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LETTER

The performance of REBCO coated conductor during *in situ* cryogenic irradiation with fusion-spectrum neutrons

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Abstract

Understanding the tolerance of $REBa_2Cu_3O_{7-x}$ (REBCO) high-temperature superconductors to neutron damage is essential for compact fusion reactor design. Here we report the first *in situ* measurements of the superconducting performance of REBCO coated conductor (CC) during neutron irradiation. The CC was exposed to 14 MeV neutrons at fluxes up to 7.3×10^7 n cm^{-2} s^{-1} while carrying current at 40 K. *In situ* voltage measurements revealed no instantaneous disruption of superconductivity, but the critical current (I_c) decreased linearly with fluence at 0.03 A per 10^{12} n cm^{-2}. Careful analysis excluded thermal effects as the origin of this degradation. Consistent with a point-defect damage mechanism, superconducting performance was recovered fully following room temperature annealing. This observed onset of I_c reduction occurred several orders of magnitude below the critical neutron fluences anticipated by previous *ex situ* studies, indicating that service lifetimes of REBCO-based magnets may be substantially shorter than current projections.

1. Introduction

$REBa_2Cu_3O_{7-x}$ coated conductors (REBCO CCs) will form the superconducting windings of magnetic confinement systems in next generation compact spherical tokamaks such as STEP or SPARC [1–3]. However, the compact design of these reactors will restrict the thickness of shielding protecting the superconductor from damage by 14 MeV neutrons emitted in the D-T fusion reaction [4]. Consequently, it is important to understand the performance of REBCO CC exposed to fusion-spectrum neutrons. There is currently no test facility reproducing the combination of neutron flux and energy, temperature, magnetic field, strain and high-current conditions that superconducting components will experience in operation, but several groups are exploring the effect of some of these parameters (or proxies for them) to understand how the fusion environment will influence the performance and durability of REBCO CC. From previous work on the I_c/strain performance of REBCO CC [5, 6], it is clear that magnet designers must seriously consider the effects of stresses introduced by both the cooling/warming processes and the Lorentz forces in operation, and that these may prove to be the limiting factors on magnet performance. However, since the effects of mechanical damage and irradiation are additive, the first being induced as the magnet is cooled and energised and the second gradually accumulating, it is important to understand how irradiation can change the superconducting properties of the CC during a power generation cycle. This degradation during neutron irradiation of CC samples at 40 K is the focus of this letter.

Initial irradiation studies focused on the long-term degradation of superconducting properties using light ions or fission neutrons as proxies for fusion-spectrum neutrons. These measurements generated the damage around 300 K and the superconducting properties were measured after irradiation, potentially allowing partial annealing out of the damage created. Summarising these observations, the superconducting critical temperature, T_c, monotonically decreases as a function of ion or neutron fluence at a fractional rate of 0.024 per mdpa (milli- displacements per atom) [7], accompanied by an increased transition width [8]. The critical current density, J_c, likewise decreases monotonically if no external field is applied, although little zero-field data has been published. In the presence of an applied field, an initial improvement in J_c is observed at low fluences followed by a decline in performance at a normalised rate of 0.34 ± 0.04 per 10^{18} n cm^{-2} [9]. The initial enhancement in J_c is dependent on the total defect density; CCs containing artificial pinning centres or greater initial numbers of natural defects start to decline at a lower fluence than those with a low initial defect count [10, 11].

The first *in situ* measurements, where the REBCO was in the superconducting state as the damage was accumulated but the ion beam was off during the measurements, showed, for samples irradiated both at room temperature and 40 K, a characteristic fractional I_c degradation rate of 0.30 per mdpa in REBCO CC irradiated by 2 MeV He^+ ions over the damage range of 0.0–2.0 mdpa [12]. These measurements also demonstrated partial recovery of the superconducting performance after cryogenically irradiated samples were returned to room temperature, resulting in a lower level of degradation in the recovered samples compared to samples irradiated at room temperature to the same fluence. An earlier *ex situ* 1.2 MeV proton irradiation study found I_c at 30 K in a 5 T applied field to be 7% greater in samples irradiated to 1×10^{16} p cm^{-2} at 80 K and warmed up to room temperature prior to measurement, compared to those irradiated at 323 K [13]. However, recent *in situ* studies with 1.2 MeV protons observed that irradiation at <200 K degraded REBCO CC performance at 1.6 times the rate of identical irradiation at 300 K [14].

