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***Abstract*— The UKAEA's Spherical Tokamak for Energy Production (STEP) program aims to demonstrate the ability of a low aspect ratio tokamak to generate net electricity from deuterium-tritium fusion. Specifically, its aim is to deliver a prototype fusion power plant, targeting 2040, and a path to the commercial viability of fusion, by engaging with and invigorating relevant industries and the supply chain.**

STEP will utilize REBCO coated conductors as the current carrier in the bulk of its magnets. It has been recognized that neutron irradiation leads to the degradation of REBCO's superconducting properties, and that this degradation will limit STEP's availability. However, current knowledge does not cover all the conditions that REBCO coated conductors will be subjected to whilst operating in STEP's magnets. Recent preliminary works have shown that these additional service conditions could exacerbate the degradation in REBCO's superconducting properties, and therefore they each require further investigation.

STEP's Confinement Systems' Materials group has developed a plan to characterize the superconducting properties of REBCO under conditions as-close-as-reasonably-possible to those within STEP prior to its construction. The campaign will thoroughly test and validate the choice of REBCO coated conductors used in the construction of STEP magnets. Here STEP's current understanding of REBCO and how it is affected by irradiation are presented, followed by details of experiments designed to develop our knowledge of how REBCO will fare when subjected to fusion neutron irradiation.

***Index Terms*—REBCO, neutron irradiation, coated conductors, ion irradiation, fusion, STEP, superconducting magnets**

I. Introduction

The Spherical Tokamak for Energy Production (STEP) program aims to design and build the world's first compact tokamak pilot power plant by building on the UKAEA's rich experience in fusion reactor design whilst building up a wider base of supporting industries to facilitate the UK fusion power industry as it grows.

Like any product, the economic viability of a fusion power plant is a function of its initial cost, plant efficiency and operating lifetime. The initial cost is itself a function of the size ($\propto R^3$) of the tokamak – hence the drive for a compact design – whilst the plant efficiency is a strong function of the field strength of the tokamak's toroidal field ($\propto B^4$) [1]. This need for continuous high fields, coupled with the space limitation inherent in a compact design, has driven the case for using coated conductors (CC) that utilize the superconductor REBCO. The issue with using REBCO CC as the current carrier in tokamak magnets is that fusing deuterium-tritium plasmas release an abundance of 14 MeV neutrons, and neutron irradiation has been shown to affect REBCO's superconducting properties (eg. [2]). The goal of STEP's REBCO irradiation test plan is to build on what is currently understood about REBCO and its response to irradiation towards:

- defining the best understanding possible of how the superconducting properties of REBCO CC will change when subjected to fluences and fluxes of neutrons and gammas in STEP, and
- provide information and tools so STEP's engineers can account for the property-altering effects of irradiation when designing STEP's magnets, reducing the risk of coil failures in service.

This paper seeks to present STEP's current understanding of the effects of different types of irradiation on REBCO (section 2) and the scientific basis and experimental plan for several projects being undertaken by STEP to understand how REBCO responds to energetic particle environments (section 3).

II. REBCO and its Response to Irradiation

As with all cuprate superconductors, REBCO has a structure consisting of alternating conduction and charge reservior layers (**Fig1a**). The conduction layer consists of 2 CuO_2 planes, bound in REBCO by the rare-earth element, and it is the electrons released by these Cu^{3+} ions that conduct current when $T>T_c$ and form Cooper pairs to conduct supercurrents when $T<T_c$. The layers that link the conduction layers take the form BaO-CuO-BaO, giving REBCO a triple perovskite structure [3], [4].

