YBCO Coated Conductors for Fusion Magnets

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***Abstract*—Coated conductors (CCs) are considered as an alternative to low temperature superconductors in fusion magnets. High magnetic fields are needed to confine the plasma, which can be generated by YBCO coated conductors at relatively high temperatures (50–77 K). The critical current densities of CCs improved continuously during the last few years and the production was scaled up. The conductors will be exposed to neutron radiation in a fusion magnet, which could potentially improve or degrade their properties. Industrial YBCO coated conductors were characterized by magnetization and direct transport measurements in magnetic fields of up to 15 Tesla and at temperatures between 50 and 85 K. The critical current, its anisotropy and the irreversibility line were determined. The measurements were performed on different samples, which were sequentially irradiated up to a fluence of $2 \times 10^{22}\mathrm{m}^{-2}$ (two times the ITER specification). The measurements were repeated after each irradiation step to investigate the change in the superconducting parameters. Depending on the production process of the CC and on the actual operation conditions, an increase or a decrease of the critical current density is observed. The measurements show that the performance of the CC nearly reaches the required specification for ITER conductors at present. Neutron irradiation generally does not degrade their properties in the operating range of fusion magnets.**

***Index Terms*—Critical current density, irreversibilitity line, neutron irradiation.**

I. INTRODUCTION

THE PRESENT generation of fusion devices (e.g. ITER) are based on low temperature superconductors. Coated Conductors (CCs) seem to be one of the most interesting options for the next generation of fusion magnets. Their advantages are higher operation temperatures and higher achievable fields. YBCO CCs are the best investigated high temperature superconductors (HTS) at present. Especially their potential performance in high magnetic fields at relatively high temperatures (50–77 K) favor them for magnet applications. The production of CCs increases rapidly and they recently became commercially available. Also the lengths of high quality conductors increased considerably.

Large differences between different samples appear in the irreversibility fields, the critical current densities and their angular dependence. The superconducting properties strongly depend on the preparation methods and the parameters used during this processing. Furthermore, small test samples produced in laboratories often show much better properties than industrial CCs. Many current investigations focus on improving commercially available CCs to attain similar results as on small test samples. The samples of the present study were provided by American Superconductor (AMSC) [1] and by European High Temperatures Superconductors (EHTS) [2] and represent tapes from their standard production.

A major issue for fusion magnets is their response to neutron radiation. Additional artificial defects are generated in the superconductor during neutron irradiation, which may degrade the superconductor or result in pinning centers [3]. Therefore, the CCs were sequentially irradiated by neutrons up to the expected ITER life time fluence $(10^{22}\ \mathrm{m}^{-2})$ and beyond. The superconducting properties were monitored and the influences on ITER relevant parameters [4] were determined.

Since the aim was to characterize commercially available high temperature superconducting tapes under potential operating conditions of magnets in fusion devices, the measurements were limited to temperatures in the range of liquid nitrogen (64 to 77 K).

II. EXPERIMENTAL

The field dependence of the critical current density (J_C) and the irreversibility line were determined by transport measurements up to a magnetic field of 15 T. A four point method was employed to determine the critical current using a criterion of 1 $\mu V/cm$. The current was ramped continuously during the measurements until an abort criterion was reached. The measurements were done in liquid nitrogen or under helium gas flow at different fields and sample orientations. Pressed current contacts turned out to be favorable due to their low resistivity, reproducibility and easy removability, which is important in view of the irradiation process. The transition temperature (T_C) and the irreversibility line (IL) were measured by applying a small current (3 to 10 mA) while reducing the temperature slowly until the electric field dropped below 0.1 μV/cm. Additional magnetization measurements in a vector vibrating-sample magnetometer (VSM) were performed (up to 5 T) to confirm the transport results. The Bean model was used to calculate the critical current density (J_C) from the irreversible magnetic moments [5].

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 into a quartz tube for irradiation. The temperature during irradiation did not exceed 60 °C. The introduced defect structure was already studied in detail [6]. All given fluences refer to fast neutrons (E $\geq$ 0.1 MeV).

