Reaction of REBaCuO CC Tapes to Neutron Irradiation

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Superconducting REBaCuO (RE=Gd, Y+Gd) tapes intended for wiring magnets for fusion reactors were investigated in response to neutron irradiation by fast neutron fluences up to 4×10^{22} m^{-2}. The results indicate that the tapes are appropriate for the given purpose, in particular at temperatures below 25 K. There, due to neutron irradiation, the critical currents at low magnetic fields are gradually reduced, while in high magnetic fields they are first enhanced, then degraded. The position of the crossover differs from one tape type to another, in dependence on the initial pinning landscape. To find reasons for such behavior, SEM and TEM analyses started. Some preliminary SEM results are presented. The effect of irradiation on pinning landscape is discussed.

1. Introduction

In pursuit of developing a powerful and clean source of energy for future demands, fusion reactors as a source of energy have received a great interest as one of the best candidates. Fusion reactor is based on plasma confined in a relatively small space by a mighty magnetic field. Currently, only superconducting magnets are capable of delivering magnetic field high enough. Now constructed and designed fusion reactors, like DEMO, ITER, CFETR etc., rely on well-established classical superconductors, cooled by liquid helium [1]. In parallel, attempts are being made to use high temperature magnets, e.g., [2–5]. Although high-T_c superconductors exhibit satisfactory properties only at temperatures below 25 K [6, 7], they are good for use at high magnetic fields, while compared to conventional counterpart they possess great advantages in wide safety margins, both in temperature and magnetic field. One of the important issues to be understood is the tapes' response to neutron irradiation, which is always present in the fusion reactors. In dependence on the neutron energy and the superconductor type, the irradiation produces in superconductor point-like defects or their cascades [8–10]. In most cases the pinning defect structure densifies, which leads to vortex pinning increase and the associated critical current enhancement. The process, however, depends on the initial pinning structure. The increasing neutron fluence finally brings the structure to the stage when vortex lattice does not further react on the defect densification, and the electromagnetic properties start degrading. This process depends on temperature, magnetic field, superconductor type, and neutron fluence.

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In this paper, we present some data observed on tapes of various producers, and thus complementing the complex behavioral map of the superconducting tape in response to neutron irradiation.

2. Experimental details

The tapes studied in this paper, i.e., Gd-123 (SuperOx) and (Y+Gd)-123 (SuperPower) are superconducting tapes of the second generation (2G) prepared on Hastelloy substrates and protected by a copper sheaths. The width of the tapes w was 4 mm, and the total thickness ranged between 0.1 and 0.3 mm. The superconducting layer was about 1 μm thick. The tapes were first measured before irradiation [11], and next after each irradiation step. Electromagnetic properties were evaluated in terms of critical currents I_c calculated from magnetic hysteresis loops (MHL) measured by means of a vibrating sample magnetometer (VSM). For a rectangular sample one used the Bean model formula [12, 13]

$$I_c = wcJ_c = \frac{20\Delta m}{a^2 bc\left(1 - \frac{a}{3b}\right)}, \qquad (1)$$

where $w = 4$ mm is the tape width, c is the superconducting layer thickness, J_c is critical current density, sample dimensions a and b are transversal to magnetic field direction, such that $b \geq a$, and Δm is the MHL height. For the inductive measurements samples were cut by an electrical discharge of wire-cut machine in dimensions $a \times b = 1.5 \times 1.5$ mm^2. In most cases the tests were done at temperatures: 10, 50, and 77 K. When a, b and w are given in mm, c in μm, and Δm in memu (i.e., 10^{-6} A m^2), then the J_c goes as 10^6 A/cm^2. The VSM magnetometer is an option of the Physical Property Measuring system with 9 T magnet (PPMS 9).

To avoid the problem of, not always exactly known, superconductor thickness c, we use the I_c representation. From (1) one can deduced I_c and it should be equivalent to the transport currents measured on the same tapes
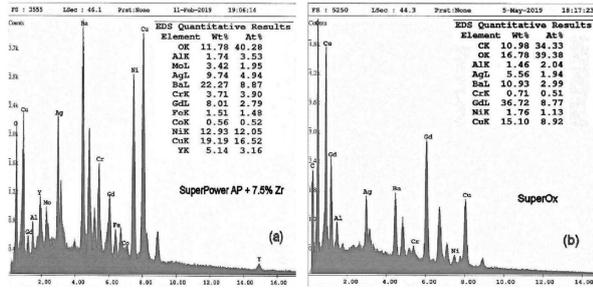
Fig. 1.   EDX spectra measured on the superconducting layers of the tapes.

