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UKAEA

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

Requirements for Current Carriers in Fusion Magnets

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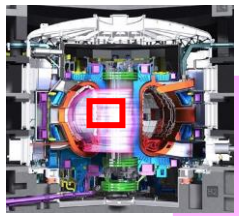
$$P \propto B^4$$



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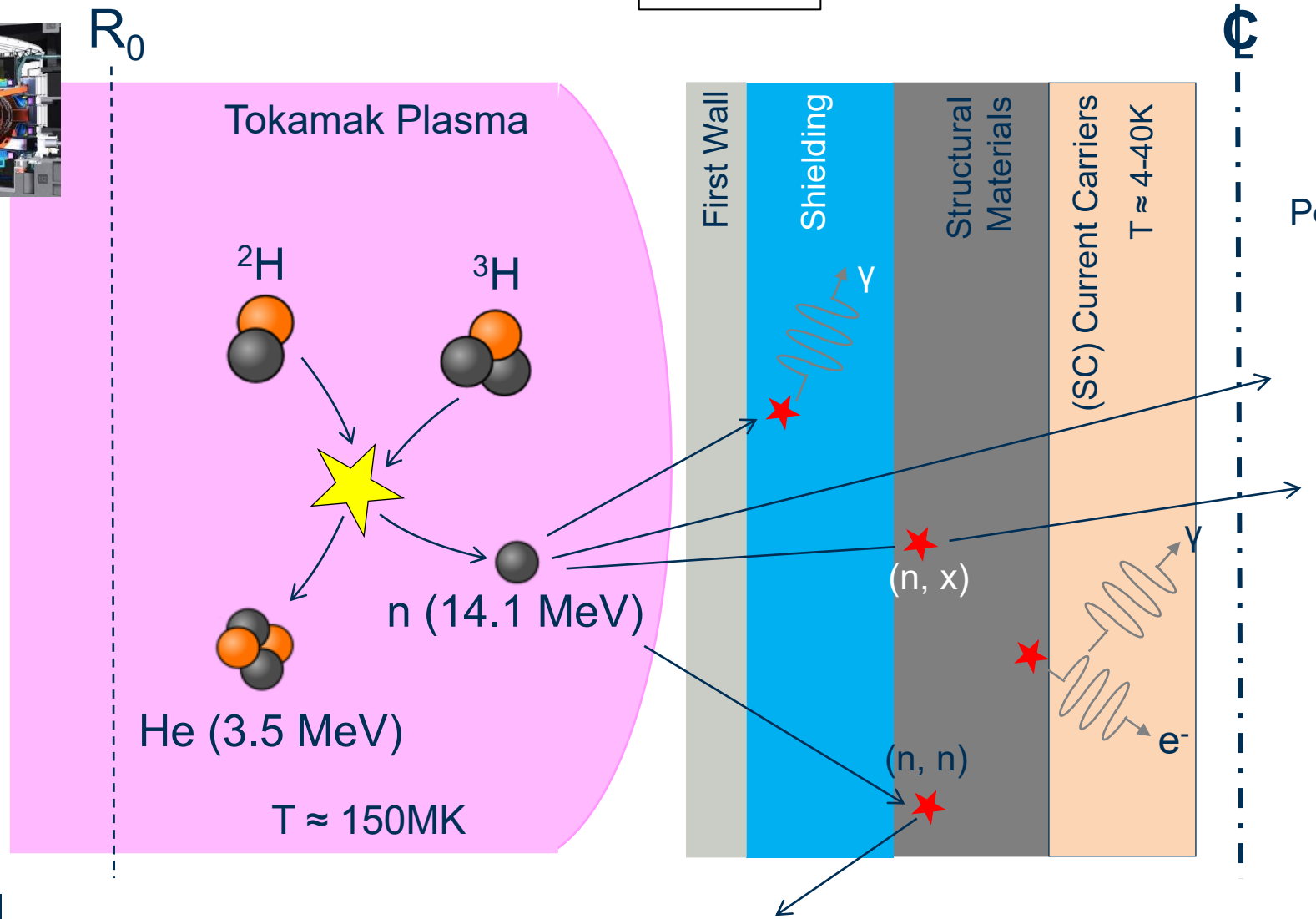
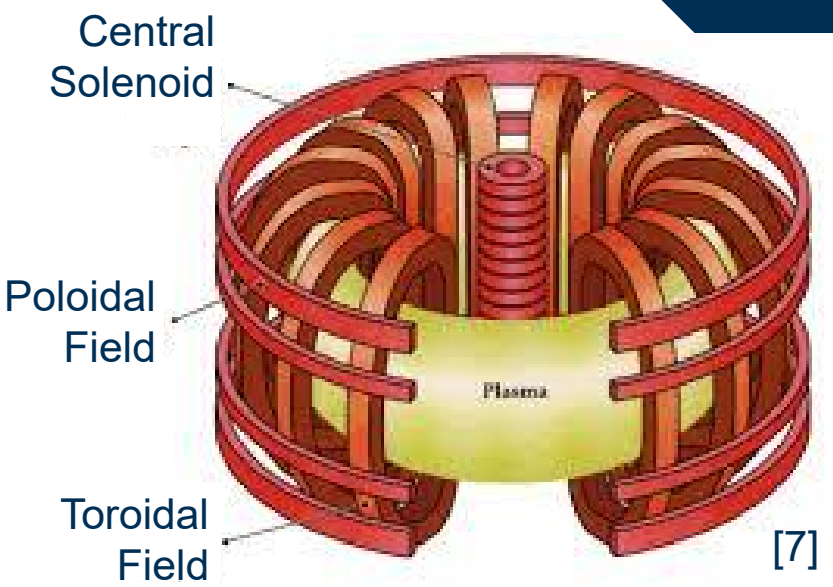




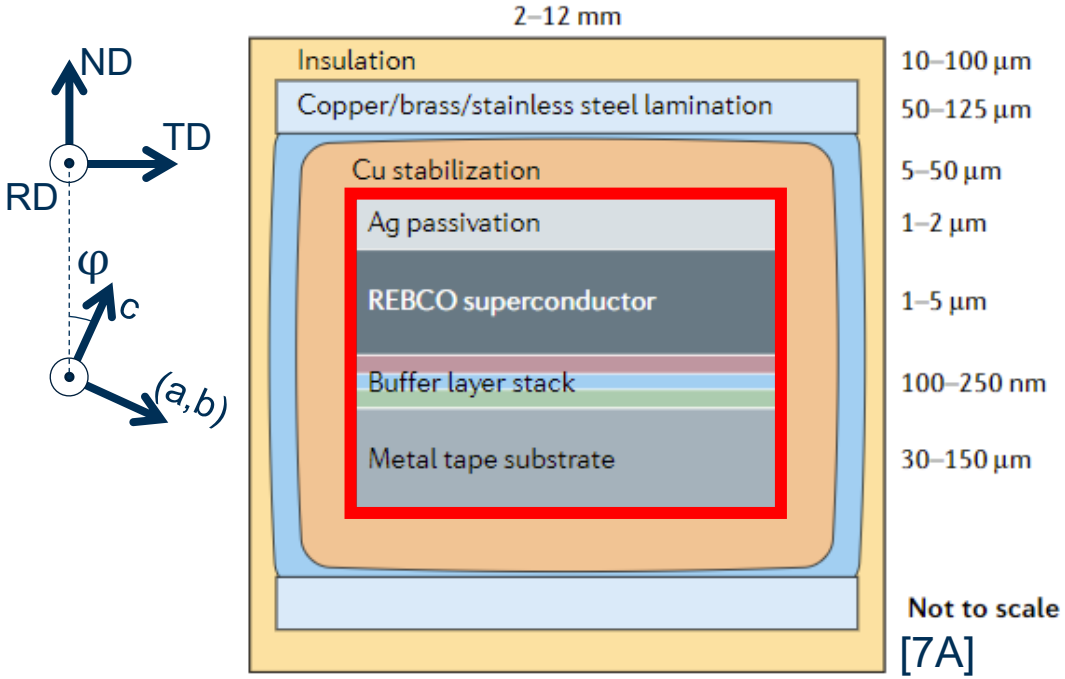
[7]

Tokamak User Requirements

Magnet Current Carriers must:

- Carry their Rated Current
- In (High) Magnetic Fields
- Whilst subject to Strain
- And whilst being irradiated with
  - Fusion Spectrum Neutrons
  - And Gammas

Anatomy of a REBCO Coated Conductor



[7A]

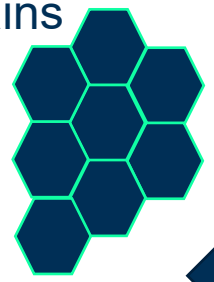
Manufacturer	Technology
SuNAM (Korea)	IBAD / **RCE-DR**
Theva (Germany)	RABiTS / **ISD**-eBAD / **RCE**
MetOx (USA)	IBAD / **RCE-CDR**
AMSC (USA)	RaBITS / **MOD**
Shanghai Creative (China)	IBAD / **MOD**
SuperPower (USA)	IBAD / rMS / **MOCVD**
Fujikura (Japan)	IBAD / **PLD**
Shanghai ST (China)	IBAD / **PLD**
Faraday Factory (formerly SuperOx, Japan)	IBAD / **PLD**

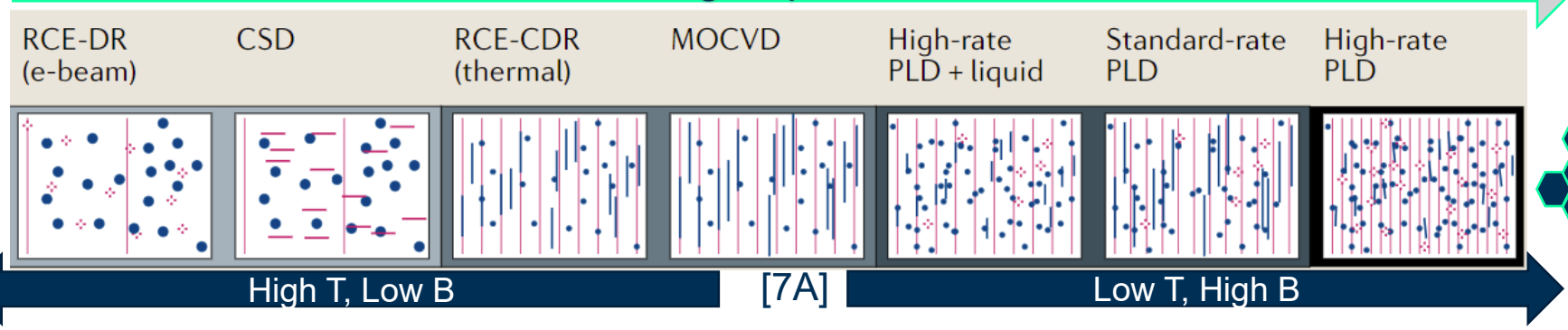
Increasing Super-saturation

Resultant REBCO Defect Structures:

