
STEP's progress understanding REBCO coated conductors in the Fusion Environment

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Progress in the STEP Programme Towards Understanding REBCO Coated Conductors in the Fusion Environment

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Abstract— The UKAEA’s Spherical Tokamak for Energy Production (STEP) programme aims to demonstrate the ability of low aspect ratio tokamaks to generate net electricity from deuterium-tritium (DT) fusion. As STEP have selected REBCO coated conductor (CC) as the current carrier in most magnet systems, understanding how REBCO CC responds to the energetic particle environment of a compact tokamak is crucial, especially given reported changes to the properties of REBCO following neutron irradiation.

The STEP confinement system materials group has developed a plan to thoroughly test and validate the superconducting properties of REBCO under conditions as close as reasonably possible to those within STEP prior to its construction. Here our progress in carrying out this experimental plan is presented, followed by details of experiments still in development.

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

I. INTRODUCTION

The economic viability of fusion power plants such as the Spherical Tokamak for Energy Production (STEP) is a function of their size, toroidal field (TF) strength and availability during their operating lifetime. This optimisation has led the designers of STEP to adopt both a compact design and the use of coated conductors (CC) made with the superconductor rare-earth barium copper oxide (REBCO) as the current carriers for their magnets. However, it is known that neutrons emitted by fusion reactions cause damage to REBCO CC that affect their ability to carry current [1]. The STEP programme has therefore developed a plan to quantify the effects of irradiation on REBCO CC, providing designers with the information required to maximise the chances of STEP achieving its scientific objectives.

Current understanding of the effects of different types of

irradiation on REBCO CC have been presented in [2]. Here we present the progress of experiments to quantify the effects of irradiation on REBCO CC made using a variety of methods, including in each case their scientific basis, experimental plan, the results generated so far, and discussion.

II. REBCO IN STEP

As a tokamak [3], STEP will confine a hot plasma using a combination of toroidal, poloidal, and vertical magnetic fields, each generated by its own set of electromagnets, and each with its own unique design challenges [4]. The toroidal field (TF) coils have the highest operating field, will be demountable and are subjected to a significant fusion neutron load from the plasma during DT operation. Given that the critical current density per unit width (I_{cpw}) of REBCO CC is determined by flux pinning provided by microstructural defects, and that this defect landscape is affected by irradiation [5], [6], I_{cpw} is expected to evolve with time in service, whilst carrying current at high field and being subjected to Lorentz forces and a flux of neutrons. As such, it is necessary to evaluate if REBCO in the TF magnets of STEP is subjected to combinations of field and field direction which will either limit its operation or provide opportunities to reduce the risk and cost associated with the magnet.

In this analysis, each cable in STEP’s TF coil is partitioned into short sections along its length. The magnetic field strength and direction vector (\vec{B}) at the location of each short section is then simulated using the OPERA™ electromagnetic simulation tool [7]. The field direction relative to the CC plane (θ) is then calculated at each location using $\theta = 90 - \varphi$ where:

$$\cos \varphi = \frac{\vec{B} \cdot \vec{ND}}{|\vec{B}| |\vec{ND}|} \quad (1)$$

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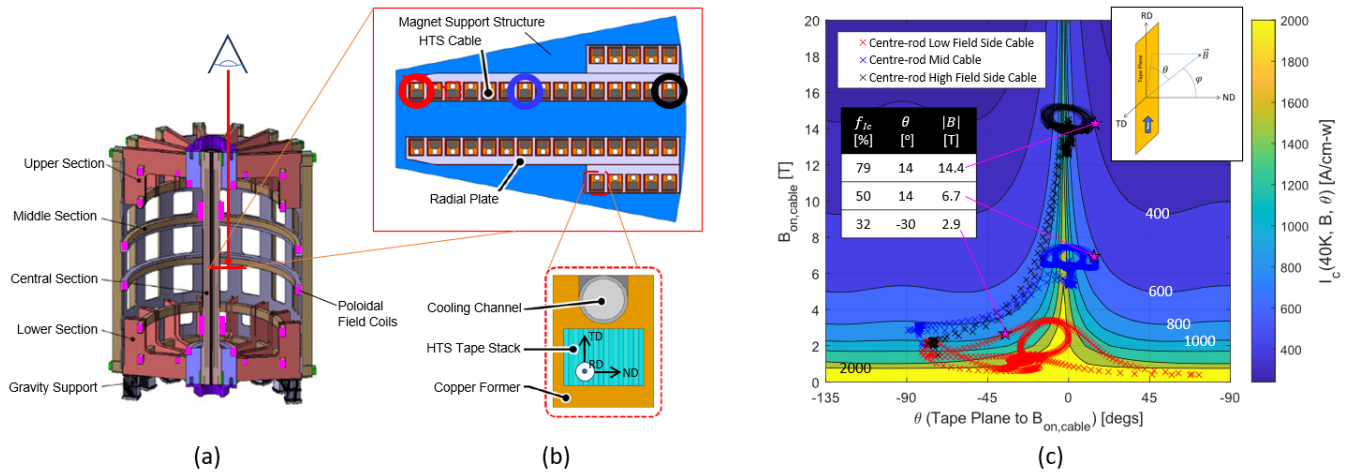


Figure 1: (a) 180° section of the STEP 3.2T TF coil, including 90kA cables, support structure and location of poloidal field coils (pink). (b) Top: Cutaway view of the centre-rod at the STEP mid-plane, showing the arrangement of the TF cables within the centre-rod, the radial plate, and the magnet support structure. Bottom: a close-up of the cable cross section, showing where the HTS tape stack and the CC axes with respect to the cable. RD, TD and ND are the rolling, transverse and normal directions of the CC respectively. (c) Example field vs field angle results for the three centre-rod cables circled in (b), superimposed on an $I_{cpw}(B, 40 K, \theta)$ plot for Faraday Factory sample #477-R. Each 'x' denotes the (B, θ) combination at a small section of the cable as it runs from the top to the bottom of the centre-rod which defines its I_{cpw} . Also marked is the small cable section with the lowest I_{cpw} (★), coupled to an inset table showing the field, field angle with respect to the CC (RD,TD) plane and ratio of the operating current to I_{cpw} (f_{ic}) for the limiting point of the cable. Inset: Visualisation of geometric calculation solved using equation (1).

and \vec{ND} is the CC's normal direction (ND) vector (visualised in Figure 1c, inset).

