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Abstract. Rare-earth-barium-copper-oxide (REBCO) coated conductor tapes within next-generation tokamak pilot and power plant magnets will be exposed to broad-spectrum gamma-ray and neutron irradiation concurrently. It has been known since the 1980s that cumulative neutron fluence affects the superconducting properties of REBCO, but the effects of gamma rays are less certain, as are the effects of radiation (of any kind) during current flow. However, the use of superconductors as photon detectors suggests that energetic photons interact directly with the superconducting state, locally destroying superconductivity. Hence, as well as the effect of the overall radiation dose (fluence), the effect of radiation dose rate (flux) on the superconductor's properties must be quantified to understand how REBCO magnets will perform during fusion magnet operation.

In-situ measurements of the self-field critical current at 77 K, of several REBCO coated conductor tapes were performed during Co-60 gamma ray exposure at a dose rate of 86 $\mathrm{Gy\,min^{-1}}$. Samples were fully submerged in liquid nitrogen throughout the measurements. No change in the critical current of any sample during or after irradiation was observed within standard error. These are the first reported in-situ measurements of critical current during fusion-relevant gamma irradiation. Two samples were irradiated to a further dose of 208 kGy at room temperature and a second round of in-situ measurements was performed. No change in the critical current of these samples was observed within standard error. This corroborates recent studies, but is in conflict with older literature.

Keywords: REBCO, irradiation, gamma irradiation, coated conductors, fusion

1. Introduction

The high critical current densities, fields and temperatures of rare-earth-barium-copper-oxide (REBCO) superconductors make them an attractive material choice for the primary magnets of next-generation fusion reactors and pilot power plants [1, 2, 3]. Fusion reactors however present a novel and challenging environment for superconducting magnet operation, due in part to the high neutron fluxes and consequent gamma radiation to which the magnets will be subjected. (n,γ) interactions within the material layers between the plasma and the magnets (first wall, blanket, neutron shielding etc.) and within the magnets themselves lead to the production of a broad-spectrum photon flux, including gamma rays with energies exceeding 10 MeV (Figure 1). These gamma rays primarily interact with REBCO through photoelectric absorption ($E_\gamma < 0.3$ MeV) and Compton scattering (0.3 MeV $< E_\gamma <$ 10 MeV) (Figure 2). Both processes generate scattered electrons with energies up to the the incident gamma ray energy. These scattered electrons impart their energy to the superconductor generating a transient "hot spot" as they travel through and interact with the ion lattice destroying superconductivity locally [4, 5]. Energetic electrons can also collide with and displace atoms out of their lattice locations if the energy imparted to the atom exceeds its threshold displacement energy [6]. Stable defects in the lattice can reduce Cooper-pair density and affect the material superconducting properties [7].

Reproducing the broad fusion gamma spectrum artificially is prohibitively difficult outside of a fusion reactor. For the work detailed here, we have used the Dalton Cumbrian Facility's (DCF) Co-60 gamma source [8]. The spectrum of gamma ray energies produced by Co-60 decay has peaks at 1.17 MeV and 1.33 MeV which primarily interact with REBCO through Compton scattering (Figure 2). All previously published gamma-irradiation measurements of macroscopic REBCO samples were performed ex-situ – that is, measurements of critical current were taken after samples were irradiated (at room temperature or cryogenic temperature). Such experiments are valuable to determine the engineering lifetime of superconductors as a function of radiation fluence but offer no information as to how radiation affects superconductivity during current flow. They also have conflicting conclusions: some observe no change in critical current with fluence [9, 10]; others show an initial increase in critical current, followed by a decrease at larger fluences [10, 11]; others still only show a decrease in critical current with fluence [12].

This paper reports an in-situ experiment to investigate the effect of gamma rays on the critical current of REBCO coated conductor tapes. Current-voltage (I-V) traces were measured during gamma irradiation with samples submerged in liquid nitrogen at 77 K at self-field. The dose rate on the REBCO samples was $\approx 86\ \mathrm{Gy\,min^{-1}}$, roughly equal to the maximum expected dose rate on the magnets of proposed fusion power pilot plants.

