



THE EFFECT OF FILTERED OXYGEN ION IRRADIATION ON REBCO COATED CONDUCTORS

IRRADIATION EFFECTS ON HTS FOR FUSION (IREF25) CONFERENCE
17TH - 22ND JUNE 2025, GALLIPOLI, ITALY

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(* Now moved on)



WHAT I'M GOING TO TALK ABOUT



1) Introduced the STEP programme.

- UK Public Sector route to commercial Fusion
- STEP Tokamak concept design
- Neutron Loading of the STEP Toroidal Field Coil
- STEP's open questions about REBCO in the Fusion Environment

2) Present Filtered Oxygen Ion Irradiation Experiment

- How we emulated neutrons irradiation with ions
- The experiment design
- & some Results



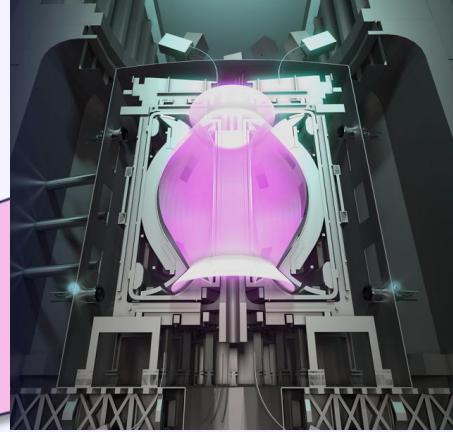
UK PUBLIC SECTION ROUTE TO COMMERCIAL FUSION



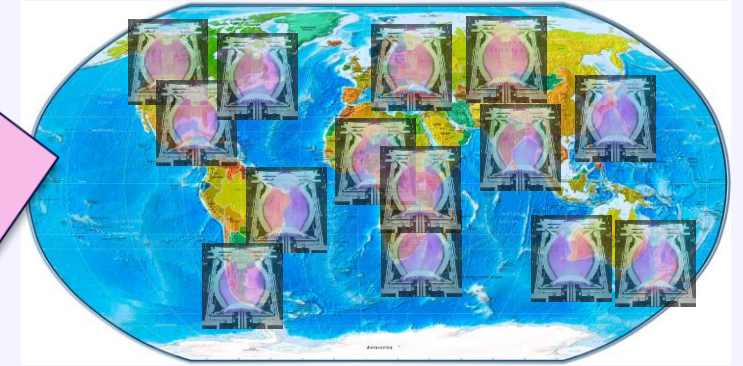
In Operation Goals:

1. To investigate novel exhaust concepts
2. To de-risk / advance the spherical tokamak design, as a future power plant
3. To extend physics knowledge in support of the broader fusion programme

Design Phase



Spherical
Tokamak For
Energy
Productions



Commercial Fusion

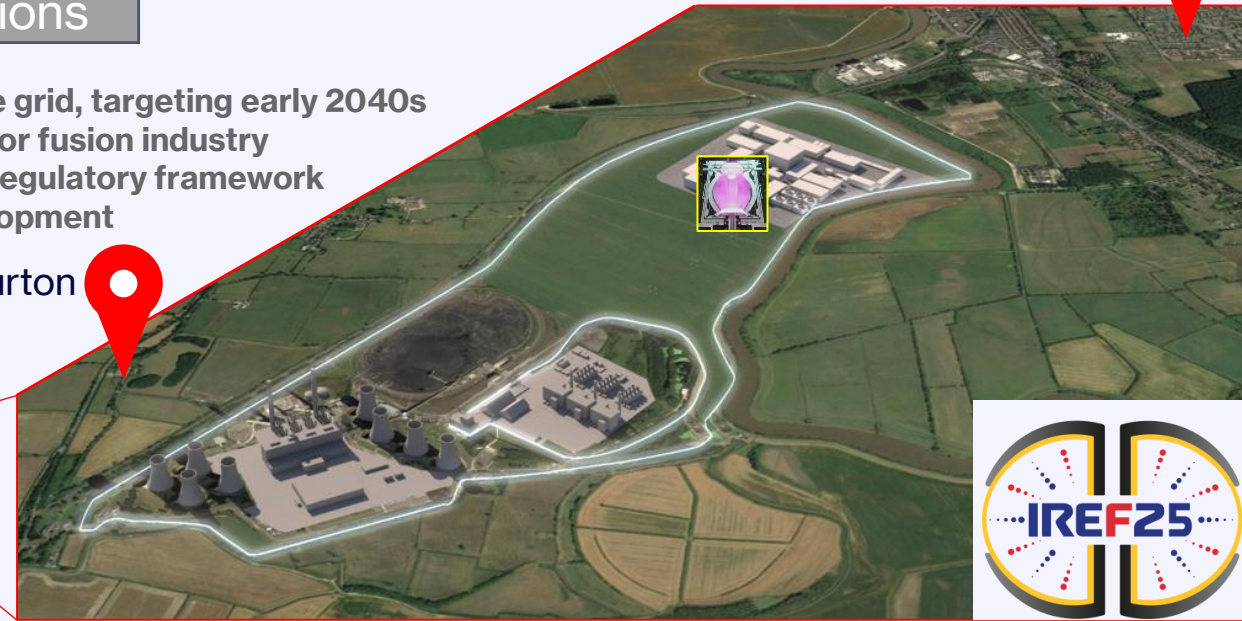
Gainsborough



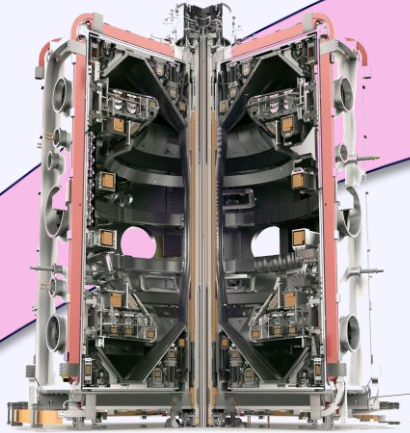
Main Goals:

- Put electricity of the grid, targeting early 2040s
- Build Supply chain for fusion industry
- Develop UK fusion regulatory framework
- Nurture Skills development

West Burton

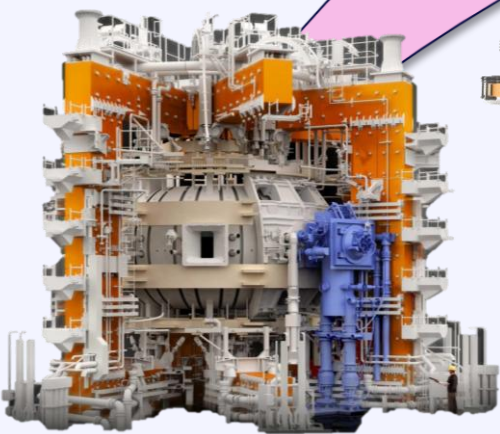


1997: $Q = 0.67$, 16 MW.
2021: 59 MJ over 5 s.
2023: 69 MJ over 5 s.
Now beginning decommissioning.



Mega
Amp
Spherical
Tokamak
-Upgrade

Joint
European
Torus



THE STEP TOKAMAK

STEP Special Issue



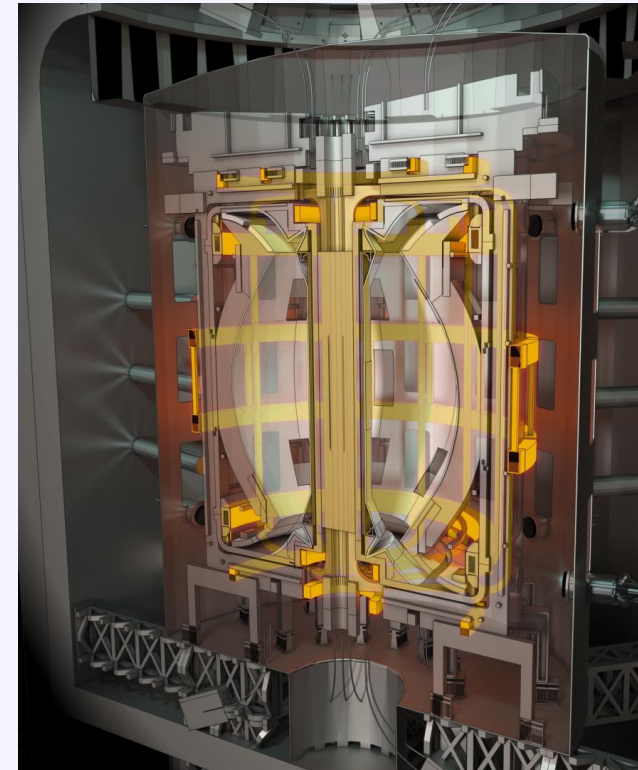
Q. What is the current STEP design?

