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Stuart Wimbush

The light side and the dark side of irradiation

ROBINSON RESEARCH INSTITUTE

VICTORIA UNIVERSITY OF WELLINGTON NEW ZEALAND

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Irradiation of HTS tapes for pinning optimisation

Arya Ambadiyil Soman, Nick Strickland – Robinson

Commercial wires – real-world effects

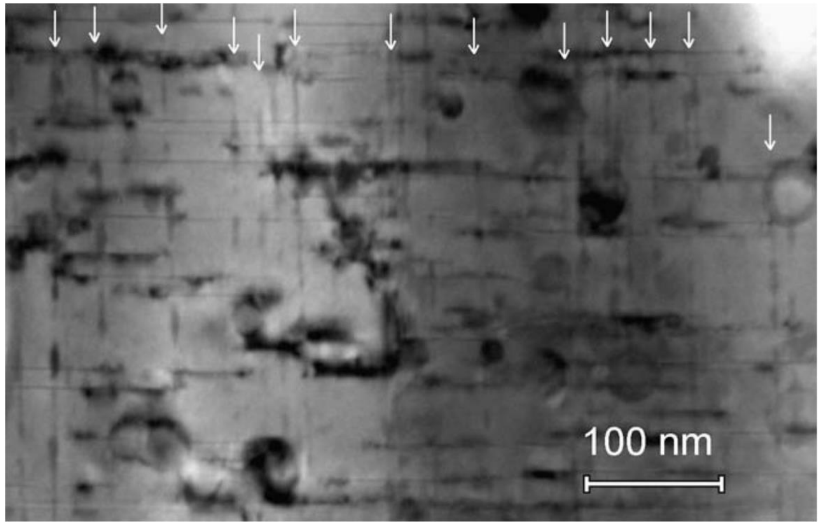
Combinations of irradiations for maximum benefit

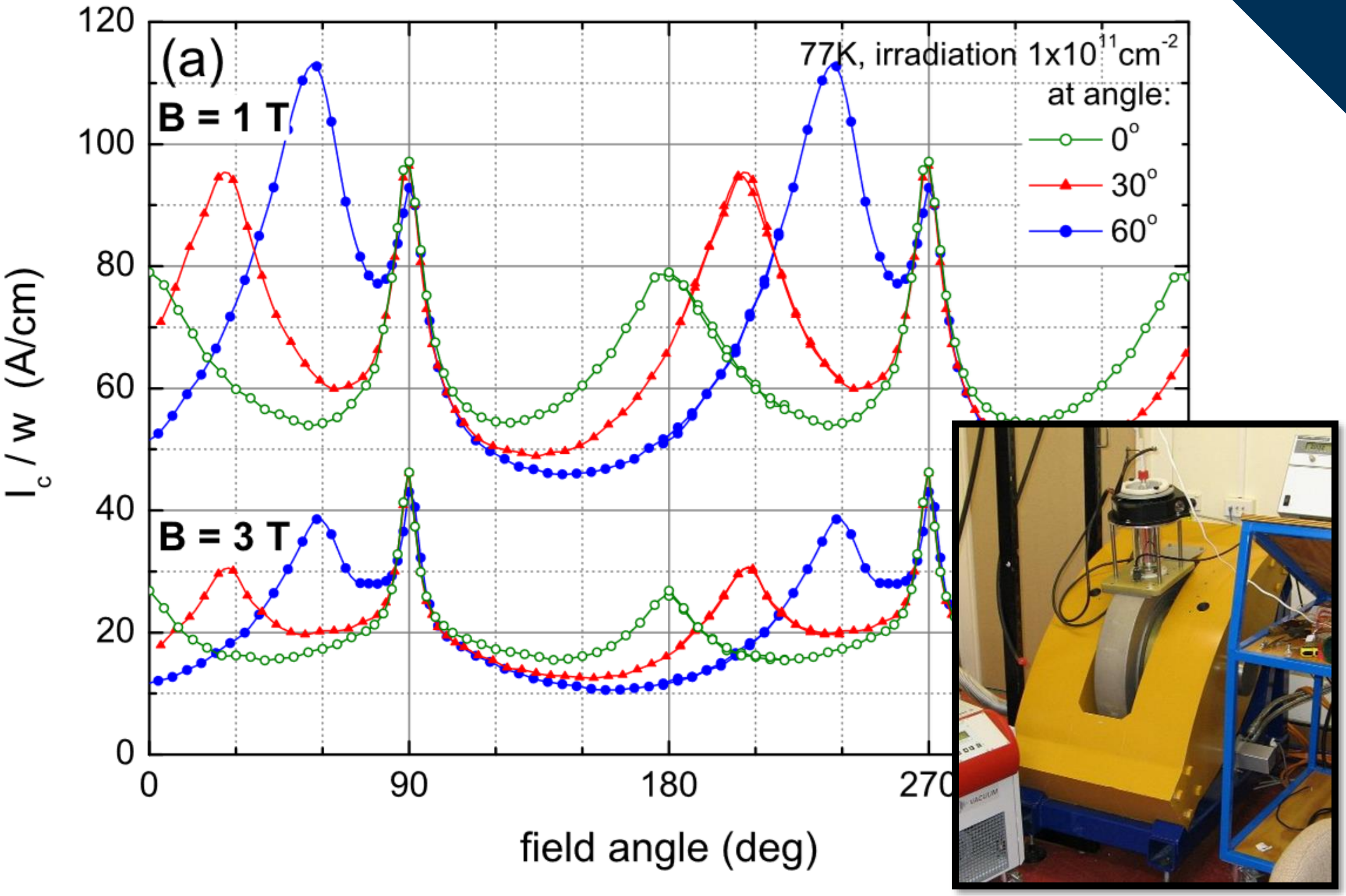
Fusion (and other application)-relevant conditions (temperature, field angle)

Early work

Physica C 469 (2009) 2060:

- 74 MeV inclined Ag-ion irradiation.
- Fluence up to 3 × 10^{15} ions/m^2.
- Discontinuous damage tracks.
- Measurement limited to 77 K, 3 T.





N. M. Strickland et al. *Physica C* 469 (2009) 2060.

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This work

SuperCurrent system extends temperature range down to sub-20 K and field range up to 8 T – closer to the conditions required for fusion.

- Proton irradiation *vs* heavy ion (silver) irradiation.
- Varying energy and varying fluence.
  1.2 and 2.5 MeV, 1–50 × 10^{19} protons/m^2
  18, 50–150 MeV, 1–10 × 10^{15} ions/m^2
- Inclined irradiation (including multiple inclinations).