Figure 1c shows the (B, θ) combinations for each short section of cable ('x') for three cables in the centre-rod of the STEP design (circled in Figure 1b) as described in [4], superimposed on a contour plot of the $I_{cpw}(B, \theta)$ so the limiting I_{cpw} for each cable section can be determined. In this case, the CC being used is Faraday Factory sample #477-R (420-763), with $I_{cpw}(B, 40 K, \theta)$ data collected and distributed by the Robinson Research Institute [8], [9] and extrapolated to high field using equation 2 from [10]. Note that the $I_{cpw}(B, 40 K, \theta)$ reference data used here assumes the field is perpendicular to the RD of the CC only, which is not reflected in how the field generated by the TF interacts with its cables. Though I_{cpw} data exists for when θ is a rotated about multiple CC axis [11], [12], the I_{cpw} data for three-axis rotation required for this analysis does not yet exist, hence φ here is assumed to be equivalent to the same angle when the field is perpendicular to the RD of the CC.

These results show that the STEP TF coil design can operate at its rated current without quenching at 40K. Cables on the high field side of the centre-rod are subjected to the highest field and are thus operating closest to I_{cpw} of the CC (21%). However, the limiting sections of all cables (★ in Figure 1c) are adjacent to poloidal field coils designed to shape the plasma which offset the field angle to a location in $I_{cpw}(B, \theta)$ space with much lower current carrying capacity. Also noteworthy is the low operating current fraction of I_{cpw} (f_{ic}) of the mid- and low field side cables, suggesting that the number of CC in those cables could be reduced, and the section of cable limiting its current carrying capacity is within the typical in-plane peak in REBCO $I_{cpw}(\theta)$ as $\theta \rightarrow 0$, suggesting that how this peak in I_{cpw} widens and flattens with

increasing radiation damage, as demonstrated in [13], will affect the trade-off between magnet lifetime and the number of CC used for these cables.

III. INITIAL CC PROPERTIES SURVEY

Section II highlights that the REBCO CC assembled into STEP TF cables must meet a minimum current carrying requirement dependent on its location within the magnet, both before and after the CC is irradiated. Assessing the ability of a CC to meet these specifications requires measurements of $I_{cpw}(B, \theta)$ for each CC at STEP relevant temperatures (T), strains (ε), and damage levels (Φ). Figure 1c is an example for zero strain and damage at 40 K. Given the difficulty inherent in assessing $I_{cpw}(T, B, \theta, \varepsilon, \Phi)$ when $\varepsilon \neq 0$, $\Phi \neq 0$ and $\vec{B} \nparallel \vec{ND}$, an initial survey with $\varepsilon = 0$, $\Phi = 0$ and $\vec{B} \parallel \vec{ND}$ of various commercially available CC samples from a variety of different

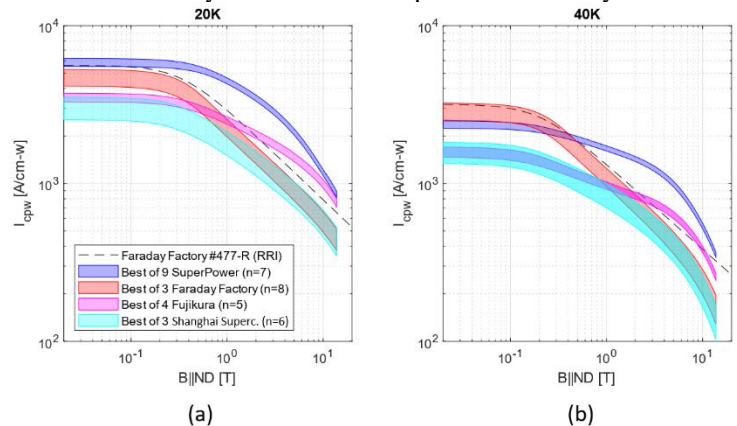


Figure 2: Critical current per unit width (I_{cpw}) at 20 K and 40 K versus field strength parallel to the CC ND ($B_{||ND}$) for the best performing type of CC sample from four different tape manufacturers, compared with a reference sample measured by the Robinson Research Institute. The bands denote the range of I_{cpw} measured for 'n' samples of each type.

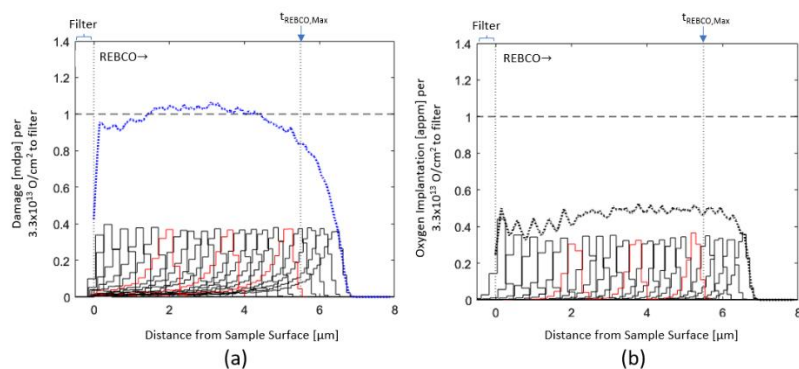


Figure 3: Damage (a) and implantation (b) profiles versus depth from the REBCO surface resulting from 20 MeV oxygen ion irradiation through a textured silicon energy filter [21] into REBCO. Calculated using SRIM [22] by summing profiles from 20 equal width bins, each containing a different thickness of silicon filter (black, except 5th 10th and 15th bin which are shown in red).

manufacturers was conducted to evaluate the range of different CC performance, with the tentative hypothesis that better initial performance is a good indicator of better post irradiation performance.