Increasing Super-saturation

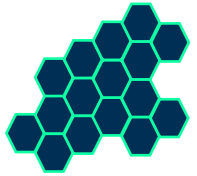
Big Grains



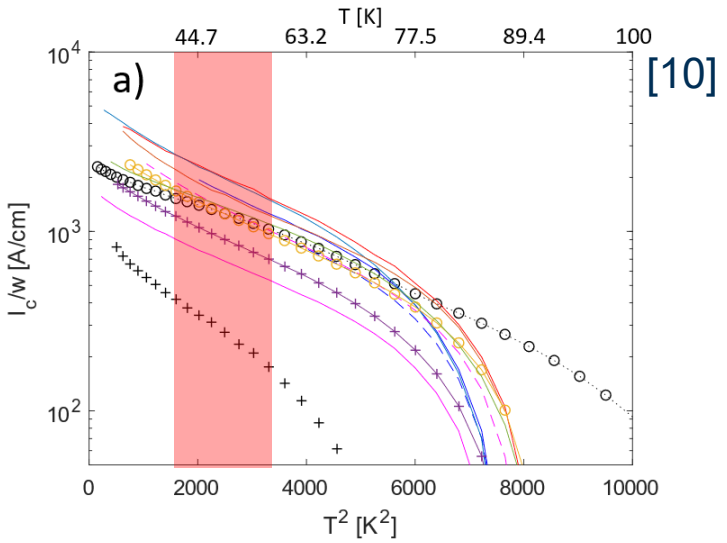


[7A]

Small Grains



Properties of REBCO CC



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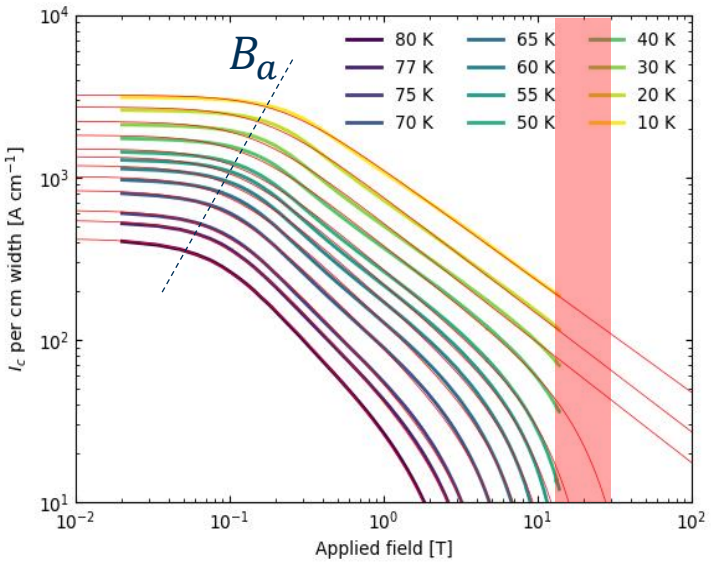


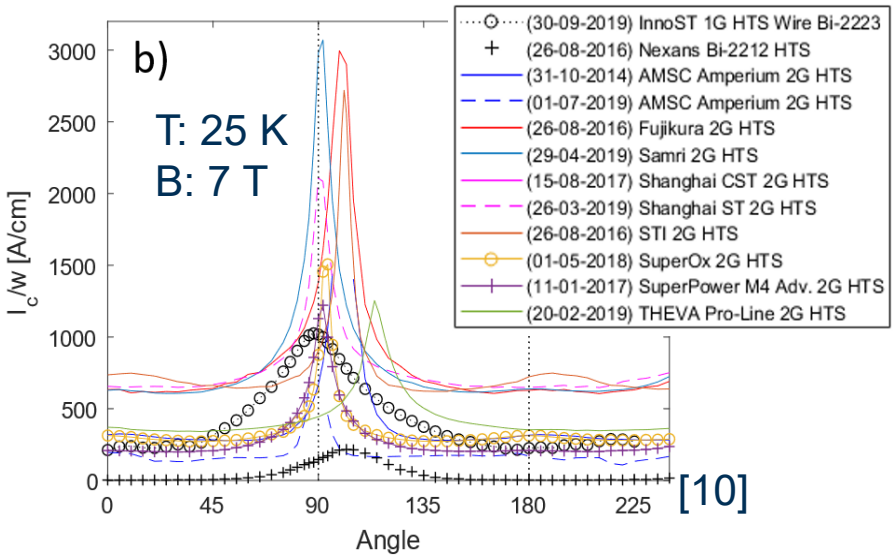
$$J_c(B,\theta) = J_c(\tilde{B}) \quad [12]$$

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

$$J_c^{wk}(T) = J_c^{wk}(0)\exp\left\{-\frac{T}{T_0}\right\} \quad [11]$$

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

$$I_c^*(B) = I_{c0}(0)\left(1+\frac{B^2}{B_a^2}\right)^{-\alpha}\left(1+\frac{B^2}{B_\beta^2}\right)^{-\beta} \quad [13]$$



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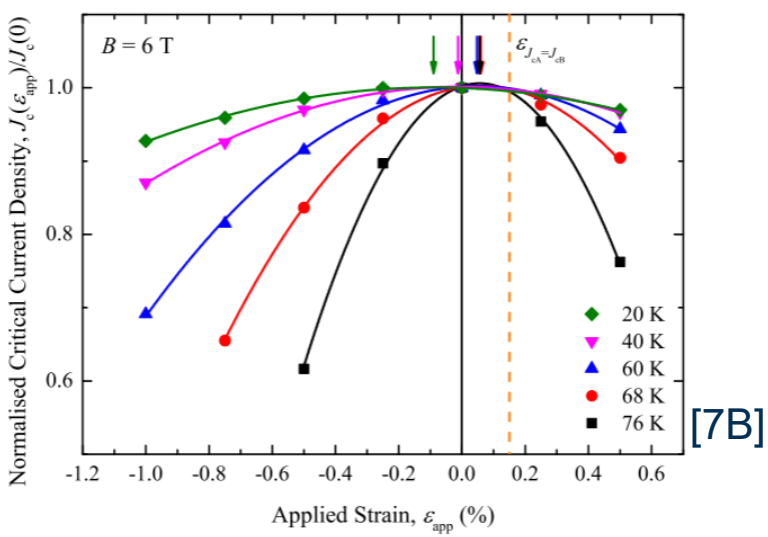
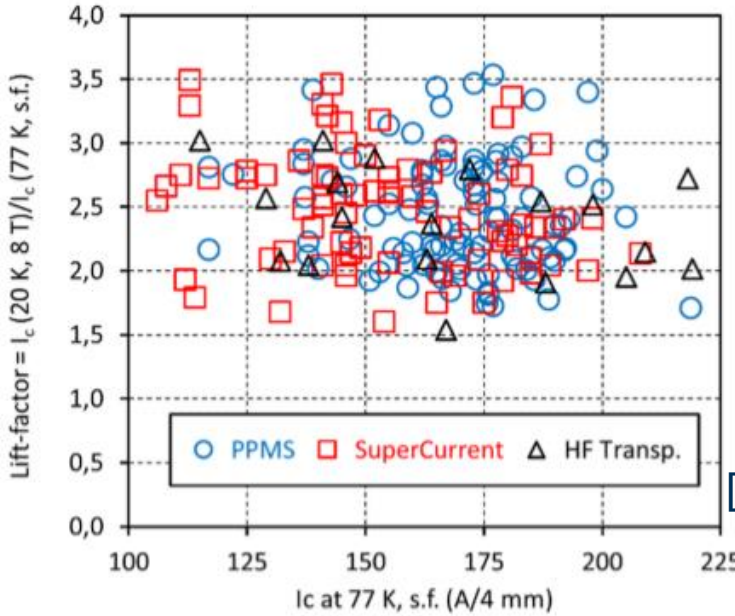


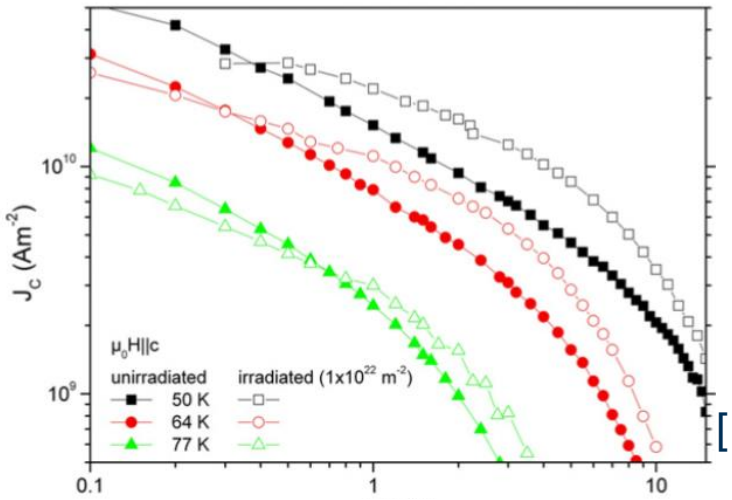
[7B]

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



[9]

Neutron Irradiation Experiments on REBCO



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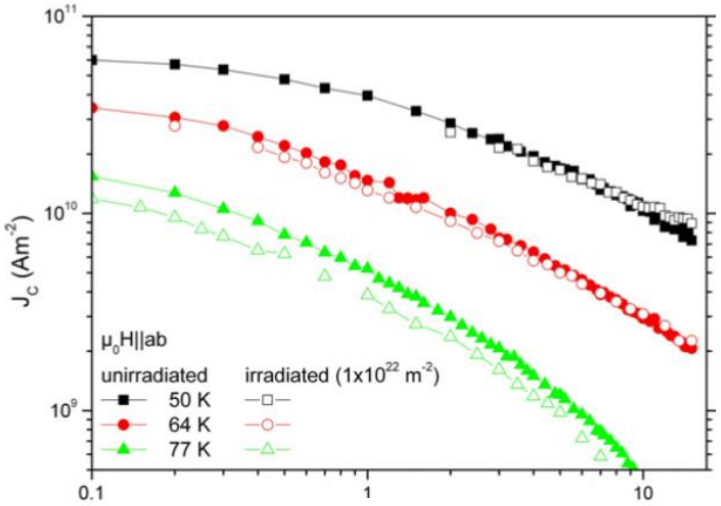