In situ measurements while the ion beam is on were first reported in 2023 and showed a factor of three suppression in I_c by a 100 nA cm^{-2} beam of 2 MeV He^+ ions [15]. A disruption of the superconducting state due to electronic interactions between electrons and irradiating ions was initially hypothesised, but recent evidence suggests that this behaviour results primarily from direct heating effects from the rather intense ion beam [16].

To date, there have been no *in situ* studies utilising neutrons as the irradiating particle. This is an important gap given the requirement for the superconducting magnets to carry very high current densities throughout the operational cycles of a future fusion power plant while simultaneously exposed to neutron bombardment. High energy ion beams can be a convenient proxy for neutron damage, not least because they are widely available and offer higher fluxes that shorten the time to generate significant damage levels. However, the nuclear fission community have argued for decades about whether the damage from ions is a reliable proxy for neutron damage, and carefully designed experimental protocols are used to achieve similar levels of damage [17]. Here we report the first *in situ* analysis of the superconducting properties of REBCO CC under irradiation by 14 MeV neutrons. We have also carried out extended *in-situ* experiments to provide more detailed understanding of the performance of REBCO CC under operational conditions.

2. Experimental methods

CC featuring a 2 μm thick EuBCO + 3.5 wt.% Hf superconducting layer, produced commercially by Fujikura Ltd., was patterned into a 4 mm long, 20 μm wide bridge by standard photolithography and wet etching. The macroscopic J_c (40 K, 0.01 T) of this CC was determined to be ∼6.5 MA cm^{-2} via magnetometry measurements of a 3 mm diameter punched disc.

Once patterned, the sample was mounted to an aluminium stage with GE varnish and cigarette paper, then loaded into a custom-built cryostat optimised for the Neutron Irradiation Laboratory for Electronics (NILE) beamline of the ISIS Neutron and Muon Source [18] (figure 1).

Reference [19] contains a thorough overview of the NILE facility, including calibration data. In short, NILE contains a compact neutron generator produced by Adelphi Technologies. Within this device, a deuterium-tritium gas is ionised by a microwave generator and the plasma accelerated towards a 13 mm × 13 mm metal-alloy target biased to a maximum of 130 kV. D-T fusion occurs within this target, acting as a source of 14 MeV neutrons up to a peak rate of 10^{10} n s^{-1} (but typical operational neutron yields are of the order of 10^9 n s^{-1} with the device operated at 110 kV).

The metal-alloy target is recessed 8 mm from the neutron exit window. Here, leaving a gap of 1–2 mm, we place the 1 mm thick Al window of the cryostat. The REBCO sample is sited 7 mm from this window, giving a total sample-to-source distance of 16–17 mm. In this experiment, neutrons were initially produced at 2×10^9 n s^{-1}, yielding 5.5×10^7 n cm^{-2} s^{-1} flux at the sample. These values were later increased to 2.6×10^9 n s^{-1} and 7.3×10^7 n cm^{-2} s^{-1} respectively, and are comparable with anticipated

