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Influence of neutron irradiation on high temperature superconducting coated conductors

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ABSTRACT

High temperature superconductors (HTS) might be applied for the magnets in a next step fusion device. The magnets could operate in the temperature range of liquid nitrogen or slightly below. Apart from the special requirements on the mechanical properties, the conductors will be exposed to radiation. We examine the influence of neutron irradiation on coated conductors. These conductors were irradiated sequentially to the ITER specification of 10^{22} m^{-2}. The samples were examined by magnetisation measurements and by direct transport measurements with regard to changes in their superconducting parameters. The critical current, its anisotropy and the irreversibility line were determined under different conditions. The magnetisation measurements were carried out in a vector vibrating-sample magnetometer (VSM) in a wide temperature range with a maximum field of 5 T. The transport measurements were carried out in fields up to 15 T. An increase of the critical current for fields parallel to the *c*-axis is observed in the high field region. A crossover of the critical current between the unirradiated and the irradiated state is found at lower fields. Also a peak in I_C (shoulder effects) can be observed in anisotropy measurements at small angles (close to the *ab*-plane) in highly irradiated samples.

1. Introduction

The properties and the production process of coated conductors (cc's) were improved dramatically during the last few years. Long lengths of RE-123 tapes are now commercially available and offer excellent superconducting properties. Especially their potential for applications in high magnetic fields at relatively high temperatures (50–77 K) is of great interest. For example, fusion devices represent a promising application of HTS, since high magnetic fields are needed for the plasma confinement, which can be economically generated only by superconducting coils. The present generation of fusion devices (e.g. ITER) is based on low temperature superconductors. Apart from the special requirements on the mechanical properties, the conductors will be exposed to neutron radiation.

Current investigations are focused on improving of the critical current density (J_C) and on reducing the anisotropy of the conductors by the addition of artificial pinning centres such as nanoparticle [1,2]. Another possibility to create additional pinning centres is to irradiate the samples with neutrons. These studies were done on single crystal [3], bulks [4] and thick films [5]. It is also known that too many defects degrade the superconducting parameters. Therefore, it is important to asses the changes in the superconducting properties by neutron irradiation during the life time of a reactor. In this study coated conductors were irradiated by neutrons to a fluence of 1×10^{22} m^{-2}, i.e. the fluence expected for ITER during its life time. The influence on critical current densities, transition temperature, irreversibility field and angular dependence are reported.

2. Experimental

State-of-the-art coated conductors, provided from American Superconductor (AMSC) [6], were characterised by transport and magnetization measurements prior to and after irradiation. The substrate is made of a textured nickel tungsten alloy (5 at.% W) which was rolled to a thickness of 75 μm before recrystallization in a furnace to form the cube-textured template. The buffer layer consists of a Y_2O_3 seed layer followed by a YSZ barrier and a CeO_2 cap layer, which were grown epitaxially. The superconductor ($YBa_2Cu_3O_{7-\delta}$) is formed by decomposition of chemically deposited metal-organic precursors (MOD). The resulting YBCO thickness is 1 μm. After coating the YBCO layer with a silver cap layer the tape is laminated on both sides with hardened copper. The conductor is 4.4 mm wide and about 0.2 mm thick. All samples were cut from the same tape and pre-characterised by magnetoscan measurements to ensure similar properties [7].

The field dependence of the critical current density (J_C) was determined in the low and intermediate field range (up to 5 T) by VSM and transport, at higher fields (up to 15 T) only by

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transport. The measurements were done in liquid nitrogen or under helium gas flow for fields parallel and perpendicular to the *c*-axis. The length of the transport samples was limited to 27 mm. Pressed current contacts turned out to be favourable due to their lower resistivity, reproducibility and easy removability, which is important in view of the irradiation process. The 1 μV/cm criterion was used to determine the critical current.

The magnetization measurements were performed in a vector vibrating-sample magnetometer (VSM), where the magnetic moment of the sample is measured as a function of the applied magnetic field. The Bean model was used to calculate the critical current density (J_C) from the irreversible magnetic moment [8]. All measurements in the VSM were performed with the field parallel to the *c*-axis (perpendicular to the tape surface). The electric field criterion, which depends on the sweep rate of the magnetic field, was 0.02 μV/cm.

