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Roadmap

Roadmap for the investigation of irradiation effects in HTS for fusion

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Abstract
Energy production by nuclear fusion can be the breakthrough in the decarbonization process, and high temperature superconductors (HTSs) represent a game changer for the design of compact reactors. However, reduced size implies that the superconducting tapes will be exposed to an intense flux of neutrons and of secondary particles while carrying a high current; in order to employ HTS in compact fusion reactors it is therefore crucial to precisely assess the effects of irradiation on HTS tapes at the working conditions. To achieve this goal, researchers from different fields met at the irradiation effects on HTS for (IREF) fusion workshop to discuss all the aspects of this topic. This roadmap paper, that reflects the common view of the participants, aims at condensing the outcome of the intense and thorough discussion that took place during the conference, providing a path for the investigation of irradiation effects in HTS to assess their limits of operation in a fusion radiation environment.

Keywords: HTS magnets technology, radiation hardness, REBCO tapes, compact fusion reactors, HTS irradiation

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1. Background and introduction to the roadmap

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High temperature superconductor (HTS) technology and compact fusion reactors

Magnetic confinement nuclear fusion is inextricably linked to superconductor technology, since lossless current transport is required to affordably produce the high magnetic field necessary to confine a plasma in a fusion reactor [1]. In fact, the construction of large fusion experiments and demonstrators has contributed to drive the development of the NbTi and Nb_3Sn wires industry in the past [2].

In the last decade, the attention shifted to the compact fusion reactor design [3, 4]. This approach allows to deploy demonstrators with a much lower cost, that can be borne by single entities such as research centers, start ups and private companies instead of large collaborations and huge public projects such as ITER, JT-60, EAST and KSTAR. As a consequence, in recent years, several private companies aiming to develop fusion power plants have adopted similar concepts and proposed ambitious roadmaps toward net fusion energy production [5, 6]. For the majority of current magnetic confinement fusion designs, this development was enabled by the maturation of the HTSs tape industry, that is in turn now being pushed to scale up by the large orders placed by fusion companies [7, 8].

The reason for the strong connection between HTS and compact fusion reactors can be traced in the expression for a key figure of merit for fusion: the triple product $nT\tau_E$. This quantity is connected to the thermal fusion power gain at a fixed power generated, and depends on the confinement magnetic field to the third power [9, 10]:

$$nT\tau_E \sim R^{1.3}B^3. \tag{1}$$

Here n is the plasma density, τ_E the confinement time, T the plasma temperature, R the reactor size, and B the confinement magnetic field. Therefore, if one wants to decrease the size of the reactor to contain the costs and still achieve a high power gain he needs to work at higher magnetic fields [11]. The industrialized superconductors that can operate at the highest magnetic fields are nowadays HTS, and REBCO ($REBa_2Cu_3O_{7-\delta}$, where RE is a Rare Earth, often Y) tapes in particular [12].

The problem of fusion radiation

The most accessible fusion reaction (i.e. the reaction with the largest cross section peaking at the lowest temperature) is that between deuterium (D) and tritium (T). The main branch of this reaction produces a 3.5 MeV alpha particle and a 14.1 MeV neutron, the latter representing both the vector that can be used to collect the energy generated in the plasma and the source of some of the main engineering and materials science challenges in fusion technology [13].

Due to their neutral nature, neutron pass through materials with few interactions, reaching virtually every part of the reactor, especially in compact designs [14, 15]. Regardless of how small the cross section is, the displacement cascade generated by each interaction with the target material can have a huge impact on the materials properties. A lot of effort has been (and still is) devoted to study fusion radiation damage in structural and first wall materials, because being the closest ones to the plasma are the most exposed in any reactor design [16]. These materials therefore have to withstand damage levels of tens to hundreds of displacement per atom (dpa) without losing the required mechanical properties [17].

When considering compact reactors, the geometrical constraints are such that also the radiation damage in functional materials becomes particularly worrisome: this is the case of the superconductors employed in the magnetic system [18]. As an example, in DEMO the superconductors in the toroidal field (TF) coil would experience a neutron flux of 4.5×10^9 cm^{-2} s^{-1}, and 4×10^{-6} dpa per Full Power Year, whereas in an ARC-like the corresponding values can be estimated to be one order of magnitude higher for the flux and two for the dpa, when 50 cm of dedicated shielding material (ZrH_2) is employed [19].

When the properties of interest in a material are related to the electronic structure (and in particular in superconductors where the involved energy scales are in the meV range) the level of structural damage that results in an excessive suppression of the performance is much lower than in structural materials. For the case of HTS, the superconducting critical temperature T_c and critical current density J_c are suppressed already for damage levels in the *m*dpa range [20, 21]. Moreover, the superconducting properties are affected by the interplay of atomic displacements, structural distortions and crystal amorphization, through carrier scattering, density of state decrease and vortex pinning [22, 23]. Due to this complex scenario, describing the radiation damage only in terms of dpa is not sufficient, and a comprehensive description of the damage needs to be achieved in order to thoroughly understand the mechanisms of superconducting properties modification.

The IREF workshop

Considering the importance and the possible impact of radiation effects in HTS for fusion applications, as well as the interdisciplinarity of the topic, we felt the urge to promote a dedicated scientific community. Taking the opportunity of funding from the bilateral project 'SUPERNEON—Study of high-temperature SUPERconductors NEutron radiation damage for compact fusiON reactors' between Politecnico di Torino and MIT-PSFC, the first international workshop 'IREF—Irradiation Effects on HTS for Fusion', was organized in Arona (Piedmont, Italy) from 12 to 16 November 2023.

The workshop contributed to building an international network of researchers that combines the expertise in fusion technology and that in superconductivity; involving both scientists working in companies, academia and research institutions, fueling the interplay between these 'worlds' that is absolutely crucial for the fast development of the field.

The 2 chairmen of the workshop, 4 organizers, 7 members of the scientific committee, 16 invited speakers, 16 contributed speakers and 5 attendees actively participated in the workshop.

The topics covered all the aspects related to radiation damage of HTS for fusion: from HTS tape production to magnet development, from the simulation of radiation environment and damage to experimental investigations of irradiated HTS, also including an overview of existing and planned facilities for advanced irradiation and characterization.

The key moment of the workshop has been the round table, where an engaging and cooperative discussion took place, setting the basis for this roadmap paper.

In this manuscript, rather than collecting a series of separate point of views, we attempted to find a set of shared opinions of the whole community to lay the foundations for a rapid, collaborative and efficient development of research in this field, as necessary to achieve the ambitious goals of achieving commercial fusion prototypes within the next decade.