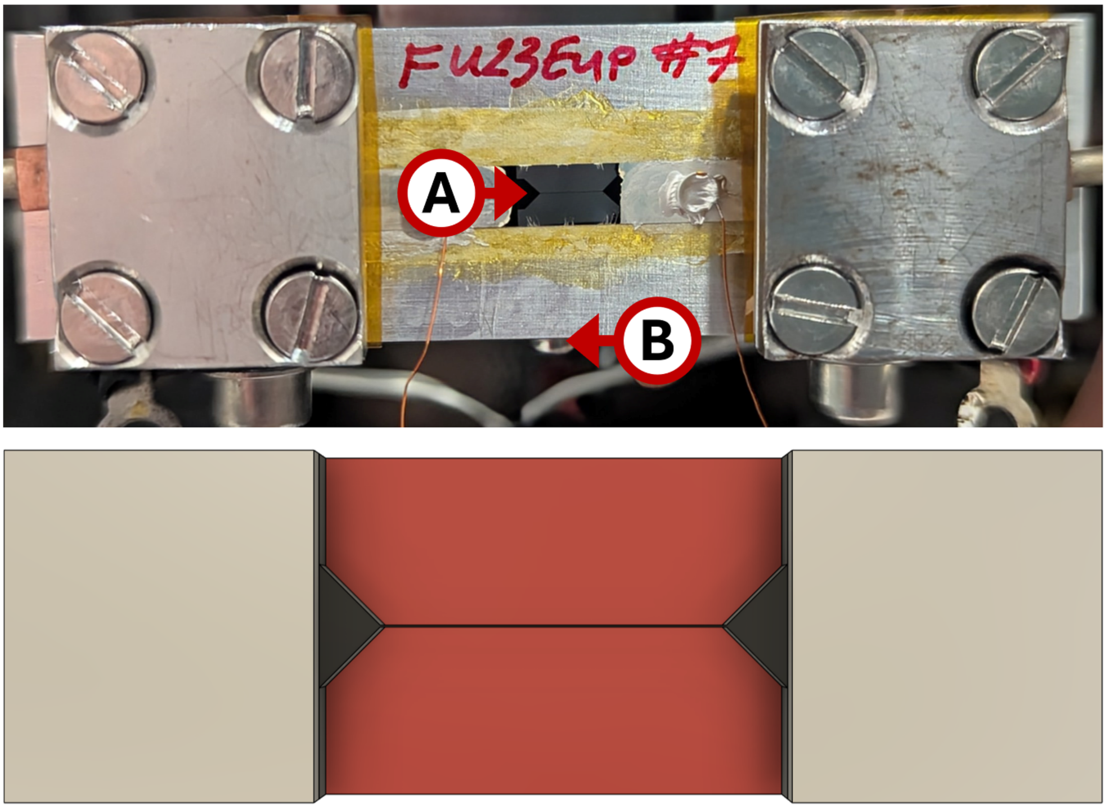

Figure 1. Top: a patterned coated conductor sample loaded into the cryostat. Position A shows the REBCO bridge, whilst the Cernox temperature sensor is located at point B. Bottom: CAD render of the REBCO bridge (black) atop exposed oxide buffers (red).

14 MeV neutron flux in compact spherical tokamaks (though remain at least a factor of 10^2 below the projected $E > 0.1$ MeV flux) [20].

All measurements were performed with the sample held constant at 40 K using a Lakeshore Model 335 temperature controller, Keysight N6971a DC power supply, and Keithley DMM6500 digital multimeter. First, the current was increased in 0.1 A s^{-1} increments, with the maximum voltage limited to 20 μV to reduce the risk of irreparable damage to the sample track. From this, I_c values could be extracted using the standard 1 μV cm^{-1} criterion. The sample was then biased to currents greater than I_c and held constant. These currents, in the range 115%–120% of initial I_c, were increased gradually over time, as confidence grew in the performance of the CC track. In combination with the 20 μm bridge width which reduces the superconducting cross-section to 40 μm^2, this methodology was intended to maximise sensitivity to single neutron collisions within the sample, analogous to the operational strategy of a single photon detector [21]. If the knock-ons caused by a nuclear collision create an ephemeral normal-state region across a significant fraction of the track by transient effects reducing the superconducting order parameter (breaking Cooper pairs), this should appear as a spike in the measured voltage. For a 20 μm REBCO bridge of 4 mm length and 2 μm thickness subjected to 5.5×10^7 n cm^{-2} s^{-1} flux, the expected primary knock-on (PKA) rate is 3 PKA s^{-1}. This value is derived from simulations using SPECTRA-PKA, which estimate the fraction of neutrons inducing a PKA in 2 μm thick REBCO to be 6×10^{-5} [22].

3. Results

The pre-irradiation I_c (40 K) value for the first track studied was 6.46 A ($J_c \simeq 16$ MA cm^{-2}). Figure 2(a) shows the voltage response to a constant 7.50 A current (116% $I_{c,initial}$) applied over a 2 h period with and without 5.5×10^7 n cm^{-2} s^{-1} neutron flux incident on the sample. With no neutron flux, a linear fit of the region $t > 60$ min shows the voltage to be essentially flat with a negligible increase at around 0.2 nV min^{-1}. However, with neutron flux the corresponding gradient is significantly steeper at 7.8 nV min^{-1}.

