IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

STEP

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

William Iliffe[1]
Simon Chislett-McDonald[1*]
Kirk Adams[2]
James Tufnall[2]
Susannah Speller[2]
Chris Grovenor[2]
Stuart Wimbush[3]
Ezzat Nasr[3]

[1] United Kingdom Atomic Energy Authority (UKAEA), Abingdon, United Kingdom.
[2] Oxford University Material Department, Oxford, United Kingdom.
[3] United Kingdom Industrial Fusion Solutions Ltd (UKIFS), Abingdon, United Kingdom.
(* Now moved on)

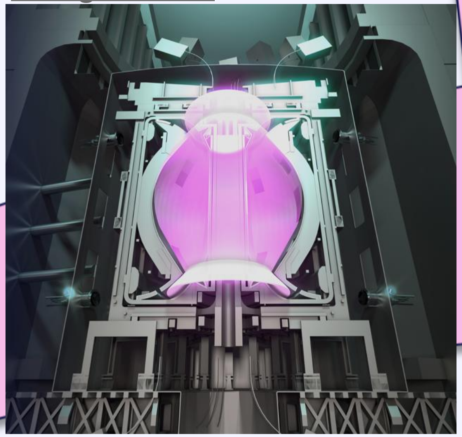
IREF25

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

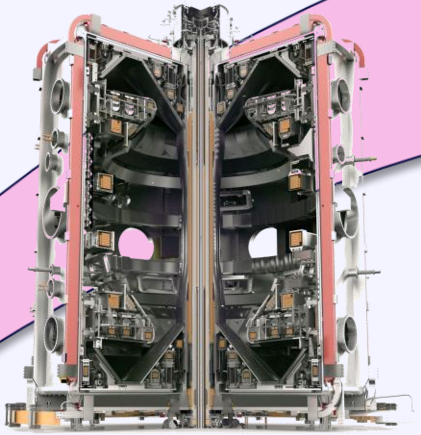
Design Phase



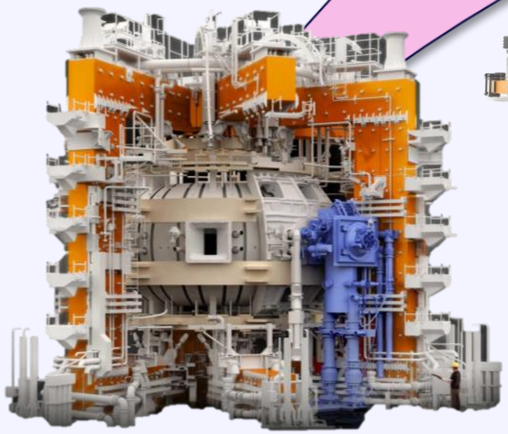
In Operation Goals:
1. To investigate novel exhaust concepts
2. To de-risk / advance the spherical tokamak design, as a future power plant
3. To extend physics knowledge in support of the broader fusion programme

Commercial Fusion

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



Spherical
Tokamak For
Energy
Productions



Joint
European
Torus

Mega
Amp
Spherical
Tokamak
-Upgrade

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

Gainsborough

West Burton

THE STEP TOKAMAK

STEP Special Issue

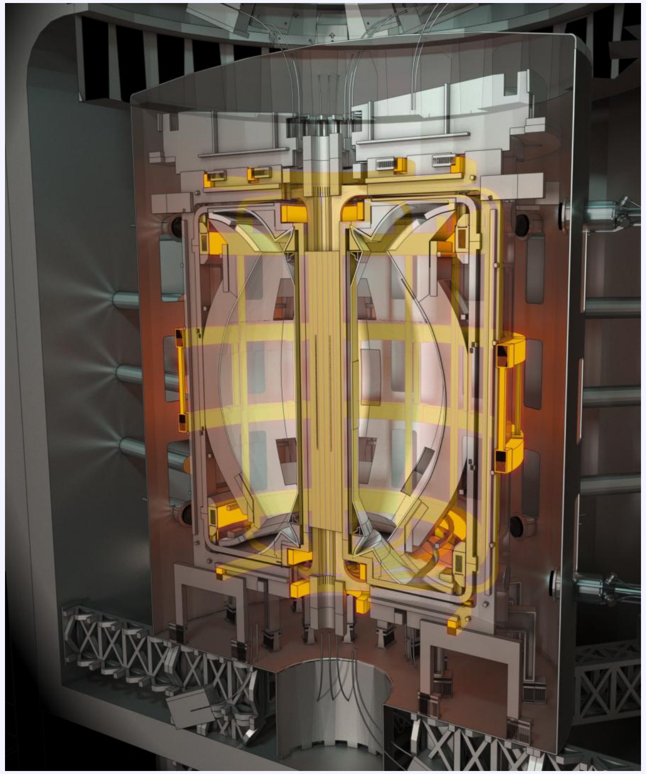
Q. What is the current STEP design?

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 x10^{20} n/s

Maintenance Strategy	Vertical with **Remountable** TF Coils



Hagues et al. "An Overview of STEP Nuclear Analysis" 16th Fusion Neutronics Meeting, April 2025

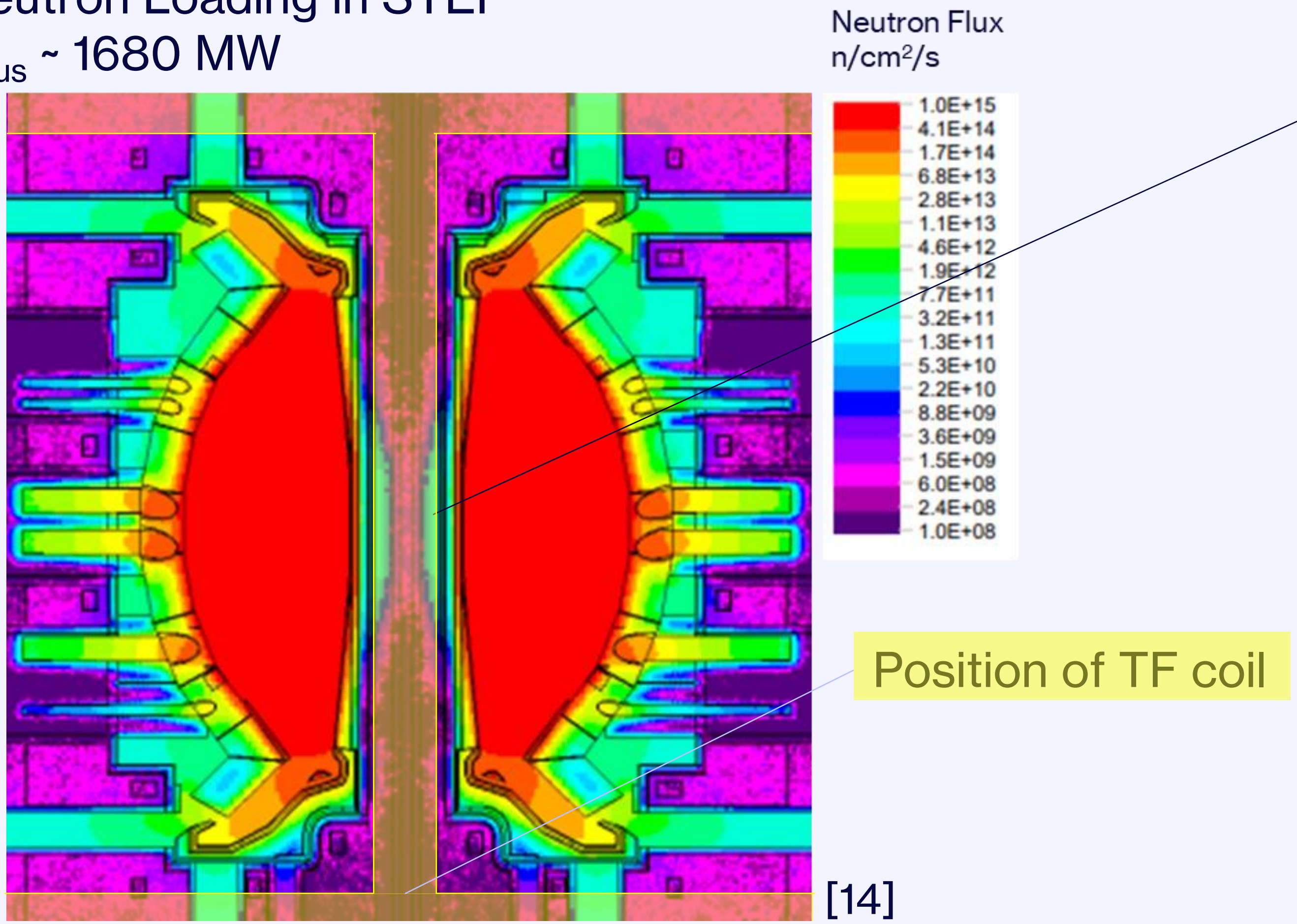
IREF25

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

THE STEP TOKAMAK

Q. What level of irradiation do we expect?

Neutron Loading in STEP
P_{fus} ~ 1680 MW



[14]