Given REBCO is a brittle ceramic and has anisotropic superconducting properties, methods to manufacture high performance CCs economically are the subject of active

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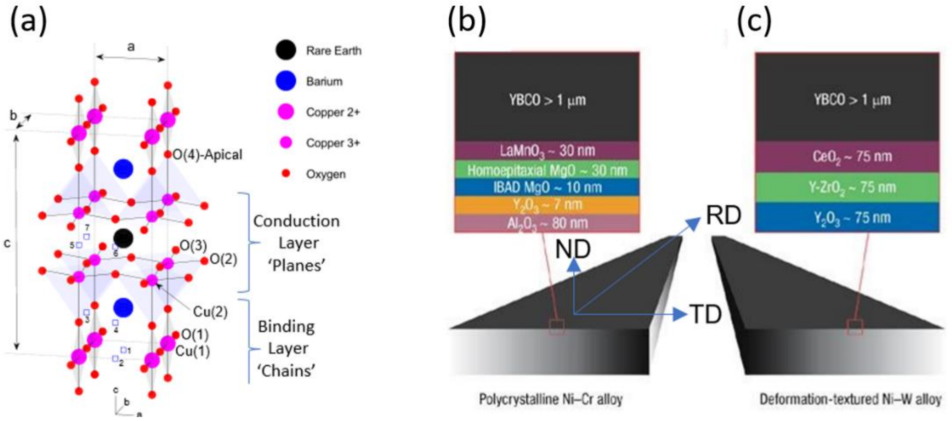

Fig. 1. (a): REBCO unit cell showing the conduction layer (plane sites) – Cu(2) & O(2,3) – and the Binding layer (chain site) – Cu(1) & O(1) atoms – joined by an apical oxygen layer – O(4). The unit cell is symmetric in the (a,b)-plane about the central rare-earth element. Each colored sphere represents a different atom type (see the key, top right). a, b & c dimensions refer the unit cell parameters [36]. (b): coated conductor architecture based on a polycrystalline Ni-alloy, buffer layers deposited using IBAD to apply texture, with the YBCO layer laid down by MOCVD or PLD. (c) coated conductor architecture based on a Ni-alloy substrate with associated buffer layers, textured by the RABITs process and then the YBCO layer laid down using MOD-TFA. The texturing axes of a REBCO CC are defined in (b) with RD, TD and ND defined as the Rolling, Transverse and Normal directions of the CC respectively. Modified from Foltyn et al. [37].

research by several companies (eg. [5]), all aiming to produce dense, biaxially textured and chemically stable films of REBCO of the order of a micrometre thick with good stoichiometry, sub degree grain alignment over long lengths (~1000m) and protected from brittle failure using a metallic substrate (**Fig1bc**) [5]. Some manufacturers also include controlled concentrations of precipitates uniformly dispersed through the REBCO to act as artificial flux pinning centres (APCs). Several technologies are utilized to achieve this (e.g. [6], [7]) in conjunction with techniques used to ensure high quality bi-axial texturing of the REBCO layer (eg. [8]). The result is generally a REBCO layer where the c-axis of the unit cell is aligned within a few degrees of the CC's normal direction (ND), unless the manufacturer intentionally rotates the unit cell to aid in manufacturing (eg. [9]).

As with all type II superconductors, the superconducting performance of the REBCO layer in a CC is determined by the flux pinning landscape produced by microstructural defects [10]. This leads to limits on the maximum supercurrent density the REBCO layer can carry, known as the critical current density (J_c), and is dependent on field (B), field angle relative to the CC (θ), temperature (T) and applied strain (ε). The dependence of J_c on B (at constant T and ε) can be split into three distinct regions: the plateau region at low fields where $J_c \propto B^0$; the power law region at intermediate fields ($\approx 1-8$ T) where $J_c \propto B^{-\alpha}$ with $\alpha = 0.4-0.6$, and the flux creep region at higher fields (> 8 T) where the ability of REBCO to maintain a supercurrent drops significantly below that predicted by the power law [10]. The dependence of J_c on T (at constant B and ε) is exponential with two different characteristic temperatures depending on the relative contributions of strong ($\propto T^2$) and weak ($\propto T$) pinning sites [11]. In REBCO, strong pinning sites predominate at all temperatures, with weak pinning sites adding a significant contribution at temperatures below 10 K. The J_c dependence of a REBCO CC on tensile strain ε has been shown to be reversible for ε < 0.5-1% [12] and varies between manufacturers given the different architectures of CC. Above this limit, the original J_c does not typically recover upon the removal of the load due to microcracks that form in the REBCO layer. As yet, there is no such equivalent limit for compressive strains. Below the reversible limit, J_c degradation due to ε generally increases with B and/or T [13]. The response of J_c to strain for CC samples from different manufacturers also varies quite differently, with

