

Radiation-Induced Defect Engineering in REBCO High-Temperature Superconductors: Defect Morphology, Vortex Pinning, and Technological Reliability

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Abstract

Radiation-induced defect engineering is an effective approach for modifying the vortex-pinning landscape in high-temperature superconductors, particularly REBCO-coated conductors and Bi-based cuprates. This review critically summarizes the relationship between irradiation parameters, defect morphology, and superconducting performance. The discussion covers point defects, defect clusters, columnar tracks, planar defects, and displacement cascades generated by electrons, gamma rays, light ions, heavy ions, and neutrons. Special attention is given to the dual role of irradiation: moderate defect concentrations can enhance the critical current density by introducing artificial pinning centers, whereas excessive disorder suppresses the superconducting transition temperature and degrades current transport. The review also discusses the relevance of irradiation effects for fusion magnets, space technologies, accelerator systems, and high-field applications. Finally, the review identifies key challenges for future HTS radiation engineering, including cryogenic in situ irradiation, coupled radiation–strain–field experiments, damage metrics beyond dpa, and multi-scale models capable of linking atomic defect production, oxygen disorder, vortex pinning, and macroscopic J_c/T_c degradation.

Keywords: high-temperature superconductors; REBCO-coated conductors; radiation-induced defects; vortex pinning; critical current density; neutron irradiation; heavy-ion irradiation; defect engineering; fusion magnets; cryogenic irradiation



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1. Introduction

High-temperature superconductors (HTSs), particularly REBCO-coated conductors, are among the most promising materials for next-generation high-field magnets, compact fusion devices, accelerator systems, superconducting power technologies, and space-related applications [1,2]. Their technological relevance is determined not only by their superconducting transition temperature but also by their ability to maintain a high critical current density when subjected to applied magnetic fields, mechanical stress, thermal cycling, and radiation exposure.

Despite these advantages, the practical performance of HTSs under magnetic field is often limited by the motion of Abrikosov vortices. The dissipation and decrease in J_c due

to vortex motion lead to a limitation in the current-carrying capacity of superconducting conductors. Thus, the creation of effective vortex-pinning centers that can be used to trap vortices has become a key issue in the study and application of HTSs [2].

Radiation-induced defect engineering (RDE) is one of the most effective ways of managing the behavior of vortices. The creation of defects in the crystal lattice in this process ranges from atomic-scale point defects and Frenkel pairs to dislocation loops, collision cascades, amorphous nanoclusters, and extended columnar tracks [3,4]. Unlike chemical doping or nanoparticle addition, irradiation can introduce defects without intentionally changing the nominal chemical composition of the superconductor. By selecting the irradiation particle, energy, fluence, geometry, and temperature, it is possible to tune the defect density, spatial distribution, and morphology over a wide range of length scales. Consequently, defects created by the irradiation can be very efficient artificial pinning centers for Abrikosov vortices, greatly improving the superconducting properties in magnetic fields.

The study of radiation effects on superconductors started in the 1960s and, at first, only conventional superconductors like NbTi and Nb₃Sn were considered [5,6]. Early experiments showed that neutron irradiations could lead to improvements or degradations in superconducting properties depending on the defect size and concentration, and on the microstructure. After the discovery of high-temperature superconductors, research quickly turned to cuprate superconductors, which were shown to be especially susceptible to nano-scale disorder with a short coherence length [1]. A breakthrough was made when it was demonstrated that heavy-ion irradiation produces columnar defects that effectively trap vortices, thus greatly enhancing J_c under high magnetic fields.

In the last three decades, radiation-induced defect engineering has evolved from a technique for the study of radiation damage into a well-developed technique to tailor superconducting properties. The understanding of defect formation and evolution in irradiated HTSs has been greatly advanced by recent developments in electron microscopy, synchrotron spectroscopy, atomistic simulations, and machine-learning-assisted radiation modeling (MLRM) [3,7]. These studies have shown the existence of a basic duality in that moderate levels of irradiation-induced defects can lead to increased vortex pinning and increased J_c [8], whereas high levels of disorder reduce the superconducting T_c and reduce the superconducting coherence length [9].

The aim of this review is to provide a structured analysis of radiation-induced defect engineering in HTSs by connecting irradiation conditions with defect morphology, vortex-pinning efficiency, and superconducting degradation. Particular emphasis is placed on REBCO-coated conductors because of their importance for fusion and high-field magnet technologies. Bi-based cuprates and iron-based superconductors are discussed only as limited comparative examples where they help clarify material-dependent irradiation tolerance or defect-controlled pinning mechanisms. They are not treated as the primary focus of this review.

The novelty of this review lies in organizing radiation-induced defect engineering in REBCO-coated conductors through a defect–performance–degradation–reliability framework. In contrast to reviews that mainly summarize irradiation methods and pinning enhancement [10], the present work follows the full sequence from irradiation parameters and defect morphology to vortex-pinning performance, superconducting degradation, and conductor-level reliability. This framework is used to compare conflicting experimental results and to identify irradiation conditions in which improved J_c does not come at the cost of unacceptable T_c suppression, oxygen disorder, or loss of current-path connectivity.

1.1. Review Methodology

This review was prepared by analyzing peer-reviewed publications indexed in Web of Science, Scopus, and Google Scholar, with emphasis on works published between 2018 and 2026. The literature selection focused primarily on experimental and modeling studies in which irradiation parameters, defect morphology, and superconducting properties were reported together. Particular attention was paid to papers that provided quantitative information on particle type, irradiation energy, fluence, irradiation temperature, critical temperature (T_c), critical current density (J_c), and microstructural evidence of defect formation. Older foundational studies were also included when they established key concepts such as columnar-defect pinning, Bose-glass behavior, and neutron-induced displacement cascades. Search terms included ‘REBCO irradiation’, ‘YBCO radiation defects’, ‘vortex pinning’, ‘neutron irradiation’, ‘heavy-ion irradiation’, ‘coated conductors’, and ‘fusion magnets’. Priority was given to studies reporting irradiation parameters, defect morphology, and superconducting properties, such as T_c and J_c . Studies were excluded if they did not report irradiation parameters, superconducting properties, defect morphology, or a mechanistic interpretation of irradiation-induced changes. This review is structured as a narrative critical review rather than a systematic review or meta-analysis; therefore, no PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)-based statistical screening or statistical aggregation of published data was performed. The selected literature was evaluated according to its relevance for linking irradiation conditions, defect morphology, superconducting response, and technological applicability. Therefore, the emphasis is placed on mechanistic interpretation, comparison of irradiation strategies, and identification of research gaps rather than on statistical aggregation of published data. The initial search identified approximately 156 records. After removing duplicates and clearly irrelevant papers, 106 records were screened by title, abstract, and keywords. Full texts were assessed for eligibility if they reported at least two of the following elements: particle type and energy; fluence or dose; irradiation temperature; measurement temperature; magnetic field; T_c , J_c or I_c ; microstructural evidence of defect formation; and technological relevance. The final set of papers included 86 studies, selected for their relevance in linking irradiation conditions, defect morphology, vortex-pinning response, superconducting degradation, and conductor-level reliability.

1.2. Limitations of the Review Methodology

The present review has several methodological limitations. First, it is a narrative critical review rather than a systematic review or meta-analysis; therefore, the selection of literature inevitably contains a degree of expert judgment and subjectivity. Second, the available irradiation studies differ substantially in particle type, energy, fluence, irradiation temperature, sample architecture, magnetic-field orientation, J_c criterion, and post-irradiation characterization method. These differences prevent statistically rigorous aggregation of all reported J_c , T_c , fluence, and dpa values into a single universal scaling law. Third, the review prioritizes studies that report irradiation conditions, defect morphology, and superconducting response together, which may underrepresent studies focused only on either microstructure or electromagnetic performance. Therefore, the quantitative comparisons presented here should be understood as representative mechanistic benchmarks rather than as a complete statistical ranking of irradiation methods.

2. Types and Morphology of Radiation Defects in HTSs and Their Impact on Superconducting Performance

High-temperature superconductors—particularly REBCO/YBCO-coated conductors and Bi-based cuprates—possess short coherence lengths, pronounced anisotropy, and

strong sensitivity to oxygen stoichiometry. Therefore, irradiation-induced disorder at the nanometer scale can significantly affect vortex dynamics, flux pinning, critical current density, and superconducting transition temperatures [1,4,11,12].

Irradiation-induced defects influence HTSs through two competing effects. At an optimized defect density and morphology, they can enhance vortex pinning and improve in-field J_c . At an excessive defect density, however, oxygen disorder, pair breaking, cascade overlap, and current-path disruption suppress T_c and degrade current transport. Therefore, the central problem in radiation-induced defect engineering is to identify the irradiation window in which pinning enhancement exceeds superconducting degradation [12–16].

HTS materials naturally contain numerous crystal imperfections generated during synthesis, epitaxial growth, and oxygenation processes. These intrinsic defects include oxygen vacancies, dislocations, grain boundaries, stacking faults, and secondary non-superconducting phases. Many of these defects already contribute to vortex pinning and therefore define the initial pinning landscape of coated conductors [17–19].

Based on their dimensionality, the defects of HTSs induced by radiation [20] can be categorized into point defects (0D), line defects (1D), planar defects (2D), and volume defects (3D). The most frequently occurring defects in HTS films are shown in Figure 1. The morphology, spatial distribution, and density of these defects are strongly dependent on the irradiation conditions (particle type, energy, fluence, irradiation geometry). The different defect classes have a different effect on the superconducting properties through varying vortex pinning, current transport, and superconducting order parameters [21].