A. As described in Special Issue of Phil. Trans. Roy. Soc. A: “Delivering Fusion Energy – The Spherical Tokamak for Energy Production (STEP)”

Major Radius	3.6m
Aspect Ratio	1.8
Elongation	3
Triangularity	+0.5
Magnetic Field (plasma centre)	3.2 T

DT Fusion Power	~1.68 GW
Fusion Power Gain	10.2
Net electric power	~100 MWe
DT Neutron source rate	~ 6×10^{20} n/s

Maintenance Strategy	Vertical with Remountable TF Coils
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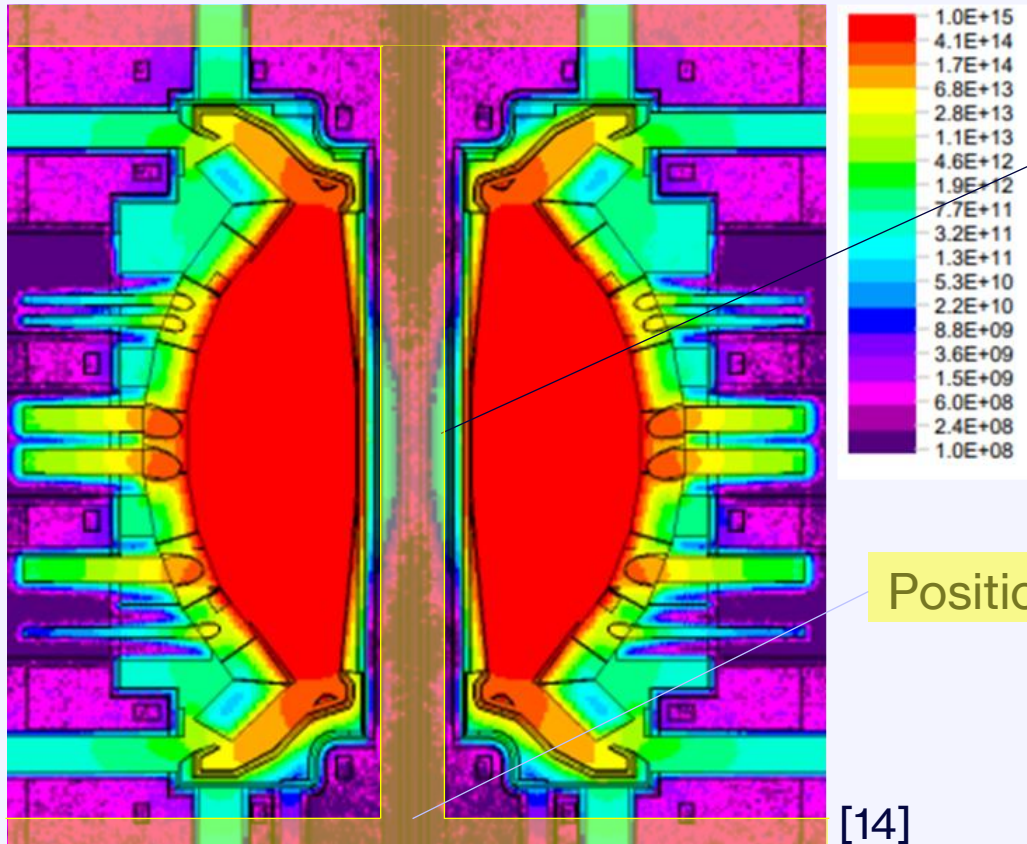
THE STEP TOKAMAK



Q. What level of irradiation do we expect?

Neutron Loading in STEP

$P_{fus} \sim 1680$ MW



- Inboard region of the TF coils sees $\sim 2 \times 10^{11}$ n/cm²/s neutron fluxes with 8×10^{10} n/cm²/s (40%) with energy > 0.1 MeV.
- At this rate, STEP fast neutron fluence limit for REBCO - 3×10^{18} n_f/cm² - is reached in just ~ 430 days operating at full power (or ~ 1.18 FPY).
- STEP fast neutron fluence limit for REBCO definition: fluence up to which *pre-irradiation properties can be maintained*.



THE STEP TOKAMAK



Open questions about TF lifetime

DT Fusion Power	1.68 GW
DT Neutron source rate	$\sim 6 \times 10^{20}$ n/s
Plasma First Wall Flux	$>10^{15}$ n/cm ² /s
Peak Neutron flux to REBCO in TF	2×10^{11} n/cm ² /s
Peak Fast Neutron flux to REBCO in TF	8×10^{10} n/cm ² /s
Useful Life of TF Centre-rod	1.18 FPY
Peak Fluence to REBCO at end of useful life	3×10^{18} n/cm ²

Paper: STEP's understanding of REBCO in irradiation environment



- Is this lifetime sufficient for STEP to achieve its goals?
Yes but...
- Are we sure? How sure are we?
 - Need more data on more tapes!
- Data implies how tape is made affects its resilience to irradiation...
- How do we test REBCO CC destined for the STEP magnets?
- Does a flux of neutrons influence current carrying capacity of REBCO?

STEP HTS IRRADIATION TEST PLAN



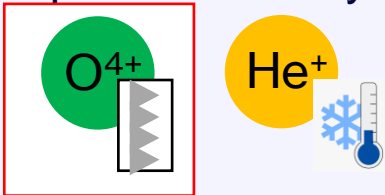
Q. How are STEP addressing these open questions?

A. Perform Experiments!

- In-situ, flux (i.e. irradiation with any source and superconductivity measurements performed **at same time & location**)



- Ex-situ, fluence, proxy (i.e. uses **ions as a proxy** for neutrons for irradiation and superconductivity measurements performed at *different* time/location)



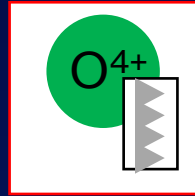
- Ex-situ, fluence, neutrons (i.e. uses **neutrons** for irradiation and superconductivity measurements performed at *different* time/location)



Paper: STEP's progress understanding of REBCO in irradiation environment



The Filter Oxygen Ion Irradiation



GOALS

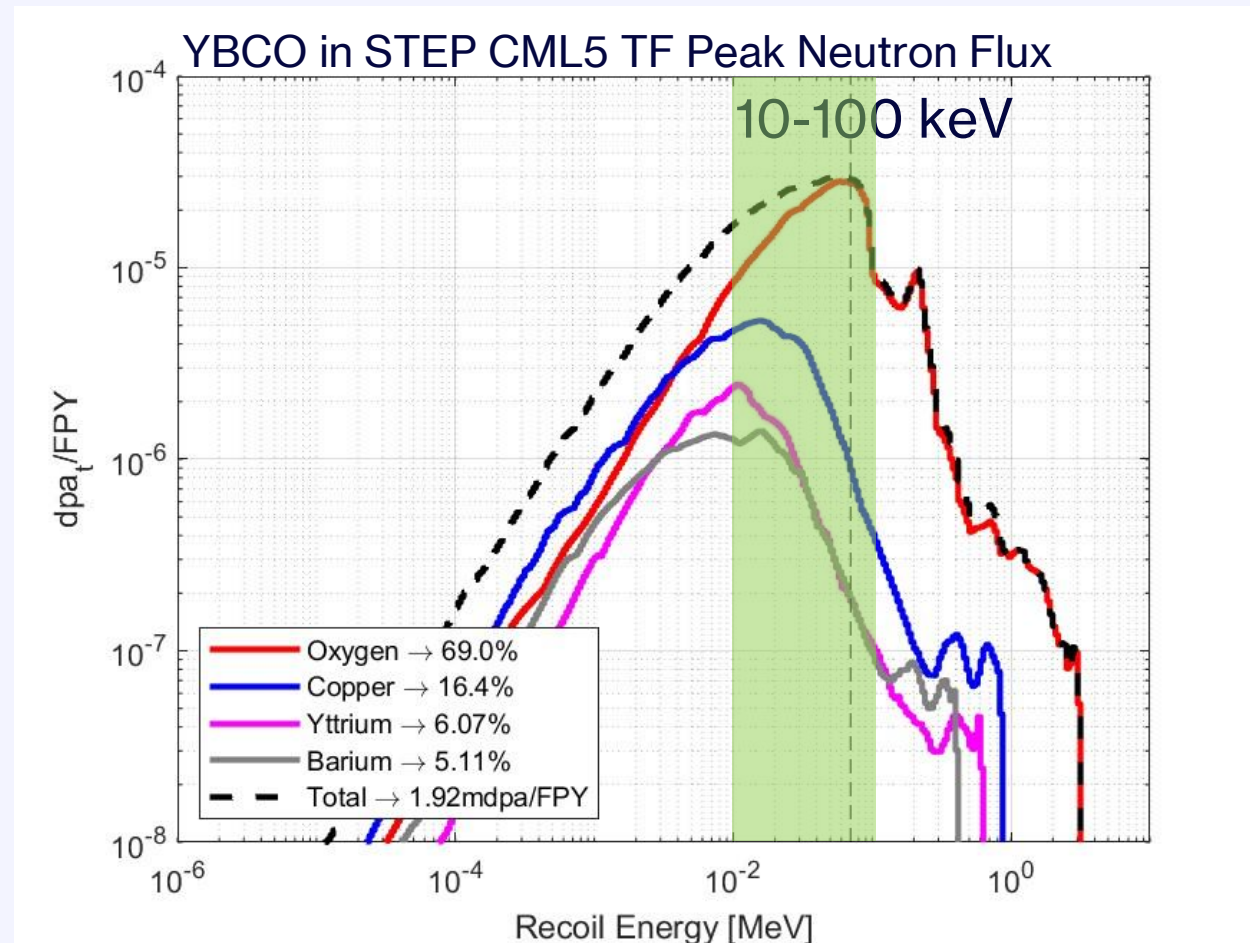
Survey response to irradiation of many types of REBCO coated conductor

- Must include tapes from as many suppliers as possible
- Must reach and exceed STEP relevant damage levels
- Should be comparable to literature data

