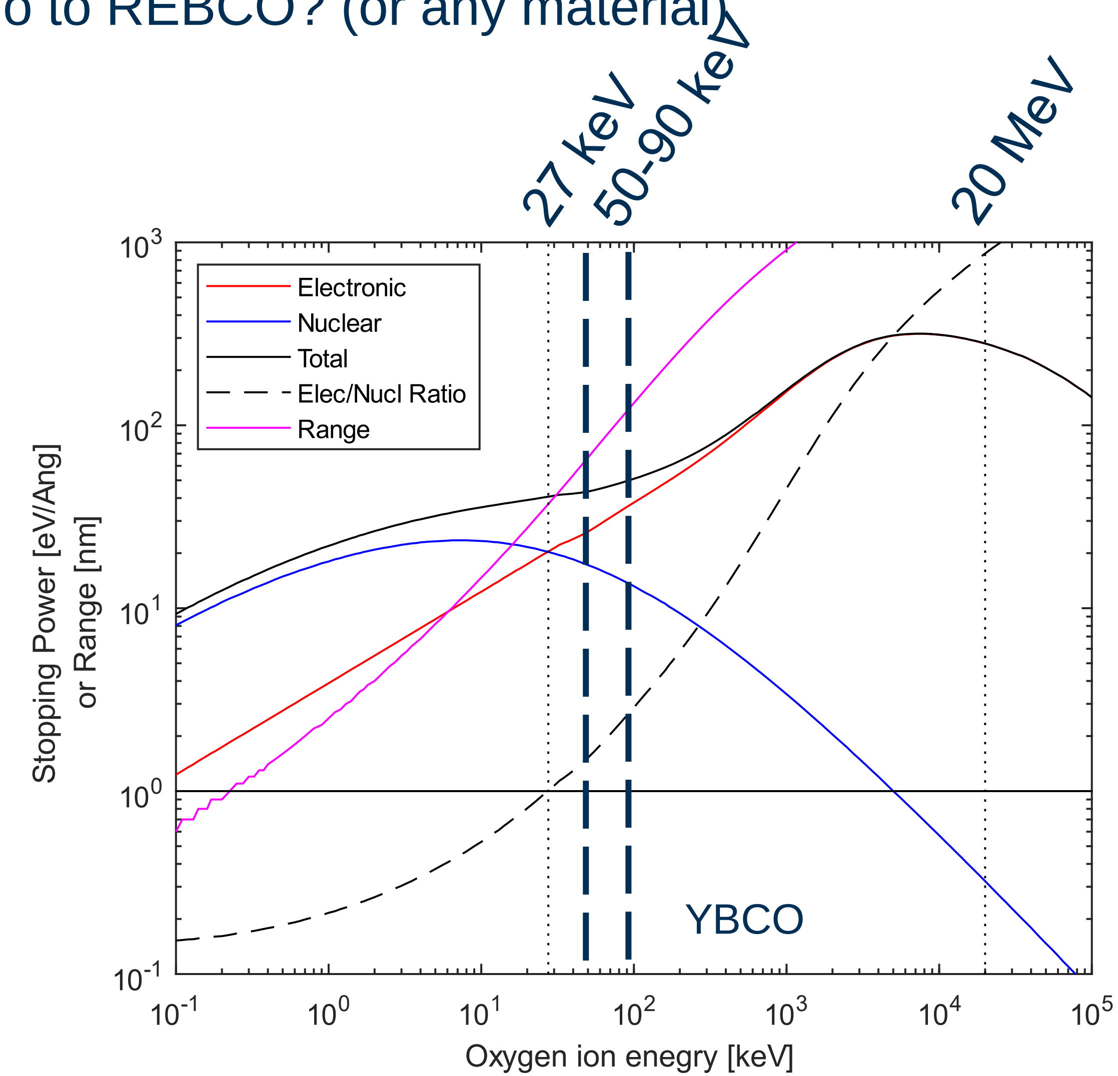
In both spectra, 10% of the total damage due to 50-90keV Oxygen PKAs