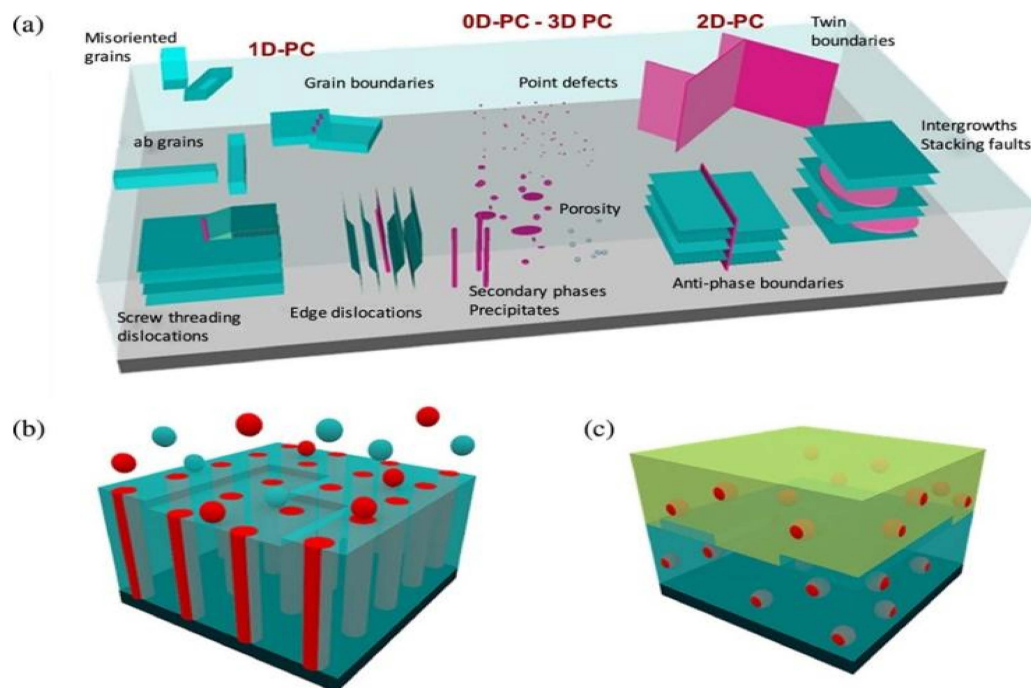


Figure 1. Schematic representation of (a) different defects present in HTS films and nanocomposites. Pink regions represent the nano-scale regions that can act as pinning centers. The dimensionality of the pinning centers (0D, 1D, 2D, or 3D) is also indicated. In (b,c), the growth of nanocomposites are shown with simultaneous and sequential nucleation of secondary phases and the HTS matrix, respectively [19].

2.1. Point Defects and Small Defect Clusters

Point defects constitute the smallest form of irradiation-induced disorder and include oxygen vacancies, Frenkel pairs, interstitial atoms, antisite substitutions, and small substitutional clusters [22]. Such defects are typically generated by electron irradiation, gamma

irradiation, and low- to medium-energy light-ion irradiation. Neutron irradiation can also generate point defects, but fast neutrons usually produce more complex displacement cascades and defect clusters rather than isolated Frenkel pairs alone.

Nicholls et al. [23] showed, using high-resolution X-ray absorption spectroscopy combined with DFT modeling, that He^+ irradiation of REBCO mainly produces oxygen Frenkel pairs in the CuO_2 planes. In contrast, the Cu–O chains are affected primarily by oxygen disorder through O(1) migration rather than by the formation of stable Frenkel pairs. This behavior differs from thermal reduction, where oxygen is preferentially removed from CuO chain sites. The resulting oxygen disorder and c-axis lattice expansion indicate that irradiation-induced oxygen defects are a primary mechanism controlling both vortex pinning and superconducting degradation.

Recent irradiation experiments suggest that the electronic inhomogeneity and local changes in the superconducting gap are also tightly related to oxygen-related point defects in cuprates. Eisterer [24] stated that point defects gradually increase the scattering of quasiparticles and decrease the phase coherence of the superconducting state, especially in highly anisotropic REBCO systems.

A similar mechanism was identified by Murphy (2020) [25] using density functional theory (DFT) calculations for $\text{YBa}_2\text{Cu}_3\text{O}_7$. The energetically favorable defect configurations identified in REBCO included oxygen vacancies at O4 chain sites and Y/Ba antisite defects, which help explain the strong sensitivity of REBCO superconductors to small variations in oxygen stoichiometry. These results emphasize that oxygen disorder is not simply a secondary irradiation effect but rather a primary mechanism controlling superconducting degradation in irradiated cuprates.

Similar oxygen-related disorders have also been reported following thermal neutron irradiation. Neutron irradiation of GdBCO-coated conductors was studied by Unterrainer et al. [26], who found two majorities among the types of defects: isolated point defects and small collision-induced clusters. In molecular dynamics simulations, characteristic Frenkel pairs of O, antisite defects, and defect clusters containing up to several defects with characteristic dimensions close to the coherence length were found. Notably, small defects were substantially more efficient in suppressing T_c than large cascades when normalized to displacement damage.

2.2. Line Defects and Columnar Tracks

A line defect is a one-dimensional pinning center that can create correlated vortex confinement over extended distances [11]. This category includes edge dislocations, screw dislocations, irradiation tracks, and engineered columnar defects [27,28], all of which provide extended spatial confinement of vortices and enhance pinning efficiency under high magnetic fields [29].

Heavy-ion irradiation of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) creates amorphous columnar tracks, which serve as highly effective vortex-pinning centers, as was first demonstrated by Civale et al. (1991) [30]. Such systems are well-described by the Bose-glass model, in which vortices are localized on the defect lines, and the optimum pinning efficiency is found near the matching field B_ϕ [31].

Zhang et al. [32] irradiated YBCO tapes with Au^{5+} ions at an energy of 18 MeV, and found amorphous nanoclusters and defect areas depleted of oxygen in the range 2–5 nm in diameter. There was high local oxygen loss and a reduction in Cu valence state ($\text{Cu}^{2+} \rightarrow \text{Cu}^+$) in irradiated regions, as identified by electron energy-loss spectroscopy. These defects proved to be highly efficient vortex-pinning centers at low irradiation doses; however, excessive irradiation leads to a reduction in T_c and degradation of self-field J_c due to disrupted superconducting connectivity.

The morphology of columnar defects strongly depends on irradiation geometry. Sueyoshi et al. [33] demonstrated that 80 MeV Xe ion irradiation parallel to the c-axis generates segmented columnar defects, whereas tilted irradiation produces continuous tracks near the surface. Segmented tracks suppress vortex sliding and improve isotropic pinning. In contrast, continuous tracks allow vortex kink motion, increasing anisotropy [18].

In addition, patterned irradiation methods can provide further control over defect geometry. Aichner et al. [27] demonstrated that focused He^+ irradiation can be used to create artificial arrays of defect-rich regions in YBCO thin films, producing pronounced vortex-matching effects. An alternative approach is broad-beam irradiation through a stencil mask, which enables the simultaneous fabrication of large-area periodic defect arrays. These two irradiation strategies are schematically compared in Figure 2.

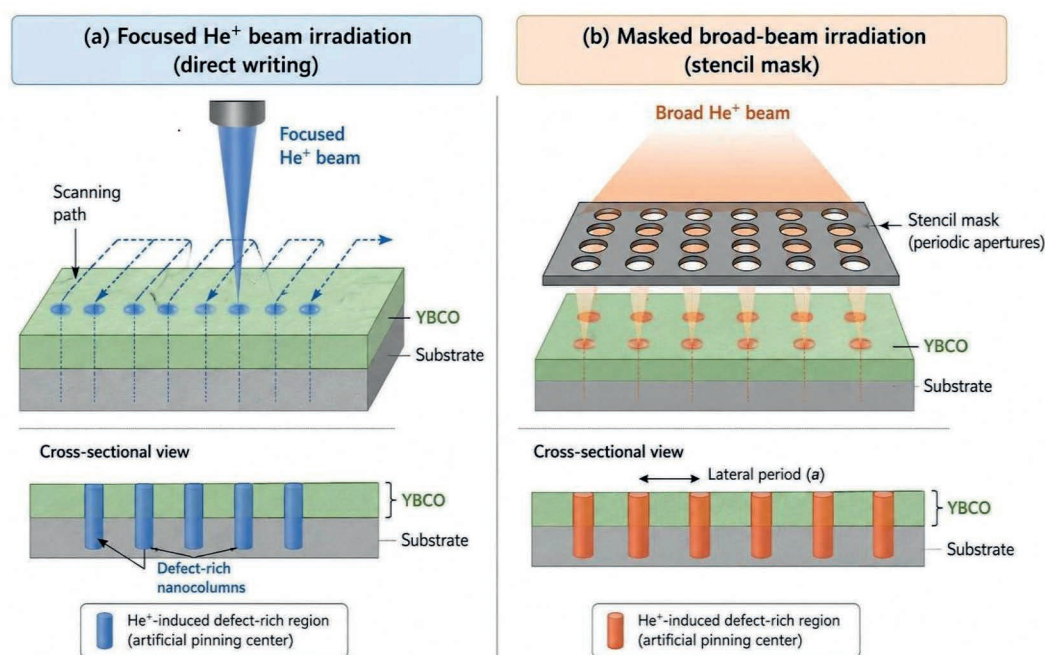


Figure 2. Author-prepared schematic comparison of two approaches for patterned He^+ irradiation of YBCO thin films: (a) direct writing with a focused He^+ beam and (b) broad-beam irradiation through a stencil mask. The schematic illustrates the formation of spatially controlled defect-rich regions that act as artificial vortex-pinning centers. The irradiation approaches are based on the methods discussed in Ref. [27].

In addition to irradiation-induced tracks, self-assembling nanostructures have emerged as an alternative approach to creating correlated pinning centers. McManus-Driscoll et al. [34] demonstrated that BaZrO_3 nanorods formed in YBCO films act as quasi-columnar defects located mainly along the c axis, providing strong vortex pinning under strong magnetic fields. Subsequent studies have shown that the combination of columnar defects with point defects and nanoparticles creates a synergistic pinning effect that suppresses the formation of vortex channels and improves J_c over a wide range of temperatures and magnetic fields. Such hybrid pinning architectures are currently widely used in modern coated conductors for use in strong magnetic field conditions [35,36]. Correlated one-dimensional defects offer vortex confinement over a much longer length scale than point defects and are thus a promising way to further enhance in-field J_c .

Recent dislocation-engineering studies have also shown that correlated pinning structures can be introduced without significant T_c degradation. Han et al. [37] have produced dense dislocation arrays in iron-based superconductors by using an asymmetric stress-field technique to obtain the highest J_c values for high magnetic fields ($44.5 \times 10^5 \text{ A/cm}^2$ at

4.2 K and 10 T) whilst maintaining T_c . The results emphasize the general significance of engineering defects in one dimension for future high-field superconducting technology [38].

Vortex Localization and Bose-Glass Physics

The strong pinning efficiency of columnar defects originates from the reduction in vortex core energy when a vortex overlaps with a non-superconducting or strongly damaged cylindrical region. In this case, part of the normal vortex core is replaced by an already disordered region, lowering the free energy of the vortex configuration. Unlike isolated point defects, columnar defects provide a correlated pinning potential along the film thickness or along the ion-track direction. This suppresses transverse vortex wandering and localizes flux lines over extended distances.