The $I_{cpw}(B||ND, T)$ of each REBCO CC was measured in the ranges $0\text{ T} < B||ND < 13.5\text{ T}$ and $10\text{ K} < T < 50\text{ K}$ using magnetisation methods in conjunction with Bean's model for cylindrical samples [14] in a Quantum Design[®] DynaCool[™] PPMS[®] using the vibrating sample magnetometer of the AC Measurement System (ACMS-II) module. All samples measured were 3 mm diameter disks cut from the CC using either a TEM punch tool or laser micromachining, and at a field ramp rate of 0.01 mT/s giving an effective electric field criterion of 7.5 $\mu\text{V}/\text{m}$ based on [15]. Though all samples were provided with protective silver and copper layers, superconducting property measurements were performed on samples both with and without these layers as some of the samples were used in the irradiation experiments described in section IV.

The results for the best performing CC from each manufacturer (SuperPower SF12050-HM, Faraday Factory 4-20Ag-05Cu-35H, Fujikura FESC-SCH04 & Shanghai Superconductor ST-4-E) at 20 K and 40 K are shown in Figure 2, with the Robinson Research Institute's Faraday Factory sample #477-R (420-763) data, previously shown in Figure 1, as a basis for comparison. These show that the performance at $B||ND = 13\text{ T}$ on all tapes exceeds 350 A/cm-w at 20 K and 100 A/cm-w at 40 K and comparing with the best performing samples suggests that there is scope for improving this critical value by 2–3 \times . The results also highlight how increasing self-field I_{cpw} and decreasing the slope of the power-law region using artificial pinning centres, used by all but the Faraday Factory CC, combine to result in better high field performance.

IV. FILTERED OXYGEN ION IRRADIATION

In this experiment, the evolution of $I_{cpw}(B||ND, T)$ is tracked with increasing irradiation damage using O^{4+} ions as a proxy for neutrons, like other experiments described in the literature (e.g. [5],

[16], [17]). Oxygen ions were used to simulate oxygen primary knock-ons in the REBCO sublattice, similar to the effects reported for neutron irradiation [18], [19]. $I_{cpw}(B||ND, T)$ is measured using the PPMS described in section III. The critical temperature (T_{c0}) was also tracked with radiation dose as this property is known to change with irradiation (e.g. [20]) and is a measure of the thermodynamic stability of the superconducting state independent of how flux pinning limits I_{cpw} . T_{c0} was measured using the ACMS-II in the PPMS and is defined as when the measured susceptibility $\chi = -0.02$.

Samples were irradiated at room temperature at the Ion Beam Centre of the Helmholtz Zentrum Dresden Rossendorf (IBC-HZDR) using a 6 MV Tandemron accelerator. Samples are irradiated using oxygen ions accelerated to 20 MeV and then passed through an energy filter [21] provided by mi2-factory. The filter has the effect of defocusing the Bragg peak of the irradiation, resulting in a near-uniform damage and implantation profiles for REBCO samples up to $\approx 5\text{ }\mu\text{m}$ thick, shown in Figure 3, and confirmed using Secondary Ion Mass Spectroscopy (SIMS) as reported in [2]. To make the damage levels comparable with those from other types of irradiations, the damage is converted using SRIM [22] to units of Frenkel pairs (or lattice atom displacements) created by the irradiation per target atom, known as displacements per atom (dpa). To date, most materials tested have at least one sample that has reached $2\text{--}2.5 \times 10^{-3}$ dpa (2–2.5 mdpa), and further irradiations are planned to increase this damage level toward the goal of 5 mdpa, similar to [1].

A representative sample of the results obtained so far is shown in Figure 4. As seen in previously reported irradiation experiments on REBCO (e.g. [1]), T_{c0} for all samples showed a monotonic decrease with fluence. Plotting $T_{c0}(\Phi = 0)$ against $dT_{c0}/d\Phi$ for all samples tested (Figure 4a) showed a tendency for CC with similar rare earths to cluster together, regardless of manufacturer or whether the sample included artificial pinning centres (APCs). However, EuBCO based CC showed both highest $T_{c0}(\Phi = 0)$ and steepest rate of decline with damage $dT_{c0}/d\Phi$. Notable is that YBCO-based CC showed the lowest starting T_{c0} but also the slowest rate of decline of T_{c0} at -1.5 to $-2\text{ K}/\text{mdpa}$ with irradiation damage (compared to -2.35

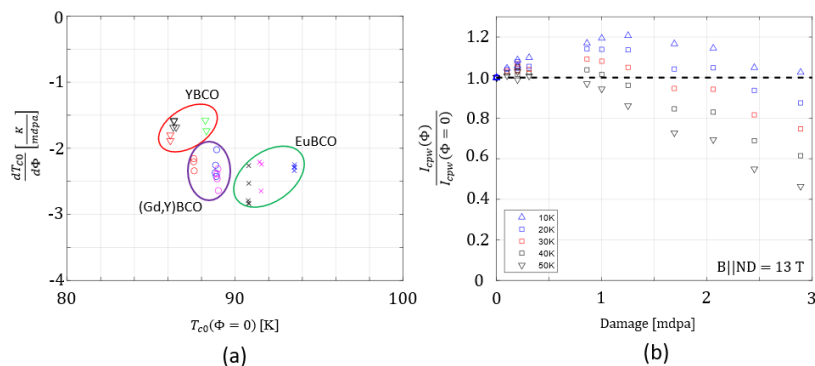


Figure 4: Results from the filter ion irradiation experiment showing (a) the relationship between starting T_{c0} and the rate of change of T_{c0} with irradiation damage. (b) the relative change in I_{cpw} with irradiation damage at different temperatures between 10–50 K for the SuperPower sample with the best initial properties.