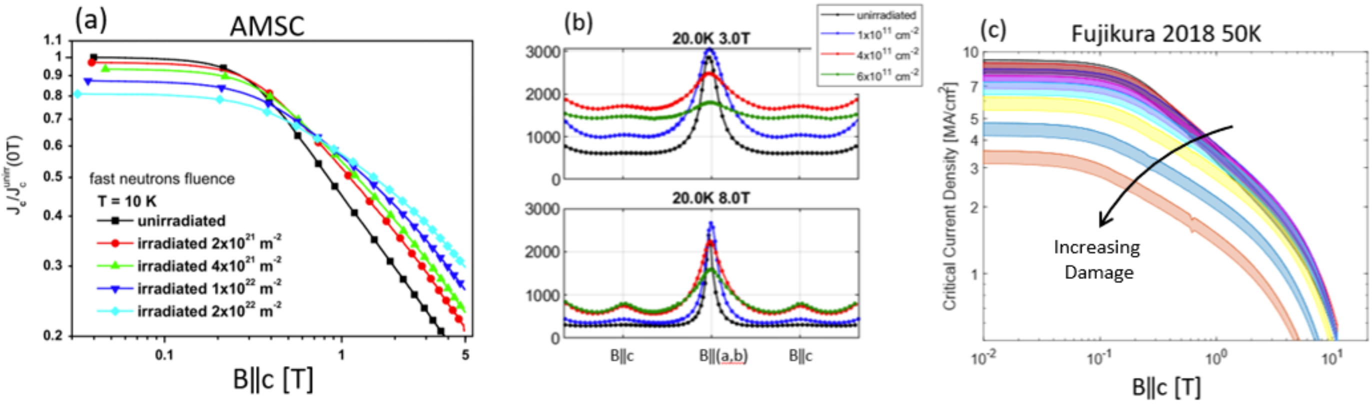

Fig. 2. (a) Change in YBCO CC's J$_c$, normalised to its pre-irradiation value at ≈0 T (y-axis) versus applied field in response to an increasing fluence of fission spectrum neutrons from the Vienna TRIGA Central Irradiation Facility, from Eisterer et al. 2010 [19]. (b) the effect of increasing fluence of 100 MeV Ag ions on a REBCO CC samples from Strickland et al. 2023. In this case, the minimum I$_c$ moves from 30-90° to a trough nearer ~60° [21]. (c) Effect on J$_c$(B∥c) of 2MeV helium ion irradiation on a Fujikura YBCO CC at 50 K data from Iliffe 2022 [23]. Note that the upper field limit of the power law region decreases with added damage.

CC from THEVA and SuperPower – each made using different technologies – varying linearly and parabolically, respectively [14].

As irradiation with energetic particles evolves the REBCO microstructural defect landscape [8], $J_c(B, T, \theta, \varepsilon)$ also evolves as the number and nature of interactions between the irradiating particles and the superconducting volume increases. Irradiator-target interaction concentration is typically given as a cumulative fluence (ϕ) of a particular type of irradiation, either neutrons and/or gammas of a given spectrum, or ions of a given species, ionization level and energy. As such, the extreme conditions experienced by STEP's toroidal field coil within its central column combine to make it one of the most challenging applications for REBCO CC [15].