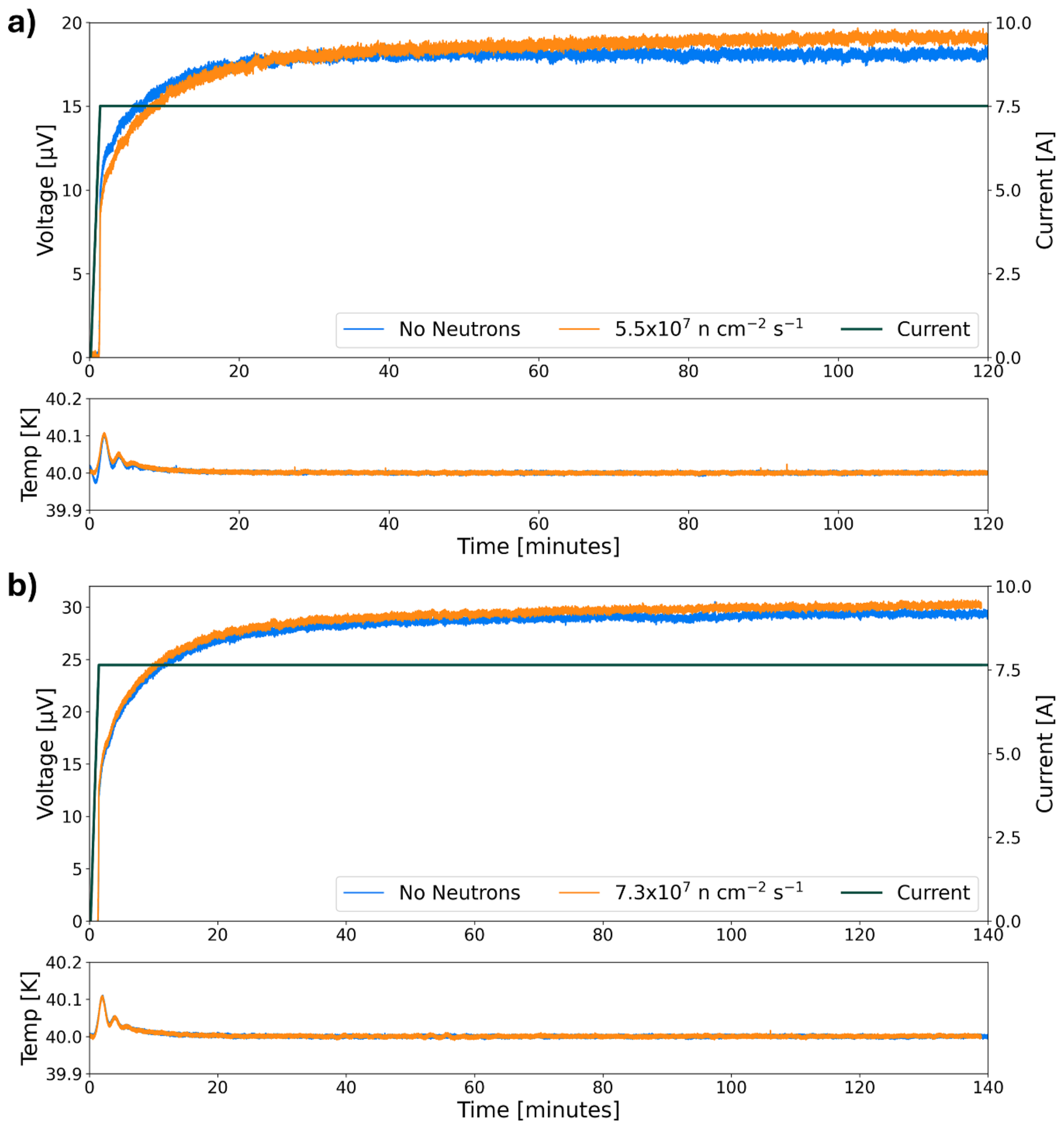

Figure 2. a) The voltage response for a 7.50 A constant current applied without (blue) and during neutron irradiation (orange). (b) The voltage response for a 7.65 A constant current applied without (blue) and during an increased rate of neutron irradiation.

The bias current was increased incrementally between pairs of measurements. Figure 2(b) displays the voltage response to a 7.65 A constant current (118% $I_{c,\mathrm{initial}}$) with and without 7.3×10^{7} n cm^{-2} s^{-1} neutron flux. This time, a higher gradient of 6.0 nV min^{-1} fits the region $t > 60$ min in the unirradiated case, the cause of which is discussed below, but once again the voltage gradient is steeper under neutron irradiation (10 nV min^{-1}).