2. HTS technology

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Although the superconducting properties of the HTS compounds belonging to the REBCO family (high T_c, high critical fields, and large J_c in epitaxial thin films), are well suited for high field magnet applications, fabricating wires out of these brittle ceramic materials was quite challenging. The solution was found through the development of coated conductors (CCs) [24–26], which are REBCO coatings on flexible metal tapes. The key difficulty is that large angle grain boundaries in REBCO act as weak links [27], reducing the macroscopic transport J_c to values far too low for applications. To preclude this detrimental effect, the superconducting films in the CCs are biaxially textured, with the *c*-axis perpendicular to the tape and very small misalignment in the *ab*-plane (less than $\sim 3^\circ$) between adjacent grains [28]. There are different approaches to impart this crystalline orientation to the REBCO films. One route is to start with a polycrystalline tape of a metallic alloy, such as Hastelloy, and use ion beam assisted deposition (IBAD) to grow a thin highly textured layer of MgO (or other alternative materials) that acts as an almost single-crystalline substrate on top of which the biaxially textured REBCO films can be deposited [29–31]. Another approach, known as RABiTS™ (Rolling Assisted Bi-axially Textured Substrates) is to texture the metal tape itself [32–34]. In both methods, several additional thin layers (buffers) of different materials are grown between the metal and the REBCO, for various purposes. Usually, a protecting silver layer is deposited on top of the superconductor, and a thicker thermal stabilizer Cu layer is added as needed. These complex CC architectures are the result of two decades of R&D by many groups and are by now quite mature [35].

State of the art of HTS wires and tapes

Tapes manufacturing. As a result of these R&D activities, the IBAD approach emerged as the most robust texturing technique suitable for production on an industrial scale. REBCO tapes are nowadays commercially available from a dozen companies mostly located in Eastern Asia and the US. High aspect ratio tapes are typically produced with 2–12 mm in width and 50–150 μm in thickness, with REBCO films contributing a little to the cross-section (just 1–2 μm) and the major components being the substrate and the metal stabilizers (silver and copper coatings). A schematic view is represented in figure 1. Manufacturers offer tapes in unit lengths of several hundreds of meters, with rather high critical current uniformity within a few percent along the tape length [8]. In the last ten years manufacturers largely improved the consistency of their product, minimizing dropout occurrence and the variability of the critical current [36–38]. Even though there is still room for further improvements, today performances are considered reasonably good for applications in high-fields and low temperature operation ranges.

After decades of intense studies on vortex pinning mechanisms, material processing and thin film growth technology, REBCO films with artificial pinning centers (APCs) can be produced with excellent vortex pinning strength, showing high critical current values and J_c magnetic field retention [35]. According to this technology, some HTS producers are now able to manufacture tapes with optimal performances within fusion-relevant operating conditions, i.e. high-field and low temperatures, by growing REBCO films with tailored vortex pinning landscapes [39, 40]. Such advanced REBCO tape is one of the key technologies of the recent fusion development towards a new concept of compact reactors exploiting extremely high magnetic field strength and a wide range of operation temperatures beyond the limits set by Nb_3Sn-based technology [12].

Tapes production and price. Today, the REBCO technology suffers from two main concerns: the limited commercial production capability and the high tape costs. The global annual production of REBCO tapes is about 3.000 km of 12 mm-wide tape. The amount of REBCO tape required for the realization of the magnetic system of the recently proposed demonstrative power plant reactors is 6.000–10.000 km for each reactor, largely saturating the whole annual production of all suppliers. However, the great interest and demand from the fusion sector on HTS tapes is triggering a substantial increase in the production capabilities, pushing tape suppliers to invest in the manufacturing process efficiency and production yield. Considering the high number of companies interested in fusion energy founded in the last years and the growth of investments (total funding reached 6 billion USD in 2023), it is believed this will happen in the very next few years as reported by several manufacturers [41, 42].

Due to the complexity of the manufacturing process, costs of REBCO CCs are rather high if compared to Nb-based wire costs per unit length (typical unit €$(\mathrm{kA\ m})^{-1}$, normalized to the tape/wire performances). However, the difference in price is progressively reducing as a result of the continuous performance improvements of REBCO tapes and of the economy of scale. The price of a recent production of commercial 4 mm wide tapes, spans from 20 to 30 €m^{-1}. Based on the current performance at 4.2 K and 12 T operation conditions the wire price per unit length turns to be about 30 €$(\mathrm{kA\ m})^{-1}$, about three times larger than that of Nb_3Sn wire at the same conditions (8–10 €$(\mathrm{kA\ m})^{-1}$. This is less than half of the value reported 5 years ago [7, 8]. Due to the increasing demand for tapes triggered by fusion incoming projects, prices will likely be further decreased due to the increased production and market size expansion and higher competition. The ultimate hope

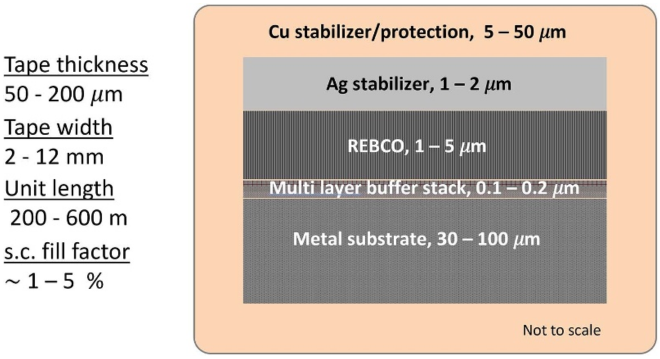

Figure 1. Schematic description of a typical REBCO CC architecture.

is that fusion could play for REBCO CCs the same virtuous role as MRI played for NbTi [7].

Tapes development and irradiation. Regarding the irradiation behavior, several issues related to REBCO tapes have been identified based on the experimental and theoretical studies carried out. The most relevant ones related to tape quality, that emerged from the workshop debates, are listed in the following:

- Nickel in the substrate is a concern due to its neutron multiplication cross section, but choice of alternative substrates is not urgent and can be a later improvement. In fact, dedicating efforts to developing new substrates would slow down the progress in scaling up the production, that could represent the limiting factor for fusion development at the moment. The more pressing issue related to the substrate is delamination.
- Characterization of tapes in the working conditions (temperature T, magnetic field B, angle of the magnetic field with respect to the c axis Θ, strain) is mandatory. At the moment, the reference working point is (20 K, 20 T).
- Careful characterization of the same specific samples for a wide range of irradiation experiments is needed for high accuracy determination of defect landscape, structural problems (delamination, strain due to ion implantation in the buffer layer or in the substrate, etc) and electromagnetic properties (J_c, dependence on T, B, Θ strain).

Needs for magnets in compact fusion reactors

The very high performance of REBCO tapes produced in the last years, with a critical current normalized to tape width of 1200 A cm^{-1} at 4.2 K, 19 T and of 590 A cm^{-1} at 20 K, 19 T [8], make them suitable for building high field magnets. For fusion compact reactors HTS conductors are the only enabling technology to achieve a magnetic field higher than 20 T on the TF coils. The excellent results obtained by the SPARC TF Model Coil project [43] demonstrate that a large-size TF magnet can be manufactured and successfully operated at 20 K, 20 T. However, there are some issues that can affect magnets in a real tokamak environment that cannot be reproduced in a single-coil experimental campaign:

(i) HTS tapes are optimized for achieving higher critical currents but not for being radiation resistant. In fact, several experiments show that for neutron fluences higher than 3–4 $\times$ 10^{22} n m^{-2} J_c rapidly degrades to 25% of its initial value. As a programmatic step, the scientific community should collaborate to determine precise damage limits for the design of magnets and shielding systems to ensure long term operability.