K/mdpa for neutron irradiation [1]), and that $dT_{c0}/d\Phi$ for (Gd,Y)BCO and EuBCO was roughly similar at -2 to -3 K/mdpa (compared to -2.5 to -2.9 K/mdpa for neutron irradiation of pure GdBCO sample [1]).

Another key result of this experiment is how I_{cpw} at different temperatures and $B||ND = 13$ T evolves with increasing damage. Though I_{cpw} was measured for all samples, example results for the SuperPower SF12050-HM sample, previously shown in Figure 2, are shown in Figure 4b and suggest that the pre-irradiation I_{cpw} can be maintained up to a damage level that increases as temperature decreases. The change is also significant, being ~ 1.1 mdpa at 40 K, rising to ~ 2.5 mdpa at 20 K and closer to 3 mdpa at 10 K. The implication of this result for STEP is that, all other things being equal, the operating temperature range influences the lifetime of the TF magnet, with there being little difference between operation at 10 K and 20 K, but increasing to 40 K introduces a significant change. Further, as shown in Section II, the field is rarely parallel to the ND of the CC for much of a tokamak magnet. Further work is required to determine the effect of radiation on the I_{cpw} of CCs as a function of field angle and temperature.

V. WORK WITH CENTRUM VÝZKUMU ŘEŽ

Centrum Výzkumu Řež (CVŘ) is part of the Czech International Centre of Research Reactors [23]. The facility operates the LVR-15 research reactor, which has several horizontal channels into its core. STEP plans to install the High Neutron Fluence Cryogenic Irradiation of Superconductors (HiCRIS) experiment into one of these horizontal channels (HK5). HiCRIS will track the evolving I_{cpw} of neutron irradiated REBCO samples, targeting a flux of 10^{13} n/cm²/s and maximum fluence of $>5 \times 10^{18}$ n/cm², whilst being maintained throughout at cryogenic temperatures (20 K). Design work is ongoing with the aim to have the experiment commissioned towards the end of 2026 at CVR.

In the meantime, a preliminary room temperature irradiation experiment is being designed for the HiCRIS channel, aiming to irradiate fusion magnet materials to fluences between 10^{16} and 7×10^{20} n/cm². Fluence control will be achieved by placing samples at different locations within the HK5 channel, with 7×10^{20} n/cm² being achieved at the channel's reactor end after 2 reactor cycles (≈ 60 days). The materials that will be included are REBCO CC (as a comparison with the main HiCRIS experiment), insulators, neutron shielding materials, copper alloys and solders, as well as materials and/or components that are being considered for the HiCRIS experiment. The plan is to monitor sample temperatures and neutron fluxes using neutron hard temperature sensors and activation foils of iron, titanium and nickel.

VI. IN-SITU IRRADIATION EXPERIMENTS

Apart from HiCRIS, in all the experiments described above the irradiation of samples is performed at or above room temperature. However, in a tokamak magnet, the REBCO CCs will be exposed to neutron and gamma irradiation at their cryogenic operating temperature, carrying their rated current and being subject to Lorentz forces. As described in more detail in [2], several experiments are being performed to measure CC

I_c at the same time as irradiation is applied to the sample ('in-situ'). Irradiating species used so far include protons [24], helium [25], gammas from Co-60 source [26] and neutrons using the ISIS Neutron and Muon Source Neutron Irradiation Laboratory for Electronics (NILE) [27]. Progress to date indicates that interpreting results from in-situ ion irradiation-based experiments has been complicated by the beam heating of the samples. Recent activities to progress the investigation of the effects of in-situ neutrons of REBCO have included building a new experiment situate samples closer to the neutron source, increasing the flux of NILE neutrons incident on a sample from 10^9 to 10^{10} n/cm²/s. A device to achieve this has been designed and is currently being built and commissioned (Figure 5), with first experimental results expected towards the end of 2024. Due to the relatively low fluxes, the plan is to compare the effect of in-situ neutrons on unirradiated samples and samples irradiated elsewhere using both ions and neutron sources, targeting irradiation & measurement temperatures of 20 to 40 K.

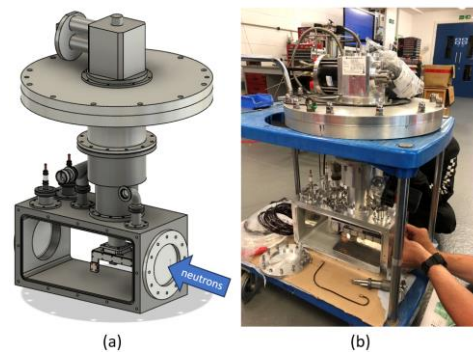


Figure 5: Design (a) and Build progress to date (b) of the in-situ neutron irradiation experiment to be performed at NILE.

VII. CONCLUDING REMARKS

The STEP programme aims to de-risk the design of its magnets by performing experiments to understand how REBCO CC will respond to the energetic particle environment inside a fusion reactor. In this paper, several experiments in the STEP experimental programme have been presented. This has included a more precise examination of the conditions the REBCO CC in the STEP TF magnet are to be subjected to (section II), a survey of the properties of available commercial CC (section III) and an ion-irradiation experiment to determine how CC current carrying capacity evolves with increasing irradiation damage (section IV). Design work continues on experiments to track evolving current carrying capacity in CCs damaged by neutrons, both at room and cryogenic temperatures (section V), as well as with in-situ fusion spectrum neutrons (section VI).