Work to assess the ability of REBCO CCs to withstand neutron irradiation has been undertaken by several groups, including those from Argonne National Laboratory [16], Los Alamos National Laboratory [17], TU Wien using the Vienna TRIGA reactor [2] and, most recently, the Prague Institute of Physics CAS using the LVR reactor at Research Centre Rez [18]. The results of these experiments show that the J_c of a REBCO CC changes due to irradiation in the following ways:

- J_c at any temperature and low field decreases with fluence (Fig2**a**) [19].
- J_c at any temperature and high field perpendicular to the CC's tape plane ($B\|$ND) increases up to some CC-dependent fluence before decreasing with further irradiation past its original J_c [2], [20].
- The fluence at peak J_c and the relative increase in J_c both tend to increase as temperature decreases.
- The relative rise in J_c is a function of whether the CC has been designed to include artificial pining centres to enhance its pre-irradiation J_c [2], [20].
- The fluence range over which the above phenomena manifest themselves is $10^{18} – 10^{19}$ n/cm^2.

Though not shown in the literature pertaining to neutron irradiation, experiments involving fast ion irradiation show similar consequences to those described above and, given the irradiation stage is significantly less complex to manage, also highlight the following:

- As fluence increases, J_c at any temperature and high field aligned with the CC's tape plane – $B\|$(RD, TD) – increases to peak J_c before decreasing through its original J_c (Fig2**b**) [21]. Compared to the similar phenomenon shown when ($B\|$ND), the peak increase is less pronounced and the fluence at which the peak occurs is at lower fluence.
- The anisotropy of $J_c(\theta)$ decreases with increasing fluence. As the peak $J_c(B\|$(RD, TD)) decreases, the width of the peak widens and J_c at most other angles increases (Fig2**b**) [22].
- The $B\|$ND at which flux flow starts to affect J_c decreases as fluence increases [23]. No reference could be found reporting on whether this occurs when the field is aligned with $B\|$(RD, TD) (Fig2**c**).
- The θ of minimum J_c moves to a different intermediate angle between $B\|$ND and $B\|$(RD, TD) [21] (Fig2b).

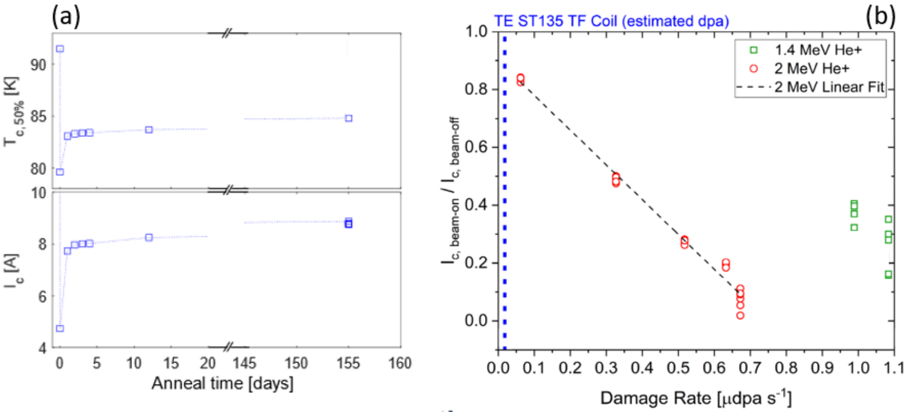

Fig. 3. (a) T_c and I_c (40 K) recovery due to annealing at room temperature of a Fujikura CC sample irradiated at 40K. Response shows that bulk of recovery is within 1-2 days with the properties continuing to recover over periods of more than 100 days. Reproduced from iliffe et al. [25]. (b) Effect of varying damage rate on the observed drop in I_c (40 K) when a beam of 2 MeV helium ions is irradiating the sample compared to when the beam is off. Reproduced from Adams et al. 2023 [29].