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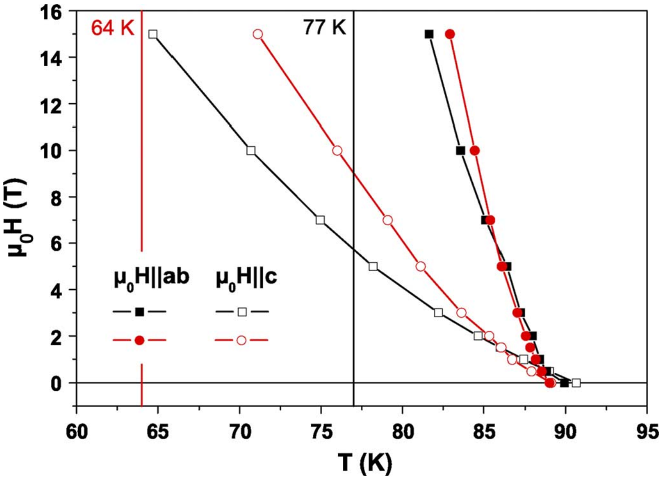

Fig. 1. Irreversibility lines. Squares and circles refer to the worst and best samples, respectively.

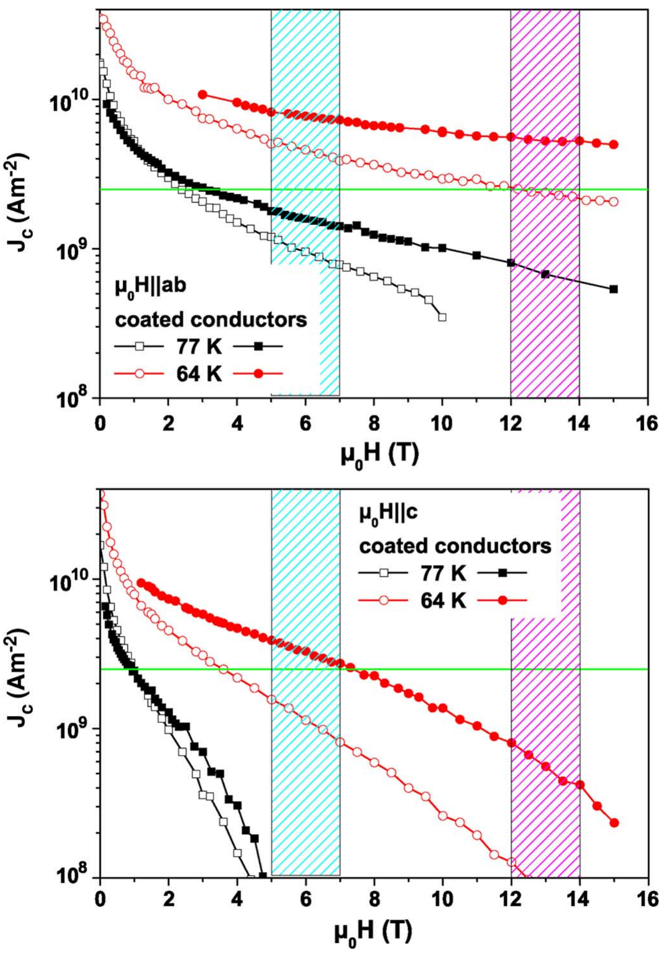

Fig. 2. Critical current densities at 64 K and 77 K. Open and solid symbols refer to the worst and best samples. Critical currents for the field parallel to the ab planes (top) and to the c-axis (bottom).