EMULATING NEUTRON IRRADIATION WITH FAST IONS



Simulating Neutron Damage in YBCO – SPECTRA-PKA



10% of the total damage due to 50-90keV Oxygen PKAs

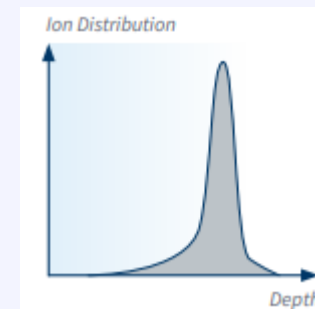


FAST ION ENERGY FILTER



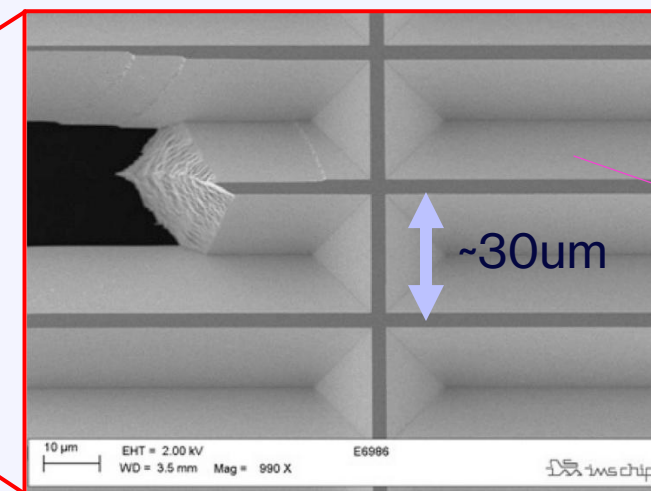
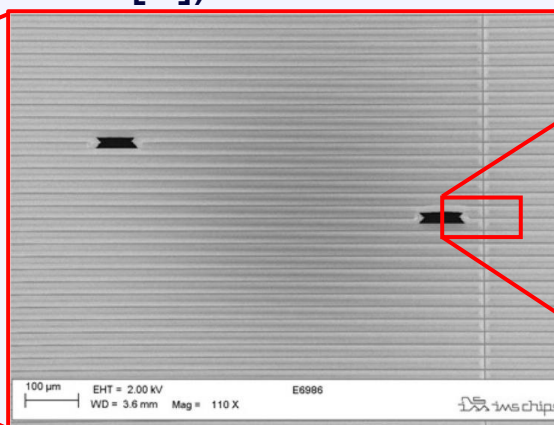
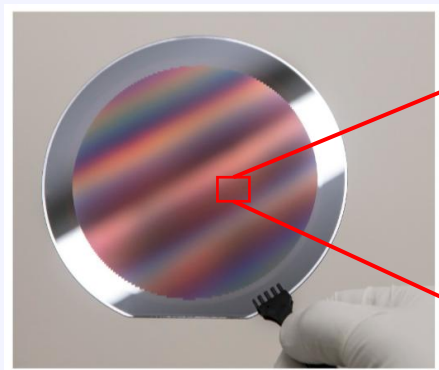
Q. What are they & what do they do?

[mi2-factory are] "developing and supplying a highly innovative tool for manufacturing efficient power semiconductor microchip"



[15]

Filter design as of 2019 (Steinbach et al. [4])



t: ~16μm
t: ~1.5μm

Linear Slope

[4]

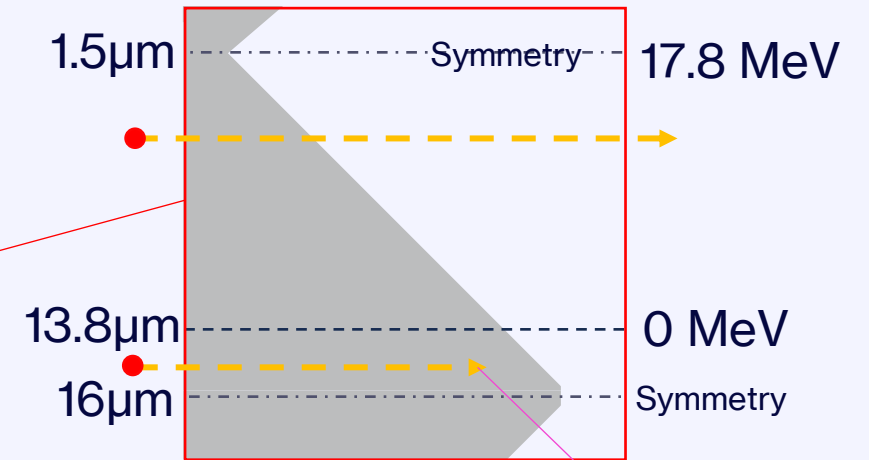
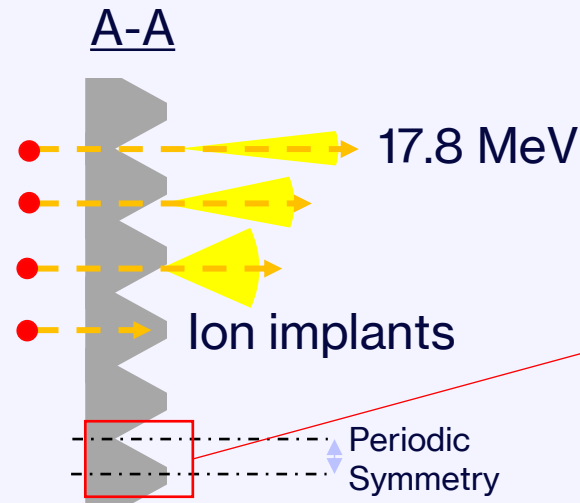
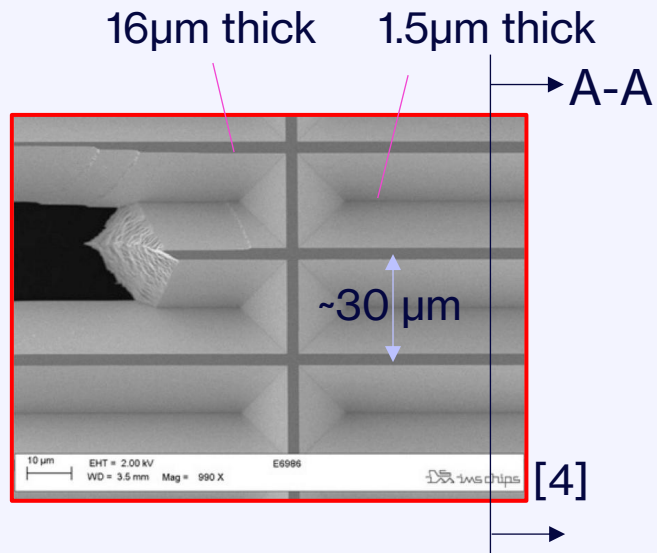


