Effect of non-uniform proton irradiation on the critical current of REBCO tapes

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Abstract. Generally, uniformly-distributed irradiation defects such as artificial pinning centers improve the critical current, \(I_c\), of REBCO tapes in strong external field. On the other hand, at self-field or low field, irradiation is not effective for improving \(I_c\). However, if non-uniform pinning center distribution similar to vortex profile is assumed, this would increase \(I_c\) at self-field. Therefore, in this study, we experimentally investigated the effect of partial irradiation on \(I_c\) based on the assumption. We prepared REBCO tapes irradiated with trihydrogen cations in the c-axis direction. Three different patterns of defects were examined; overall, edge-only and center-only irradiations. We measured \(I_c\) at 77 K, 25 K and 15 K using the four terminal method. Results showed that, while \(I_c\) was not improved after the irradiations for each pattern, \(I_c\) behaviour depends on the patterns; edge-only-irradiated tapes showed the highest \(I_c\) and overall irradiation caused the largest \(I_c\) degradation at 77 K. However, center-only-irradiated tapes showed the lowest critical current at 25 K and 15 K which may be due to enhancement of flux pinning effect at lower temperature. Moreover, pinning centers in the edge region might be more effective to increase \(I_c\), though further investigation on the effect of non-uniform pinning centers is required.

Introduction

The effects of particle irradiation on the critical current of REBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-\textgamma} (REBCO) tapes have been widely studied [1-3] for superconducting material science and magnet applications such as accelerators and fusion reactors under radiation environment. The irradiation effects depend on external magnetic field and temperature. For example, critical current increases significantly generally in higher fields (>0.5 T) and at lower temperature [1, 2], where irradiation defects work as artificial pinning centers (APC). On the contrary, critical current suppression occurs in lower fields (<0.1 T) and high temperatures, where the irradiation reduces critical temperature, and deterioration in grain boundary critical current density \((J_c, g_b)\) limits transport current. In the case without external fields, the magnetic field is only self-field (s.f.) generated by the transport current. The field distribution is non-uniform across the tape width, and the strength of the field is higher at the edges [4]. Here, we assumed APC distribution similar to fluxoid profile would increase critical current at self-field. Based on the assumption, in this study, we investigated the effect of non-uniform proton irradiation on the critical current of REBCO tapes. For that purpose, three different patterns (overall, edge-only and center-only irradiations) of defects were introduced by irradiation with trihydrogen cations using a dynamitron accelerator at the First Neutron Laboratory (FNL), Tohoku University. First, we obtained the current-voltage (\(I-V\)) curve for the samples cooled by liquid nitrogen with the four terminal method to evaluate critical current as a function of fluence of the proton irradiation depending on the patterns. Then the
critical current was also evaluated at 25 K and 15 K for selected samples using a cryogen-free cryostat at the High Field Laboratory for Superconducting Materials (HFLSM), Tohoku University.

**Experiment**

2.1 Overview of the experiment

To evaluate the effect of proton irradiation on the critical current of REBCO tapes, we conducted each experiment following the next steps: first, the critical current ($I_{c0}$) was measured at selected temperatures for original REBCO tapes. Then, these samples were irradiated and after that, the critical currents ($I_c$) of the irradiated samples were measured again at the selected temperatures. A commercial GdBCO tape (ST-4-10, no-APC) provided by SuperOx Japan LLC (Sagamihara Japan) was used for this study. This tape has a width of 4 mm and a critical current of about 40 A at 77 K, s.f.. The REBCO tape consists of upper Ag layer of 2 µm thickness, GdBCO layer of 1 µm, buffer layer of about 0.3 µm, Hastelloy C-276 layer of 60 µm and lower Ag layer of 1 µm. The superconducting layer was deposited with pulsed laser deposition (PLD). Each sample was cut into a length of 9 cm.

2.2 Evaluation of the critical current

Conventional four terminal method was used to acquire $I$-$V$ curves of samples prepared. Two voltage taps were attached on the REBCO tape at 4 cm apart from each other, and the current terminals were attached to the sample 5 cm apart from each other. The critical currents were determined with the electric field criterion of 1 µVcm$^{-1}$. Two cooling methods were used to obtain the temperature dependence of the critical currents. One is cryogen cooling using liquid nitrogen of 77 K. The other is conduction cooling to achieve lower temperature (15 K and 25 K). The cryostat with 4K-GM cryocooler at the HFLSM, Tohoku University was used to measure the critical currents at the lower temperatures.