- Inboard region of the TF coils sees ~ 2×10^{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/cm^2 - 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.*

Hagues et al. "An Overview of STEP Nuclear Analysis" 16th Fusion Neutronics Meeting, April 2025

THE STEP TOKAMAK

Open questions about TF lifetime

DT Fusion Power	1.68 GW
DT Neutron source rate	~ 6 x10^{20} n/s
Plasma First Wall Flux	>10^{15} n/cm^2/s
Peak Neutron flux to REBCO in TF	2x10^{11} n/cm^2/s
Peak Fast Neutron flux to REBCO in TF	8x10^{10} n/cm^2/s
Useful Life of TF Centre-rod	1.18 FPY
Peak Fluence to REBCO at end of useful life	3x10^{18} n/cm^2

Paper: STEP's understanding of REBCO in irradiation environment

- Is this lifetime sufficient for STEP is achieve its goals?
  Yes but…
- Are we sure? How sure are we?
  - Need more data on more tapes!
- Data implies how tape is made effects 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

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

The Filter Oxygen Ion Irradiation

GOALS

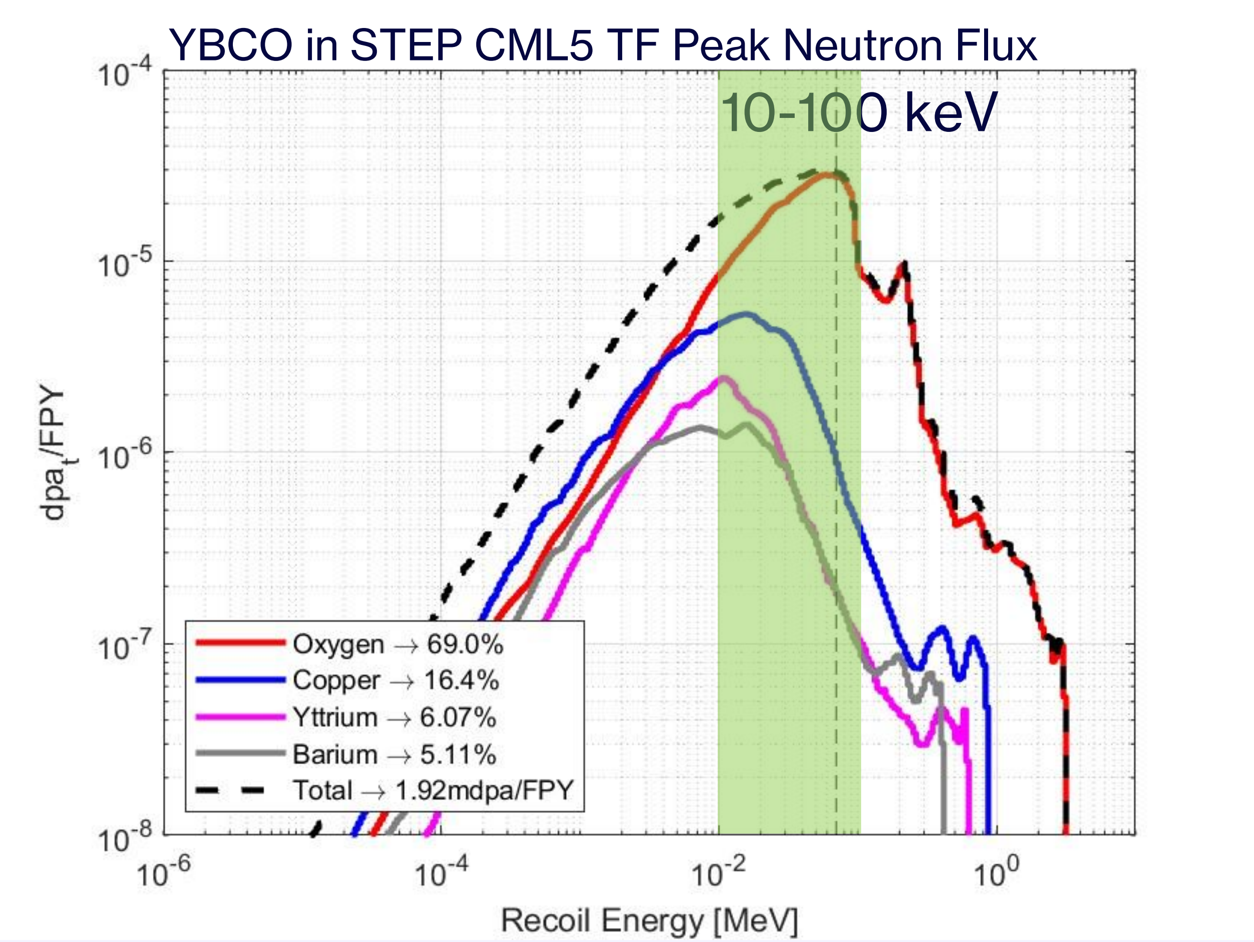
Survey response to irradiation of many types of REBCO coated conductor

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

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

EMULATING NEUTRON IRRADIATION WITH FAST IONS

Simulating Neutron Damage in YBCO — SPECTRA-PKA



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

M.R. Gilbert, J.-Ch. Sublet 2018 doi: 10.1016/j.jnucmat.2018.03.032

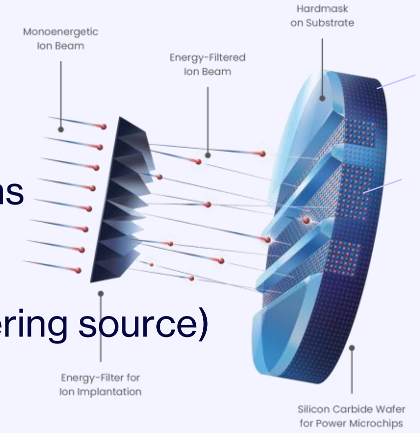
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

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"

N or Al ions



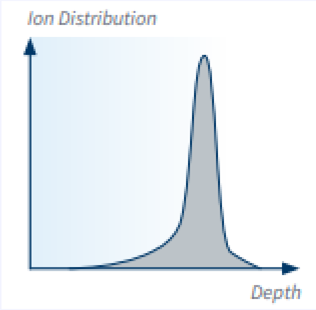
(rastering source)

SiC Wafer

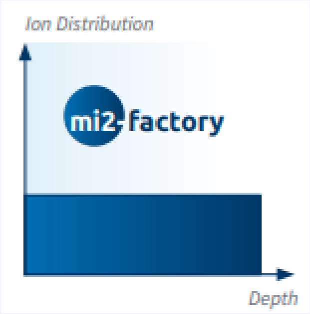
Doped SiC Wafer

High Power IGBT with improved breakdown voltage

[15]



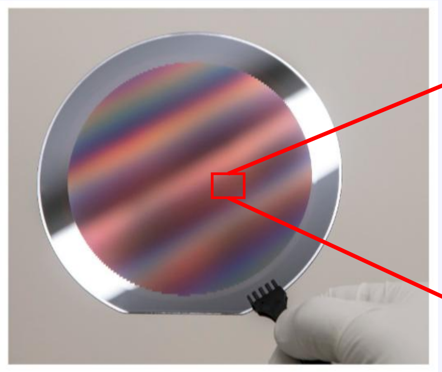
Without Filter

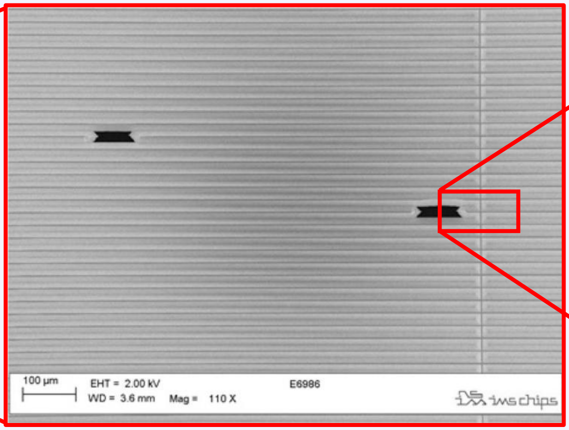


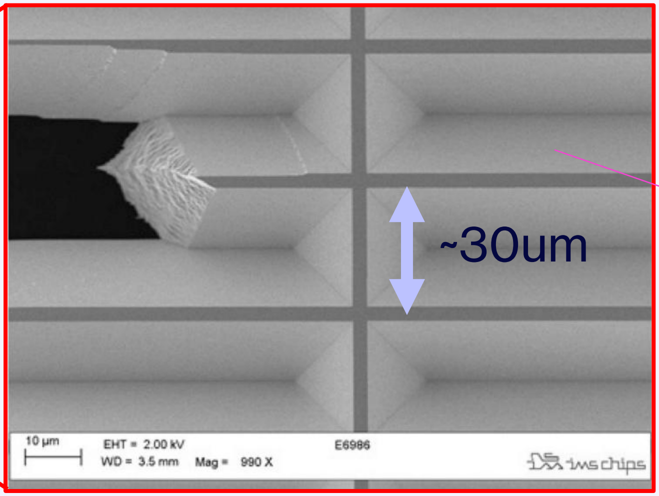
With Filter

[15]