2. Experimental Details

2.1. Sample Preparation

The REBCO tapes tested were SuperPower SCS4050-AP (2011) coated conductors. Bridges of widths 0.5 and 0.25 mm were laser-cut into 100 mm long, 4 mm wide samples (Figure 3). Using bridges reduces the tapes' effective critical current thereby reducing the current required from the power supply unit and the power deposited in the tape as a result of resistive heating during measurements. The laser cut channel had an ablation depth of 33.8 µm (approximately 10 µm into the Hastelloy substrate) and width of 30 µm. The copper stabiliser and silver diffusion barrier over-layers were not removed from the samples. This was done for ease of electrical connection, to assist with heat conduction away from the REBCO layer and to protect the REBCO layer from chemical damage.

2.2. Sample Mounting and Measurement Procedure

Three samples with 0.5 mm bridge width (A, B and C) and three samples with 0.25 mm bridge width (D, E and F) were prepared as above. Samples were individually affixed to the test fixture (see Figure 3) using copper clamps, which also acted as the current supply and voltage tap connections. There is a gap of 40 mm between the voltage taps. The test was then introduced to a 2 L liquid nitrogen dewar. The dewar was then placed inside the DCF gamma irradiation chamber. For each sample, an I-V trace was measured once prior to irradiation. The Co-60 rods were then raised into the irradiation chamber, and I-V traces were measured three times whilst the sample was exposed to gamma irradiation. The Co-60 rods were then lowered and an I-V trace was measured again after irradiation. Samples remained submerged in liquid nitrogen throughout the five measurements.

The current was set to increase at 0.1 A intervals and held at each interval for 10 seconds, and the voltage was recorded. A cut-off voltage of 50 µV was set for each measurement. When the voltage reached this value the power supply unit was immediately shut down to avoid damage to the sample. The maximum power through the samples was approximately $22.5\ \text{A}\times 50\ \mu\text{V} = 1.125$ mW in the case of samples A, B and C, and approx. $12.5\ \text{A}\times 50\ \mu\text{V} = 0.625$ mW in the case of samples D, E and F. Only three in-situ measurements could be performed at one time due to the safe maximum dose for 5 kGy on liquid nitrogen, which has been known to explode after a dose of 10 kGy [13]. A total dose of ≈ 3.5 kGy was received by the samples during the three in-situ measurements. Samples A and B were additionally irradiated to a further dose of 208 kGy at room temperature. The samples were tested again as above, with the exception that no post-irradiation measurement was undertaken.

3. Radiation Transport Calculations

Monte Carlo N-Particle (MCNP) calculations of the DCF gamma chamber were performed to calculate the expected dose rate of the samples during testing. The dose rate calculations were validated against Radcal 10X6-0.18 high dose-rate ion chamber measurements [14], performed within the irradiation chamber prior to the experiment by DCF staff - accurate to ± 4 %. The modelled samples were treated as a homogenised bulk weighted by percentage mass of the various tape constituent atomic species (inclusive of the tape Cu stabiliser, Ag diffusion barrier, REBCO, buffer layers and Hastelloy substrate). The calculations yielded an average dose rate of 86 $\text{Gy}\,\text{min}^{-1}$ to the sample. The dose rate of the parts of the samples in the shadow of the clamps and bolts is approximately two times lower than the parts of the tape that were fully exposed. The flux across the bridge region was uniform. Figure 4 shows a 2D map of the flux across the irradiation chamber and the dose rate of the sample.

4. Results

The standard $E_c = 100\ \mu\mathrm{V\,m^{-1}}$ electric field criterion was used for critical current density. This corresponds to a voltage criterion of $\mathrm{V}_c = 4\ \mu\mathrm{V}$ in this study. Data were fitted between electric fields of $\mathrm{E} = 0.4\ \mu\mathrm{V}$ and $\mathrm{E} = 8\ \mu\mathrm{V}$ to the power law [15]

$$V(I) = V_c \times \left(\frac{I}{I_c}\right)^n , \tag{1}$$

where I is current, I_c is critical current. The mean critical currents (and standard error) of each sample are summarised in Table 1. Individual I-V curves for the five measurements (once before irradiation, three in-situ tests and once after irradiation) are shown in Figure 5 for samples A-F. Individual I-V curves for the four further measurements (once prior to irradiation and three in-situ tests) on samples A and B after an additional room temperature dose of 208 kGy are shown in Figure 6.