(ii) REBCO tapes in superconducting magnets are subject to mechanical loads that can degrade their initial performances. Intrinsic strain in REBCO layers exists because of the transverse load due to production and winding processes. In addition, various loads are applied to REBCO tapes due to cool-down and operational conditions: cycling or stationary, longitudinal or transversal to the tape direction, compressive or tensile, or combinations of them. In pulsed tokamaks, where the conductors have to sustain thousands of electromagnetic cycles, the mechanical support of REBCO tapes must be a driver of the design. In conductors based on CORC-like cables a key parameter is the size of the gap between adjacent tapes to guarantee mechanical sustain [44]. Similarly, for stacks of REBCO tapes impregnated with structural materials, such as solders, the voids within in the stack can induce damaging localized stress within adjacent tapes for the lack of mechanical support [45]. Despite the vacuum pressure impregnation solder process adopted for VIPER cables [46] has improved this effect, the plastic deformation and stress concentration in the solder may explain the early-stage degradation observed in the experiments [47]. Another important source of performance degradation, especially in epoxy-impregnated coils [48], is the delamination, due to the weak tensile strength of the REBCO tapes in the transversal direction.

(iii) The insulation material used in the TF coils is a limiting factor regarding the neutron irradiation. This is the case in ITER, where the TF coil insulation will undergo fast neutron fluences up to 3.2 $\times$ 10^{21} n m^{-2}, which is equivalent to an absorbed dose of 10 MGy. Under this assumption the epoxy/cyanate ester resins developed for ITER are still able to withstand the estimated shear stress of about 45 MPa [49]. For large tokamaks a neutron fluence on the insulation of 1 $\times$ 10^{22} n m^{-2} is considered a safe limit, whereas for compact tokamaks the expected value is one order of magnitude higher [18], therefore the development of advanced radiation tolerant insulating materials is crucial. Cyanate ester based polymers [50] have a similar radiation tolerance as CCs, whereas ceramic insulators are way more robust against radiation, but more difficult to apply. Another possibility to get around the obstacle is to adopt no insulation (NI) or partial insulation (PI) schemes [51], with the further advantage to reduce the voltage across the coil during fast discharges due to quench. The drawback of the NI approach is the long charging time and the unpredictable mechanical loads on the magnet due to the unbalanced distribution of the leak currents in the coil. In PI coils these two disadvantages may be mitigated, but the problem of the radiation hardness on the insulation material between pancakes (or layers) remains.

(iv) Optical fibers, especially Fiber Bragg Grating, are increasingly considered as rapid and reliable method for quench detection in high-field superconducting magnets fabricated with HTS cables [52, 53]. However, the investigation on their behavior under severe irradiation conditions are limited [54, 55] and should be better explored for a safe integration in a compact tokamak.

3. Simulations

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Understanding the evolution of superconducting magnets performance in a fusion environment requires knowledge of the radiation environment, the resulting structural damage to the material and the consequent modification of its functional properties [18]. The links between these aspects are far from trivial, and the absence of ideal irradiation sources (i.e. able to reproduce the expected neutron flux and fluence in the correct sample environment) [56] means that there is strong emphasis on developing predictive models directed towards understanding these relations and guiding the experimental investigation as well as extrapolating any experimental result to the operating conditions. An excellent example of where this approach is needed, is the common use of an experimentally evaluated limiting neutron fluence value to characterize the radiation hardness of HTS [3, 57, 58]. This approach fails when the neutron spectra considered differs largely from the one used in the experiment [18] or when the target material changes, and a limit in terms of damage would be preferable. For example, GdBCO exhibits a more dramatic decrease in critical temperature than YBCO when exposed to thermal neutrons [22, 59] due to the high neutron absorption cross section of some Gd isotopes [60].

The first step on this path is to have a clear picture of the radiation environment that the HTS will encounter in a fusion reactor, starting from the details of its design. Once this is known, simulations can be also used to characterize the expected damage in the HTS materials in terms of size, morphology and distribution of defects, and their evolution with time. Finally, these structural changes should be related to the modification of superconducting properties. In the following, we discuss each of these aspects, proposing a simulation workflow for a comprehensive analysis of radiation effects in HTS, as summarized in figure 2.

Radiation environment

The best tools to evaluate the radiation environment of a material in a fusion reactor are based on the Monte Carlo (MC) method. This approach, coupled to modern computing tools, allows for the prediction of the flux of particles (both neutral and charged) in extended, detailed, and complex geometries in a reasonable time [15, 61–63]. Moreover, it is possible to obtain several useful quantities for the evaluation of the performance of superconductors, such as the heat load [64], the damage in terms of dpa [19], the activation [65], and the generation of transmutation products that can lead to extended damage formation [66].

Historically, extended studies of this kind have been carried out focusing on the materials and devices that are exposed to the harshest radiation environment (first wall, structural materials, the divertor, etc). However, with the attention of the fusion community shifting towards compact reactors, greater focus on the magnet system and its materials is required. Here, the complexity increases: first because, these systems being further away from the plasma, the computational effort needed to achieve sufficient statistics is larger, but mostly because the characterization of irradiation effects in functional materials requires a more detailed description of the radiation environment and damage, due to their higher sensitivity to structural modifications.

Let us consider the radiation environment: typically it is sufficient to describe the neutron spectrum and flux on a component, possibly accompanied by the same information for photon, and the total power deposited by radiation. In the case of a superconductor, it is crucial to ensure that the superconducting condensate is not strongly affected by this radiation environment, therefore charged particles could also play a role. Moreover, due to the need to keep the material at a operationally-safe cryogenic temperature, the heat load distribution needs to be evaluated in detail in order to design an efficient cooling system.

In this frame, we note that several MC codes are in use and are being actively developed. The most used by the fusion and HTS community are MCNP [67], OpenMC [68] and PHITS [69], all codes that allow detailed analysis on CAD imported complex geometries by parallelization. In order to ensure the comparability of results across the literature, extensive benchmarks of these codes for fusion radiation damage investigations should be encouraged, and some positive first results have been reported [15, 63].

Here we propose an ideal minimal set of information that should be obtained by MC codes to characterize the radiation environment of superconductors in a fusion application:

- the neutron spectrum on the magnet region ($1\,(\mathrm{cm}^2\mathrm{s})^{-1}$)
- the photon spectrum on the magnet region ($1\,(\mathrm{cm}^2\mathrm{s})^{-1}$)
- the dpa in the superconducting material over 10 years of full power operation
- the total heat deposited by the radiation in the superconductor
- the amount of generated H and He (appm dpa^{-1})
- the total flux of electrons and protons above 1 MeV ($1\,(\mathrm{cm}^2\mathrm{s})^{-1}$)
- the Primary Knock-on Atom (PKA) spectra for all atoms in the target material ($1\,(\mathrm{cm}^3\mathrm{s})^{-1}$).