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







t: ~16um

t: ~1.5um

Linear Slope

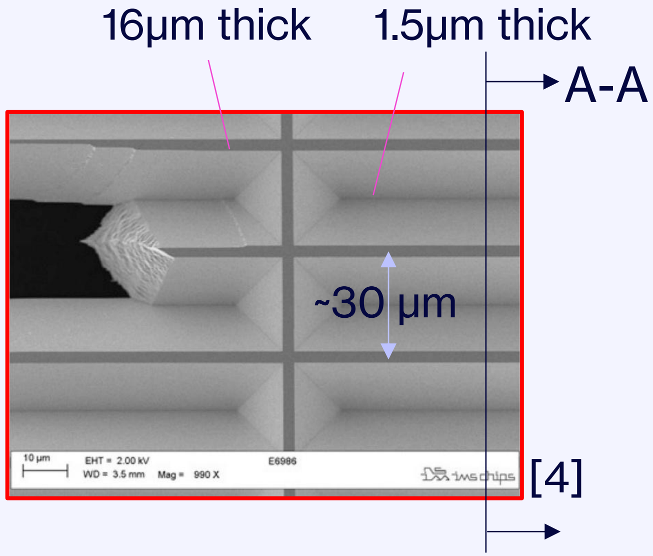
[4]

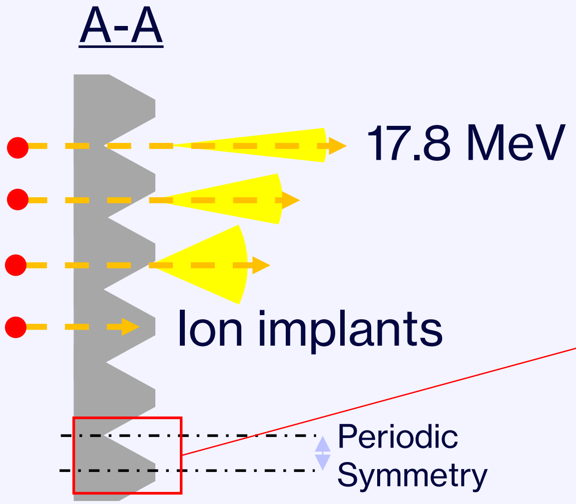
Steinbach et al. doi: 10.1016/j.mee.2019.111203

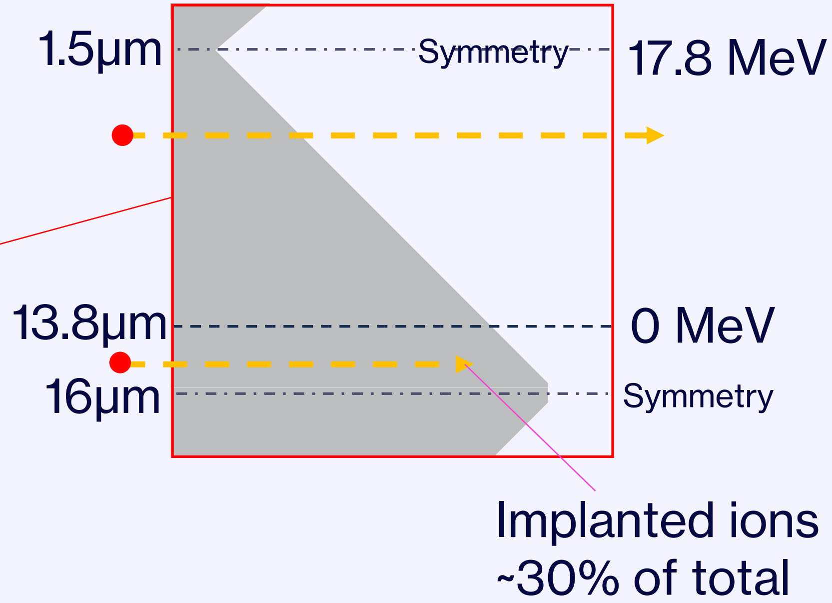
FAST ION ENERGY FILTER

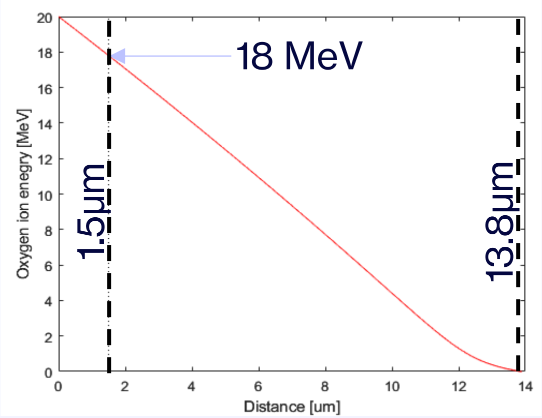
Q. But what about the damage profile?

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







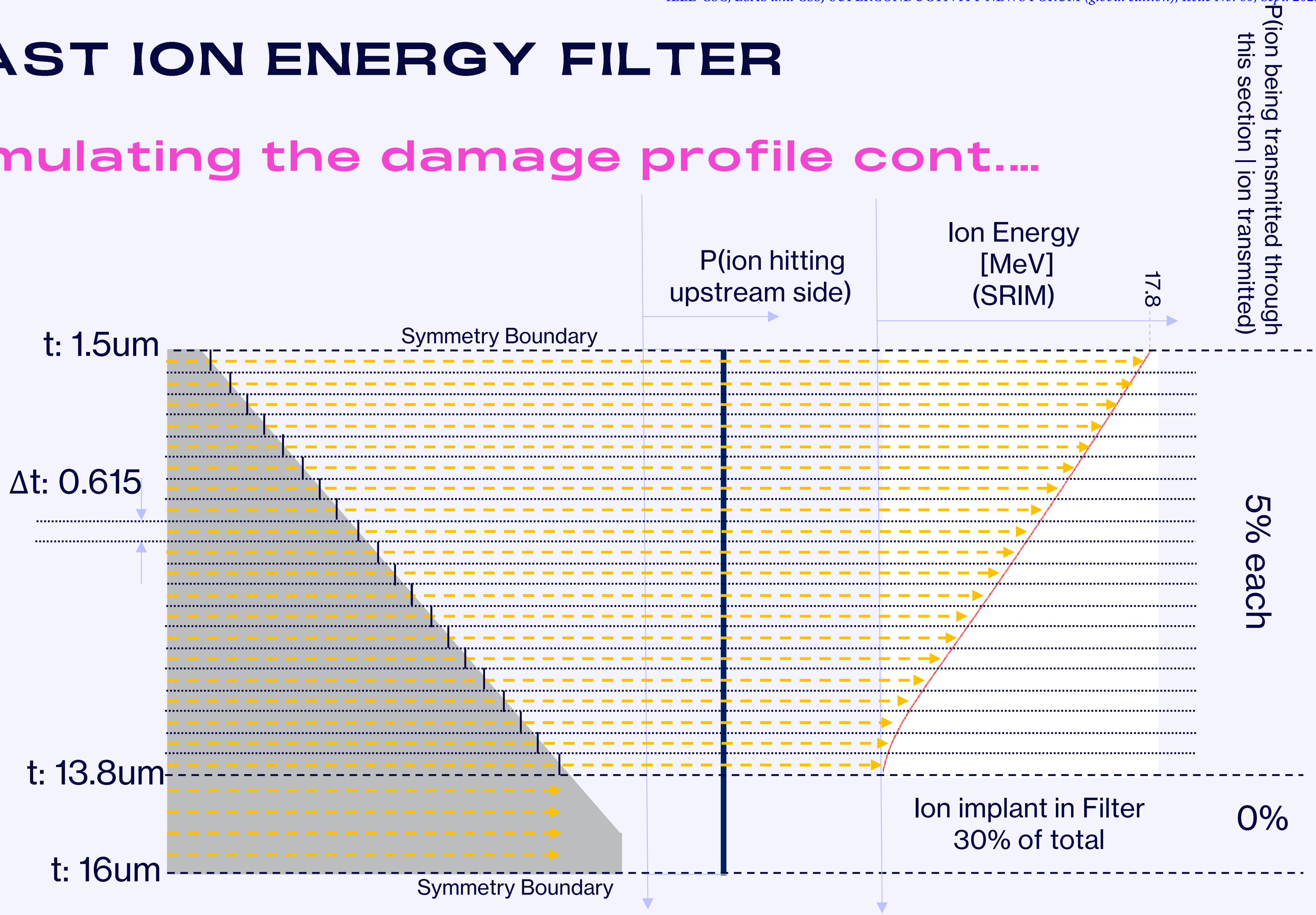


Filter Provided by mi2-factory

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

FAST ION ENERGY FILTER

Simulating the damage profile cont....