Filtered Ion Irradiation Experiment

Q. What do monoenergetic oxygen ions do to REBCO? (or any material)



[16]



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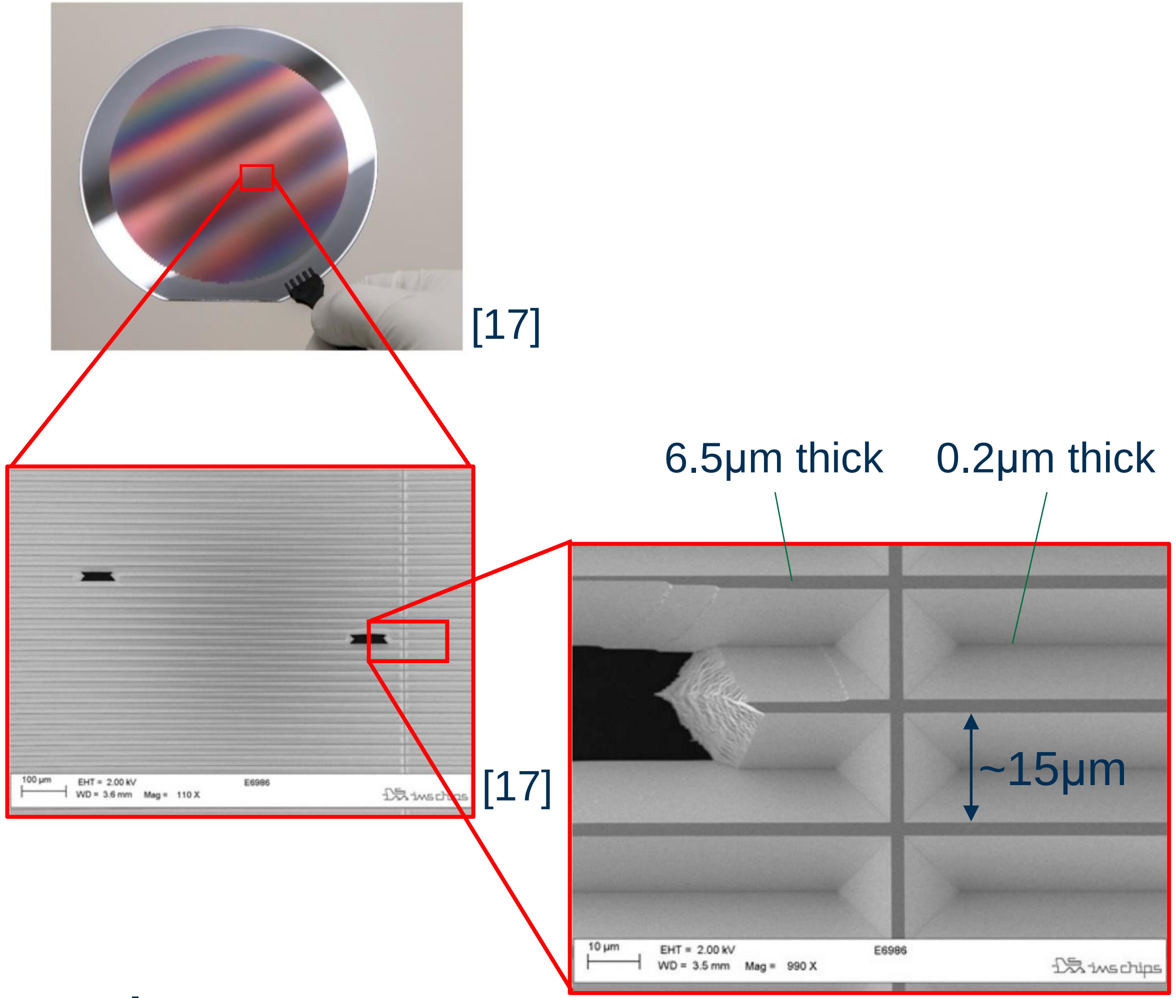
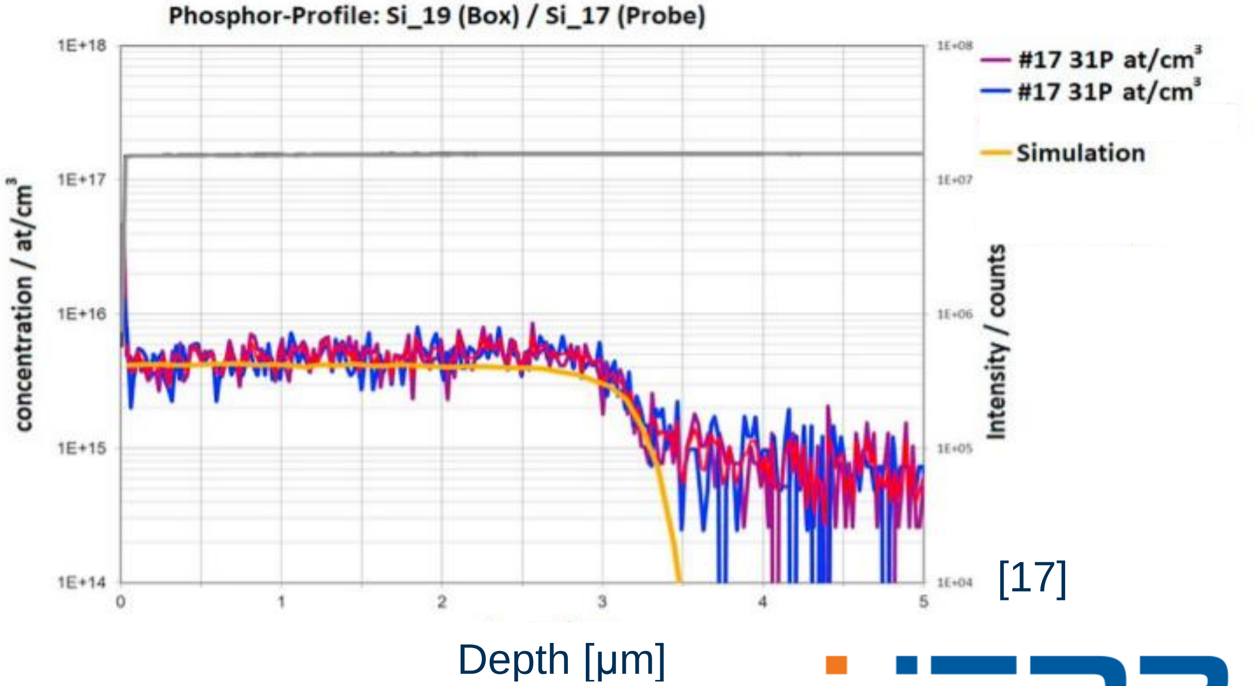
Filtered Ion Irradiation Experiment