A total dose of 2.6×10^{12} n cm^{-2} was reached on this sample. FISPACT-II simulations of EuBCO + 3.5 wt.% Hf irradiated by 14 MeV neutrons relates this fluence to a damage level of 6×10^{-9} dpa. Periodic I–V measurements showed an overall decrease of 0.08 A in I_c, with a linear relationship between I_c and neutron fluence of −0.03 A per 10^{12} n cm^{-2} (figure 3). Following passive warming to room temperature, where the sample remained under vacuum at room temperature for 24 d, the superconducting performance was recovered in full (figures 3 and 4). As a control, a second sample with 4.21 A I_c ($J_c \simeq 10.5$ MA cm^{-2}) was irradiated by a 2.8×10^{11} n cm^{-2} fluence without any bias current, with I–V curves measured both before and 1 h post-irradiation (to allow any possible beam heating to dissipate). Under these beam-on, current-off conditions (which effectively form an *ex-situ* measurement without warming the sample between damage and testing), the I_c was reduced by 0.03 A (−0.11 A per 10^{12} n cm^{-2}). These I–V curves can be viewed in figures 2 and 3 of the supplementary information.

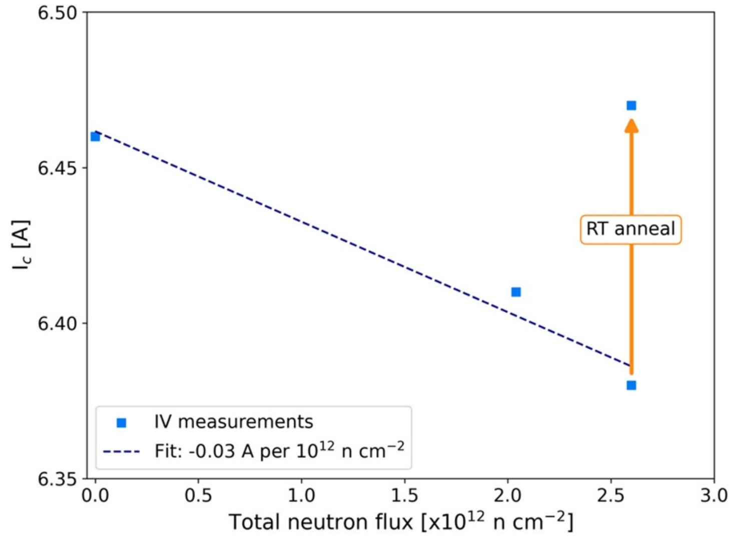

Figure 3. *I*–*V* measurements performed *in situ* at 40 K show linearly decreasing critical current as a function of neutron fluence. Cooling again after 24 d in vacuum at room temperature, the unirradiated performance is wholly recovered.

