Nuclear Engineering and Technology 54 (2022) 2586–2591

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Deuterium ion irradiation impact on the current-carrying capacity of DI-BSCCO superconducting tape

M. Rajput [a, *], H.L. Swami [a], R. Kumar [a], A. Bano [a], S. Vala [a, b], M. Abhangi [a, b], Upendra Prasad [a], Rajesh Kumar [a, b], R. Srinivasan [a, b]

[a] Institute for Plasma Research, Gandhinagar, 382428, India
[b] Homi Bhabha National Institute, Anushaktinagar, 400094, India

A R T I C L E I N F O

Article history:
Received 14 December 2021
Received in revised form
1 February 2022
Accepted 7 February 2022
Available online 9 February 2022

Keywords:
High-temperature superconductors
Ion and neutron irradiation
Ion transport simulations
DI-BSCCO

A B S T R A C T

In the present work, we have irradiated the DI-BSCCO superconducting tapes with the 100 keV deuterium ions to investigate the effect of ion irradiation on their critical current (Ic). The damage simulations are carried out using the binary collision approximation method to get the spatial distribution and depth profile of the damage events in the high temperature superconducting (HTS) tape. The point defects are formed near the surface of the HTS tape. These point defects change the vortex profile in the superconducting tape. Due to the long-range interaction of vortices with each other, the Ic of the tape degrades at the 77 K and self magnetic field. The radiation dose of 2.90 MGy degrades the 44% critical current of the tape. The results of the displacement per atom (dpa) and dose deposited by the deuterium ions are used to fit an empirical relation for predicting the degradation of the Ic of the tape. We include the dpa, dose and columnar defect terms produced by the incident particles in the empirical relation. The fitted empirical relation predicts that light ion irradiation degrades the Ic in the DI-BSCCO tape at the self field. This empirical relation can also be used in neutron irradiation to predict the lifetime of the DI-BSCCO tape. The change in the Ic of the DI-BSCCO tape due to deuterium irradiation is compared with the other second-generation HTS tape irradiated with energetic radiation.

1. Introduction

Due to recent advancements in superconducting technology, certain superconducting compositions especially Sumitomo made DI-BSCCO (Type HT-CA) remain superconducting up to ≈ 110 K [1]. Besides the excellent critical temperature, these second-generation (2G) high-temperature superconductors also have a high critical current (Ic). Their performance has increased significantly in the past and their applications are explored in various high-power systems such as fusion reactors, tokamaks, and high energy ion accelerators [1]. The DI-BSCCO (bismuth–-strontium–calcium–copper oxide), YBCO (yttrium barium copper oxide) and REBCO (rare-earth barium–copper oxide) superconducting tapes have the potential to be used in the fusion reactor magnets [2,3]. The superconducting tape due to its resistance-less nature below critical temperature can be used to generate a strong enough magnetic field in a fusion reactor. These type II superconductors (DI-BSCOO and REBCO) are capable of producing a 12T magnetic field at the centre of plasma compared to the 5T produced in the ITER with the Nb_3Sn low-temperature superconductors [4].

The artificial defects produced by the energetic particle irradiation are often used to optimize the critical current of the HTS tape. The energetic particles such as light ions e.g., proton, deuterium, and helium ions, heavy ions, and high energy neutrons produce displacement defects, cascade effects, and voids and change the vortex profile in the superconducting tape. The defect type and its shape primarily depend on the type of particles and their energy. The charged particles transfer their energy via electronic excitation and by collision with the nuclei of the lattice [5,6]. The light ions such as deuterium, proton, helium ions create point defects that exist randomly in the materials. These point defects change the

* Corresponding author.
E-mail address: mmayankrajput@outlook.com (M. Rajput).

https://doi.org/10.1016/j.net.2022.02.008

vortex pinning profile and alter the superconducting properties of the HTS tapes at the 77 K and self field. This alteration degrades the current carrying capacity of DI-BSCCO tapes [7], Zr-BCO tapes [8], and SmBCO superconducting tapes [9]. Zeller et al. [7] irradiated the DI-BSCCO tape samples with the 2E18 protons.cm^{-2} of 50 MeV energy and observed that the Ic of the tape is decreased to 25% of the Ic of the pristine samples.