Q. How does one create a uniform ion implantation profile?
A. Use a Steinbach et al. energy filter



Implantation Concentration Experiment:
P into Si
Starting P energy: 7 MeV
Dose: 7 x 10^{12} P ions/cm^2
Concentration determined by SIMS



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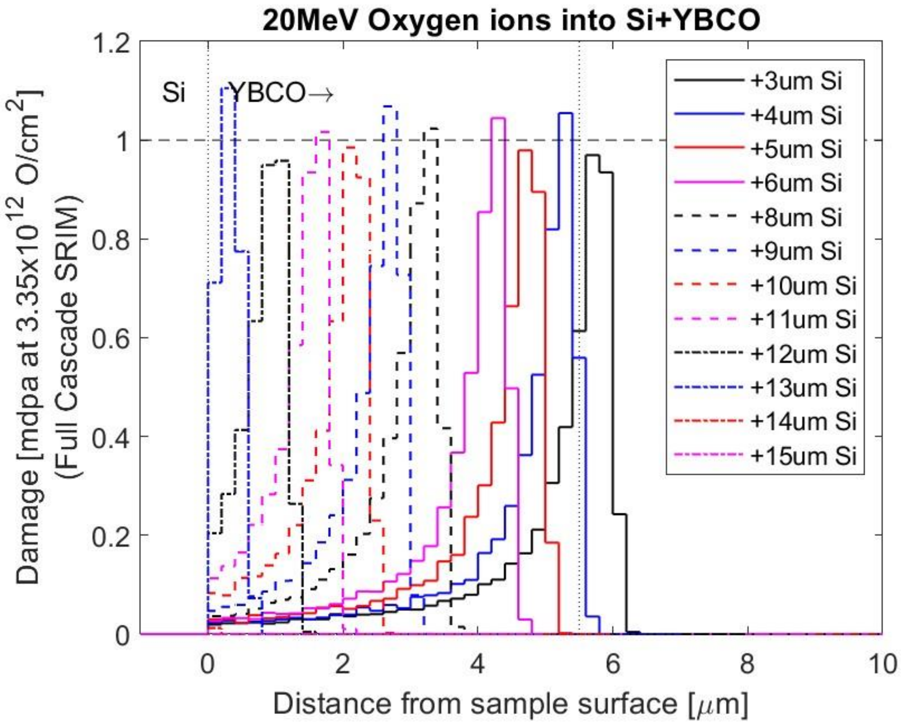
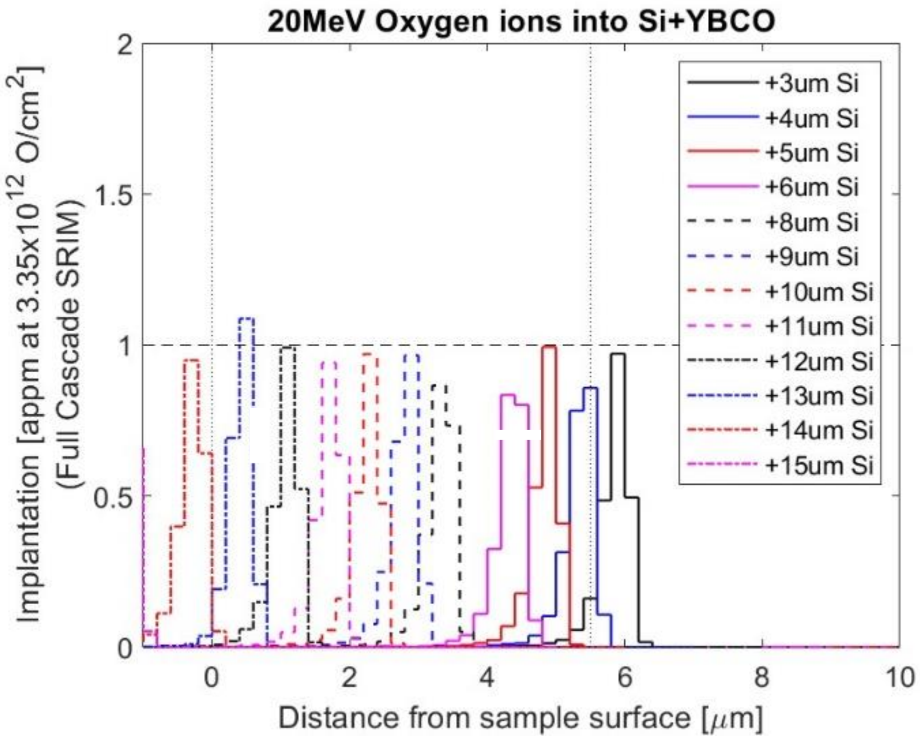
Filtered Ion Irradiation Experiment