FAST ION ENERGY FILTER

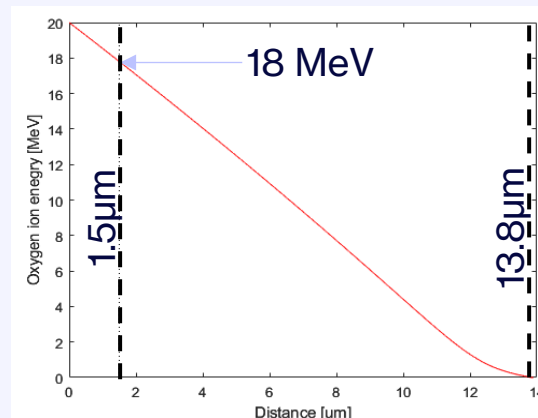


Q. But what about the damage profile?

A. We simulated the effect of the filter on ions from a rastering source of 20MeV Oxygen ions



Implanted ions
~30% of total

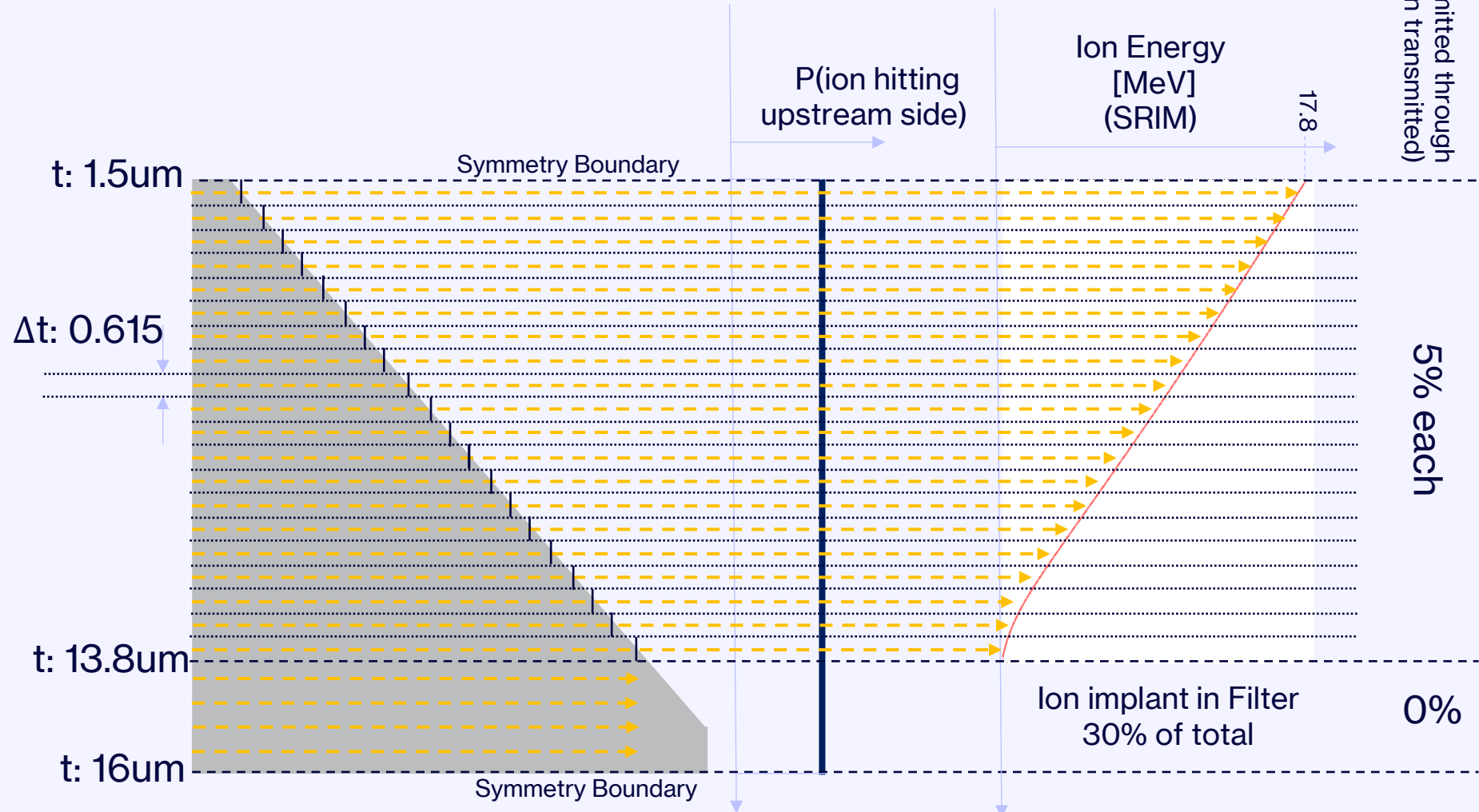


Filter Provided by



FAST ION ENERGY FILTER

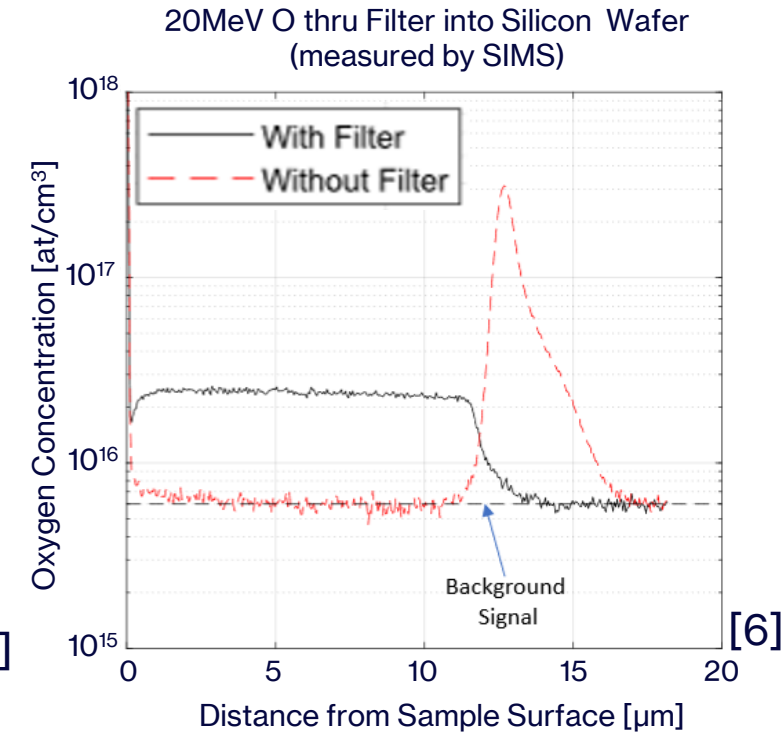
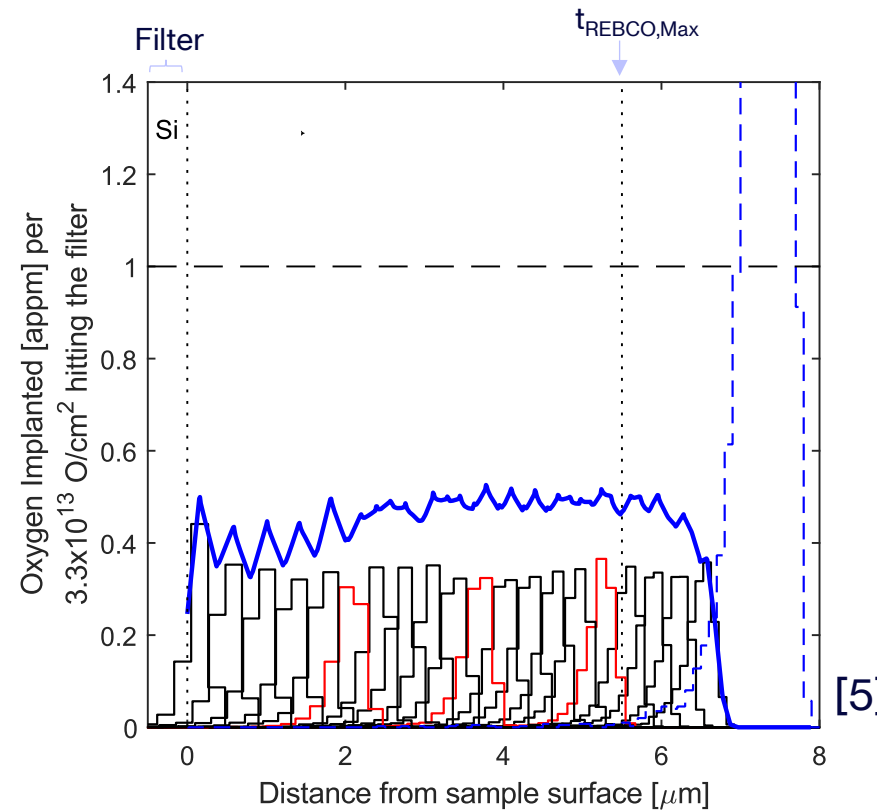
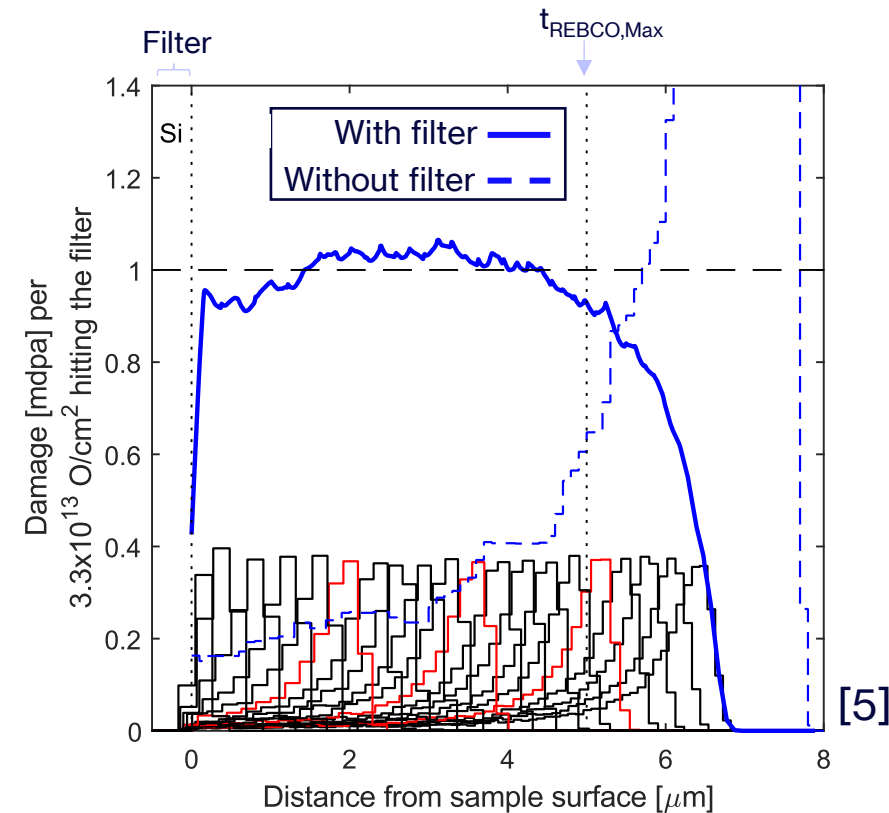
Simulating the damage profile cont....



