TE Magnetics

Effect of Gamma Radiation on HTS – Present Understanding

Simon Chislett-McDonald

Contents

- Rationale – why care about gamma irradiation?
- Historical overview
- Recent work overview
- Comments on conflicting literature
- Summarising the present understanding & future outlook

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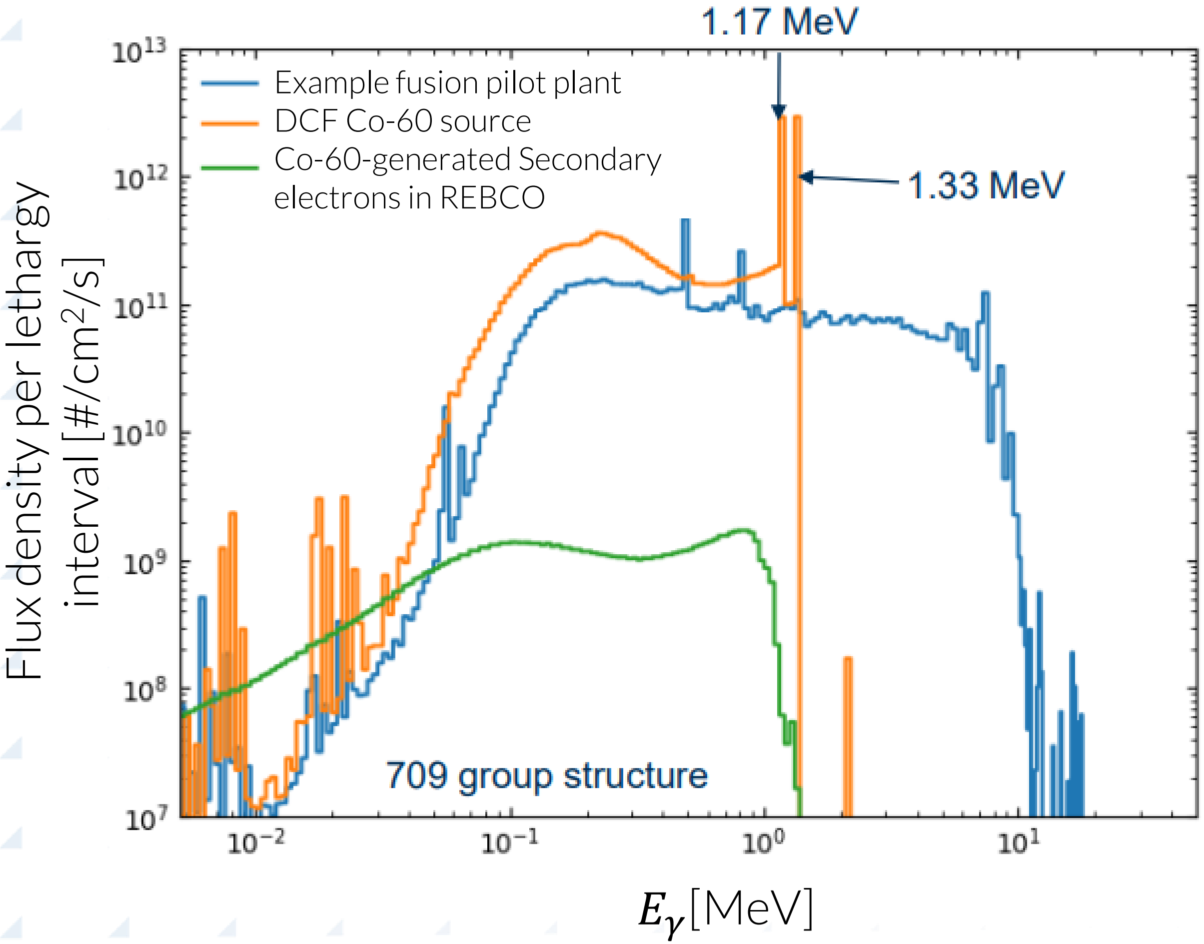
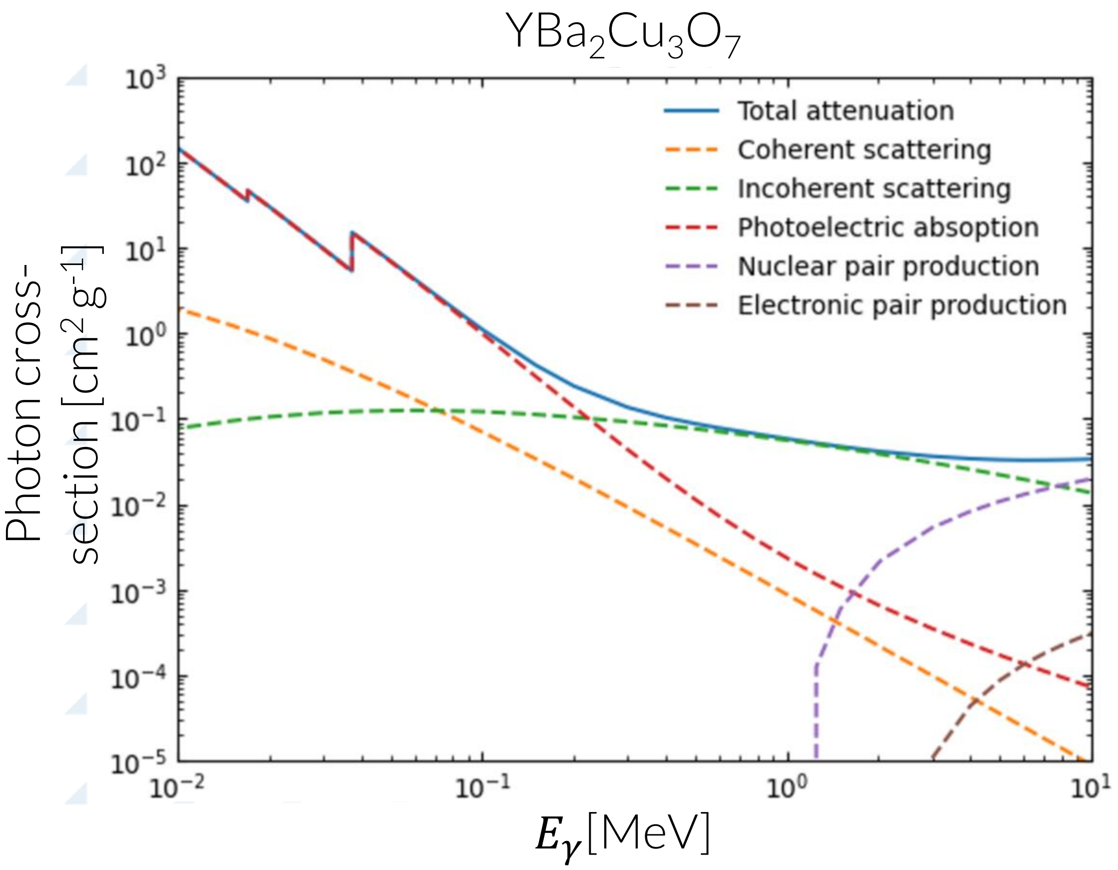
Why care about gamma irradiation?