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Abstract— The UKAEA’s Spherical Tokamak for Energy Production (STEP) programme aims to demonstrate the ability of low aspect ratio tokamaks to generate net electricity from deuterium-tritium (DT) fusion. As STEP have selected REBCO coated conductor (CC) as the current carrier in most magnet systems, understanding how REBCO CC responds to the energetic particle environment of a compact tokamak is crucial, especially given reported changes to the properties of REBCO following neutron irradiation.

The STEP confinement system materials group has developed a plan to thoroughly test and validate the superconducting properties of REBCO under conditions as close as reasonably possible to those within STEP prior to its construction. Here our progress in carrying out this experimental plan is presented, followed by details of experiments still in development.

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

I. INTRODUCTION

The economic viability of fusion power plants such as the Spherical Tokamak for Energy Production (STEP) is a function of their size, toroidal field (TF) strength and availability during their operating lifetime. This optimisation has led the designers of STEP to adopt both a compact design and the use of coated conductors (CC) made with the superconductor rare-earth barium copper oxide (REBCO) as the current carriers for their magnets. However, it is known that neutrons emitted by fusion reactions cause damage to REBCO

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CC that affect their ability to carry current [1]. The STEP programme has therefore developed a plan to quantify the effects of irradiation on REBCO CC, providing designers with the information required to maximise the chances of STEP achieving its scientific objectives.

Current understanding of the effects of different types of irradiations on REBCO CC have been presented in [2]. Here we present the progress of experiments to quantify the effects of irradiation on REBCO CC made using a variety of methods, including in each case their scientific basis, experimental plan, the results generated so far, and discussion.

II. REBCO IN STEP

As a tokamak [3], STEP will confine a hot plasma using a combination of toroidal, poloidal, and vertical magnetic fields, each generated by its own set of electromagnets, and each with its own unique design challenges [4]. The toroidal field (TF) coils have the highest operating field, will be demountable and are subjected to a significant fusion neutron load from the plasma during DT operation. Given that the critical current density per unit width (I_{cpw}) of REBCO CC is determined by flux pinning provided by microstructural defects, and that this defect landscape is affected by irradiation [5], [6], I_{cpw} is expected to evolve with time in service, whilst carrying current at high field and being subjected to Lorentz forces and a flux of neutrons. As such, it is necessary to evaluate if REBCO in the TF magnets of STEP is subjected to combinations of field and field direction which will either limit its operation or provide opportunities to reduce the risk and cost associated with the magnet.

In this analysis, each cable in STEP’s TF coil is partitioned into short sections along its length. The magnetic field strength and direction vector (\vec{B}) at the location of each short section is then simulated using the OPERA™ electromagnetic simulation tool [7]. The field direction relative to the CC plane (θ) is then calculated at each location using $\theta = 90 - \varphi$ where:

$$\cos \varphi = \frac{\vec{B} \cdot \vec{ND}}{|\vec{B}| |\vec{ND}|} \quad (1)$$

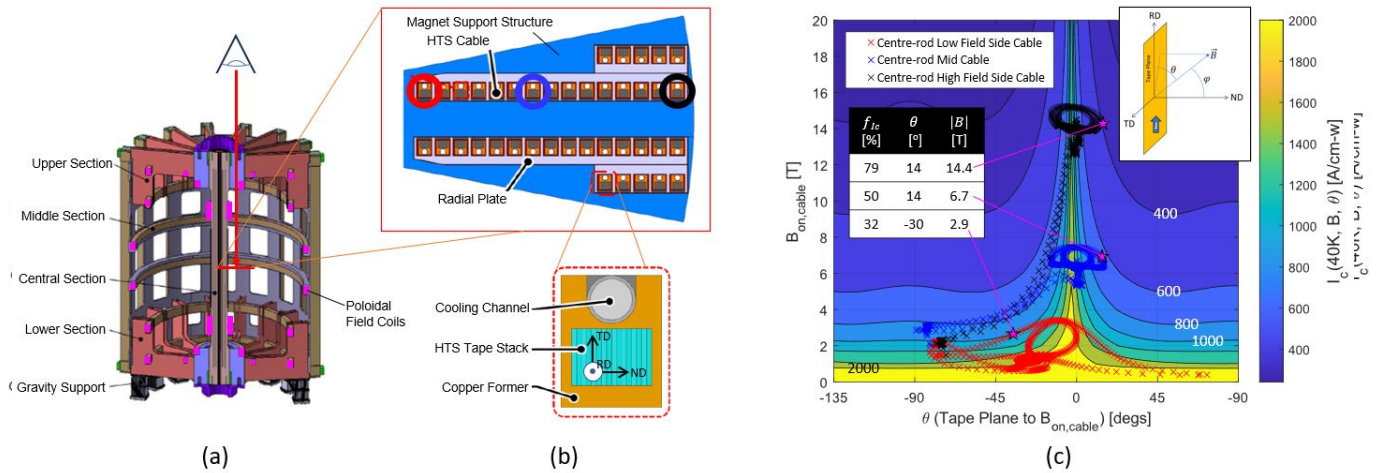


Figure 1: (a) 180° section of the STEP 3.2T TF coil, including 90kA conductors cables, support structure and location of poloidal field coils (pink). (b) Top: Cutaway view of the centre-rod at the STEP mid-plane, showing the arrangement of the TF cables within the centre-rod, the radial plate, and the magnet support structure. Bottom: a close-up of the cable cross section, showing where the HTS tape stack and the CC axes with respect to the cable. RD, TD and ND are the rolling, transverse and normal directions of the CC respectively. (c) Example field vs field angle results for the three centre-rod cables circled in (b), superimposed on an $I_{cpw}(B, 40 K, \theta)$ plot for Faraday Factory sample #477-R. Each 'x' denotes the (B, θ) combination at a small section of the cable as it runs from the top the bottom of the centre-rod which defines its I_{cpw} . Also marked is the small cable section with the lowest I_{cpw} (★), coupled to an inset table showing the field, field angle with respect to the CC (RD, TD) plane and ratio of the operating current to I_{cpw} (f_{1c}) for the limiting point of the cable. Inset: Visualisation of geometric calculation solved using equation 2 and \vec{ND} is the CC's normal direction (ND) vector (visualised in Figure 1c, inset).