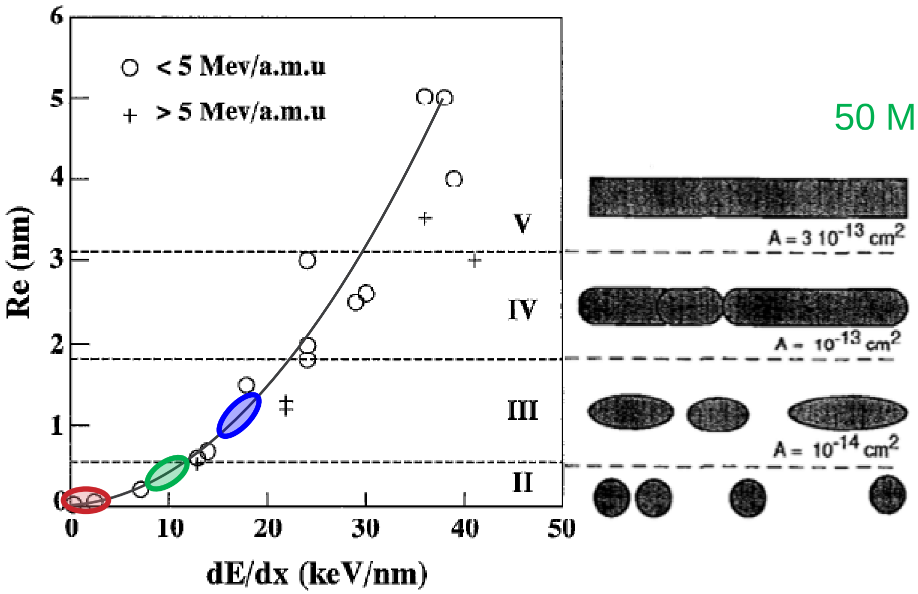
↳ Engineering the pinning landscape (combined irradiation).

Starting material:
Commercially available HTS wire (AMSC) with industry-typical 350 A/cm-w at 77 K sf; application-optimised microstructure – performance enhancements are genuine.

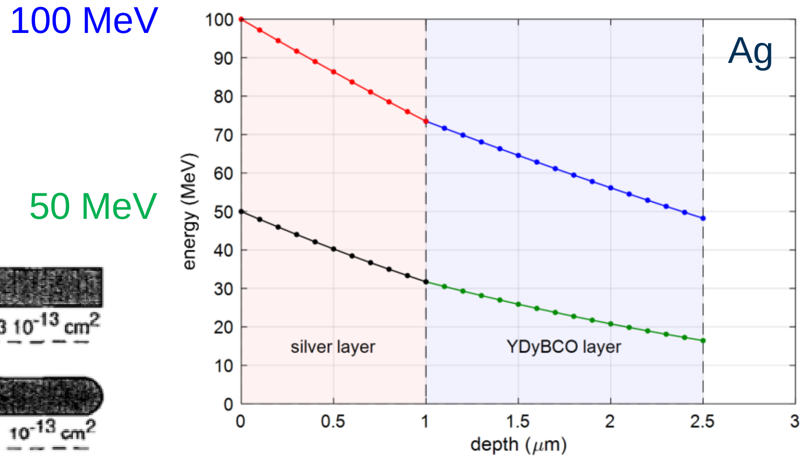
Aim
To increase I_c^{min} under relevant operating conditions (e.g. for fusion: low T, high B).

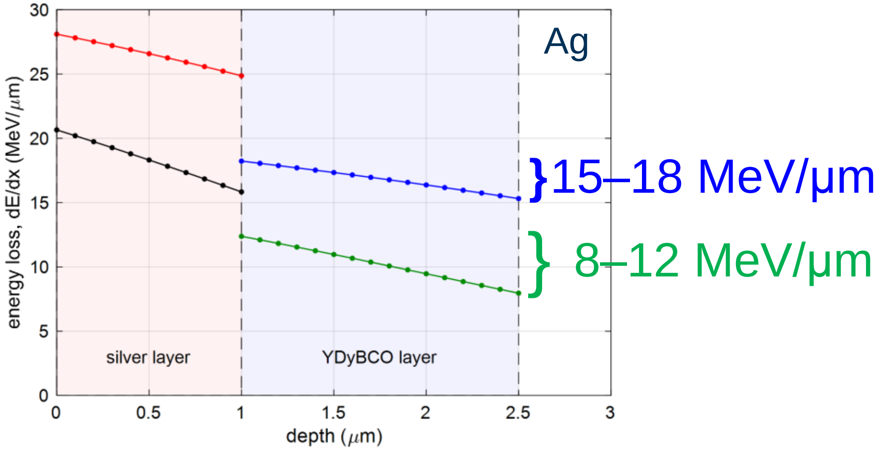
Proton irradiation *vs* heavy ion irradiation

What is the best analogue for neutron irradiation? Protons have similar size and mass but primarily electronic (Coulomb) interactions, generating point defects. Varying the energy of ion irradiation spans the range of induced defects from point-like (similar to proton irradiation) to continuous columnar damage tracks.