III. RESULTS

A. Irreversibility Line

The irreversibility lines (Fig. 1) were measured for the two main field directions ($\mathrm{H}||\mathrm{c}$ and $\mathrm{H}||\mathrm{ab}$). Pronounced differences in the irreversibility field appear for fields parallel to the c-axis (H_{irr} ranges from 5.6 T to 9 T at 77 K). A difference in the irreversibility temperature (T_{irr}) of 6 K was found at 15 T. No significant differences were found for fields perpendicular to the c-axis (1 K at 15 T). T_{irr} is always higher than 80 K at the maximum field of 15 T $(\mathrm{H}||\mathrm{ab})$. If we compare the IL for the field perpendicular to the c-axis with the design fields of ITER, they are all clearly below H_{irr} at 77 K. This is not the case for the other field orientation. The minimum required field (ca. 6 T) lies almost exactly on the IL of the better tapes at 77 K. However, the maximum fields of the ITER toroidal and central field coils are below the irreversibility fields at 64 K.

B. Critical Current Density (J_C)

Since the critical currents in HTS are anisotropic, they were determined for different orientations and fields. In order to reduce the influence of sample-to-sample variations, several samples were measured and the average determined. The currents are usually highest, when the field is oriented parallel to the ab-planes, and often lowest for the other main field orientation, but in some cases the minimum can occur also at other orientations [7]. The angular dependence of J_C has to be taken into account in future coil designs. However, we only discuss the two main field orientations in the following and assume that these two cases represent a reasonable estimation for the minimum and the maximum of the critical currents in our samples.

The critical current densities for the field parallel to the ab-planes are plotted in Fig. 2 (upper panel). The specified fields for the ITER coils are marked by the shaded areas [4]. The necessary current densities strongly depend on the design and the stabilization of the wires. The overall engineering critical current density of the ITER TF cables is around 5.3×10^7 A/m^2, but possible designs of HTS cables might be strongly different and need a higher J_C to achieve similar overall engineering critical current densities. The mechanical reinforcement (substrate) as well as the stabilization (copper layer) are already included in the CC architecture. If we assume a ROEBEL assembled cable [8], which seems to be a promising choice, the ratio between J_C and the engineering current density of the cable is given by the superconducting volume fraction of the CC. This ratio is rather low in today's CCs and, assuming 2 %, a critical current density of around $2.5 \times 10^9 A/m^2$ is needed to obtain the engineering current density of the ITER TF cable. We will assume this J_C as the design limit in the following (horizontal line in Figs. 2 and 4). The CCs meet this criterion at 64 K $H||ab$ (circles). Even higher temperatures seem to be feasible after further conductor development, although the best sample under consideration misses our criterion for J_C by a factor of around 4 at 77 K and 13 T. The situation is much worse, when the field is applied perpendicular to the tape (Fig. 2, lower panel). The critical current densities are too low at 77 K and the estimated requirements can only be met at 64 K for the low field coils. Thus, the true field orientation inside the coils and angular dependent measurements of J_C are needed to clarify the suitability of CCs for fusion magnets and their operating conditions.

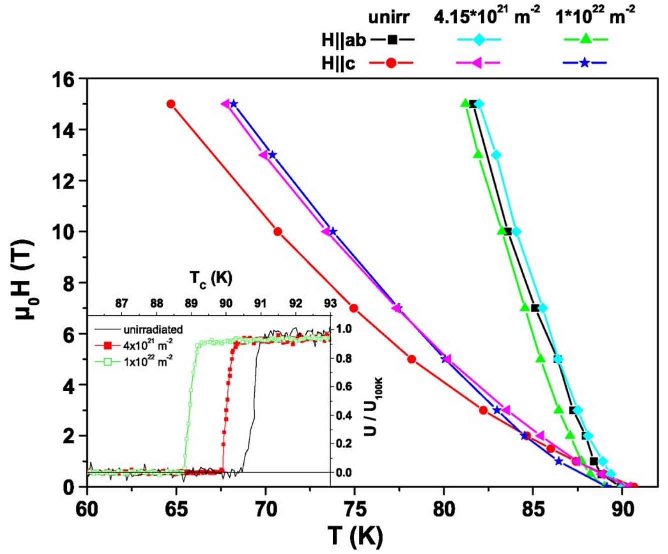

Fig. 3. Irreversibility line of the unirradiated and irradiated sample for the two main field orientations. The inset shows the transition temperatures after each irradiation step.

