IRradiation Effects on HTS for Fusion

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Book of Abstracts

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Scope:

The goal of the workshop is to create a strong network of researchers that unites the competences coming from the nuclear fusion community with those from scholars who worked on the high temperature superconductors (HTS). In our view this is a crucial step to tackle the several challenges related to the effects of particle radiation on the HTS tapes that are enabling the development of compact fusion reactors.

Topics:

- HTS technology for fusion
  – State-of-the-art of HTS wires and tapes
  – Needs for magnets in compact fusion reactors
- Radiation damage
  – Neutronics and radiation environment
  – Advanced methods and facilities
  – Simulations and experiments on HTS
  – Irradiation of HTS for pinning optimization

The workshop is organized in the framework of the bilateral project "SUPERNEON - Study of high-temperature SUPERconductors NEutron radiation damage for compact fusiON reactors" between Politecnico di Torino and MIT.

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Overview on the research and development of HTS conductors and irradiation studies within the European DEMO project

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Despite the EU-DEMO tokamak design is mainly based on LTS conductors, the hybrid design of the Central Solenoid (CS) foresees a graded layered structure, making use of HTS conductors in the high field region of the coil. A set of requirements have been defined in order to compare the different layouts proposed for the central solenoid: an operating current of 60 kA, a peak field ok 18 T, an inlet temperature of 4.5 K and a minimum bending radius of 1.5 m.

Presently two designs have been proposed within the WPMAG project: ASTRA (Aligned Stacks Transposed in Roebel Arrangement) and SECAS (SECtor ASsembled cable). For ASTRA that is a Roebel cable designed by EPFL composed of non-twisted stacks, the results of the SULTAN tests will be presented. SECAS conductor, which is based on braided stacks enclosed in copper sectors, has been recently proposed by ENEA. The preliminary results on sub-cable samples will be shown. In addition, I will present the modelling and optimization activity carried out by the University of Twente on the CORC-like conductors manufactured by ASIPP within the European-Chinese collaboration on magnet design. The main goal is to understand if the CORC-like conductors may be suitable for the EU-DEMO CS.

EU-DEMO programme is also supporting studies for modelling of radiation effects on TF cables and coils and, since 2014, experiments on irradiation of HTS tapes under different conditions, addressed to future power plants that could potentially involve HTS conductors in TF coils. A brief outline will be given on these topics covered in the project.

Acknowledgments

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Development of Coated Conductors by IBAD/PLD process Suitable for High Field Applications

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Though varied magnet applications were pursued in past decades using REBCO coated conductors which have the widest superconducting critical surface, both the practical application ever established as high-end NMR systems, and the very large wire demands as compact nuclear fusion development activity, are mainly used in very high field at low temperatures which could not be reached by LTS metal wires as Nb_3Sn. REBCO coated conductors for such high field applications should be required to have excellent and uniform in-field J_c properties and robust mechanical strain strength for strong hoop stress, especially for inner magnet coils of high-end NMR systems which strongly requires good transporting and dimensional uniformity in long piece length [1]. They are so far obtained by peculiar vapor phase deposition processes as combination of thin and strong alloy substrates textured by using ion-beam-assisted deposition (IBAD), and desirably formed REBCO films by pulsed-laser-deposition (PLD) or also chemical vapor deposition.

PLD is a non-equilibrium vapor process characterized to have high deposition rate with quite largely supersaturated conditions though it has also excellent controllability of varied deposition conditions for complexed multi-element oxide films as REBCO. It allows to get high density crystalline dislocations and small-size secondary phase particles dispersed inside good textured REBCO films growing at extremely high rates. These PLD advantages should be facilitated if the most severe parameter of substrate temperature were enough controlled during long length contentious depositions. Fujikura group had designed and developed “Hot-Wall Type” reel-to-reel PLD apparatuses, which realized quite robust and reproducible temperature uniformity by furnace like heating system [2].

We succeeded to commercialization of long length and uniform REBCO wires including $BaHfO_3$ doped artificial pinning type line-ups, preserving deposition conditions within narrower windows. Though strong c-axis correlated pinning could be only observed in quite low growth rate samples, high-growth rate samples of >20 nm/sec had a scattered short length $BaHfO_3$ nano-rod structure, less angular dependent but higher J_c compared to non-doped samples, which also had a random pinning like scaling behaviour observed in wide temperature range. The growth rate dependence of low temperature in-field J_c was quite flat for upper growth rate. In-field J_c properties of ~2-times bigger than non-doped ones were eventually obtained in temperature below 40 K [3].

It was also important to choose RE elements of Gd, or Eu, that the crystalline growth stability was so excellent that good c-axis aligned high quality thick films were reproducibly obtained by hot-wall PLD. There are also controversies for neutron radiation damage come from exceptionally large cross section of low energy (~1 eV) thermal neutron capture of Gd or Eu. Though main radiation damage at fusion magnets would come from high energy (> 0.1 MeV) neutron bombardment, sufficient experimental confirmations are not completed yet [4].

Thus IBAD/PLD is so suitable process to obtain desired flux pinning and uniform in-field transporting current without spoiling processing throughput, with affordable materials cost. We are now investing to increase production capacity with better productivity and quality control, without degrading uniformity for long piece length over 1 km long. Transport tests of 16-layered pancake coils have conducted to assess the longitudinal uniformity of in-field J_c for $BaHfO_3$ doped REBCO wires and the I-V characteristics of the coils agreed very well with numerical estimations of angular dependent in-field J_c [5]. Mechanical reliability of those wires was also surveyed as tensile/compressive strain strength including cyclic fatigue test.

Acknowledgments

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Research, development and commercialization of coated conductors for fusion application by Faraday Factory Japan

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Founded 12 years ago in 2011, Faraday Factory Japan (FFJ) now stands as a leading producer and key player in manufacturing high-temperature superconducting tapes of second-generation (2G-HTS), focusing on the development and use of Ion Beam Assisted Deposition (IBAD) and Pulsed Laser Deposition (PLD) techniques. The presentation will discuss the long-term vision of the IBAD/PLD process in future HTS wires manufacturing from both scientific and business perspectives.

In 2023 FFJ plans to produce over 2,500 km of 4mm 2G-HTS tapes (the maximal production capacity reported so far for companies working in this field), operating on a 24/7 schedule. From October 2023 the company started relocation to the new factory and installation of manufacturing equipment to reach the total production capacity of 500 MAm/year.

2G HTS tapes based on YBCO with Y203 nanoparticles have become the leading FFJ product for high magnetic field, particular for fusion applications market. This is so because YBCO tapes exhibit excellent performance that meets and exceeds most applications requirements and also, not to the lesser extent, because YBCO tape technology is robust enough that it has been successfully scaled to large industrial volumes.

This presentation will outline the current manufacturing process at FFJ, highlighting the use of advanced PLD in the production of high-performance REBCO coated conductors. The discussion will include an overview of the research directions and results aimed at potential future developments of novel superconducting compositions and more advanced production equipment.

Microstructural landscape and vortex pinning scenarios in REBCO coated conductors prepared at high growth rate

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High temperature superconducting REBa2Cu3O7 (RE=Rare Earth or Yttrium, REBCO) coated conductors (CCs) have emerged as a complex class of materials with exceptional superconducting properties. Understanding the vortex pinning scenarios in correlation with a controlled microstructural landscape is a key objective to design the CCs performance and achieve exceptional values of superconducting properties which enable their integration into devices.