No effect was observed on the critical currents of any samples under Co-60 gamma irradiation at a dose rate of 86 $\mathrm{Gy\,min^{-1}}$. Any gamma interactions with the REBCO tapes were sufficiently small as to be within the error of the measurement. MCNP calculations predict a total gamma-induced heat load on the tapes of 0.21 W so it is therefore not surprising that the effective cooling method of liquid nitrogen submersion eliminated any effect of heating (as was the intention). The variation in the critical currents of different samples is attributed to variation in critical current along and across a tape, or defects caused during sample preparation. The in-situ critical currents of samples A and B were also unchanged after receiving an additional room temperature 208 kGy dose. This suggests that total absorbed dose does not affect whether a gamma flux during current flow has an affect on superconductivity. Similarly, the critical currents of samples A and B after the additional 208 kGy dose were unchanged with respect to the initial before-irradiation, measurements.

5. Discussion

The observed null effect of gamma fluence corroborates the negligible effect of gamma flux on 77 K critical current, I_c(77K), at a dose of up to 27.4 MGy reported in recent work by Lio et al. [9]. Older studies however observe conflicting effects. Cooksey et al. [10] irradiated two YBCO samples using a Cs-137 source. In one sample they observed an initial increase to to $1.2{\times}I_{c0}$(77K) after a 6 kGy dose followed by a drop to $0.9{\times}I_{c0}$(77K) after a 15 kGy dose. In a second sample they observed no change in I_c with dose. Aksenova et al. [11] report an initial increase to $1.2{\times}I_{c0}$(77K) after a 1 MGy dose followed by a decrease to $0.7{\times}I_{c0}$(77K) after a dose of 7 MGy. However, the spectrum of the gamma rays to which the REBCO bulk sample was subjected to was not reported, making direct comparison difficult due to the different possible gamma ray interactions with matter depending on energy. Leyva et al. [12] observe an initial rapid decrease in I_c(77K) of thick film, polycrystalline, REBCO samples to $0.8\times I_{c0}$(77K) for Co-60 doses up to 100 kGy followed by a plateau in degradation up to a dose of 250 kGy and gradual degradation to $0.6\times I_{c0}$(77K) by a dose of 400 kGy. The initial sharp drop is attributed to radiation induced damage at grain boundaries; the plateau is attributed to a combined effect of improvement in T_c with doses up to 300 kGy with this grain boundary damage; and the gradual degradation is attributed to an over-saturation of radiation induced point defects. However, in all of these studies [10, 11, 12], the YBCO layer was exposed to air during irradiation and would therefore have been subject to gamma-induced chemical reactions which may have contributed to the observed change in I_c [11]. In the aforementioned work by Lio et al. [9] the samples were commercial REBCO tapes complete with their protective silver and copper layers (as in our study), which were additionally sealed in vacuum during irradiation and measurement to prevent these chemical reactions. The results from these works are summarised in Table 2.

Other related work pertains to the effect of gamma irradiation on the critical temperature, T_c, of high temperature superconductors which was not measured during this work. For completeness, the experiments are also summarised in Table 2. The conclusions of different studies are inconsistent. Bohandy et al. [16], Kutsukake et al. [17], Albiss et al. [18] and Özkan et al. [19] observed no change in T_c after Co-60 gamma ray doses of 13 kGy, 1 MGy, 0.8 MGy and 0.8 MGy, respectively. Cooksey et al. [10] similarly saw no change in T_c after a 15 kGy Cs-137 dose. Elkholy et al. [20] saw no change in T_c in Sr doped $YBa_2Cu_3O_{7-x}$ up to doses of 200 kGy after which T_c steadily dropped with fluence, falling by 7 K by 500 kGy. Akduran [21] observed an unprecedented 47.1 K drop in the T_c of $Y_3Ba_5Cu_8O_{18}$ after a dose of 45 kGy and a drop of 8.1 K in T_c of $EuBa_2Cu_3O_{7-x}$ after 30 kGy. The significant decrease in T_c of the Y-based sample would render $I_c(77K) = 0$, which is clearly in contrast with the unchanged I_c measured in this work. The environment of the irradiation chamber use by Akduran is not described, so the reduction in T_c could perhaps be due to gamma-catalysed chemical reactions as proposed in [11]. Leyva et al. witnessed improvements in the T_c of $YBa_2Cu_3O_{7-x}$ of ≈ 2 K after 150 kGy Co-60 dose [12] and after a 270 mGy Cs-137 dose [22]. The cause suggested was gamma ray induced oxygen reordering and overall greater crystal uniformity (assumed to be non-optimal prior to irradiation), followed by degradation from “overdoping”. The T_c of Bi-system has also been observed to increase by 16 K after a dose of 600 kGy [23]. Zhao. et al. [24] performed cryogenic irradiation of Bi-system (the chemistry was undefined) at 30 K using gamma rays derived from a proton irradiated lithium target. An initial increase in T_c of 5 K was measured, followed by an eventual drop of 3 K after 90 days. The spectrum of the gamma rays was however not disclosed, making comparison with other work difficult. Different electronic (and indeed nuclear) interactions may take place depending on the incident gamma ray energy leading to, in principle, different microstructural damage. The conflicting nature of the literature suggests that more research is required before any firm conclusions can be drawn on the effect of gamma dose on high temperature superconductors. Future investigations should take pains to prevent chemical degradation of REBCO samples.