To ensure reproducibility, the data should be accompanied by the nuclear library used, the model employed to compute dpa and the threshold displacement energy for each of the involved atomic species. We note that the threshold displacement energy is a delicate parameter since it depends on the

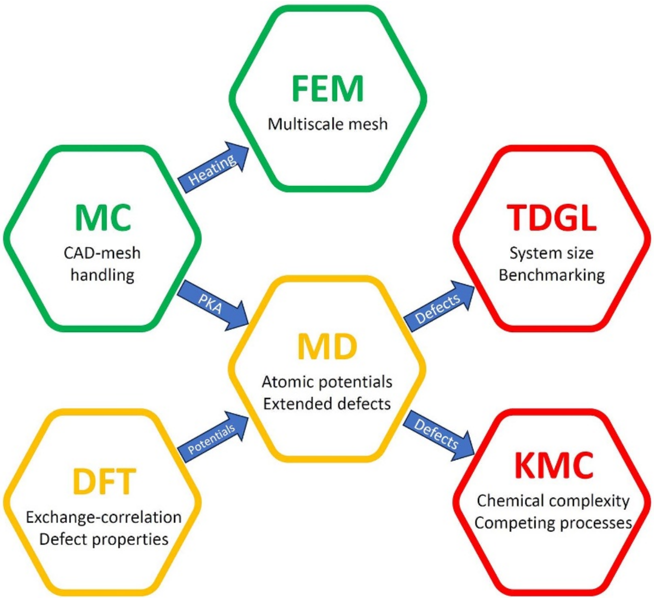

Figure 2. Proposed workflow for a comprehensive computational analysis of radiation damage in HTS for fusion applications. For each approach, the color indicates its maturity when applied to HTS materials: green indicates that it has already been successfully employed and validated, orange that it has been proposed but extensive studies are still missing or that important limitations are still present, and red that it has never been reported in the literature. The main challenges for each approach are indicated in black.

material, temperature, and direction, but in MC codes only a single (often standard) value is used for each atomic species.

This comprehensive description of the radiation environment is not only a necessary first step to understand radiation effects, but is also required for the optimization of fusion reactor designs taking into account all the most relevant technological and scientific bottlenecks, such as activation, embrittlement, thermal resistance, corrosion, etc [70, 71]. In fact, the radiation environment is going to play a crucial role, because in the absence of breakthroughs in shielding materials or technologies, the only way to enhance shielding capabilities is by increasing the thickness of the shield. Due to the limited space available this might negatively impact on the design of the magnets, leading to an increase of their size, in turn affecting the total costs and operation complexity.

Irradiation effects

Once the expected radiation environment is known, the focus can shift on understanding what the impact of this environment is on the microstructure of the HTS. Here several aspects need to be taken into account, the main being radiation damage and radiation induced heating.

Radiation damage. In the high energy, or ballistic, part of a cascade the atoms travel in almost straight lines and each collision can be considered as a separate event. Therefore, the relatively simplistic binary collision approximation (BCA) provides a reasonable model [72]. However, as the energy dissipates and the collisions become more dense and local, the evolution of the microstructure is dictated by complex many body interactions and the specific kind of the interaction between the particles, something that cannot be accounted for in the BCA. These shortcomings can be addressed using molecular dynamics (MD) simulations to study the evolution of cascades on short timescales, as they explicitly consider the interactions between atoms. This approach allows the reproduction of the chain of events following from the formation of a PKA, i.e. right after a collision of a neutron with an atom of the target material. A systematic evaluation of these events yields the size distribution of damage cascades (crucial for pinning efficiency) and their morphology. Moreover, it is possible to compute several quantities that could be compared to experiments and provide validation of the simulation model. A comprehensive investigation of damage cascades should lead to the definition of a standard description of radiation damage in HTS that goes beyond dpa, giving the relevant information about defects size and distribution needed to estimate the impact on the superconducting properties. It is worth spending a few more words on the dpa: this quantity measures the damage level in terms of the fraction of displaced atoms, without distinction on how they are distributed. As an example, ten large cascades with 1000 disordered atoms in it contribute to dpa in the same way as 1000 small clusters of ten displaced atoms, despite affecting superconductivity in very different ways. Models capturing the morphology and distribution of the created defects are therefore an essential basis to achieve an understanding of the relation between structural defects and the effects on superconductivity. Moreover, it should be noted that exist several models for the calculation of dpa (NRT [73], ARC [74], CRC [75]), each developed with specific cases in mind and none for complex ordered materials. The most used is the NRT model that was developed for metallic systems and that is known to overestimate the number of Frenkel pairs by a factor of about 2–3, and underestimate the number of replacements by a factor of 30 [74]. Besides stressing the importance of always reporting the method employed, we want to highlight the need for this community to find a new model for the easy computation of damage, that suits the characteristics of HTS materials and the impact of defects on the superconducting properties.

However, the chemical and structural complexity of HTS makes such studies particularly difficult. A number of empirical MD potentials have been developed for YBCO [76, 77], however, it is only recently that a model suitable for studying radiation damage has been constructed [78]. Recent developments in the field of interatomic potentials have exploited the speed and accuracy of machine learning (ML) methods to represent interactions in solids [79]. Such methods rely on a descriptor or basis to represent atomic local environments, and then the atomic interactions are learned from first-principles calculations mainly based on density functional theory (DFT). ML potentials are becoming the workhorse of computational material science since they combine the speed of classical interatomic potentials with near-DFT accuracy, with many applications in the study of radiation damage [80–83]. Examples of such potentials can be found in the many available reviews [79, 84–87]. Potentials for chemically complex systems are becoming available [82, 88, 89], and developments regarding simulation of collision cascades are also being brought forward [80].

Of course, ML potentials are only as good as the underlying calculations in the training set.

For HTS, DFT cannot reproduce superconducting properties because of its mean-field nature; nonetheless, it seems to be able to capture many properties in the normal state [78, 90–93], therefore justifying the use of this method to construct the training set for ML potentials. In addition, recent advances in exchange-correlation approximations seem to have improved the description of several properties of these correlated materials [88, 94, 95].

Irrespective of their functional form, the improvement and experimental benchmark of interatomic potentials and MD simulations for radiation damage is a crucial and urgent matter. Further, the potentials need to be expanded to encompass other species, in particular Gd, and adapted to allow deviations in oxygen stoichiometry.

We notice in passing that there is still a lack of knowledge regarding the underlying mechanism of superconductivity in cuprates. State-of-the-art DFT + dynamical mean field theory (DMFT) calculations have shown some progresses in addressing this question [96, 97], even though this technique is computationally very intensive and is still being applied only on simplified, parametric, Hamiltonians based on the Hubbard model. If DMFT will be shown to capture the superconducting properties of specific materials by calculating from *ab initio* the relevant parameters and including realistic band structures in the initial model, a full first principles investigation of temperature-dependent defect properties and their effect on critical temperature and current could in principle become feasible in future.