Neutrons interact with the matter via scattering or absorption nuclear reactions and do not have a well-defined depth distribution in the targets. Aoki et al. [10] irradiated DI-BSCCO HTS tape samples with the $\approx 10^{10}$ neutrons.cm^{-2} of 14 MeV energy and observed no significant change. The commercial DI-BSCCO tapes will have to endure the intense neutron environment of up to 14.1 MeV energy in the fusion reactors [11–13]. The estimation of the alterations in critical current due to the ion or neutron irradiation is essential for designing the radiation-resistant HTS tape and predicting their lifecycle in the fusion reactor and accelerator applications. Due to the limited availability of neutron fluences at the laboratory level, and induced radioactivity after the neutron irradiation, neutron-induced defects in the DI-BSCCO tapes are not extensively studied. The light ions e.g. proton, deuterium, etc can be used to surrogate the neutron effects on the superconductors if they produce a similar order of defects and radiation dose in them. High energy heavy ions create larger defects of cylindrical and columnar shape due to their very high stopping power in the matter [14]. The displacement defects produced by the light ions are mobile during the irradiation period and end up accumulating at the grain boundaries. This deterioration in grain boundaries limits the critical current of the HTS tape in the self and low magnetic fields [15–17].

In the present work, we address the radiation damage caused by the 100 keV deuterium ions irradiation on the DI-BSCCO (HT-CA) tape and its impacts on the critical current of the tape at the self field. We later compare the damage caused by the deuterium ions with those produced by the 14.1 MeV neutrons. Based on our experimental data, we have empirically fitted a formula to predict the degradation of Ic of the tape due to deuterium ions irradiation. We also compare the Ic degradation in DI-BSCCO tape with the RECBO tape irradiated with the 3 MeV trihydrogen cations [18].

The present manuscript is structured as follows. In section 2, we have explained the ion distribution, numbers of defects, and vacancies distribution in the tape due to 100 keV deuterium ions irradiation. In section 3, we have presented our experimental results of critical current degradation due to deuterium ion irradiation. In section 4, we have correlated and compared these effects with the effect caused by the 14.1 MeV neutron irradiation. In section 5, we have fitted an empirical expression to predict the degradation of critical current in the DI-BSCCO.

2. Simulation of radiation damage in the HTS tape by the deuterium ion of 100 keV energy

The formation of Frenkel pairs, ion distribution in the HTS tape, and vacancies distribution are simulated with the Monte Carlo code SRIM/TRIM [19]. The SRIM (Stopping Power of Ions in Matter) simulates the projected range and energy deposition by the ion irradiation and TRIM (Transport of Ions in Matter) simulates the slowing down of ions, recoils, sputtering and damage produced by the ion irradiations. This code uses the binary collision approximation approach. In its full cascade mode, SRIM uses electronics stopping power calculated with the Bethe Bloch approach, Zeigler Biersack and Littmark (ZBL) universal potentials and cross-sections, and tracks each knocked on atom with the Monte-Carlo approach [20]. We have used the full damage cascade mode of the SRIM/TRIM code. In the next subsections, we present the results of the SRIM/TRIM simulations of displacement damage in the DI-BSCCO tape.

Fig. 1. Cross-sectional architecture of the DI BSCCO-HT-CA tape.

2.1. Production of dpa and dose deposition in HTS tape by deuterium ions

We have simulated the effect of energetic deuterium ions on the DI-BSCCO tape. The tape's cross-sectional architecture is presented in Fig. 1. This DI-BSCCO (HT-CA) tape assembly consists of Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$) filaments in the silver matrix, and is further laminated with the copper-alloy. This copper alloy provides high mechanical strength and low resistance at the splices between the superconductors. In the simulations and irradiation experiments, the copper-alloy layer is chemically removed. The number of interstitials and vacancies collectively known as Frenkel pairs is simulated for the deuterium ion of up to 10 MeV energy. The number of Frenkel pairs are calculated for up to 10 MeV deuterium ion energy to check the maximum damage as this HTS tape can stop up to 10 MeV of deuterium ions. The results of the simulations are presented in Fig. 2.

2.2. Ion distribution in HTS tape due to 100 keV deuterium irradiation

We have simulated the ion deposition profile of 100 keV deuterium ion on the DI-BSCCO tape. The 100 keV deuterium ion can only penetrate up to 1.15 μm thickness. This 100 keV energy can only cause damage near the surface of the HTS tape. Due to the short penetration range of ions, the outer layer of the copper is removed in the irradiation experiments. The 2-dimensional depth penetration profile of deuterium ions is shown in Fig. 3 and vacancy distribution in Fig. 4. It is clear from Fig. 4 that all of the vacancies and displacements are produced up to 1.15 μm depth. Some of the displacements recombine with each other thus the number of vacancies are lower than the displacements. The effect of these damage events are later checked by the deuterium ion irradiation of 100 keV ions on the tape and are discussed in section 3.