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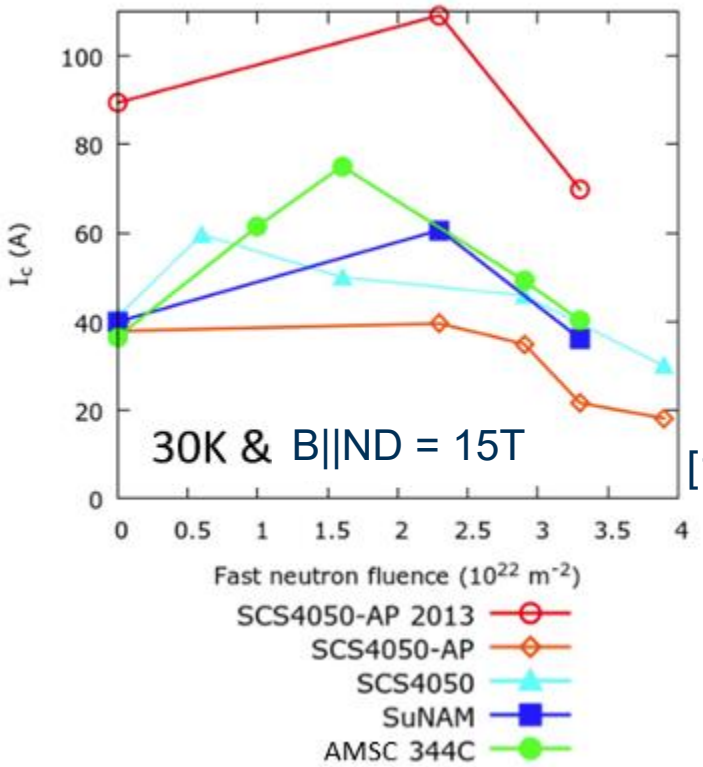

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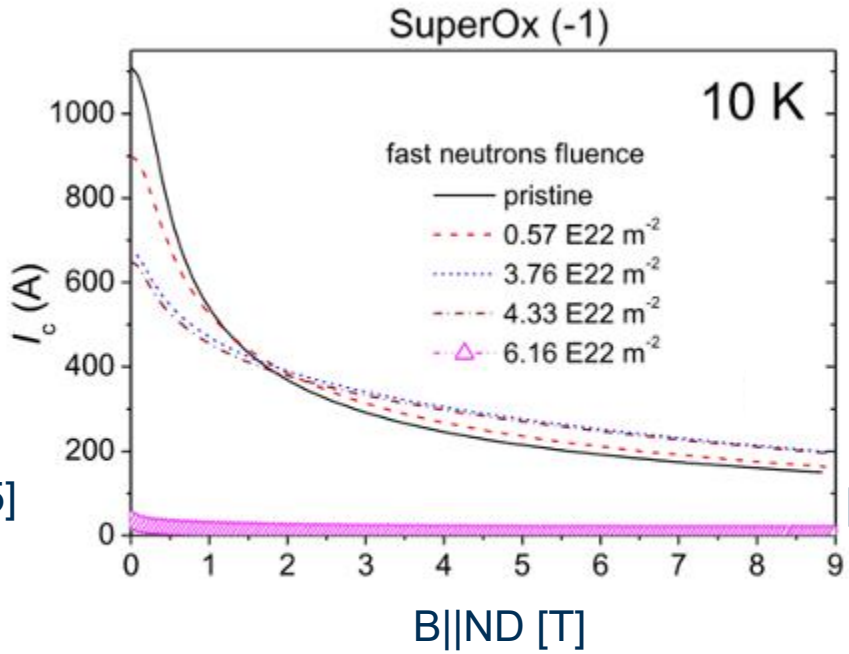

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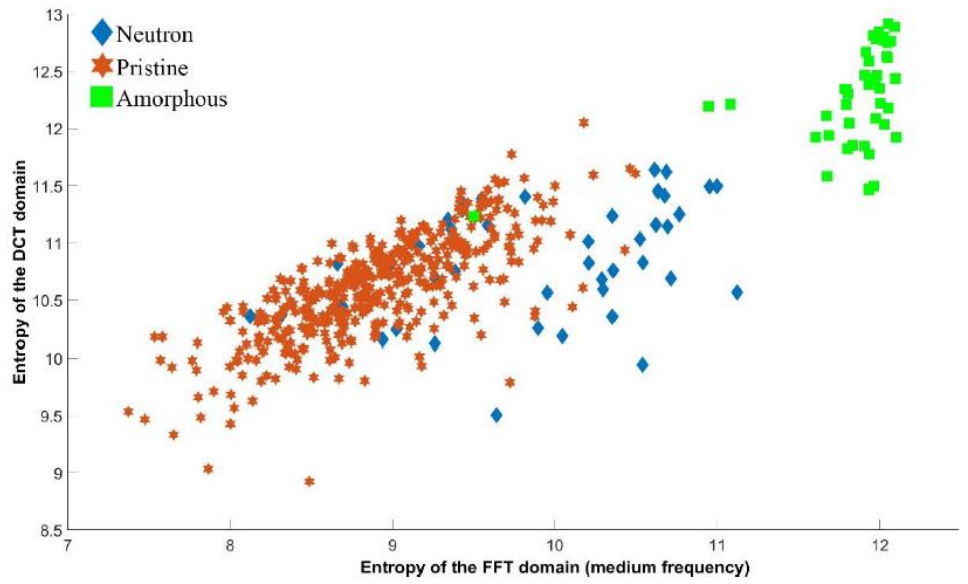

[16A]

STEP HTS Irradiation Test plan

Presented by Chris Grovenor

Presented 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.

Ex-situ, fluence

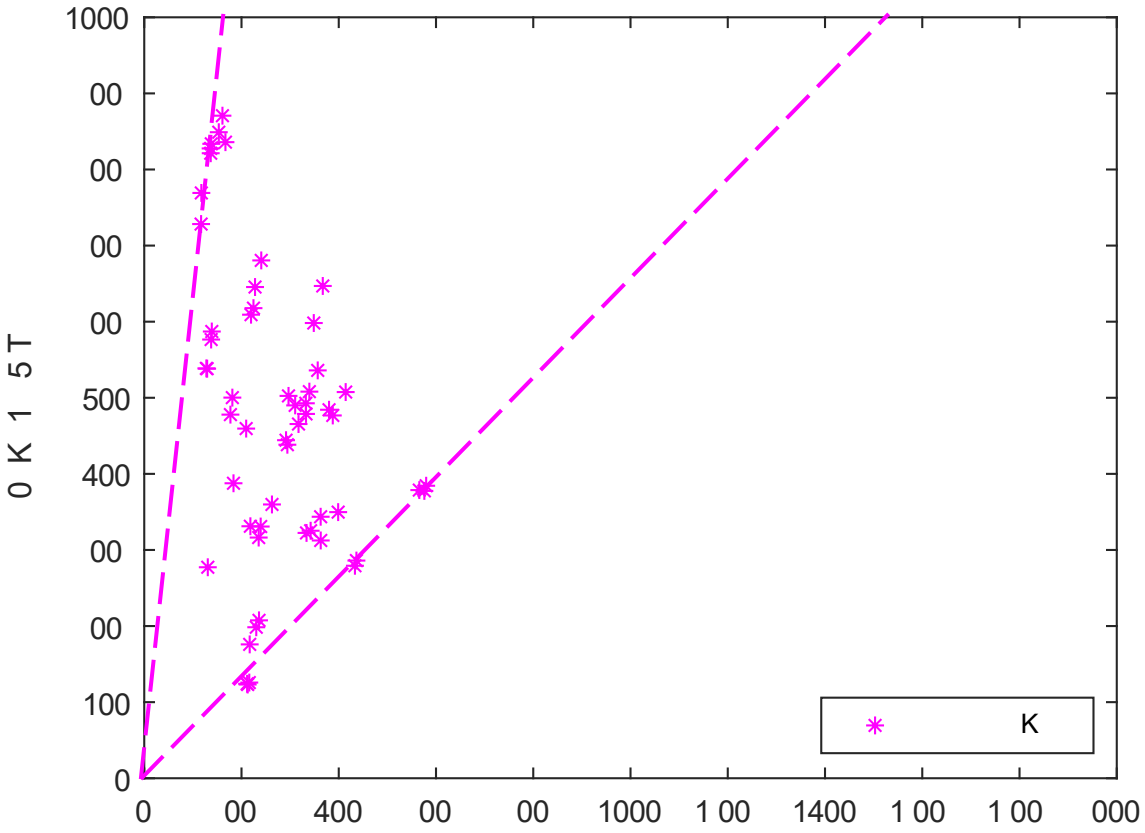
- Filter O ion Irradiation Experiments
- N-irradiation Exp. at HF-ADNF Bham
- Cold Ion Irradiation Experiments
- ISIS-STEP Strain Experiment
- High fluence Cryo-irradiation of REBCO superconductors experiment