M. Toulemonde et al. *Nucl. Instrum. Meth. B* 91 (1994) 108.





100 MeV Ag: (1D) elongated defects

50 MeV Ag: (3D) spherical defects + (2D) stacking faults

Protons: (0D) point defects

N. M. Strickland, S. C. Wimbush, et al. *IEEE Trans. Appl. Supercond.* 32 (2022) 8000505.

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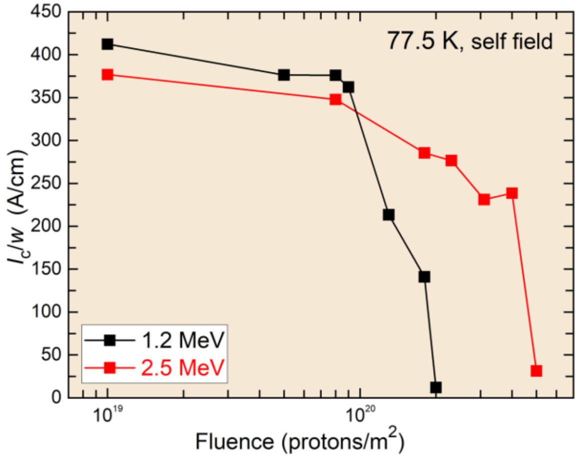
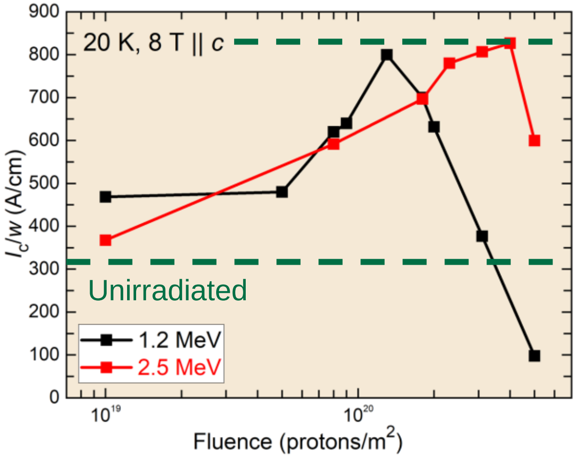
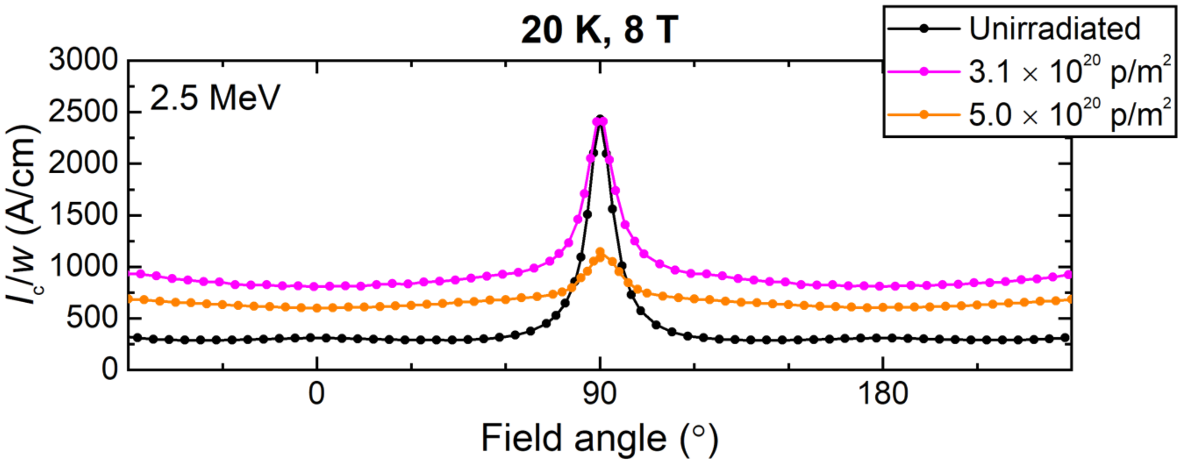
Proton irradiation at different energies

- Samples irradiated with 1.2 MeV and 2.5 MeV protons over a range of fluences (1–50 × 10^{19} p/m^2).
- Strong ~3× isotropic **low-temperature** pinning enhancement from generated point defects.
- Same I_c enhancement achieved with ~3× higher fluence at 2.5 MeV as at 1.2 MeV.
  - Broadly consistent with SRIM simulations of 2.3-fold increase in dpa for 1.2 MeV protons.
- No improvement but also no detriment in *ab* pinning – no interaction between point and planar pins.
- General suppression (including *ab* peak) on high-fluence side.



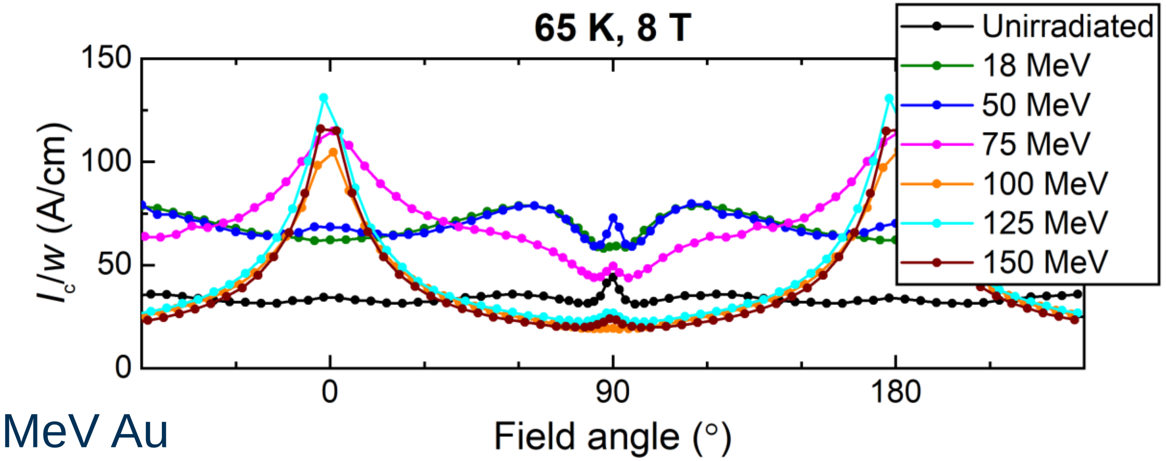


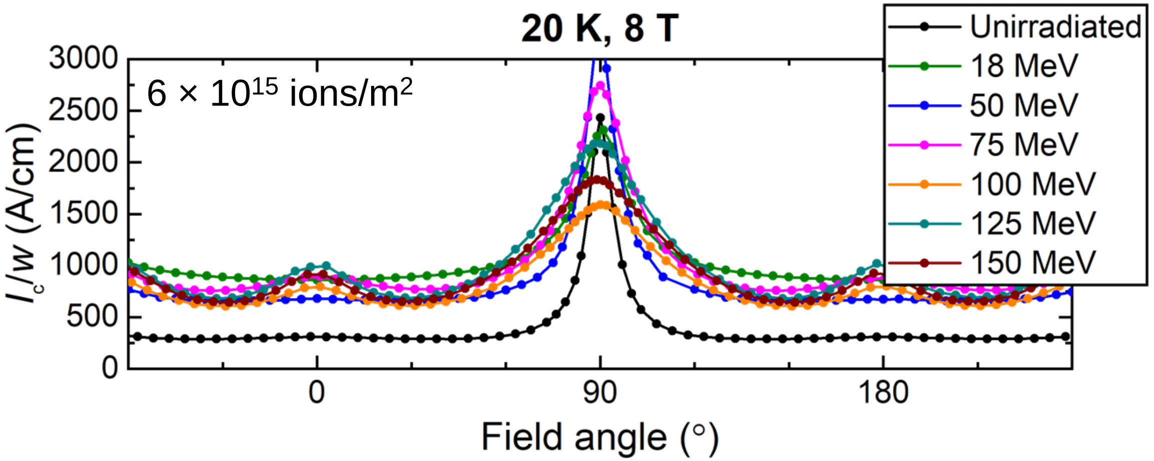


Heavy ion irradiation at different energies

- Samples irradiated with 18–150 MeV Ag* ions.
- At high temperature, the effect depends on defect dimensionality. Isotropic factor of 2 for 0D, 3D. For 1D, *c*-axis peak enhancement of up to a factor 3.6, but a decrease in I_c^{min} if continuous.
- At low temperature, in all cases, a broadly isotropic enhancement in I_c^{min} of a factor 2–3 is observed.