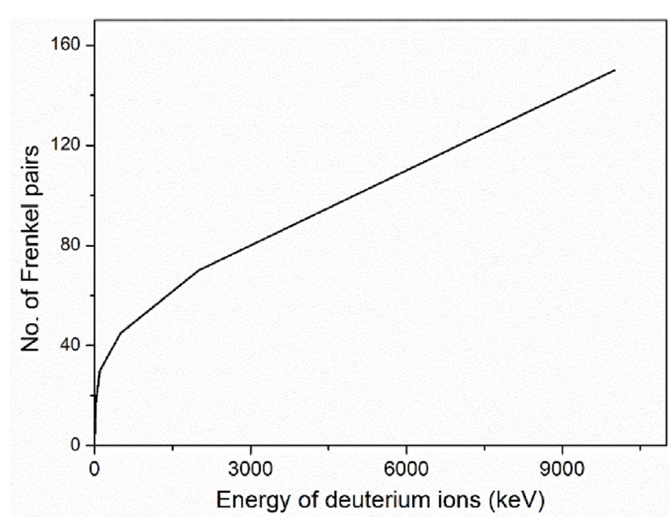

Fig. 2. The number of Frenkel pairs vs energy of deuterium ion.

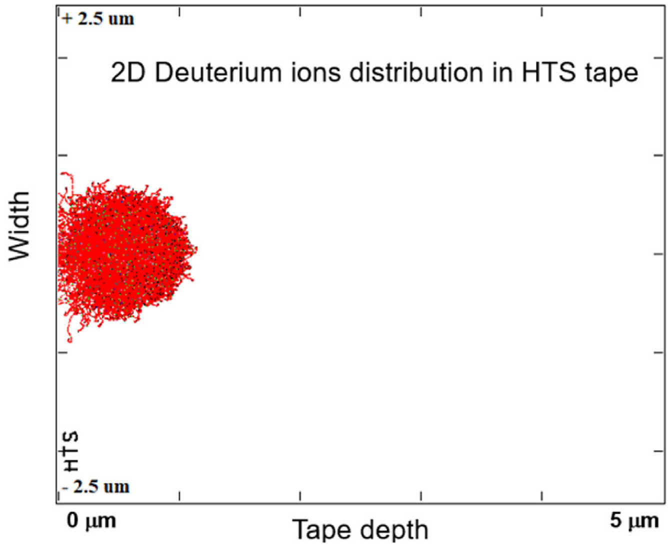

Fig. 3. 2-Dimensional ion penetration profile in HTS tape.

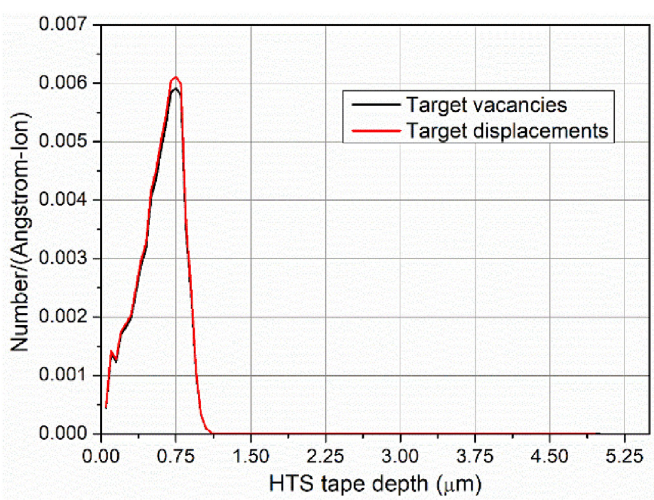

Fig. 4. Vacancies distribution in the HTS tape for the 100 keV deuterium irradiation.

3. Deuterium ion irradiation on the HTS tape

The tape dimensions used in these irradiation experiments are 70 mm long, 4.4 mm wide and 0.340 thick. Due to the low penetration range of the deuterium ions of 100 keV energy, we have chemically removed the outer layers of copper-alloy from the DI-BSCCO tape at its centre. The deuterium beam is produced with an electron cyclotron ion source (ECRIS) and accelerated to 100 keV energy at the neutronics laboratory, Institute for Plasma Research [21]. The samples are placed in the scattering chamber having the vacuum of the order of 10^{-6} torr. No degradation in the critical current (Ic) of the HTS tape sample was observed due to the chemical removal of the copper layer. We place a circular aperture of a 1 cm diameter in front of the DI-BSCCO tape. This aperture acts as a beam window to the deuterium beam. The ion beam hits the HTS samples at the centre. During the irradiation experiments, a low deuterium beam current is desired to avoid the excessive heating of the sample. The sample is irradiated with 5 μA beam current for 35 min (1.2E16 particles.cm^{-2}) and the tape temperature is monitored. The maximum temperature reaches 68 °C and this heating does not have any effects on the current-carrying capacity of HTS tape. The standard four-probe method is used to measure the I-V characteristic of the HTS tape samples before and after irradiation. The electric field criterion of 1 μV/cm is used to measure the critical current of the HTS tape samples. In these experiments, the samples are mounted on the G-10 sample holder and current leads and voltage taps are soldered to pass electrical current and to measure the voltage drop across the HTS tape samples. The AMI make magnet power supply (Model No. XFR 12-220 DC PS 0–12V, 220 A) has been used as a current source and KeithleyTM make Nano Voltmeter (Model No.2182 A) has been used for voltage measurement at 77 K. The separation between two voltage taps across the pristine and irradiation samples are 48 mm and 25 mm, respectively. All the samples are cooled to 77 K by liquid Nitrogen and charged up to 180 A. Using the electric field criteria of 1 μV/cm, the critical current of pristine samples is measured and its values come out to be 161.8 ± 3.24 A.