MD allows the characterization of defect production and the short-term stability of these radiation induced defects, however, to enable predictions of the lifetime of the material it is necessary to understand how these defects evolve on the long-term (from seconds and beyond) stability of such defects and all the aspects related to their annealing. Here the microstructure plays a crucial role. For simple systems some approaches, such as Kinetic MC (KMC) and Rate Equations Methods, have been developed exploiting kinetic parameters extracted from experiments or computed from first principles (DFT-based), but they have yet to be applied to HTS, where the chemical complexity is a great computational challenge because it requires the identification of several competing diffusion mechanisms. In addition, extended defects such as dislocations and grain boundaries are of great importance as sources and sinks for defects: investigation of the role of these important defects on the annealing properties of HTS in MD and KMC is an important future development. Overall, detailed knowledge of diffusion mechanisms at the atomic scale and the impact of anharmonicity in HTS is still lacking: such insights from DFT and interatomic potentials are fundamental for the accurate determination of long-term diffusion properties at the mesoscale within a complete multiscale framework.

Knowing the morphology of defects can be the starting point to investigate how they affect pinning (and hence the critical current) by solving the time dependent Ginzburg Landau (TDGL) equations [98–100], and the superfluid density (and consequently T_c) by investigating their impact on the electronic structure.

Due to the fact that superconducting properties cannot be directly computed from the simulations, there is the need of finding different quantities that are easily accessible both computationally and experimentally so that a consistent benchmarking of the approach can be achieved. Moreover, this kind of approach can also improve the understanding of experimental results [93].

Radiation heating. Thermal aspects induced by the radiation environment should be taken into account on two levels: local and global. Locally, each particle interacting with the superconductors releases some energy (in an amount dependent on its charge, mass and interaction mechanism) that leads to a local (on the nanometer scale) increase of temperature that is rapidly dissipated. What is crucial on this scale is that the temperature increase must be not so drastic to lead to a macroscopic disruption of the superconducting state, and that broken Cooper pairs must have the time to recombine before additional events take place. These phenomena are exploited in particle detectors where the operating temperature is set near to T_c and the width of the conductor is decreased to the point where the hot spot formed following the interaction of a particle with the superconductor and the consequent current redistribution result in a macroscopic voltage change across the device [101]. In fusion applications the operating conditions are far from this regime, and the incoming particle fluxes should be small enough that successive events do not happen on the time scale of electron–electron interactions (ps), despite local deposited energy densities of the order of $\mathrm{TW\,cm^{-3}}$ for typical PKA energies ($\sim$10 keV), interaction times ($\sim$100 ps) and cascade volumes ($\sim$10 nm radius) [18].

On a macroscopic scale, one has to take into account the average heat load continuously deposited by the neutron and secondary particles flux on the components of the superconducting magnet during operation (including the time modulation during the reference plasma scenario), in order to suitable dimension the cooling system [102, 103]. The average heat load on the TF magnet largely differs between large fusion reactors (e.g. DEMO 5×10^{-5} $\mathrm{W\,cm^{-3}}$) and compact ones (shielded ARC-like 2.3×10^{-3} $\mathrm{W\,cm^{-3}}$). Moreover, its spatial distribution can be very inhomogeneous [104]. Each material has a different cross section and therefore the deposited power is modulated across the components of a magnet, leading to the development of thermal gradients in the system [64]. Finite element method (FEM) models and object oriented approaches [105] can be employed to estimate the temperature rise due to the nuclear load and the required cooling power. Such studies can be carried out with a high level of detail employing power deposition maps on small portion of the magnet system (such as superconducting cables) [64], or on a coarser scale with averaged heat loads on whole coils, portion of winding packs or magnets [106]. One of the main bottlenecks of FEM simulations for such studies is represented by the several orders of magnitude spanned by the relevant spatial scales that make it difficult to generate suitable meshes for the discretization of the problem and strongly increase the computational cost.

4. Experiments

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Even if primary sources of radiation with the characteristic energy spectrum and intensity are still lacking, experimental investigation of irradiation effects in REBCO-based CCs has been greatly boosted in recent years due to their application for compact fusion reactors. In this section, we summarize the main results obtained from irradiation experiments with different particles, energies and fluences on HTS materials, before highlighting the current activities and needed future developments. Not all choices of particles necessarily reflect in a direct way the expected radiation environment, but they all contribute to the creation of a comprehensive understanding of how irradiation affects the superconducting properties. Two classes of experiments are linked to the fusion working conditions more directly than others: neutron irradiation and irradiation with *in-situ* measurements. In general, a clear trend emerges: after a possible initial improvement of J_c, during reactor operation the superconducting properties will inevitably decline. Irradiation experiments are therefore crucial to yield the maximum damage a practical conductor can sustain, allowing the determination of the total lifetime and driving the design of neutron shields.

State of the art

First of all, it is important to recognize that the presence of material disorder (defects) is required to produce vortex pinning, otherwise J_c would be zero [107]. Some defects always appear during the fabrication process of any superconductor, but when seeking for high J_c in HTS the common approach is to add APCs specifically designed to produce strong pinning [31, 34, 35]. Although the distinction between naturally occurring defects and APCs is somewhat arbitrary, the latter usually refers to deliberate incorporation of non-superconducting secondary phases and to irradiation damage, while the former includes natural structural disorder such as twin boundaries, dislocations, grain boundaries and stacking faults that occur during growth. Since each type of defect produces pinning with characteristic dependencies on temperature (T) and the intensity and orientation (Θ) of the magnetic field (H) (see figure 3 for some examples), measurements of $J_c(T, H, \Theta)$ can be used as fingerprints of the pinning mechanisms and regimes [109, 110].

Historical background, irradiation of clean YBCO single crystals. Historically, significant knowledge about vortex pinning in HTS was gained through particle irradiation studies, which started as soon as those materials were discovered, with the main goal of finding methods to increase J_c. In 1987, Sekula *et al* [111] showed that fast neutron irradiation of $La_{1.85}Sr_{0.15}CuO_4$ ceramics produced a modest factor 2 increase in J_c at 4.2 K. However, early results on polycrystalline samples were hard to interpret, because the J_c enhancement within the grains was partially masked by the deterioration of the weak-links behavior at the grain boundaries [112].

A clearer picture started to emerge when high quality single crystals of the various HTS compounds became available. In particular, the pinning enhancement in YBCO single crystals produced by different particles (neutrons, electrons, protons, light and heavy ions) over a broad spectrum of energies was explored by many research groups [113–121]. The main conclusion was that J_c could be increased by orders of magnitude, but it must be kept in mind that the pristine crystals were quite clean, thus the pre-irradiation J_c values were very low. This had the additional benefit that the $J_c(T, H, \Theta)$ of the irradiated samples could be almost solely attributed to the added defects, simplifying the interpretation.