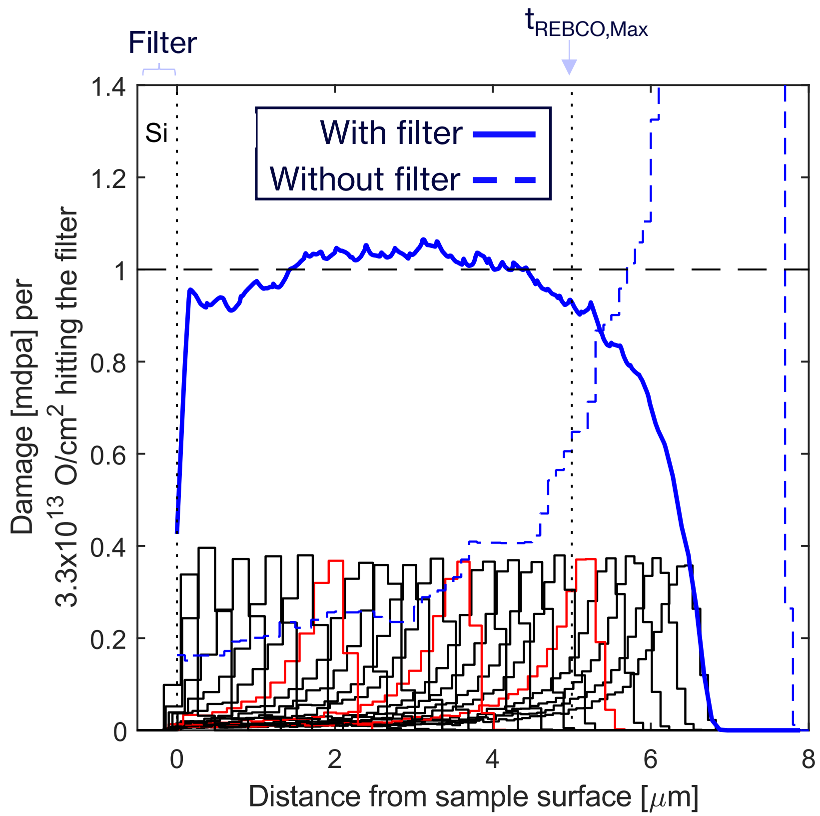


IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

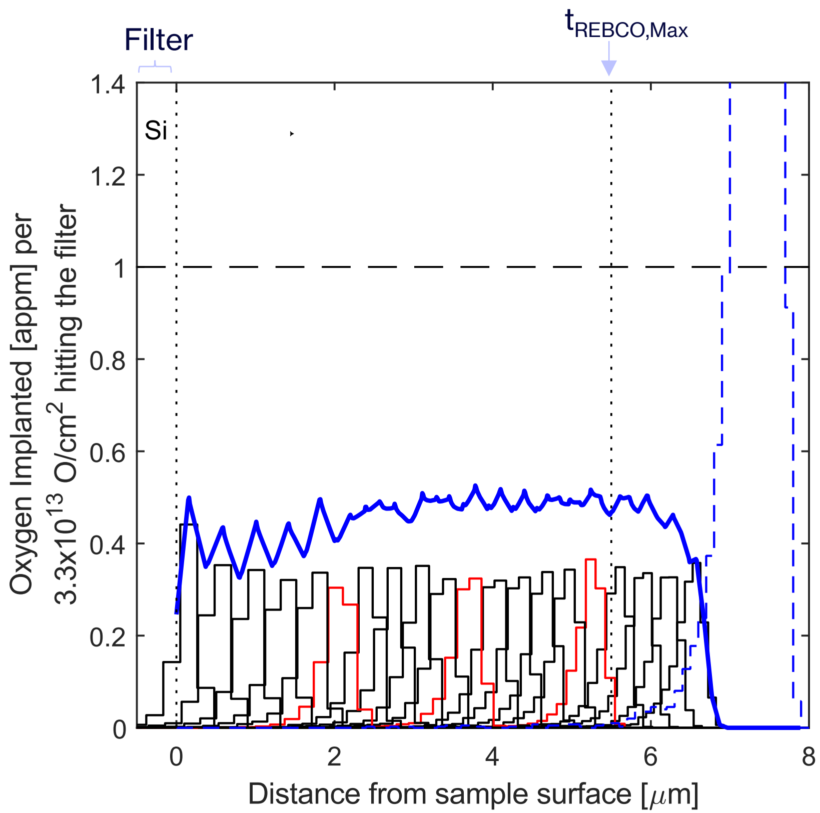
Iliffe et al. doi: 10.1109/TASC.2024.3523248 (ASC)
Iliffe et al. doi: 10.1109/TPS.2024.3432992 (SOFE)

FAST ION ENERGY FILTER

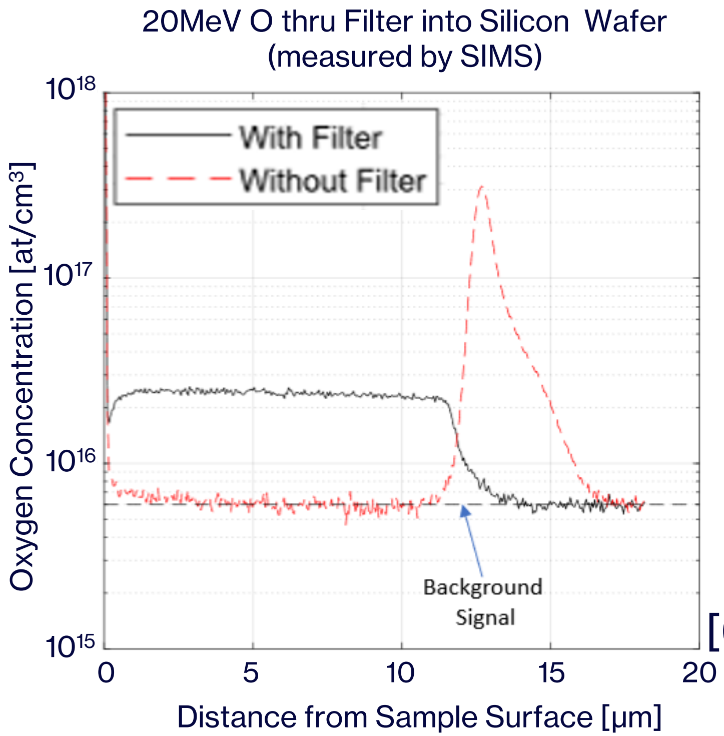
Resulting Damage profile for 20MeV O through a filter



[5]



[5]



[6]

∴ 3.3x10^{13} O/cm^2 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_c)

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

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

METHODS: IRRADIATION CHARACTERISTICS

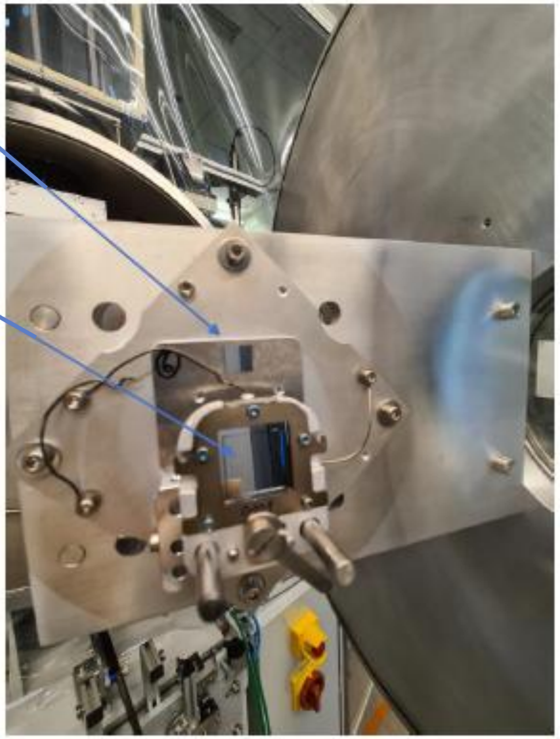
Q. What is the experiment set-up?