The samples are irradiated with the 1E15, 1E16, and 6.9E16 deuterium fluence (particle.cm^{-2}), and later their critical current is measured at 77 K. The details of the irradiation scenario, their corresponding dose, dpa, and degradation in their critical current are given in Table 1. The 4th irradiation data is taken from Zeller et al. [7]. Zeller et al. irradiated the DI-BSCCO tape with the proton ion beam of 50 MeV energy. The thickness of the tape is 200 μm. Zeller et al. estimated the dpa with the PHITS code which uses the Norgett Robinson and Torrens (NRT) mechanism [22–24].

The deuterium ion irradiation causes the formation of voids, inter-site atoms, and cascade defects in the tape. This formation of point defects leads to the deflection of vortex lines from their equilibrium position. The critical current density in HTS tapes can be defined by the balance of pinning force and Lorentz force in HTS tapes [25]. The pinning force is produced when the defects pin vortices in a strongly interacting flux line. The effectiveness of pinning defects is given by their density, spatial distribution, and pinning force. The elementary pinning interactions can be either due to short-range interactions of vortices with point defects or due to long-range interactions of larger size defects e.g., columnar defects and grain boundaries. As a vortex core crosses radiation-induced defects, superconducting condensation energy is enhanced [25]. In the case of DI-BSCCO tape, formed point defects degrade the critical current carrying. A similar type of degradation is also reported for Zr-BCO tapes [8], and REBCO [18] superconducting tapes. The displacement defects are mobile during the irradiation phase and end up accumulating at the grain boundaries and causing deterioration in them. In the self and low field region, intergranular current sets an upper limit on the lossless current flow in the HTS tapes and degrade the Ic. The degradation in the grain boundary and increased shielding current within the grains generates an additional field at the grains that can provide an understanding of the Ic degradation of the HTS tapes [12,13,18]. These mechanisms change the vortex profiles at the surface and also affect other vortices of the tape as there exists a long-range repulsion between these vortex lines and allowing them to influence the motion of other vortices in the superconducting tape [17]. Due to these reasons, we have observed the degradation of the critical current carrying capacity of the tape although the defects were only formed up to 1.15 μm depth. The damage produced by the neutrons might affect the superconductor properties of HTS tapes differently and degradation depends on the defect density, superconducting alloy composition, and neutron energy [26,27]. We use our experimental results of Ic degradation due to ion irradiation to fit an empirical formula and discuss in section 5.

Table 1
Deuterium irradiation and its impact on the critical current carrying capacity of HTS tape.

Sr. no.	Fluence (particles.cm^{-2})		Incident Energy	Dpa	Dose Gy(J/kg)	Ic/Ic$_0$
1	1.00E+15	Irradiated with deuterium ion fluence	100 keV	8.68857E-05	4.21E+04	95%
2	1.00E+16		100 keV	0.000868857	4.21E+05	69%
3	6.90E+16		100 keV	0.005995111	2.90E+06	56%
4	2E18 [6]	Exp. data of proton irradiation by Zeller et al. [6]	50 MeV	1.34E-02	7.00E+08	25%