The transition temperature and the irreversibility line were measured resistively by applying a small current (10 mA) and reducing the temperature slowly until the electric field dropped to below 0.1 μV/cm. The irreversibility field (H_{irr}) for fields parallel ($H||c$) and perpendicular ($H||ab$) to the *c*-axis was measured up to a maximum field of 15 T.

The samples were irradiated in the central irradiation facility of the TRIGA Mark II research reactor in Vienna at a power of 250 kW. The samples were sealed in a quartz tube for irradiation. The temperature during irradiation does not exceed 60 °C. The type of artificial defects introduced by irradiation, strongly depends on the kinetic energy of the neutrons, e.g. spherical defects of amorphous material (collision cascades) with a diameter of about 6 nm, point defects and point defect clusters. Thermal neutrons do not lead to defects in the material. All fluences refer to fast neutrons ($E > 0.1$ MeV).

3. Results

In order to reduce the influence of sample-to-sample variations, 2–6 samples were measured and the average values determined. The differences between the samples were very small and comparable to the accuracy of the measurements.

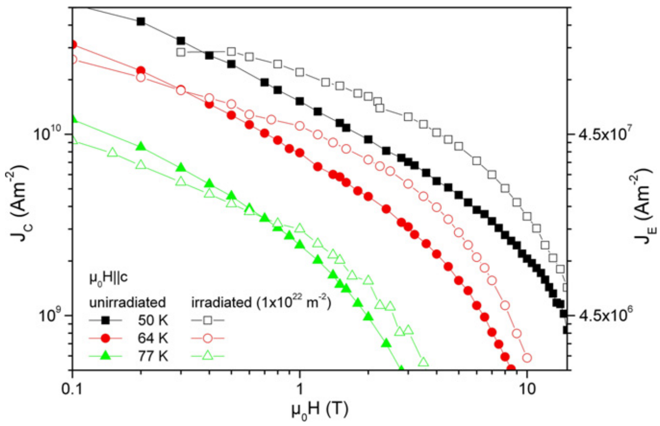

Fig. 2. Critical current densities and engineering critical current densities at three temperatures. The field was applied parallel to the *c*-axis. The open symbols show the results on the irradiated sample.

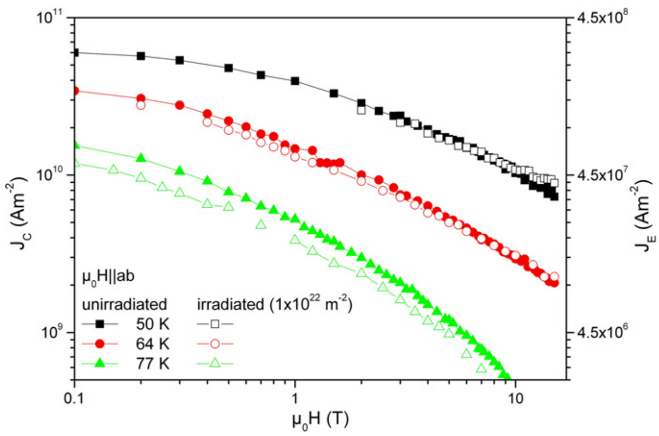

Fig. 3. Critical current densities and engineering critical current densities at three temperatures. The field was applied perpendicular to the *c*-axis. The open symbols show the results on the irradiated sample.