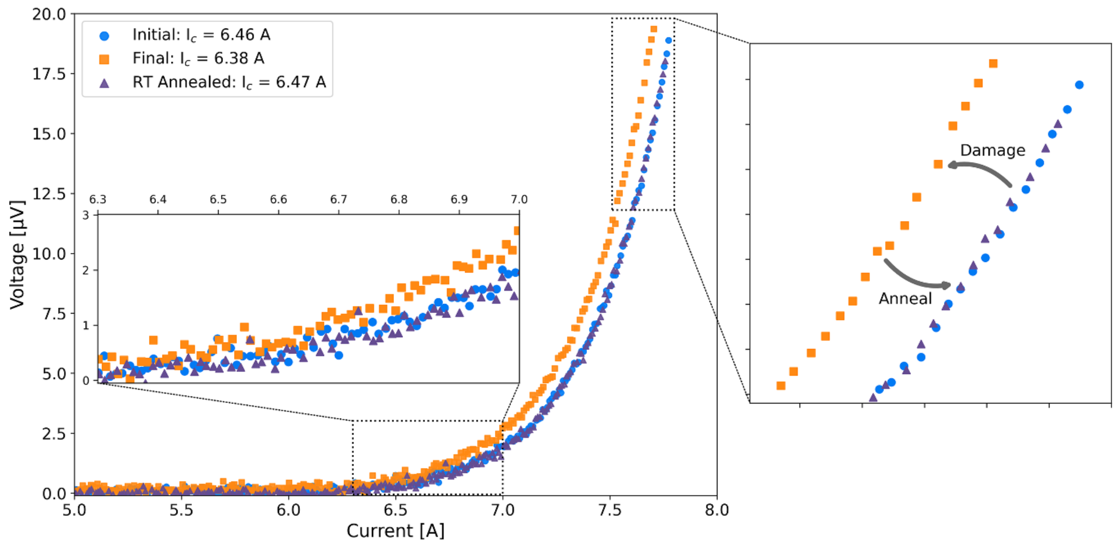

Figure 4. Comparison of the *I*–*V* behaviour (40 K) of the track before irradiation ('Initial', blue), after 2.6×10^{12} n cm^{-2} dose ('Final', orange), and following a 24 d room temperature anneal under vacuum ('RT Annealed', purple). I_c has fully recovered (purple) from the post-experiment pre-warming value (orange).

4. Discussion

The performance of these REBCO CC tracks over extended periods at currents greater than I_c show little variation in the voltage following an initial 30 min equilibration period. Datasets taken during irradiation show no difference in power spectral density when compared to identical measurements recorded in the absence of neutrons (see figure 1 of the supplementary information). Thus, D-T spectrum neutron irradiation with 7.3×10^7 n cm^{-2} s^{-1} flux (corresponding to 4 collision events per second) does not result in any instantaneous change in the DC performance of this REBCO CC, even though we are deliberately biasing the narrow samples at a high current density to maximise the sensitivity to small amounts of damage. Although the operational fast neutron flux at the superconducting windings of a compact spherical tokamak will be 2–3 orders of magnitude greater than available here, it should be noted that these windings will consist of a significantly wider CC carrying a DC current at a considerably lower fraction of I_c than we have used and will therefore be less sensitive to the effects of an individual neutron impacts.

However, we cannot conclude that there is no degradation in the superconducting performance. Our data shows both a higher rate of voltage creep for measurements during neutron irradiation, and

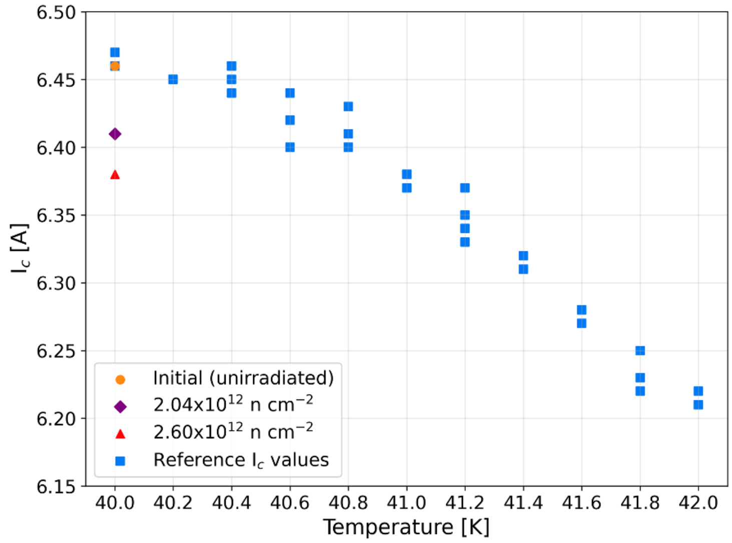

Figure 5. For sample 1, I_c was determined at 0.2 K increments between 40.0 and 42.0 K (blue) to enable estimation of the reliability of and the heating required for any observed I_c reductions (purple, red).

that the I_c values decrease at a minimum gradient of -0.03 A per 10^{12} n cm^{-2}. There are two possible scenarios that could explain these observations; a heating effect like that seen in previous ion beam experiments [15, 16], or the real accumulation of damage from neutron irradiation. The full recovery of I_c following a return to room temperature for a period of 24 d is also useful in exploring the nature of any damage.