4. Correlation and comparison with neutron irradiation

The neutrons can induce various nuclear reactions including scattering and absorption reactions. These reactions create outgoing particles and energetic recoils and produce the Frenkel pairs and degrade the engineering properties of the HTS tape. The dpa due to neutron irradiation can be estimated using the dpa cross-section of the elements and alloys [12,23]. In this work, dpa cross-section (dpa XS) of constituents elements have been extracted from the dpa cross-section library of IAEA [28]. This cross-section library is based on the ENDF-VIII data library and contains the dpa cross-section predicted by the Norgett Robinson and Torrens (NRT) approach [22]. In the NRT approach, dpa is equal to 0.8 $\frac{Td}{2Ed}$. Here, T_d is the damage energy which is the kinetic energy available for producing atomic displacements and E_d is the threshold displacement damage energy [12,22]. The damage energy (T_d) is calculated with Robinson's analytical representation of Lindhard's model of energy partition between electrons and atoms [22]. All the open reaction channels e.g., (n,el), (n,n'), (n,2n), (n,p), (n,np), (n,α), and (n,nα) are included in this cross-section data. We present the dpa cross-section of the DI-BSCCO tape in Fig. 5. In the epithermal neutron range, the dpa cross-section fluctuates due to several resonance absorptions in the alloying elements of the HTS tape. The neutron spectrum of fusion reactors peaks at 14.1 MeV energy, thus we have calculated the dose deposition in the HTS tape by the 14.1 MeV neutrons with the Monte Carlo transport method to compare the dose deposited by 100 keV deuterium ions. The 14.1 MeV neutron fluence (1 n.cm^{-2}) deposit 0.018831 MeV/g dose in the superconducting DI-BSCCO tape which is equivalent to 3.008E-12 Gy. We present the dpa and dose deposition by the 14.1 MeV neutron and 100 keV deuterium ions in the HTS tape in Fig. 6.

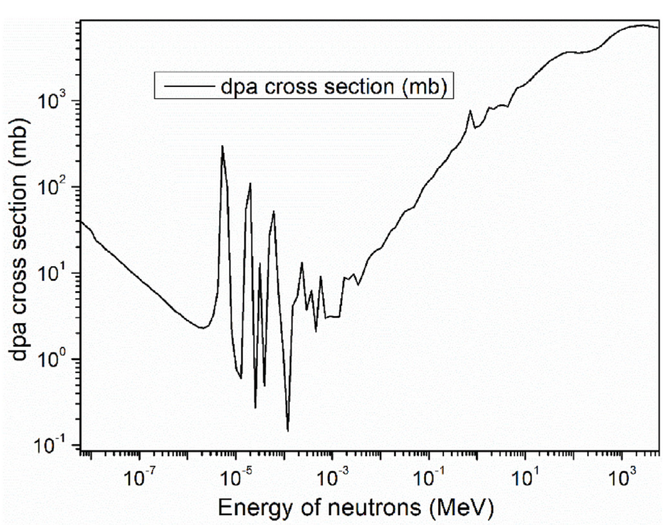

Fig. 5. The dpa cross-section of HTS tape vs incident neutron energy for the DI-BSCCO tape. The dpa cross-section is extracted from the dpa XS library [26].

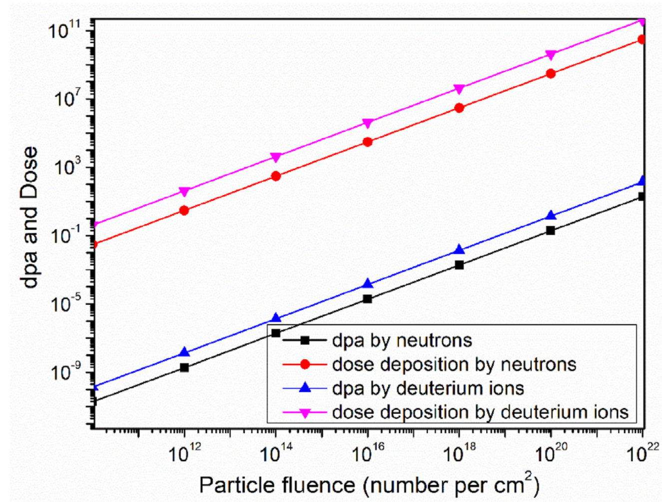

Fig. 6. Dose deposition (Gy) and dpa produced by the 100 keV deuterium ion and 14.1 MeV neutrons in the DI-BSCCO tape.

The 14.1 MeV neutrons deposit a fraction of their energy in the tape while deuterium ions of 100 keV deposit all of their energy. The dose and dpa produced by the deuterium are 8 times higher than those produced by the neutrons. The important things to consider in the case of neutron irradiation are that they produce damage in the HTS tape throughout its full thickness and can also transmute alloying elements.