Q. What does the experiment look like?





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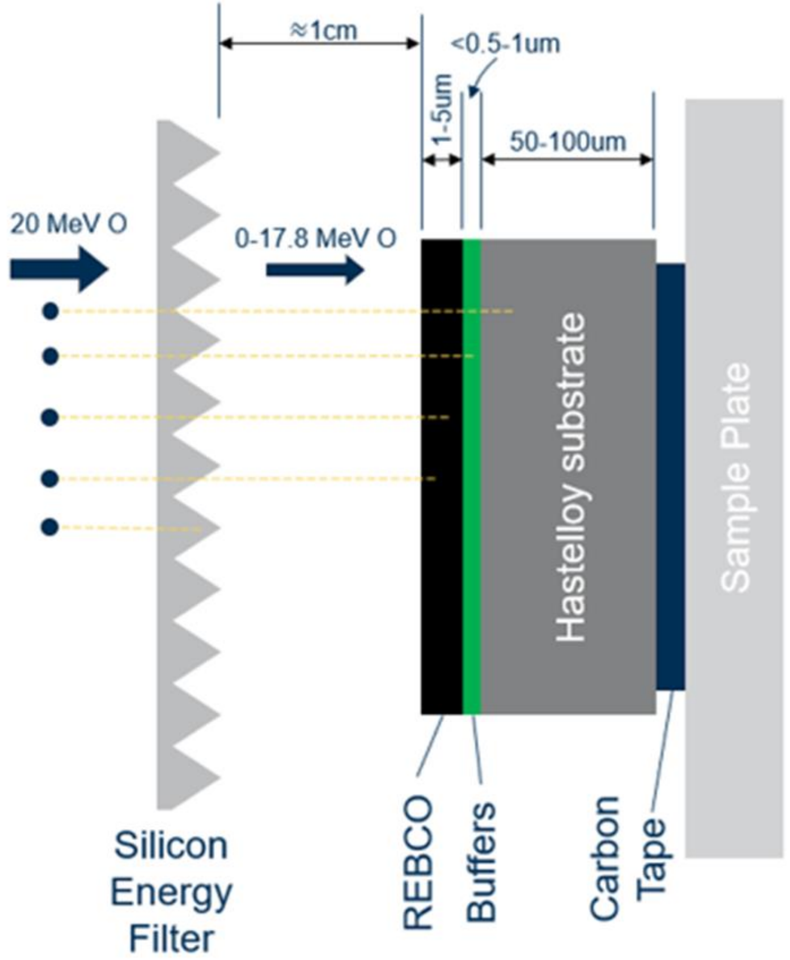
Filtered Ion Irradiation Experiment

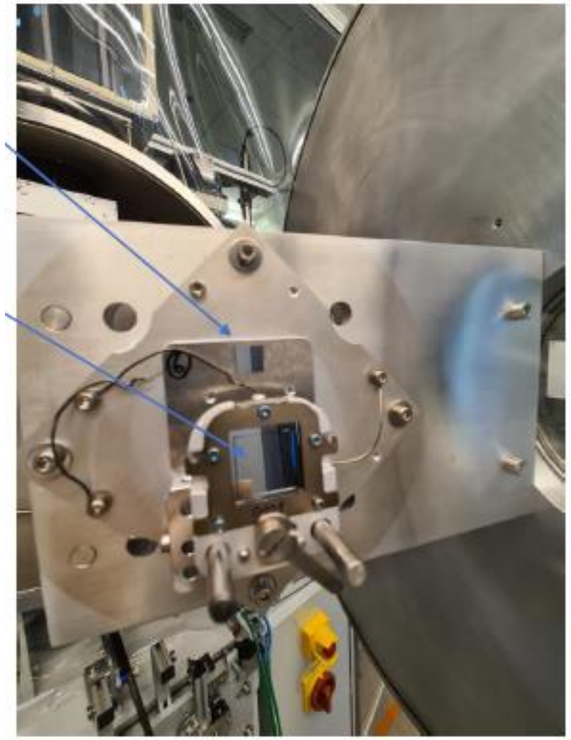
Q. What is the experiment set-up?