The microstructural landscapes of CCs may deeply differ depending on the selected growth methodology, the compositional selection and the processing conditions.

In order to improve performance together with costs reduction, faster growth methods are now being explored, which raise new vortex physics scenarios. In this presentation, we will discuss the rich vortex pinning microstructure for vapour-solid, solid-solid and liquid-solid growth methods and how it is modified through fast-growth processes. The interplay between vortex physics and defect structure generated at high growth rates will be addressed, as well as the implications of the electronic structure on vortex physics. We will also discuss how irradiation research could help to further understand the influence of the induced defect structure on the observed vortex pinning scenarios and which impact may have on CCs use for fusion magnets.

Acknowledgments

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Comparative analysis of particle irradiation and second-phase additions effects on the critical current densities of $YBa_2Cu_3O_7$ single crystals, thin films, and coated conductors

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The study of irradiation effects in cuprate HTS has been a topic of interest since their discovery in the late 1980's. Enormous progress in the understanding of vortex physics and pinning mechanisms was made in the early 1990's through the irradiation of high temperature superconductor (HTS) single crystals with a variety of particles over a broad range of energies. In the case of $YBa_2Cu_3O_7$ (YBCO), the overall conclusion was that irradiation could increase the critical current density (J_c) by orders of magnitude [1-4]. The interpretation of the results was simplified by the fact that the pristine crystals were very clean, with few strong pinning centers and quite low J_c, thus essentially all the pinning in the irradiated crystals could be attributed to the controllably added disorder. The case of the YBCO epitaxial thin films and coated conductors (CC) is more complex, because the pristine samples already have high J c due to the presence of large densities of strong pinning centers, which are fabrication-method and processing dependent. The most popular and efficient method to further increase J_c in CC has been the incorporation of artificial pinning centers (APC) by chemical incorporation of second phases. Efforts by many groups worldwide demonstrated that a diversity of APC can be effective [5-13], and it is now clear that mixed pinning landscapes, nanoengineered by the combination of defects of various shapes and sizes, produce the best results [7,17]. In some cases, particle irradiation is still effective at enhancing J_c in CCs, but by more modest factors than in the single crystals [14-18]. Interaction with pre-existing defects cannot be ignored, resulting in both cooperating and competing effects [16,17]. In this talk, I will compare and contrast the vortex pinning generated in YBCO by defects of various geometries (aligned columnar, splayed columnar, randomly distributed nanoparticles, point defects) created either by particle irradiation, incorporation of second phases, or combinations of both routes.

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Radiation Challenges in Compact High-Temperature Superconducting Tokamaks

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High-temperature superconductors (HTS) have opened the door to compact tokamak designs, heralding a new era in fusion reactor technology. However, this innovation presents formidable challenges in the radiation environment affecting the superconducting magnets. This presentation focuses on the modeling and analysis of neutron and photon radiation using OpenMC within these HTS-enabled tokamaks. Our insights highlight the critical importance of addressing radiation challenges in harnessing the full potential of compact fusion reactors empowered by HTS.

Neutron and secondary particle analysis in PHITS of HTS components for compact fusion reactors

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High temperature superconductor (HTS) technology enables the design of compact fusion reactors, allowing faster development in the field [1]. The reduced size makes even more important the evaluation of neutron flux on all components and at every region, including at the HTS magnet position, to assess the lifetime of the materials and their performances during operations. Compactness, indeed, introduces new technological challenges, considering the reduced shielding and a consequently stronger interaction with fusion products [2]. Many different particles transport codes have been developed for nuclear engineering and fundamental physics purposes, each one relying on different algorithms and nuclear models, with different features and capabilities. In the present work, two transport codes, PHITS [3] and OpenMC [4], are compared, with the aim of testing the impact on integral results (as the tritium breeding ratio) and on spatially resolved neutron spectra of different nuclear libraries and codes, by using a CAD imported 3D geometry of an ARC-like fusion machine. Starting from this point, after the identification of the most loaded position on the outer layer of the vacuum vessel, further simulations were carried out on a detailed 3D model of a VIPER HTS cable [5], providing a comprehensive analysis of the radiation damage and of the energy deposition, including an investigation of the secondary particles that will reach the HTS.

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The light side and the dark side of irradiation

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Particle beam irradiation of high temperature superconductors has long been studied as a means of controllably introducing well-defined pinning defects into a pre-existing highly complex microstructure [1 and references therein] for fundamental studies [2] if not commercial wire production [3]. Now, with the advent of compact fusion devices (and to a lesser extent other prominent applications in space or aviation), the less beneficial aspects of sustained long-term radiation damage to the HTS (and other) materials are coming to the fore [4]. This has been accompanied by a paradigm shift in the operating regime of intended application of HTS devices to the low temperature (10–20 K), high field (15–20 T) end, necessitating a growing understanding of the nature of effective – and ineffective – flux pins in this regime [5].

This talk balances the two sides of this dilemma, first examining recent attempts to understand and engineer optimised pinning landscapes for targeted application regimes through systematically combined irradiation processes and treatments (Figure 1) [6] before acknowledging that the present indications are that pinning-optimised conductors may be of limited long-term benefit to operation in a radiation-harsh environment [4].

As a reactor designed from the outset to have the capacity to operate for an extended period under full-power conditions, STEP has an extensive plan to examine the impact of high-fluence irradiation on the HTS material of its conductors. That plan will be outlined [7] and some early results presented [8,9].

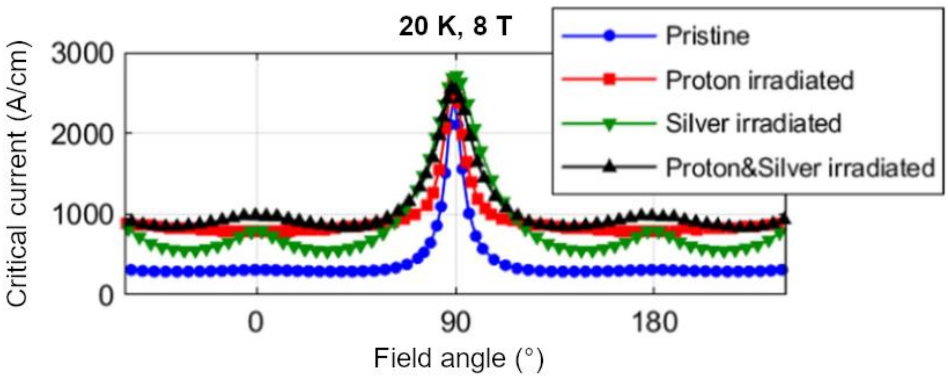

Figure 1: Angle dependence of the critical current of an AMSC wire as received and after various irradiation treatments. From [6].

Acknowledgments

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Molecular dynamics simulations of radiation damage and recovery in high temperature superconductors

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The bombardment by high energy neutrons ejected from the fusion reaction may damage the HTS tapes and impair their operation. Recreating the conditions present in an operational fusion reactor is experimentally challenging, therefore, this work uses molecular dynamics simulations to understand how radiation modifies the underlying crystal structure of $YBa_2Cu_3O_7$. Radiation damage cascades predict the formation of amorphous regions, similar to those observed in experiments, surrounded by regions decorated with Cu and O defects found predominantly in the CuO-chains. The simulations suggest that the level of recombination that occurs is relatively low, resulting in a large number of remnant defects. Interestingly, the number of remnant defects predicted when the simulations are performed at operation temperatures (25 K) are predicted to be slightly lower than at the temperature of existing neutron irradiations (360 K). Also of note, we observe increased levels of annealing at elevated temperatures when the irradiation is itself was performed at operational temperatures, which matches experimental observations of some recovery in superconducting properties in ion irradiated superconducting tapes.