5. Empirical formula to predict the degradation in the critical current of the DI-BSCCO tape

In this section, we have fitted an empirical relation between the dpa, dose deposition by the incident ions and alteration of the critical current carrying capacity of the HTS tape. Previous studies [6–8,29,30] reveal that the critical current of the superconducting tapes is affected by the point defects, columnar defects and deterioration in grain boundaries. The effect of the irradiation on the critical current of LTS (low-temperature superconductors) and HTS was observed to be exponential [31,32]. We have also observed in our experiment that change in the critical current of HTS tape is proportional to the exponential function of the incident particle fluence as;

$$\frac{I_{Cirradiated}}{I_{Cpristine}} \alpha \exp\left(\text{constant } \phi\right) \tag{1}$$

Here ϕ is incident particle flux. The incident radiation can produce point defects, columnar defects and deposit their energy in the HTS tape. We have fitted an empirical expression with our experimental data to predict the change in the critical current due to the radiation dependent variables e.g., dpa, dose and formation of columnar defects with the regression analysis and random sampling.

The fitted empirical formula is given as;

$$\frac{I_{Cirradiated}}{I_{Cpristine}} = exp\left(\left(0.03814\right)dpa^{0.528}.\ln\left(\frac{D}{2TD}\right)\ln\left(\frac{En}{TEn}\right)\right) \quad (2)$$

Here, D is the dose deposited in the HTS tape, TD is the threshold dose to produce a single defect, En is the energy deposited by the particles per nanometer, and TEn is the optimized energy to create a columnar type of defect. The optimized energy to form columnar defects is 11.6 keV/nm in BSCCO type tape [29,30]. This energy is optimized from the work of Sasase et al. [29]. The predictions of the empirical relation are presented in Fig. 7 for deuterium ions. We have used our experimental data of Ic degradation due to deuterium irradiation to fit an empirical formula. The TD for 100 keV deuterium ion is 1.05219E-14 Gy. The En is 143.3 eV/nm for deuterium ions of 100 keV energy and TEn is taken as 11.6 keV/nm. The empirical formula shows good agreement with Zeller et al. [7]. For proton irradiation of 50 MeV, En is 5.2 eV/nm. This relation is applicable for the self magnetic fields and 77 K temperature. The prediction of this empirical relation and its comparison with our experimental data and Zeller et al. data are presented in Fig. 7. H. Yamamoto [18] irradiated the trihydrogen ion of 3 MeV on the REBCO ($REBa_2Cu_3O_{7-\delta}$) and measured the degradation of the critical current of the tape at 77 K. Yamamoto did these measurements at the self magnetic field and observed that the critical current of these REBCO tapes also degraded to 40% of its initial values at 4E15 proton fluence (cm^{-2}).

We have also checked the applicability of this empirical expression for the heavy ion irradiation e.i., Silver ions of 500 MeV and presented the predictions in Fig. 8. The Silver ion has a stopping power of 34,050 eV/nm. In the case of silver ion irradiation, higher En causes the $\ln(\frac{En}{TEn})$ to be positive thus enhancing the critical current carrying capacity of the tape. This behaviour of the tape due to irradiation was also observed by various previous works [7–10,29–31]. Due to the non-availability of quantitative data of Ic enhancement after heavy ion irradiation on DI-BSCCO tape at a self magnetic field, this expression is not yet tested for the heavy ions.

As discussed in section 4, neutrons produce similar order of dpa and dose as that deposited by the deuterium ions of 100 keV energy in the HTS tape and will degrade the Ic of DI-BSCCO tape at the 77 K and self field. The energy of neutrons plays a vital role in predicting

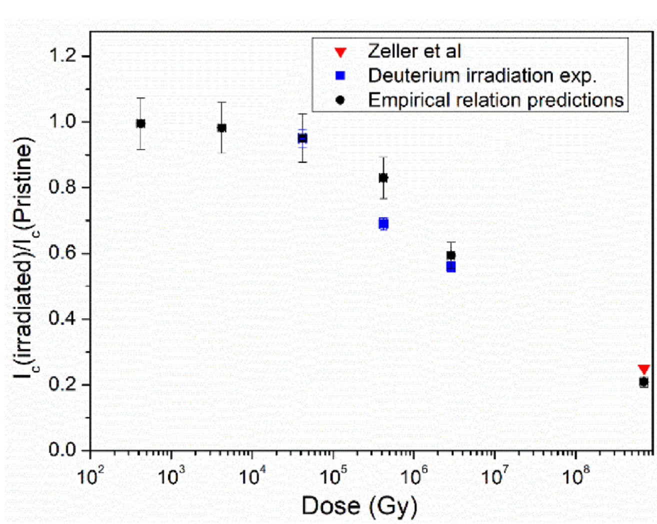

Fig. 7. Comparison of the experimental and modelled results.