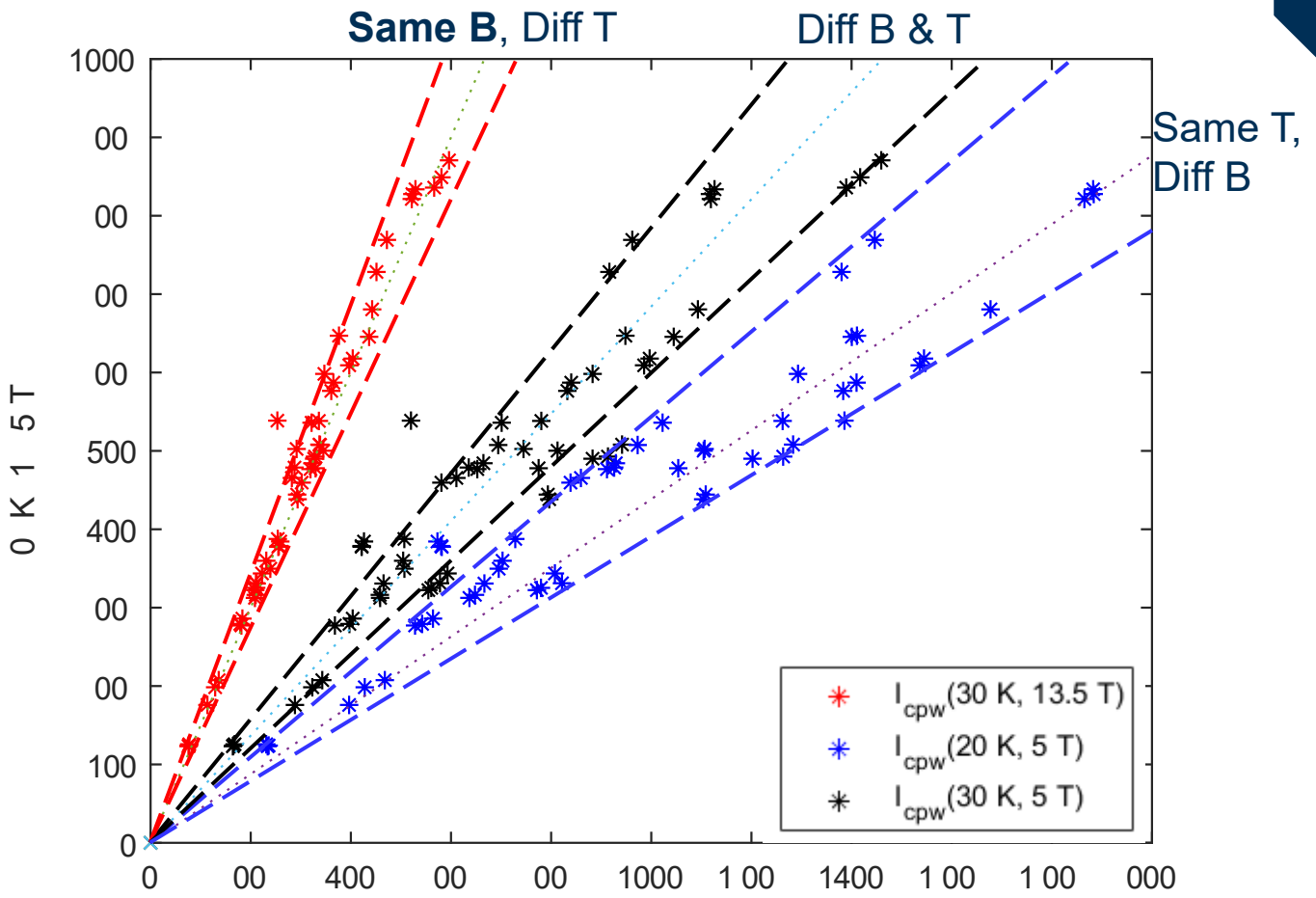
Magnet Institute

REBCO Coupons in STEP

Initial Tape Properties Survey

Q. Can we use of a proxy measurement to predict properties at high B properties?





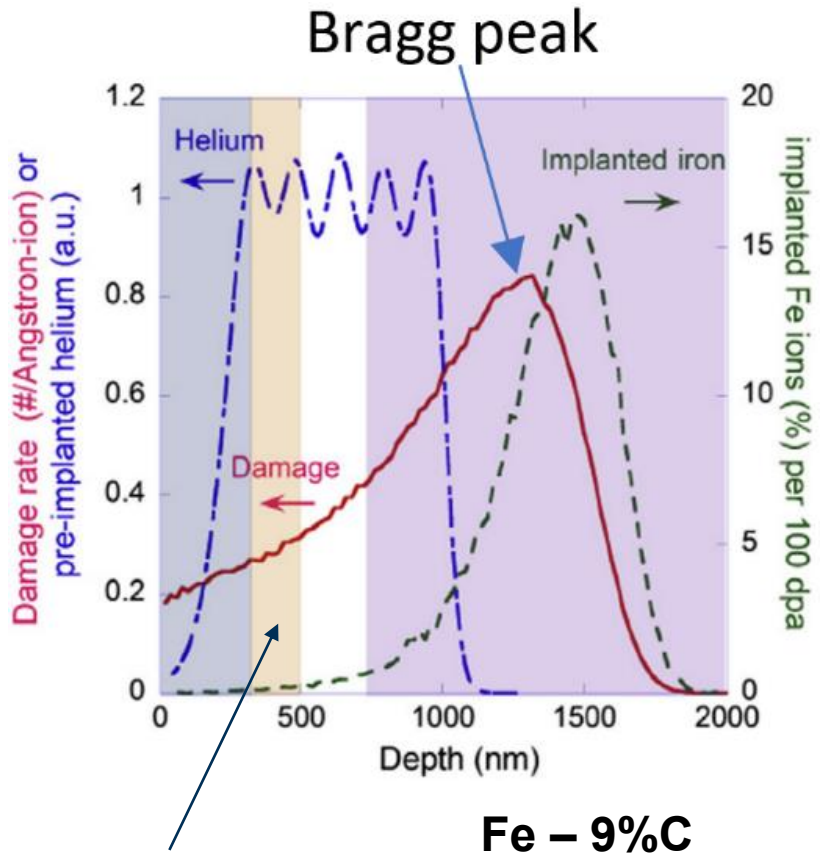
Filtered Ion Irradiation Experiment

UK Atomic Energy Authority

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.



[23]

Fe – 9%C

Volume considered to have "neutron-like" damage

What do Fusion Neutrons do to REBCO?

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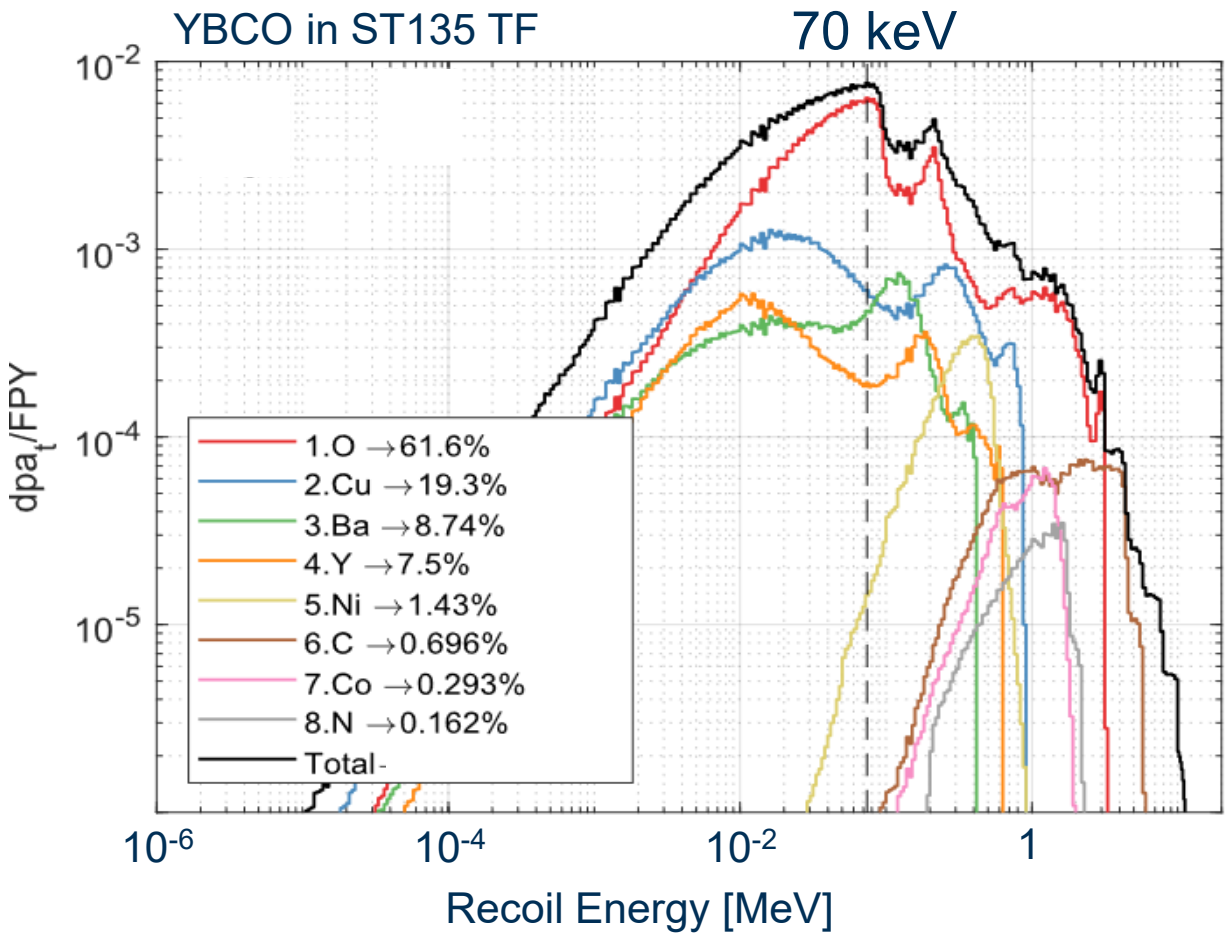
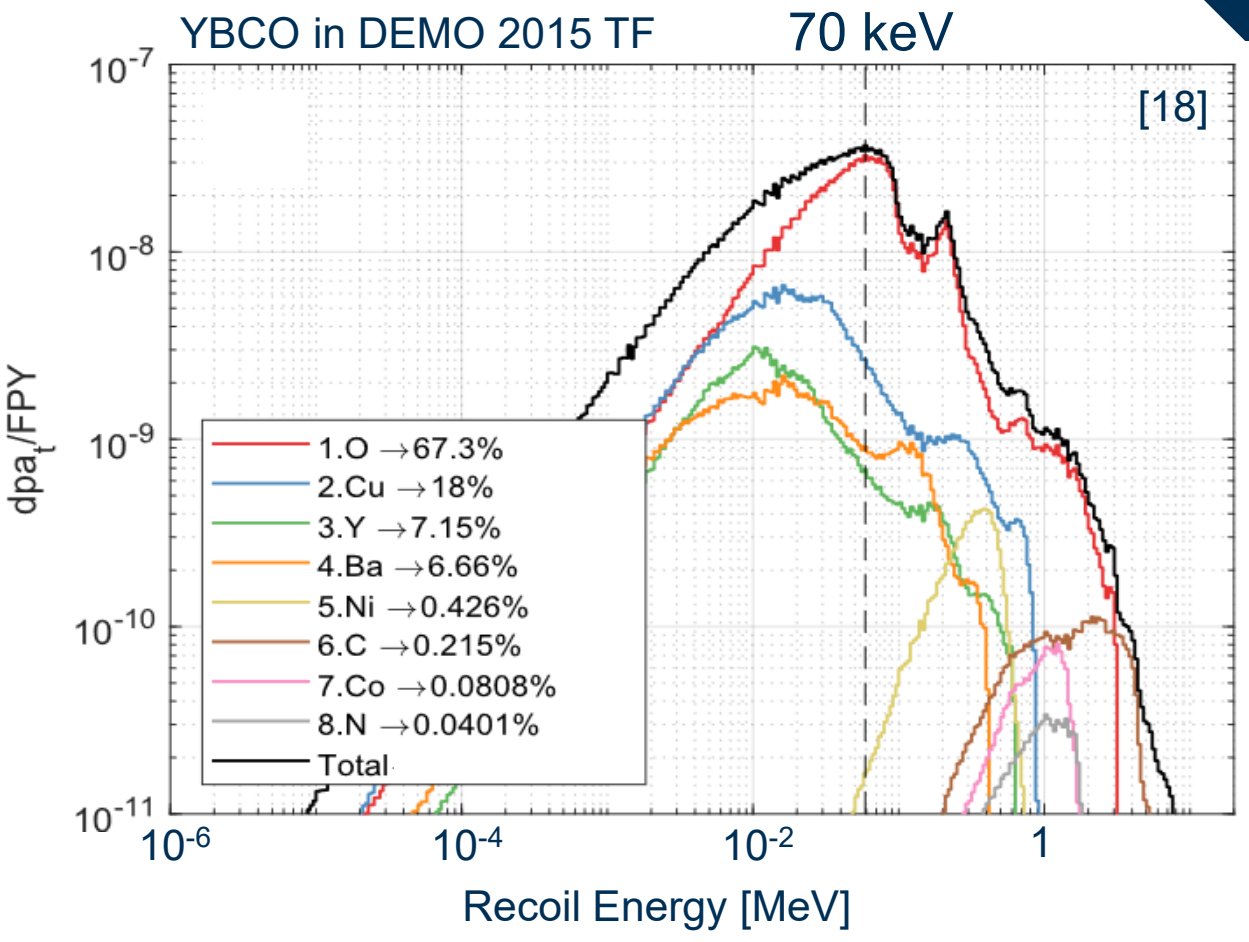
Q. What do fusion spectrum neutrons do to YBCO?