- (n, gamma) interactions produce a broad spectrum photon flux incident on the magnets (the spectrum is a function of shielding material and thickness).
- The interaction of gamma rays with the magnet cold mass can generate a significant heat load on the cryogenics system.

Chislett-McDonald S B L et al., "Gamma In-Situ Cryogenic Experiment (ICE)", IREF 2023

Why care about gamma irradiation?



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

- The primary interaction mechanisms with fusion spectrum gamma rays are via electrons:
    - Photoelectric absorption (< 0.3 MeV)
    - Incoherent scattering (0.3 – 6 MeV)
    - Nuclear pair production (> 6 MeV)
- Gamma ray and secondary electron energies far exceed the binding energies of lattice ions (few 10s eV) or Cooper-pairs (few 10s meV).
- Is the REBCO lattice sufficiently damaged to degrade I_c & T_c?
- Are sufficient Cooper-pairs unbound to suppress superconductivity in-situ?

Chislett-McDonald S B L et al., Superconductor Science and Technology, 36, 095019

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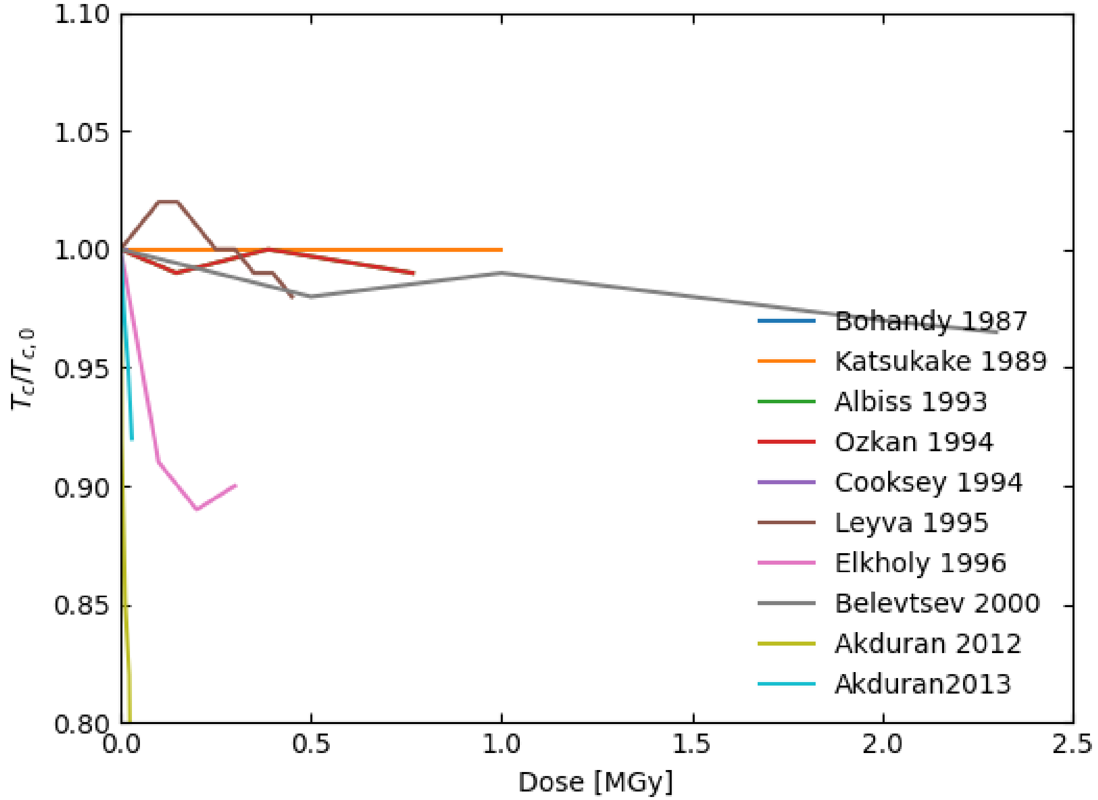