The matching field B_ϕ is a central parameter for describing columnar-defect pinning. It is defined as $B_\phi = n_d \Phi_0$, where n_d is the areal density of columnar defects and Φ_0 is the magnetic flux quantum. Physically, B_ϕ corresponds to the external magnetic field at which the areal density of vortices equals the areal density of columnar defects. Thus, B_ϕ links the irradiation fluence directly to the magnetic-field range in which correlated pinning is most effective. For $B < B_\phi$, the number of available columnar defects exceeds the number of vortices. In this regime, most vortices can occupy individual columnar tracks, so vortex motion is strongly suppressed, vortex creep is reduced, and J_c can increase substantially. For $B \sim B_\phi$, the vortex density approximately matches the defect density, and the strongest matching-related enhancement is often observed. For $B > B_\phi$, the number of vortices exceeds the number of available columnar defects. The additional vortices must then occupy interstitial positions between tracks, and are pinned only indirectly by vortex–vortex interactions and the surrounding defect landscape. These interstitial vortices are more mobile, so the accommodation mechanism changes and the J_c enhancement decreases rapidly above B_ϕ . Therefore, the optimum irradiation fluence for columnar-defect engineering should be selected with respect to the intended operating magnetic-field range rather than by simply maximizing the density of tracks [30,31].

From a statistical–mechanical viewpoint, the Bose-glass phase describes a state in which vortex lines are localized by correlated disorder. The mapping between vortex lines in a three-dimensional superconductor and interacting bosons in imaginary time provides the conceptual basis for this description. Columnar defects act as a time-independent random potential for these bosons, producing localized vortex states, a strongly enhanced tilt modulus, suppressed vortex creep, and vanishing linear resistivity in the ideal glassy limit. However, at high temperatures, high current densities, or defect densities far above the optimum matching condition, vortex hopping, kink formation, and interstitial vortex motion can restore dissipation. This explains why columnar defects can strongly enhance J_c in selected field orientations but do not provide unlimited improvement at all fields and temperatures [30,31].

2.3. Planar and Volume Defects

Planar defects are common in epitaxial HTS films, such as grain boundaries, twin boundaries, stacking faults, and antiphase boundaries [28]. Planar defects strongly affect superconducting transport, depending on crystallographic orientation and defect density. Low-angle grain boundaries (typically 5–7°) are mostly considered as weak correlated pinning centers which locally distort the superconducting order parameter and the vortex energy landscape. High angle boundaries, on the contrary, act as weak links which drastically lower the intergranular current transport and decrease the superconducting connectivity. Thus, the effect of grain boundaries on the superconductor's properties is highly dependent on the misorientation angle, density, and spatial distribution of these

boundaries. In addition, the vortex pinning can also be caused by twin boundaries and antiphase boundaries, which can locally change the superconducting order parameter and generate correlated pinning regions. Therefore, planar defects may either enhance vortex pinning or suppress macroscopic current transport, depending on their crystallographic orientation, density, connectivity, and misorientation angle. In REBCO, low-angle boundaries may contribute to pinning, whereas high-angle grain boundaries often behave as weak links and limit intergranular current flow [29,35].

Volume defects are the largest irradiation-induced defect structures, including precipitates, secondary phases, amorphous nanoclusters, and displacement cascades [39]. Neutron irradiation and high-energy heavy ions are sources of such defects [40,41].

To study the radiation damage formation in YBCO during neutron irradiation, Gray et al. [40] used molecular dynamics simulations. They found that neutron irradiation produces amorphous nanometer-sized clusters with oxygen vacancies preferentially located near the cluster periphery, while fewer vacancies are formed within the CuO_2 planes. These nanoclusters have dimensions on the order of several nanometers and therefore can contribute to vortex pinning, while the extensive cascade overlap eventually reduces superconducting connectivity.

Similarly, Torsello et al. [41] found a dual behavior in YBCO under neutron irradiation relevant to fusion reactors. Displacement cascades comparable to the coherence length initially enhance vortex pinning. However, high fluences (projected dpa (displacements per atom) = 0.52 over 10 years) cause strong suppression of superconductivity. Damage is highly sensitive to temperature (residual defects increase $1.5\times$ from 20 K to 300 K) and neutron energy, highlighting the need for realistic fusion-relevant irradiation conditions when evaluating HTS performance.

Temperature-dependent defect evolution and recovery processes play an important role in the response of HTS materials to irradiation. At higher temperatures, defect migration and recombination may partially anneal irradiation damage, whereas low-temperature irradiation tends to stabilize defect clusters and vacancy-rich regions. This makes defect generation/recovery balancing an important factor in the long term radiation tolerance of the superconducting materials.

These results indicate that the effect of volume defects strongly depends on the type of material and the defect morphology, as well as the intrinsic radiation tolerance of the material. Some of the HTS systems have pinning centers induced by the irradiation, while others have other dominant degradation mechanisms, such as defect accumulation, grain fragmentation, and loss of superconducting coherence [42,43].

Polycrystalline Bi-2223 ceramics are mentioned here only as a comparative counterexample and should not be directly generalized to REBCO-coated conductors. In Bi-2223 ceramics, irradiation-induced degradation is often dominated by weak links, porosity, grain-boundary damage, and intergranular connectivity loss. In contrast, REBCO-coated conductors are highly textured multilayer architectures in which intragrain pinning, artificial pinning centers, strain state, and oxygen disorder play a more central role. Therefore, Bi-2223 data are used only to illustrate material-dependent irradiation responses, not as a direct model for REBCO conductor performance [44]. Conversely, Sueyoshi et al. [45] demonstrated that in NdBCO, spherical defects created by Kr irradiation preserve percolation paths better than continuous Xe-induced columnar tracks, leading to superior high-field J_c despite weaker individual pinning strength.

2.4. Defect Length Scale and Vortex-Pinning Efficiency

The pinning efficiency of radiation-induced defects is strongly governed by their characteristic size relative to the superconducting coherence length. In REBCO, the coherence

length is only a few nanometers, so defects with dimensions in the range of several nanometers can interact effectively with vortex cores. Isolated point defects generally provide weak and nearly isotropic pinning, whereas nanoclusters, displacement cascades, and columnar tracks can generate stronger pinning potentials.

Defect morphology is equally important. Point defects and small clusters primarily provide random pinning, whereas columnar defects act as correlated pinning centers and can strongly enhance in-field J_c when the magnetic field is favorably aligned with the defect direction.

Modern coated conductors often benefit from multi-scale pinning landscapes, where point defects, nanoparticles, dislocations, and correlated defects act simultaneously. Such hybrid landscapes can suppress vortex channeling and broaden the field–temperature range over which high J_c is maintained [12,36,46].

2.5. Thermodynamic and Electronic Mechanisms of Vortex Pinning

Vortex pinning in REBCO-coated conductors originates from spatial variations in the free energy of a vortex line. When a vortex core overlaps with a region where superconductivity is locally weakened or suppressed, the total free energy of the vortex configuration is reduced. This energy reduction produces a pinning force that opposes vortex motion and therefore increases the critical current density J_c . Two limiting pinning mechanisms are commonly distinguished: δT_c pinning and $\delta \ell$ pinning. δT_c pinning arises from local variations in the superconducting transition temperature T_c and condensation energy. It is usually associated with composition fluctuations, oxygen-stoichiometry variations, non-superconducting inclusions, second phases, or locally degraded regions where the superconducting order parameter is suppressed. In irradiated REBCO, oxygen-deficient regions, amorphous clusters, and locally damaged regions can therefore contribute to δT_c -type pinning when they locally reduce T_c or the superconducting condensation energy.

In contrast, $\delta \ell$ pinning originates from spatial variations in the quasiparticle mean free path ℓ . This mechanism is typical of structural disorder, point defects, Frenkel pairs, oxygen vacancies, and small irradiation-induced defect clusters. Electron, proton, helium, and neutron irradiation can introduce such scattering centers, which locally modify quasiparticle scattering and the electronic mean free path. Therefore, point-defect-dominated irradiation damage is often more closely associated with $\delta \ell$ -type pinning, although oxygen disorder and local suppression of superconductivity may also introduce a δT_c contribution [47].

The dominant pinning regime also depends strongly on defect dimensionality. Zero-dimensional point defects and small clusters usually generate random pinning. Individually, such defects are weak, but collectively they can immobilize vortices through statistical interactions with the vortex lattice. In contrast, one-dimensional columnar defects provide correlated pinning because the pinning potential extends along the vortex-line direction. These defects can localize vortices over long distances, suppress transverse vortex wandering, and strongly enhance in-field J_c when the applied magnetic field is aligned with the columnar-defect direction.

2.6. Microscopic Origin of Superconducting Degradation Under Irradiation

The degradation of superconducting properties under irradiation is controlled by several coupled microscopic mechanisms rather than by structural damage alone. In REBCO and other cuprate superconductors, the superconducting state is highly sensitive to the oxygen sublattice, carrier concentration in the CuO_2 planes, and nano-scale electronic homogeneity. Irradiation-induced oxygen vacancies, Frenkel pairs, antisite defects, and small defect clusters can modify charge transfer between Cu-O chains and CuO_2 planes,

thereby changing the local hole concentration and reducing the superconducting order parameter [23–26].

A second degradation channel is quasiparticle scattering. Because cuprate superconductors have a short coherence length and an anisotropic superconducting gap, even nonmagnetic disorder can act as an effective pair-breaking source when it produces strong local scattering or spatial fluctuations of the order parameter. Point defects and oxygen disorder broaden the quasiparticle spectrum, reduce the superfluid density, and weaken phase stiffness. As a result, the local superconducting gap may remain finite in some regions while long-range phase coherence and macroscopic current transport are progressively degraded [48,49].

A third mechanism is connectivity loss. At low and moderate defect densities, nano-scale defects can act as pinning centers if their size is comparable to the vortex core diameter. However, when defect density becomes excessive, overlap between damaged regions disrupts superconducting percolation paths. This effect is especially important in coated conductors with complex architectures, and in polycrystalline materials where grain boundaries and weak links already limit current transport. Therefore, the suppression of T_c and J_c under a high irradiation dose should be understood as the combined consequence of oxygen disorder, pair breaking, reduced phase coherence, and loss of superconducting connectivity [23–26,48,49]. Within the framework of this review, Sections 2.1–2.6 therefore establish the first three links of the analysis: irradiation-induced defect morphology, its contribution to vortex-pinning performance, and the microscopic mechanisms that impose the corresponding degradation penalty.

3. Irradiation Techniques, Damage Mechanisms, and Superconducting Response in HTSs

This section compares the principal irradiation methods used for HTSs and their effects on defect formation and superconducting performance. The discussion focuses primarily on REBCO-coated conductors, with selected studies on other superconducting systems included only where they provide relevant comparative insight [50–53].

3.1. Defect Formation Mechanisms Under Irradiation

Radiation-induced defect formation is primarily controlled by the interaction between energetic particles and the crystal lattice. Depending on particle mass and energy, energy deposition occurs through nuclear stopping (Sn) and electronic stopping (Se), producing distinct defect morphologies ranging from isolated Frenkel pairs to extended collision cascades and amorphous columnar tracks.