Reality

Silicon Implantation Experiment (SIMS)

Silicon Wafer subject to unfiltered beam

Energy Filter

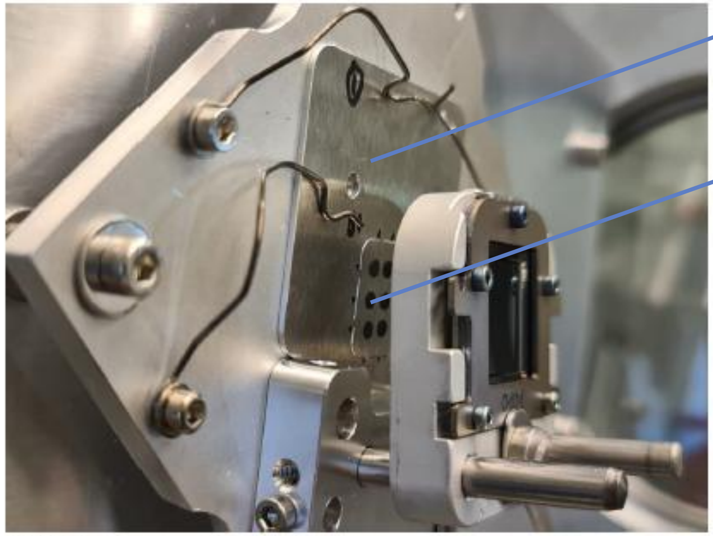


 [8]

Sample Plate Assembled behind Filter on Beamline

Aluminium sample plate

REBCO CC Disk Sample

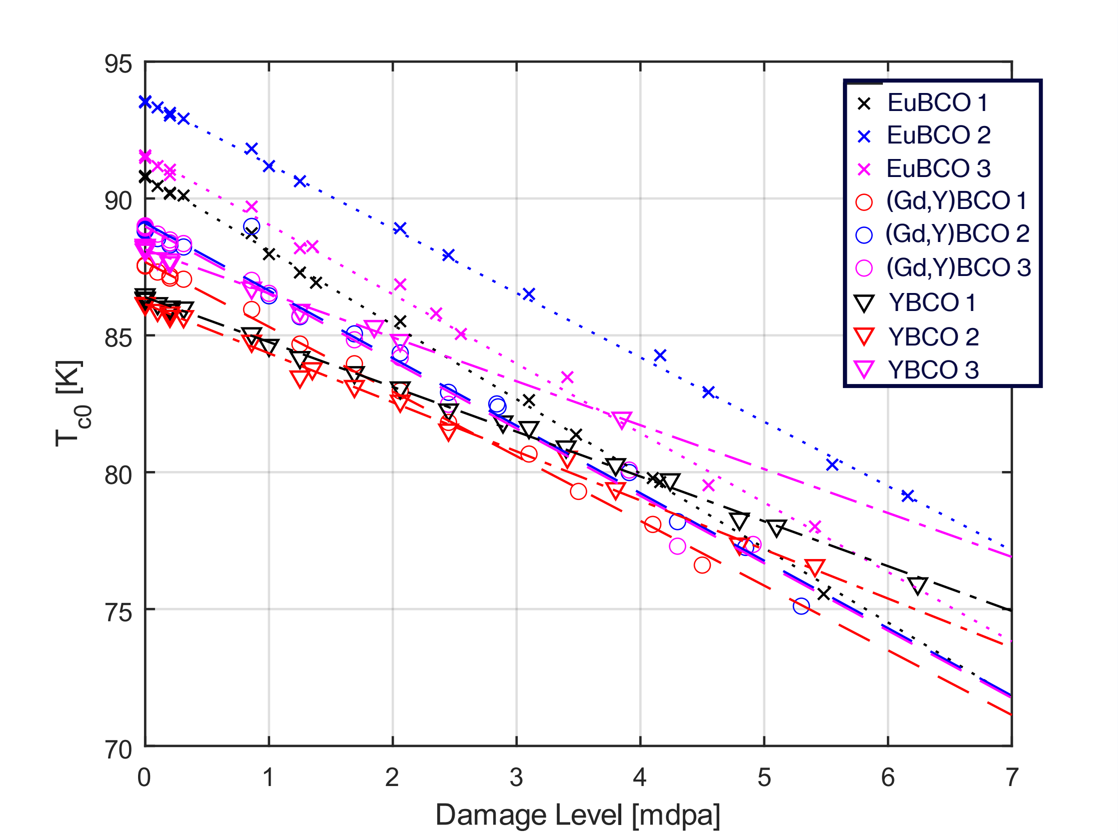


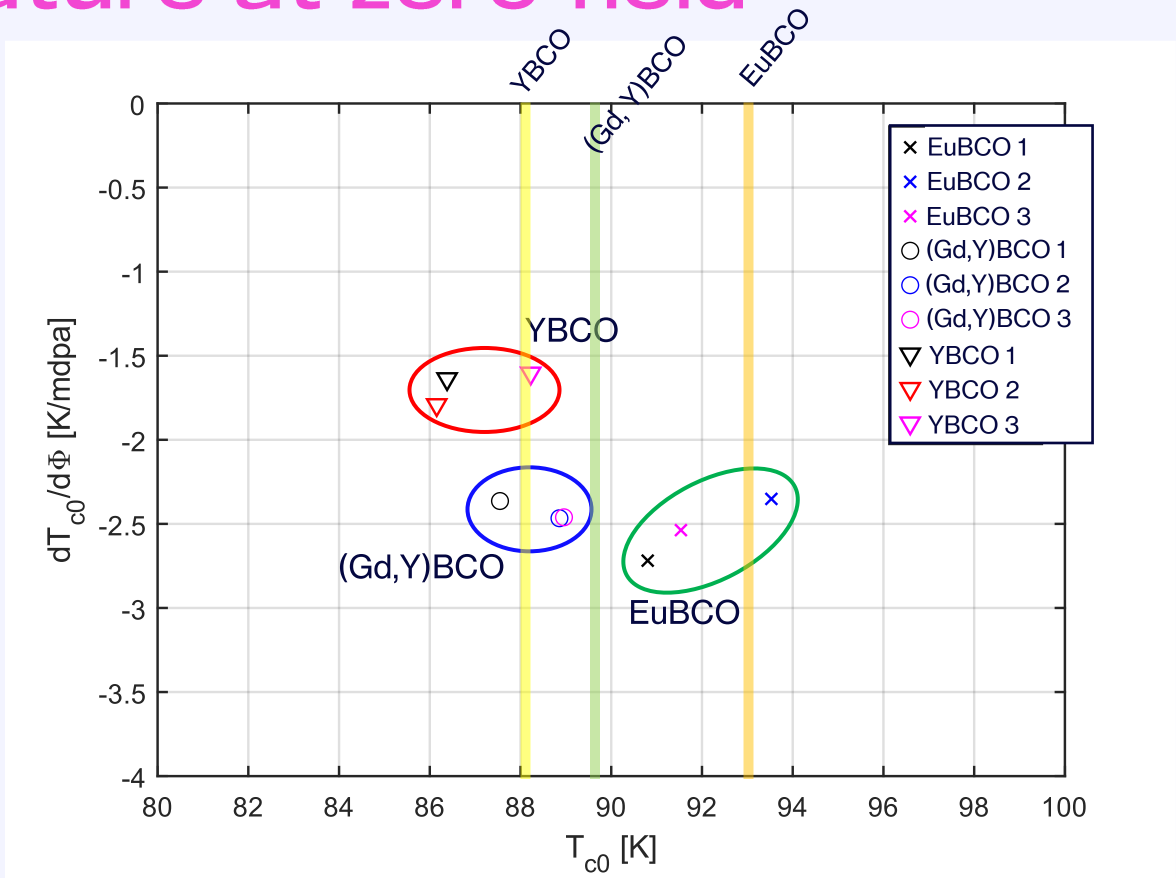
 [8]

Iliffe et al. Superconductivity News Forum **18,** Issue 55 (SNF Issue No. 55, January 2024 | SNF)

RESULTS

Q. Effect on Critical Temperature at zero field





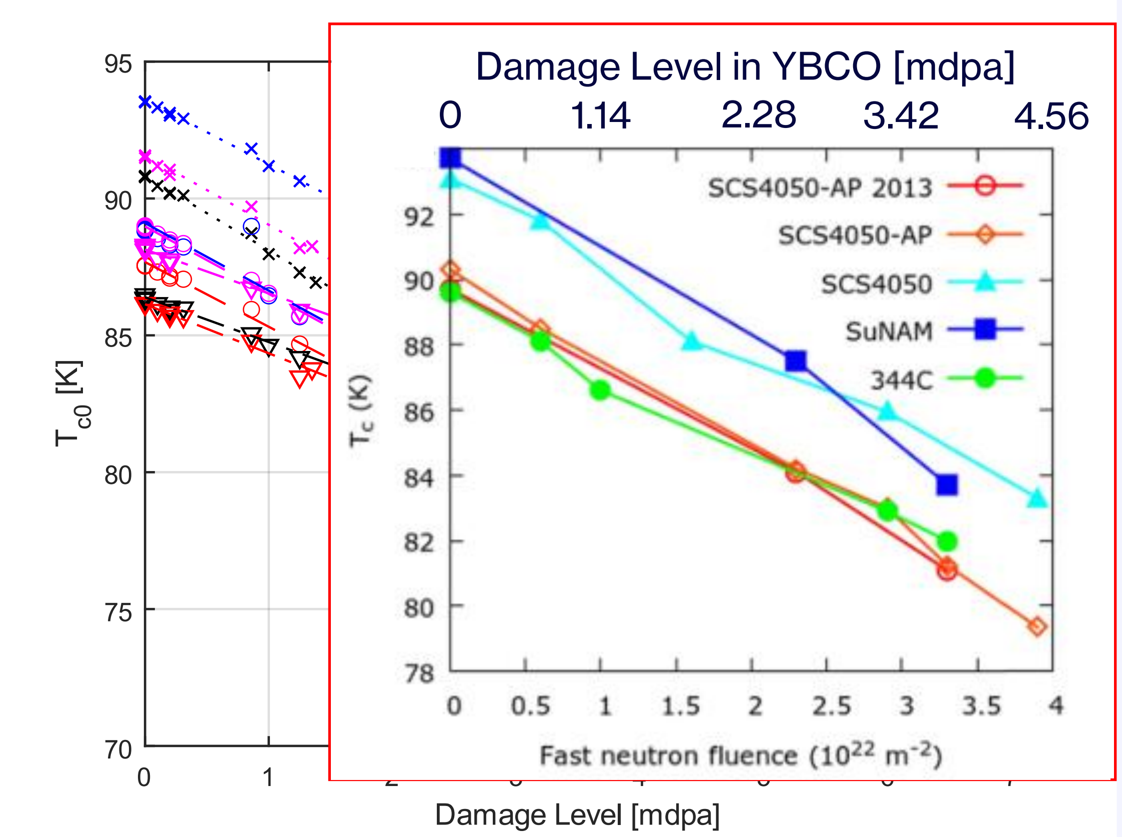
- CC with similar rare earths cluster together, regardless of manufacturer or whether the sample included artificial pinning centres (APCs).