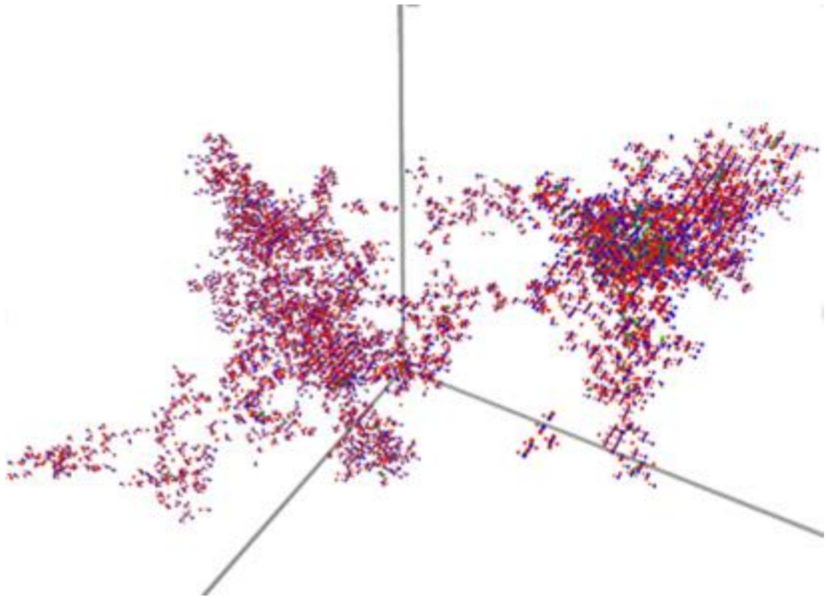

Figure 1: Image showing the result of a 50 KeV Ba cascade in $YBa_2Cu_3O_7$. Only defects are shown and the colour of the defect refers to the atom type, where red is oxygen, blue is copper, green is barium and yellow is yttrium. The cascade was performed at 25 K.

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Molecular dynamics investigation of radiation damage in high temperature superconducting tapes for compact fusion reactors

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High temperature superconducting (HTS) tapes are the key technology that enables compact fusion reactor designs. However, radiation damage will worsen the superconducting properties of the HTS tapes both at short and long timescales, posing serious challenges on the lifetime of these important components and constraints on the reactor design as a whole. Molecular dynamics (MD) simulations can give insights into the microscopic mechanism of defect generation and evolution, providing important information regarding the limits of this technology.

In this talk, I will show our efforts in the MD modeling of radiation damage in $YBa_2Cu_3O_7$ at operational conditions [1] and recent developments. Starting from the design of an ARC-like reactor [2], we have derived neutron spectra at the HTS tape position and resulting energy distributions for Primary Knock-on Atoms (PKAs), from which we select energies for MD simulations of collision cascades using the interatomic potential developed by Gray et al. [3]. We have analyzed the collision cascades in terms of number of generated point defects, defect morphologies, and local transient temperatures. Simulations at room temperature have also been carried out, enabling a comparison with available experimental results.

Finally, I will show recent refinement of the model and further analysis of computational results. We have included in the simulations the electronic stopping power and I will show how this reduces the number of generated defects of about 30 %, being therefore important for a quantitative analysis of defects. In addition, we further explore the PKA energy-PKA species landscape and find that Y, Ba, and Cu PKAs show virtually identical final number of generated defects, although with different recombination rates; O PKA, instead, produce less defects at the same PKA energy and temperature conditions. Outlooks of the present investigations will be discussed.

Acknowledgments

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Quantifying stored energy release in HTS magnets through molecular dynamics

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Radiation-induced defects within YBCO magnets will limit the electrical output of fusion reactors. Over time, these defects will accumulate and degrade the ability of the superconducting magnets to produce the confining magnetic field. In addition, defects store energy within the YBCO, which can be released upon annealing. While Unterrainer [1] experimentally demonstrated that Jc and Tc can be recovered via controlled annealing, uncontrolled annealing may result in a magnet quench. As a result, the relationship between defect stored energy release and magnet quench energy must be investigated. A defected YBCO perovskite supercell was created using the creation relaxation algorithm (CRA) [2], and annealing was simulated using the LAMMPS code [3]. The energy released per unit volume can be determined by comparing the total potential energy of a perfect YBCO supercell to the defected YBCO supercell during annealing. This energy release can then be compared to the minimum-quench energy of YBCO, which is a few J/m^3, to determine the additional quench-risk incurred by accumulating defects [4]. These simulations will inform quench mitigation strategies for YBCO magnets and increase the operational certainty of large-scale YBCO fusion magnets.

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X-ray absorption spectroscopy as a tool for characterising irradiation damage in REBCO coated conductors

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Predicting the behaviour of REBCO coated conductors under fusion-relevant irradiation conditions is a major challenge because of the lack of high flux sources of fusion spectrum neutrons and the complexities of performing neutron irradiation experiments, especially at cryogenic temperatures. Ion irradiation is a widely available, relatively cheap and quick alternative to irradiation in a nuclear fission reactor, and it does not activate the samples making them easier to characterise. A wide range of different ion species and energies are available, opening up a wealth of experimental opportunities. The question is – *can ion irradiation successfully emulate neutron irradiation using a suitable choice of ion?* T_c is found to decrease monotonically with neutron fluence for both neutron and ion irradiation [1], and this is attributed to the generation of point defects throughout the REBCO lattice. However, this damage cannot easily be observed with atomic resolution electron microscopy, even in samples that have been irradiated to a high enough fluence for superconductivity to have been entirely lost, because many of the defects are believed to be in the oxygen sublattice and oxygen atoms are not strong electron scatterers [2].

X-ray absorption spectroscopy is a powerful technique that probes the local environment around specific atomic species. The near edge (XANES) gives information about the chemical and electronic environment and the extended edge (EXAFS) gives information about the structure. Here we will present a series of experiments using the I20-scanning beamline at Diamond Light Source that demonstrate the use of high energy resolution Cu K-edge XANES is sensitive to irradiation induced changes in the Cu-O bonding environment in REBCO. DFT simulations of spectra from pristine and defect structures have been used to simulate the spectra, enabling features from the Cu(1) chain site and Cu(2) plane site in the REBCO crystal structure to be distinguished. Initial experiments using 300 keV He^+ ions revealed that substantial changes occurred in the CuO_2 planes, even though earlier literature speculated that the chains were more likely to be affected [2]. More recently, we have performed the same experiments on coated conductors that had been neutron irradiated as part of the Vienna study by Fischer et al [3]. Although the total damage level of these samples was lower than the He^+ irradiated samples, we found similar spectral changes, suggesting that the defect landscape is not entirely different, as shown in Figure 1 [1]. We will also present preliminary analysis of EXAFS data on the Cu K-edge and Ba L-edge, and discuss our plans for performing experiments on cold-irradiated samples.