Nuclear stopping dominates when energetic particles transfer momentum directly to lattice atoms, producing vacancies, interstitials, Frenkel pairs, and displacement cascades. Electronic stopping dominates when energy is deposited mainly into the electronic subsystem, which can lead to thermal spikes and continuous columnar tracks if the deposited energy exceeds the threshold for local amorphization. Therefore, the same ion species may produce very different defect morphologies depending on its energy, projected range, and stopping regime.

Fluence controls the density and overlap of irradiation-induced defects, whereas irradiation temperature determines the degree of defect recombination, migration, and recovery. Cryogenic irradiation is particularly important for fusion magnets because defects generated at low temperature may be retained more efficiently than defects produced during room-temperature irradiation. Damage is often expressed in displacements per atom, but dpa alone cannot fully describe superconducting degradation because oxygen disorder, defect morphology, strain state, and local connectivity are also critical for J_c and T_c .

3.2. Ion Irradiation: From Medium-Ion Damage to Heavy-Ion Correlated Pinning

Ion irradiation is widely used to introduce artificial pinning centers in HTSs, but the resulting defect morphology depends strongly on ion mass, energy, and stopping regime. For clarity, light ions, such as H and He; medium ions, such as O, Ne, and Ni; and heavy ions, such as Kr, Xe, Au, and Pb should be distinguished. High-energy heavy ions can generate correlated columnar tracks, whereas low-energy medium ions may produce mainly point defects, oxygen disorder, or near-surface damage. Leroux et al. [54] demonstrated that 3.5 MeV oxygen irradiation was able to double the in-field critical current of commercial REBCO tapes within seconds (1 s per 0.8 cm²) which is suitable for industrial reel-to-reel post processing. Selected iron-based superconductor studies are mentioned only for comparison because they demonstrate that extended irradiation defects can enhance vortex pinning in superconductors with different anisotropy and disorder sensitivity. However, the engineering discussion in this review remains centered on REBCO-coated conductors, where oxygen disorder, conductor architecture, strain state, and artificial pinning landscapes control the balance between J_c enhancement and T_c degradation [55,56].

In both REBCO- and iron-based superconductors (IBSs), extended defect cascades or columnar tracks are created in the superconductor by heavy-ion irradiation, which become strong correlated pinning centers, leading to a significant increase in the critical current density J_c . Petrykin et al. [57] showed that 12 MeV Ni³⁺ and 18 MeV Au⁵⁺ irradiations of 2G-HTS tapes (YBCO, GdBCO, (Nd, Eu, Gd) BCO) increased J_c (B, T) by 1.5–1.8 times at 65 K/3 T and 40 K/5 T, with an enhanced effect for heavy rare-earth elements. The TRIM simulations indicated that the scale of defect cascades generated by Ni and Au ions are between 3.5 and 6 nm, which are of the order of the optimal scale of pinning centers. Furthermore, the irradiation time is related to the tape speed of 20–25 m/h, which is industrially feasible. Similar behavior has also been reported for heavy-ion irradiation of iron-based superconductors (BaFe₂As₂ family) (250 MeV Au, 1.2 GeV Pb) of Torsello et al. [58] where the degradation of T_c with dpa follows a scaling law of $E^{1.3}$ due to nuclear energy loss, showing that even beneficial pinning centers cause some pair-breaking.

However, ion irradiation does not always improve superconducting performance. The outcome depends not only on ion mass but also on energy loss regime, projected range, fluence, and the resulting defect morphology. Pęczkowski et al. [59] irradiated GdBCO tapes with 250 keV Ne⁺ ions (see in Figure 3). Although Ne is heavier than He, 250 keV Ne⁺ irradiation does not generate extended columnar tracks. Instead, it produces a high density of oxygen vacancies and point-defect clusters that damage both Cu–O chains and CuO₂ planes. Consequently, the critical current will not increase with these enhancements, and it will even decrease by 33–60% at the fluence of 10¹³ cm^{−2}, followed by exfoliation and blistering at 10¹⁴ cm^{−2}. This contrasting behavior illustrates the necessity of not only a heavy ion, but also of a suitable energy loss regime (high electronic stopping power) to create continuous columnar tracks or correlated cascades instead of homogeneously distributed point defects for successful pinning enhancement. Therefore, if heavy-ion irradiation is used to improve the pinning condition, there is a requirement that the irradiation parameters, namely ion species, energy and fluence, be optimized for the defect size (≈3–6 nm in the case of REBCO) and to minimize the pair-breaking effect.

These results demonstrate that ion irradiation can create effective pinning landscapes in commercial HTSs, although practical scalability depends strongly on particle type, irradiation energy, throughput, penetration depth, and irradiation uniformity.

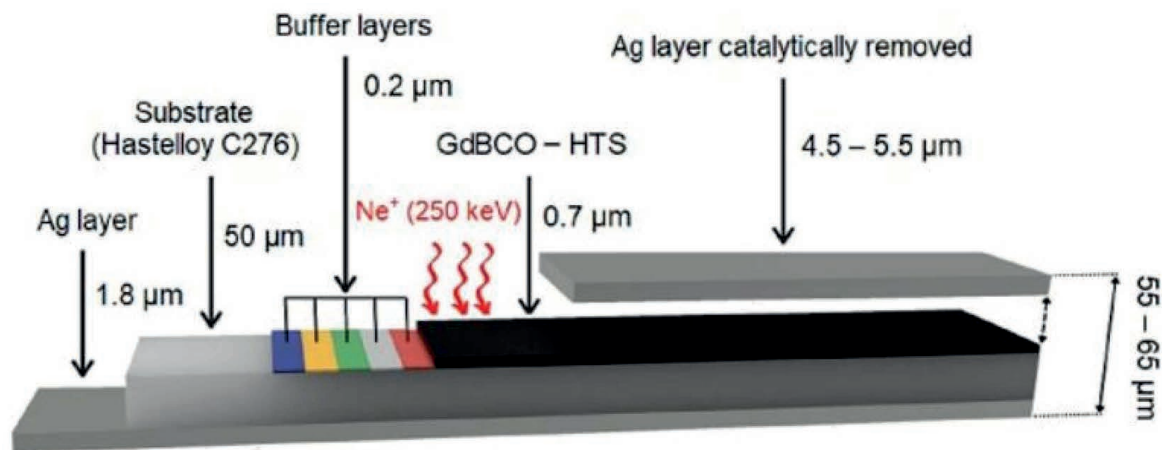


Figure 3. Cross-section of the 2G HTS SF 12050 superconducting tape by SuperPower Inc. The superconducting GdBCO layer was irradiated with Ne^+ ions after removal of the Ag layer. Reproduced from Ref. [59] under the Creative Commons Attribution 4.0 International (CC BY 4.0) license.

3.3. Light-Ion and Neutron Irradiation: Simulating Fusion Environments

Heavy ions are used for pinning optimization whereas light ions and neutrons are employed as key tools to evaluate the radiation hardness of conditions relevant to fusion reactors and space applications. A recent study of 1.2 MeV protons on commercial REBCO tapes over the temperature range 20–300 K showed a degradation of self-field critical current of 1.6 times faster at 20–200 K (cryogenic temperatures) than at 300 K [48]. This finding challenges the common assumption that room-temperature irradiation data can be directly extrapolated to cryogenic operating conditions. These two parameters, superfluid density and degradation, are found to be correlated well, indicating that pair-breaking is the main degradation mechanism [48] instead of just structural damage.

The most straightforward analog to reactor conditions is neutron irradiation, which produces mixed effects. Defects induced by neutrons at lower doses can improve pinning. At higher fluences, however, suppression is the predominant effect. The degradation of T_c per dpa was very similar for both fast neutrons and 2 MeV He^+ ions, which is considered good validation for using He^+ ions as a proxy for neutron damage studies (≈ 0.024 K/mdpa) [49]. There have been recent in-core irradiations, however, that show that at cryogenic temperatures the degradation of T_c and J_c can be increased by as much as $\sim 40\%$ over what was previously estimated from room-temperature studies [46]. In addition, atomic-scale molecular dynamics simulations are now able to supply the requisite information, as new multiphysics models have correctly predicted the threshold displacement energies for oxygen in YBCO, an important parameter for the design of shielding for fusion reactors [60]. The studies reported here demonstrate the effectiveness of light-ion irradiation as a surrogate method to study neutron-induced damage in materials relevant to fusion applications.

3.4. Gamma-Ray and Electron Irradiation

Irradiation with gamma rays and MeV electrons results in mainly homogeneous distributions of point defects, especially oxygen Frenkel pairs. The effect of Co^{60} gamma irradiation leads to a non-monotonic change in J_c , (with the peak around 390–520 kGy, followed by a decrease) while the effect on T_c is almost constant, as seen in REBCO tapes [61]. This indicates that the result is strongly influenced by mechanical influences during irradiation, such as bending. A radius of 0.75 cm (at 77 K) resulted in a 30% decrease in J_c due to strain-induced oxygen vacancies, demonstrating that mechanical stress and radiation damage can have a synergistic effect.

More recent in situ measurements of REBCO-coated conductors during gamma irradiation showed no measurable degradation in critical current up to a total dose of 208 kGy at a dose rate of 86 Gy/min, indicating that commercial tapes with copper/silver layers may show greater radiation resistance than laboratory-fabricated samples [62].

A systematic comparison of electron, gamma-ray, and neutron irradiation in Bi-2223 ceramics showed that neutron irradiation causes the most severe degradation, mainly because it produces stronger collision cascades and damages intergranular connectivity. Additional studies indicate that neutron irradiation can create deeper pinning centers, which may enhance J_c at low temperatures but degrade it at higher temperatures, whereas electron irradiation tends to produce more homogeneous point-defect disorder. Therefore, electron and gamma irradiation are useful platforms for isolating the role of point defects, while neutron irradiation better represents cascade-dominated damage relevant to reactor environments [44,63].

The irradiation response of high-temperature superconductors strongly depends on the type of energetic particle, irradiation energy, fluence, and temperature. These parameters determine whether the dominant damage consists of isolated point defects, oxygen vacancies, small defect clusters, displacement cascades, or extended columnar tracks. To clarify the relationship between irradiation conditions and defect morphologies, Table 1 summarizes the main irradiation methods used for HTS materials and the characteristic defects produced by each approach. Table 2 then compares the corresponding superconducting response, main limitations, and technological relevance of these irradiation strategies. Because relative changes in J_c can be misleading when the initial conductor quality differs between studies, Table 3 reports the peak J_c performance together with the corresponding measurement conditions. Where available in the original publications, absolute J_c or I_c values are reported together with temperature and magnetic field. When only normalized or relative values were reported, this limitation is explicitly indicated. Therefore, the engineering relevance of irradiation treatments is evaluated using both relative enhancement and absolute post-irradiation performance.