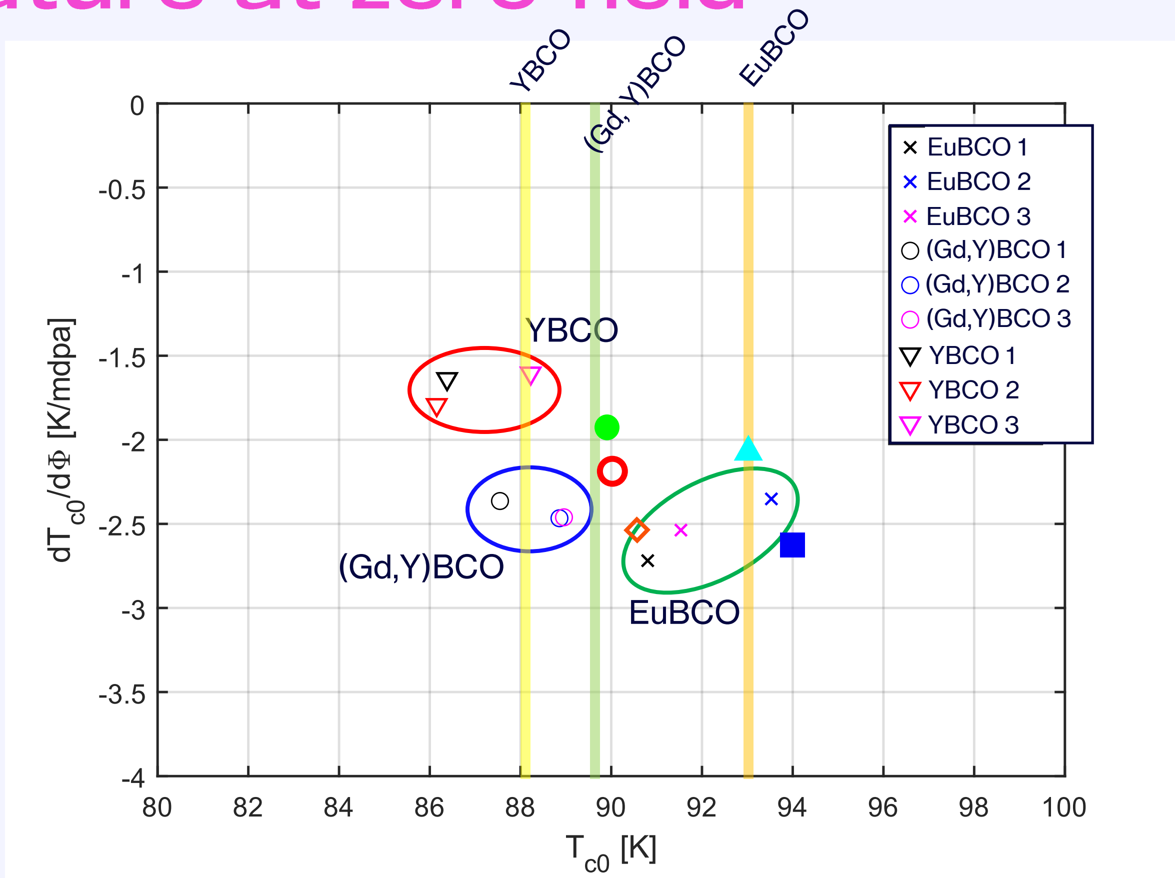
Iliffe thesis, Oxford University 2021; Fischer et al. 2018 doi: 10.1088/1361-6668/aaadf2 ; Lin et al. 1995 doi: 10.1103/PhysRevB.51.12900

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

RESULTS

Q. Effect on Critical Temperature at zero field





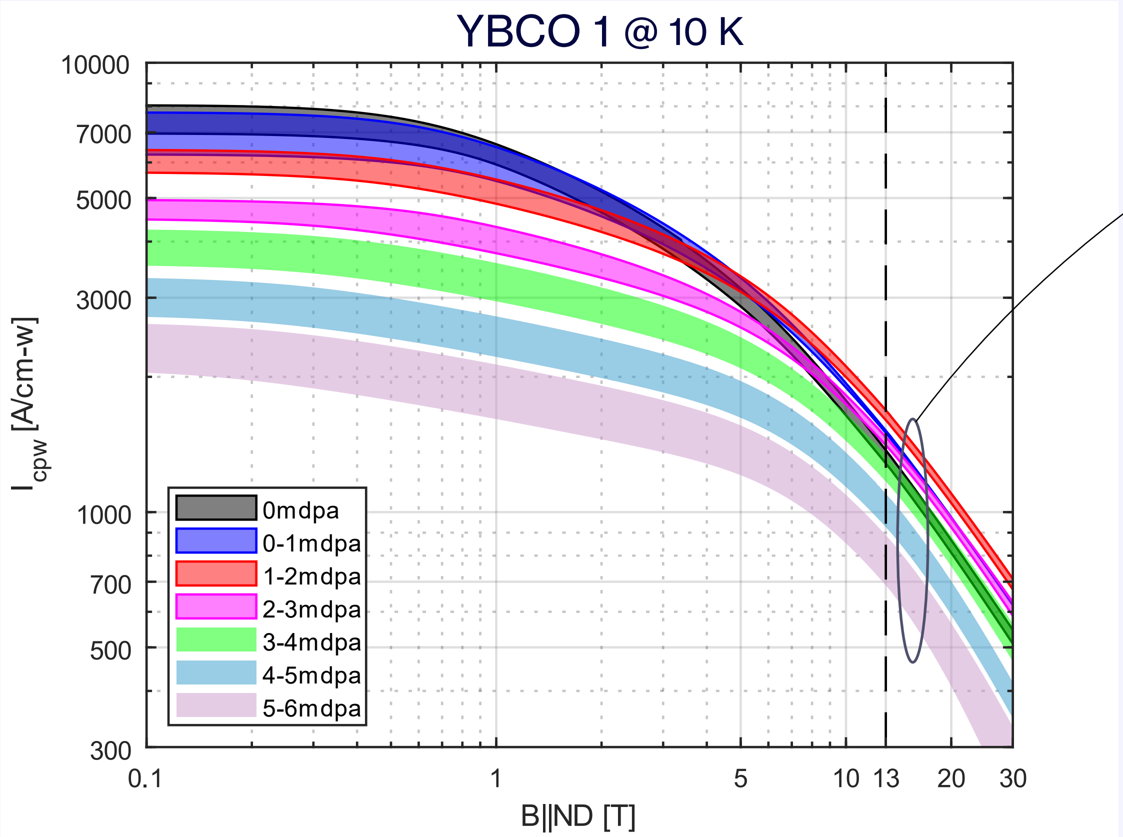
- CC with similar rare earths cluster together, regardless of manufacturer or whether the sample included artificial pinning centres (APCs).
- Comparison to results of neutron irradiation experiment shows results in similar damage rates though not T_c, perhaps due to different measurement methods.