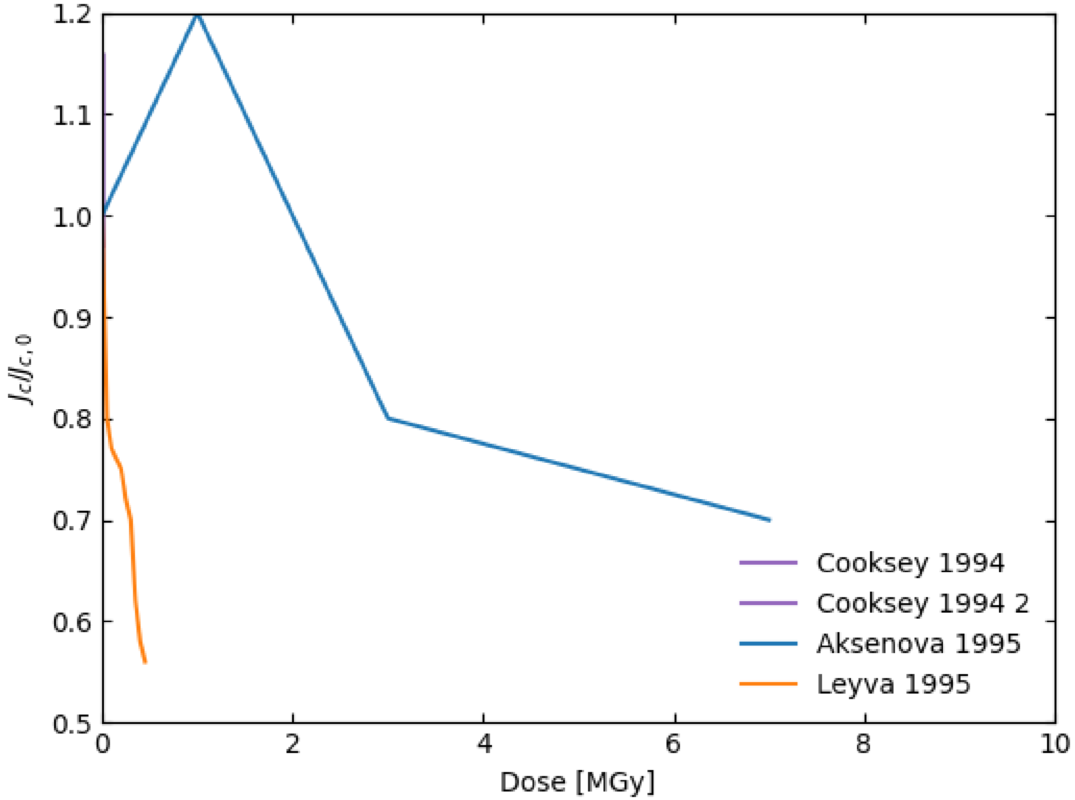

It's difficult to draw quantitative conclusions from these studies…

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Iio M et. al. "Investigation of Irradiation Effect on REBCO Coated Conductors for Future Radiation-Resistant Magnet Applications"

Max Dose: 27.4 MGy

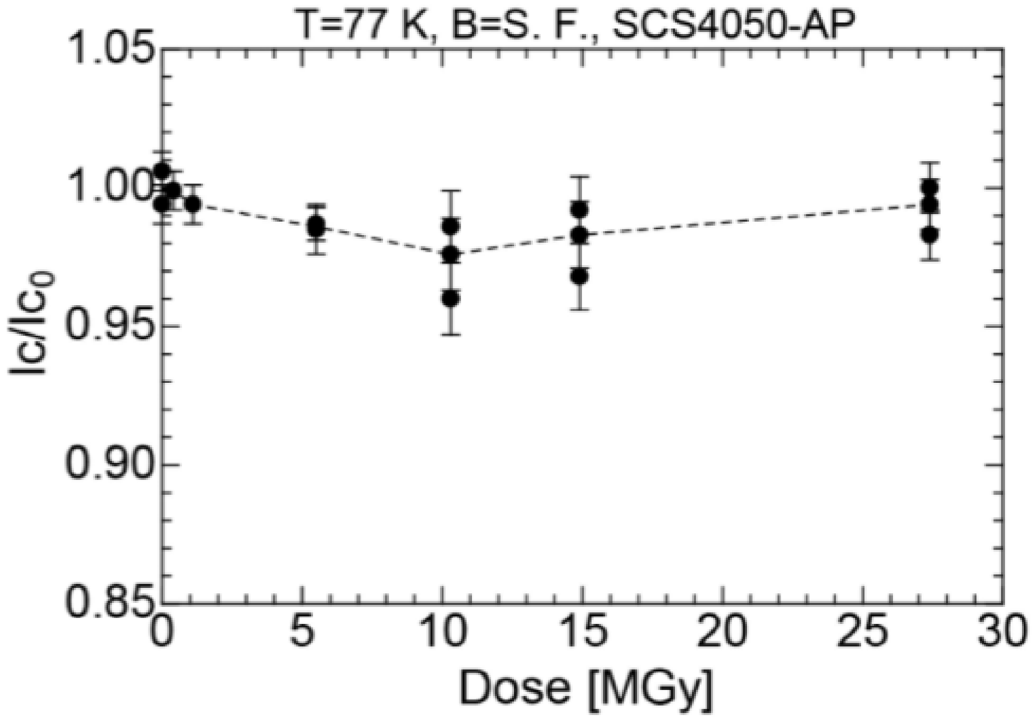
Change in ex-situ $I_{c,\ transport}$: No.

Sample type: Commercial REBCO tape

Sample condition: Irradiated at room temperature, inside evacuated capsules

Irradiation location: National institutes for Quantum Science and Technology, Takasaki, Japan

Gamma ray source: Co-60



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

Chislett-McDonald S B L et al. “In-situ critical current measurements of REBCO coated conductors during gamma irradiation”

Max Dose: 208 kGy

Change in in-situ $I_{c,\ transport}$: No

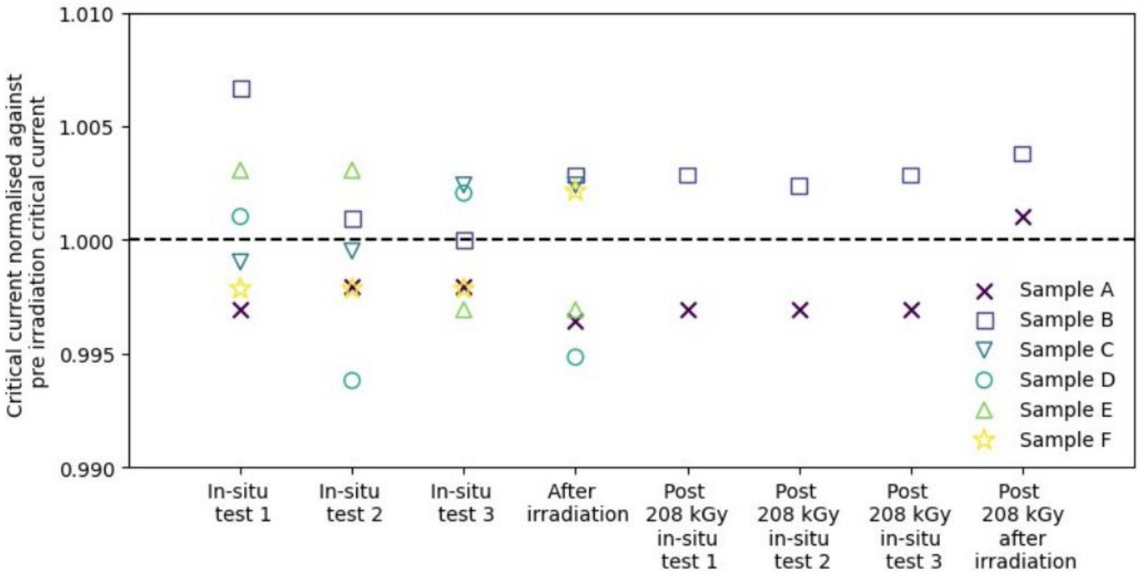
Change in ex-situ $I_{c,\ transport}$: No

