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Gamma In-Situ Cryogenic Experiment (ICE)

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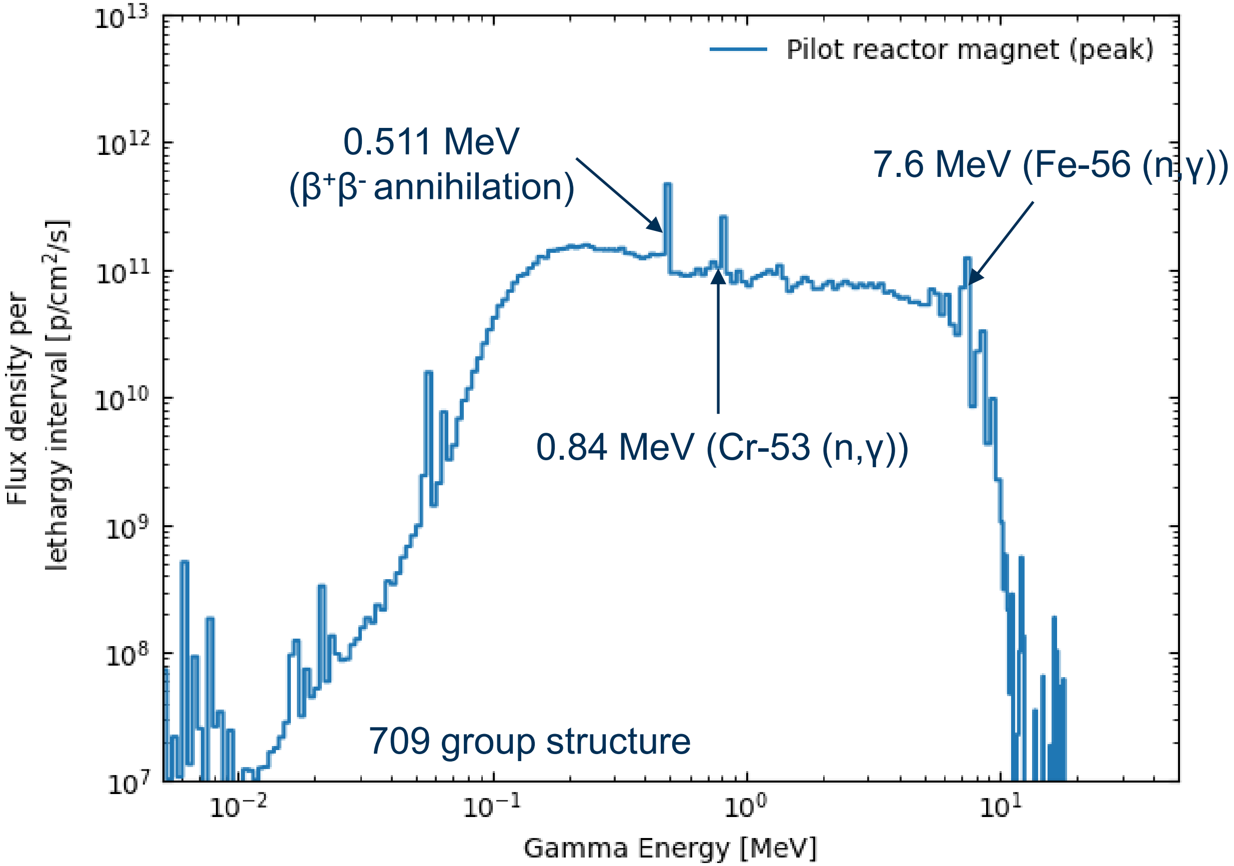
Rationale

Rationale – why care about γ-irradiation?



*Lethargy interval: natural log of the ratio of an energy bin's upper and lower bound. See e.g. M. R. Gilbert et al. Nuclear Fusion **52** (2012) 083019

- (n,γ) interactions produce a broad-spectrum photon flux incident on the magnets
- Fluence effects:
  - Photoelectrons can collide with and excite atoms out of their lattice locations. Stable defects can affect superconducting properties. (Though literature is contradictory).
- Flux effects:
  - Gamma heating
  - Cooper-pair unbinding?
  - Superconducting volume reduction?

Rationale – why care about γ-flux effects?

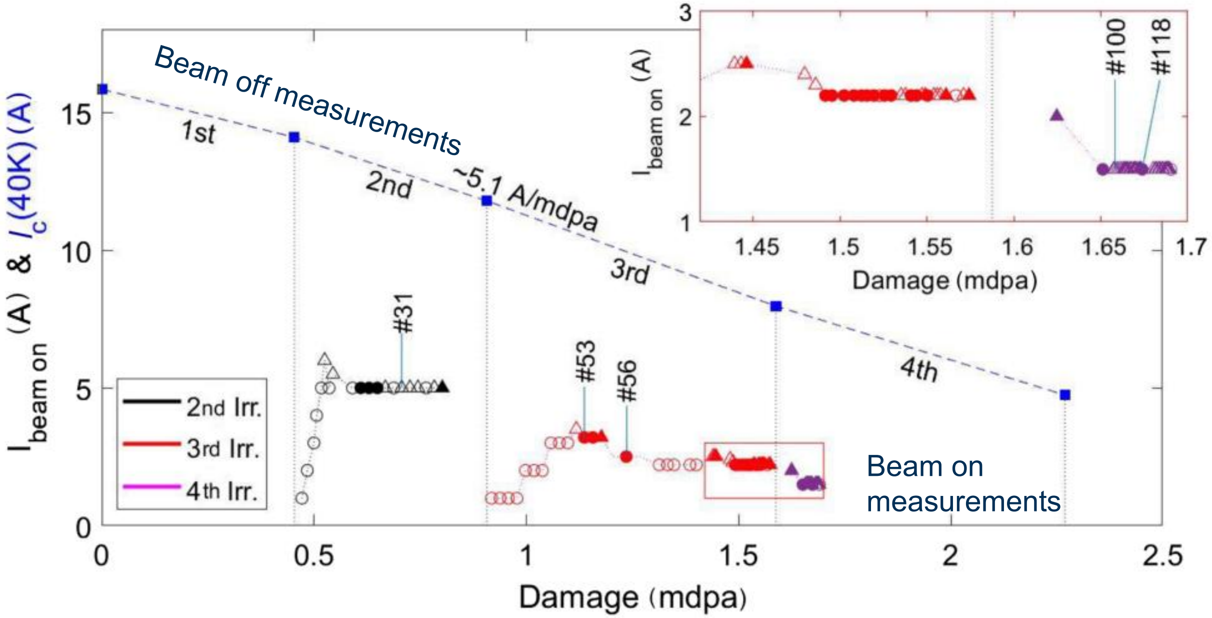
- Does radiation suppress superconductivity by directly unbinding Cooper-pairs? keV and MeV photos/photo electrons vs eV Cooper-pairs.

- Photoelectrons create transient ‘channels’ of > T_c material, reducing the superconducting volume (superconducting photon detectors exploit this phenomenon).

- Requires synchronous cryogenic irradiation and critical current testing capability to observe: “in-situ” testing.

- Is a fusion relevant γ flux a problem for commercial REBCO tapes?