2.3 Irradiation experiment

Irradiation experiments were conducted at FNLS, Tohoku University. Trihydrogen cations ($H_3^+$) were accelerated in the dynamiton accelerator [6, 7] with a voltage of 3 MV. One $H_3^+$ particle with 3 MeV is equivalent to three proton particles with 1 MeV. The ion beam was focused to a diameter of ~1 mm and projected on the samples as seen in Figure 1. The ion beam was scanned in the horizontal direction. The sample holder moved vertically to scan in the vertical direction. Irradiation area on the samples was controlled by masking non-irradiation area with copper ribbons as shown in Figure 2. During the irradiation, temperature of the samples attached on the holder with water-cooling channel was observed with the radiation thermometer (Fluke Ti25), and the temperature did not exceed the deoxygenation temperature of 200–250 °C. The number of incident proton particles irradiated to the samples was estimated by beam current. Then, the fluence ($\phi$) was calculated based on the number of incident proton particles per irradiated unit area. The range of fluence was $10^{13}$–$10^{16}$ cm$^{-2}$ in this study.

For the preparation of the irradiation experiment, the Stopping and Range of Ions in Matter (SRIM) calculation was also conducted to analyze the interaction between irradiated proton and the REBCO tape. $H^+$ (1 MeV) ions were irradiated parallel to the c-axis of the REBCO layer in the calculation. In the analytical model, the REBCO tape consists of upper Ag layer of 2 µm thickness, GdBCO layer of 1 µm, Hastelloy C-276 layer of 60 µm and lower Ag layer of 1 µm. Figure 3 and 4 show the range of ions and total displacements per atom (DPA) along the thickness direction of the REBCO tape. Almost all the ions pass through GdBCO layer and the Bragg peak appears in the Hastelloy layer. Averaged DPA in GdBCO layer becomes $0.5–1\times10^4$ Displacements/(Angstrom-Ion).
Result and Discussion

3.1 Non-uniform irradiation effect at 77 K

Figure 5 shows fluence dependence of the normalized critical current \((I_c/I_{c0})\) at 77 K, s.f.. Proton irradiation decreased the critical current, which is apparent as fluence increases. The critical current degradation might be caused by grain boundary deterioration as mentioned in [1]. \(J_{c,\text{GB}}\) is dominant in entire critical current of the tape in the lower field. Defects are mobile during irradiation and accumulated at grain boundaries, hence irradiation decreased critical current in self-field. However, the critical current of the tapes with three irradiation patterns behave differently. The critical current of
However, the critical current of 2 mm and edge parts of 1 mm was about 6:4. The overall critical current of REBCO tapes estimated from the solid curve of the overall-irradiated tapes was measured and the current ratio between center part and edge parts of 1 mm was about 6:4. The dashed curves in figure 5 show the behavior of critical current of partial irradiated tapes estimated from the solid curve of the overall-irradiated tapes based on the assumption above. The estimated curves approximately correspond with the experimental data. However, the data plot of edge-only irradiated tape at \( \Phi = 1 \times 10^{16} \text{ cm}^{-2} \) is apart from the estimated curve and we need further investigation about it.

3.2 Non-uniform irradiation effect at low temperature
Adding to this critical current density non-uniformity, the difference of self-field distribution was likely to influence the result for the case of lower temperature values (25 K and 15 K). Figure 6 shows temperature \( (T) \) dependence of \( I_c/I_{c0} \) at \( \Phi = 5 \times 10^{15} \text{ cm}^{-2} \), s.f.. This result indicated that the normalized critical current never exceeded 1.0 at the measured temperatures (77 K, 25 K and 15 K). Moreover, at lower temperature (<77 K), the critical current increments with particle irradiation were reported at external field condition [1, 2]. However, all the experiments conducted in self-field in this study and the strength of magnetic field was expected to be ~2 mT at 77 K and ~20 mT at 15 K from [5]. It is so low that critical current improvement was not observed as mentioned in Section 1. Irradiation pattern dependence of the critical current at 15 K and 25 K was different from that at 77 K. Center-only-irradiated tapes showed more critical current degradation compared with overall-irradiated and edge-only-irradiated tapes, which may reflect the difference of flux pinning effect between defect patterns. However, further investigations are needed to clarify flux pinning from non-uniform irradiation at lower temperature as future tasks.

**Figure 5.** Fluence dependence of normalized critical current for three irradiation patterns \((T=77\ \text{K},\ \text{s.f.})\)
Conclusion

We investigated the effect of non-uniform proton irradiation on the critical current of REBCO tapes at self-field. Three irradiation patterns were compared; overall, edge-only and center-only irradiations. Proton irradiation decreased the critical current for the three patterns in self-field. At 77 K, the critical current of three irradiation patterns behaved differently. Edge-only-irradiated tapes showed better performance and overall irradiation caused more degradation at 77 K. Non-uniformity of critical current density and effect of self-field may be the main cause of different behavior. On the other hand, irradiation area dependence of the critical current at 15 K and 25 K was different from that at 77 K. Center-only-irradiated tapes showed more critical current degradation compared with overall-irradiated and edge-only-irradiated tapes which may reflect the difference between flux pinning effect between defect patterns.

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