Sample type: Commercial REBCO tape

Sample condition: Irradiated submerged in LN_2, followed by room temperature irradiation in air

Irradiation location: Dalton Cumbrian Facility, UK

Gamma ray source: Co-60



Chislett-McDonald S. B. L. et al. 2023 Superconductor Science and Technology, 26, 095019

Krkotić P et al. "Performance of high-temperature superconducting REBCO coated conductors under synchrotron irradiation for future circular colliders"

Max Dose: 400 Gy

Change in ex-situ surface resistivity: No

Change in in-situ $T_{c,\ resistivity}$: No

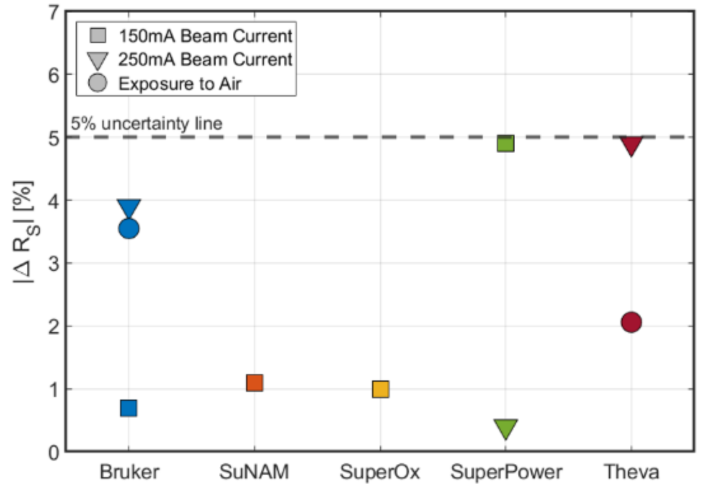
Change in in-situ surface impedance: Yes* (changes in surface impedance consistent with a drop in performance due to beam heating)

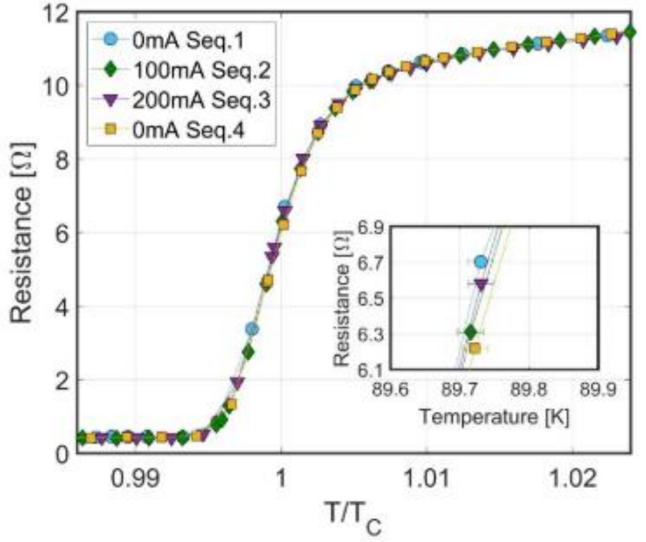
Sample type: Commercial REBCO tape

Sample condition: Irradiated (1) inside a vacuum chamber at room temperature (2) on cold-finger inside a cryostat

Irradiation location: ALBA synchrotron, Spain

X- ray source: see paper for spectrum





Krkotić P et al. 2023, Superconductor Science and Technology, 36, 105009

Campbell H J et al. Probing Evolution of the Flux-Pinning Landscape in REBCO Coated Conductors Caused by Gamma Irradiation Using DC and AC Magnetometry

Max Dose: 1 MGy

Change in ex-situ $J_{c,\ magnetisation}$: Yes

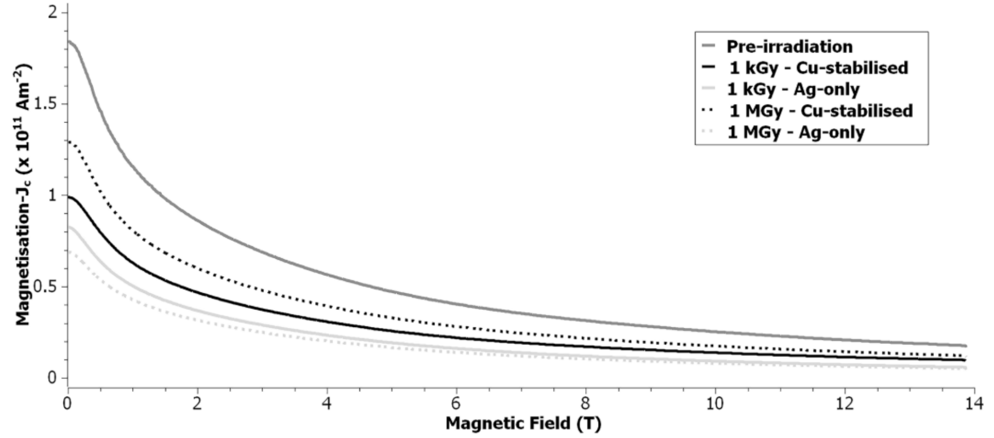
Change in ex-situ $T_{c,\ susceptibility}$: Yes