Energy	Defect type	Enhancement
18 MeV	point-like (0D)	isotropic
50 MeV	spherical (3D)	isotropic
75 MeV	elongated (1D)	broad *c*-axis peak
100–150 MeV	segmented columnar (1D)	sharp *c*-axis peak, reduction in *ab*





*18 MeV Au

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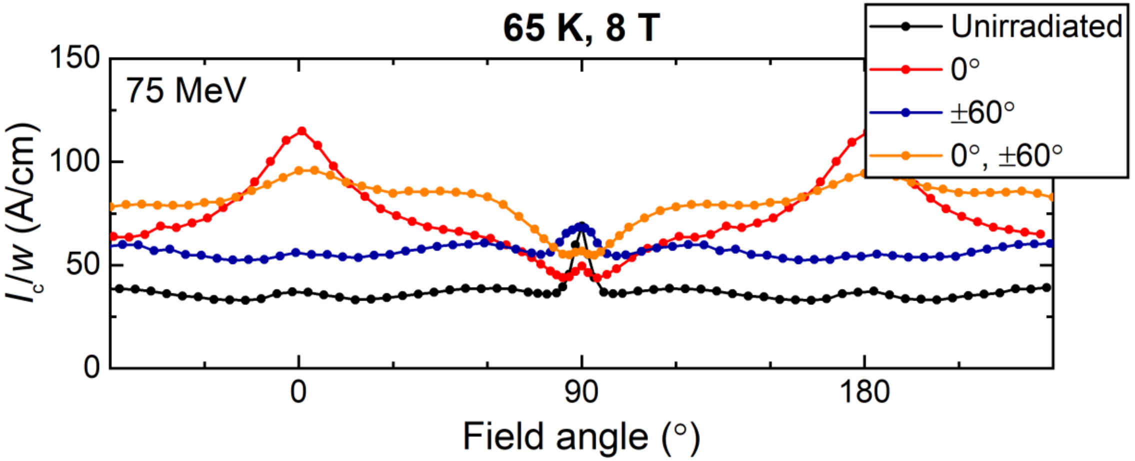
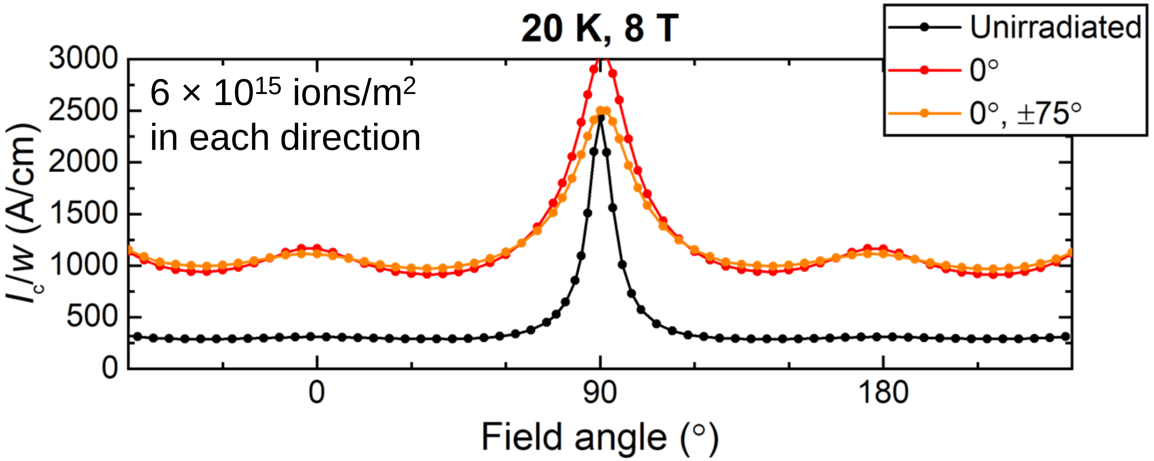
Multiple inclined irradiations

- The aim was to “isotropise” the I_c peaks created at high temperatures through multiple irradiations.
- However, for fusion a more interesting question is the cumulative impact of irradiation in different directions. I’m told that the irradiation in a fusion reactor impinges from all directions (?).
  - If true, we need to consider the cumulative impact, not always studied in experiments.
  - If false, we need to consider the specific effect of different directions of irradiation.
- Comparing 0° irradiation with 0° and ±75°, we see that we can **triple the total fluence** without any detrimental impact on I_c. This is not accounted for by current unidirectional irradiation experiments.