Fig. 2.   Development of the field dependence of I_c on the fast neutron fluence for a SuperOx tape.

Fig. 3.   Development of I_c the fast neutron fluence at 10 K (a), and 50 K (b) for a SuperOx tape.

(4 mm wide). However, in reality these two currents need not be exactly identical because they are measured at different relaxation states and on significantly different sample sizes. In all induction measurements magnetic field was applied parallel to *c*-axis.

The neutron irradiation was made with total neutron fluences of 2.1×10^{22} m^{-2}, 1×10^{22} m^{-2}, and 8.03×10^{22} m^{-2} in the LVR-15 research reactor [14]. Selected samples were fixed, each in one of the bores drilled into an Al block-holder. This holder was placed into a glass ampule wrapped by Cd foil to shield the samples from thermal neutrons (with energies 0–0.55 eV). For the highest fluence step, the fluence of thermal neutrons was 6.08×10^{20} m^{-2}, while fluence of the part with intermediate energies (0.55 eV–0.11 MeV) was 5.07×10^{22} m^{-2}. The fluence of fast neutrons ($E \geq 0.1$ MeV) was 2.9×10^{22} m^{-2}, which represented cca 36% of the total fluence. Fluences were measured with three sets of activation detectors fixed near the irradiated samples, inside the Cd foil. Each set contained four detectors based on Ti, Fe, Ni and Co foils. Induced activities were measured with the HPGe detector, while fluences were evaluated by the STAYSL code [15]. The ampule was cooled to 55 °C during irradiation, however, temperature inside the sample might be even higher, i.e., between 70 °C and 130 °C (guess) due to further radiation heating. In this point one can see that the irradiation conditions differ from reality in future fusion reactors. The sample irradiation at low temperatures requires a substantial reconstruction of the facility, which is still under consideration.

Some basic information on the structure and composition of the tapes was achieved by scanning electron microscopy (SEM) by means of SEM-FEI Phenom (5 kV, 24k magnification, 60 nm resolution) BSE detector (material contrast), SEM/FIB-FEI QUANTA 3S FEG with EDAX EDX. Some results on the tapes composition are shown in Fig. 1.

3. Experimental results

Results concerning the superconductor composition are shown in Fig. 1. The main result of the EDX analysis is that the SuperPower AP+7.5% Zr tape is $\approx$ (Y$_{0.5}$Gd$_{0.5}$)BaCuO, while the SuperOx tape is
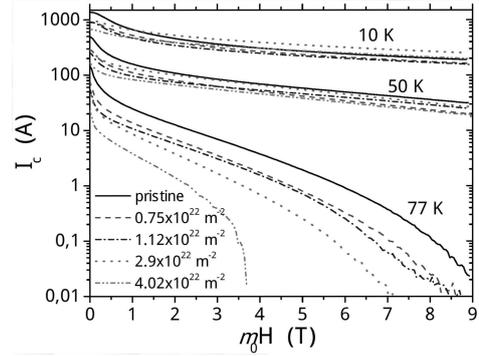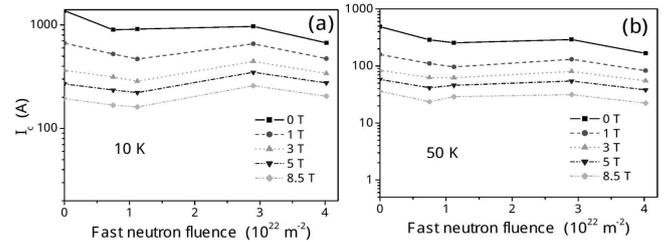
GdBaCuO with rather high content of Gd and surprisingly low amount of Ba. The declination of the composition from the stoichiometric one in the latter tape might be due to a rather high content of 211 secondary phase and Gd$_2$O$_3$ particles added usually as vortex lattice pins. Both tapes are nearly equally oxygenated. To our surprise, no zirconium was detected in the SuperPower tape. A more precise information is expected from TEM.