Table 1. Irradiation methods and dominant defect morphology in HTSs.

Irradiation Method	Typical Energy/Dose Range	Representative HTS Systems	Dominant Defect Morphology	Key Physical Origin	Key References
Electron irradiation	MeV range; typically $\sim 10^{15}$ – 10^{16} cm $^{-2}$	Cuprates, Bi-2223, iron-based superconductors (comparative example only)	Frenkel pairs, oxygen vacancies, relatively homogeneous point defects	Electronic excitation and displacement of light atoms, especially oxygen	[46,64]
Gamma irradiation	kGy–MGy dose range	REBCO-coated conductors, Bi-based cuprates	Mostly homogeneous point defects; possible radiation-strain-induced defects	Ionization effects, oxygen disorder, and radiation-mechanical strain interaction	[46,62,63]
Proton irradiation	~ 0.1 – 5 MeV; sometimes higher-energy proton irradiation	REBCO/YBCO-coated conductors	Point defects, dislocation loops, small defect clusters, near-surface damage depending on energy	Nuclear stopping, oxygen disorder, and local pair breaking	[16,17,59,65]
He $^+$ / α -particle irradiation	keV–MeV range; typically $\sim 10^{14}$ – 10^{16} cm $^{-2}$	REBCO/YBCO-coated conductors, iron-based superconductors	Oxygen Frenkel pairs, isolated vacancies, small defect clusters	Oxygen-sublattice disorder and neutron-damage surrogate effects	[25,60,66]
Ne $^+$ / medium-ion irradiation	~ 250 keV to tens of MeV	GdBCO- and REBCO-coated conductors	Oxygen depletion, dense point-defect clusters, near-surface damage, possible blistering at high fluence	Cu–O chain disorder, CuO $_2$ -plane damage, and connectivity degradation	[58]

Table 1. *Cont.*

Irradiation Method	Typical Energy/Dose Range	Representative HTS Systems	Dominant Defect Morphology	Key Physical Origin	Key References
O/Ni ion irradiation	~3.5–12 MeV	REBCO/YBCO and 2G HTS tapes	Nanoclusters, collision cascades, oxygen-deficient regions	Nano-scale cascade formation with defect sizes close to the vortex core scale	[53,56,65]
Heavy-ion irradiation: Au, Xe, Kr, Pb	~10 MeV–GeV; typically $\sim 10^{10}$ – 10^{12} cm ⁻²	YBCO, GdBCO, REBCO films/tapes, iron-based superconductors	Columnar tracks, amorphous nanoclusters, correlated defects	High electronic stopping, thermal spikes, and local amorphization	[32,33,35,47,49–51,54–57]
Patterned He ⁺ irradiation	~30 keV focused or masked He ⁺ beam	YBCO thin films	Artificial columnar arrays and defect-rich nanocylinders	Spatially controlled ion-beam damage and artificial pinning-array formation	[29]
Thermal neutron irradiation	Reactor fluence; dpa controlled	GdBCO, REBCO, Bi-based cuprates	Point defects, oxygen Frenkel pairs, small clusters, secondary particle damage	Neutron-induced displacement damage and secondary reactions	[28,46,60,67]
Fast neutron irradiation	Reactor fluence; typically ~0.1–0.5 dpa	REBCO/YBCO-coated conductors	Dense displacement cascades and 1–10 nm defect clusters	Cascade formation, defect accumulation, and oxygen disorder	[4,42,43,59,67]
Mixed/multistep irradiation	Combined particle types or sequential irradiation	REBCO-coated conductors	Hybrid defects: point defects, clusters, cascades, and correlated tracks	Synergistic multi-scale defect formation	[14,39,65]

Table 2. Superconducting response, limitations, and technological relevance of irradiation-induced defects in HTSs.

Irradiation Method	Typical Superconducting Response	Main Limitations	Technological Relevance
Electron irradiation	Weak J _c enhancement or nearly neutral effect at low dose; degradation at high dose	Mainly produces weak random pinning; excessive point-defect disorder can suppress superconductivity	Useful as a model method to isolate the role of homogeneous point defects and oxygen disorder
Gamma irradiation	T _c is often weakly affected; J _c may remain stable, increase, or decrease depending on conductor architecture and mechanical state	Response is strongly affected by tape bending, strain state, stabilizer layers, and oxygen disorder	Relevant for radiation-rich environments where ionizing radiation dominates, but less representative of cascade damage
Proton irradiation	Moderate fluence may enhance J _c ; high fluence suppresses J _c and T _c	Near-surface damage, pair-breaking, oxygen disorder, and stronger degradation under cryogenic irradiation	Useful for controlled damage studies and partial simulation of fusion-relevant displacement damage
He ⁺ / α -particle irradiation	Can improve pinning at moderate fluence; high fluence suppresses T _c and increases degradation	Gas accumulation, oxygen Frenkel pair formation, and defect retention at low temperature	Important as a surrogate for neutron damage and for studying oxygen-sublattice disorder
Ne ⁺ /medium-ion irradiation	Often causes J _c degradation if continuous correlated tracks are not formed	High density of point defects, oxygen depletion, exfoliation, blistering, and current-path disruption at high fluence	Useful for studying harmful near-surface damage and limits of medium-ion irradiation
O/Ni ion irradiation	J _c can increase when defect size is comparable to the vortex core scale; excessive fluence degrades T _c and J _c	Requires precise optimization of ion energy, fluence, and projected range	Promising for scalable post-processing of commercial REBCO tapes if irradiation conditions are optimized

Table 2. Cont.

Irradiation Method	Typical Superconducting Response	Main Limitations	Technological Relevance
Heavy-ion irradiation: Au, Xe, Kr, Pb	Strong in-field J_c enhancement at optimized fluence; T_c suppression at excessive dose	High cost, limited penetration depth, track overlap, irradiation uniformity issues, and poor scalability for long tapes	Excellent for fundamental vortex-pinning studies; industrial implementation remains challenging
Patterned He^+ irradiation	Produces matching effects in I_c/J_c at designed magnetic fields; local T_c suppression may occur	Mainly applicable to thin films and micro/nanostructured devices; limited scalability	Useful for artificial vortex-lattice engineering and superconducting nanodevices
Thermal neutron irradiation	Low/intermediate fluence may enhance pinning; high fluence suppresses T_c and J_c	Insufficient with dpa alone; oxygen disorder and defect morphology strongly affect superconducting degradation	Important for assessing HTS performance in nuclear and fusion-related environments
Fast neutron irradiation	Initial J_c enhancement is possible; high fluence causes rapid degradation of T_c and J_c	Cascade overlap, percolation breakdown, cryogenic defect retention, and superconducting connectivity loss	Most relevant for fusion magnets, accelerator magnets, and radiation-tolerant REBCO qualification
Mixed/multistep irradiation	May broaden the field–temperature range of enhanced J_c if optimized	Complex optimization; difficult to separate contributions from different defect types	Promising for hybrid pinning landscapes combining random and correlated pinning centers

Table 3. Representative absolute and relative J_c/I_c performance after irradiation in REBCO and selected comparative HTS systems.

System	Irradiation Condition	Measurement Conditions	Baseline J_c or I_c	Peak Post-Irradiation J_c or I_c	Relative Change	Defect/Damage Descriptor	Ref.
Commercial YBCO-coated conductor	3.5 MeV O ions; dose $0.3 \times 10^{13} \text{ O cm}^{-2}$	27 K, 6 T, (B c)	Not tabulated as a single value; enhancement factor reported relative to pristine sample	$J_c \sim 3.5 \text{ MA cm}^{-2}$	Nearly doubled at high field	Finely dispersed irradiation-induced clusters, approximately 5 nm	[54]
Commercial YBCO-coated conductor	3.5 MeV O ions; dose $0.3 \times 10^{13} \text{ O cm}^{-2}$	5 K, 6 T, (B c)	Not tabulated as a single value; enhancement factor reported relative to pristine sample	$J_c \sim 8.5 \text{ MA cm}^{-2}$	Strong in-field enhancement	Small irradiation-induced clusters and mixed pinning landscape	[54]
Commercial YBCO-coated conductor	4 MeV proton irradiation; fluence $8 \times 10^{16} \text{ p cm}^{-2}$	27 K, 3 T, (B c)	$I_c = 143.6 \text{ A}$ for the reference bridge	$I_c = 234.5 \text{ A}$ for the irradiated bridge; also reported as $J_c = 7.8 \text{ MA cm}^{-2}$	Approximately $1.6\times$ for the bridge example	Point defects and small clusters, approximately 2–5 nm	[68]
Commercial YBCO-coated conductor	4 MeV proton irradiation; fluence $8 \times 10^{16} \text{ p cm}^{-2}$	27 K, 6 T, (B c)	Approximately 350 A cm^{-1} -width in pristine wire	$I_c = 634 \text{ A cm}^{-1}$ -width; $J_c = 5.3 \text{ MA cm}^{-2}$	Near-doubling at 6 T	Mixed pinning landscape with small irradiation-induced defects	[68]
2G HTS tapes: YBCO, GdBCO, REBCO	12 MeV Ni^{3+} ; 18 MeV Au^{5+} ions	65 K/3 T and 40 K/5 T	Not reported in directly comparable units	Not reported in directly comparable units	J_c increased by approximately $1.5\text{--}1.8\times$	Defect cascades with characteristic size about 3.5–6 nm	[57]

Table 3. Cont.