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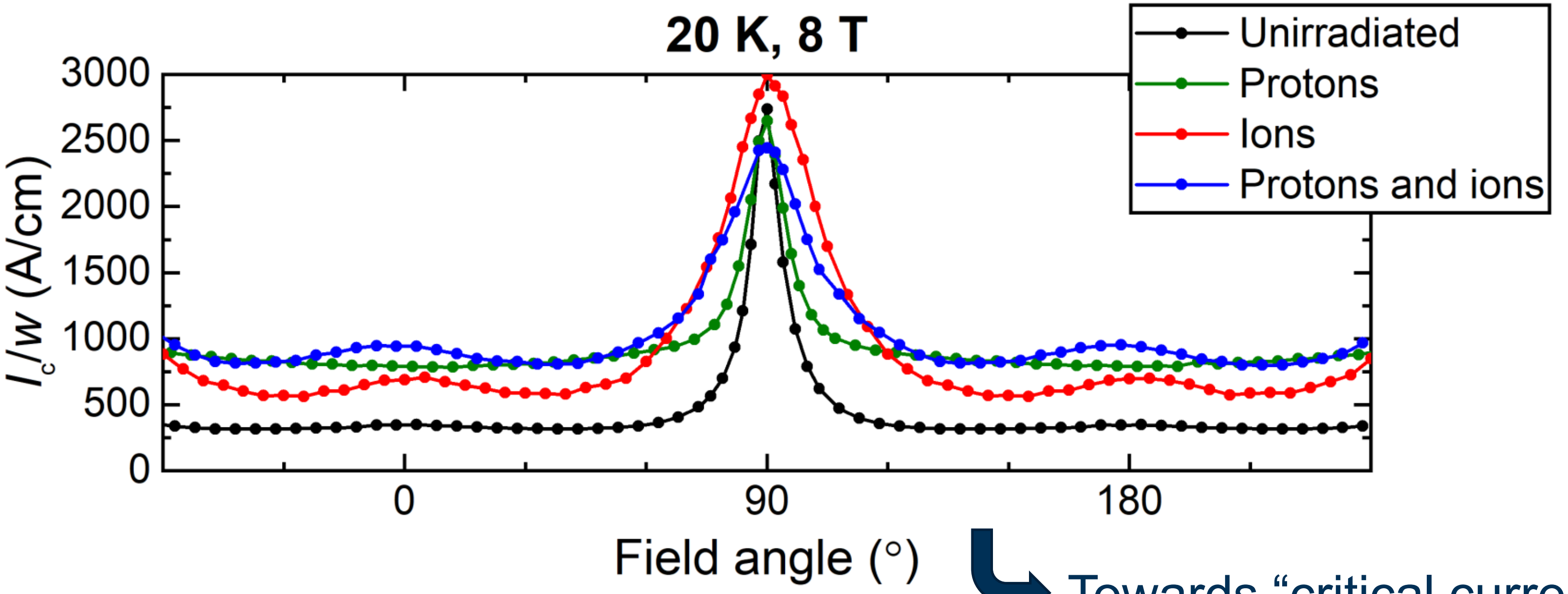
Composite pinning landscape

For targeted low-temperature enhancement:

- Combine the isotropic enhancement of proton-induced point defects with the (small) *c*-axis peak and *ab*-peak broadening of nearly continuous columnar defects of 125 MeV silver ion irradiation.
- No improvement in I_c^{min} over pure proton irradiation, but nonetheless a beneficial combination of pinning effects.



Towards "critical current by design".

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Implications of irradiation damage on the STEP reactor design

Simon Chislett-McDonald, Will Iliffe – UKAEA

Machine lifetime

Impact of different types of irradiation and fluence *vs* flux

STEP’s experimental plan

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The STEP prototype power plant

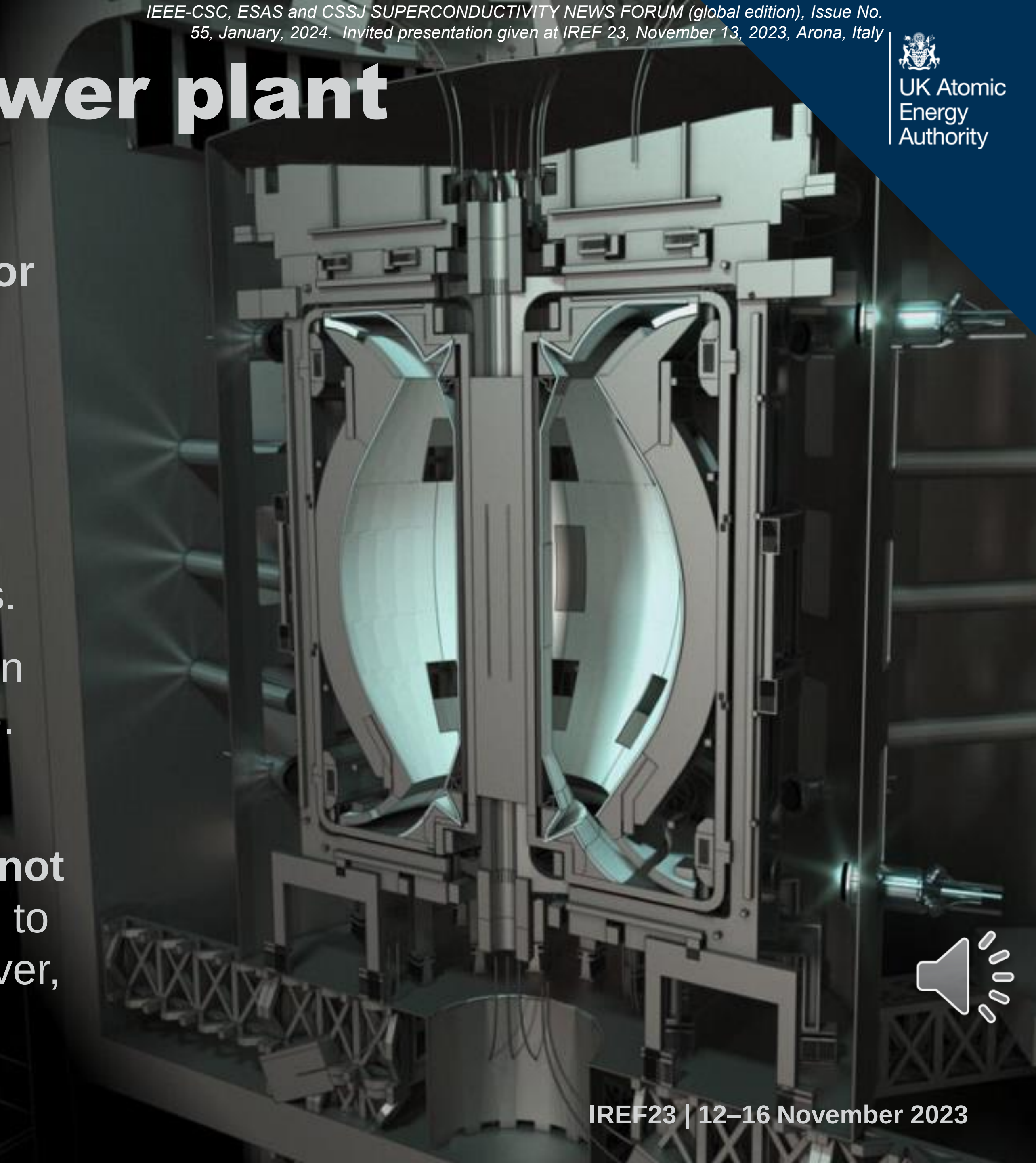
STEP will be a power plant, not a research reactor

– **S**pherical **T**okamak for **E**nergy **P**roduction**.**

Design implications: maintainable architecture (replaceable central column), realised through incorporating remountable joints in the HTS TF coils.