Figure 1c shows the (B, θ) combinations for each short section of cable ('x') for three cables in the centre-rod of the STEP design (circled in Figure 1b) as described in [4], superimposed on a contour plot of the limiting $I_{cpw}(B, \theta)$ so the limiting I_{cpw} for each cable section can be determined. In this case, the CC being used is Faraday Factory sample #477-R (420-763), with $I_{cpw}(B, 40 K, \theta)$ data collected and distributed by the Robinson Research Institute [8], [9] and extrapolated to high field using equation 2 from [10]. Note that the $I_{cpw}(B, 40 K, \theta)$ reference data used here assumes the field is perpendicular to the RD of the CC only, which is not reflected in how the field generated by the TF interacts with its cables. Though I_{cpw} data exists for when θ is a rotation about multiple CC axis [11], [12], the I_{cpw} data for three-axis rotation required for this analysis does not yet exist, hence φ here is assumed to be equivalent to the same angle when the field is perpendicular to the RD of the CC.

These results show that the STEP TF coil design can operate at its rated current without quenching at 40K. Cables on the high field side of the centre-rod are subjected to the highest field and are thus operating closest to I_{cpw} of the CC (21%). However, the limiting sections of all cables (★ in Figure 1c) are adjacent to poloidal field coils designed to shape the plasma which offset the field angle to a location in $I_{cpw}(B, \theta)$ space with much lower current carrying capacity. Also noteworthy is the low operating current fraction of I_{cpw} (f_{1c}) of the mid- and low field side cables, suggesting that the number of CC in those cables could be reduced, and the section of cable limiting its current carrying

capacity is within the typical in-plane peak in REBCO $I_{cpw}(\theta)$ as $\theta \rightarrow 0$, suggesting that how this peak in I_{cpw} widens and flattens with increasing radiation damage, as demonstrated in [13], will affect the trade-off between magnet lifetime and the number of CC used for these cables.

III. INITIAL CC PROPERTIES SURVEY

Section II highlights that the REBCO CC assembled into STEP TF cables must meet a minimum current carrying requirement dependent on its location within the magnet, both before and after the CC is irradiated. Assessing the ability of a CC to meet these specifications requires measurements of $I_{cpw}(B, \theta)$ for each CC at STEP relevant temperatures (T), strains (ϵ), and damage levels (Φ). Figure 1c is an example for zero strain and damage at 40 K. Given the difficulty inherent in assessing

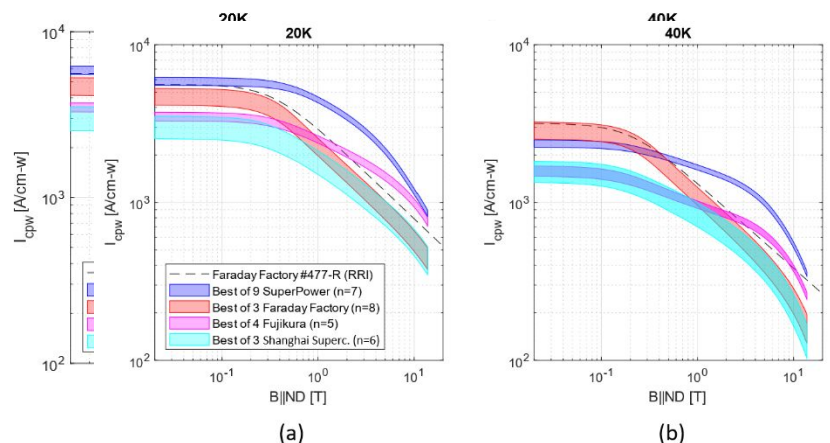


Figure 2: Critical current per unit width (I_{cpw}) at 20 K and 40 K versus field strength parallel to the CC ND ($B||ND$) for the best performing type of CC sample from four different tape manufacturers, (SCST—Shanghai Superconducting Technology), compared with a reference sample measured by the Robinson Research Institute. The bands denote the range of I_{cpw} measured for each sample type, g The bands denote the range of I_{cpw} measured for 'n' samples of each type, even the number of repeats measured (n) The bands denote the range of I_{cpw} measured for each sample type.

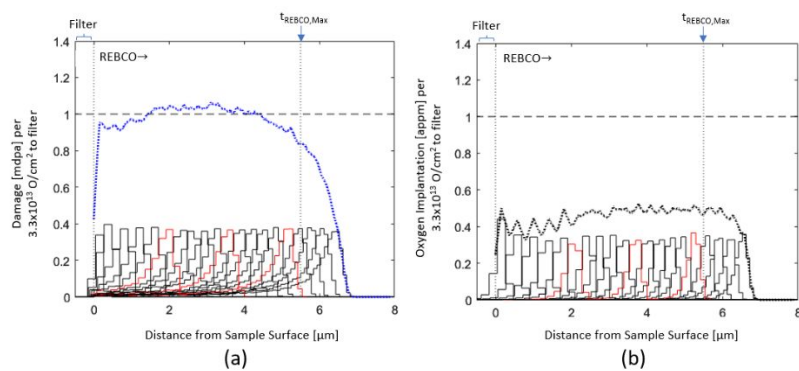


Figure 3: Damage (a) and implantation (b) profiles versus depth from the REBCO surface resulting from 20 MeV oxygen ion irradiation through a textured silicon energy filter [21] into REBCO. Calculated using SRIM [22] by summing profiles from 20 equal width bins, each containing a different thickness of silicon filter (black, except 5th 10th and 15th bin which are shown in red).

available CC samples from a variety of different manufacturers was conducted to evaluate the range of different CC performance, with the tentative hypothesis that better initial performance is a good indicator of better post irradiation performance.