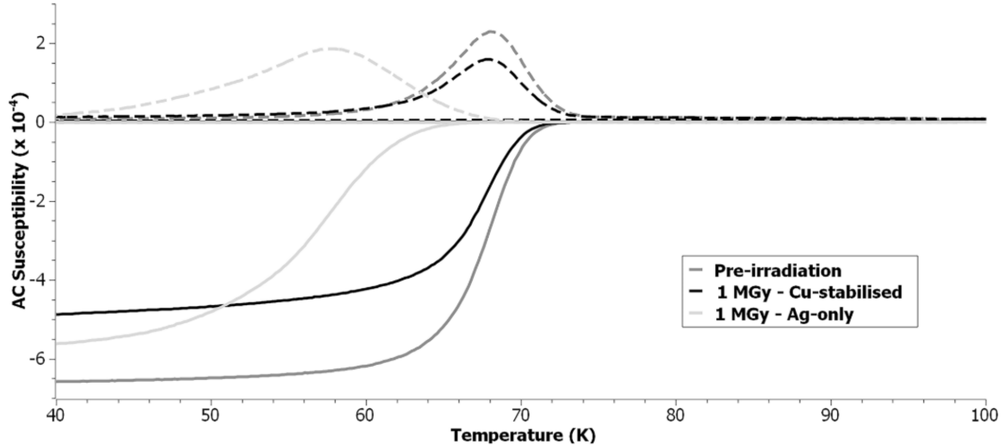
Sample type: Commercial REBCO tape (some without Cu outer layer)

Sample condition: Irradiated at room temperature in air

Irradiation location: Dalton Cumbrian Facility, UK

Gamma ray source: Co-60





Campbell H J et al. 2024, Journal of Superconductivity and Novel Magnetism, 37, 41-55

Taheri B et al. "Sensitivity of REBCO Tapes and Thin Film to Y-Irradiation"

Max Dose: 1 kGy

Change in ex-situ $T_{c\,,resistivity}$: No

Change in ex-situ $I_{c,\,transport}$: No

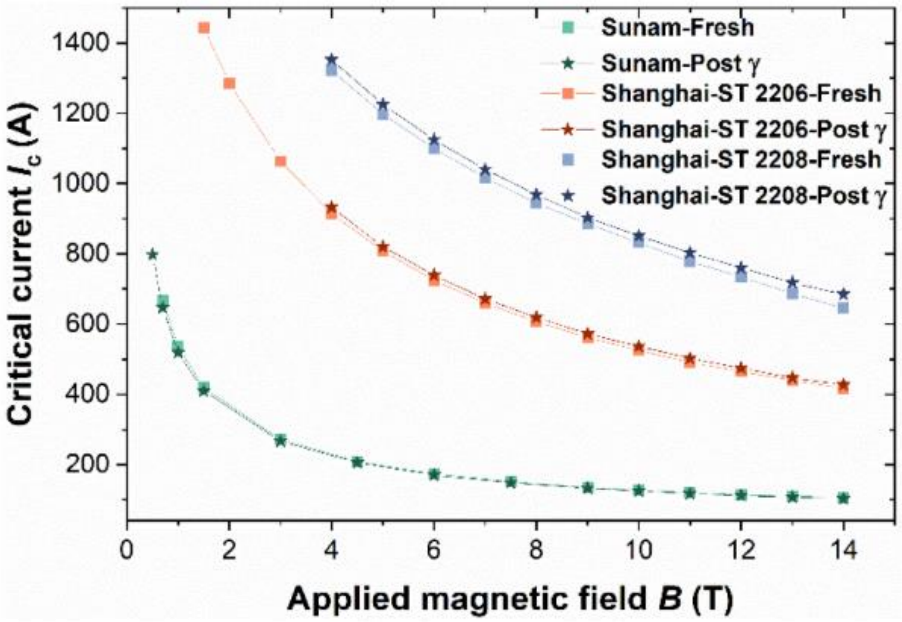
Change in ex-situ c-axis lattice parameter: No.

Sample type: Commercial REBCO tape & thin films

Sample condition: Irradiated at room temperature, inside evacuated capsules

Irradiation location: Calliope irradiation facility, Italy

Gamma ray source: Co-60



Sample	Parameter	Fresh	Post γ-exposure
YBCO/STO	T_c (K)	90.4 ± 0.2	89.9 ± 0.2
	RRR	2.9 ± 0.1	3.1 ±0.2
	ΔT (K)	0.39 ± 0.06	0.42 ± 0.05
YBCO/LAO	T_c (K)	89.8 ± 0.1	89.3 ± 0.3
	RRR	3.1 ± 0.1	3.1 ± 0.1
	ΔT (K)	0.43 ± 0.02	0.45 ± 0.03

Taheri B et al. 2024, IEEE Transactions on Applied Superconductivity, 34, 6600105

Zheng Y et al "Gamma radiation effects on high-temperature superconducting ReBCO tape"