6. Conclusions

The self field, 77 K critical currents of SuperPower SCS4050-AP (2011) tapes were measured during 86 $\mathrm{Gy\,min^{-1}}$ Co-60 gamma ray flux (approximately equal to the peak flux expected on the magnets of proposed fusion pilot power plants). No effect on the critical current was observed within error. This is a promising result for fusion magnets, suggesting that the current carrying capacity of REBCO magnets will not degrade as a result of incident gamma ray flux (of these energies) in-situ. The questions of the effects of (n,γ) interactions within the REBCO itself, higher energy gamma flux, and fusion-relevant in-situ neutron flux must still be answered. Additionally, no effect on critical current was observed for tapes that were irradiated to a total dose of $\approx$ 215 kGy within error. This finding corroborates more recent studies on the effects of gamma dose on commercial REBCO tapes, but is in conflict with older literature on the effects on REBCO lab-manufactured samples. This is perhaps due to protection offered by the tape copper and silver layers from gamma-catalysed chemical reactions not present in older work.

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Table 1. 77 K, self field critical currents of samples A, B and C with bridge widths of 0.5 mm and samples D, E and F with bridge widths of 0.25 mm. I-V traces were measured before and after irradiation and three times during irradiation. Samples A and B were irradiated with a further dose of 208 kGy at room temperature and a second round of in-situ tests was performed. Mean and standard error on critical currents are shown.

	Critical Current I_c(77 K) [A]		
	Before and After Irradiation	During Irradiation	During Irradiation post 208 kGy dose
Sample A, 0.5 mm bridge	19.78 ± 0.04	19.76 ± 0.01	19.75 ± 0.01
Sample B, 0.5 mm bridge	21.06 ± 0.03	21.11 ± 0.06	21.09 ± 0.01
Sample C, 0.5 mm bridge	20.72 ± 0.02	20.68 ± 0.03	-
Sample D, 0.25 mm bridge	9.69 ± 0.03	9.68 ± 0.03	-
Sample E, 0.25 mm bridge	9.76 ± 0.01	9.81 ± 0.03	-
Sample F, 0.25 mm bridge	9.34 ± 0.01	9.31 ± 0.01	-

Table 2. Summary of the literature on the effects of gamma irradiation dose on high temperature superconductors on their critical current and critical temperature.