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

Filtered Ion Irradiation Experiment

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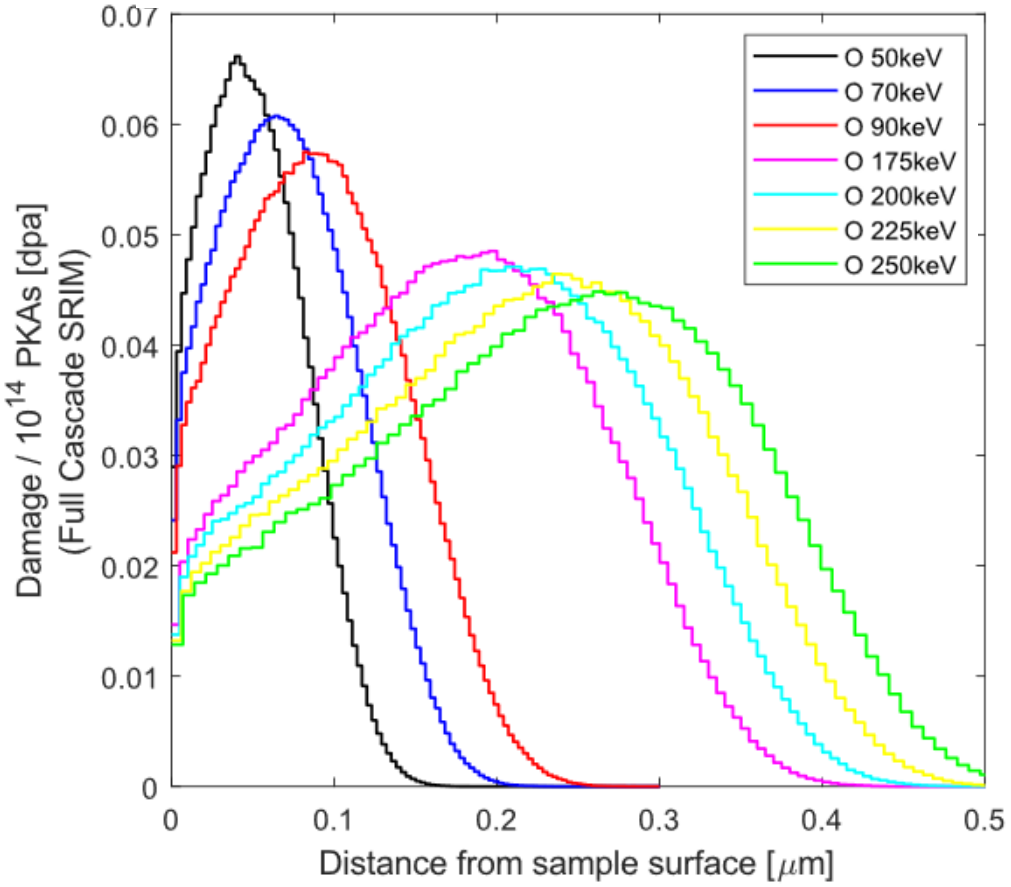
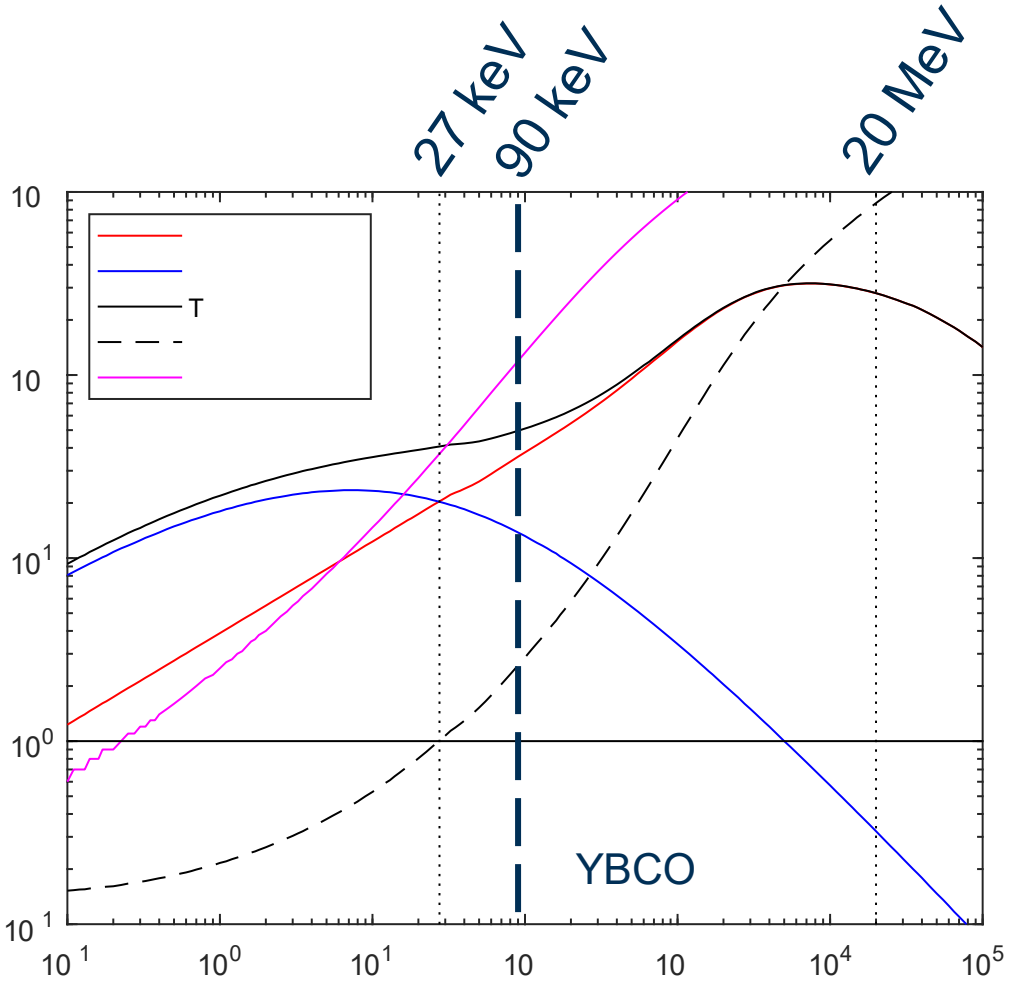
Q. What do monoenergetic oxygen ions do to REBCO? (or any material)





Filtered Ion Irradiation Experiment

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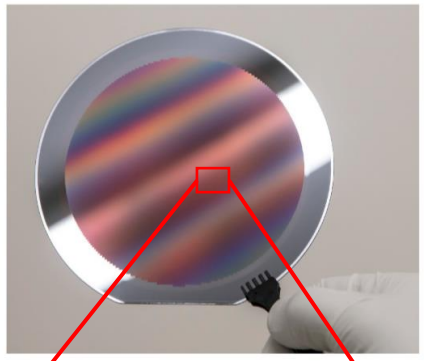
Q. How does one create a uniform ion implantation profile?
A. Use a Steinbach et al. energy filter



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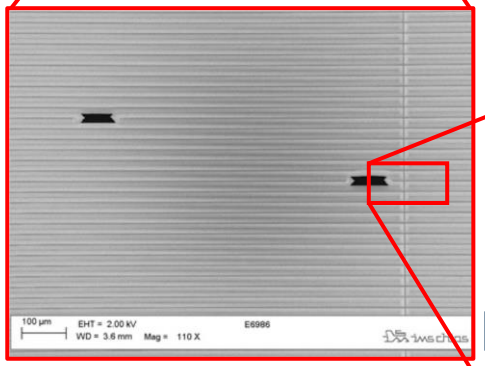
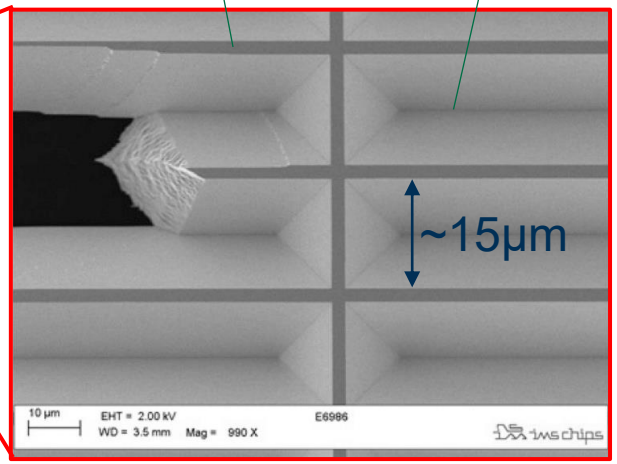