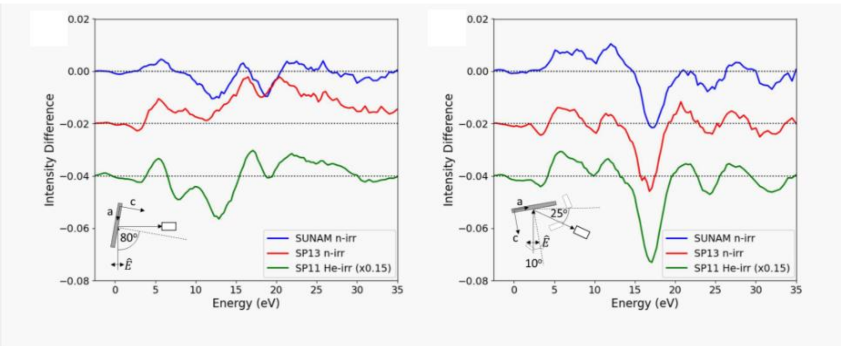

Figure 1: XANES difference spectra for 300 keV He^+ and neutron irradiated coated conductors in two orientations.

Acknowledgments
The work in Oxford has been supported by EPSRC fellowships (EP/L022907/1 and EP/W011743/1).

[1] K. Adams et al. Superc. Sci. Technol. 36 10LT01 (2023)
[2] R. Nicholls et al. Comms. Mater. 3 52 (2022)
[3] D. Fischer et al. Superc. Sci. Technol. 31 044006 (2018)

Combining experimental and simulated X-ray absorption spectra to understand irradiation damage in REBCO coated conductors

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Understanding irradiation damage in high-temperature superconductors is important as new compact fusion reactors rely on these materials to generate the high magnetic fields needed to confine the plasma[1]. The material of choice is $(RE)Ba_2Cu_3O_{7-\delta}$ (RE = rare earth element), REBCO, which can be processed into a flexible tape using coated conductor technology[2]. We have used high-energy-resolution X-ray absorption spectroscopy (XAS) to probe the local environment around the Cu atoms in irradiated REBCO coated conductors as a way of understanding the defects that form[3].

In X-ray absorption spectroscopy (XAS), a core-electron is excited into the unoccupied states and the resulting spectrum reflects the local environment of that atom. Spectra from all the atoms of a particular element add together to form the experimental spectrum and interpretation of the edge features can be challenging. Using density functional theory (DFT), we have simulated spectra from a variety of specific atom environments (including a number of defects), which allows us to interpret our experimental spectra in terms of atomistic structures. We find that the differences between spectra from pristine and irradiated materials can be explained by the presence of Frenkel defects (Figure 1) in the irradiated sample[3]. DFT is not the only way of simulating XAS spectra, and the link between DFT and multiple scattering and molecular orbital interpretations will be discussed.

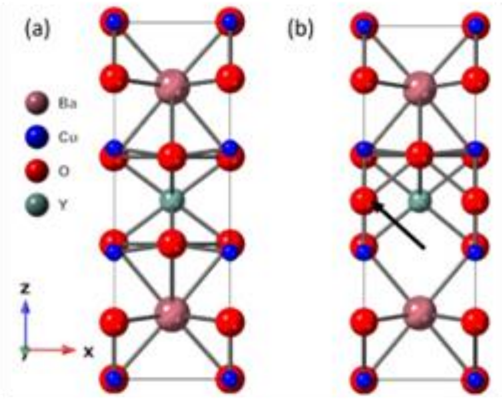

Figure 1: Structures of (a) pristine REBCO (RE=Y) and (b) a Frenkel defect

Acknowledgments
We acknowledge Diamond Light Source for time on Beamline I20-Scanning under Proposals SP23408, SP27236 and SP28846 and time at ePSIC on E02 under proposal MG28480. We also acknowledge the David Cockayne Centre for Electron Microscopy for access to sample preparation facilities and Surrey Ion Beam centre for the He+ ion irradiation. RJN gratefully acknowledges financial support from the EPSRC, grant EP/L022907/1.

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[2] A. Umezawa *et al., Phys. Rev. B,* 36 7151 (1987)
[3] R.J. Nicholls *et al*., Communications Materials, 3 52 (2022)

Effect of irradiation temperature on degradation in REBCO tapes

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In compact fusion devices like ARC, REBCO magnets will be used to produce the field for plasma confinement. They will be operated at temperatures of around 20 K and are subject to radiation damage from fusion neutrons. Induced defects modify the initial REBCO microstructure, and eventually degrade the critical currents below acceptable levels.

We investigated the radiation tolerance of REBCO tapes in our cryogenic ion irradiation facility at the Plasma Science and Fusion Center. REBCO tapes were irradiated with 1.2 MeV protons at different temperatures, ranging from 20 K to 300 K and to damage levels that are fusion relevant. The irradiation effects on critical currents and transition temperature were measured in-situ. We found that low-temperature irradiation leads to a faster degradation of the superconducting properties and will present our most recent experimental results.

How can we understand the effects of in-service radiation damage in REBCO for fusion magnets?

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Now that it is clear that REBCO coated conductors (CC) will be the superconducting material of choice in at least some of the magnets that will be used in compact fusion reactors, the question has been asked – Will these materials last the design lifetime under service conditions where they will be close to the radiation generated by the fusion plasma? Of these radiation types, it is the fusion-spectrum neutrons that probably generate the most concern. However, in the absence of intense sources of these 14 MeV neutrons, it is not easy to study directly the precise damage mechanisms that these energetic particles will generate. Two ways have been taken to approach this question; the use of the relatively more available fission-spectrum neutrons [1], and following the wider nuclear materials community by exploring the use of the widely available ion beams as a proxy for neutrons. We have taken this second approach, specifically in the design of experiments for the measurement of superconducting performance under in-situ ion beam irradiation [2], [3].

This presentation will describe how we in Oxford went about designing first the experiments we wished to attempt, including the careful selection of ion species and energy, and then the apparatus that was constructed to make in-situ measurements using the Surrey Ion Beam facility. The first set of experiments on in-situ but beam off experiments gave an indication of the effect of stored damage after irradiation, and the effect of room temperature 'annealing'. Subsequently, we have shown the dramatic effect of beam-on measurement, and will discuss possible artefacts in those experiments. At the same time, we have been using high resolution STEM analysis of ion beam damaged REBCO to try and understand the microstructural changes that might be contributing to the in-situ effects. Finally, we will consider what the next generation of our experiments should attempt to achieve if we are to answer the question above before very expensive magnets are exposed to in service conditions.

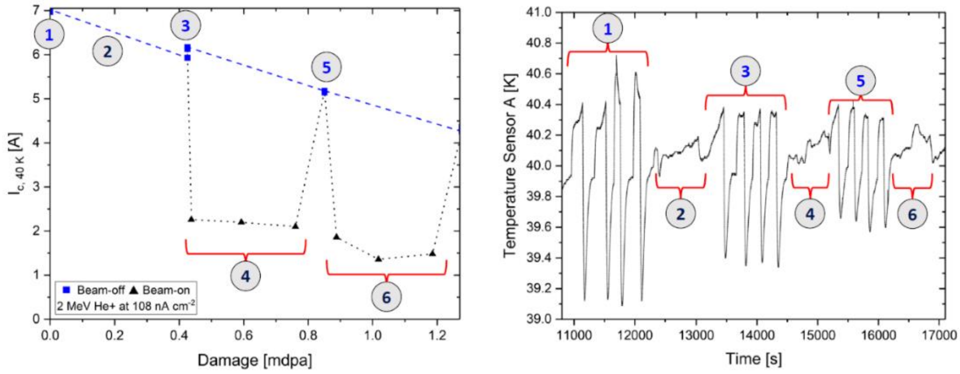

Figure 1: Typical in-situ I_c measurements on a 50 µm track showing the effect of beam-on conditions, and the temperature variations during I_c measurements showing that it is the applied currents that give the strongest temperature effects.