Design

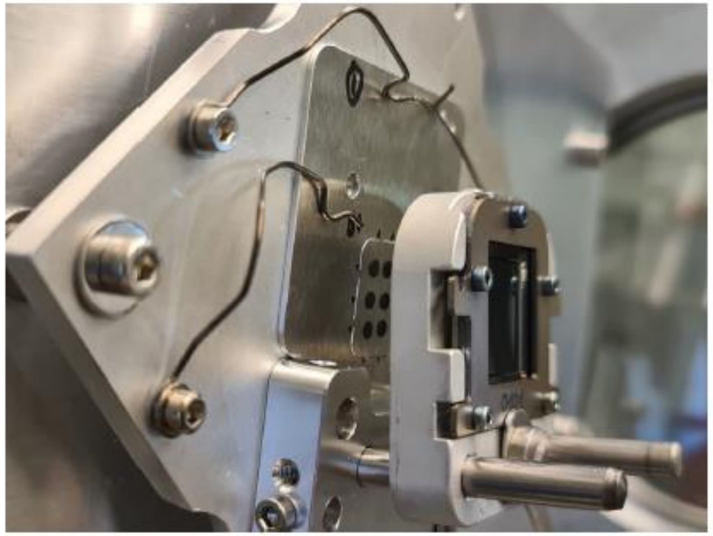


Reality

Silicon Implantation Experiment (SIMS)