FAST ION ENERGY FILTER



Resulting Damage profile for 20MeV O through a filter



∴ 3.3×10^{13} O/cm² to the filter → 1 ± 0.1 mdpa damage to sample down to ~ 5μm

→ 0.4 ± 0.1 appm oxygen implantation down to ~ 6μm

(compared to 200 appm required to effect T_D)

[Definition: 1 “mdpa” = 1 in every 1000 target atoms has been displaced from its original location by irradiation]



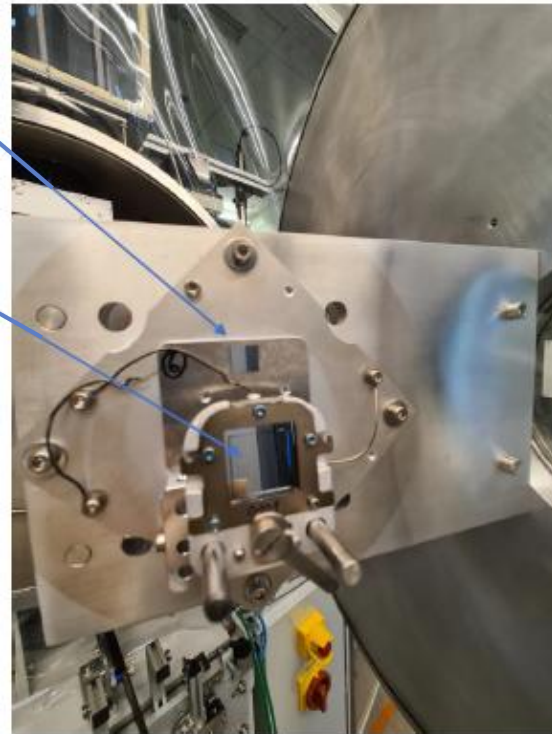
METHODS: IRRADIATION CHARACTERISTICS



Q. What is the experiment set-up?

Reality

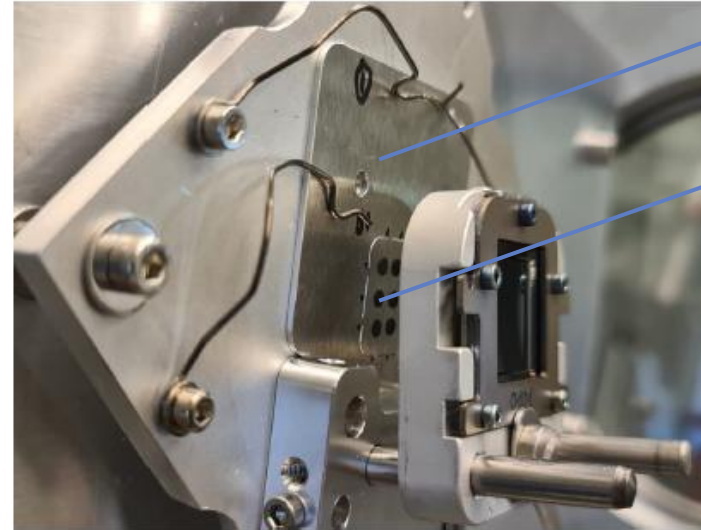
Silicon Implantation Experiment (SIMS)



[8]

Mi2-factory : All rights reserved

Sample Plate Assembled behind Filter on Beamline



[8]

Mi2-factory : All rights reserved



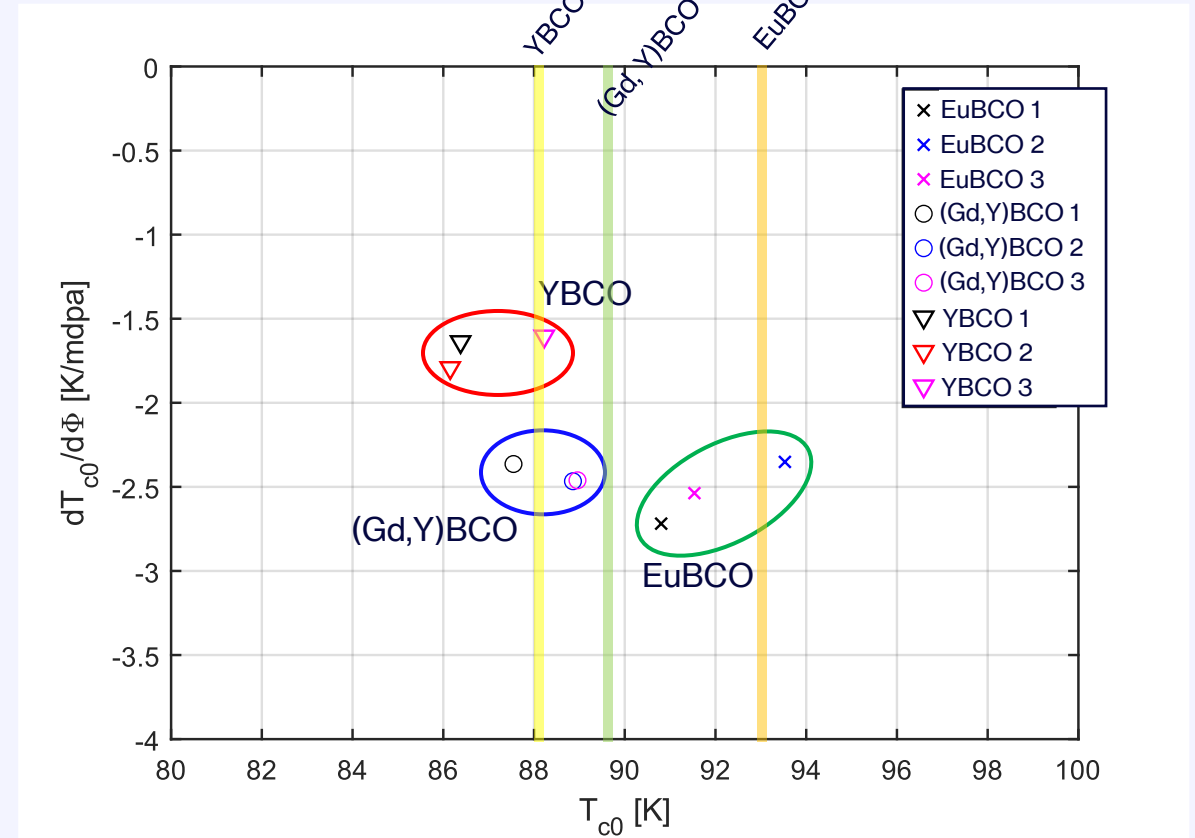
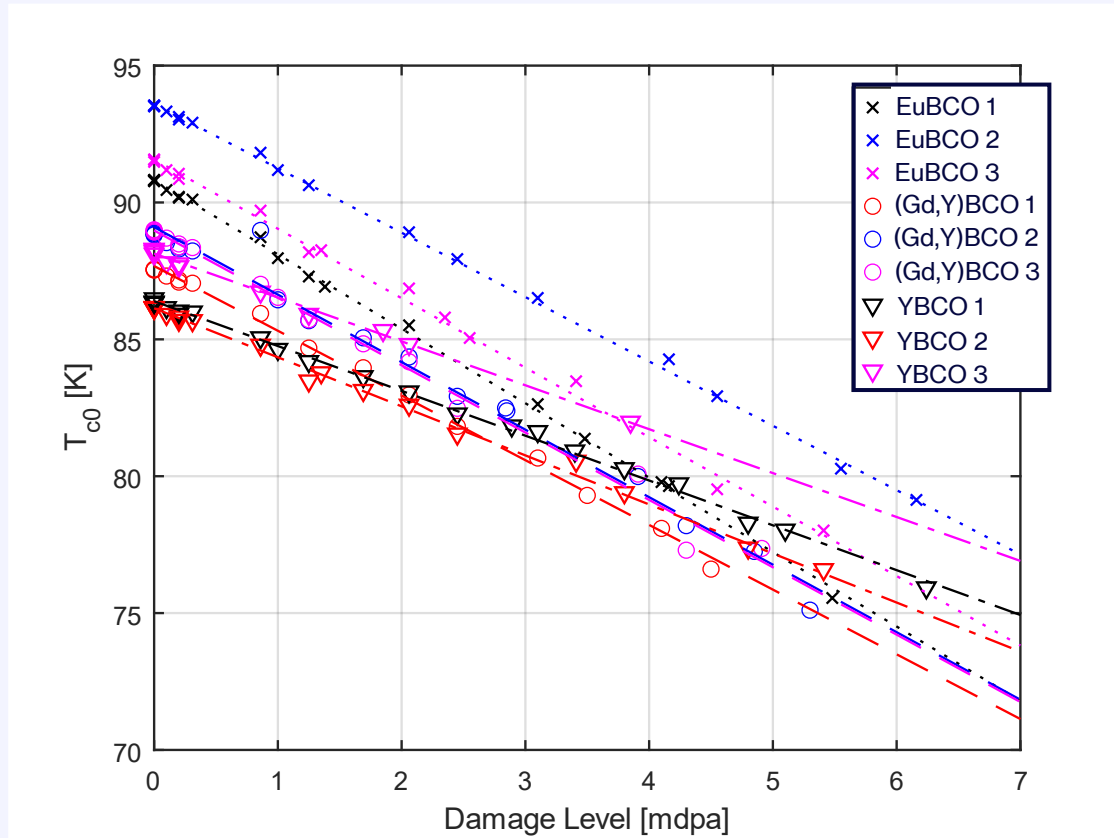
Aluminium sample plate
REBCO CC Disk Sample