Acknowledgments

The work in Oxford has been supported by studentships for WI and KA from Tokamak Energy and EUROfusion (UKAEA) respectively.

[1] D. Fischer et al Superc. Sci. Technol. 31 044006 (2018)
[2] W. Iliffe et al. Superc. Sci. Technol. 34 09LT01 (2021)
[3] W. Iliffe et al. MRS Bulletin Impact Article 48 p.1 (2023)

In-situ critical current measurements of REBCO coated conductors during gamma irradiation

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The 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 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. This is a presentation on the work published in [1].

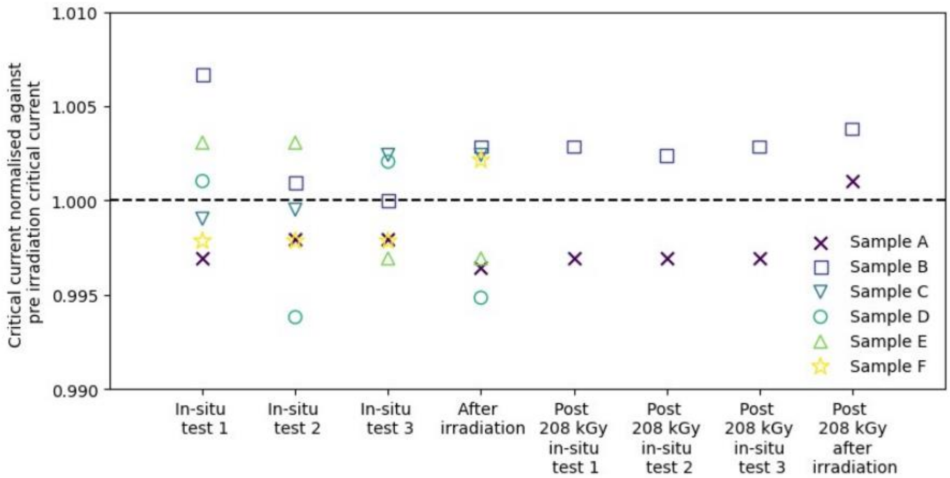

Figure 1: 77 K, self field critical currents of samples A, B and C with bridge widths of 0.5 mm and samples D, E and F with bridge widths of 0.25 mm. Measurements were taken before and after irradiation and three times during irradiation. Samples A and B were irradiated with a further dose of 208 kGy at room temperature and a second round of in-situ tests was performed. Critical currents have been normalised against the pre-irradiation measurement of each sample. The dashed line is a guide to the eye.

Acknowledgments
We acknowledge the support of The University of Manchester's Dalton Cumbrian Facility (DCF), a partner in the National Nuclear User Facility, the EPSRC UK National Ion Beam Centre and the Henry Royce Institute. We recognise R. Edge, C. Tyagi and K. Warren for their assistance during the experiment. Thanks to H. Campbell for organising sample laser cutting. Thanks also to T. Todd, W. Iliffe, S. C. Wimbush and S Speller for enlightening discussion.

[1] S. B. L. Chislett-McDonald et al. Supercond. Sci. Technol. 36 095019 (2023)

Can beam heating alone explain the suppression of Jc during ion-irradiation of REBCO coated-conductors?

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Fusion magnets will operate under the bombardment of neutrons born in DT reactions. Neutron impacts can cause hundreds to thousands of Frenkel-pairs, most of which recombine and disappear after tens of picoseconds. Until recently, only the effect of stable defects was considered in irradiation experiments aiming to assess the performance-degradation of REBCO in a nuclear fusion environment. Reproducing *in-operando* conditions requires a cryogenic irradiation-target with the ability to perform transport current measurements during irradiation, which have been commissioned at MIT and Oxford. By measuring transport current before, during, and after short exposures to a proton beam, we find a large suppression of Ic and Tc, which is proportional to beam current and disappears when the beam is steered off the sample. We present experimental and finite-element simulation results quantifying the magnitude of beam-heating, and its contribution to the suppression of Ic. Identifying all major contributions to this effect bears practical consequences for the design and operational certainty of fusion magnets. While localized beam-heating is likely not a concern with neutron bombardment, other mechanisms could conceivably perturb the loss-free transport of current, setting a new limit on the power-density of fusion power plants.

Finite Element Modeling for Revealing the Thermal Response of 2G HTS tapes in Operando Conditions.

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Neutron irradiation damage and induced heating can lead to superconducting performance degradation and hence magnet lifetime limitation. Therefore, they are key aspects in the design and optimization of next-generation compact fusion reactor magnets [1]. Recently, a lot of attention was devoted to the use of ion irradiation experiments for investigating the electromagnetic response of High Temperature Superconductors (HTS) at beam-on conditions (with protons and alpha particles). However, experimental observations are very difficult to be interpreted [2], [3]. In this framework, numerical techniques can be a valuable support for decoupling interrelated phenomena, such as irradiation-induced defects (both in terms of pinning centers and induced strain), heating, and microstructural damage, isolating each contribution to the overall behavior.

In this work, a subscale experiment-like 3D analysis has been performed on COMSOL Multiphysics® [4] to critically assess the thermal response of HTS-based materials in operando conditions. The linear (along the thickness of the sample) power distribution, and the mean volume and time of interaction are evaluated through a SRIM Monte Carlo code and imported in COMSOL Multiphysics® as input parameters. This model reproduces, as precisely as possible, the randomly spaced heat power deposition following from single particle impact – for different scenarios and conditions – in a controlled and repeatable environment, including the possibility to perform sensitivity analysis on the most influencing parameters. The discretization approach spans from fraction of millimeters down to the nanoscale, while nine orders of magnitude are covered in the temporal domain. The local transient temperature evolution and the average long-term one are discussed. The latter has also been fitted with a double exponent and compared with a simplified model in which the heat deposition has been consistently time- and space- integrated (i.e., conserving the deposited energy), to study the behavior on experimentally relevant time scales while preserving a mK accuracy.

Acknowledgments
This work is partially supported by the Ministry of Education, Universities and Research through the "Programma Operativo Nazionale (PON) Ricerca e Innovazione 2014–2020", and through the National Recovery and Resilience Plan funded by the European Union NextGenerationEU, by the European Cooperation in Science and Technology (COST) action CA19108: "High-Temperature Superconductivity for Accelerating the Energy Transition", by the Italian Ministry of Foreign Affairs and International Cooperation, grant number US23GR16, and by Eni S.p.A..

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[2] W. Iliffe, et.al., " The effect of in situ irradiation on the superconducting performance of REBa2Cu3O7-δ-coated conductors", MRS BULLETIN, vol. 48, pag. 710–719 (2023).
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Impact of neutron induced ex-situ defects on the properties of coated conductors and their thermal stability.

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Fusion will produce high energy neutrons at 14 MeV, which, with a broadened spectrum due to scattering, will introduce various defects into the conductor of the superconducting magnets. The lifetime of the coils will mainly be restricted by the neutron flux and thus their distance to the burning plasma. While the price of energy output by large reactor designs will mainly be defined by the price of the initial construction, the expected short lifetime of superconducting magnets might drive the cost in small designs as e.g. SPARC and STEP. Since the price of energy needs to be competitive in order for fusion to be economically feasible, mitigation strategies have to be developed. This however, requires a deep understanding of the underlying degradation processes.