Sample Plate Assembled behind Filter on Beamline



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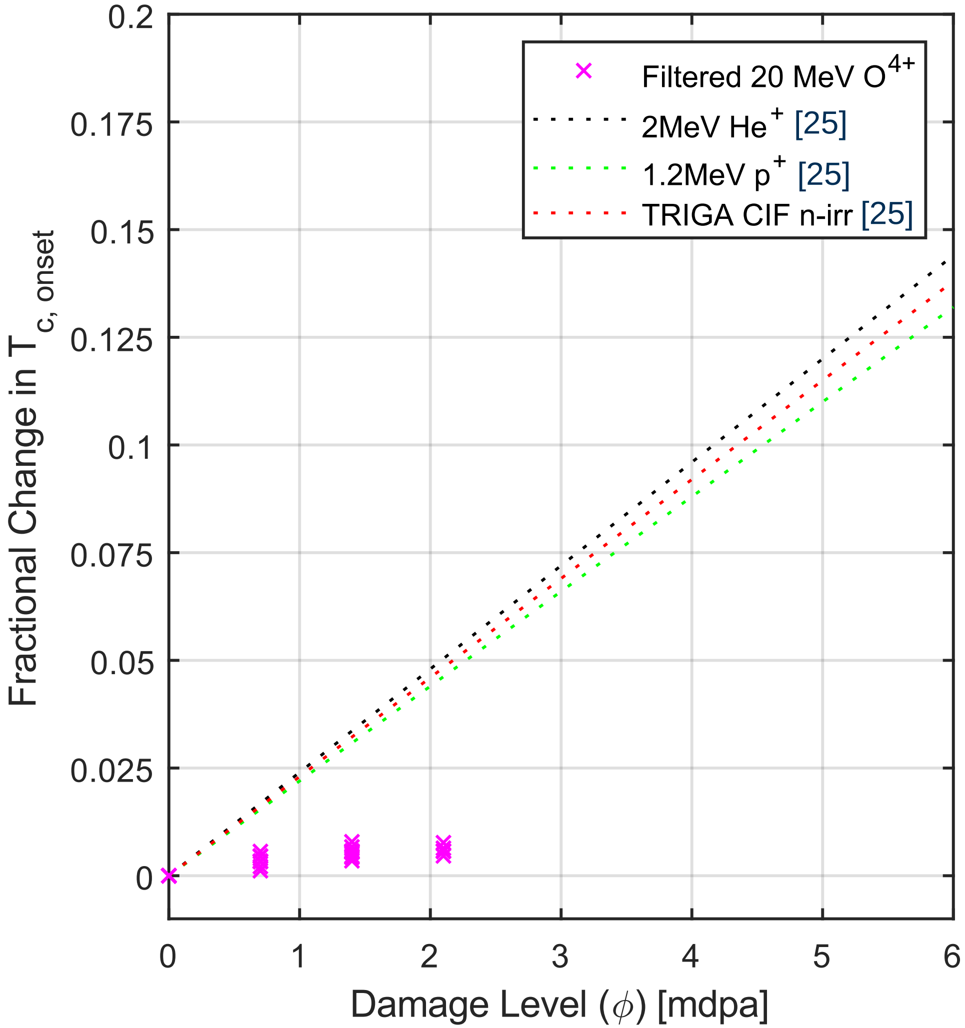
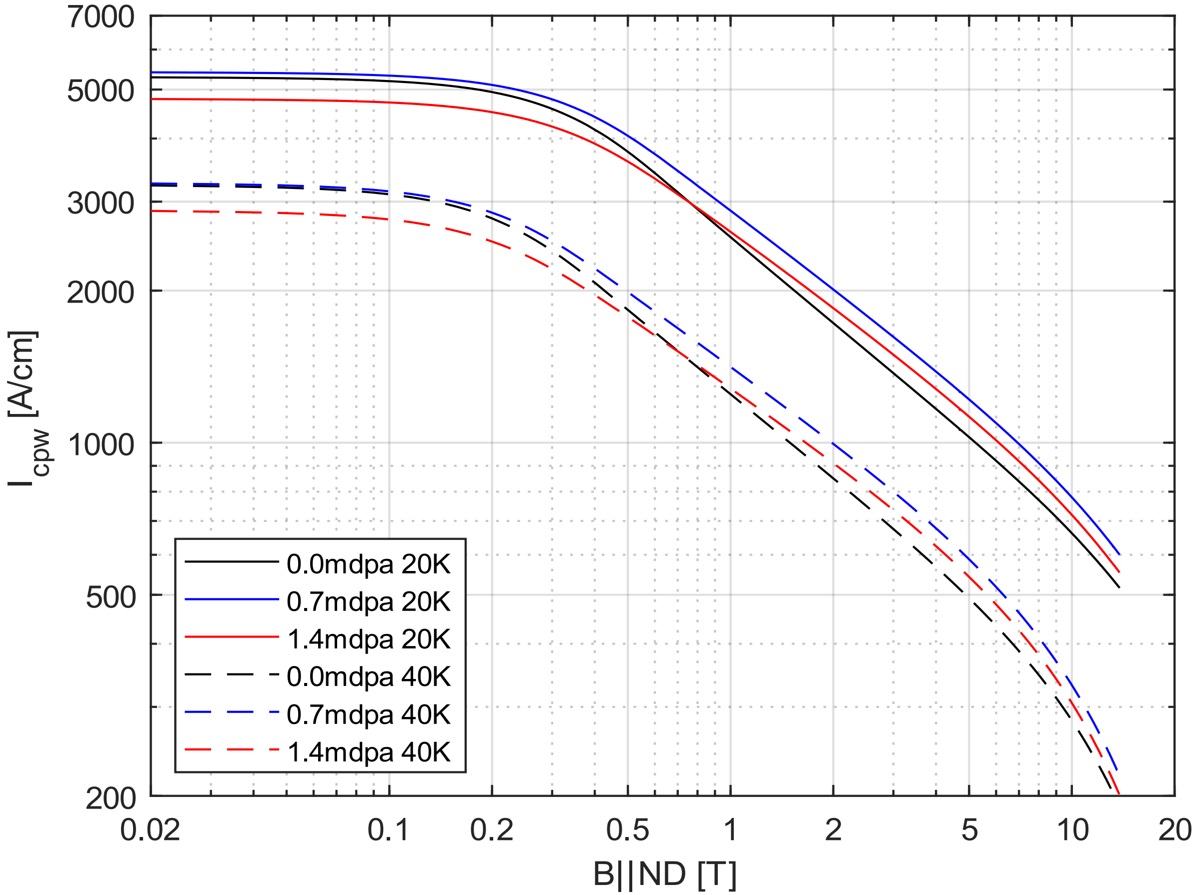
Filtered Ion Irradiation Experiment