RESULTS



Q. Effect on Critical Temperature at zero field



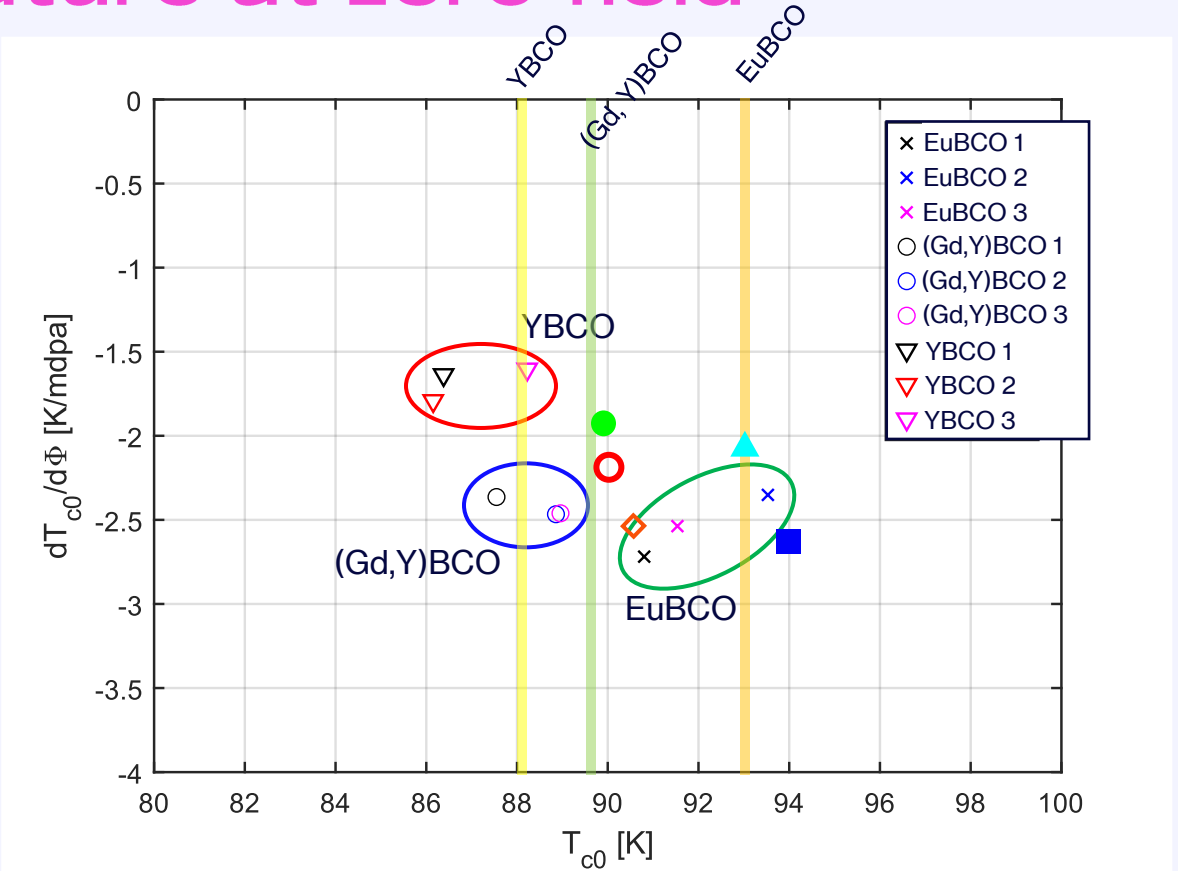
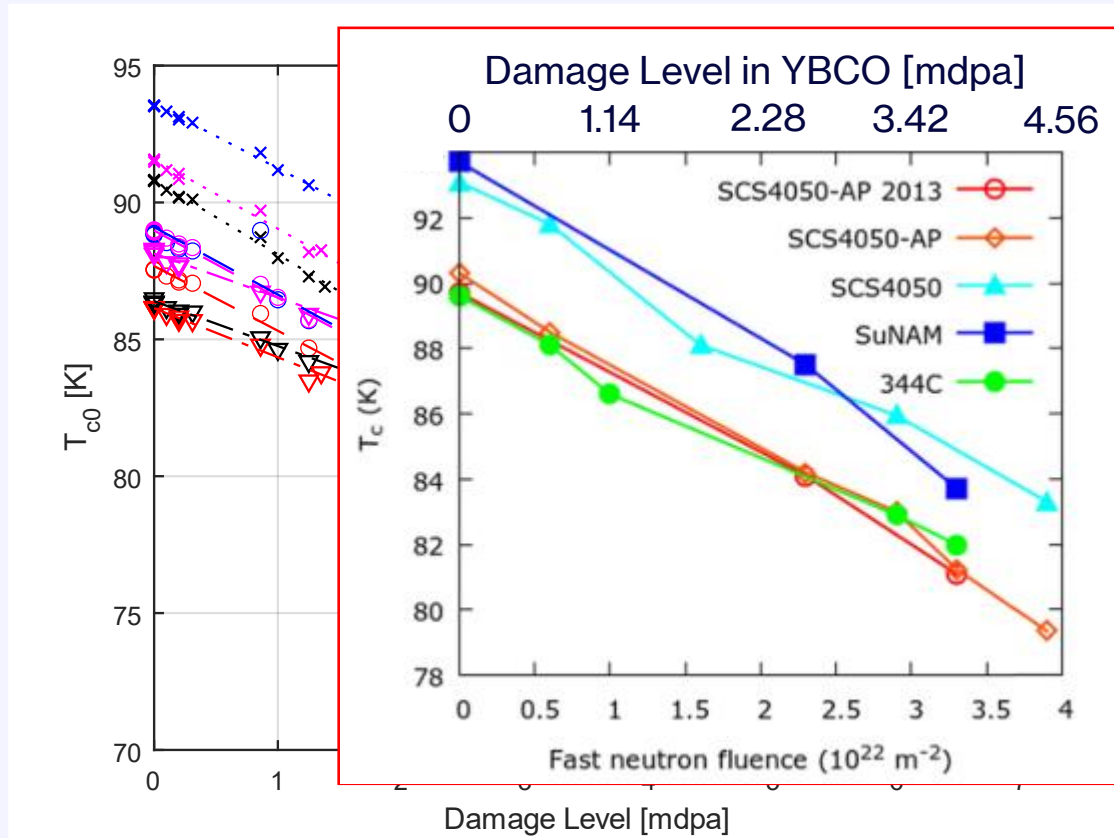
- CC with similar rare earths cluster together, regardless of manufacturer or whether the sample included artificial pinning centres (APCs).



RESULTS



Q. Effect on Critical Temperature at zero field



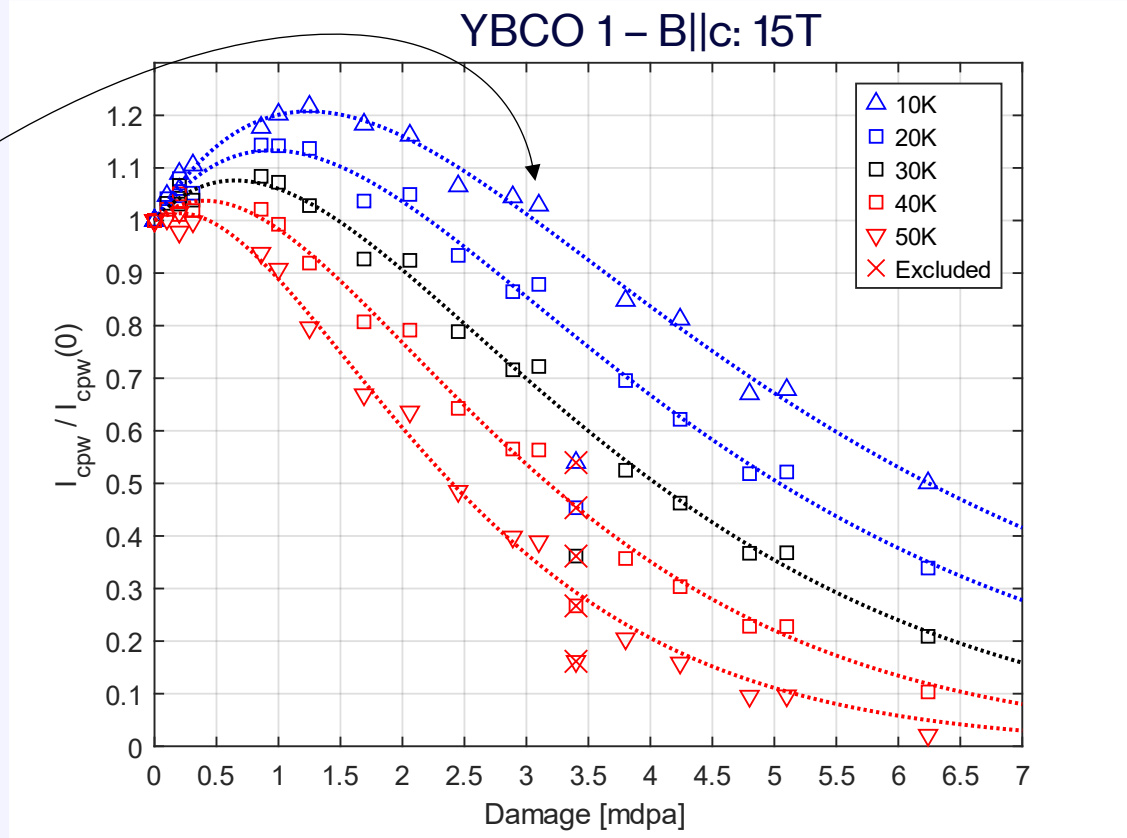
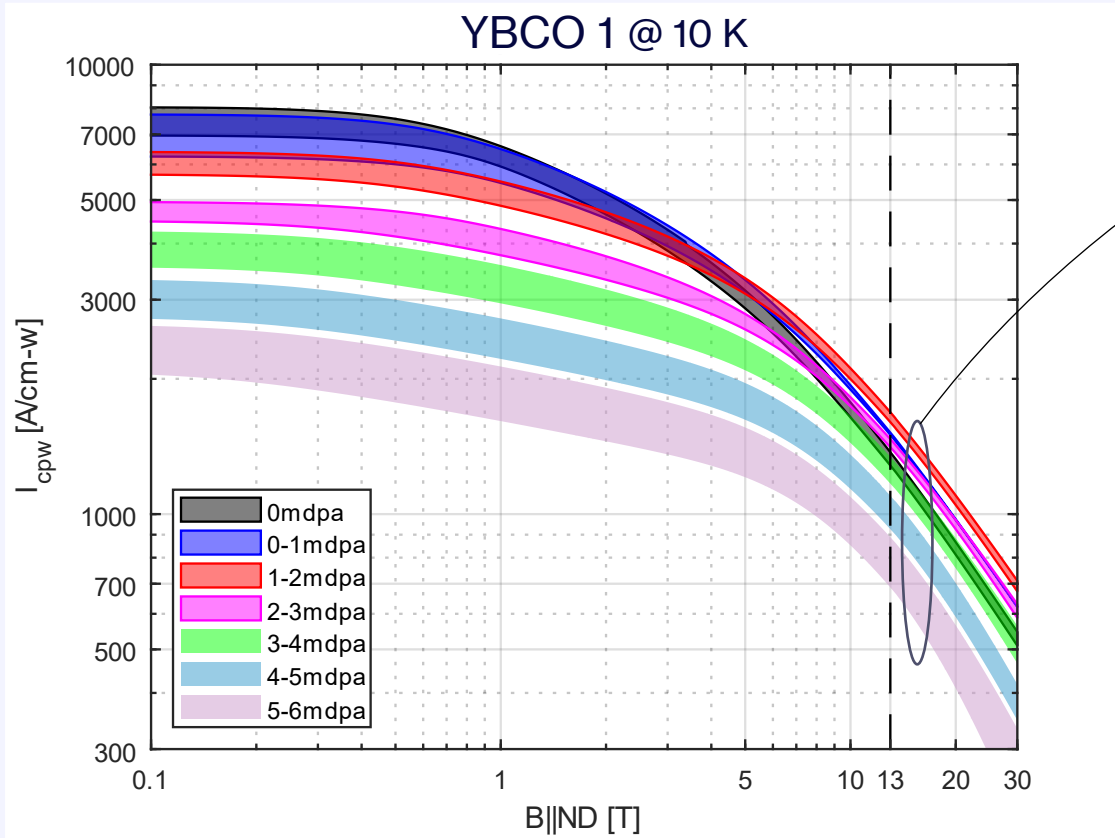
- CC with similar rare earths cluster together, regardless of manufacturer or whether the sample included artificial pinning centres (APCs).
- Comparison to results of neutron irradiation experiment shows results in similar damage rates though not T_c , perhaps due to different measurement methods.