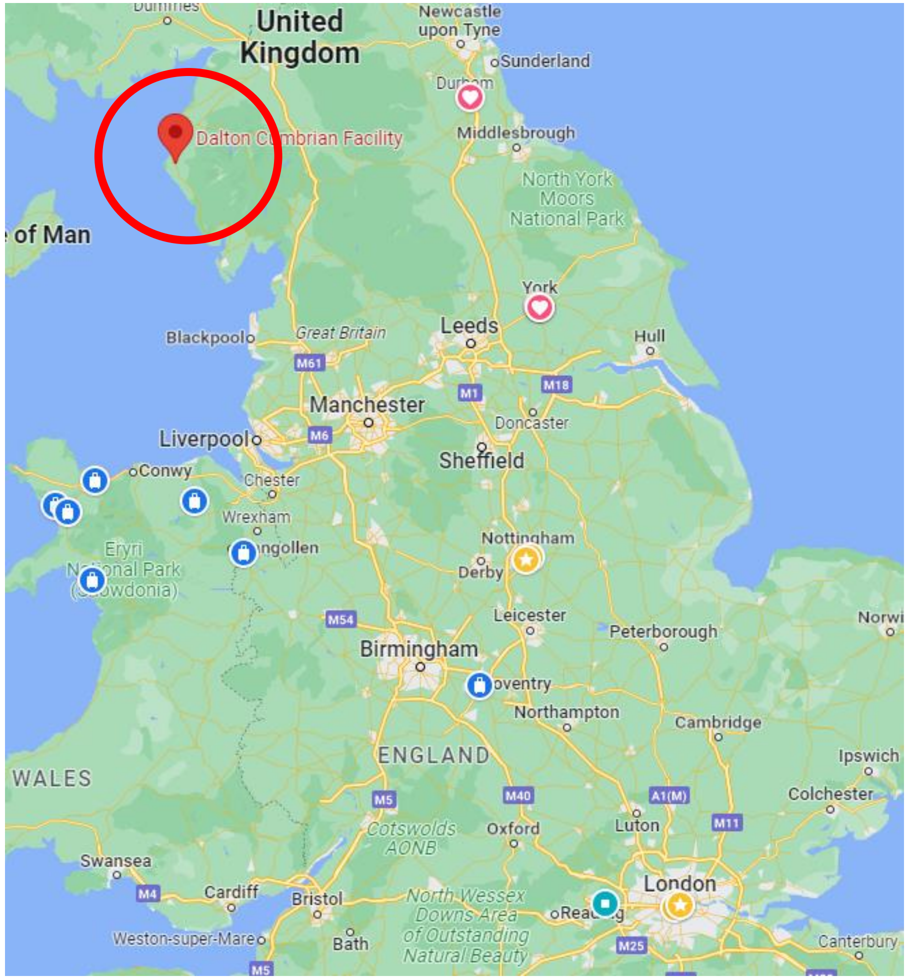
W. Iliffe et al MRS Bulletin 48 (2023) 710-719



Visible effect during 2 MeV He ion irradiation

γ Irradiation Facility

Facility Location



https://www.dalton.manchester.ac.uk/research/facilities/cumbria-facilities/

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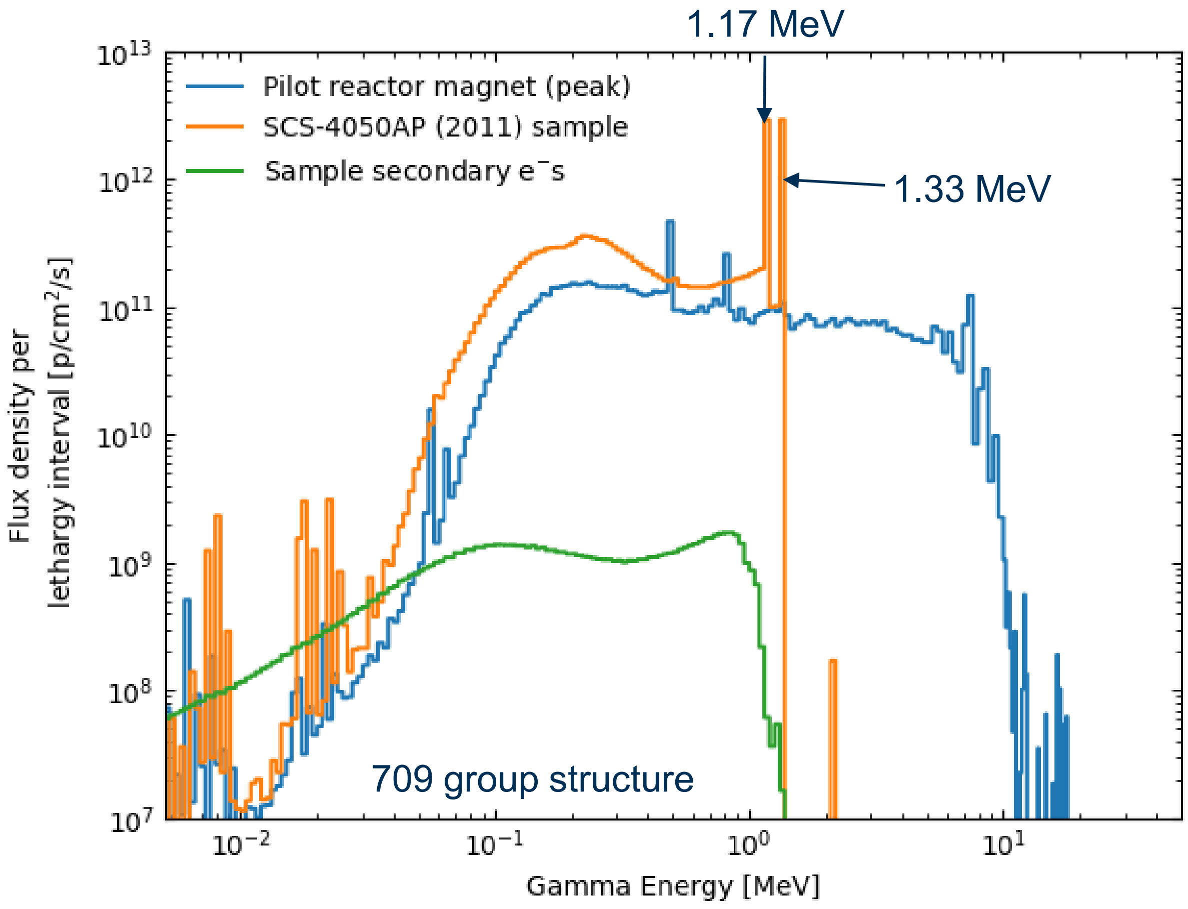
MANCHESTER 1824