The development of I_c field dependence with increasing fast neutron fluence is displayed in Fig. 2 for SuperOx tape. One can see that irradiation effect differs at different temperatures and magnetic fields.

In order to get more precise insight into I_c dependence on neutron fluence, the data for 10 K were transformed and presented in Fig. 3 as I_c dependence on the fluence of fast neutrons for various magnetic fields (Fig. 3a). The same was done for 50 K in Fig. 3b. It is evident that at various magnetic fields the response was different.

We have normalized the data from Fig. 3 by the I_c values of the intact tape (zero neutron fluence) to be able to quantify the I_c enhancement/degradation. The results are shown in Figs. 4a and 4b, for 10 K and 50 K, respectively.

Figure 4a shows that at low temperatures, the neutron irradiation causes degradation of I_c values in all investigated fields. Then, the $I_c(\varphi)$ curves turn up, and those for high magnetic fields rise above the value for the intact tape, reaching maximum and again falling gradually below the "intact" value. In opposite, at s.f. (0 T),
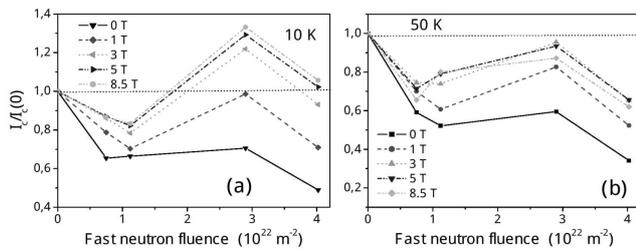
Fig. 4. The relative enhancement and/or degradation of I_c due to neutron irradiation with respect to the value of the intact tape at 10 K (a), and (b) 50 K for a SuperOx tape.
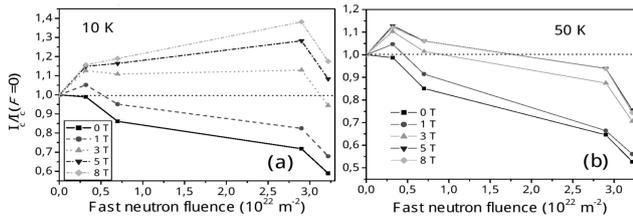
Fig. 5. The relative enhancement and/or degradation of I_c due to neutron irradiation with respect to the I_c value of the intact tape at 10 K (a), and (b) 50 K, for a SuperPower tape 4050 AP with 7.5% Zr.

I_c degrades and then stays nearly constant over a wide range of neutron fluences (the lowest curve in Fig. 4a). Such a behavior is qualitatively in accord with the experiments done by current transport [16]. At intermediate and high temperatures (Fig. 4b), the $I_c(\varphi)$ dependence behaves similar to that at low temperatures (Fig. 4a), however the cross-over at the intermediate irradiation fluence does not reach the intact tape level for any magnetic field. At temperatures above 70 K, relaxation support through intense thermal activation [7] is so high that I_c degrades with both growing neutron fluence and increasing magnetic field. A similar behavior, at least qualitatively, is quite general, as shown in Fig. 5 on the SuperPower tape 4050 AP doped by 7.5% Zr. There are small differences caused by a different initial pinning landscape of the two superconductors. Increasing temperature shifts the turn point of the $I_c(\varphi)/I_c(0)$ curves to lower neutron fluences. TEM investigation is just underway, which will provide a detail information on the tapes' microstructure.

4. Conclusion

Effect of neutron irradiation was studied on a series of commercial 2G superconducting tapes. Results of two of them, that come from different manufacturers, indicate that the irradiation effect is quite general, despite of the tape type and the experimental method employed. At temperatures below 30 K, the values of I_c at high magnetic fields grows with the irradiation fluence but at a certain value this tendency changes into a gradual degradation of I_c. However, at about 4×10^{22} m^{-2}, I_c is still close to the value of intact tape, which is a good message for potential use of these tapes in fusion reactors as this fluence is above the total life-time value in most reactors.

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