RESULTS



Q. Effect on $I_{cpw}(B, T)$?



- Decreasing temperature \rightarrow better irradiation resistance.
- Trajectory of change in I_{cpw} fit well with combination of flux pinning enhancement (from [9]) and exponential decay, characteristic of a loss in superconducting volume.

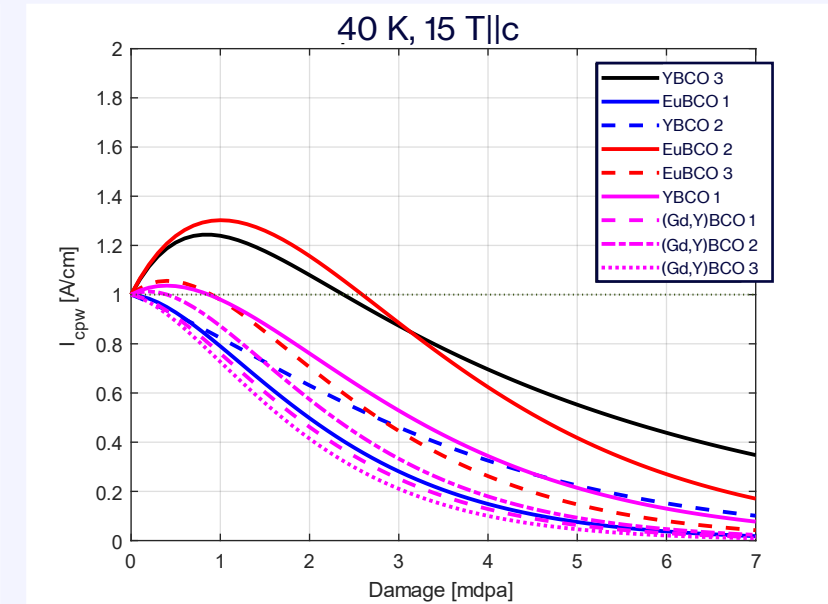
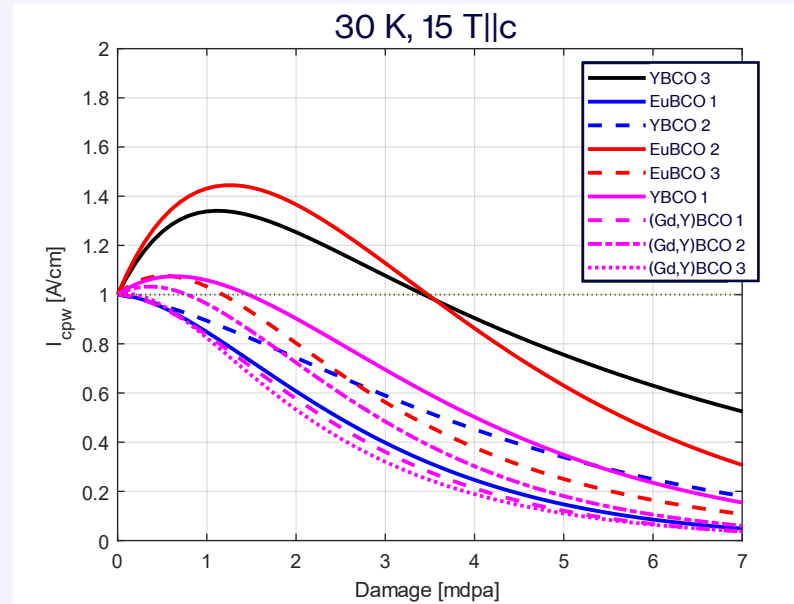
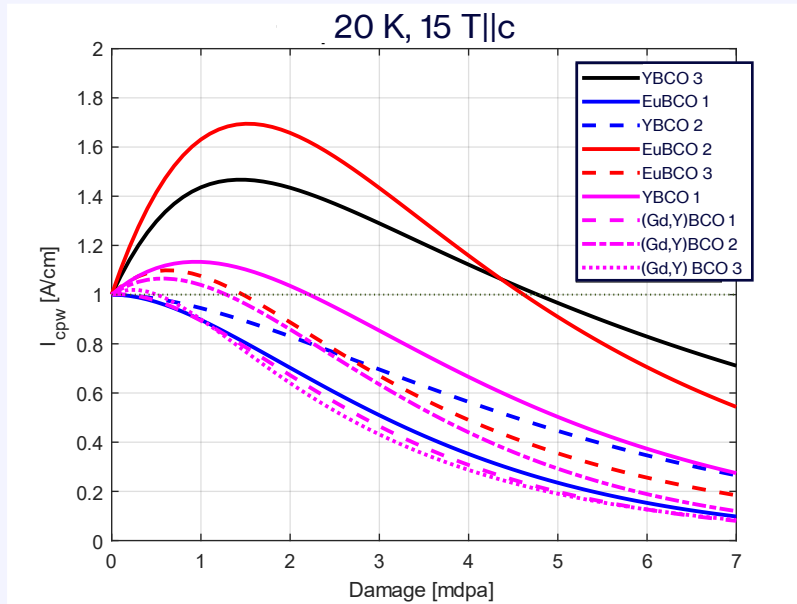
$$\frac{I_{cpw}}{I_{cpw}(0)} = \underbrace{D_{enh} \tanh\left(\frac{D+D_0}{D_n}\right)}_{\text{Pinning Efficiency}} \underbrace{\exp\{-\lambda D\}}_{\text{Superconducting Volume Loss}}$$



RESULTS



Q. Effects on $I_{cpw}(B, T)$ – Comparing Samples Types



Next, we compare the relative change in I_{cpw} between samples of different types.

As suggested by literature, sample types with **no artificial pinning** show **most improvement** in I_{cpw} upon irradiation.

Some samples show **zero improvement** in I_{cpw} with irradiation, suggesting **artificial pinning** has **over saturated** REBCO layer with defects.