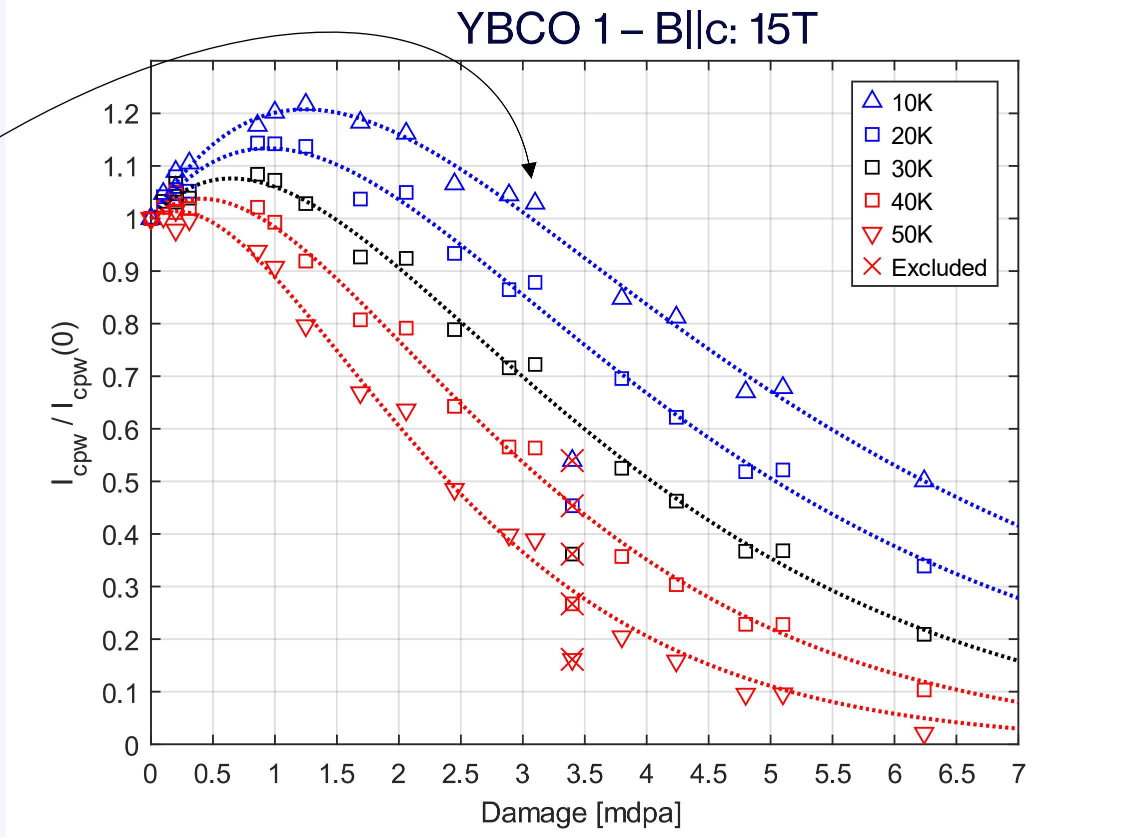
Iliffe thesis, Oxford University 2021; Fischer et al. 2018 doi: 10.1088/1361-6668/aaadf2 ; Lin et al. 1995 doi: 10.1103/PhysRevB.51.12900

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

RESULTS

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





- Decreasing temperature ➔ 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.

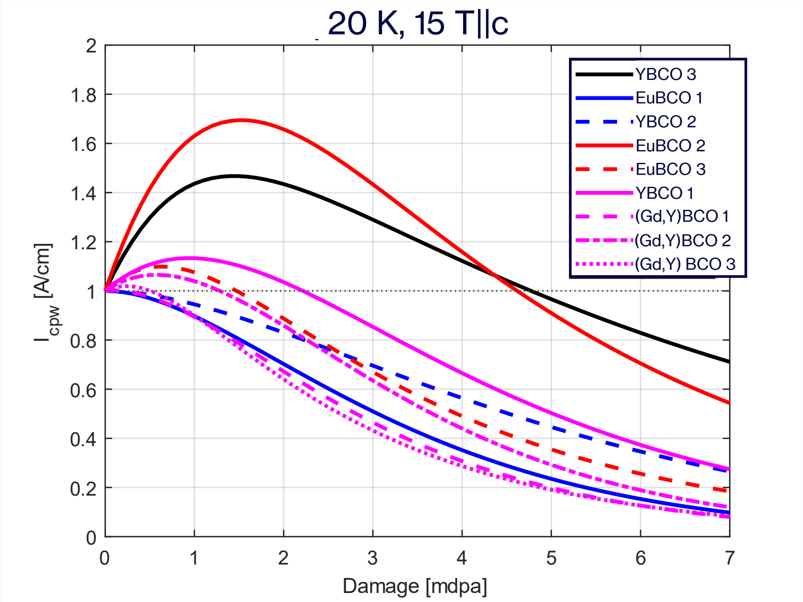
$$\frac{I_{cpw}}{I_{cpw}(0)} = \underbrace{D_{enh} \tanh\left(\frac{D+D_0}{D_n}\right)}_{\text{Pinning Efficiency}} \underbrace{\exp\{-\lambda D\}}_{\text{Superconducting Volume Loss}}$$

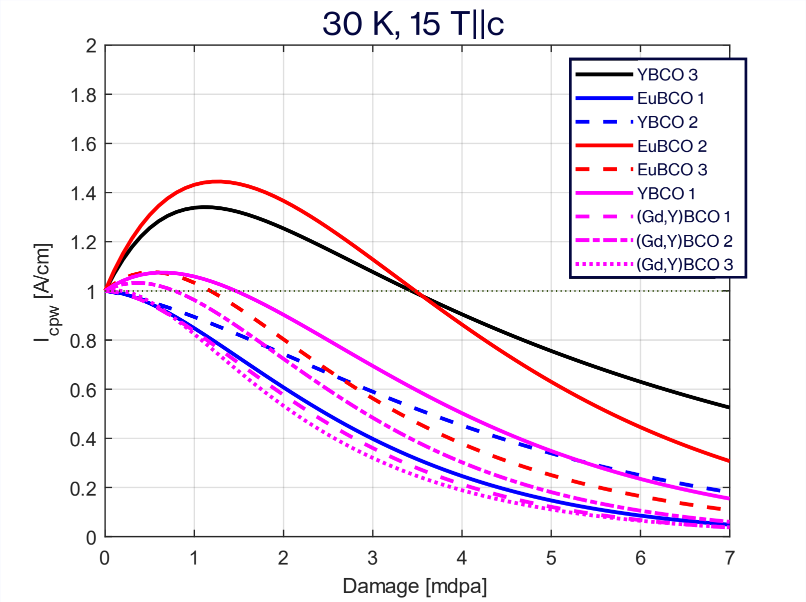
Eisterer, Bodenseher, Unterrainer. doi: 10.48550/arXiv.2409.01376

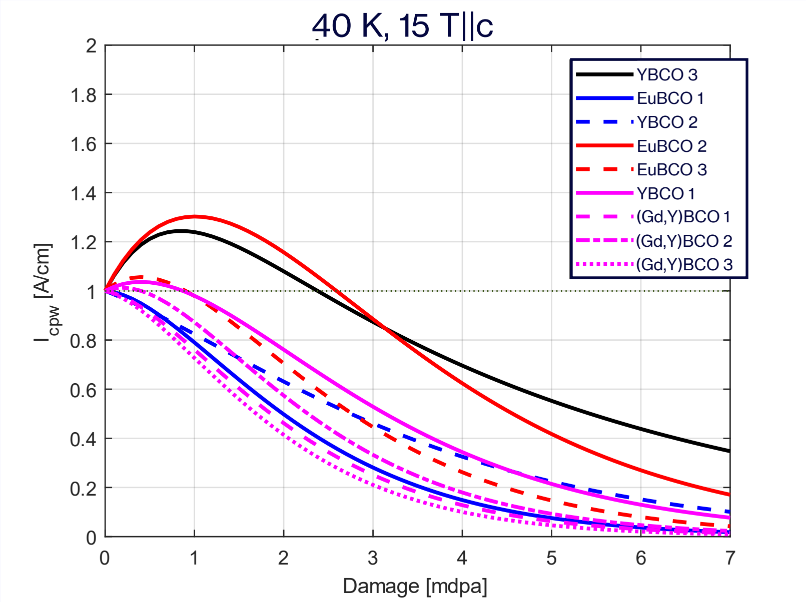
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

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.