The University of Manchester

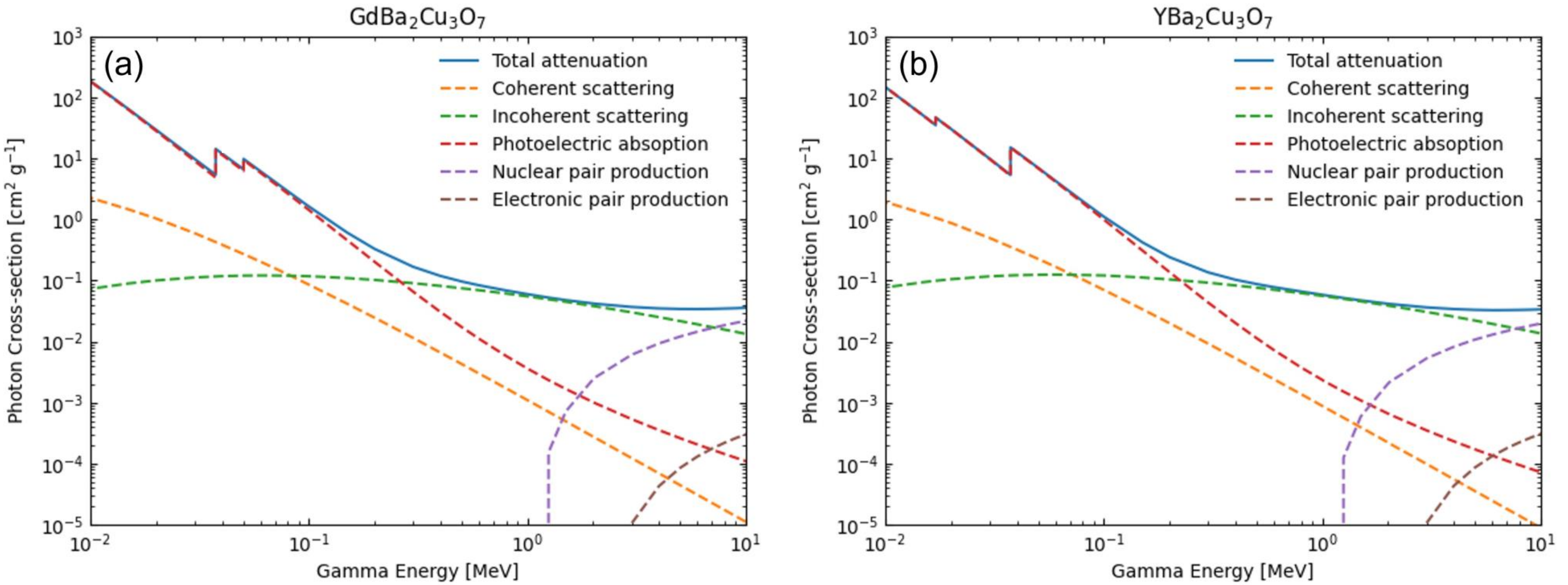
Experimental Details: γ chamber

Co-60 vs STEP centre column midplane γ spectra



- Total γ flux density of 3.7e11 cm^{-2} s^{-1}
- Total absorbed γ dose of ~ 86 Gy min^{-1}
- Total secondary e^- flux density of 2.0e9 cm^{-2} s^{-1}
- Total γ flux density on samples ~ 0.9 x total γ flux density expected on STEP centre column midplane
- Secondary electrons have energies up to 1.33 MeV – far more than REBCO lattice binding energies (~ few 10s eV).

REBCO γ cross section



- Primarily incoherent scattering at Co-60 1.17 and 1.33 MeV peaks.

- In STEP centre column midplane, primarily photoelectric absorption (E_γ < 0.3 MeV) and incoherent scattering (0.3 MeV < E_γ < 6 MeV). Nuclear pair production > 6 MeV.

https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

Measurement set-up

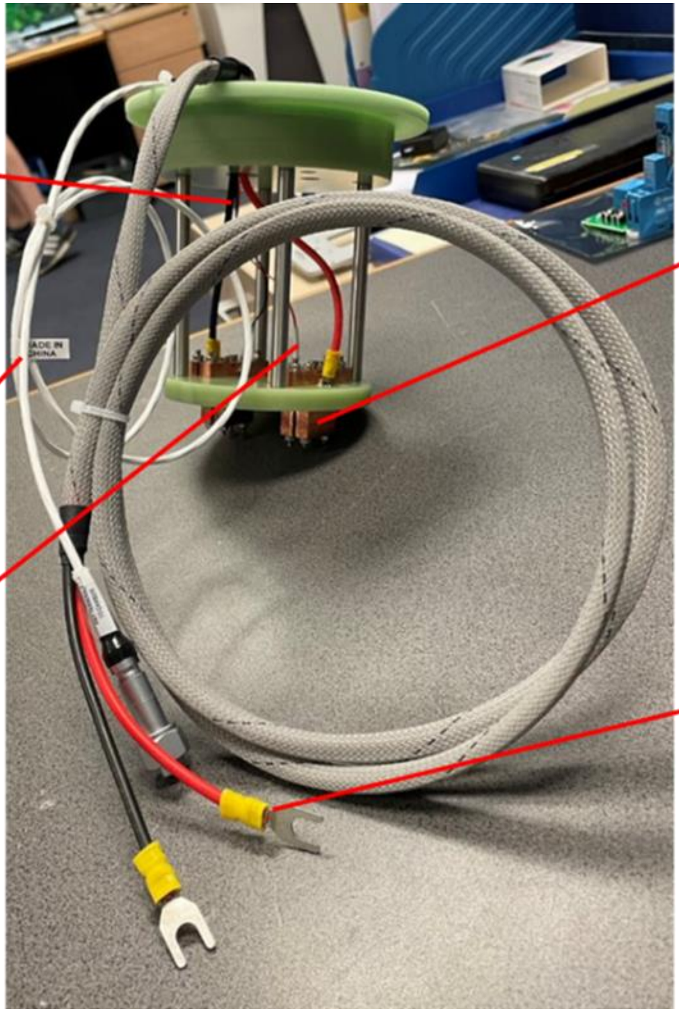
REBCO samples

- SuperPower® (2011) SCS-4050-AP (4 mm)
- Nominally ~160 A @ 77 K (4 mm)
- Laser cut bridges of 0.25 mm and 0.5 mm width
  - 3 samples of each tested
- Laser cut channel of depth ~ 33.8 μm (approx. 10 μm into the substrate).

Experimental Details: Equipment

- Keysight 200 A power supply
- Keithley 2 channel nanovoltmeter
- Test fixture
- 2 L liquid nitrogen dewar