Despite the enormous progress evaluating REBCO for fusion applications, the experiments described above irradiated REBCO at room temperature or above and the measurement of properties was performed often long after the irradiation. This stands in stark contrast to the operating conditions of REBCO CC in a tokamak where the conductors will be simultaneously irradiated with fusion spectrum neutrons and gammas whilst maintained at their cryogenic operating temperature, carrying their design current and subject to applied fields and strain. More recently, the first steps towards testing REBCO in more fusion-like conditions has been taken by Sorbom [24], Iliffe et al. [25], Fischer et al.[26], Devitre et al. [27], Chislett-McDonald et al. [28] and Adams et al. [29]. The conclusions of these works include:

- The $I_c(B_{self}$, 77K) of REBCO samples showed no decrease whilst being irradiated with Co-60 gammas at 60 Gy/min [28].
- That samples irradiated at fusion relevant temperatures recover some of their supercurrent carrying capacity if allowed to anneal at room temperature [25] (Fig3**a**). This finding was extended by Fischer et al. [30] who showed that property recovery does not occur at all until the sample temperature rises above 110 K.
- That the instantaneous effect of helium ion irradiation leads to an equally instantaneous drop in the supercurrent carrying capacity of a REBCO sample and the size of this drop, relative to I_c pre-irradiation, increases linearly with the sample-volume-averaged damage rate of the irradiating ions (Fig3**b**). This experiment also showed that a decrease in the flux flow exponent accompanied the drop in I_c, implying that enhanced

flux flow is the mechanism causing the drop in current carrying capacity [29].

The experiments described above all constitute progress towards evaluating how REBCO will be affected by fusion conditions. STEP has therefore designed a set of experiments to push the study of the change in REBCO's properties due to irradiation as-close-as-reasonably-possible towards fusion conditions prior to an operating tokamak fusion reactor being constructed. Providing this data is key to ensuring STEP's magnets can operate at their rated current, maximum on-coil field and survive the resultant Lorentz forces for their required lifetime. It would also allow comparison to be made with the best currently available data and allow models trying to bridge the gap between experiments and fusion conditions to be validated. Secondarily, the goal of the entire set of experiments (and modelling) is to thoroughly test and validate the choice of specific REBCO CC used in the construction of STEP's superconducting magnets, with sufficient time so that the chosen CC can be manufactured and delivered in time to meet STEP deadlines. We also need to determine which quality assurance steps are essential to validate on REBCO CC newly arrived from manufacturers, and to determine the infrastructure required to perform these activities.

III. STEP REBCO CC IRRADIATION TEST PLAN

In this section, selected experiments from STEP's plan to test the effects of irradiation on REBCO CC are presented.

A. Filtered Oxygen Ion Irradiation Experiment

Creating lattice damage in materials with fast ions instead of neutrons is useful because damage can be inflicted at rates $\approx 10^4$ times higher that of a fission reactor, with near-zero sample activation, at low cost and with significantly better control over experimental conditions [31]. Though part of STEP's plan involves subjecting REBCO CCs to neutron irradiation (section 3B), the goal of this experiment is to leverage these benefits to provide STEP as soon as possible with a preliminary indication of how the supercurrent carrying capacity of several CC changes with accumulated lattice damage.

Although the damage mechanisms of fast ions and neutrons are not the same, this experiment has been designed to account for the differences as-far-as-reasonably-possible. Based on simulations of REBCO's response to neutron damage performed using SPECTRA-PKA [32], the REBCO self-ion oxygen are being used. To increase the proportion of the total damage created due to ion-lattice atom interactions (ie. nuclear stopping), a mi2-factory [33] energy filter is being used. Simulation using GEANT4 [34] showed that using an energy filter and a starting oxygen ion energy of 20 MeV produces a roughly uniform oxygen implantation profile through a layer of REBCO up to 10 µm thick. This promotes damage due to nuclear stopping as this stopping mechanism is dominant for oxygen ions of <20 keV, which only have a range of < 0.1µm.