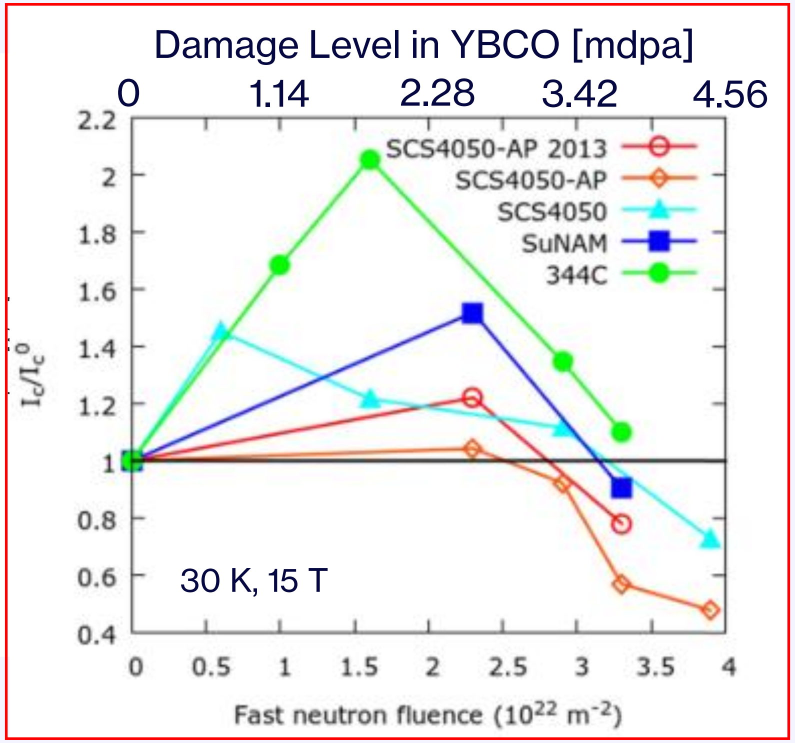
Some samples show **zero improvement** in I_{cpw} with irradiation, suggesting **artificial pinning** has **over saturated** REBCO layer with defects.

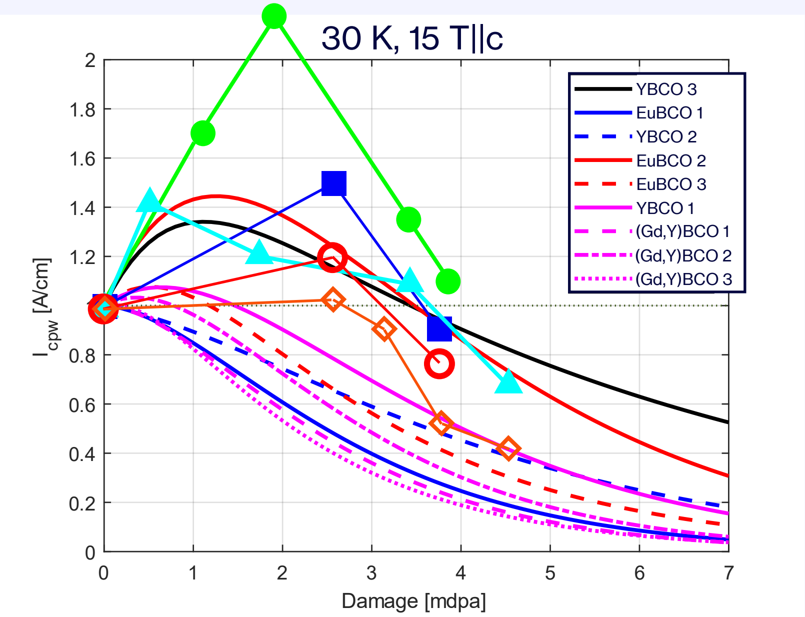
When comparing to neutron irradiation results, point where initial I_{cpw} reestablished for non-pinned samples is comparable.

Fischer et al. 2018 doi: 10.1088/1361-6668/aaadf2

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.

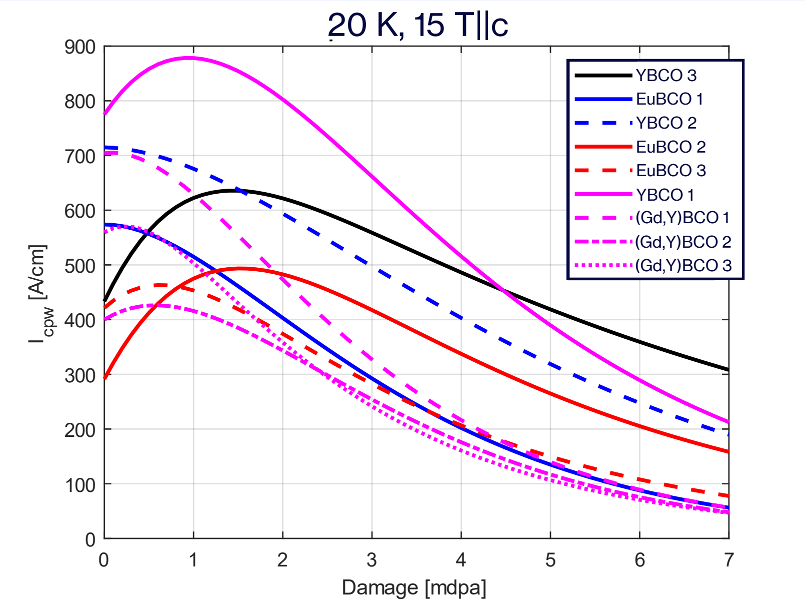
When comparing to neutron irradiation results, point where initial I_{cpw} reestablished for non-pinned samples is comparable.

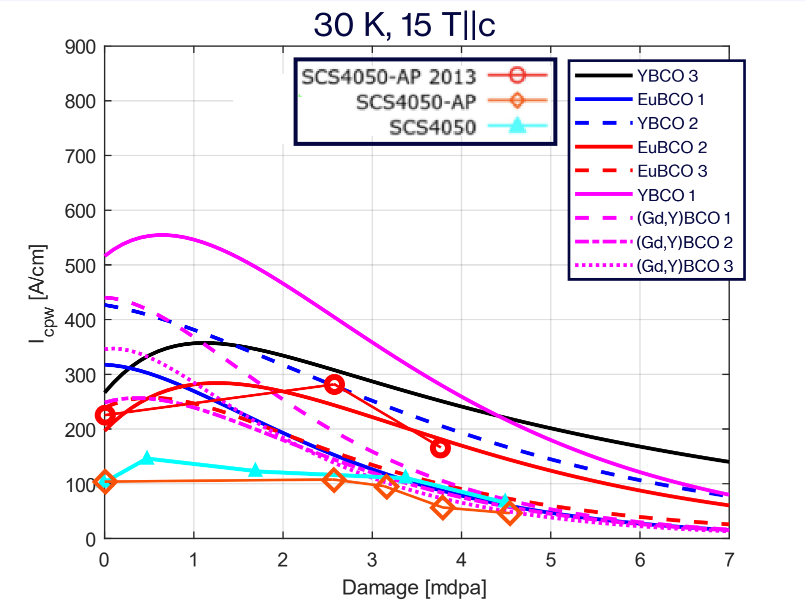
Fischer et al. 2018 doi: 10.1088/1361-6668/aaadf2

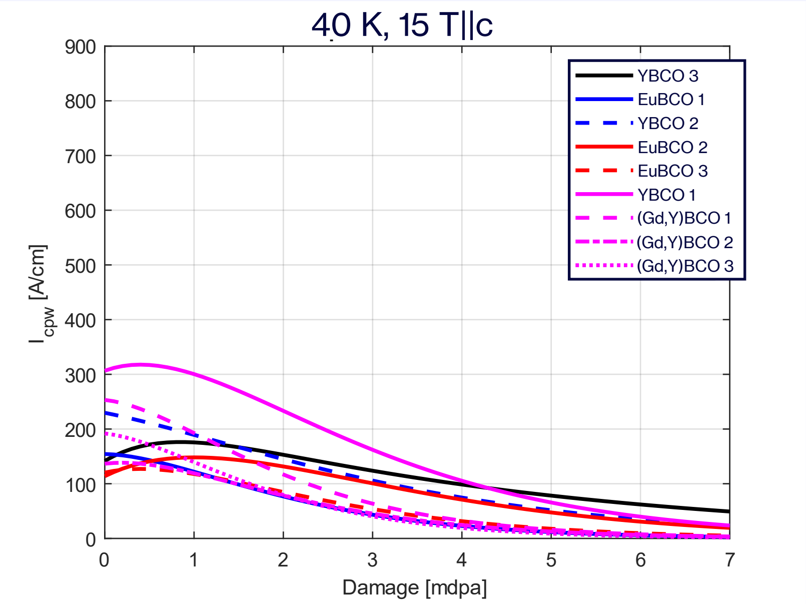
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

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.

Fischer et al. 2018 doi: 10.1088/1361-6668/aaadf2

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

This work has been funded by **STEP**, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (**UKIFS**), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.

This work was supported by the Ion Beam Centre at **HZDR**, Dresden, Germany and **mi2-factory** based in Jena, Germany.

The research used UKAEA's **Materials Research Facility**, which has been funded by and is part of the UK's National Nuclear User Facility and Henry Royce Institute for Advanced Materials.

Thanks go to:

@ HZDR & mi2 Factory
- Constantin Csato
- Shavkat Akhmadaliev
- Florian Krippendorf
- Stefan Illhardt
- Beam operators at HZDR

University of Oxford

University of Surrey

Manchester 1824 — The University of Manchester Dalton Nuclear Institute

University of Birmingham

UKRI Science and Technology Facilities Council — ISIS Neutron and Muon Source

HZDR Helmholtz Zentrum Dresden Rossendorf

CVŘ Research Centre Řež

mi2-factory

Materials Research Facility

STEP

COPYRIGHT NOTICE