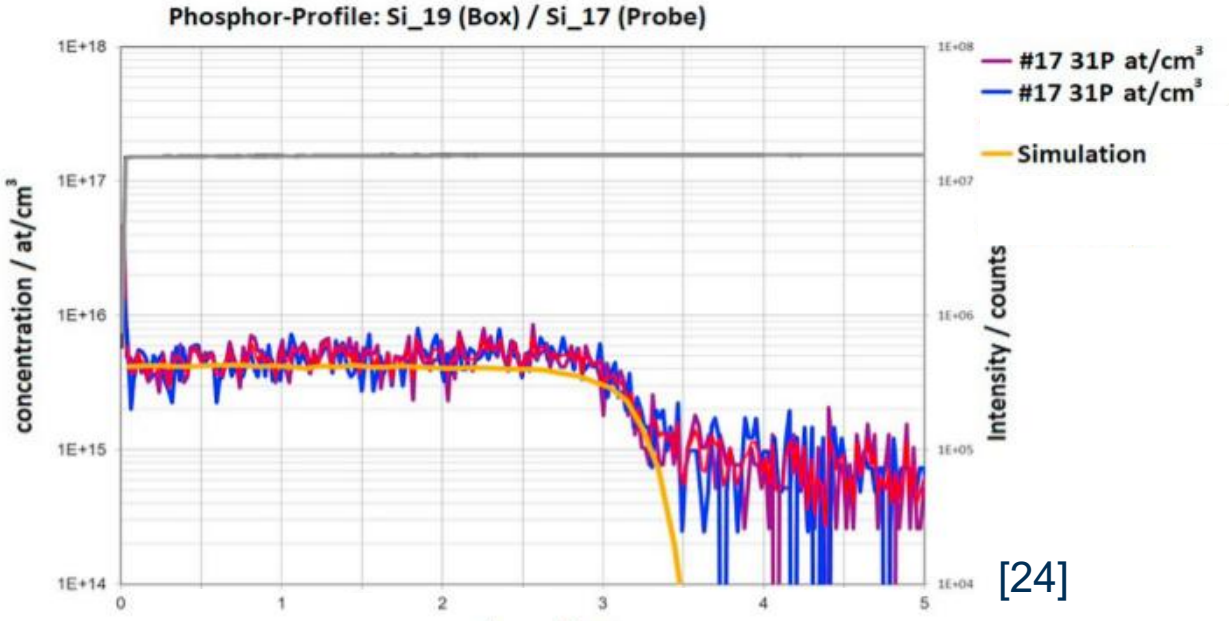
[24]

6.5µm thick 0.2µm thick



[24]

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



[24]

mi2-factory

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Filtered Ion Irradiation Experiment

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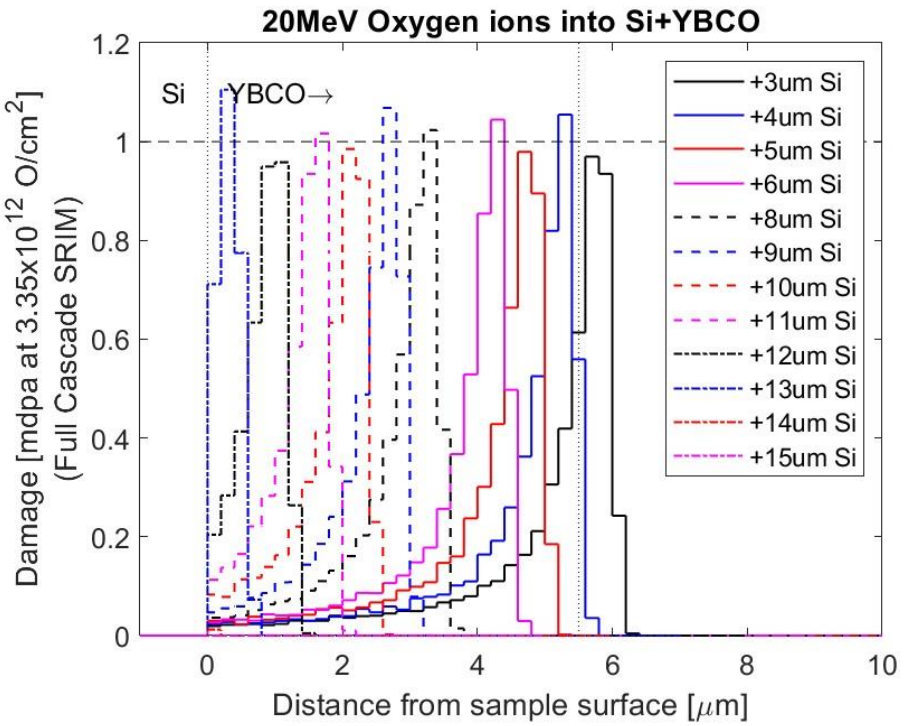
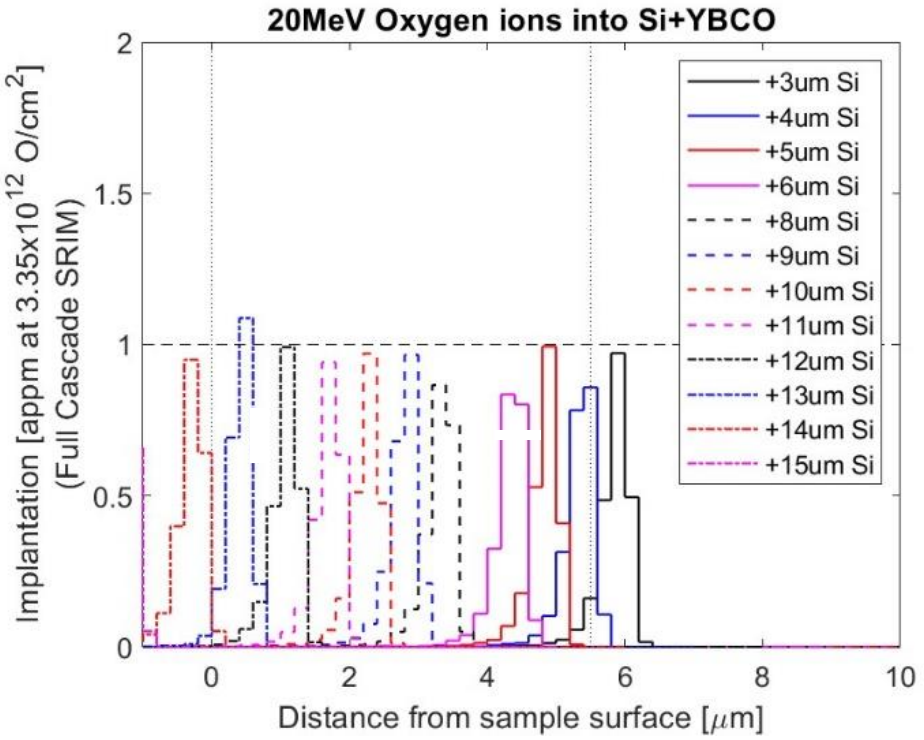
Q. What does the experiment look like?





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Filtered Ion Irradiation Experiment

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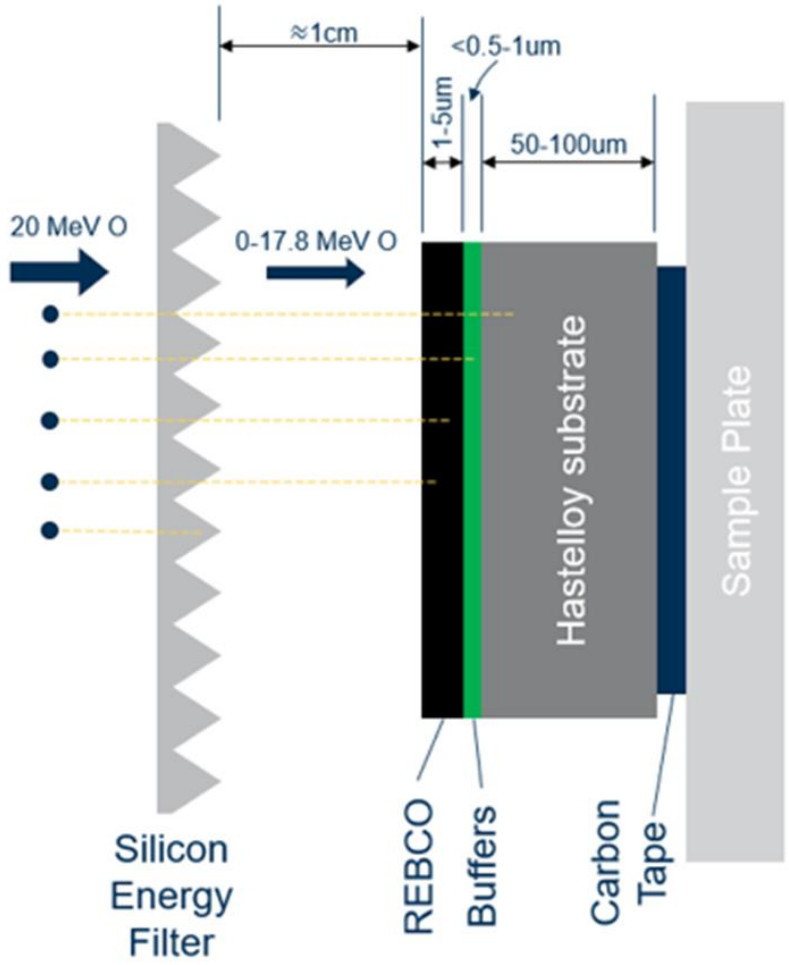
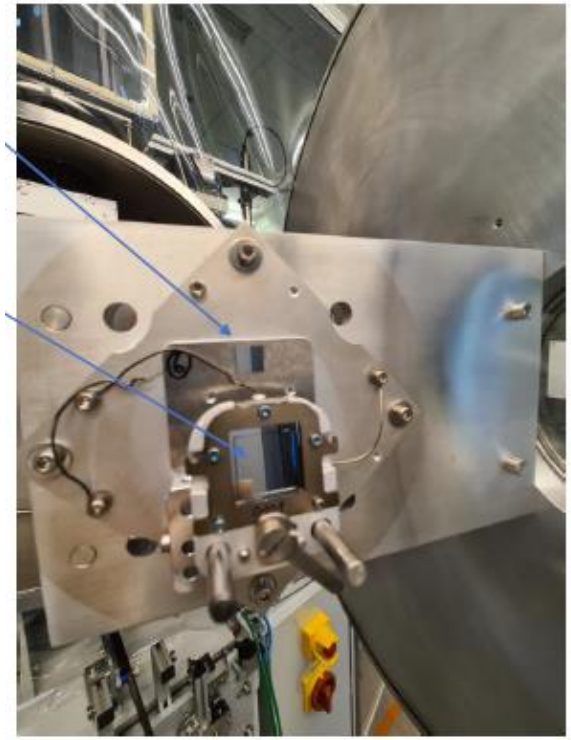
Q. What is the experiment set-up?