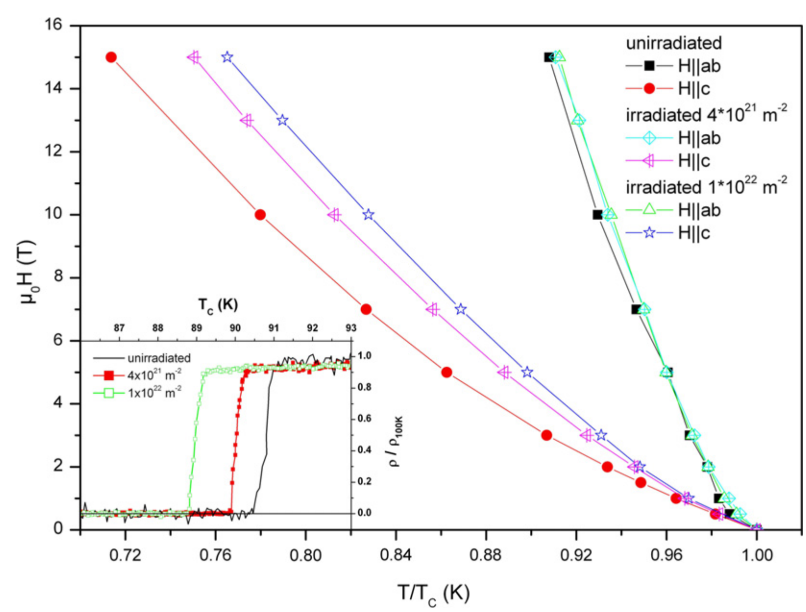

Fig. 1. Irreversibility line for the unirradiated and irradiated sample for the two main field orientations. The temperature is normalized by the transition temperature. The inset shows the transition temperatures after each irradiation step.

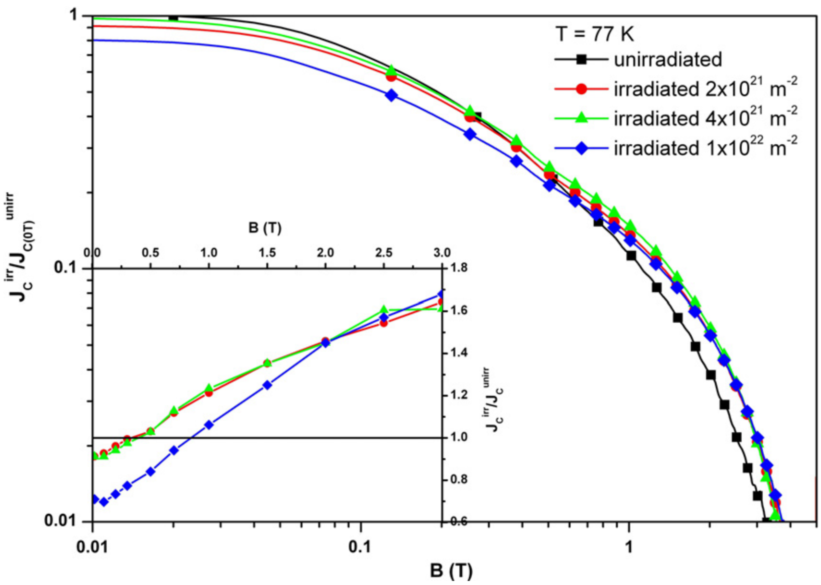

Fig. 4. Reduced critical currents measured in a VSM at 77 K after different irradiation steps.

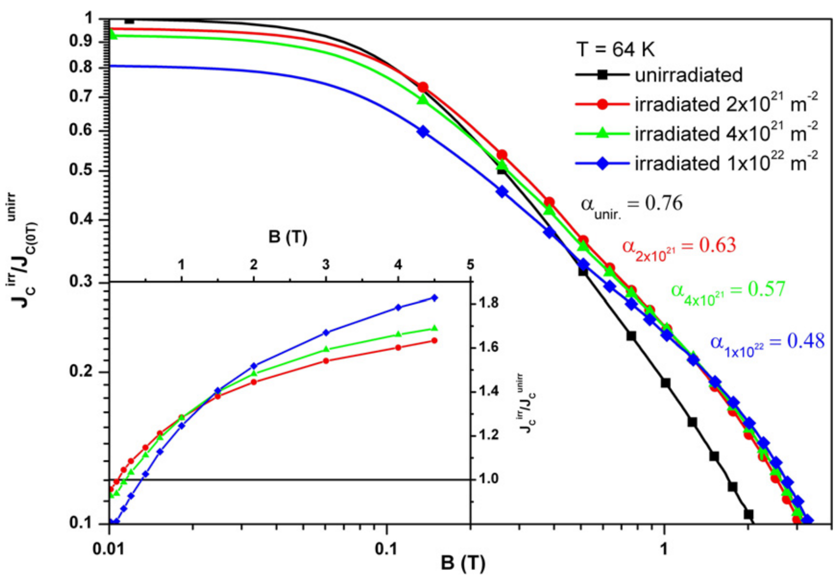

Fig. 5. Reduced critical currents measured in a VSM at 64 K after different irradiation steps. α was determined from data at intermediate fields.