Ref.	HTS	Irradiation temperature [K]	γ source	γ dose [MGy]	Observation
[9]	SCS4050-AP	293	Co-60	27.4	$I_c/I_{c0} = 1.0$
[10]	^{a}YBa$_2$Cu$_3$O$_{7-x}$	293	Cs-137	6.0×10^{-3}	$I_c/I_{c0} = 1.2$
				1.5×10^{-2}	$I_c/I_{c0} = 0.9$
[10]	^{b}YBa$_2$Cu$_3$O$_{7-x}$	293	Cs-137	6.0×10^{-3}	$I_c/I_{c0} = 1.0$
				1.5×10^{-2}	$I_c/I_{c0} = 1.0$
[11]	YBa$_2$Cu$_3$O$_{7-x}$	293	?	1.0	$I_c/I_{c0} = 1.2$
				3.0	$I_c/I_{c0} = 0.8$
				7.0	$I_c/I_{c0} = 0.7$
[12]	YBa$_2$Cu$_3$O$_{7-x}$	293	Co-60	0.1	$I_c/I_{c0} = 0.8$
				0.2	$I_c/I_{c0} = 0.8$
				0.3	$I_c/I_{c0} = 0.7$
				0.4	$I_c/I_{c0} = 0.6$
[12]	YBa$_2$Cu$_3$O$_{7-x}$	293	Co-60	0.1	$\Delta T_c = 1.5$ K
				0.2	$\Delta T_c = 2.0$ K
				0.3	$\Delta T_c = 0.0$ K
				0.4	$\Delta T_c =$ -1.0 K
[16]	YBa$_2$Cu$_3$O$_{7-x}$	293	Co-60	$1.3{\times}10^{-2}$	$\Delta T_c = 0.0$ K
[17]	YBa$_2$Cu$_3$O$_{7-x}$	293	Co-60	1.0	$\Delta T_c = 0.0$ K
[18, 19]	YBa$_2$Cu$_3$O$_{7-x}$	293	Co-60	0.8	$\Delta T_c = 0.0$ K
[20]	YBa$_{2-y}$Sr$_y$Cu$_3$O$_{7-x}$	293	Co-60	0.2	$\Delta T_c = 0.0$ K
				0.5	$\Delta T_c =$ -7.0 K
[21]	Y$_3$Ba$_5$Cu$_8$O$_{18}$	293	Co-60	2.4×10^{-3}	$\Delta T_c =$ -8.0 K
				1.2×10^{-2}	$\Delta T_c =$ -14.5 K
				2.3×10^{-2}	$\Delta T_c =$ -17.4 K
				4.5×10^{-2}	$\Delta T_c =$ -47.1 K
[22]	YBa$_2$Cu$_3$O$_{7-x}$	293	Cs-137	2.7×10^{-7}	$\Delta T_c = 2.2$ K
[23]	Bi$_2$Sr$_2$CaCu$_2$O$_x$	293	Cs-137	$5.0{\times}10^{-7}$	$\Delta T_c = 9.0$ K
			Co-60	0.6	$\Delta T_c = 16.0$ K
[24]	Bi-system	30	Proton irrad. Li	?	$\Delta T_c = 5.0$ K(1 h) $\Delta T_c =$ -5.0 K(90 d)
[25]	EuBa$_2$Cu$_3$O$_{7-x}$	293	Co-60	1.0×10^{-2}	$\Delta T_c =$ -3.3 K
				2.0×10^{-2}	$\Delta T_c =$ -4.7 K
				3.0×10^{-2}	$\Delta T_c =$ -8.1 K

[a] 0.2 µm thickness, on MgO substrate. [b] 1.0 µm thickness, on LaAlO$_3$ substrate.

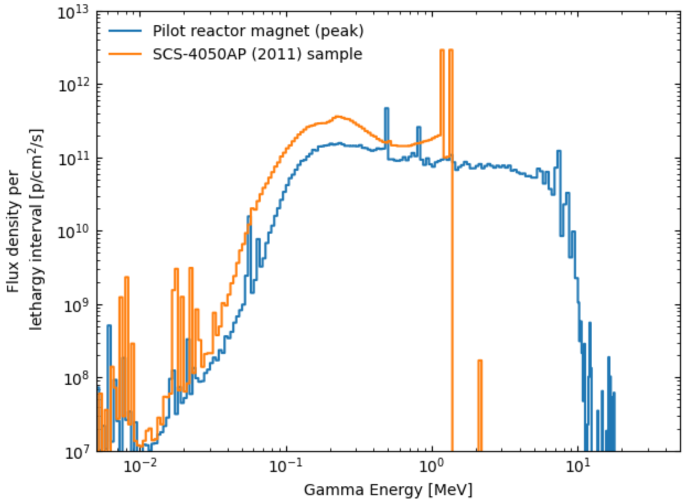

Figure 1. Example peak gamma flux density per lethargy interval incident on a fusion pilot power plant magnet (in this case STEP [26]) and gamma flux on the SuperPower SCS-4050AP (2011) samples in this work. Lethargy interval is defined as the natural logarithm of the ratio of an energy bin's upper bound and lower bound. The energy bins of both spectra follow the 709 group structure.