Experimental Details: Test Fixture



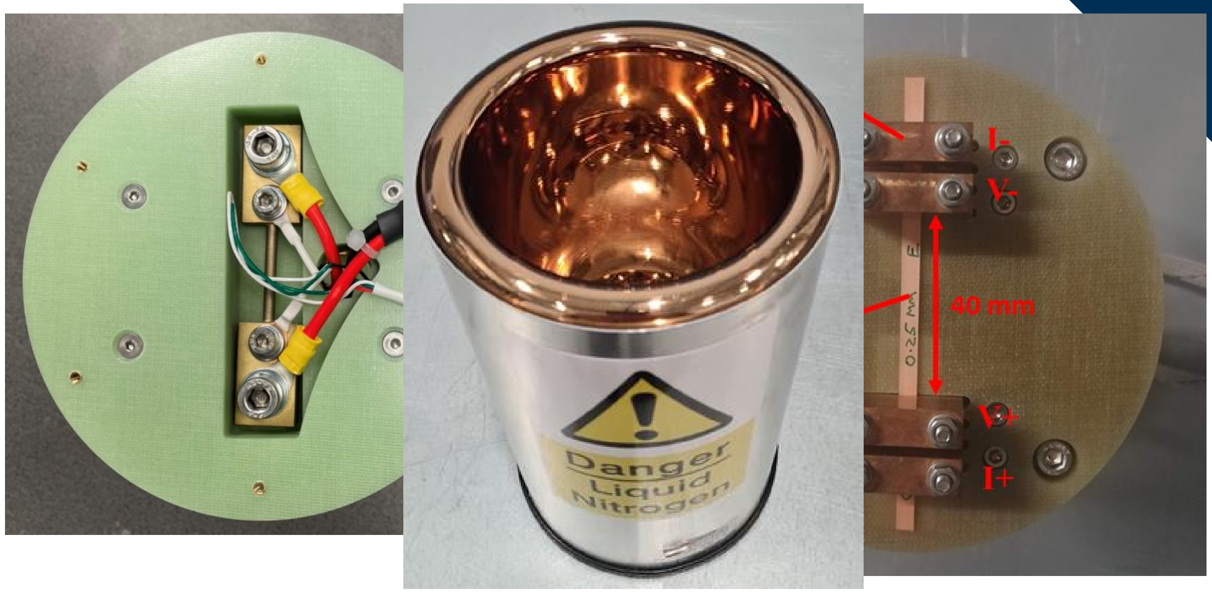
Current leads to sample

Voltage leads to nanovoltmeter

Voltage leads from sample

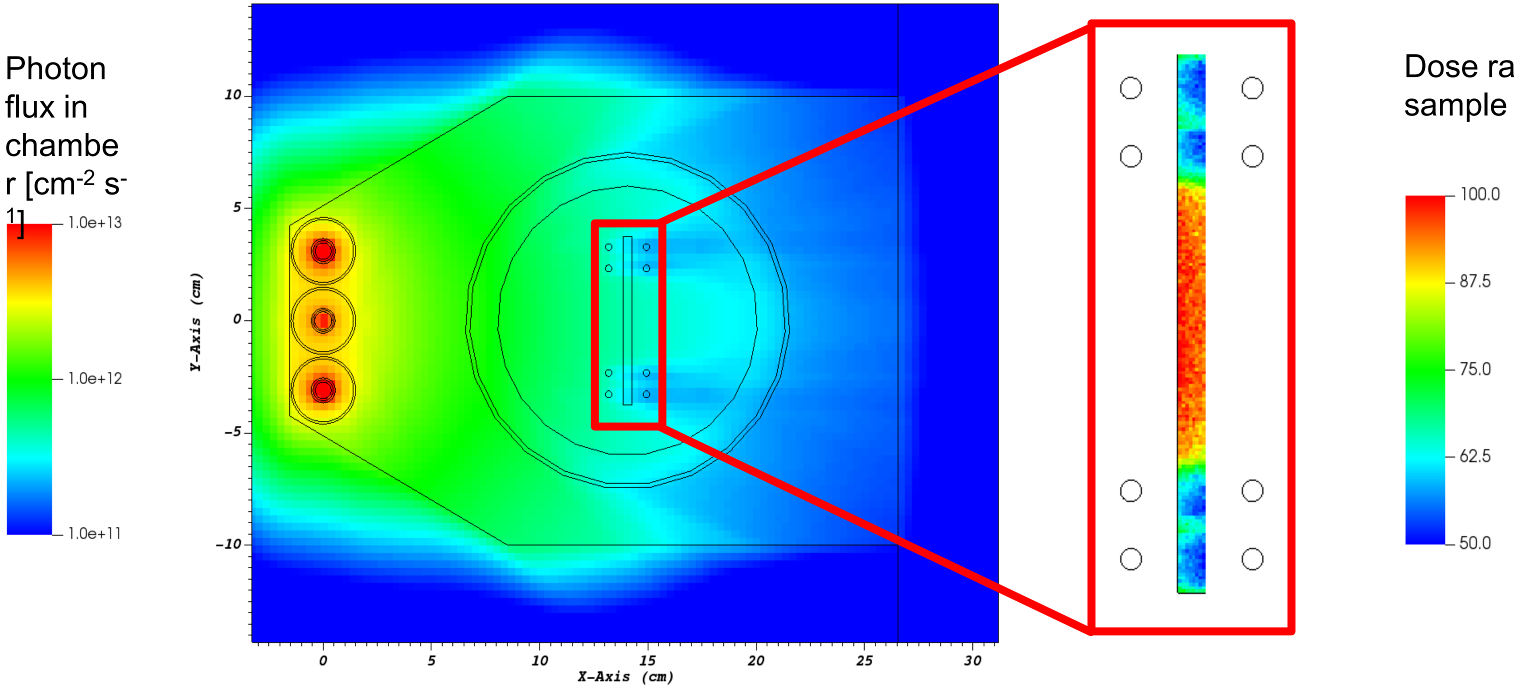
Sample stage + clamps

Current leads to power supply unit



- Current shunt in lid-top
- Samples clamped with screw tightened copper clamps
- Clamps coupled as electrical contacts
- 40 mm between V clamps, 2 mm between I and V clamps

Experimental Details: MCNP calculations



- Average γ dose rate on sample ~ 86 Gy min^{-1}.
- REBCO tape simulated as a homogenised bulk
- Steel clamp pins and copper clamps reduced flux by ~ 2x
- Tape length under investigation saw ~ uniform dose

I_C Measurements

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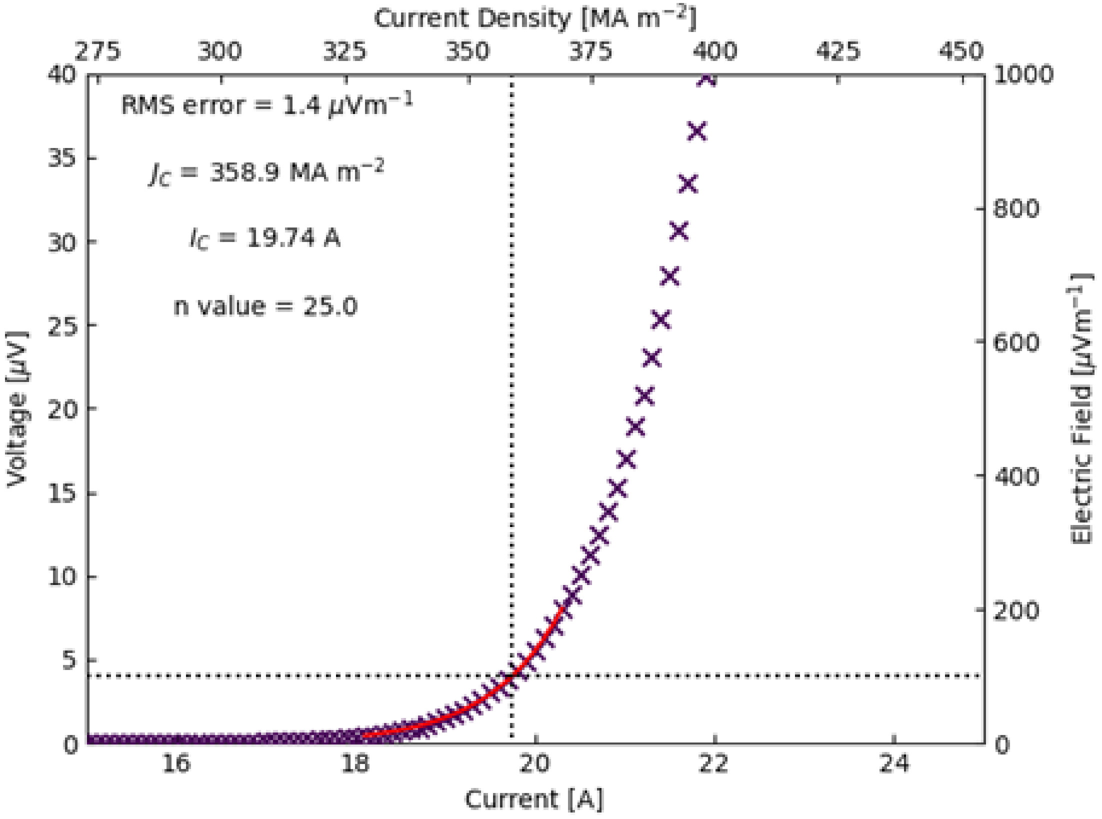