Samples based on commercial coated conductors containing YBCO and GdBCO were irradiated with neutrons at approximately 70 °C in our fission reactor TRIGA MARK II to introduce comparable defects and study the behavior of the critical current, the n-value and the critical temperature. Samples containing GdBCO showed a fundamentally different degradation behavior, if irradiated with a neutron spectrum containing particle energies below 0.55 eV. We attribute the behavior to the formation of a high density of almost point-like defects, induced by the high absorption cross section of Gadolinium to thermal neutrons. The Gadolinium nucleus enters an excited state after the absorption of a thermal neutron. This state decays by the emission of a gamma particle that leads to the recoil of the Gd atom and in consequence to a high density of Oxygen defects. Data from molecular dynamics simulations indicate that, due to its position in the REBCO lattice, some of the formed defects are located in the Cu-O plains, which could have a strong impact on the superconducting properties.

These very specific defects allow us to distinguish the influence of small versus large defective structures on the superconducting properties of REBCO. In further consequence fundamentally different defect structures are expected to be stable up to different temperatures enabling a study of the capability of heat treatments to recover neutron induced degradation.

Annealing cryogenically irradiated REBCO with current pulses

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Compact tokamak fusion power plants rely on REBCO magnets to confine a thermonuclear grade plasma. The magnet performance must be predictable despite radiation damage to the REBCO microstructure caused by fast fusion neutrons. This damage eventually decreases the magnet's critical current, lowering the reactor's achievable magnetic field and therefore performance. However, the damage is not necessarily permanent - annealing could restore some of the damage and improve the magnet's lifetime.

We found that applying a short current pulse above the critical current after irradiation briefly raises the REBCO's temperature above that of the cryogenic environment via resistive heating. This resistive heating anneals out defects and recovers some of the performance losses. In this experiment, we send high current pulses of different lengths through an irradiated HTS tape to identify the optimal duration for critical current recovery. Using a cryogenic proton irradiation facility capable of applying current pulses up to 2000 A and as short as 100 ns, we found that 400 A pulses can display 400 % critical current recovery as defined by the difference between the post-irradiation and postannealing values. The optimal length for this current pulse was found to be 5.5 ms, which results in a maximum calculated temperature of 630 K in the REBCO microstructure. We further present the effect of repeated current pulses to uncover the time dependence of the recovery at a fixed peak temperature.

Irradiation of YBCO thin films and REBCO tapes: effect of 14.1 MeV fusion neutron and gamma rays

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The concern for radiation hardness of $REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = Y or lanthanide series) materials is rapidly growing due to the recent increase of their use in environments where radiation and high-energy ionizing particles are present, such as space and nuclear applications. In this work, the effect of neutron and gamma irradiation on chemically-deposited YBCO thin films and commercial REBCO coated conductors was investigated.

The irradiation procedures were carried out at ENEA laboratories, the Frascati Neutron Generator Facility and the Calliope Facility for neutron and gamma irradiation tests, respectively. In the first case, 14.1 MeV neutrons produced by T(d,n)α fusion reaction were employed and three different fluences, i.e. 0.4, 0.8 and $1.2\cdot10^{14}$ neutrons · cm^{-2}, were evaluated using a flux of $1.9\cdot10^{9}$ neutrons·$cm^{-2}s^{-1}$. For the second study, a ^{60}Co gamma source was used to test samples with a dose rate of 7.5 Gy·h^{-1} and a total absorbed dose of 1.016 kGy (irradiation condition commonly applied for standard space environment tests).

In both cases, the radiation hardness of commercial REBCO tapes provided by various suppliers and with different characteristics was investigated comparing their superconducting properties before and after irradiation. Moreover, YBCO thin films deposited by metal-organic decomposition route on two substrates, namely $SrTiO_3$ and $LaAlO_3$, were used as reference samples and exposed together with the tapes. In addition to superconducting properties, also the YBCO crystalline structure was compared before and after the radiation exposure. The obtained results evidenced no relevant effect on samples properties, for both thin films and tapes, indicating the resistance of films up to the irradiation conditions tested in this study.

Future experiments with higher fluences or doses will be performed, possibly at cryogenic temperatures and with *in situ* measurements of superconducting properties.

Acknowledgments
This work is partially supported by the Ministry of Education, Universities and Research through the "Programma Operativo Nazionale (PON) Ricerca e Innovazione 2014–2020", by the European Cooperation in Science and Technology (COST) action CA19108: "High-Temperature Superconductivity for Accelerating the Energy Transition", by the Italian Ministry of Foreign Affairs and International Cooperation, grant number US23GR16, and by Eni S.p.A.

UK National Ion Beam Centre

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As an integral part of EPSRC research portfolio of mid-range research facilities, UK National Ion Beam Centre is designed to provide various energetic ion beams from H+ to Yb+ with ion beam accelerators installed at Universities of Huddersfield, Manchester and Surrey for research, development and manufacture activities involving ion beam modification and analysis of materials.

Semiconductor research and development community is our major user base, however, research activities on energy materials, such as materials related to nuclear energy industry, and quantum materials are growing fast. For high temperature superconductors, we have been involved in fabrication of Josephson junction prototype devices, synthesis of MgB_2 thin films, exploration of pinning mechanisms and performance of coated conductors under irradiation using light energetic ions like H^+, He^+ and B^+. We are developing samples stages to provide ion irradiation under mechanical stress and at different temperatures.

As for the development of ion beam analysis capability, we are progressing well on developing comprehensive facilities such as RBS, ToF-EDRA and high resolution PIXE for characterisation of chemical composition profiles, in particular, mapping light element concentration like proton and oxygen, in samples under different processing conditions.

We aim to provide a single point of access of world-leading ion beam facilities and promote knowledge exchange and joint scientific research with researchers both in UK and overseas.

The Frascati Neutron Generator: fast neutrons for fusion and beyond

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The Frascati Neutron Generator is an accelerator-driven fusion neutron source. Its nominal beam power is 300 W obtained by 300 keV / 1 mA deuteron beam impinging on a deuterated or tritiated Titanium layered Cu substrate.

IN DD mode the neutron emission rate is about 10^9 s^{-1} while in DT is 10^{11} s^{-1}. The facility is mainly devoted to fusion related activities, such as diagnostic testing and assessment of cross sections for relevant materials in fusion technologies.

The highly versatility of the plant allow at hosting experiments devoted to the study of the neutron-induced damaging in electronics, e.g. investigation of Single Event Effects in electronic devices of interest in automotive, medicals and aerospace.

FNG is, also, included in the RADNEXT project, a transnational access program, leaded by CERN, which allows researchers from EU countries to ask for beam time at FNG for irradiation experiments with different finalities.

In this contribution the facility is presented with an overview of the main activities and a brief description of the RADNEXT context.