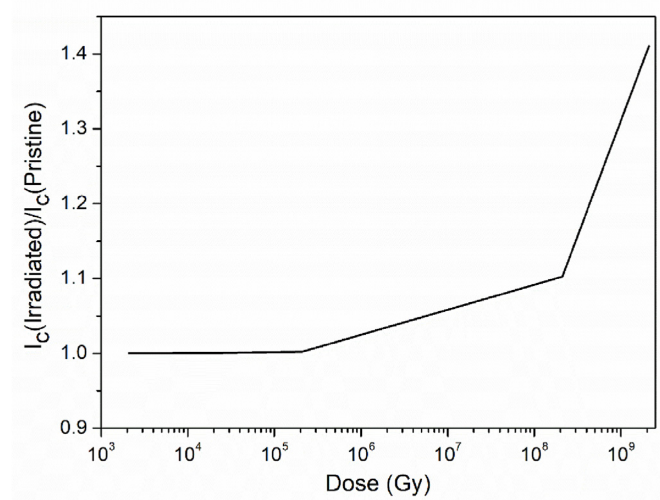

Fig. 8. Prediction of Ic enhancement due to 500 MeV silver ion irradiation.

the behaviour of HTS tape in neutron environments. The energy deposition in the tape by the neutrons is governed by their mode of reactions. For the 14.1 MeV neutrons in the medium Z materials, neutron mostly transfers their energy via charged particles production reaction or scattering reactions, and their stopping power remains far less than 11.6 keV/nm, thus behaving like a light ion. But thermal and epithermal neutrons can cause fission in high Z or actinides materials which cause the formation of the fission fragments of approximately 200 MeV energy and can produce columnar defects and behave like heavy-ion of high energy [6]. With the estimation of En, dpa, and dose deposition, change in the Ic can also be predicted for neutron irradiation. In the case of 14.1 MeV neutron irradiation, the DI-BSCCO tape performs considerably good up to ~10^6 Gy dose which is equivalent to ~10^{18}n.cm^{-2}. At this dose and fluence, the tape's critical current remains 80% of the initial value. This limit is similar to the recommended limit for the Nb_3Sn superconductor for which the limit is set to ~10^{18}n.cm^{-2} [33].