3.1. Transition temperature and irreversibility line

The transition temperature (T_C) of the pristine sample was 90.8 K. It decreased slowly with every irradiation step to finally 89 K after irradiation to a fluence of $1 \times 10^{22}\,m^{-2}$. This reduction is caused by disorder in the oxygen sublattice. The width of the transition increases slightly (inset of Fig. 1).

One sample was irradiated to $4 \times 10^{21}\,m^{-2}$ and another one to $1 \times 10^{22}\,m^{-2}$ to investigate the influence of neutron irradiation on H_{irr} (Fig. 1). No significant changes are observed for $H||ab$. For the other field orientation ($H||c$), H_{irr} shifts to higher temperatures depending on neutron fluence. An increase by 4.5 K is observed at 15 T ($H||c$) and H_{irr} increases from 5.7 T to 7.4 T at 77 K. Temperatures below 67 K are required to generate a field of 13 T, the maximum field specified for the ITER coils.

Table 1
Crossover field at different temperatures and neutron fluences

Crossover field (mT)	$2 \times 10^{21}\,m^{-2}$	$4 \times 10^{21}\,m^{-2}$	$1 \times 10^{22}\,m^{-2}$
77 K	244	382	630
64 K	114	219	440
50 K	130	195	334

3.2. Critical current density (J_C)

The field dependence of J_C for $H||c$ and $H||ab$ is plotted in Figs. 2 and 3, respectively. The observed J_C at self field in the unirradiated state is $1.75 \times 10^{10}\,A\,m^{-2}$ (77 K), $3.7 \times 10^{10}\,Am^{-2}$ (64 K) and $6 \times 10^{10}\,Am^{-2}$ (50 K). The engineering current density (J_E) is around 220 times smaller than J_C because of the small superconducting fraction.

The influence of the irradiation on J_C differs for the two main field orientations, similar to the irreversibility field. A small decrease of J_C was found in the whole field range at 77 K for $H||ab$

(Fig. 3) after irradiation to a fast neutron fluence of $1 \times 10^{22}\ m^{-2}$. The influence depends on the applied field at the other temperatures and is not significant over a wide field range. The changes in J_C are more pronounced for $H||c$ and also depend on field and temperature, especially in the low field region (Fig. 2).

Magnetization measurements were performed to explore the critical current density more carefully, especially at low magnetic fields, where thermal problems occur in transport measurements. Excellent agreement between the transport and magnetization measurements was observed. This indicates a highly homogeneous tape and the dominance of inter-granular currents for the magnetic moments. Small deviations at higher magnetic fields can be explained by the smaller electric field criterion associated with VSM measurements (~0.02 μV/cm).

The obtained critical current densities (J_C) were normalized to the self field J_C of the unirradiated samples and plotted in Figs. 4 and 5. A crossover is observed, which depends on temperature and neutron fluence. J_C increases above the crossover field and decreases at lower fields. The crossover shifts to lower fields at lower temperature which is summarized in Table 1.

J_C is primarily limited by the intra-grain currents at higher fields, which can be enhanced by the introduction of effective pinning centres. At low fields the critical current density is limited by the inter-grain currents, which cannot be improved by irradiation [9]. The grain boundaries rather deteriorate under irradiation leading to a reduction of J_C. The enhancement of J_C as function of the applied field after irradiation is plotted in the inset of Figs. 4 and 5. A monotonic increase of the enhancement factor with increasing field is found.

The decay of the current density with field can be described by a power law $J_C \propto H^{-\alpha}$ at intermediate fields range. After irradiation, α decreases from 0.76 to 0.48 (64 K) because of the additional pinning centres.