The Calliope Gamma Irradiation Facility

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The Calliope gamma irradiation Facility is located at the Casaccia Research Center (Rome, Italy) of the Italian Agency for New Technology, Energy and Sustainable Economic Development (ENEA). Calliope is a pool-type irradiation facility, equipped with a ^{60}Co gamma source (mean energy of 1.25 MeV) in a high volume (7.0 m ×6.0 m × 3.9 m) shielded cell (Fig. 1). The source is constituted by 25 cylindrical rods of ^{60}Co doubly encapsulated in stainless steel and mounted on a rack with plane geometry and an active area of 41 cm × 75 cm [1]. The maximum licensed activity is 3.7 x 10^{15}Bq (100 kCi) and the current maximum dose rate (Oct. 2023) is 6.3 kGy/h. The Facility, due to the large dimension of the irradiation cell allowing to perform irradiation test at different dose rates, is the only one in Italy and Europe. No material can be activated with gamma photons and the irradiated samples can be manipulated immediately after the treatment. Irradiation tests can be also performed in special environments such as vacuum, gas mixtures other than air and at different temperatures. For electronic devices, it is possible to perform the test under bias and to monitor the parameters by remote dedicated measurement set-up. Several dosimetric systems for the determination of the irradiation parameters (dose rate, absorbed dose) are available at the Calliope Dosimetric Laboratory. The radiation-induced effects on the irradiated materials can be studied by optical and spectroscopic techniques, while accelerated ageing tests can be performed to investigate their stability. The Facility will follow ISO 9001 by 2023 and ISO 17025 by 2024.

The Facility is involved in qualification and radiation processing research on materials and devices for hostile radiation environment such as nuclear facilities, Space, High Energy Physics experiments, as well as in cultural heritage, medicine, biological applications, agro-food and environment. These research activities are performed in the framework of national and international projects and collaborations with industries and research institutions.

In recent years, several research activities focused on nuclear fusion applications, such as radiation damage studies of optical components, detectors, and devices for the International Thermonuclear Experimental Reactor (ITER) Project [2].

The Calliope Facility is part of the ASIF Program (ASI Supported Irradiation Facilities, funded by the Italian Space Agency) for the creation of a coordinated network of the Italian irradiation facilities dedicated to space testing and qualification, in compliance with the international standard procedures [3].

Preliminary irradiation tests are carried out on YBCO thin film samples for total absorbed dose up 1 kGy.

Figure 1: Irradiation cell with 60 Co sources rack and the platform for sample positioning.

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[3] http://www.asif.asi.it/

HTS fusion magnet development and irradiation considerations

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Tokamak Energy is developing spherical tokamaks based on high temperature superconducting (HTS) magnets as a source of a clean, secure and abundant fusion energy. This talk will present Tokamak Energy's approach to fusion magnet development, HTS conductor utilisation, and a cross section of projects conducted on HTS irradiation and shielding. This will include the GAMMA project in which cold, energised HTS coils are subjected to a lifetime-dose of gamma irradiation. This project is currently under way at Sandia National Laboratories, New Mexico.

Au ion irradiation of $GdBa_2Cu_3O_y$ coated conductors: superconducting properties and induced defects

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High in-field critical current properties in $REBa_2Cu_3O_y$ (REBCO, RE: Y and rare earth) coated conductors (CCs) is very important for nuclear fusion reactors to achieve very high magnetic fields in compact winding. The high critical current density J c in the magnetic fields could be obtained by the introduction of precipitates and defects with nanometer size, which can pin the vortices. The desirable pinning structures could be provided by ion irradiation, which enable the creation of a variety of defects, such as points, clusters and tracks, by choosing appropriate ion species and energy. Recently, a low-energy ion irradiation has been revisited as a practically feasible approach to improve vortex pinning in superconducting films. [1-3] In this talk, we present the superconducting properties and induced defects in GdBCO CCs irradiated with 2 and10 MeV Au-ions.

Figure 1(a) and 1(b) summarize the magnetic field dependence of the J_c enhancement, (J_c^{after} - J_c^{before}) J_c^{before}, with H//c for GdBCO CCs irradiated with (a) 2 MeV and (b) 10 MeV Au ions at 30 K. [4] In the case of 2 MeV Au ion irradiation (2 MeV Au ions would stop in the GdBCO layer), an over 60% increase in J c is observed at around 3 T. We found that the 10 MeV Au-ion irradiation (10 MeV Au ions would penetrate through the GdBCO layer) yields up to over 70% J c increase at around 3 T, indicative of effective pinning defects by the irradiation. The superconducting transition temperature T c 's of the GdBCO CCs irradiated by both 2 and 10 MeV Au ions decrease gradually with increasing fluence up to around 8.0×10^{11} ions/cm^2 and then significantly started to drop. We will also report several results on the irradiated GdBCO coated conductors such as the transmission electron microscopy (TEM) observation, positron annihilation measurement [5] and effect of oxygen annealing.

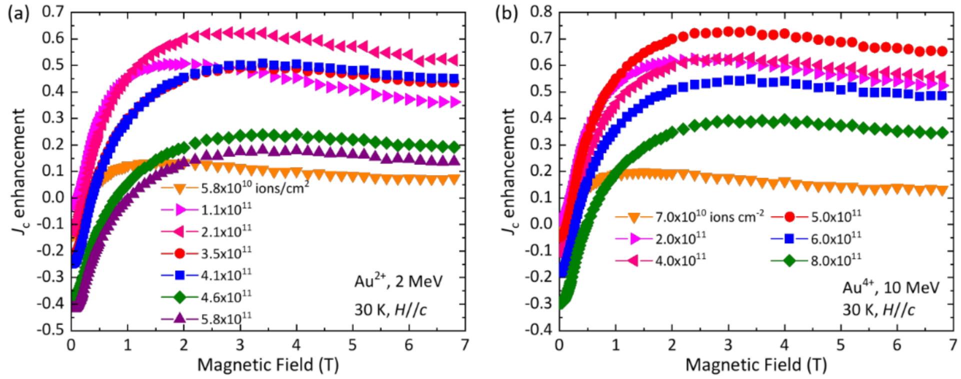

Figure 1: J_c enhancement as a function of the magnetic field for GdBCO CCs irradiated with (a)2 MeV and (b)10 MeV Au ions.

Acknowledgments
We would like to thank Sumitomo Electric Industries, Ltd. for providing the GdBCO coated conductors.

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Heavy ions irradiation for pinning landscape modification of YBCO films with columnar secondary phase

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An essential issue in the design process of applications based on high temperature superconductors (HTS) is the in-field performance of the critical current density (J_c) in the temperature (T) regime of the operating conditions. In particular, when considering coated conductor (CC) tapes for fusion energy applications it is essential to obtain films with strong pinning features in the low T and high magnetic field (H) range [1]. On the other hand, an equally important aspect that should be considered is the anisotropic J_c behaviour as a function of the angle (θ) between the CC and H [2]. A recent approach to mitigate the J_c angular anisotropy, improving at the same time the in-field performances in $YBa_2Cu_3O_{7-x}$ (YBCO) films, was the combined use of a $Ba_2Y(Ta/Nb)O_6$ (BYNTO) based c-axis oriented columnar secondary phase with strain field and stacking faults associated to the chemical decoration, with oxide nanoparticles, of the substrate surface prior to the YBCO film deposition [3].

In this work, we focus our attention to the possibility of further tailor the angular pinning landscape of YBCO-BYNTO films grown over nano-decorated substrates by investigating the additional effect introduced on $J_c(\theta)$ through irradiation with heavy ions. In particular, 250 MeV Au ions irradiation was performed at Tandem−XTU facility of the Legnaro National Laboratories of Italian National Institute for Nuclear Physics. The beam direction was tilted at $\theta = 30°$ with respect to the plane perpendicular to the direction of the current, introducing amorphous columnar defects at directions far from the growth direction of the nanocolumns. Peculiar structural properties of these structures are shown by transmission electron microscopy (TEM) analyses and connected to the angular transport behaviour studied by means of in-field D.C. electrical measurements. This study highlights the pinning effectiveness of these compounds in several ranges of the YBCO H-T phase diagram and the validity of the heavy ions irradiation as a powerful technique for the YBCO pinning landscape fine tuning.