System	Irradiation Condition	Measurement Conditions	Baseline J_c or I_c	Peak Post-Irradiation J_c or I_c	Relative Change	Defect/Damage Descriptor	Ref.
GdBCO-coated conductor	250 keV Ne^{+} ; fluence 10^{12} – 10^{14} ions cm^{-2}	Field-dependent J_c measurements; 77 K	Absolute baseline J_c not reported in directly comparable form in the summary data	Absolute post-irradiation J_c not reported in directly comparable form	J_c decreased by approximately 33–60%, depending on magnetic field	Oxygen depletion, dense point-defect disorder, structural damage, exfoliation/blistering at high fluence	[59]
Commercial REBCO-coated conductor	1.2 MeV proton irradiation	In situ self-field I_c , 20–300 K	Reported mainly as normalized degradation	Absolute post-irradiation I_c/J_c not reported in directly comparable units	Degradation at 20–200 K approximately $1.6\times$ faster than at 300 K	Cryogenic defect retention and pair-breaking effects	[48]
REBCO/GdBCO-coated conductors	Fast neutron and 2 MeV He^{+} irradiation comparison	T_c degradation per dpa; J_c not always directly comparable	Not applicable for direct J_c comparison	Not applicable for direct J_c comparison	T_c degradation rate approximately $0.024\text{ K mdp}a^{-1}$ in selected studies	Displacement damage; $He^{+}(\{+ \})$ as a surrogate for neutron damage	[49]
REBCO tapes	Co^{60} gamma irradiation; dose around hundreds of kGy	77 K; J_c affected by dose and bending state	Absolute J_c not reported in directly comparable units	Absolute J_c not reported in directly comparable units	Non-monotonic J_c response; maximum reported around 390–520 kGy; bending radius of 0.75 cm caused about 30% J_c decrease	Ionization effects coupled with strain-induced oxygen disorder	[61]
Commercial REBCO-coated conductor bridges	Co^{60} gamma irradiation; 86 Gy min^{-1} ; total dose up to approximately 208–215 kGy	77 K, self-field, transport I_c ; bridge widths 0.5 and 0.25 mm	$I_c = 19.78, 21.06, 20.72, 9.69, 9.76$, and 9.34 A before irradiation, depending on bridge width/sample	$I_c = 19.76, 21.11, 20.68, 9.68, 9.81$, and 9.31 A during irradiation; 19.75 and 21.09 A after additional 208 kGy dose for samples A and B	No measurable degradation within standard error	Commercial tape architecture with Cu/Ag stabilizer layers showed high gamma tolerance	[62]

The absolute J_c and I_c values summarized in Table 3 should be compared with caution because the cited studies use different conductor architectures, superconducting-layer thicknesses, bridge widths, electric-field criteria, magnetic-field orientations, irradiation temperatures, and measurement temperatures. Nevertheless, reporting absolute post-irradiation performance together with relative changes provides a more realistic assessment of engineering relevance than percentage enhancement alone. Where absolute values were not reported in directly comparable units in the original publications, this limitation is explicitly indicated rather than estimated. Thus, Table 3 is used not only as a data summary but also as a critical benchmarking tool. It highlights that a large relative increase in J_c does not necessarily imply superior engineering performance unless the absolute post-irradiation J_c/I_c , measurement temperature, magnetic field, and baseline conductor quality are considered together. Because the literature has reported J_c under different temperatures, magnetic fields, field orientations, conductor architectures, and measurement criteria, the values in Table 3 should not be interpreted as a formal meta-analysis. Instead, they provide representative quantitative benchmarks for identifying irradiation windows in which vortex-pinning enhancement dominates over superconducting degradation. A robust comparison requires normalization by J_c/J_{c0} , ΔT_c , irradiation temperature, defect size, and damage morphology rather than by fluence or dpa alone [32,48,49,54,57,59–62].

3.5. Critical Comparison of Irradiation Strategies

Using the defect–performance–degradation–reliability framework, the following comparison evaluates each irradiation strategy not only by the defects it produces and the resulting J_c response, but also by the associated degradation mechanisms and implica-

tions for conductor-level use. Although the irradiation strategies summarized in Tables 1 and 2 can generate artificial pinning centers in high-temperature superconductors, their effectiveness cannot be evaluated solely by the amount of introduced disorder or by the nominal irradiation fluence. The superconducting response is controlled by a more complex relationship between particle type, energy-loss mechanism, defect morphology, irradiation temperature, and the initial microstructure of the conductor. Therefore, irradiation should not be considered a universally beneficial treatment, but rather a defect-engineering tool with a narrow optimum window.

A direct comparison of individual studies shows that nominally similar irradiation strategies can produce opposite superconducting responses, because the relevant control parameter is not particle mass or fluence alone but the defect morphology actually generated within the superconducting layer. Leroux et al. [54] reported nearly a two-fold enhancement of in-field J_c after 3.5 MeV O ion irradiation of commercial YBCO-coated conductors, while Petrykin et al. [57] obtained a 1.5–1.8-fold J_c enhancement using 12 MeV Ni^{3+} and 18 MeV Au^{5+} irradiation. In both cases, the beneficial response was associated with nano-scale defect clusters or cascades with characteristic dimensions of approximately 3.5–6 nm, comparable to the relevant vortex core length scale. In contrast, Pęczkowski et al. [59] observed a 33–60% reduction in J_c after 250 keV Ne^+ irradiation of GdBCO tapes, followed by exfoliation and blistering at higher fluence. This apparent contradiction cannot be explained by ion mass alone, as although Ne is heavier than O, the lower ion energy and different stopping regime produced dense near-surface point-defect disorder and oxygen depletion rather than an optimized distribution of nano-scale pinning defects. Taken together, these studies indicate that the stopping mechanism, projected range, and resulting defect morphology are more predictive of the superconducting response than the simple classification of ions as light, medium, or heavy.

A second clear discrepancy is found among gamma-irradiation studies. One study reported a non-monotonic J_c response, with a maximum at approximately 390–520 kGy, while mechanical bending to a radius of 0.75 cm produced an approximately 30% decrease in J_c [61]. In contrast, in situ measurements of commercial REBCO-coated conductor bridges showed no measurable I_c degradation up to approximately 208–215 kGy [62]. These results should not be interpreted as evidence that one study demonstrates intrinsic gamma sensitivity whereas the other demonstrates intrinsic gamma immunity. The irradiation dose range, conductor architecture, stabilizer configuration, mechanical boundary conditions, and measurement protocol were different. In particular, the strong effect of bending in [61] indicates that irradiation-induced oxygen disorder can be amplified by mechanical strain, whereas the commercial Cu/Ag-stabilized architecture examined in [62] remained electrically stable within the investigated dose range. Thus, gamma-radiation tolerance is not a universal material constant but depends strongly on conductor architecture and mechanical state.

Irradiation temperature provides another explanation for apparently conflicting estimates of radiation tolerance. Room-temperature ex situ irradiation studies generally allow at least partial defect migration and recombination before superconducting properties are evaluated. In contrast, the 1.2 MeV proton-irradiation study discussed in [48] showed that critical current degradation at 20–200 K was approximately 1.6 times faster than at 300 K. More generally, recent cryogenic irradiation studies indicate that low-temperature conditions can increase effective damage retention compared with conventional room-temperature irradiation protocols. Although proton and neutron irradiation generate different primary damage spectra, both observations point to the same physical interpretation: suppressed defect recovery and enhanced retention of oxygen-related disorder at low temperatures increase the effective damage experienced by the superconducting

state. Therefore, part of the disagreement between earlier room-temperature studies and recent cryogenic measurements reflects different defect-retention conditions rather than fundamentally inconsistent irradiation physics.

Even among extended defects, stronger individual pinning does not necessarily produce superior macroscopic current transport. Sueyoshi et al. [45] found that spherical defects produced by Kr irradiation in NdBCO could preserve superconducting percolation paths more effectively than continuous Xe-induced columnar tracks, resulting in superior high-field J_c despite the potentially stronger correlated pinning associated with extended tracks. This comparison qualifies the common assumption that columnar defects are universally the optimum irradiation-induced pinning centers. In a real conductor, the benefit of a high local pinning energy can be offset by excessive suppression of the superconducting order parameter, disruption of current paths, or the formation of unfavorable vortex-motion channels. Consequently, the optimum defect structure must be evaluated at the level of macroscopic J_c and connectivity rather than from defect dimensionality or individual pinning strength alone.

These comparisons demonstrate that the apparently conflicting results in the irradiation literature are not random inconsistencies. In most cases, they can be traced to differences in defect morphology, damage-depth profile, irradiation temperature, pre-existing pinning landscape, conductor architecture, mechanical state, and measurement conditions. Accordingly, irradiation dose or particle type alone cannot provide a universal predictor of superconducting performance. A physically meaningful comparison requires simultaneous consideration of the defect structure produced in the superconducting layer and of the mechanisms by which that structure affects vortex pinning, oxygen ordering, pair breaking, and current-path connectivity.

From an application perspective, irradiation-induced defect engineering must also be evaluated differently for laboratory films, bulk ceramics, and commercial coated conductors. Thin films and single crystals are useful for identifying fundamental pinning mechanisms, but they do not fully reproduce the architecture of coated conductors, where the substrate, buffer layers, stabilizer, residual strain, oxygenation state, and pre-existing artificial pinning centers strongly influence the final response. Similarly, Bi-based cuprates and polycrystalline ceramics often show stronger degradation because their performance is more limited by intergranular connectivity, porosity, and weak-link behavior. This explains why irradiation may enhance J_c in optimized REBCO conductors but degrade superconducting properties in Bi-2223 bulk samples.

Overall, the literature indicates that irradiation-induced defect engineering is most effective when it is integrated with the pre-existing pinning landscape of the conductor rather than applied as an independent post-treatment. Future optimization should therefore focus on hybrid pinning architectures combining intrinsic defects, chemically introduced nanoparticles, dislocations, and irradiation-induced defects. Such an approach may broaden the field–temperature range of high J_c while minimizing T_c suppression. However, before irradiation can be considered a practical processing route for industrial HTSs, further work is required on scalability, reproducibility, cryogenic damage retention, radiation–strain synergy, and predictive models linking atomic defect production to macroscopic superconducting performance.

From the reviewed evidence, irradiation-induced defect engineering for commercial REBCO-coated conductors should be evaluated using a practical decision sequence. First, the selected particle and energy must generate defects with dimensions comparable to the vortex core scale. Second, the projected range must overlap the superconducting REBCO layer without causing excessive damage to the stabilizer, buffer, or substrate layers. Third, the defect density should correspond to the intended operating magnetic-field range rather

than simply maximize irradiation fluence. Fourth, oxygen disorder, pair breaking, and current-path degradation must remain below the threshold at which T_c and J_c suppression outweigh pinning enhancement. Finally, the process must be uniform, reproducible, and compatible with long-length coated conductors. Only when these conditions are satisfied can irradiation be considered technologically relevant rather than only scientifically useful.

Figure 4 summarizes the central concept of this review: irradiation-induced improvement and degradation are not separate phenomena but competing outcomes of the same defect-generation process. The particle type, energy-loss mechanism, fluence, irradiation temperature, and geometry determine the resulting defect morphology. This morphology then controls the balance between vortex-pinning enhancement, oxygen disorder, pair breaking, and current-path degradation. Therefore, reliable HTS design for fusion, accelerator, and space applications requires simultaneous optimization of pinning efficiency, oxygen stability, superconducting connectivity, and mechanical robustness.