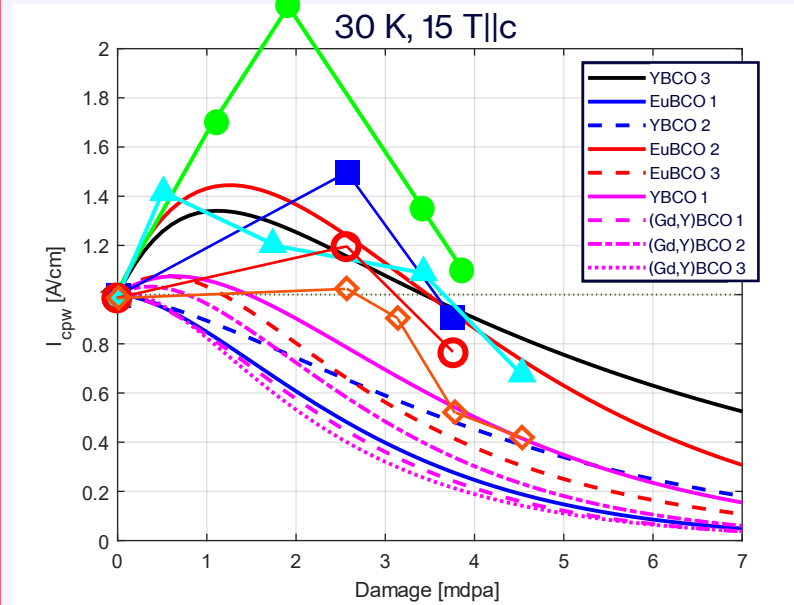
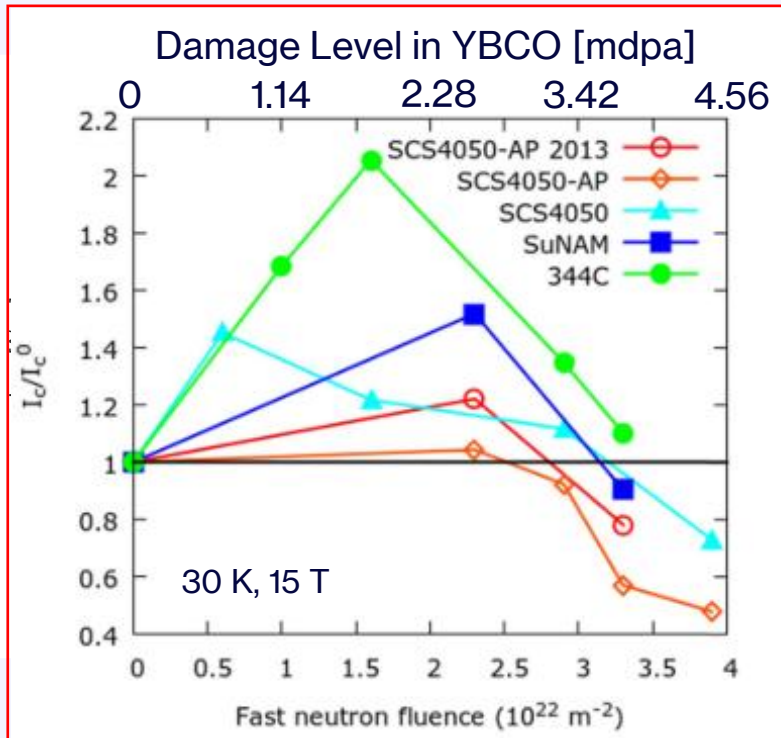
When comparing to neutron irradiation results, point where initial I_{cpw} reestablished for non-pinned samples is comparable.



RESULTS



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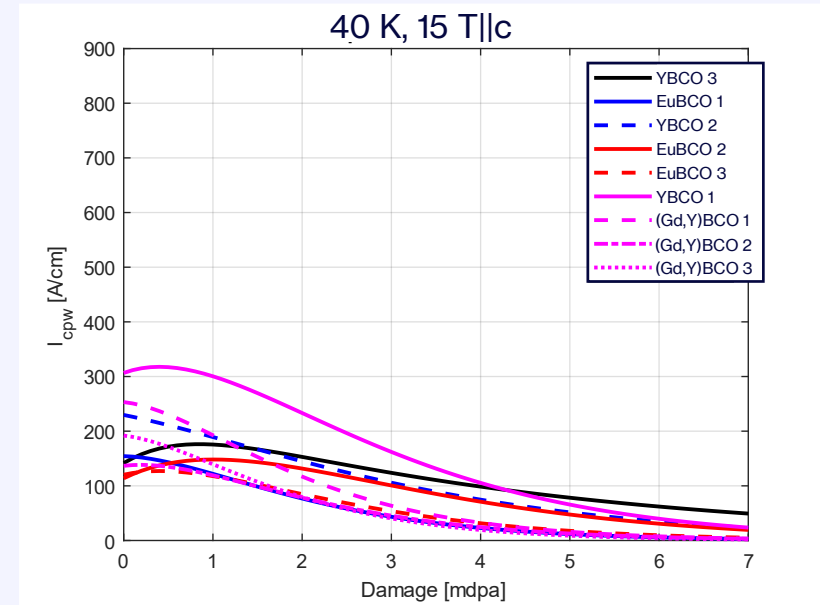
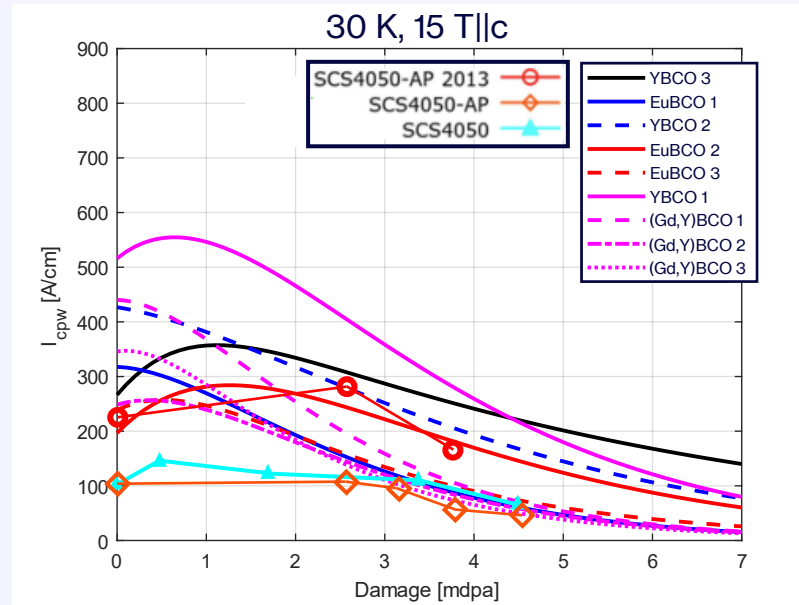
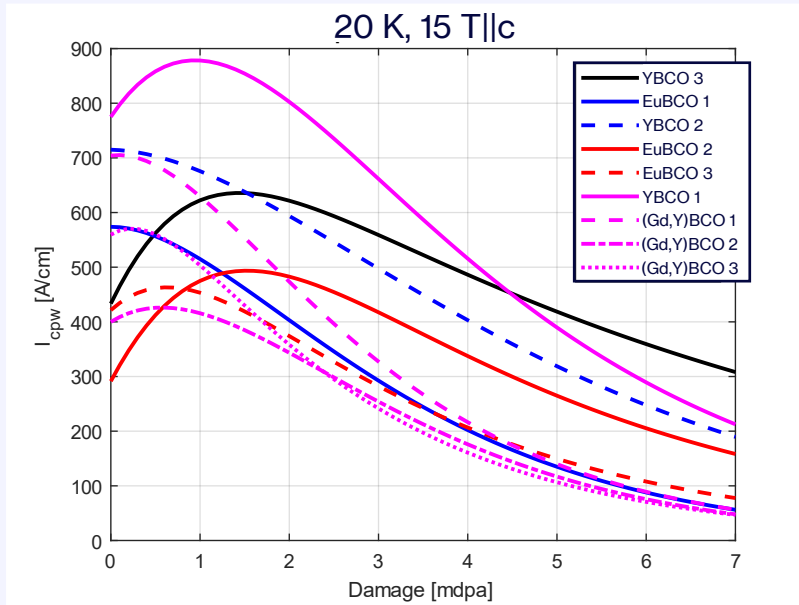
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RESULTS



Q. Effects on $I_{cpw}(B, T)$ – Comparing Samples Types



Relative changes are great... but, for fusion applications, absolute current carrying capacity is key...

Shown are the fits of high field I_{cpw} for all sample type, **scaled by sample averaged initial values.**

Results show that Temperature control, not only effects magnet performance, **but also effects magnet lifetime!**

Un-artificially pinned tapes have **slower exponential decay** than pinned tapes.

Many tapes **converge to similar critical current levels** at 3-4mdpa. Suggests pinning now dominated by defects created by irradiation.



SUMMARY & CONCLUSIONS



In this work:

- Introduced the STEP programme.
- Several commercially available coated conductors were oxygen ion irradiated through an energy filter in steps up to and beyond the damage level expected in STEP.
- The irradiation used an energy filter to more closely mimic irradiation with fusion spectrum neutrons.

Conclusions:

- Compared to using monoenergetic ions, using an **energy filter** results in:
 - More uniform volume homogeneity of irradiation damage and bombarding ion implantation.
 - 1/3 fluence needed to achieve same damage level.
 - Larger fraction of total collisions ion-to-target nuclei.
- Choice of **rare-earth in REBCO** affects both the starting critical temperature and the rate of its monotonic decline with damage level.
- $\frac{I_{cpw}(D)}{I_{cpw}(0)}$ trajectory affected by temperature, field strength and defect density in REBCO.
- That $\frac{I_{cpw}(D)}{I_{cpw}(0)}$ can be modelled as a combination of **changing pinning efficiency** and a **loss in superconducting volume**.
- Some CC over-saturated with defect, leading to no improvement in I_{cpw} upon irradiation.
- Un-artificially pinned samples show slower exponential decay in I_{cpw} after their pinning efficiency has saturated.
- Many tapes converge to similar I_{cpw} at 3 - 4mdpa, suggesting pinning now **dominated by defects created by irradiation**.



ACKNOWLEDGEMENTS



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