- Current increased in 0.1 A intervals
- 50 μV cut-off voltage employed
- E_c = 100 μV m^{-1} criterion for J_C. V_c = 4 μV (with voltage tap distance of 40 mm).
- V-I data fit using standard power law:

$$V(I) = V_c \times \left(\frac{I}{I_C}\right)^n$$

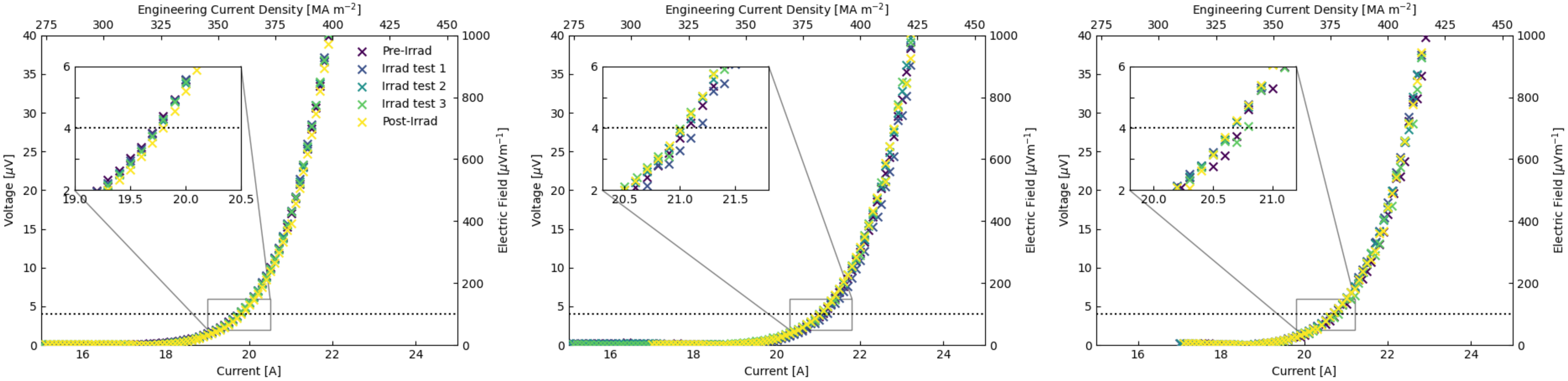
between 0.4 μV and 8 μV.

- Fit using python scipy.optimize.curve_fit function

Results

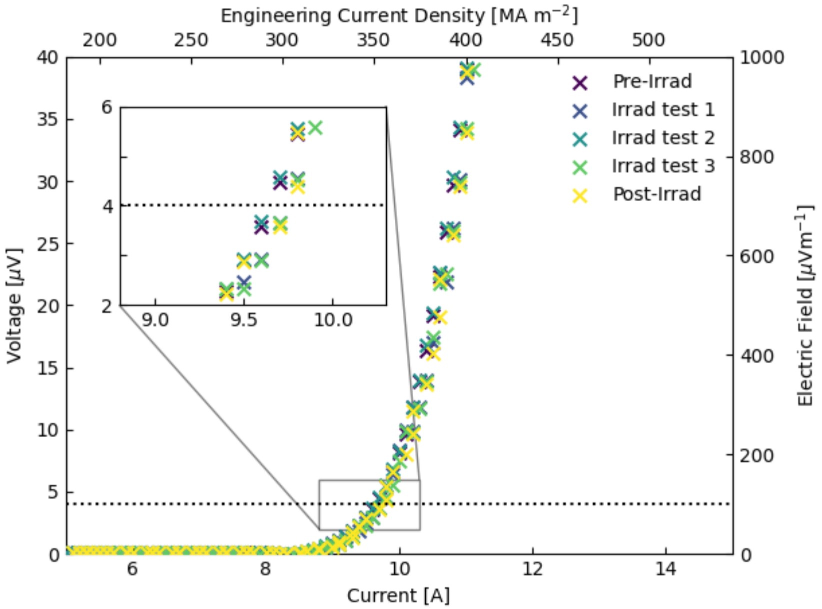
Results – in-situ

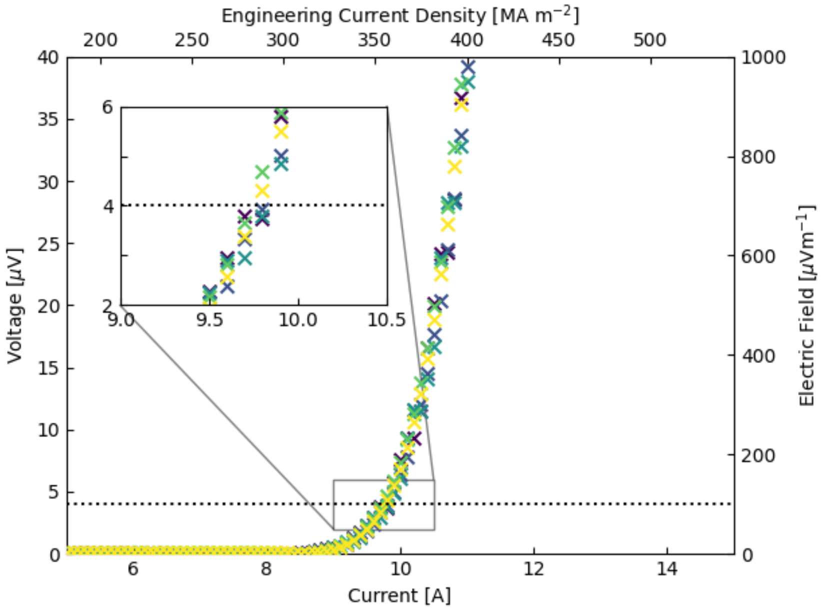
- Samples A, B, C
- 0.5 mm bridge width
- ~ 1.1 kGy dose per I-V measurement