Design

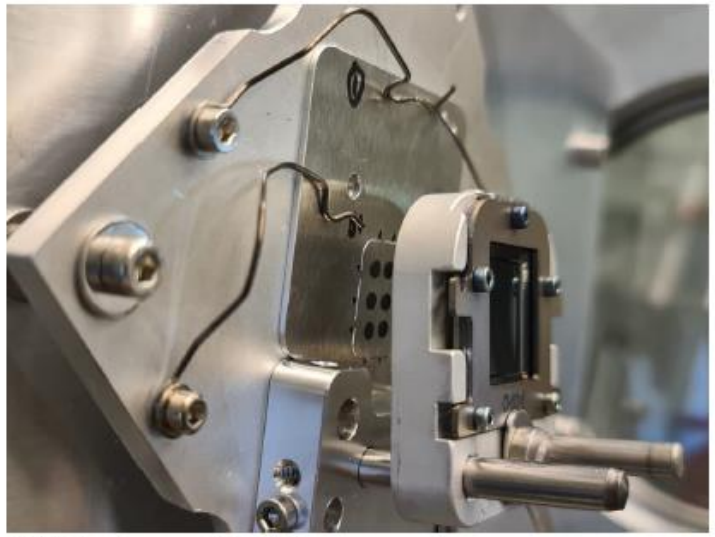


Reality

Silicon Implantation Experiment (SIMS)



Sample Plate Assembled behind Filter on Beamline



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Filtered Ion Irradiation Experiment

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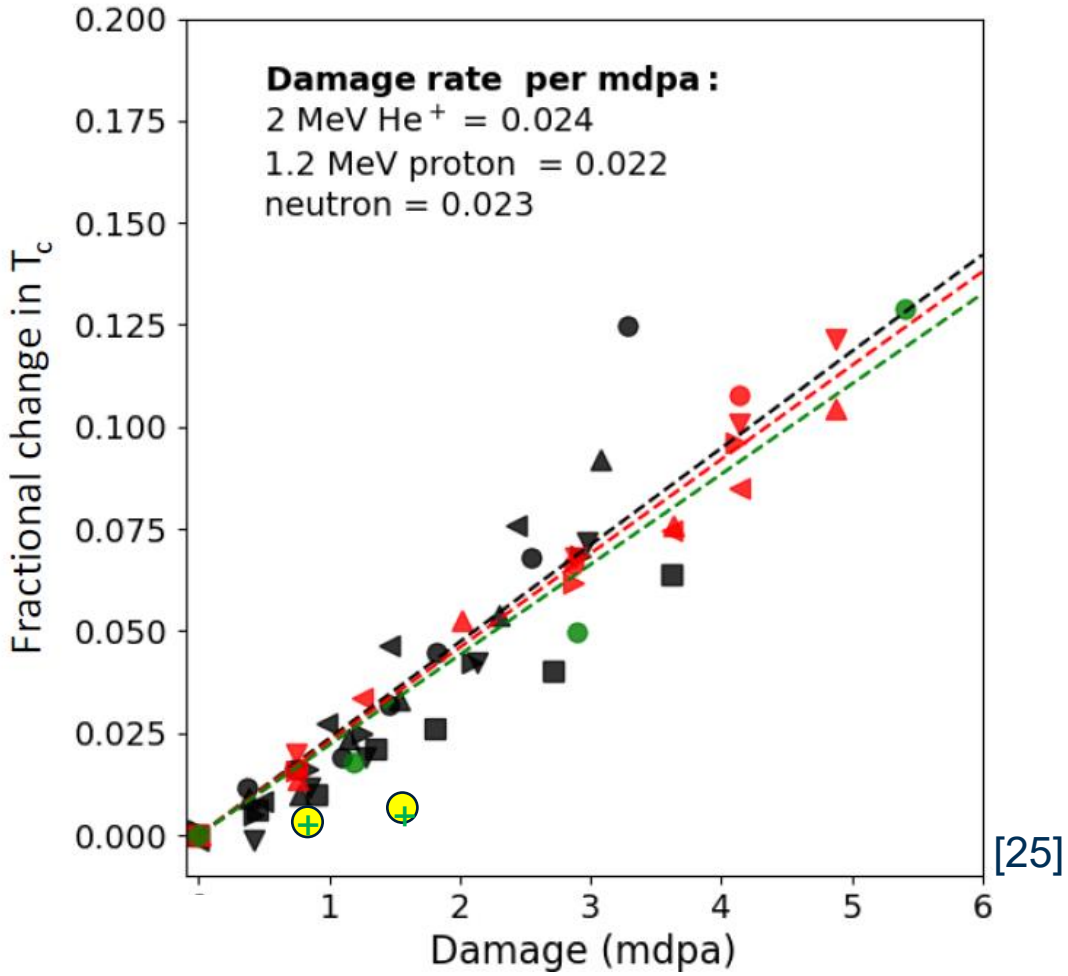
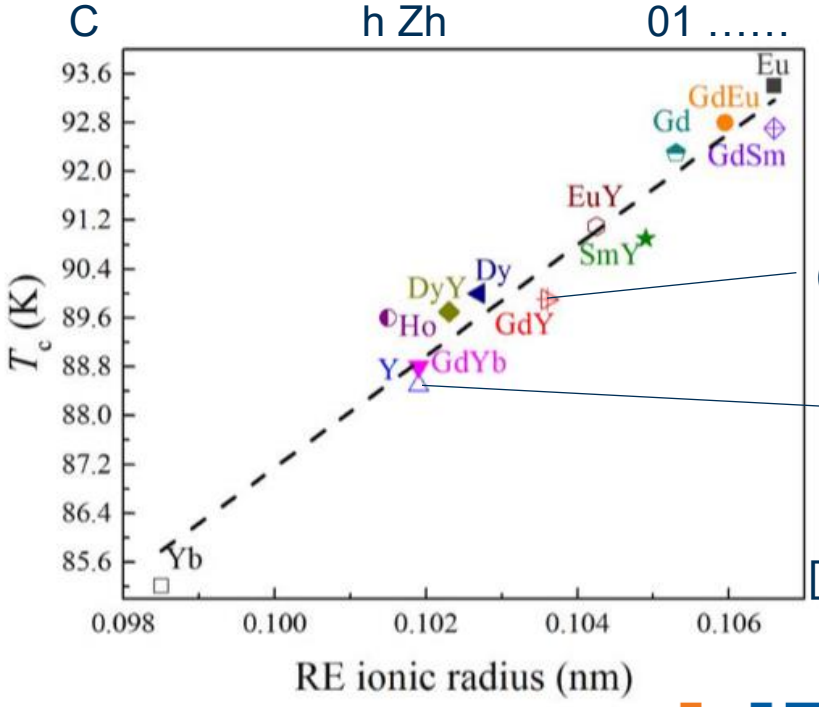
Q. Any change in T_c?



[25]

- Sample 1 T_{c0} = 88.8 K YBCO
- Sample 2 T_{c0} = 87.0 K (Gd/Y)BCO



(Gd,Y)BCO: 90K

YBCO: 88.4K

[26]

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Filtered Ion Irradiation Experiment

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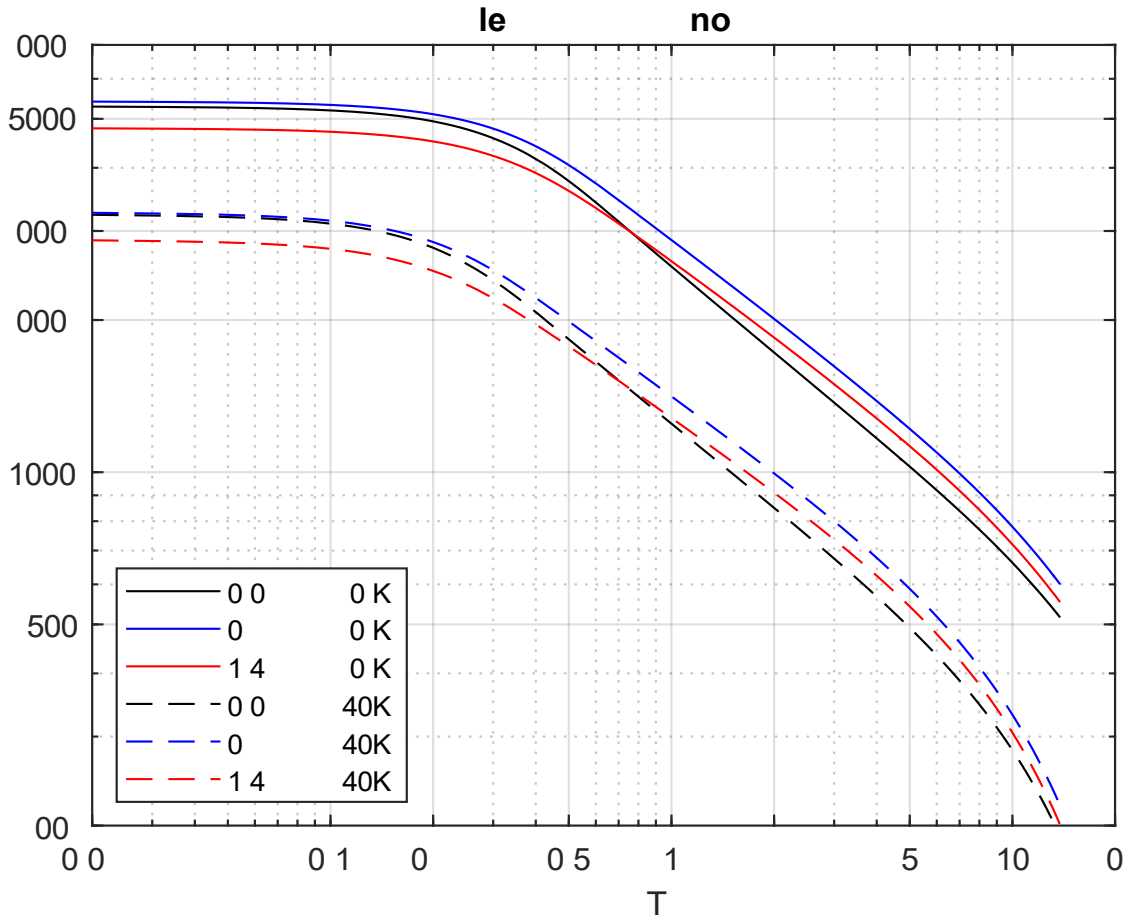
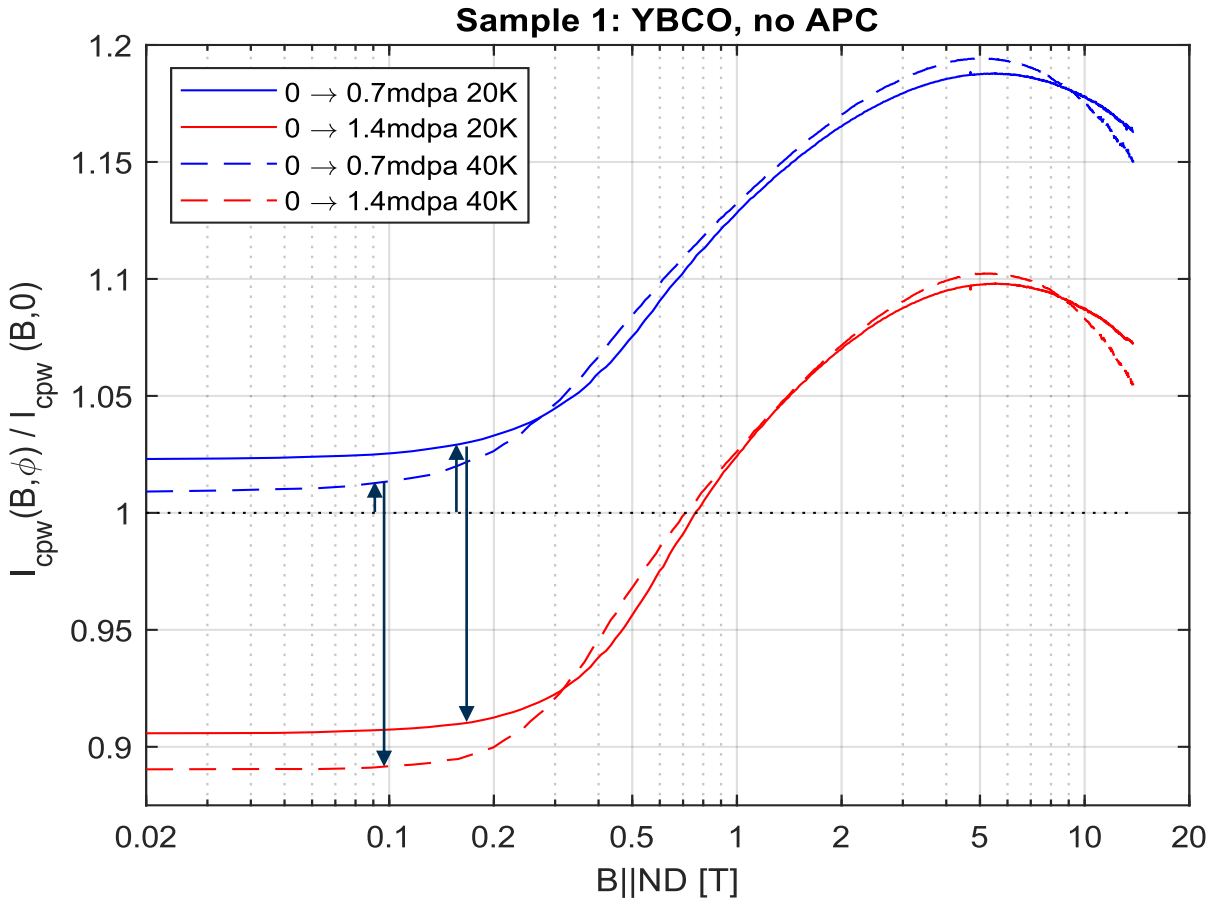
Q. Any change in J_c?