Electron irradiations, which only produce Frenkel pairs, resulted in modest J_c enhancements in YBCO crystals [120], demonstrating that even point defects produce pinning in YBCO, which is consistent with the small radius of the vortex core (of the order of the coherence length ξ) [107]. Proton irradiations, which in addition to Frenkel pairs create larger defect clusters, resulted in one to two orders of magnitude J_c enhancements (depending on T and H) [116], and a variety of light ions produced similar effects.

Of particular relevance to the fusion technology are the early studies of fast neutron irradiations, which created cascade defects and produced orders of magnitude J_c enhancements in YBCO single crystals [114, 115, 117, 119]. It was also shown that irradiation at cryogenic temperatures leads to a stronger effect on both, T_c and J_c, than irradiation at ambient temperature due to the evolution and annealing of defects promoted by higher temperatures [121].

In all these cases, the defects are localized and randomly distributed, resulting in isotropic pinning. In contrast, high-energy heavy-ion irradiations create approximately parallel amorphized tracks, or columnar defects (CDs) [118] that produce directional pinning, being extremely effective for H parallel to the CDs and below the matching field (i.e. the field where the density of vortices = density of CDs), but less so at tilted orientations and/or higher H. Irradiation of uranium doped YBCO crystals with thermal neutrons also resulted in large J_c increases, in that case attributed to the defects associated with the fission of U atoms (fission tracks) [122, 123].

Of course, for all types of irradiations there is an optimum fluence for J_c enhancement, beyond which the structural damage becomes too large and J_c starts to decrease. This fluence depends on the operation conditions and tends to increase with decreasing temperature but increasing magnetic field.

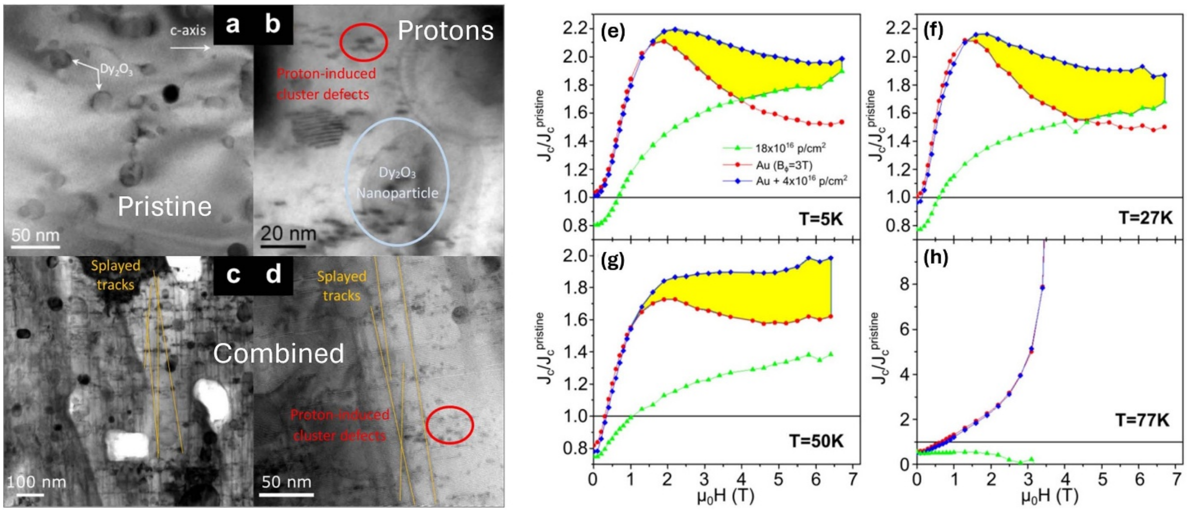

Figure 3. Pinning by combined irradiations in YBCO coated conductors grown by metal organic deposition (MOD). (a)–(d) TEM images. (a) Pristine CC. (b) after irradiation with 4 MeV protons to a fluence of 1.8×10^{17} cm^{-2}. (c), (d) combined pinning landscape after subsequent irradiation with 250 MeV Au to a dose-equivalent matching field $B_\Phi = 3$ T. (e) Enhancement factors $J_{c,\mathrm{irrad}}/J_{c,\mathrm{as-grown}}$ as a function of field (parallel to the c axis) at $T = 5$ K, for CC pieces irradiated with 4 MeV protons to a fluence of 1.8×10^{17} cm^{-2} (green), with 250 MeV Au to a dose-equivalent matching field $B_\Phi = 3$ T (red) and both irradiations combined (blue). (f), (g) and (h) Same at $T =$ 27 K, 50 K and 77 K, respectively. Reproduced from [108].

Irradiation of thin films and CCs, complex pinning landscapes. Good quality epitaxial YBCO thin films deposited on single crystal substrates also became available early on, and irradiation studies were performed on those films. For instance, Schindler *et al* [124] and Roas *et al* [125] observed increases in the in-field J_c after fast neutron and 25 MeV ^{16}O ions irradiation respectively. The enhancement factors were much lower than in single crystals, never exceeding a factor 3, in some cases accompanied by a decrease in self-field J_c.

More recently, studies of the effects of particle irradiation on the pinning properties of REBCO-based CCs were performed. In several cases J_c increases were indeed observed, although not by orders of magnitude as in the single crystals, but rather by modest factors of 2–3, which nevertheless could be quite relevant from the technological perspective [108, 126–128]. The quantitative difference between the enhancement factors in single crystals and in films and CCs is to be expected, as the pre-irradiation J_c values in the later are already very large, thus reducing the margin for improvement. An important caveat is that the J_c enhancement factor is a function of T, H and Θ; in particular it has been observed that irradiation parameters that produce J_c increases at high H may also produce a deterioration of J_c at self-field and low fields. This difference can be understood in terms of the double role of defects in a superconductor: they increase scattering of charge carriers suppressing superconductivity, but also act as pinning centers decreasing dissipation from vortex motion. For high fluence irradiation at low magnetic field, the beneficial effect of the increased pinning could be hidden by the decreased superfluid density.

Understanding the irradiation-dose dependence of $J_c(T,H,\Theta)$ is essential for the design of fusion reactor magnets. The ultimate question is how long the magnet will survive until the radiation damage drags it below the operational limits, and that will depend on how the different portions of the coils will be affected.