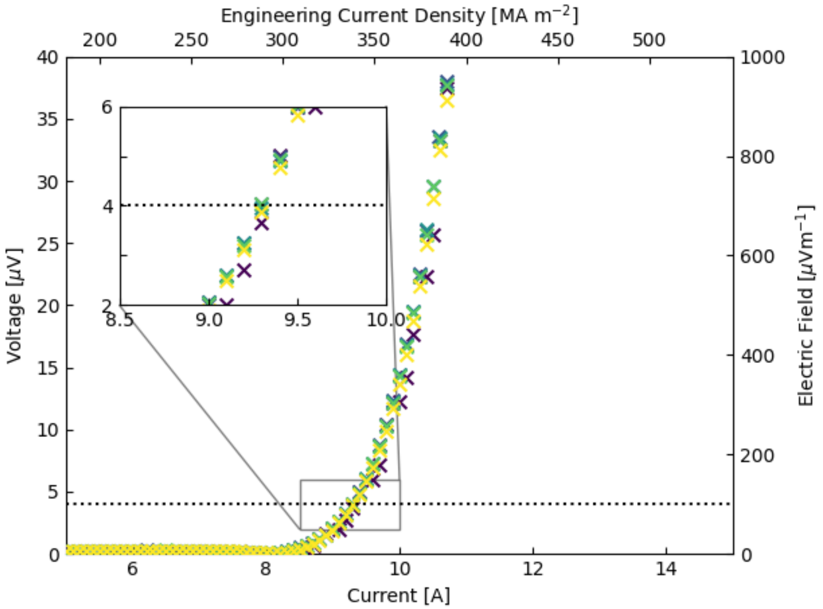


Results – in-situ

- Samples D, E, F
- 0.25 mm bridge width
- ~ 1.1 kGy dose per I-V measurement

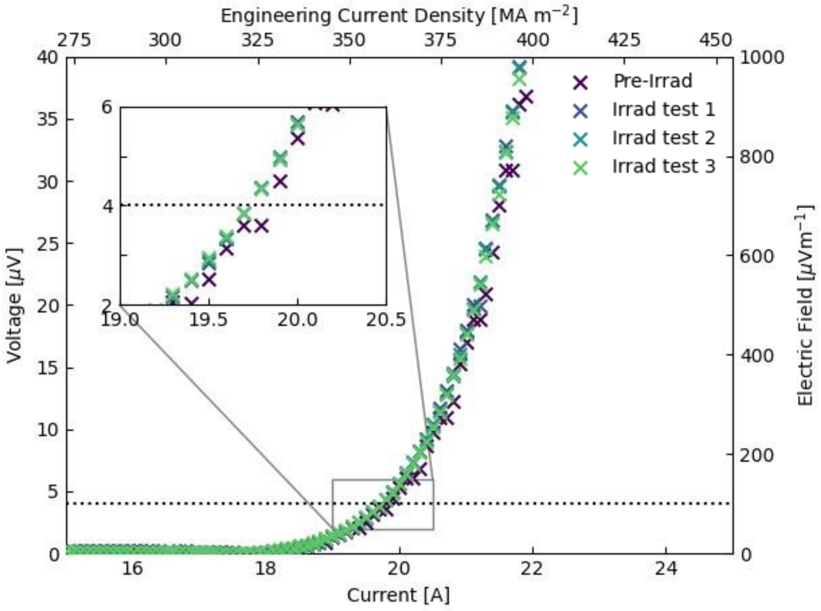


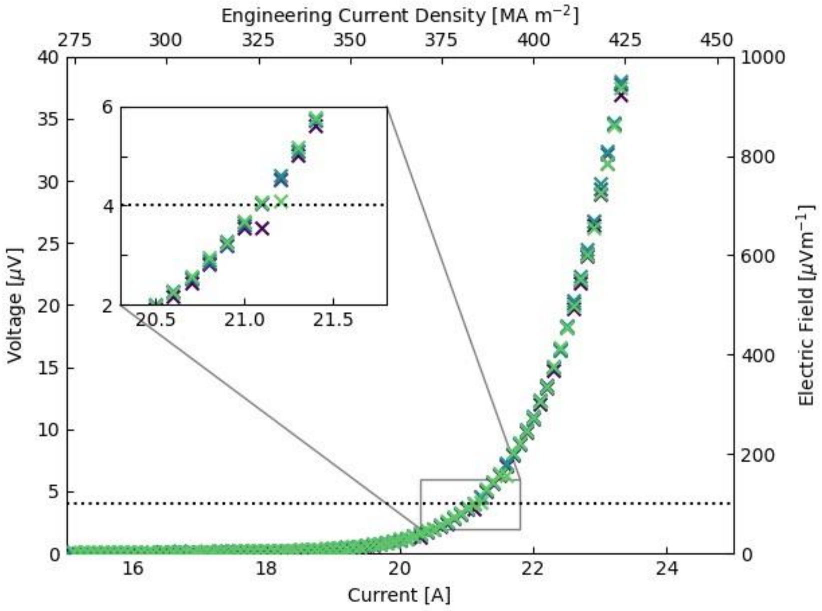


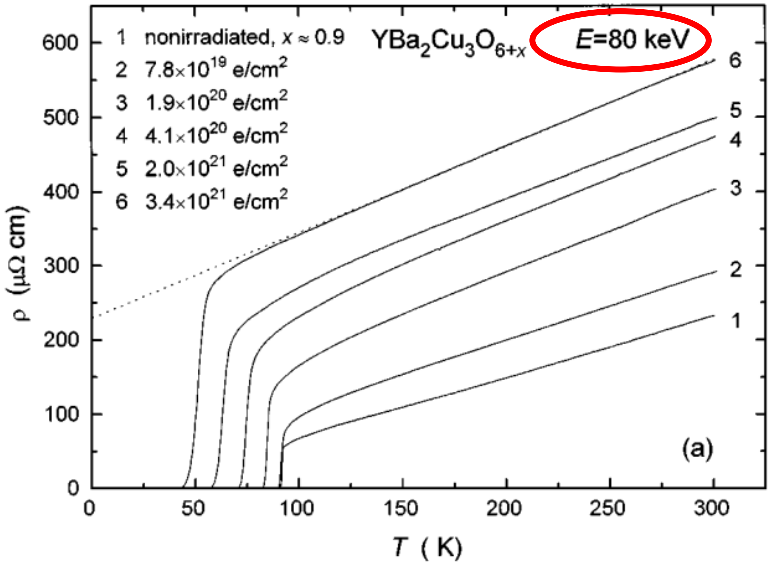


Results – in-situ, post 208 kGy fluence

- Samples A, B
- Total secondary e$^-$ fluence of 4.9e12 cm^{-2}
- 0.5 mm bridge width
- ~ 1.1 kGy dose per I-V measurement (total dose of ~ 215 kGy)







S. K. Tolypgo et al. Phys. Rev. B **53**, 18 (1996) 12462

Aside: γ fluence literature I_c

Reference	HTS	Irrad .Temp. (K)	γ-source	γ-dose (MGy)	Effect
This work	SCS4050-AP	293 (and 77)	Co-60	2.1e-1 (+0.1e-1)	I_c/I_{c0} = 1.0
Cooksey 1994	$YBa_2Cu_3O_{7-x}$ (0.2 μm, on MgO)	293	Cs-137	6.0e-3 1.5e-2	I_c/I_{c0} = 1.2 I_c/I_{c0} = 0.9
Cooksey 1994	$YBa_2Cu_3O_{7-x}$ (1.0 μm, on $LaAlO_3$)	293	Cs-137	6.0e-3 1.5e-2	I_c/I_{c0} = 1.0 I_c/I_{c0} = 1.0
Aksenova 1995	$YBa_2Cu_3O_{7-x}$	293	?	1.0 3.0 7.0	I_c/I_{c0} = 1.2 I_c/I_{c0} = 0.8 I_c/I_{c0} = 0.7
Leyva 1995	$YBa_2Cu_3O_{7-x}$	293	Co-60	0.1 0.2 0.3 0.4	I_c/I_{c0} = 0.8 I_c/I_{c0} = 0.8 I_c/I_{c0} = 0.7 I_c/I_{c0} = 0.6
Iio 2022	SCS4050-AP	293	Co-60	27.4	I_c/I_{c0} = 1.0