There are several sources of heat during the experiment: Joule heating generated in the current leads, Joule heating generated in the track itself, and heat deposited into the sample by the neutron beam. To investigate the sensitivity of our sample to changes in temperature, *I–V* curves were measured without neutron irradiation at 0.2 K increments between 40.0 and 42.0 K. As shown in figure 5, a slight variation in extracted I_c values are seen at each temperature, with an average range of 0.02 A and maximum range of 0.04 A (25% and 50% of the observed post-irradiation I_c reduction, respectively). From this plot, we estimate that the sample temperature needs only to increase by 0.9 K to account for the 0.08 A decrease in critical current. No such temperature increase was measured during the experiment, but since the temperature sensor is not directly located on the REBCO track we cannot rule out the possibility that the track temperature rises during the measurement. However, this would not explain why measurements with the neutron beam on showed a higher voltage gradient (figure 2).

An upper limit for beam heating may be estimated by considering the entire flux to deposit all 14 MeV into the REBCO layer:

$$\begin{aligned}\text{Power (W)} &= \text{neutron flux } \left(\text{n cm}^{-2}\text{s}^{-1}\right) \times \text{track width (cm)} \times \text{track length (cm)} \\ &\quad \times \text{energy per neutron (eV)} \times 1.6 \times 10^{-19} \\ &= \left(7.3 \times 10^{7}\right) \times \left(20 \times 10^{-4}\right) \times \left(4 \times 10^{-1}\right) \times \left(14 \times 10^{6}\right) \times \left(1.6 \times 10^{-19}\right) \\ &= 0.13\ \mu\text{W}. \end{aligned} \tag{1}$$

The contribution from Joule heating in the first sample may be found simply from current (7.65 A) $\times$ voltage (30 μV) = 0.23 mW, approximately 3 orders of magnitude greater than even the unphysical worst-case beam heating scenario. Given the rate of PKA generation per neutron in a 2 μm REBCO layer is only 6×10^{-5} [22], we estimate that the beam heating effect is 7 orders of magnitude less than Joule heating. This strongly suggests that the increased voltage gradient observed during beam-on measurements is unlikely to arise from additional heat deposited by the neutron flux.

To investigate whether Joule heating could account for the observed I_c reduction, the experimental protocol was repeated in the absence of neutron irradiation. The sample was held at 7.65 A for >1 h to allow steady state to be reached, with *I–V* curves measured before and after the current was applied. Care was taken to ensure the same time lapsed between turning off the current and beginning the *I–V* measurement so that Joule heating in both experiments is approximately equal. In this beam-off, current-on scenario, no degradation in I_c was observed.

We conclude that the only factor that correlates uniquely with measurement of I_c degradation is whether the neutron source is on, and that both the voltage increase during the constant current measurements with the neutron beam on and the subsequent drop in I_c are the result of accrued microstructural damage rather than heating effects.

The only similar work irradiated REBCO CCs to 1.2×10^{14} n cm^{-2} with 14 MeV neutrons, equivalent to 6×10^{-7} dpa [23]. No changes to either sample T_c or XRD pattern were observed. However, their study was performed at room temperature and any induced damage may have annealed out prior to the measurement of superconducting properties.

5. Conclusions

We report the first *in situ* measurements of REBCO CC during neutron irradiation. For 14 MeV neutron fluxes up to 7.3×10^7 n cm^{-2} s^{-1}, we record no dramatic reduction the superconducting properties; an encouraging result for the robustness of planned magnetic confinement systems in compact spherical tokamaks. However, much more worrying is the observed linear degradation in I_c values at neutron fluxes several orders of magnitude below the damage threshold predicted by previous *ex situ* experiments. We can explain this discrepancy by the room temperature annealing of accumulated point defect damage observed in this work. Thus, the service lifetime of CCs under operational conditions at cryogenic temperatures may be much shorter than current predictions, and should still be of real concern to the designers of small fusion reactors. These preliminary observations also highlight the importance of performing future irradiation campaigns with the samples at the operational temperatures if the service envelope of expensive REBCO magnets is to be accurately predicted.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author Contributions

S.C.S and C.R.M.G. conceived and, with W.I. and C.F., guided the research. C.C., C.F. and M.K. designed the NILE facility. W.I. and K.A. designed the experimental apparatus and measurement protocol. C.C. operated the neutron source. K.A. was responsible for sample preparation, data collection, and data analysis. J.R.W. created the data collection programme. J.C.L. performed the FISPACT-II simulations. K.A. drafted the manuscript. S.C.S. and C.R.M.G. provided additional manuscript content. W.I. suggested manuscript revisions. All authors commented on the drafts.

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Competing Interests

The authors declare no competing interests.

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