The experiment set-up is shown in Fig4. Sample irradiations are performed at room temperature at the Ion Beam Centre at the Helmholtz Zentrum Dresden Rossendorf (IBC-HZDR) using their 6MV Tandetron accelerator. Changes in superconducting properties of the samples as a function of accumulated fluence are measured using magnetometry methods made available by the UKAEA's Material Research Facility (MRF). The samples are then available for further investigation primarily to test the hypothesis that this method of irradiation creates neutron spectrum-like damage. These include X-ray diffractometry (XRD) analysis and high energy resolution fluorescence detected x-ray absorption spectroscopy (HERFD-XAS), in conjunction with x-ray absorption near edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) modelling of REBCO, to probe the fine structure of the REBCO unit cell [35].

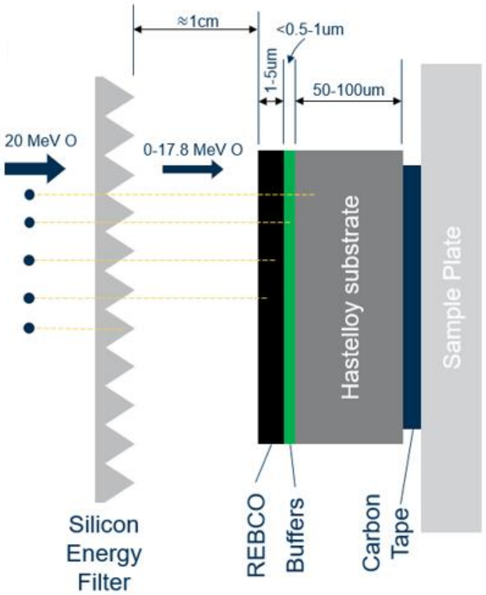

Fig. 4. Planned set-up of the oxygen ion irradiation experiment. Fast ions approach from the left-hand side, traverse the energy filter resulting in their energy levels spreading out linearly between 0-17.8 MeV. The ions then enter the REBCO CC sample and implant at a depth commensurate with their energy.

B. Neutron Irradiation Experiment

As a compliment to the Filtered Oxygen Ion Irradiation Experiment, this is a longer-term experiment that involves the neutron irradiation of REBCO HTS samples. Several ϕ3mm disks of REBCO punched from commercially available CC made available by different manufacturers are to be irradiated with neutrons at the High Flux Accelerator Driven Neutron Facility (HF-ADNF) at Birmingham University. The samples will be irradiated in parallel with other material, making use of volumes subject to neutron irradiation that are not being used by the other experiments. Changes in superconducting properties of the samples as a function of accumulated fluence will be measured using magnetometry methods, made available by the MRF, with the MRF also providing radiological protection and waste disposal assistance, because the samples and holder will be activated by the irradiation. Sample irradiation shall continue until each has accumulated a fluence of $> 10^{18}$ n/cm^2 before being returned to the MRF for testing.

C. Cold Ion Irradiation Experiment

As shown by Fischer et al. [26], REBCO irradiated at < 110 K recovers some of its properties when allowed to return to room temperature, implying that a similar anneal could extend the useful life of the magnets of fusion devices. In this experiment, the effects of irradiating samples at < 110 K and allowing them to anneal at room temperature is being investigated. The latter has been shown to have important implications for fusion magnets, potentially allowing them to repair themselves by annealing during scheduled outages, thus prolonging the life of a magnet that has been degraded by irradiation (Fig5). The required outcome is to have data showing whether commercially available CCs made to different specifications and using different technologies vary in their response to irradiation damaged at room versus cold temperatures, and/or how well (or not) they recover their properties when irradiated cold and then allowed to anneal at room temperature. To aid comparison with previous work, the experiment shall continue to use 2 MeV helium ions to create lattice damage in CC samples, with beam line service provided by Surrey University Ion Beam Centre (SIBC).