Aside: γ fluence literature T_C

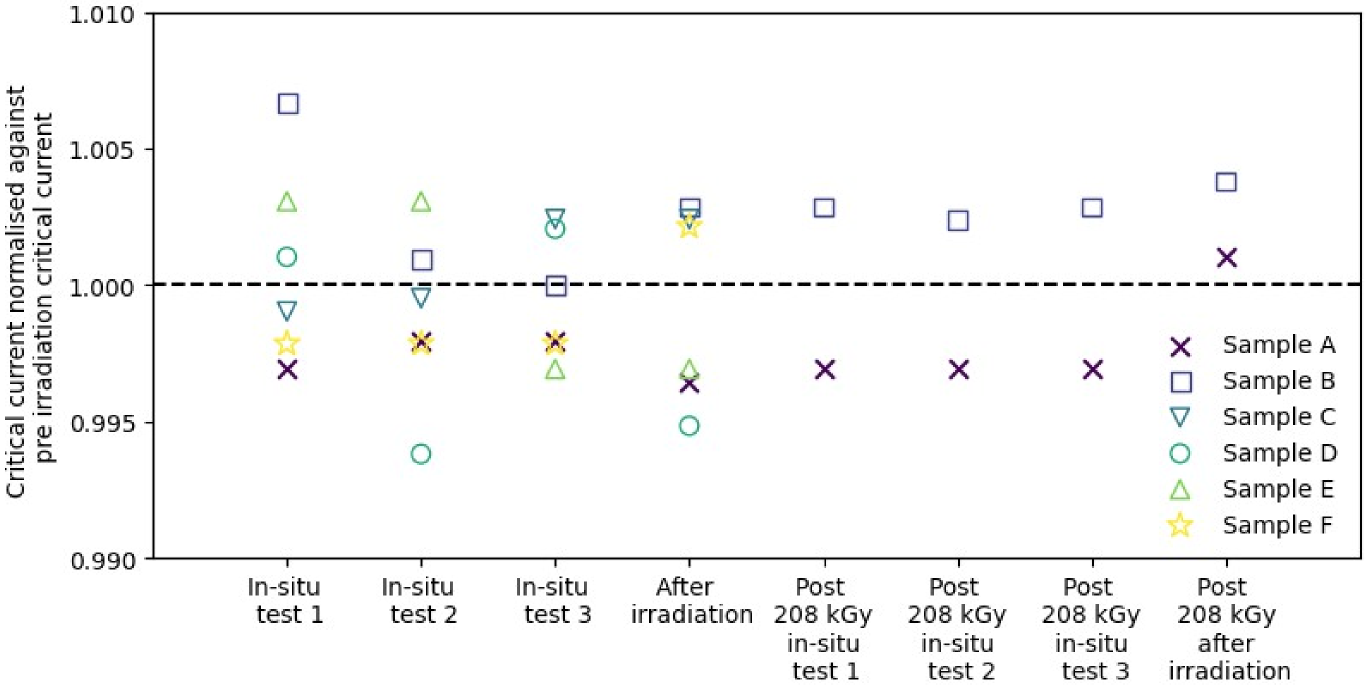
Reference	HTS	Irrad .Temp. (K)	γ-source	γ-dose (MGy)	Effect
Leyva 1995	$YBa_2Cu_3O_{7-x}$	293	Co-60	0.1 0.2 0.3 0.4	ΔT_C = + 1.5 K ΔT_C = + 2.0 K ΔT_C = 0.0 K ΔT_C = - 1.0 K
Bohandy 1987	$YBa_2Cu_3O_{7-x}$	293	Co-60	1.3e-2	ΔT_C = 0.0 K
Kutsukake 1989	$YBa_2Cu_3O_{7-x}$	293	Co-60	1.0	ΔT_C = 0.0 K
Albiss 1993, Özkan 1994	$YBa_2Cu_3O_{7-x}$	293	Co-60	0.8	ΔT_C = 0.0 K
Elkholy 1996	$YBa_{2-y}Sr_yCu_3O_{7-x}$	293	Co-60	0.2 0.5	ΔT_C = 0.0 K ΔT_C = -7.0 K
Leyva 2001	$YBa_2Cu_3O_{7-x}$	293	Cs137	2.7e-7	ΔT_C = + 2.2 K
Akduran 2012	$Y_3Ba_5Cu_8O_{18}$	293	Co-60	2.4e-3 1.2e-1 2.3e-2 4.5e-2	ΔT_C = - 8.0 K ΔT_C = - 14.5 K ΔT_C = - 17.4 K ΔT_C = - 47.1 K
Akduran 2013	$EuBa_2Cu_3O_{7-x}$	293	Co-60	1e-2 2e-2 3e-2	ΔT_C = - 3.3 K ΔT_C = - 4.7 K ΔT_C = - 8.1 K

Results - Summary

- SCS4050-AP (2011) REBCO tapes exposed to ~ 86 Gy min^{-1} Co-60 γ flux (similar total flux to STEP centre column TF coil midplane). I_C was measured in-situ: during irradiation.
  - No change in I_C was observed during irradiation

- Two samples further irradiated at 293 K with 208 kGy.
  - No change in I_C was observed during irradiation
  - No change in I_C was observed after irradiation

- Null result after 293 K, 208 kGy dose corroborates recent literature but conflicts with older literature.



Unanswered Questions, Future Plans

- Co-60 spectrum quite different from fusion spectrum; access to higher energy gamma rays required (10+ MeV). Does nuclear-pair production influence I_C?
  - (n,γ) radiation from W, steels (fusion armour-like materials) @ e.g. Birmingham
  - Using femtosecond laser driven incoherent bremsstrahlung up to 100s MeV @ e.g. Scottish Centre for the Application of Plasma-based Accelerators (SCAPA).

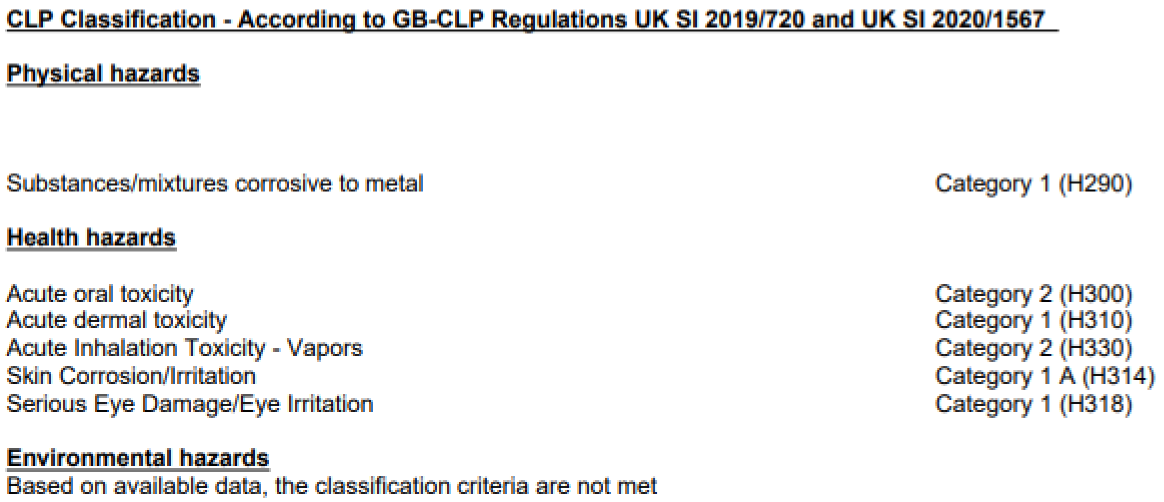
- Cooper pair binding energies ~ meV range, is there an absorption resonance at those energies (microwave-infrared)?