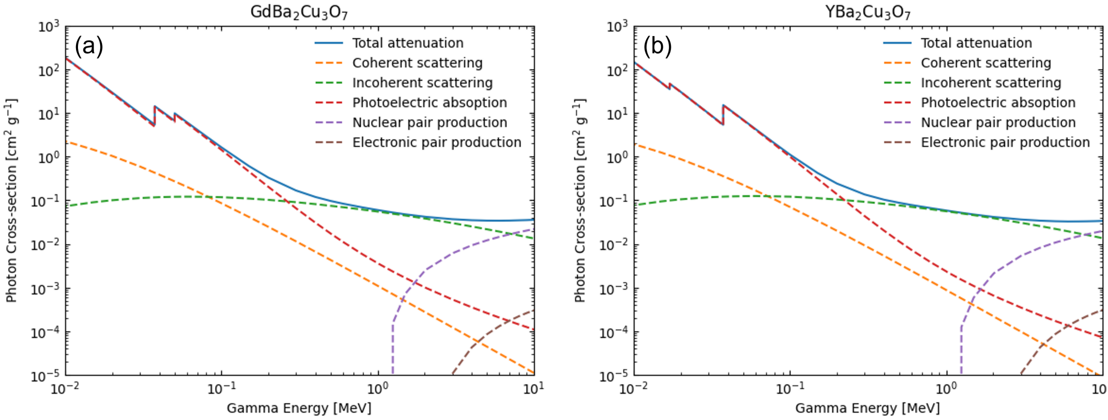

Figure 2. Photon cross sections of (a) $GdBa_2Cu_3O_7$ and (b) $YBa_2Cu_3O_7$from NIST XCOM [27]. The dominant interaction mechanism of 1.17 MeV and 1.33 MeV gamma rays with these materials is Compton scattering.

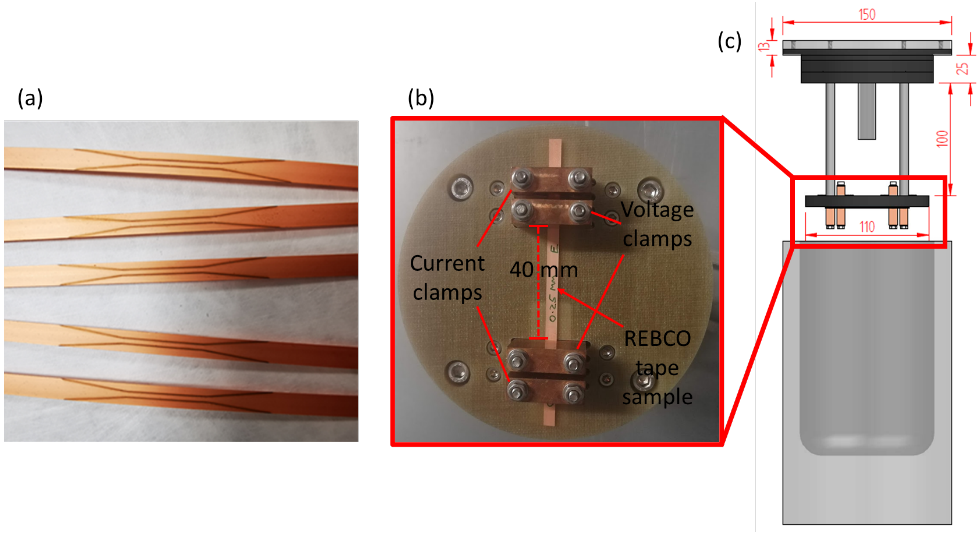

Figure 3. (a) SuperPower SCS4050-AP (4 mm wide) samples with laser-cut bridges of 1 mm width, 33.8 µm depth. (b) test fixture viewed from below. The sample is connected to the measurement circuit via copper clamps. (c) CAD model and dimensions of the Gamma ICE test fixture and 2 L dewar into which it is lowered.