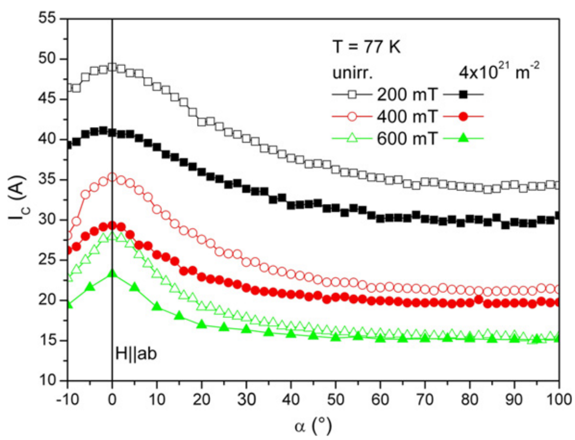

Fig. 6. Critical currents as a function of the angle between the field and the *a*/*b*-planes measured in liquid nitrogen. The field was always perpendicular to the direction of the current. The full symbols indicate measurements on irradiated samples.

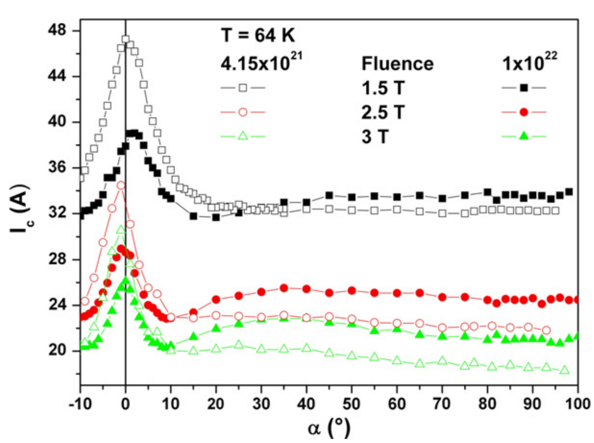

Fig. 7. Critical currents as a function of the angle between the field and the *ab*-planes measured at 64 K. The samples were irradiated to different neutron fluences. The field was always perpendicular to the direction of the current.

3.3. Angular dependence of I_C

The angular dependence of I_C was measured in liquid nitrogen and low fields (Fig. 6). During the measurements the field was always perpendicular to the direction of the current. The anisotropy of the critical currents $I_C\ (H||ab)/I_C\ (H||c)$ is 1.4, 1.6 and 1.7 at 0.2 T, 0.4 T and 0.6 T, in the unirradiated state and decreases after the irradiation to 1.3, 1.5 and 1.5, respectively. The critical currents monotonically decrease with increasing angles between the magnetic field and the *ab*-planes. A more complicated angular dependence was found at lower temperatures and higher fields (Fig. 7). Here, the critical currents decrease when the field is tilted away from the *ab*-plane. A minimum occurs at 10 from the *ab*-plane at all fields. At higher angles the current increases again and a second maximum is observed at higher fields. The peak shifts from $H||c$ at 1.5 T to around 45 at 3 T.

4. Conclusions

The influence of neutron irradiation on the irreversible properties of YBCO coated conductors was investigated. Different effects were observed for the two main field orientations. For the field perpendicular to the *c*-axis the influence was very small. No changes were found in a wide field and temperature range, otherwise a small decrease of J_C was observed. Only at low temperatures and high magnetic fields a beneficial effect was found. For fields parallel to the *c*-axis more pronounced changes were found. The irreversibility field increased by 1.7 T (to 7.4 T) at 77 K. J_C increases at high fields and decreases at low fields. These effects are related to the different limiting mechanisms, namely grain boundaries (inter-grain currents) and pinning (intra-grain currents). The J_C-anisotropy of the coated conductors decreased at all temperatures and fields.

In summary, coated conductors do not show degradations due to neutron radiation up to a fluence of $1 \times 10^{22}\ m^{-2}$ at high fields. The performance of the tapes rather improves at higher fluences over the life time of a fusion reactor.

Acknowledgements

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