Max Dose: 910 kGy

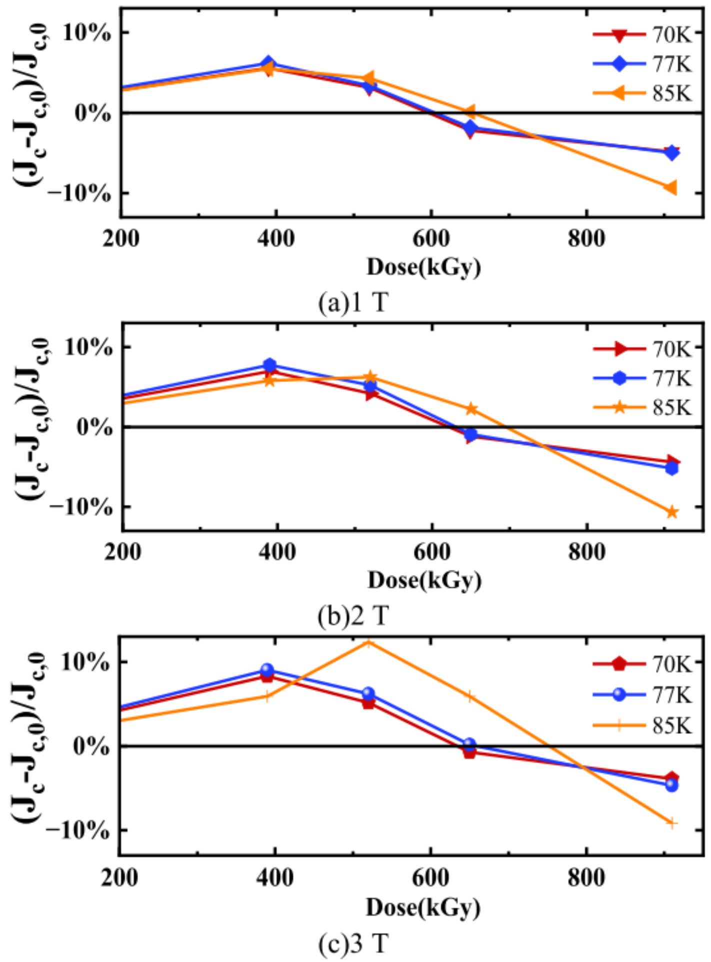
Change in ex-situ $J_{c,magnetisation}$: Yes

Sample type: Commercial REBCO tape

Sample condition: Irradiated at room temperature (atmosphere undisclosed)

Irradiation location: University of Science and Technology of China.

Gamma ray source: Co-60



Zheng Y et al. 2024, Superconductor Science and Technology, 37, 045013

Campbell H J et al. Investigation of Gamma-Induced Changes to Screening Currents and AC Losses in Mono- Versus Multi-filamentary REBCO Coated Conductors Using DC and AC Magnetometry

Max Dose: 5 MGy

Change in ex-situ $J_{c,\ magnetisation}$: Yes

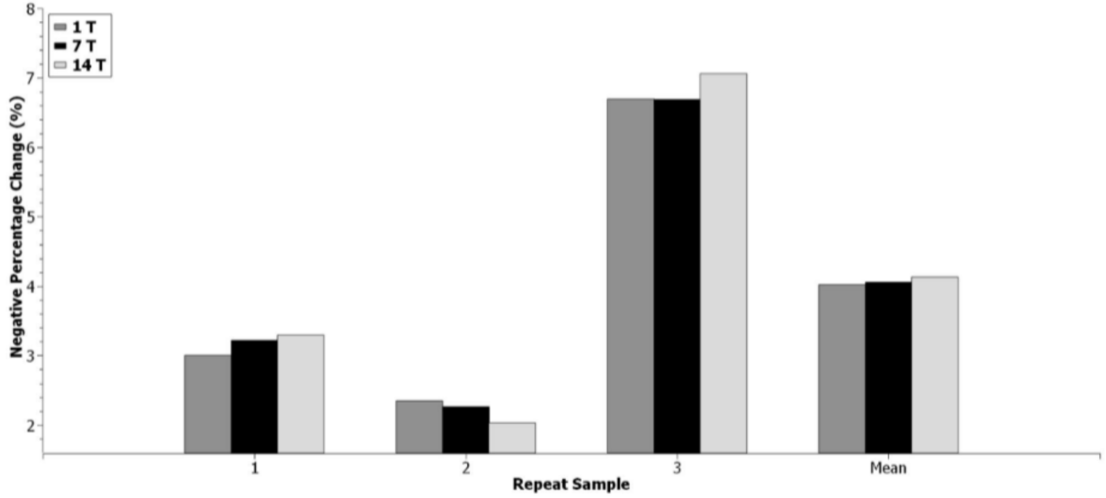
Change in ex-situ $T_{c,\ susceptibility}$: No

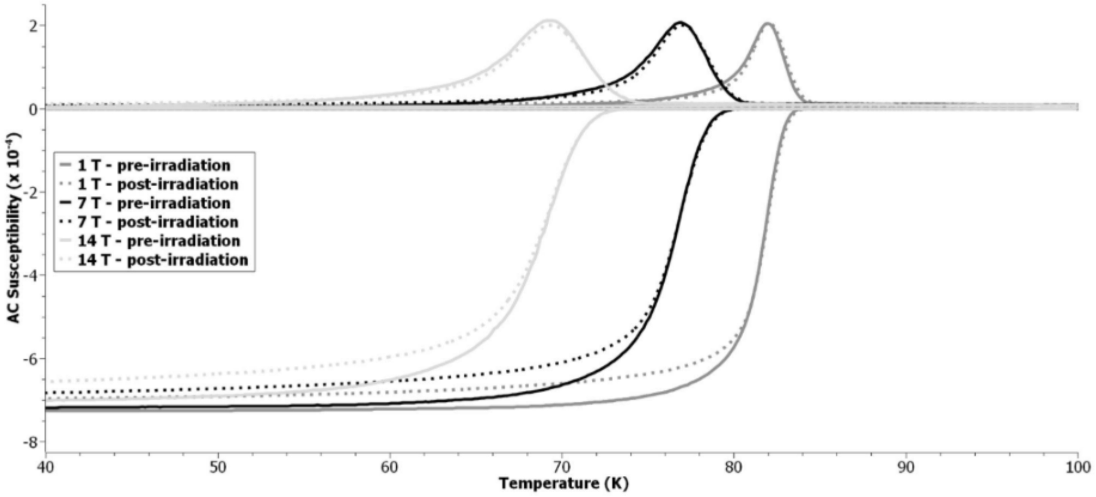
Sample type: Commercial REBCO tape (some multifilamentary)

Sample condition: Irradiated at room temperature in air

Irradiation location: Dalton Cumbrian Facility, UK

Gamma ray source: Co-60





Campbell H J et al. 2024, Journal of Superconductivity and Novel Magnetism, 37, 1349-1369

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Why is the literature so contradictory? Some thoughts…

Irradiated samples compared to a 'control' sample rather than themselves prior to irradiation.