Q. Any change in T_c?





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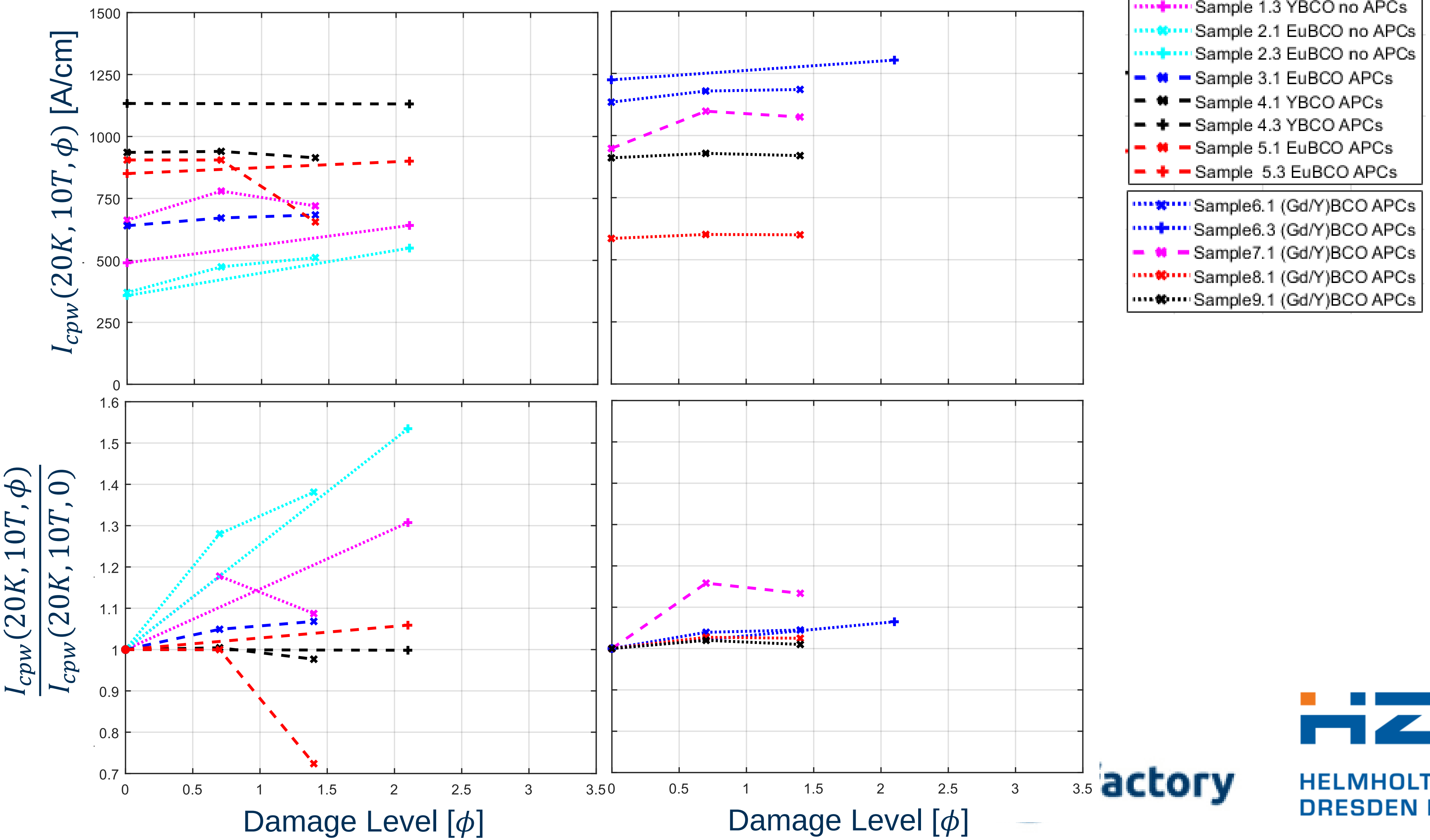
Filtered Ion Irradiation Experiment

Q. Any change in J_c?



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Acknowledgements & References

@ UKAEA:
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- James Tufnail (Phd)

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- Shavkat Akhmadaliev
- Florian Krippendorf
- Stefan Illhardt
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  - Carlo Cazzaniga
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  - Oleg Kirichek
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  - Joe Kelleher

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- Roger Webb
- Adrian Cansell

& many others!

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