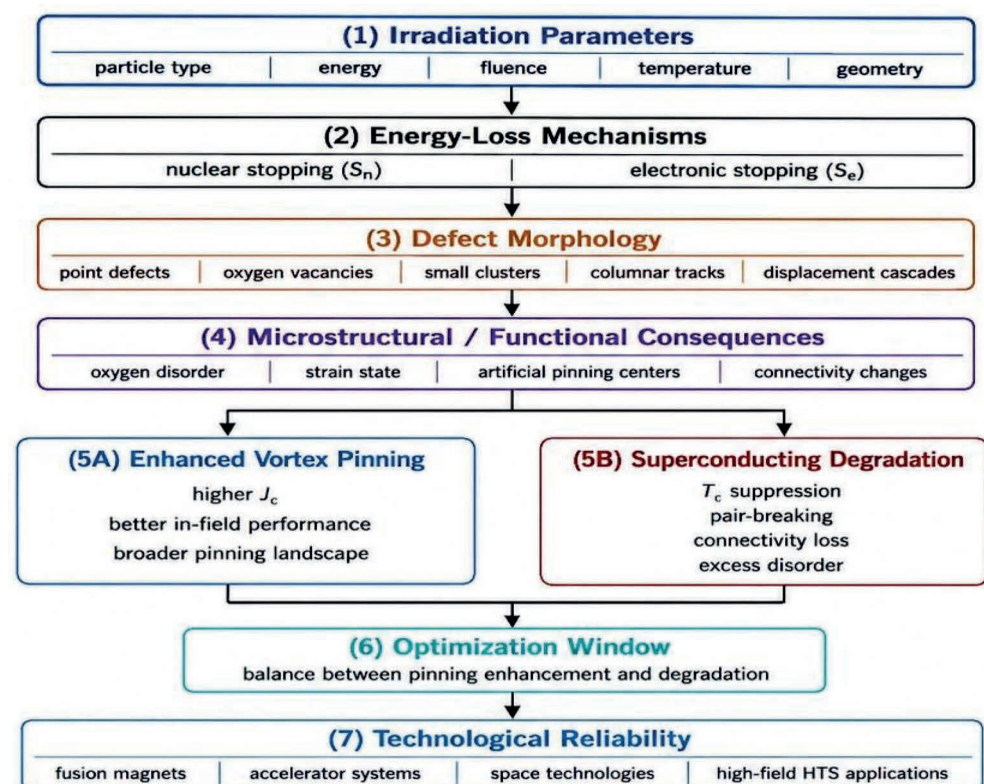


Figure 4. Conceptual framework linking irradiation conditions, defect morphology, vortex-pinning responses, superconducting degradation, and technological reliability of REBCO high-temperature superconductors (author-prepared conceptual scheme).

This author-prepared conceptual scheme represents the main synthesis of the review. It reorganizes irradiation-induced defect engineering as a coupled defect–performance–degradation–reliability problem rather than as a simple strategy for increasing the density of pinning centers. In this framework, the practical value of irradiation is determined not only by the creation of additional vortex-pinning defects but also by the preservation of oxygen ordering, superconducting connectivity, mechanical robustness, and long-length conductor reliability.

3.6. Theoretical and Computational Approaches to Irradiation Effects in HTSs

A complete description of irradiation effects in HTSs requires a multi-scale theoretical framework because the relevant processes extend from atomic defect production to

macroscopic vortex dynamics. No single model can simultaneously describe displacement cascades, oxygen disorder, electronic pair breaking, vortex pinning, and engineering-scale current transport. Therefore, different theoretical approaches provide complementary information.

The theoretical approaches summarized in Table 4 are complementary, but they address different physical questions and should not be treated as interchangeable. DFT and molecular dynamics both operate at the atomic scale, but their roles are fundamentally different. DFT is better suited to determining defect formation energies, local bonding changes, oxygen-vacancy stability, and the electronic consequences of specific defect configurations. However, its limited system size and accessible time scale prevent it from describing realistic irradiation cascades. Molecular dynamics, in contrast, can simulate collision cascades, threshold displacement events, defect clustering, and temperature-dependent defect evolution in much larger atomic systems, but it does not directly predict superconducting quantities, such as T_c , the local gap, or J_c . Thus, DFT is most useful for identifying which defects are energetically and electronically important, whereas molecular dynamics is more appropriate for determining how those defects are actually generated and evolve under irradiation.

Table 4. Theoretical and computational methods to irradiation effects in HTSs.

Method	Main Length Scale	What It Describes Well	Main Limitations	Relevance to Irradiated HTSs
Bogoliubov-de Gennes theory	Atomic to nano scale electronic structure	Spatially varying order parameter, local gap suppression, quasiparticle states, and disorder-induced inhomogeneity	Computationally expensive; limited system size; usually mean-field	Useful for oxygen disorder, pair breaking, and local superconducting degradation
Ginzburg–Landau theory	Mesoscopic scale	Vortex core interaction with defects, pinning energy, and order-parameter suppression near defects	Phenomenological; most rigorous near T_c ; parameters must be fitted	Useful for comparing defect size with coherence length and estimating pinning strength
Time-dependent Ginzburg–Landau simulations	Mesoscopic vortex dynamics	Vortex motion, depinning, flux flow, J_c , and artificial pinning arrays	Phenomenological dynamics; difficult at very low temperatures for cuprates	Useful for modeling $J_c(B, \theta, T)$ in defect-engineered conductors
Molecular dynamics	Atomic collision scale	Displacement cascades, Frenkel pairs, defect clustering, and threshold displacement energies	Does not directly calculate superconducting properties	Essential for linking particle energy and irradiation temperature to defect morphology
Monte Carlo methods	Statistical vortex/disorder scale	Vortex-glass and Bose-glass behavior, thermal activation, and disorder statistics	Requires simplified Hamiltonians; parameters may be non-unique	Useful for vortex localization, creep, and collective pinning in disordered landscapes
Density functional theory	Atomic/electronic scale	Defect formation energies, oxygen vacancies, antisite defects, local bonding, and electronic structure	Small supercells; usually ground-state; cannot directly predict engineering J_c	Useful for identifying stable irradiation-induced defects and their electronic consequences
SRIM/TRIM and damage simulations	Ion-transport scale	Stopping power, projected range, damage profile, and approximate vacancy production	Does not capture complex defect recovery or superconductivity	Useful for selecting ion species, energy, and penetration depth before irradiation

A similar distinction applies to BdG, GL, and TDGL approaches. BdG theory provides the most microscopic description of the superconducting response among these methods because it can resolve spatial variations in the superconducting order parameter, quasiparticle states, and local gap suppression around irradiation-induced disorder. Its main limitation is computational cost, which restricts simulations to relatively small systems. GL theory is computationally less demanding and is therefore more suitable for describing vortex–defect interactions on the mesoscopic scale, including the dependence of pinning energy on defect size, geometry, and coherence length. However, conventional GL theory is primarily an equilibrium framework and does not directly describe current-driven vortex motion. TDGL extends this approach to nonequilibrium vortex dynamics and is therefore better suited to calculating depinning, flux flow, and the influence of complex defect landscapes on J_c . Consequently, BdG is most appropriate for microscopic superconducting degradation, GL for equilibrium pinning energetics, and TDGL for dynamic vortex transport.

Monte Carlo methods address a different level of the problem. Unlike TDGL, which follows the time-dependent evolution of the superconducting order parameter and vortices under an applied drive, Monte Carlo simulations are particularly useful for studying statistical properties of vortex matter, disorder-driven phase transitions, thermal activation, and glassy states such as Bose glass. Their predictive capability depends strongly on the choice of the effective Hamiltonian and interaction parameters, and they do not directly describe irradiation-induced atomic defect production. Nevertheless, they provide information on collective vortex behavior that is difficult to obtain from atomistic or deterministic continuum methods.

The principal limitation of all these approaches is that none of them alone can predict the complete sequence from irradiation parameters to conductor-level performance. A realistic multiscale framework should therefore connect the methods sequentially. SRIM/TRIM or related transport calculations can first estimate stopping power, projected range, and the initial damage profile. Molecular dynamics can then determine cascade morphology and defect retention, while DFT can evaluate the stability and electronic consequences of the dominant defect configurations. BdG calculations can describe local suppression of superconductivity around these defects, whereas GL or TDGL models can translate the resulting defect landscape into vortex pinning, depinning, and J_c behavior. Monte Carlo methods can complement this framework by treating collective vortex statistics, thermal activation, and glassy phases. The major unresolved challenge is therefore not the lack of individual theoretical tools but the absence of a validated multiscale coupling between atomic defect production, superconducting order-parameter suppression, vortex dynamics, and macroscopic T_c and J_c degradation [25,40,41,60].

Spatially Correlated Disorder in the Superconducting Potential

Spatially correlated disorder and correlated vortex pinning are related but physically distinct concepts. In correlated pinning, the term “correlated” refers primarily to the geometry of the pinning centers: columnar tracks, planar defects, or aligned defect structures provide an extended pinning potential along a preferred spatial direction and can therefore localize vortices over long distances. Spatially correlated disorder, in contrast, refers to correlations in the disorder potential itself. In this case, the local disorder strength is not statistically independent from point to point but varies over a finite correlation length. The resulting disorder landscape may therefore contain extended regions with similar local potential, scattering strength, carrier concentration, or superconducting properties, even in the absence of geometrically well-defined columnar pinning centers.

The distinction is important because the superconducting response depends not only on the amplitude and concentration of disorder but also on its spatial correlation function

and characteristic correlation length. For uncorrelated point disorder, fluctuations occur on short length scales and primarily enhance quasiparticle scattering and local pair breaking. However, when disorder becomes spatially correlated over a finite length scale, neighboring regions experience related perturbations. Depending on the correlation length relative to the coherence length and other superconducting length scales, this can modify the localization of electronic states, the spatial distribution of the superconducting order parameter, phase coherence, and ultimately T_c . Thus, two systems with the same nominal disorder strength may exhibit different superconducting responses if the spatial organization of that disorder is different [69].

This concept is directly relevant to irradiation-induced disorder because real radiation damage is rarely spatially uncorrelated. Point defects may initially be generated as isolated displacement events, but collision cascades, oxygen-deficient regions, defect clusters, and local strain fields introduce spatial correlations into the disorder potential. In such cases, the resulting superconducting landscape cannot be described solely by defect density. The correlation length of the disorder, the degree of overlap between damaged regions, and the spatial variation in the local superconducting properties may become equally important. For example, a compact defect cluster may produce a correlated region of suppressed order parameter, whereas a spatially dispersed population of isolated point defects with the same total number of displaced atoms may generate a qualitatively different electronic and superconducting response.

The connection with correlated pinning therefore arises through the way spatially organized disorder modifies both the superconducting condensate and the vortex-energy landscape. A columnar defect is a clear example of a geometrically correlated pinning center, but the surrounding irradiation-induced disorder may also possess spatial correlations in local composition, oxygen occupancy, strain, or superconducting order-parameter suppression. These effects should not be treated as identical. Geometrically correlated defects primarily influence vortex localization and anisotropic pinning, whereas spatially correlated disorder can directly modify electronic localization, pairing inhomogeneity, and superconducting coherence. In irradiated HTSs, the two mechanisms may coexist and interact.