Few or no repeat samples in many studies – some conclusions are drawn from a statistically insignificant dataset.

Irradiation conditions not well controlled: Ionising radiation produces free radicals that damage REBCO via chemical processes rather than through radiation damage (per se) reducing performance (particularly for samples with no protective metal layers) see Aksenova T et al. 1995, Radiation Physics and Chemistry 46, 533-536.

Samples irradiated under vacuum, or a dry atmosphere, appear not to suffer degradation

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Present Understanding

Insufficient evidence to state that fusion relevant gamma doses have a significant effect on REBCO superconducting performance

No in-situ effect (besides heating) has been observed

Irradiation conditions matter: gamma radiation catalyses chemical degradation

Results are promising for fusion and accelerator applications

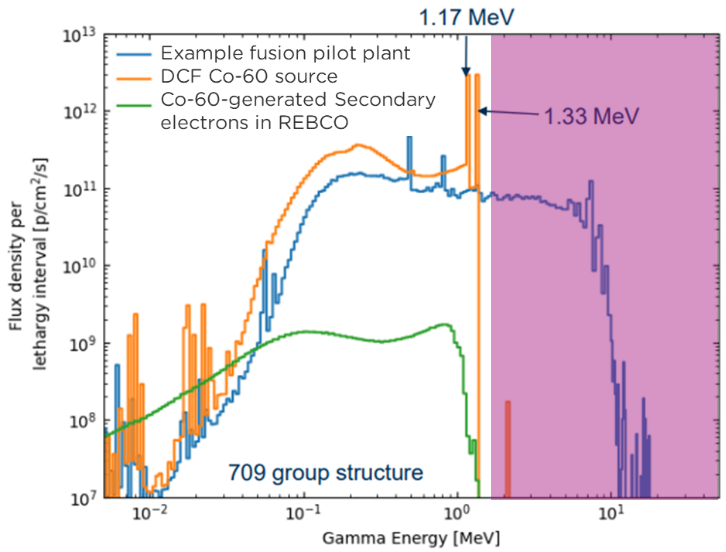
What are we missing?

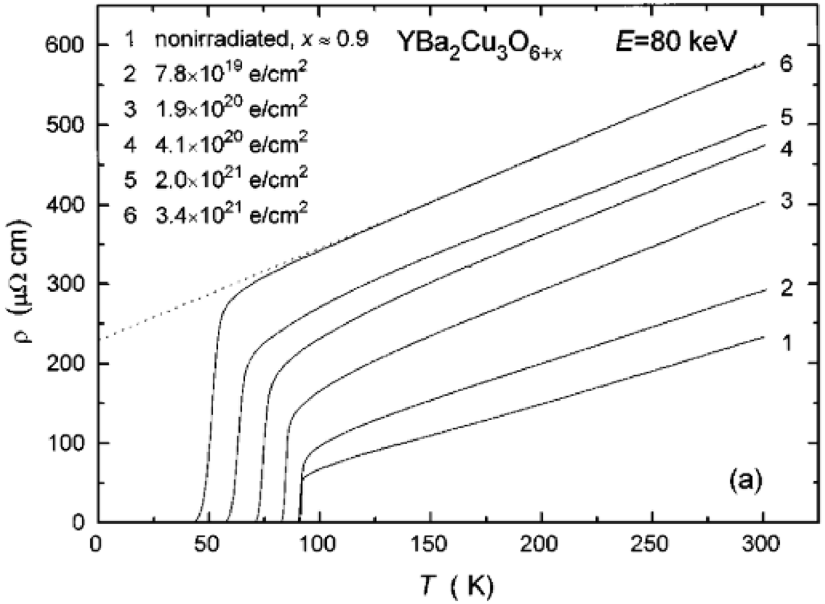
Higher energies of ~ 10 MeV

- Some fusion spectrum gamma rays are of higher energies than Co-60. These photons mainly interact through nuclear pair production – does this different mechanism result in different damage and/or interaction with Cooper-pairs?

Higher doses up to 10s MGy

- Are gammas producing *any* microstructural damage, or have the doses simply been too low to see an effect?
  - T_c has been observed to drop after a ~ 10^{20} e/cm^2 dose of electrons, and gamma irradiation produces secondary electrons… so a 'high enough' dose may degrade superconductivity. e.g. the 27 MGy from Iio et al. corresponds to a (broad band) secondary electron dose of ~ 10^{14}-10^{15} e/cm^2





Tolpygo S K et al. 1996, Physical Review B, 53, 12463-124784

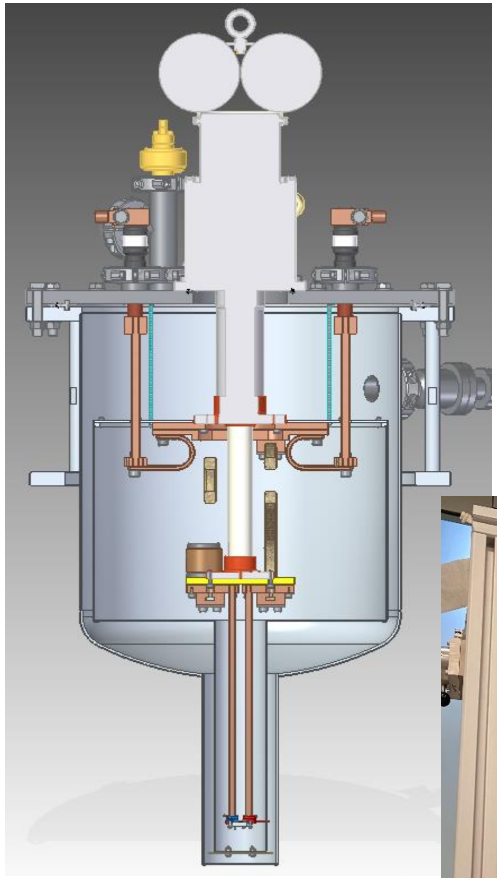
Tokamak Energy's GAMMA experiment

Coil Design

- 18 coils made with tape from key suppliers
- 4 mm x 1.6 mm radial thickness (12-24 turns depending on tape)
- No insulation coil structure
- Ensures all turns are operating at or close to I_c and the entire coil is uniformly irradiated