6. Conclusion

In the present work, the deuterium ion irradiation effect on the commercial DI-BSCCO tape is investigated. The HTS tape samples are irradiated with deuterium ions of 100 keV energy. The ion transport and the formation of the Frenkel pairs are simulated with the SRIM/TRIM code. These deuterium ions create 30 FP/ion in the HTS tape and deposit 4.21E-11 Gy/ions.cm^{-2}. These ions deposit all their energy up to 1.15 μm thickness and produce point defects in the tape. The HTS tape is irradiated with up to 6.9E16 deuterium ions.cm^{-2} and their effects on the critical current are investigated. The point defects formed at the surface interact with the vortices. The change in the vortex profile due to point defects and long-range interaction of vortex lines in the tape degrades its critical current carrying capacity. Based on the dpa and dose deposition by deuterium ions and degradation in Ic of the tape, an empirical formula is fitted. This empirical relation consists of the dpa, dose deposition, and stopping power of incident particles terms. The empirical formula confirms that the light ions such as deuterium decrease the critical current of the HTS tape and high energy heavy ions such as silver enhance the critical current. The prediction of the empirical relation is compared with the result of Zeller et al. and the prediction by the empirical relation is in good agreement. The 14.1 MeV neutron deposits 3.28E-12 Gy/neutrons.cm^{-2} in the tape which is similar to the order of dose produced by the 100 keV deuterium ions. This empirical relation can also be used to predict the neutron irradiation effect on the DI-BSCCO tape by estimating the dpa, dose deposition, and En of the neutron irradiation. It is observed that HTS tape loses 75% of Ic at 7.00E+08 Gy. This dose is equivalent to ≈2.3E20 neutron.cm^{-2} fluence.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Pierluigi Bruzzone, et al., High temperature superconductors for fusion magnets, Nucl. Fusion 58 (2018), 103001.
[2] M. Kikuchi, et al., Development of new types of DI-BSCCO wire, SEI Tech. Rev. 66 (2008) 73–80.
[3] V. Selvamanickam, et al., High critical currents in heavily doped (Gd,Y) $Ba_2Cu_3O_x$ superconductor tapes, Appl. Phys. Lett. 106 (2015), 032601.
[4] Alex Creely, Erica Salazar, A commercial path to fusion, physics world focus on instruments & vacuum. https://physicsworld.com/a/a-commercial-path-to-fusion/, 2019.
[5] Kai Nordlund, Historical review of computer simulation of radiation effects in materials, J. Nucl. Mater. 520 (2019) 273–295.
[6] M. Eisterer, Radiation effects on iron-based superconductors, Supercond. Sci. Technol. 31 (2018), 013001.
[7] Zeller, et al., Radiation damage to Bscco-2223 from 50 Mev protons, AIP Conf. Proc. 986 (2008) 416.
[8] A.A. Gapud, et al., Irradiation response of commercial high-Tc superconducting tapes: electromagnetic transport properties, J. Nucl. Mater. 462 (2015) 108–113.
[9] W.J. Choi, et al., Effect of the proton irradiation on the thermally activated flux flow in superconducting SmBCO coated conductors, Sci. Rep. 10 (2020) 11.
[10] Toru Aoki, et al., Effect of neutron irradiation on high-temperature superconductors, IEEE Trans. Appl. Supercond. 21 (2011) 3200–3202.
[11] M. Rajput, R. Srinivasan, Study of transmutation, gas production, and displacement damage in chromium for fusion neutron spectrum, Ann. Nucl. Energy 1381 (2020), 107187.
[12] M. Rajput, et al., Displacement damage study in tungsten and iron for fusion neutron irradiation, Fusion Eng. Des. 150 (2020), 111370.
[13] E. Mezzetti, et al., Control of the critical current density in $YBa_2Cu_3O_{7-\delta}$ films by means of intergrain and intragrain correlated defects, Phys. Rev. B 59 (1999) 5.
[14] A. Molodyk, et al., Development and large volume production of extremely high current density YBa2Cu3O7 superconducting wires for fusion applications, Sci. Rep. 11 (2021) 2084.
[15] Feng Xue, et al., Critical current density through grain boundaries in high-temperature superconductors, J. Supercond. Nov. Magnetism 29 (2016) 2711–2716.
[16] M. Eisterer, et al., Neutron irradiation of coated conductors, Supercond. Sci. Technol. 23 (2009), 014009.
[17] W.K. Kwok, et al., Vortices in high-performance high-temperature superconductors, Rep. Prog. Phys. 79 (2016), 116501.
[18] H. Yamamoto, et al., Effect of non-uniform proton irradiation on the critical current of REBCO tapes, J. Phys.: Conf. Ser. 1559 (2020), 012045.
[19] J.F. Ziegler, J.P. Biersack, M.D. Ziegler, SRIM – the stopping and range of ions in matter, Nucl. Instrum. Methods Phys. Res. B 268 (2010) 1818–1823, 2010.
[20] W.J. Weber, Y. Zhang, Predicting damage production in monoatomic and multi-elemental targets using stopping and range of ions in matter code: challenges and recommendations, Curr. Opin. Solid State Mater. Sci. 23 (2019), 100757.
[21] S.J. Vala, et al., Development and performance of a 14-MeV neutron generatorNucl, Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 959 (2020), 163495.
[22] M.I. Norgett, M.T. Robinson, A proposed method of calculating displacement dose rates, Nucl. Eng. Des. 33 (1976) 50–54.
[23] Kai Nordlund, et al., Improving atomic displacement and replacement calculations with physically realistic damage models, Nat. Commun. 9 (2018) 1084.
[24] M. Rajput, et al., Displacement damage study in tungsten and iron for fusion neutron irradiation, Fusion Eng. Des. 130 (2018) 114–121.
[25] A. Gurevich, Superconductivity: Critical Currents, Encyclopedia of Condensed Matter Physics, 2005, pp. 82–88.
[26] D.X. Fischer, et al., The effect of fast neutron irradiation on the superconducting properties of REBCO coated conductors with and without artificial pinning centers, Supercond. Sci. Technol. 31 (2018), 044006.
[27] K.J. Leonard, et al., Irradiation performance of rare earth and nanoparticle enhanced high temperature superconducting films based on YBCO, Nucl. Mater. Energy 9 (2016) 251–255.
[28] Konobeyev, et al., Dpa cross section library. https://www-nds.iaea.org/public/download-endf/DXS/Displacement_XS/DXS.(2018)/, 2018.
[29] Sesase, et al., Defect structure of high-Tc superconductor by high-energy heavy ion irradiation, J. Electron. Microsc. 51 (2002) S235–S238.
[30] L. Civale, et al., Vortex confinement by columnar defects in $YBa_2Cu_3O_7$ crystals: enhanced pinning at high fields and temperatures, Phys. Rev. Lett. 67 (1991) 648.
[31] Brown, et al., Radiation effects in superconducting fusion-magnet materials, J. Nucl. Mater. 97 (1981) 1–14.
[32] Troitskii, et al., The effect of Xe ion irradiation (40, 80 MeV) on HTS-2G $GdBa_2Cu_3O_{7-x}$, Physica C: Supercond. Appl. 572 (2020), 1353631.
[33] L. Bromberg, et al., Options for the use of high temperature superconductor in tokamak fusion reactor designs, Fusion Eng. Des. 54 2 (2001) 167–180.