- Testing other commercially available tapes with different REs, APCs, APC concentrations.

- “Sorting out” of gamma ray fluence literature – why is it so diverse?
  - Un-controlled-for chemical degradation of literature samples?
    - Gamma catalysed chemical reactions? Some work on subject by Aksenova et. al. in the mid-90s.
  - Something else?

‘Not Obvious’ safety points

- DO NOT use PTFE (or other fluorine compounds).
  - PTFE decomposes under ionising radiation, and, in air, forms hydrofluoric acid.
  - HF is acutely toxic and can damage equipment/irradiation chamber



CLP Classification - According to GB-CLP Regulations UK SI 2019/720 and UK SI 2020/1567

Physical hazards

Substances/mixtures corrosive to metal	Category 1 (H290)

Health hazards

Acute oral toxicity	Category 2 (H300)
Acute dermal toxicity	Category 1 (H310)
Acute Inhalation Toxicity - Vapors	Category 2 (H330)
Skin Corrosion/Irritation	Category 1 A (H314)
Serious Eye Damage/Eye Irritation	Category 1 (H318)

Environmental hazards

Based on available data, the classification criteria are not met

https://www.fishersci.co.uk/chemicalProductData_uk/wercs?itemCode=42380-0025

- Irradiate the LN_2 to a dose well below 10 kGy to reduce the risk of an ozone explosion
  - O_3 produced from O_2 and H_2O decomposition rapidly decomposes upon reaching a critical concentration
  - Do not refill an irradiated dewar – let it boil off completely

Acknowledgement

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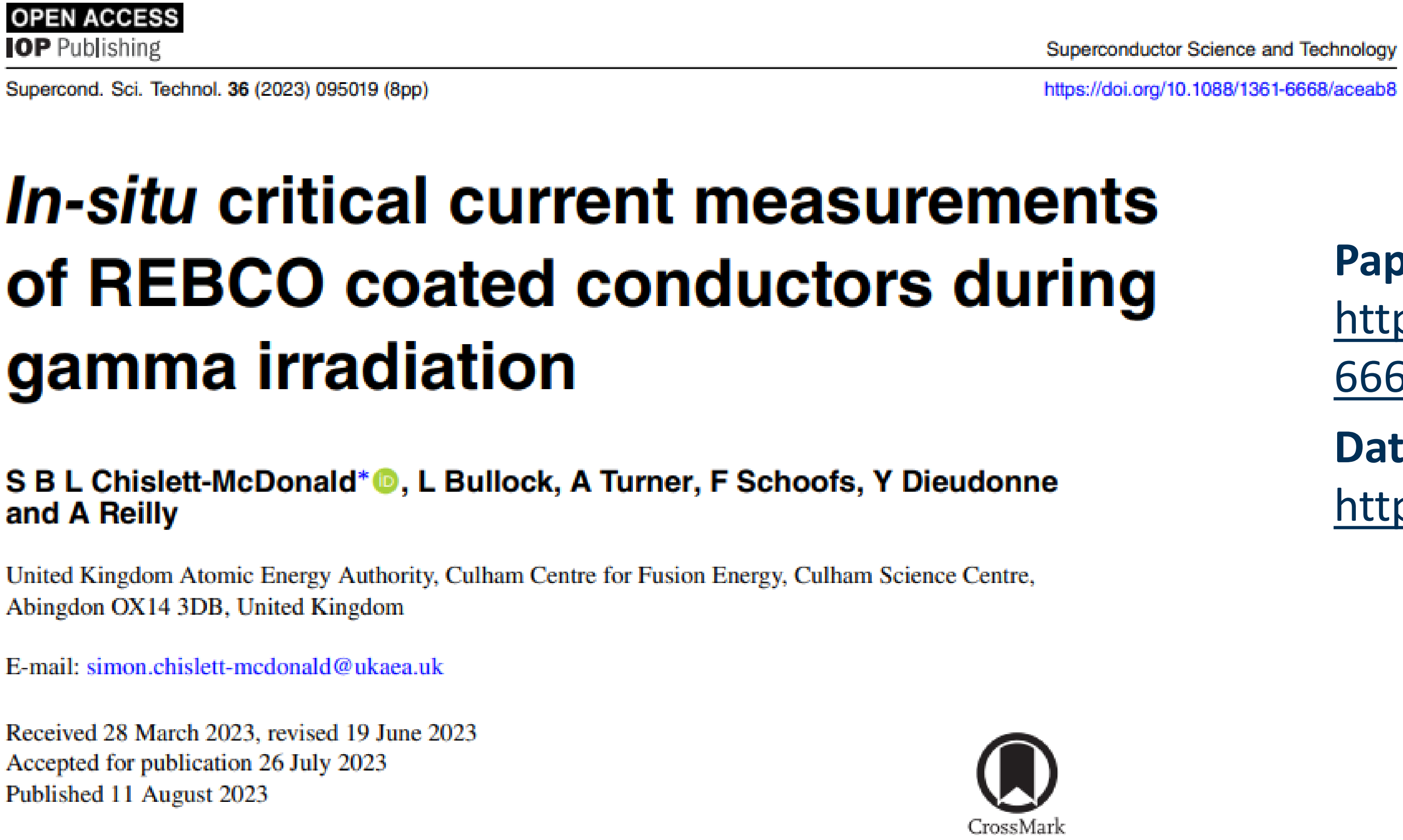

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In-situ critical current measurements of REBCO coated conductors during gamma irradiation

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Thank You

References from literature tables (slides 21 & 22)

Bohandy J et al. 1987 Applied Physics Letters 51(25), 2161

Kutsukake T et al. 1989 Japanese Journal of Applied Physics 28, L1393

Albliss B et al. 1993 Solid State Communications 88(3), 237-240

Özkan H et al. 1994 Journal of Superconductivity 7, 6

Cooksey J et al. 1994 IEEE Transactions on Nuclear Science 41(6), 2521-2524

Aksenova T et al. 1995 Radiation Physics and Chemistry 46(4-6), 533-536

Leyva A et al. 1995 Superconductor Science and Technology 8(11), 816

Elkohly M et al. 1996 Radiation Physics and Chemistry 47(5) 691-694

Zhao X et al. 2000 Physica C: Superconductivity 337(1) 234-238

Leyva A et al. 2001 Nuclear Instruments and Methods in Physics Research B 174, 222 -224

Akduran N 2012 Radiation Effects & Defects in Solids 167(4), 281- 288

Akduran N 2013 Radiation Physics and Chemistry 83 61-66

Iio M et al. 2022 IEEE Transactions on Applied Superconductivity 32(6) 6601905