The $I_{cpw}(B||ND, T)$ of each REBCO CC was measured in the ranges $0 \text{ T} < B||ND < 13.5 \text{ T}$ and $10 \text{ K} < T < 50 \text{ K}$ using magnetisation methods in conjunction with Bean's model for cylindrical samples [14] in a Quantum Design[®] DynaCool[™] PPMS[®] using the vibrating sample magnetometer of the AC Measurement System (ACMS-II) module. All samples measured were 3 mm diameter disks cut from the CC using either a TEM punch tool or laser micromachining, and at a field ramp rate of 0.01 mT/s giving an effective electric field criterion of 7.5 $\mu\text{V}/\text{m}$ based on [15]. Though all samples were provided with protective silver and copper layers, superconducting property measurements were performed on samples both with and without these layers as some of the samples were used in the irradiation experiments described in section IV.

The results for the best performing CC from each manufacturer (SuperPower SF12050-HM, Faraday Factory 4-20Ag-05Cu-35H, Fujikura FESC-SCH04 & Shanghai Superconductor ST-4-E) at 20 K and 40 K are shown in Figure 2, with the Robinson Research Institute's Faraday Factory sample #477-R (420-763) data, previously shown in Figure 1, as a basis for comparison. These show that the performance at $B||ND = 13 \text{ T}$ on all tapes exceeds 350 A/cm-w at 20 K and 100 A/cm-w at 40 K, and comparing with the best performing samples suggests that there is scope for improving this critical value by 2–3 \times . The results also highlight how increasing self-field I_{cpw} and decreasing the slope of the power-law region using artificial pinning centres, used by all but the Faraday Factory CC, combine to result in better high field performance.

IV. FILTERED OXYGEN ION IRRADIATION

In this experiment, the evolution of $I_{cpw}(B||ND, T)$ is tracked with increasing irradiation

damage using O^{4+} ions as a proxy for neutrons, like other experiments described in the literature (e.g. [5], [16], [17]). Oxygen ions were used to simulate oxygen primary knock-ons in the REBCO sublattice, similar to the effects reported for neutron irradiation [18], [19]. $I_{cpw}(B||ND, T)$ is measured using the PPMS described in section III. The critical temperature (T_{c0}) was also tracked with radiation dose as this property is known to change with irradiation (e.g. [20]) and is a measure of the thermodynamic stability of the superconducting state independent of how flux pinning limits I_{cpw} . T_{c0} was measured using the ACMS-II in the PPMS and is defined as when the measured susceptibility $\chi = -0.02$.

Samples were irradiated at room temperature at the Ion Beam Centre of the Helmholtz Zentrum Dresden Rossendorf (IBC-HZDR) using a 6 MV Tandatron accelerator. Samples are irradiated using oxygen ions accelerated to 20 MeV and then passed through an energy filter [21] provided by mi2-factory. The filter has the effect of defocusing the Bragg peak of the irradiation, resulting in a near-uniform damage and implantation profiles for REBCO samples up to $\approx 5 \mu\text{m}$ thick, shown in Figure 3, and confirmed using Secondary Ion Mass Spectroscopy (SIMS) as reported in [2]. To make the damage levels comparable with those from other types of irradiations, the damage is converted using SRIM [22] to units of Frenkel pairs (or lattice atom displacements) created by the irradiation per target atom, known as displacements per atom (dpa). To date, most materials tested have at least one sample that has reached $2\text{--}2.5 \times 10^{-3} \text{ dpa}$ (2–2.5 mdpa), and further irradiations are planned to increase this damage level toward the goal of $5 \times 10^{-3} \text{ mdpa}$, similar to [1].

A representative sample of the results obtained so far is shown in Figure 4. As seen in previously reported irradiation experiments on REBCO (e.g. [1]), T_{c0} for all samples showed a monotonic decrease with fluence. Plotting $T_{c0}(\Phi = 0)$ against $dT_{c0}/d\Phi$ for all samples tested (Figure 4a) showed a tendency for CC with similar rare earths to cluster together, regardless of manufacturer or whether the sample included artificial pinning centres (APCs). However, EuBCO based CC showed both highest $T_{c0}(\Phi = 0)$ and steepest rate of decline with damage $dT_{c0}/d\Phi$. Notable is that YBCO-based CC

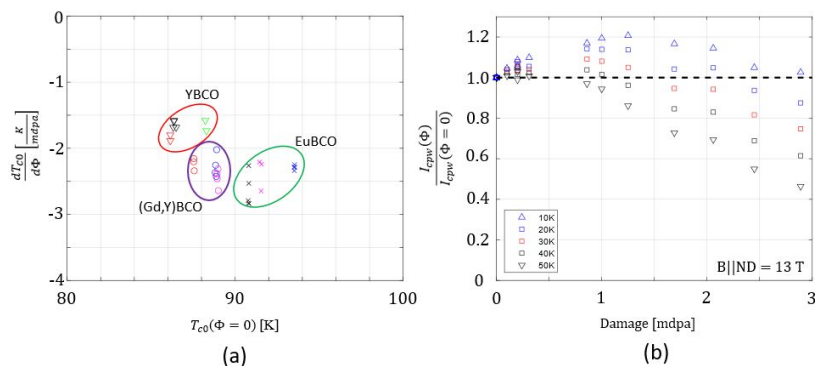


Figure 4: Results from the filter ion irradiation experiment showing (a) the relationship between starting T_{c0} and the rate of change of T_{c0} with irradiation damage. (b) the relative change in I_{cpw} with irradiation damage at different temperatures between 10–50 K for the SuperPower sample with the best initial properties.

showed the lowest starting T_{c0} but also the slowest rate of decline of T_{c0} at -1.5 to -2 K/mdpa with irradiation damage (compared to -2.35 K/mdpa for neutron irradiation ~~from~~ [1]), and that $dT_{c0}/d\Phi$ for (Gd,Y)BCO and EuBCO was roughly similar at -2 to -3 K/mdpa (compared to -2.5 to -2.9 K/mdpa for neutron irradiation of pure GdBCO sample ~~from~~ [1]).