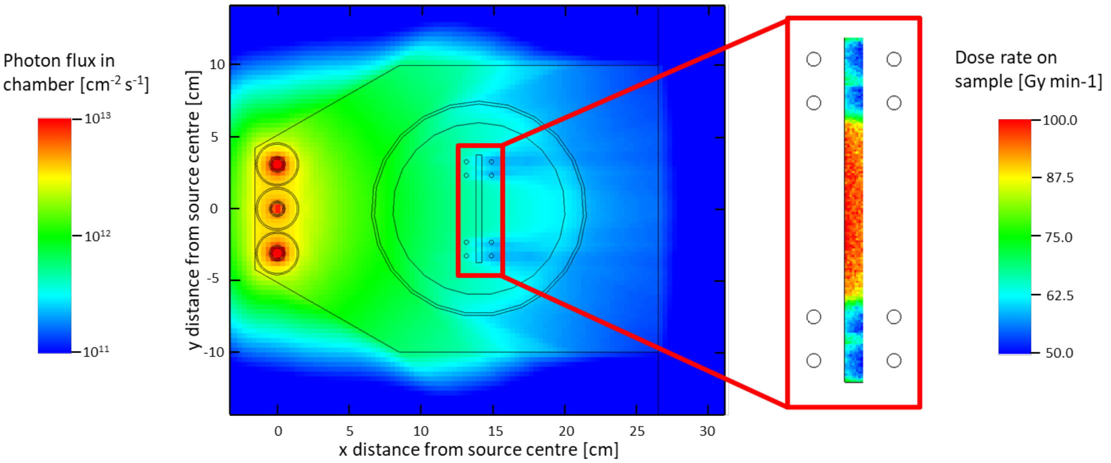

Figure 4. Left: Photon flux across the DCF gamma irradiation chamber, test fixture and dewar from above. Right: Gamma dose rate across a REBCO tape sample.