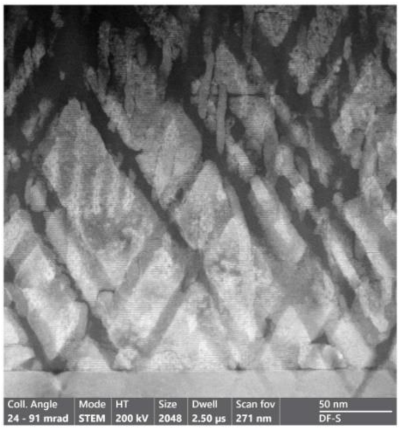

Figure 1: HAADF image showing inclined amorphous tracks due to irradiation, splayed BYNTO columns and CeO_2 oxide nanoislands at the film-substrate interface.

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STEP's plan for understanding REBCO coated conductors in the Fusion Environment

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

STEP will utilise REBCO coated conductors (CC) as the current carrier for its toroidal and poloidal field magnets. Based on the current literature (eg. [1], [2]), it has been recognised that neutron irradiation leads to the degradation of REBCO's superconducting properties, and that this degradation will limit STEP's operating life. However, this literature does not, at present, cover all the conditions that REBCO CC will be subjected to whilst operating in STEP's magnets, i.e. the simultaneous irradiation with neutrons and gammas whilst the REBCO CC is at its cryogenic operating temperature, carrying current and subject to magnetic field and strain. Recent preliminary works (e.g. [3], [4]) have shown that these additional conditions could exacerbate the degradation in REBCO's superconducting properties, and therefore they each require further investigation.

STEP's Confinement System Materials group has developed a plan to characterize the superconducting properties of REBCO CC under as-close-as-reasonably-possible operating conditions within STEP prior to its construction. The campaign will thoroughly inform and validate the choice of REBCO CC used in the construction of STEP's magnets and the magnets for other compact fusion reactor designs. In this presentation, the knowledge gaps are defined (as outlined in iliffe et al.[5]), an overview of the plan is presented, and a progress report will be given along with results where they exist.

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The research used UKAEA's Materials Research Facility, which has been funded by and is part of the UK's National Nuclear User Facility and Henry Royce Institute for Advanced Materials. The authors also acknowledge the contribution of Gyula Zilahi at the UKAEA Material Research Facility for performing X-ray Diffraction experiments, Martin Freer, Ben Pheonix and Yu-Lung Chiu at Birmingham University for their support with experiments at the Birmingham Spallation Source and Constantin Csato at mi2-factory & Shavkat Akhmadaliev at HZDR, Dresden for support designing the filtered ion irradiation experiment.

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Critical current density in HTS tapes for fusion applications: Experiments, TDGL and Irradiation.

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We present a review of some of the experiments, TDGL modelling and irradiation calculations that have been completed on the critical current density (Jc) of HTS superconducting materials for fusion applications [1]: Experiments of the current density as a function of magnetic field, temperature and strain are presented and the break-down of scaling discussed [2]; Time-dependent Ginzburg–Landau (TDGL) modelling is presented which show how the effects of varying the density, splay, and conductivity of the nanorods in HTS affect Jc [3]. We find increasing the resistivity of the nanorods changes the percolative current paths in the vicinity of matrix-pin interfaces and that they persist well above the upper critical field of the superconducting matrix [4, 5]; Finally, we discuss which critical current measurements are required under irradiation to ensure we avoid the superconducting magnets turning off as the plasma is turned on in a fusion tokamak (i.e. avoiding going to hell in a handcart [6]).

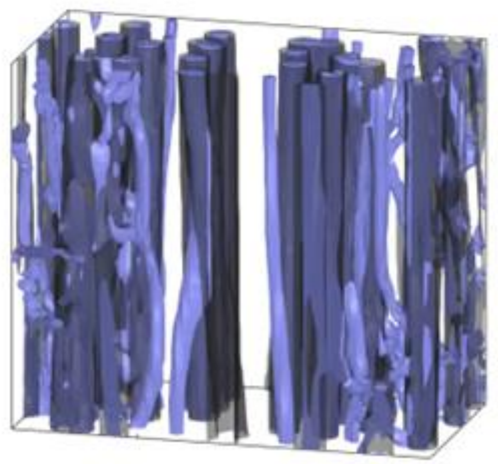

Figure 1: An HTS tape with fluxons moving through nanorods.

Acknowledgments
This work is funded by EPSRC grant EP/L01663X/1 that supports the UK EPSRC Centre for Doctoral Training in the Science and Technology of Fusion Energy. We acknowledge useful discussions with F. Schoofs and S. Chislett-McDonald at UKAEA.

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Identifying effective pinning defects and regimes using critical currents in pulsed fields

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A detailed understanding of vortex pinning and dynamics is imperative for technological applications of type II superconductors. One particularly powerful approach to probe vortex physics is nonlinear electrical transport measurements. Achieving non-linear curves and the extraction of the critical current density (Jc) and n-value in pulsed magnetic fields provides key tools for these studies. Using Fast Programmable Gate Array electronics we measured reproducible current–voltage curves (I-V) in different superconducting thin films on single crystals and metal substrates grown by different methods. We show it is possible to measure Jc in high pinning coated conductors up to 65T, if the rapid vortex movement occurring during field pulses is considered to analyze the results. We compare measurements in three magnet systems with different maximum magnetic fields (H), duration and dH/dt at Los Alamos Pulsed Field Facility of the National High Magnetic Field Laboratory, here t is the time. We show the ability to measure Jc and n up to the highest accessible fields as well as to determine Jc and n continuously as a function of H in our newly commissioned mid-pulse magnet (300ms long pulse). We determined the window of dH/dt where meaningful data can be obtained. We describe the latest advances that avoid in-situ voltage compensation. Finally, we show the different vortex pinning signatures as a function of angle, field, and temperature, that allow the identification of material defects that are effective pinning centers.

Acknowledgments

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Does the shift to HTS magnets for compact fusion reactors call for the development of a new generation of numerical tools?

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An overview of the different options currently under discussion among the candidates to produce electricity from fusion power broadly shows two main lines of thoughts, as far as the generation of the required magnetic field is concerned. On the one hand, several national roadmaps to fusion rely on tokamak designs obtained scaling up ITER, i.e. based on LTS superconducting magnets, and considering the use of HTS only as an option to increase the flux swing generated by the Central Solenoid. This line has a time horizon of several decades, and numerical tools for the multifaceted modelling of superconducting magnets, from micro-scale to system level is quite established [1-3]. On the other hand, a flourishing of private companies is betting on the use of HTS magnets to achieve commercial fusion power on a much earlier time horizon. The higher magnetic field, made possible by HTS, allows moving to more compact designs. A variety of solutions is in development, spanning from D-shaped, non-insulated coils wound with stacked HTS tapes, as foreseen in the ARC tokamak [4], to non-planar coils obtained by laser direct patterning over cylinders coated with HTS films for stellarators [5]. The layout of these HTS coils is unprecedented, and available tools are no longer optimal, nor suitable. In this presentation we address this issue, identifying the modelling needs driven by the adoption of HTS cables and coils technology for fusion machines. As a very important additional remark, the development work outlined here is also of relevance for magnets for high magnetic field research, NMR, high-energy physics, and other energy applications.

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