From a theoretical perspective, spatially correlated disorder is commonly introduced through a disorder potential characterized not only by its variance but also by a finite spatial correlation function. The correlation length then becomes an additional control parameter, alongside disorder strength. Microscopic approaches such as BdG theory can be used to examine how such a correlated potential modifies the local order parameter and quasiparticle states, while mesoscopic GL or TDGL models can determine how the resulting spatial variations in superconducting properties affect vortex pinning and dynamics. Establishing a quantitative connection between these two levels remains an important open problem for irradiation-induced defect engineering.

Accordingly, future models of irradiated HTSs should distinguish among three related but non-equivalent forms of disorder: uncorrelated point disorder, spatially correlated disorder in the superconducting potential, and geometrically correlated vortex-pinning centers. A unified description should determine how the characteristic spatial scale of disorder influences both microscopic superconducting degradation and the mesoscopic pinning landscape. This distinction is particularly important for irradiation studies, where defect cascades and clustered oxygen disorder may simultaneously modify the electronic structure and generate spatially extended regions capable of interacting with vortices [69].

4. Technological Applications, Future Perspectives, and Research Needs of Irradiated HTSs

The final element of the framework is conductor-level reliability, which determines whether irradiation-induced performance gains remain technologically meaningful under realistic operating conditions. From an engineering perspective, the central question is not whether irradiation can enhance J_c under selected laboratory conditions but whether the resulting conductor can retain sufficient superconducting performance after long-term exposure to radiation, magnetic field, mechanical stress, and thermal cycling [64–66].

For fusion magnets, the main unresolved issue is not only neutron fluence tolerance but the coupled influence of cryogenic temperature, high magnetic field, mechanical strain, stabilizer architecture, and oxygen disorder. Therefore, future qualification protocols for REBCO conductors should include simultaneous radiation–field–strain testing rather than isolated irradiation experiments performed only at room temperature.

In practical HTS systems, irradiation-induced modifications are important for systems with high magnetic fields, high radiation intensities, long operating times, such as compact fusion reactors, accelerator magnets, space technologies, and advanced electrical power systems [2,67,70–75].

4.1. Fusion, Space, and High-Field Magnet Applications

The development of radiation-tolerant REBCO-coated conductors (CCs) is critical for compact fusion reactors, such as the UK's Spherical Tokamak for Energy Production (STEP) and the US's Affordable Robust Compact (ARC) reactor concept, where superconducting magnets must withstand intense neutron irradiation while generating high magnetic fields. REBCO CCs have been chosen as the main current carrier for most magnet systems for STEP, but the energy particle environment is expected to reduce superconducting performance during the lifetime of the reactor [76]. First-of-a-kind in situ measurements of REBCO CCs during cryogenic neutron irradiation (40 K) has shown that the J_c degrades linearly from the onset of irradiation, with degradation starting at several orders of magnitude lower than previously thought critical fluences, implying that the magnet service life could be significantly reduced from current estimates [77].

In space applications, REBCO CCs are promising for next-generation superconducting technologies that are to be used in photon- and particle-rich environments, such as satellites, deep space missions, and particle detection instruments that will be exposed to galactic cosmic rays (GCRs) and solar energetic particles (SEPs). Photon-induced degradation, in the low-energy, hard X-ray regime typically encountered in space, is much less studied but crucially important for space systems to operate reliably for extended periods [78]. Furthermore, high-field accelerator magnets will need HTSs that can withstand strong radiation fields, e.g., those intended for muon source solenoids and the Future Circular Collider (FCC); the lifetime of such accelerator magnets could be a “technological showstopper” if radiation damage is not successfully managed [79–81].

4.2. Future Perspectives and Challenges

Radiation damage remains one of the major unresolved challenges for REBCO conductors in fusion magnets, particularly because defect production, retention, and recovery are strongly temperature dependent. Comparisons of proton degradation rate to the results of previous experiments have revealed degradation rates that are about 1.6 times faster at cryogenic temperatures than at room temperature, suggesting that the radiation hardness of REBCO might have been overestimated in a fusion environment [48]. Moreover, the first in situ neutron-irradiation experiments conducted at 40 K showed that J_c is measurably reduced at fluences well below the values predicted by conventional ex situ experiments,

meaning that the defect retention in cryogenic conditions and disorder of oxygen may have a significant impact on the magnet lifetime. These results emphasize the need for irradiation campaigns at realistic operating temperatures and neutron spectra for fusion [77,82].

The degradation pathway of gas production and neutron-induced transmutation effects in fusion-grade REBCO conductors is another new pathway in addition to the degradation pathway associated with displacement damage. The average of 50 appm (atomic parts per million) of helium in the superconducting layer during a reactor lifetime, as predicted by recent simulations and verified by helium implantation experiments, results in lattice swelling, microstructural modification, and degradation of the superconducting performance [83]. Such helium build-up has been correlated with losses of up to ~1 K in (T_c) and ~32% in (J_c) under reactor relevant conditions, which has the potential to affect the long-term reliability of the magnets. At the same time, neutron irradiation can cause transmutations of rare earth elements like Gd and Eu, resulting in further electronic structure changes in the material in addition to displacement damage [84]. However, the quantitative relationships between gas accumulation, bubble evolution, transmutation chemistry, and (J_c) degradation are not well-understood and need to be systematically investigated.

Synergistic multi-field effects represent another important challenge for the reliable application of REBCO-coated conductors in fusion-relevant environments. In the tokamak environment, REBCO-coated conductors are exposed to neutron irradiation, high magnetic field (up to ~17 T), mechanical stress and thermal cycling, giving rise to complex degradation processes not studied when considering only one of these factors. Recently, experimental study has demonstrated that applied tensile strain during proton irradiation can significantly promote (J_c) degradation due to the reduction in the formation energy of oxygen vacancies, while nanodoping with BaHfO₃ (BHO) can introduce partial compressive strain fields to mitigate the degeneration of performance [85]. Further, irradiation experiments in high magnetic fields reveal that defect-assisted vortex pinning and connectivity degradation compete in a highly field- and defect-landscape-dependent manner [10].

4.3. Open Issues and Further Research Needs

The practical limits of irradiation-induced defect engineering in commercial REBCO-coated conductors should be clearly recognized. Irradiation treatments that are effective in thin films, single crystals, or short laboratory samples are not automatically transferable to long-length coated conductors. The ion range must be compatible with the REBCO layer's thickness, and irradiation must not introduce excessive damage into the stabilizer, buffer, or substrate architecture. The optimum fluence is also narrow, as insufficient fluence produces weak pinning enhancement, while excessive fluence causes oxygen disorder, defect overlap, pair breaking, T_c suppression, and current-path degradation. In addition, irradiation-induced modifications must remain stable under cryogenic operation, high magnetic field, mechanical strain, and thermal cycling. Therefore, irradiation-induced defect engineering is currently most mature as a fundamental and targeted optimization tool, whereas broad industrial deployment requires further progress to qualify scalability, uniformity, cost, and reliability.

Several pathways will need to be pursued to meet the challenges listed above. First, additional in situ cryogenic irradiation facilities should be developed and made accessible to the superconductivity community [86]. Very few facilities exist in the world that can test the response of tapes from 20 K to 300 K, and the cryogenic neutron-irradiation facility is under development at MIT. The experiments on the in situ irradiation, high magnetic field, and mechanical loading have been scarce so far. Second, the predictive modeling is still incomplete, as it remains unclear whether displacements per atom alone can serve

as a sufficient damage metric for HTSs or if other more complex damage parameters are needed, because superconducting degradation is also governed by oxygen disorder, defect morphology, strain state, and current-path connectivity. Third, no scalable industrial methods to prepare long-length coated conductors with irradiation have been developed; experiments have been carried out using only small laboratory samples, not kilometer-scale commercial tapes. Fourth, the synergistic effects of simultaneous irradiation, high magnetic field, and mechanical stress have not been explored with much attention, and should be given a high priority. Finally, as emphasized in recent roadmaps for irradiation effects in HTSs, predictive engineering approaches for radiation-tolerant REBCO magnets require closer coupling between irradiation experiments, atomistic calculations, and macroscopic superconducting models.

Future studies should also report irradiation conditions and superconducting performance using standardized descriptors, including particle type, energy spectrum, fluence, estimated dpa, irradiation temperature, measurement temperature, magnetic-field orientation, initial conductor architecture, T_c , self-field J_c , in-field J_c , and post-irradiation microstructural evidence. Such reporting standards would make it easier to compare results between different laboratories and to develop predictive models for HTS verification.

5. Conclusions

Radiation-induced defect engineering provides a powerful but intrinsically competing route for modifying the performance of high-temperature superconductors. At an optimized fluence, irradiation-induced defects can act as artificial pinning centers and enhance the critical current density, particularly under a magnetic field. However, excessive disorder suppresses the superconducting transition temperature, disrupts oxygen ordering, enhances quasiparticle scattering, and degrades current transport.

The efficiency of irradiation depends not only on the total damage level but also on defect morphology, spatial distribution, irradiation temperature, conductor architecture, and the intrinsic anisotropy of the superconducting material. Point defects and small clusters mainly provide random pinning, whereas columnar tracks and extended cascades can produce strong correlated pinning. In REBCO-coated conductors, the optimum defect size is typically comparable to the nanometer-scale coherence length, making precise control of irradiation conditions essential.

For technological applications, especially fusion magnets, accelerator magnets, and space systems, radiation tolerance must be evaluated under realistic operating conditions. Room-temperature *ex situ* irradiation data are insufficient for predicting long-term performance in cryogenic, high-field, and mechanically stressed environments. Future work should prioritize cryogenic *in situ* irradiation experiments, coupled irradiation–strain–field studies, and predictive multiscale models that connect atomic defect production with macroscopic J_c and T_c degradation.

The key conclusion of this review is that radiation-induced defect engineering in REBCO is not a simple dose-dependent optimization problem. The same nominal dpa level may produce different superconducting outcomes depending on defect morphology, oxygen disorder, strain state, and current-path connectivity. Therefore, future HTS design should focus on controlled multiscale defect architectures that enhance vortex pinning while preserving T_c , oxygen ordering, superconducting connectivity, and mechanical reliability under realistic cryogenic radiation environments.

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Abbreviations

The following abbreviations are used in this manuscript:

REBCO	Rare-Earth Barium Copper Oxide
HTS	High-Temperature Superconductor
RDE	Radiation-Induced Defect Engineering
MLRM	Machine-Learning-Assisted Radiation Modeling
APC	Artificial Pinning Center
DFT	Density Functional Theory
IBS	Iron-Based Superconductor
CC	Coated Conductor
STEP	Spherical Tokamak for Energy Production
GCR	Galactic Cosmic Ray
SEP	Solar Energetic Particle
FCC	Future Circular Collider

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