Design target is a **2 full power year** lifetime between maintenance intervals (central column replacement).

Irradiation damage to the REBCO is a concern, but **not the only one**. At present, it is not clear that damage to the REBCO will be the lifetime-limiting factor. However, in the final design, we would like it to be.



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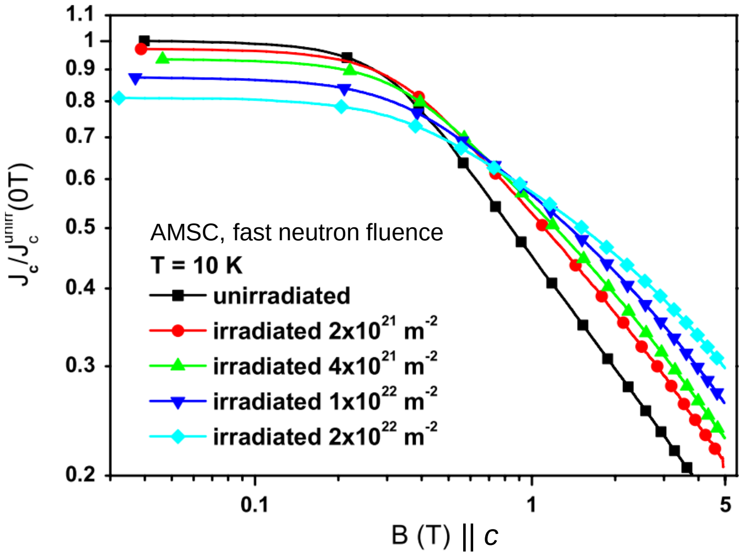
Prior work as working references

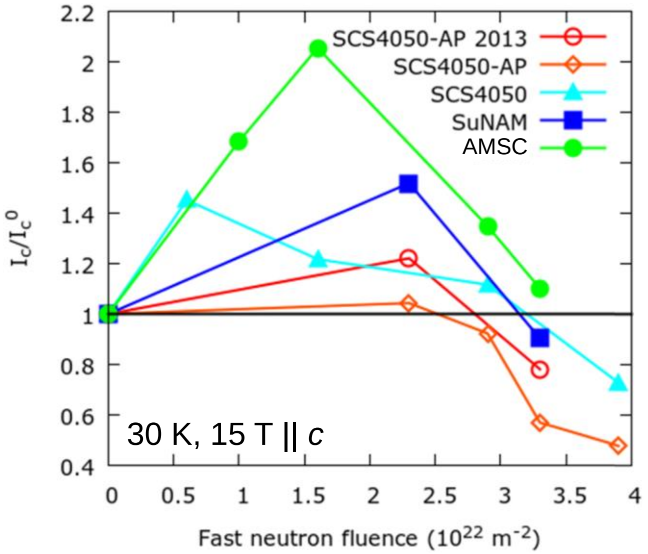
Very small amount of neutron data in the literature.

- In self-field, I_c monotonically decreases with irradiation damage.
- In field, I_c first increases due to pinning enhancement and then decreases due to damage.

Need higher fluences to know how material degrades, not just when it drops below its starting value.

Can be moderately confident that irradiation up to 3 × 10^{22} n_f/m^2 is not detrimental.





M. Eisterer et al. *Supercond. Sci. Technol.* 23 (2010) 014009.
D. X. Fischer et al. *Supercond. Sci. Technol.* 31 (2018) 044006.

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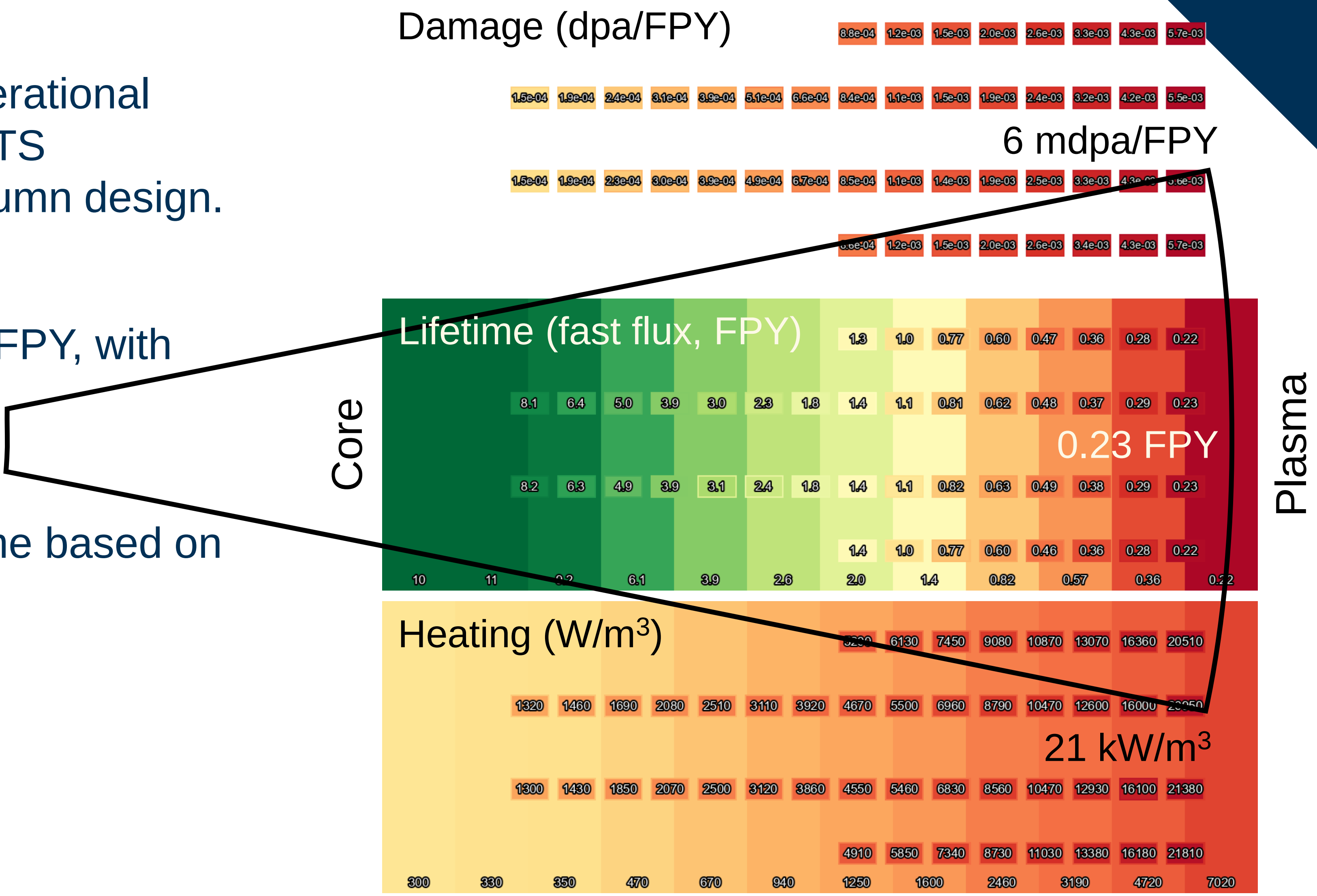
Radiation load