C. Neutron Irradiation Effects

The transition temperature of the pristine samples was between 90.8 K and 88.7 K. It decreased slowly with every irradiation step, whereas the transition width increased slightly. As an example, T_C and the IL of one unirradiated and two irradiated samples are plotted in Fig. 3. No significant changes were observed after the irradiation in many samples when the field was perpendicular to the c-axis $(\mathrm{H}\|\mathrm{ab})$ (T_{irr} changes by less than 1 K). For the other field orientation $(\mathrm{H}\|\mathrm{c})$, H_{irr} shifted to higher temperatures (above 2 T). This increase is more pronounced in samples with originally low irreversibility fields, whereas H_{irr} remains nearly unchanged in materials with high irreversibility line. This observation was made on many HTS materials and indicates the improved flux pinning capability of the newly introduced strong flux pinning centers. No further increase was observed at fluences above $10^{22}\ \mathrm{m}^{-2}$.

The influence of radiation on J_C depends on the sample. Generally, the irradiation effects are not too pronounced for the field perpendicular to the c-axis (Fig. 4). In some samples J_C at 77 K decreases by up to 23 % at a neutron fluence of $10^{22}\ \mathrm{m}^{-2}$. Other samples show an increase by a few percent at the same temperature. J_C is more or less unchanged at 64 K.

A huge increase of J_C is observed after neutron irradiation for the field parallel to the c-axis in the intermediate and high field region. The increase strongly depends on the field (Figs. 4 and 5) and lies between 50 % and 300 %. J_C decreases somewhat at low fields (below 1 T), which is attributed to a degradation of the grain boundaries. However, no degradation of the critical current density was observed in the field and temperature range relevant for fusion magnets.

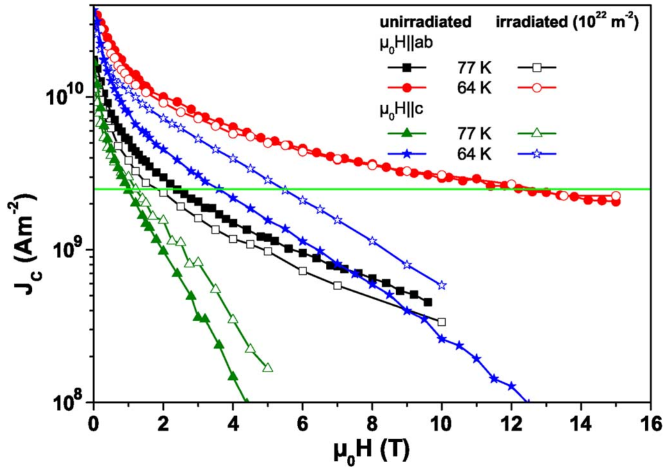

Fig. 4. Critical current density of an unirradiated and irradiated sample for the two main field orientations.

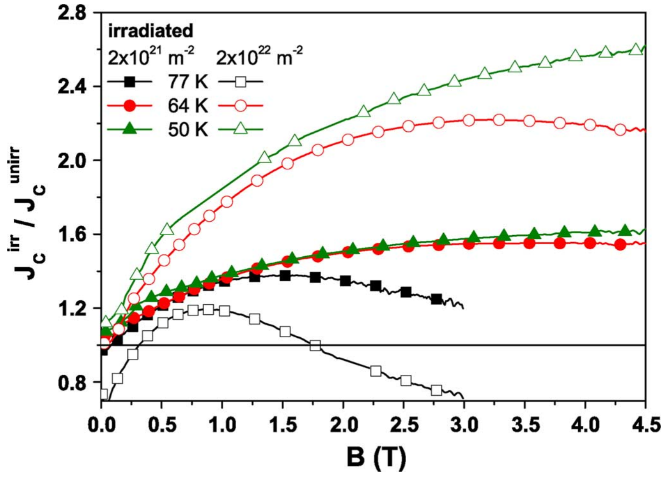

Fig. 5. Change of the critical current density after neutron irradiation to two fluences as a function of the magnetic field.