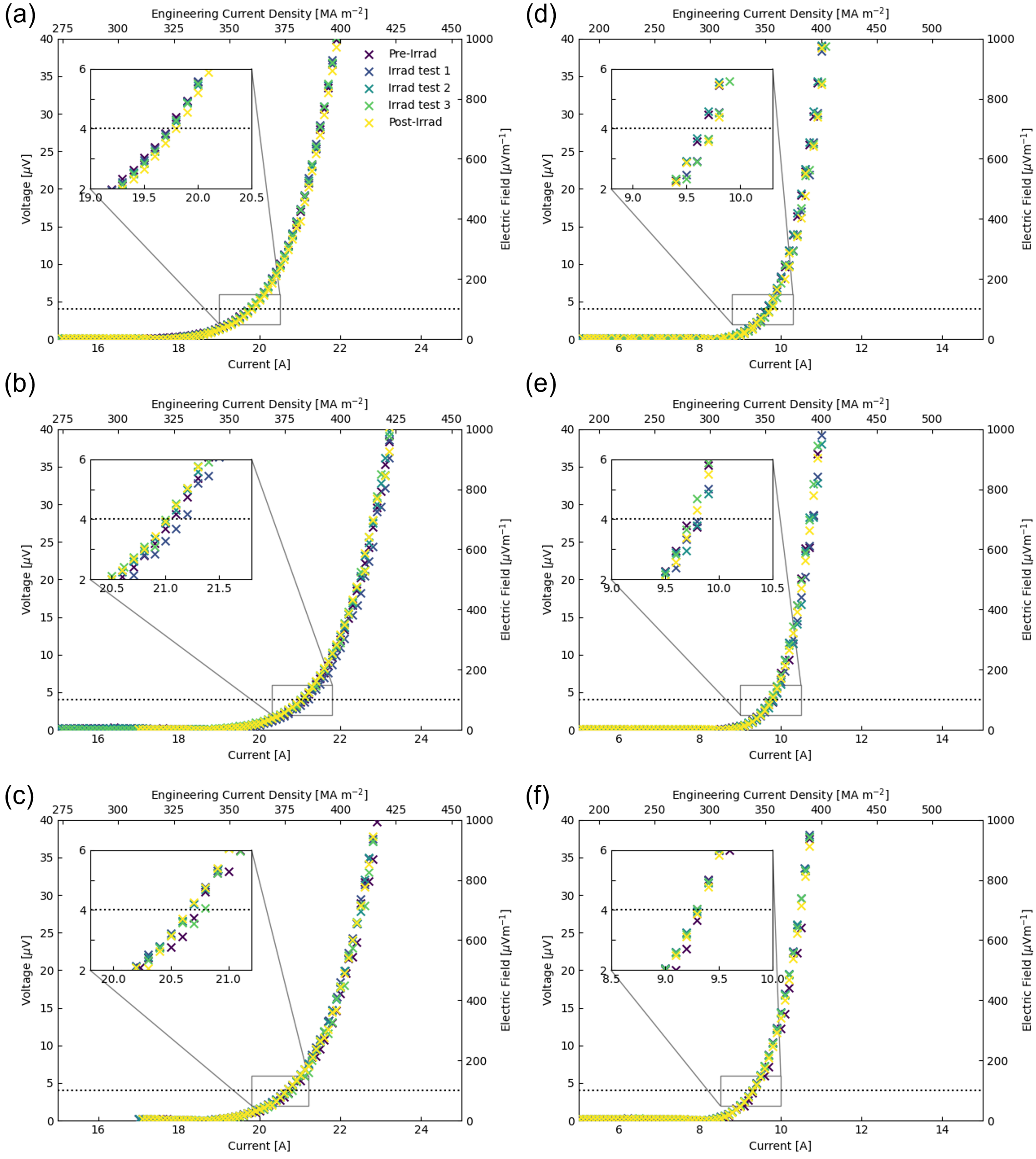

Figure 5. 77 K, self-field *I*-*V* traces of 0.5 mm bridge width samples (a) A, (b) B and (c) C; and 0.25 mm bridge width samples (d) D, (e) E and (f) F. Data comprise of a pre-irradiation test, three during-irradiation tests and one post irradiation test for each sample. The dashed line indicates an electric field criterion of $E_c = 100\ \mu\mathrm{V\,m}^{-1}$. Insets show the I-V traces in the vicinity of I_c.

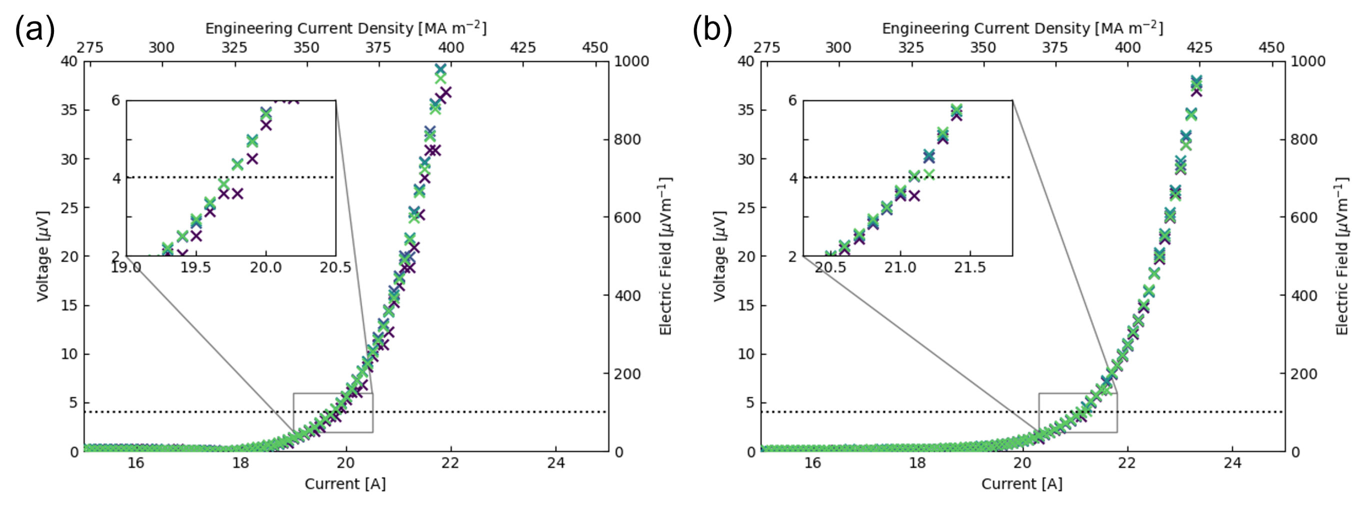

Figure 6. 77 K, self-field *I*-*V* traces of 0.5 mm bridge width samples (a) A and (b) B, post 208 kGy Co-60 gamma ray dose. Data comprise of a pre-irradiation test and three during-irradiation tests. Insets show the I-V traces in the vicinity of I_c.