Nearly all neutron irradiation experiments on CCs were done in fission reactors at ambient reactor temperature [20, 22, 59, 129–138], and only very recently first results with 14.1 MeV fusion neutrons have become available, although at a very low fluence [139]. A decrease in T_c following irradiation was observed in all these studies. This decrease is apparently linear with fluence and general, since no significant differences between CCs were observed so far, irrespective of their composition and architecture [20, 22, 138]. The peak in the fluence dependence of J_c at fusion relevant conditions is found at around $1–2 \times 10^{18}$ cm^{-2}, the absolute and relative enhancement being dependent on the CC. At higher neutron fluences the critical current decreases linearly, the slope seeming to be universal for all CCs [138]. The original J_c is then reached at around $2–3 \times 10^{18}$ cm^{-2}. However, these values depend on the actual conductor, on details of the neutron energy distribution and the irradiation temperature. This makes a prediction of the performance change in a real fusion magnet delicate, since neutron irradiation facilities at cryogenic temperatures are hardly available. However, early data on single crystal samples [121] shows similar J_c enhancement at low fluences in samples irradiated at cryogenic and room temperature, and more recent experiments with helium ions on CCs [140] to higher damage levels indicate a similar rate of degradation of self-field J_c when irradiated at 40 K compared to room temperature. Both studies show that the defects introduced by cryogenic irradiation can be partially annealed on thermal cycling to room temperature, suggesting that the defect landscape may not be the same for cryogenic and room temperature irradiation. Results presented by the MIT group [141, 142] indicate that defect annealing starts at around 100 K. Annealing well above room temperature further reduces the degradation and may hence become a mitigation strategy [22]. Pair breaking by scattering of the charge carrier seems the dominant mechanism driving the degradation intrinsically linked to the scattering rate. Hence the change in T_c being linear with fluence (defect density) turned out to be an easily accessible and useful parameter for the J_c reduction. The decrease in J_c at high fluences appears universal when plotted against the transition temperature even for very different induced defect structures [138]. This fuels hope that the degrading contribution of the neutron induced disorder can be indeed predicted by calculating the neutron spectrum, the resulting defects, their scattering potentials and finally the resulting changes in T_c and J_c.

The beneficial effect of introducing pinning centers seems much more difficult to predict, since it is not universal but dependent on the pre-existing defect structure. At the core, the reason for this complex behavior is that pinning is not additive [107], and the presence of more than one type of defect may result in cooperative but also competitive effects on J_c. The microstructures of commercially available CC are the result of years of efforts at nanoengineering the vortex pinning landscape, and the outcome is fabrication-method dependent [31, 34]. For instance, incorporation of $BaZrO_3$ (BZO) in CCs deposited by methods that promote columnar growth, such as PLD, results in self-assembled BZO nanorods (akin to CDs) [143], while the same additions in laminar growth methods such as MOD produce randomly distributed BZO nanoparticles [144]. The irradiation-induced disorder will interact with pre-existing defects in various ways. For example, clusters or cascades (nanoparticles) may disrupt large stacking faults that are effective pinning centers for H parallel to the a,b planes (competition) [110], while they may improve the pinning of nanorods, as it is well established that mixed pinning landscapes are very effective (cooperation) [145]. In summary, the starting landscape cannot be ignored; the irradiation effects will have to be investigated on the same CCs that will be used, and some results obtained for tapes from one manufacturer will not be transferable to other ones. However, the general trend that irradiation first improves J_c at relevant operation conditions due to enhanced pinning followed by an unpleasantly fast decrease at high fluences seems quite universal so far. This latter region must be avoided by designing suitable neutron shields and reactor operation schemes.

Neutron irradiation also changes the angular dependence of J_c [130, 131] and most available data only refer to the orientation of the applied magnetic field being parallel to the crystallographic $c-$direction. For the other main field orientation (field parallel to the ab-planes) the situation is generally worse, since intrinsic pinning is strong and cannot be improved by the added pinning sites; thus, one observes only the decrease of J_c and the minimum in the angular dependence of J_c shifts close to this parallel field orientation. Further observed changes are a decrease in the n-value of the power law $E \propto J^n$ and an increased strain sensitivity that can be correlated with the decrease in transition temperature [59].

Needed facilities

The body of scientific works reported above lead to the current understanding of the issue of HTS performance under irradiation, and are the starting point for future investigations and novel experiment design. The experimental characterization is mandatory for the development of suitable radiation shields and for the overall design of durable and therefore economically viable fusion reactors.

Ideal irradiation experiments should allow exposing the superconductor to the expected radiation environment as a whole: with a broad neutron spectrum including the 14 MeV component, accompanied by secondary particles. The sample should be kept at the operating temperature ($\sim$20 K) and its superconducting properties measured during the irradiation with fusion relevant fluxes. If the measurement of the transport properties is done while the sample is being irradiated (so called in-operando characterization or beam-on experiments), particular attention should be devoted to thermal stability. In addition, the response to the fluences expected to be reached in 10–40 years of operation should be investigated as well, exploiting experiments with higher fluxes. Unfortunately a facility that enables such experiments as of today does not exist, despite in the past some high brilliance 14 MeV neutron sources were developed: RTNS-II (Lawrence Livermore National Laboratory, USA) generated 10^{13} $\mathrm{n\,s^{-1}}$ and was equipped with a liquid He cryostat, while the flux of FNS (Japan Atomic Energy Agency, Japan) reached 3×10^{12} $\mathrm{n\,s^{-1}}$ and cryogenic irradiation was achieved using a Gifford–McMahon system. Both these facilities are no longer operational.

The ideal experiment can not be realized in an useful timescale, therefore we suggest an approach based on a broad set of experiments and assisted by simulations. The influence of neutron radiation can be divided into a beneficial effect of increased pinning and the detrimental effect resulting from pair breaking, both heavily depending on the actual defect structure which is given by the irradiation fluence, the neutron energy distribution, and the irradiation temperature. As pointed out above, changes in pinning are hard to predict and benchmarking experiments either with neutrons or proxies will have to be performed on the specific conductor envisaged for the fusion device. Luckily, defects relevant for strong pinning are likely not the ones recombining by warming up to room temperature, which somehow relaxes the need for cryogenic neutron irradiation in this respect.

The degrading effect may be parameterized by the change in T_c, which is much easier to measure than a full angular dependence of J_c and results mostly from the scattering rate [146] that can be either measured or numerically predicted for certain defects and their density. The defect landscape can be simulated from the predicted radiation environment. What is missing is the resulting scattering strength of the introduced defects or classes of defects. Therefore, what is needed are experiments generating predominantly one of the relevant defect species to benchmark (or confirm theoretical predictions) its scattering strength and impact on the transition temperature. Adding up the scattering strength of all predicted defects ideally leads to a reliable prediction of the performance degradation without the need of realizing precisely the real radiation conditions. Instead, one can aim for a variety of irradiation experiments with completely different particles and energies, only some of which to be performed at cryogenic temperatures (depending on the defects that are to be generated). This approach relies on exhaustive modeling of radiation effects in close collaboration with available experiments and has to be complemented by experiments mimicking the real operation condition as closely as possible confirming its validity.

Low temperature irradiation experiments are mandatory: the irradiation temperature should be kept below 100 K (ideally at the operating temperature of the magnet—$\sim$20 K) to hamper defects evolution, and the characterization of the samples should be carried out *in-situ* (i.e. always keeping the sample below 100 K after irradiation). The characterization of samples at high-fields is strongly encouraged and the effects of room temperature annealing should be investigated to better understand how to exploit also data from room temperature irradiation. Cryogenic irradiation experiments with neutrons and all kinds of secondary particles (protons and electrons, gamma rays, ions) should be pursued. Cryogenic fast neutron irradiation experiments with compact fusion reactor relevant fluxes (of the order of 10^{10}–10^{11} cm^{-2} s^{-1}) should be the overall priority, also because such experiments can help to validate the use of other particles as proxies. Light ions are the best proxy candidates, and cryogenic H and He irradiation facilities are widely accessible. To promote the comparison of results between different irradiation techniques, properties modifications should be presented as a function of damage (dpa) rather than particle fluence.