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 Experiment is on-going!

Filtered Ion Irradiation Experiment

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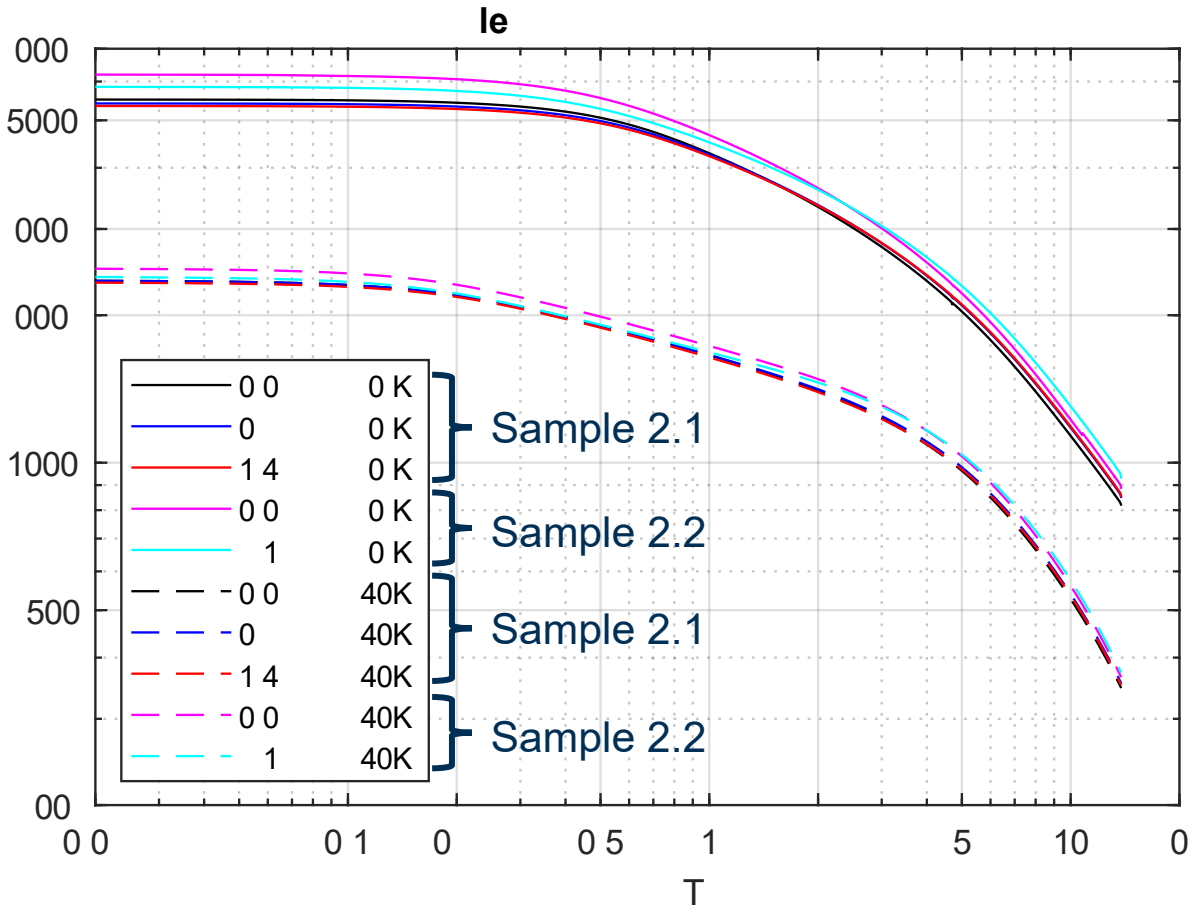
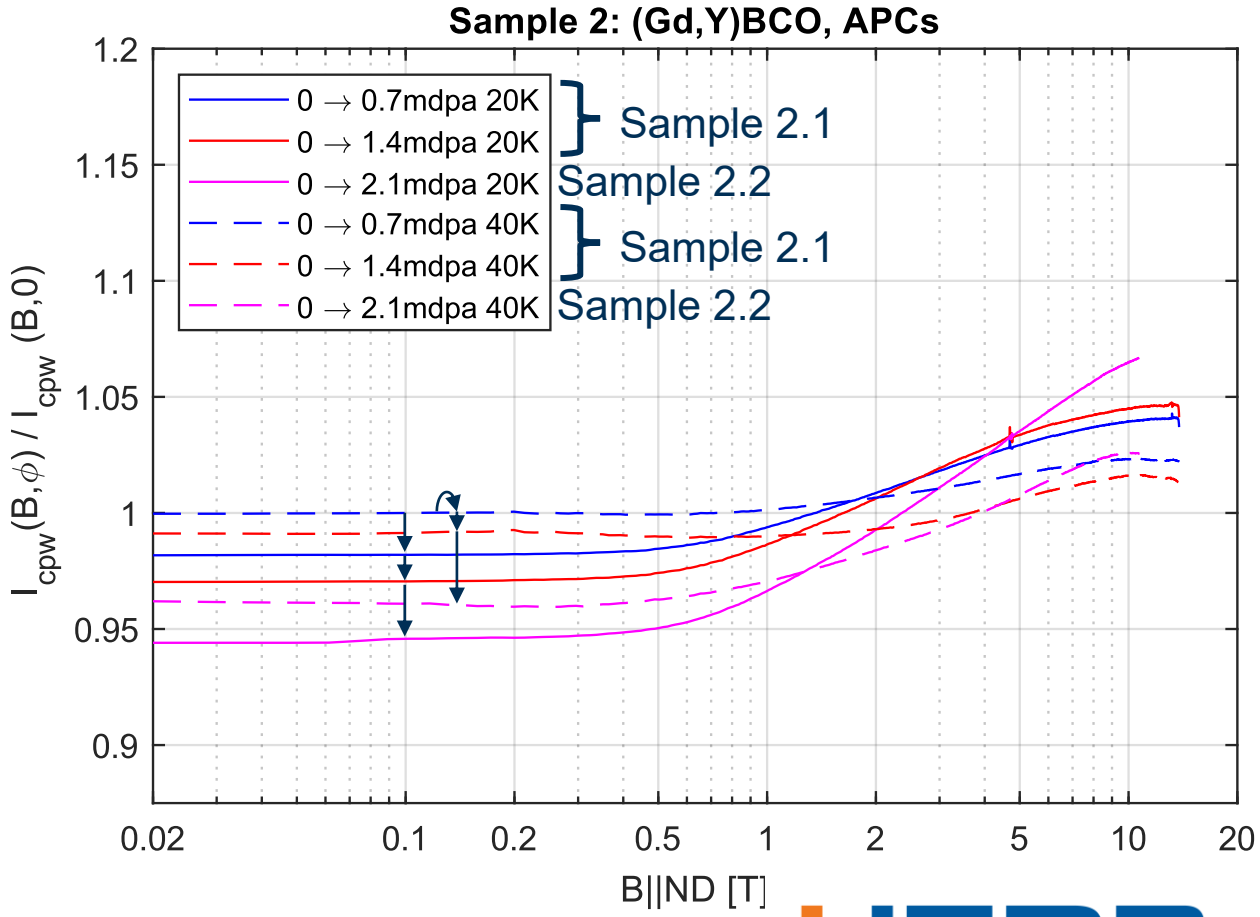
Q. Any change in J_c?





 Experiment is on-going!

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Acknowledgements & References

@ UKAEA:
- Simon Chislett-MacDonald
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- James Tufnail (Phd)

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- Shavkat Akhmadaliev
- Florian Krippendorf
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  - Chris Frost
  - Carlo Cazzaniga
  - Maria Kastriotou
  - Richard Down
  - Robert Major
- ENGIN-X
  - Oleg Kirichek
  - Alexander Jones
  - Joe Kelleher

@ Surrey Ion Beam Centre:
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- Roger Webb
- Adrian Cansell

& many others!

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STEP HTS Irradiation Test plan

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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.

Ex-situ, fluence

- Ion Irradiation Experiments
- Birmingham Ex-situ Disk Exp.
- Cold Ion Irradiation Experiments
- ISIS-STEP Strain Experiment
- High fluence Cryo-irradiation of REBCO superconductors experiment

Magnet Institute

REBCO Coupons in STEP