Another key result of this experiment is how I_{cpw} at different temperatures and $B||ND = 13$ T evolves with increasing damage. ~~Though I_{cpw} was measured for all samples, example results for the best—SuperPower SF12050-HM sample, previously shown in Figure 2, are shown in Figure 4b and suggest that the pre-irradiation I_{cpw} can be maintained up to a damage level that increases as temperature decreases. The change is also significant, being ~ 1.1 mdpa at 40 K, rising to ~ 2.5 mdpa at 20 K and closer to 3 mdpa at 10 K. The implication of this result for STEP is that, all other things being equal, the operating temperature range influences the lifetime of the TF magnet, with there being little difference between operation at 10 K and 20 K, but increasing to 40 K introduces a significant change. Further, as shown in Section II, the field is rarely parallel to the ND of the CC for much of a tokamak magnet. Further work is required to determine the effect of radiation on the I_{cpw} of CCs as a function of field angle and temperature.~~

V. WORK WITH CENTRUM VÝZKUMU ŘEŽ

Centrum Výzkumu Řež (CVŘ) is part of the Czech International Centre of Research Reactors [23]. The facility operates the LVR-15 research reactor, which has several horizontal channels into ~~its~~the core. STEP plans to install the High Neutron Fluence Cryogenic Irradiation of Superconductors (HiCRIS) experiment into one of these horizontal channels (HK5). HiCRIS will track the evolving I_{cpw} of neutron irradiated REBCO samples, targeting a flux of 10^{13} n/cm²/s and maximum fluence of $>5 \times 10^{18}$ n/cm², whilst being maintained throughout at cryogenic temperatures (20 K). Design work is ongoing with the aim to have the experiment commissioned towards the end of 2026 at CVR.

In the meantime, a preliminary room temperature irradiation experiment is being designed for the HiCRIS channel, aiming to irradiate fusion magnet materials to fluences between 10^{16} and 7×10^{20} n/cm². Fluence control will be achieved by placing samples at different locations within the HK5 channel, with 7×10^{20} n/cm² being achieved at the channel's reactor end after 2 reactor cycles (≈ 60 days). The materials that will be included are REBCO CC (as a comparison with the main HiCRIS experimentsamples), insulators, neutron shielding materials, copper alloys and solders, as well as materials and/or components that are being considered for the HiCRIS experiment. For each material type, a variety of neutron doses will be achieved by placing samples in aluminium capsules at different locations in the HK5 horizontal channel at LVR-15. The plan is to monitor sample experimental temperatures and neutron fluxes will be measured using neutron hard temperature sensors and activation foils of iron, titanium and nickel.

VI. IN-SITU IRRADIATION EXPERIMENTS

Apart from HiCRIS, in all the experiments described above the irradiation of samples is performed at or above room temperature. However, in a tokamak magnet, the REBCO CCs will be exposed to neutron and gamma irradiation at their cryogenic operating temperature, carrying their rated current and being subject to Lorentz forces. As described in more detail in [2], several experiments are being performed to measure CC I_c at the same time as irradiation is applied to the sample ('in-situ'). Irradiating species used so far include protons [24], helium [25], gammas from Co-60 source [26] and neutrons using the ISIS Neutron and Muon Source Neutron Irradiation Laboratory for Electronics (NILE) [27]. Progress to date indicates that ~~the~~ interpreting results from in-situ ion irradiation-based experiments has been complicated by the beam heating of the samples. Recent activities to progress the investigation of the effects of in-situ neutrons of REBCO have included building a new experiment situate samples closer to the neutron source, increasing the flux of NILE neutrons incidentimpinging on a sample from 10^9 to 10^{10} n/cm²/s. A device to achieve this has been designed and is currently being built and commissioned (Figure 5), with first experimental results expected by towards the end of 2024. Due to the relatively low fluxes, the plan is to compare the effect of in-situ neutrons on unirradiated samples and samples irradiated elsewhere using both ions and neutron sources, targeting irradiation & measurement temperatures of 20 to 40 K.

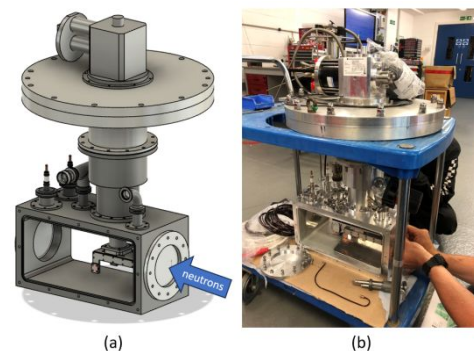


Figure 5: Design (a) and Build progress to date (b) of the in-situ neutron irradiation experiment to be performed at NILE.

VII. CONCLUDING REMARKS

The STEP programme aims to de-risk the design of its magnets by performing experiments to understand how REBCO CC will respond to the energetic particle environment inside a fusion reactor. In this paper, several experiments in the STEP experimental programme have been presented. This has included a more precise examination of the conditions the REBCO CC in the STEP TF magnet are to be subjected to (section II), a survey of the properties of available commercial CC (section III) and an ion-irradiation experiment to determine how CC current carrying capacity evolves with increasing irradiation damage (section IV). Design work continues on experiments to track evolving current carrying capacity in CCs damaged by neutrons, both at room and cryogenic temperatures (section V), as well as with in-situ fusion spectrum neutrons (section VI).

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