To satisfy the needs and requirements presented above, a widespread and collaborative effort is needed, starting from the upgrade of the experimental facilities already available and including the development of ad-hoc ones. Cryogenic ion irradiation facilities are available in several research centers, and some are already active on the topic of HTS irradiation: the Surrey Ion Beam Center, MIT-PSFC, Helsinki Accelerator Laboratory. The most brilliant 14 MeV neutron source active today is the FNG facility at ENEA Frascati, and an upgrade to allow cryogenic irradiation and *in-situ* characterization is planned. MIT is also developing a cryogenic neutron irradiation facility with a broad spectrum and the possibility of high-field (14 T) *in-situ* characterization [147], and UKAEA announced together with the Research Centre Řež (Czech Republic) the development of a facility called Hi-CrIS (High neutron fluence Cryogenic Irradiation of Superconductors), expected to be operational in 2026, for 20 K fast neutron irradiation using the light water tank-type research reactor and *in-situ* transport measurement.

In addition to the transport properties of HTS, other concerns following conductors irradiation are related to the response to mechanical stress and to the radiation hardness of insulation materials. In relation to the former, UKAEA is developing a facility for cryogenic high-field (20 T) tests of large samples, under tensile strain and with various field orientations. This facility should also accept irradiated samples from external sources.

The exchange of samples between complementary facilities could be pivotal for achieving a comprehensive understanding of radiation effects in HTS. Two kinds of samples should be favored: commercial CCs to have direct information about the technological aspects, and clean single crystals for a deeper understanding of the physics involved. On a final note, synergies with other activities could be considered for the implementation of further facilities in the future, additionally to what was discussed above. Examples are the large material irradiation facility projects envisioned in the frame of broad collaborations, such as IFMIF [148, 149], where the implementation of new samples environment could expand the applicability to HTS. Furthermore, the development of fusion demonstrators could also provide new tools for materials and component testing, exploiting the demonstrators themselves as neutron sources.

Characterization. The complex pinning landscapes of the CCs produce a rich T–H–Θ phase diagram of the pinning mechanisms and regimes. If the target operating conditions for fusion reactor magnets is (20 K, 20 T), we know that a dense distribution of small nanoparticles ($\sim$5–7 nm) will be effective. Irradiation induced cascades may have a positive effect on J_c over most field orientations, but are detrimental for H close to the a,b planes. Some portions of the magnets will see a smaller H, thus the whole field dependence must be known. It is difficult, if not impossible, to infer the effects that adding certain defects will have in one regime, by measuring their effects in another regime. For instance, point and spherical defects, as those that will be generated in the fusion reactors, are weak pinning centers that may increase J_c at low T, but decrease it at high T. Attempting to infer the irradiation effects on J_c (20 K, 20 T, Θ) by just measuring J_c (77 K, self-field) is a rather challenging task.

On the other hand, measuring J_c (20 K, 20 T, Θ) can only be done in relatively few facilities, and will be time consuming, thus some efficient approach is needed. Here, we can take advantage of some known functional dependencies and scaling rules that can be applied as long as the sample remains within the same pinning regime. For instance, many CCs exhibit an intermediate field regime over a broad temperature range where J_c has a power-law dependence on field, $J_c \propto H^{-a}$, with α depending on the fabrication method and the dominant pinning mechanism. Once the α values and the H–T boundaries of that regime have been established for a given batch of samples (e.g. through measurements with fields up to 20 T), more accessible measurements up to a few Tesla can be used to assess the irradiation effects. Similar approaches can be devised based on the scaling of the angular dependence of J_c (for instance, measuring J_c at a few reference orientations, rather than the whole angular range).

5. Summary and outlook

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The developments in HTS tape technology opened the path towards commercial fusion energy deployment by enabling the design of high-field compact reactors; as a result of this change of paradigm, new challenges arise. The diverse scientific community that gathered at the IREF workshop (Arona, Italy, 12–16 November 2023) identified the most critical aspects to be investigated in the near future and the fixed points on which it is safe to build progress.

First and foremost, it is clear that the level of performance ensured by tapes nowadays is sufficient for the manufacturing of magnets for fusion applications, and the R&D efforts of producers should be mostly directed towards production increase, price reduction, reliability enhancement and thorough characterization of the product. The former two aspects are connected through the economy of scale, and the latter two could strongly benefit from collaborations with academia for the exploitation and development of advanced characterization tools. Clearly, the optimization of tape technology and the performance improvement is always desirable, but it is not the most pressing matter as of today.

Starting from these tapes, large magnets and complex magnetic systems able to generate the required magnetic field distributions for plasma confinement have been demonstrated, and progress in this direction is ongoing. Together with quench prevention, detection and management, the most critical issues to be faced by the scientific and engineering community are related to the effects of irradiation on the materials in the magnet. In addition to the damage introduced in the HTS, concerns are directed towards insulating materials and quench detection systems.

The most sensitive component to irradiation is, however, the HTS, because the superconducting state is particularly fragile and is strongly affected even by small changes in the underlying crystal structure. For this reason, the radiation environment of HTS magnets must be carefully characterized computationally and taken into account in the design and optimization phases of fusion reactors.

Moreover, combined, extensive and widespread experimental and computational studies of irradiation effects on HTS materials and tapes are urgently needed to:

- establish a profound understanding of the mechanisms of HTS performance degradation,
- establish reference damage thresholds,
- design proper radiation shields for the magnet system,
- envision damage recovery schemes.

To achieve these goals it is crucial to perform diverse irradiation experiments in terms of particle type (to study both neutrons and secondary particles), flux, fluence and spectrum (since no ideal facility exists), and operating conditions, e.g. temperature, bias current, strain, magnetic field. It is from the combination of these puzzle pieces that a comprehensive understanding of radiation effects in HTS can emerge, with computational tools guiding and aiding the interpretation.

Facilities with dedicated irradiation setups are operational or are being developed at Surrey Ion Beam Center, MIT-PSFC, Helsinki Accelerator Laboratory, ENEA Frascati and Research Center Řež, and the characterization of samples should approach as close as possible the reference operation conditions of 20 K, 20 T. From the point of view of computational tools, MC and FEM are mature for this kind of study, whereas *ab-initio* and microscopic simulation tools (DFT, MD, KMC, TDGL) require additional efforts to be fully exploited for the study of complex materials such as REBCO.

Overall, decades of high quality research in the field of HTS irradiation, although mostly for different purposes, and of facility and methods development are the basis that can ensure a rapid and reliable advancement towards the solution of the challenges that particle irradiation poses to the achievement of energy production by nuclear fusion. The urgency of such studies for the successful development of compact fusion reactors within the desired timelines, and the evident benefit they would provide to the private sector, points to he need for increasing public–private partnership on this topic.

Data availability statement

No new data were created or analysed in this study.

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