Neutronics modelling reveals the operational impact of the radiation load on the HTS components of a nominal central column design.

- TF **HTS** lifetime is limited to ~0.2 FPY, with neutronic heating of ~21 kW/m^3.
- CS **insulator** has a ~1 FPY lifetime based on gamma dose (~5,600 Gy/hr).



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STEP's experimental plan

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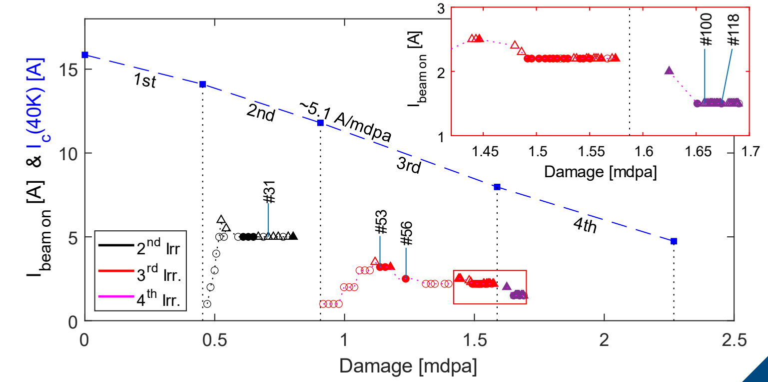
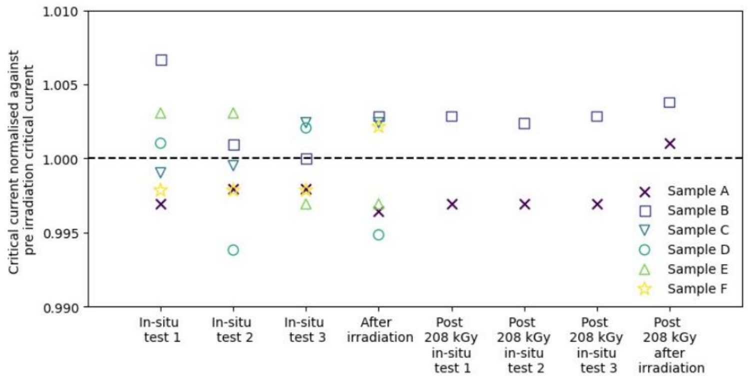
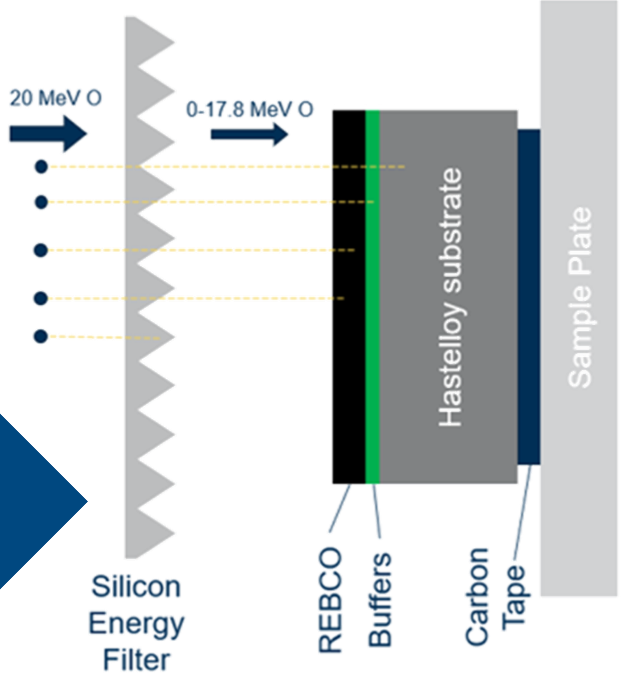




	In situ	Ex situ
Neutron	Cold He$^+$ ions + annealing (Surrey) 14 MeV neutrons (3×10^{12} n/m^2/s) (ISIS Oxford)	Filtered O^{2+} ions 0 – 17.8 MeV STEP-relevant fluence (HZDR Dresden) Cold fission neutrons – STEP-relevant fluence
Gamma	Cold gamma (Manchester)	—