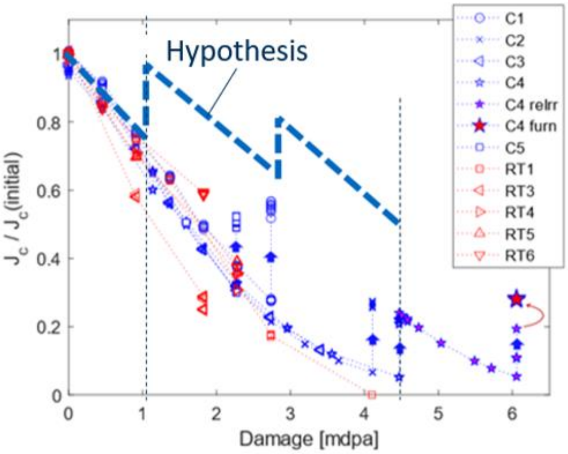

Fig. 5. Evolution of the critical current density (J_c) relative to its initial, unirradiated value (*Jc(initial)*) at 40 K. Samples C1-5 were irradiated and measured in-situ at 40 K and samples RT1-6 were irradiated at room temperature and then cooled for measurement. Filled blue arrows indicate changes due to room temperature annealing. Specific to sample C4 are 'reIrr' which indicates data collected during and after a second cold irradiation step, and 'furn' which indicate data collected after furnace annealing at 150 ^{o}C. The thick blue dashed line is added to show possible improvement in CC properties when it is occasionally annealed for > 1 day at room temperature. Modified from Iliffe et al. [25].

D. High Fluence Cryogenic Irradiation of REBCO Superconductors Experiment

This experiment includes the construction of a custom test rig to allow samples of REBCO CC to be maintained at 20 K whilst being remotely transported between the high fluence end of a horizontal beam port in a fission test reactor and a measurement station outside the reactor which will allow the sample's J_c to be measured at $B \| ND = 0 – 1$ T. The aim for each sample is that it should have its properties measured after fluence intervals of $< 5x10^{17}$ n/cm^2 up to a total fluence of $> 5x10^{18}$ n/cm^2 in less than 20-30 days. Samples will be tracks of REBCO made from CC using photolithography and wet etching as described in [23]. Based on the results of Fischer et al. [2], samples will be shielded using cadmium foil to reduce the flux of thermal neutrons to the REBCO sample and make a fission neutron spectrum more similar to a fusion neutron spectrum.

E. In-situ Experiments

STEP's experiments to further investigate how the presence of a transport current and irradiating particles together (ie. in-situ) effect REBCO's ability to carry current are continuing in collaboration with Oxford University and the MRF.

Experiments into the effects of in-situ ions shall continue using the same experiment described in section 3C. Latest results can be found in Iliffe et al. [25] and Adams et al. [29]. Future experiment shall include extending the range of ion energies and REBCO CC architectures that are subjected to in-situ ion irradiation.

Experiments into the effect of in-situ gammas have been reported in Chislett-McDonald et al. [28]. Future plans include testing samples that have been subject to ex-situ irradiation damage from other sources, either neutron, gamma or fast ion, and using gamma sources that emit gammas of different energies to Co-60 (eg. Ir-192 or Cs-137).

Experiments into the effects of in-situ neutrons shall continue using the same experiment described in section 3C. Initial experiments have been performed using the Neutron Irradiation Laboratory for Electronics' (NILE) 14 MeV neutron source. Fluxes up to ≈ 10^8 n/cm^2/s at the sample have been achieved. Plans include redesigning the experiment to increase flux and to improve the sensitivity of detection of damage events by patterning REBCO tracks.

IV. CONCLUDING REMARKS

In this paper, STEP's current understanding of the effects of irradiation on the ability of REBCO CCs to transport current in an environment as similar as possible to that experienced in a magnet for a small fusion reactor has been summarized, and the various experiments – both ex-situ and in-situ – that are being done or supported by STEP. Though these projects, STEP will extend their knowledge of REBCO subjected to fusion-like irradiation conditions with the aim of de-risking the design of the tokamak magnets. Ideally, experiments to investigate how irradiation effects REBCO CC's response to strain should also be carried out. A design for such an experiment is currently being formulated.

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