Cryogenic System Design

- Cryocooled system
- 1 kA current capacity
- 20 – 50 K coil temperature (current dependent)
- Optimised current leads taking accounting for gamma heating along leads
- Voltage, temperature and magnetic field monitoring



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Tokamak Energy’s GAMMA experiment

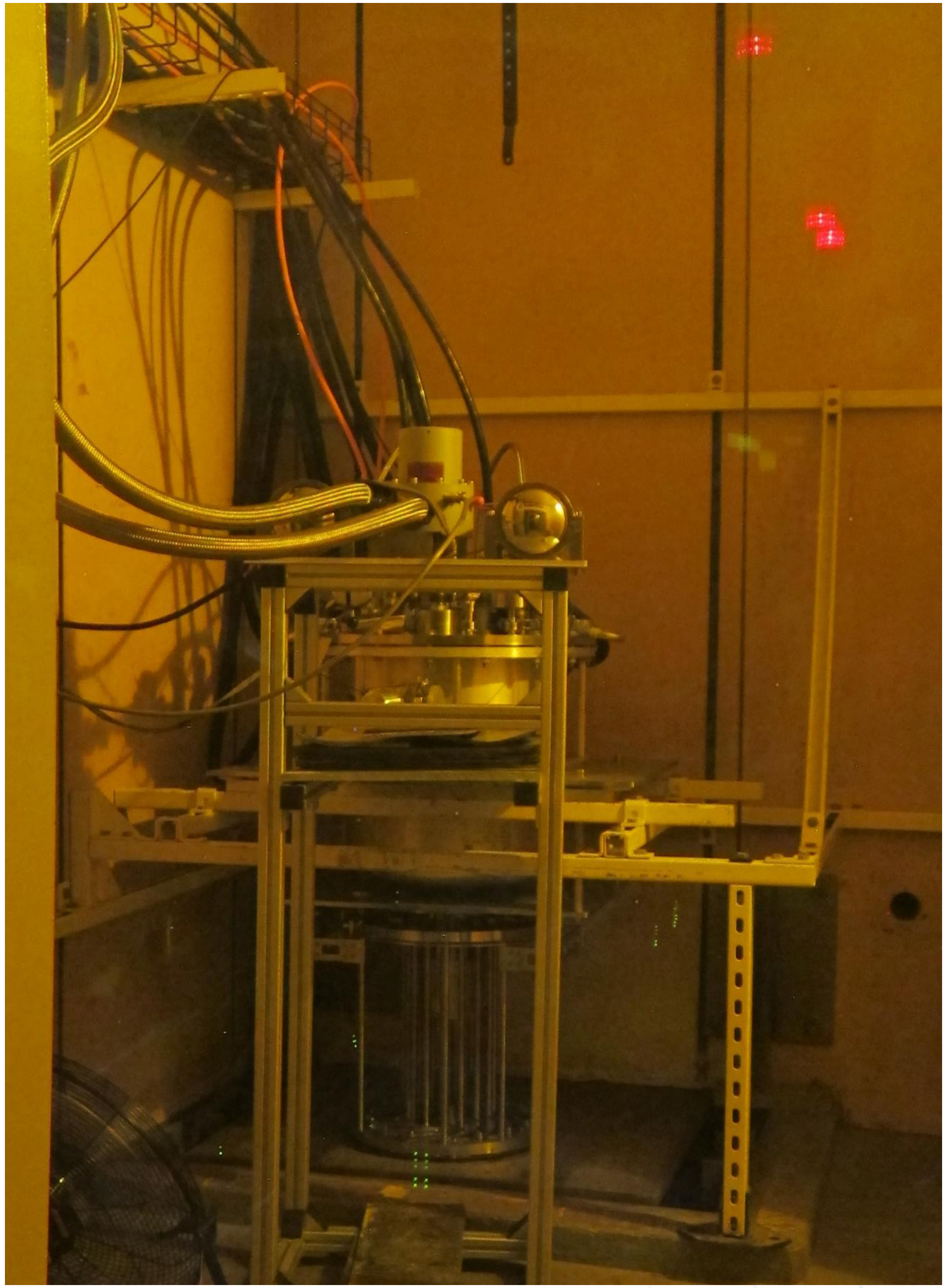
Test Protocol

- Coil cooled and energised
- Co60 array positioned to provide gamma dose of 7 Gy/sec
- System re-stabilises in reaction to heat load
- Irradiation continued for ~16.5 days to 10 MGy

✓ System functioned reliably under challenging operation conditions

✓ Key sensors worked as expected

✓ Several coils irradiated to 10 MGy



TE Magnetics

Opening new fields of performance

Magnet systems to accelerate commercial development for new applications for HTS, in fusion, renewable energy, medicine, science and propulsion in water, land, air and space.

References – Recent Work

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Campbell H J et al. 2023, Journal of Superconductivity and Novel Magnetism, 37, 41-55

Krkotić P et al. 2023, Superconductor Science and Technology, 36, 105009

Chislett-McDonald S B L et al., Superconductor Science and Technology, 36, 095019

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

Bartunek V et al. 2020 Ceramics International, 46, 15400-15407

References – Historical Work

Akduran N 2013, Radiation Physics and Chemistry 83, 61-66

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

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

Belevtsev B I et al 2000, Physica C: Superconductivity 341, 2015-2016

Elkohly M et al. 1996, Radiation Physics and Chemistry 47, 691-694

Leyva A et al. 1995, Superconductor Science and Technology 8, 816-821

Aksenova T et al. 1995, Radiation Physics and Chemistry 46, 533-536

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

Özkan H et al. 1994, Journal of Superconductivity 7, 885-888

Albiss B et al. 1993, Solid State Communications 88, 237-240

Luo L et al. 1991, Physica C: Superconductivity 178, 11-14

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

Vassek P. et al. 1989 Solid State Communications 69, 23-25

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