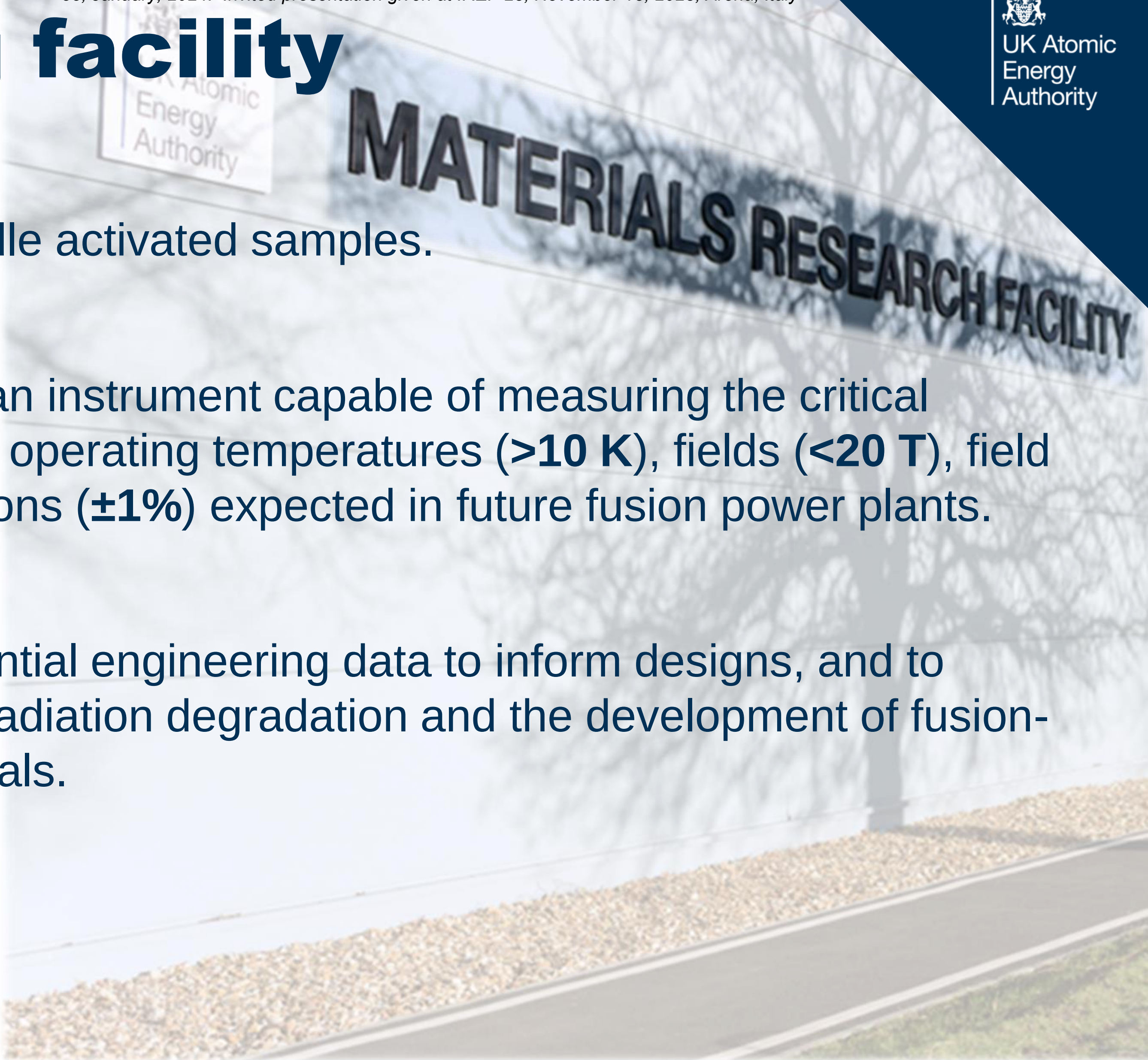
Initial properties survey



❖ REBCO samples within STEP

W. Iliffe, S. B. L. Chislett-McDonald, et al. IEEE Trans. Plasma Sci. (2023) to appear.
S. B. L. Chislett-McDonald et al. *Supercond. Sci. Technol.* 36 (2023) 095019.
W. Iliffe et al. *MRS Bull.* 48 (2023) 710.

Irradiated HTS testing facility



The UKAEA Materials Research Facility can handle activated samples.

A proposal is under development to equip it with an instrument capable of measuring the critical current (**~1 kA**) of irradiated HTS tapes under the operating temperatures (**>10 K**), fields (**<20 T**), field orientations (**360°** out-of-plane) and strain conditions (**±1%**) expected in future fusion power plants.

The facility will be employed both to provide essential engineering data to inform designs, and to facilitate research into the mechanisms behind irradiation degradation and the development of fusion-specific radiation-tolerant superconducting materials.

The facility is expected to be operational in 2026.

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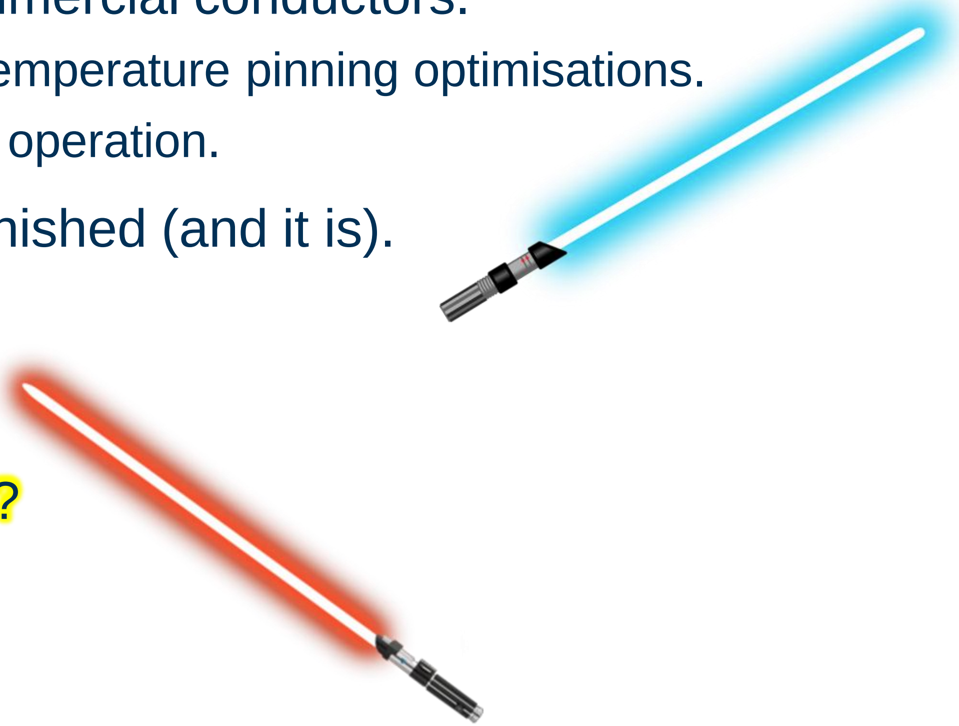
Conclusions and Questions

- Low-temperature I_c^{min} enhancements of a factor approaching 3 can generally be achieved – seemingly regardless of irradiating species or energy – in commercial conductors.
  - This is possibly what is being replicated by state-of-the-art low-temperature pinning optimisations.
  - Such pre-optimised material tends not to be further enhanced in operation.
- Vast *c*-axis pinning enhancements are irrelevant if I_c^{min} is diminished (and it is).



- What is the best analogue for neutron irradiation?
- Does irradiation impinge from all directions in a fusion reactor?
- How does HTS degrade at higher neutron fluences?
- What is the effect of flux *vs* fluence?