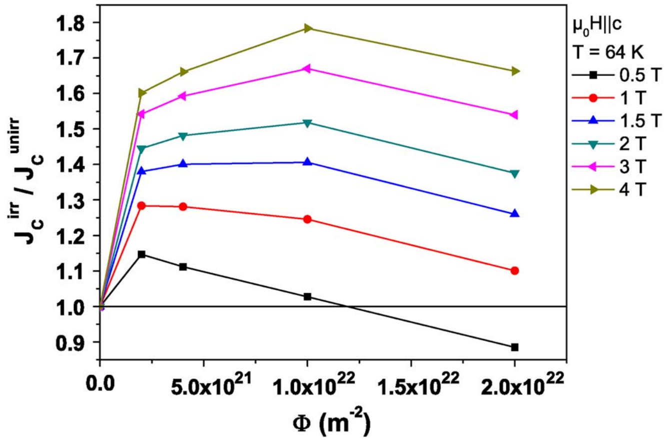

Fig. 6. Ratio of the critical current density before and after irradiation to various fluences.

Measurements after different irradiation steps were made to determine the influence of the neutron fluence (Fig. 6). Because of the residual radioactivity the measurements were done in the VSM, where smaller samples can be used and mounting is much faster. This reduces the necessary time between irradiation and measurement. A longer decay time was needed for the larger transport samples. Up to a fluence of $2\times10^{21}\ \mathrm{m}^{-2}$, an increase of J_C is observed at all fields, except at very low fields. The ratio of J_C prior to and after irradiation starts to decrease at higher fluences and a peak in J_C appears (Fig. 6). The position

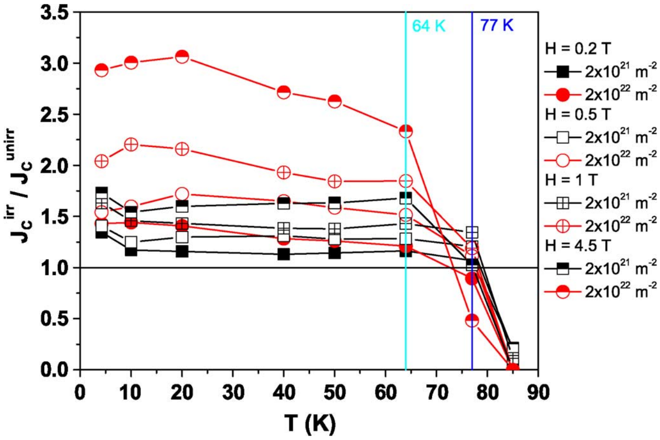

Fig. 7. Increase of the critical current density as a function of temperature at different magnetic fields and neutron fluences.

of the peak depends on the field and the maximum in J_C shifts to higher fluences at higher fields. Although the critical currents decrease with increasing fluence they remain above the level of the unirradiated state up to a fluence of 2×10^{22} m^{-2}.

The increase in J_C is rather constant over a wide temperature range, whereas the performance of the conductor decreases very rapidly at high temperatures (Fig. 7). The temperature, where J_C in the irradiated sample falls below J_C in the unirradiated state, is slightly above 77 K for a fluence of 10^{22} m^{-2}. At higher fluences this crossover appears at lower temperatures, the degradation might become relevant in future fusion devices.

IV. CONCLUSIONS

The suitability of Y-123 based coated conductors for applications in fusion magnets was reported. The critical currents and the irreversibility lines were assessed by direct transport and/or magnetization measurements. The properties required for fusion magnets can be reached under certain conditions, but an operation at 77 K seems hardly possible at present. It is not unrealistic to achieve the required performance at 64 K, especially in view of the rapid progress in conductor development. A major problem is the low J_C for fields perpendicular to the tape surface. Although the main field orientation in a coil is mainly parallel to the tape surface, field components perpendicular to the tape might represent a problem.

The coated conductors were irradiated to a fast neutron fluence of 2×10^{22} m^{-2}, i.e. two times the ITER design fluence. No degradation of the superconducting properties was observed in the relevant field and temperature range up to this fluence. At higher fluences the material starts to degrade at around 77 K.

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