30 mm Wide IBAD-MgO REBCO Coated Conductors Developed at the KC^4 Facility

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***Abstract*—In this paper we report on a novel HTS coated conductor developed at the KIT-CERN Collaboration on Coated Conductors (KC^4) facility at the Institute of Technical Physics (ITEP), Karlsruhe Institute of Technology (KIT), Germany, namely the first-ever 30 mm wide coated conductor on IBAD-MgO, which was provided by iBeam Materials. These samples are highly homogenous with self-field J_c values at 77 K and 30 K of 1.0 MA/cm^2 and 6.6 MA/cm^2 respectively. We will briefly introduce the KC^4 facility, which is a pilot production coated conductor R&D laboratory, established for material development to bridge the gap between research and manufacturing and to transfer small-scale PLD research results to large-scale coated conductors (CCs). Since the completion of the deposition line in 2023, REBCO films have been deposited on long-length metal substrates with various buffer stacks, and reasonably good I_c values of 300 A/cm width at 77 K on 12 mm wide tapes were obtained with the potential for further improvement. Efforts are in progress to upscale the R&D to wider tapes that will open new avenues for the application of CCs in the high-field, low temperature region as well as for special applications.**

***Index Terms*—HTS coated conductors, IBAD-MgO, KC^4 pilot production line, PLD, REBCO, wide HTS tapes.**

I. Introduction

SECOND-GENERATION coated conductors (CCs) containing a $RE\mathrm{Ba_2Cu_3O_{7-\delta}}$ (Rare Earth = *RE*, *RE*BCO) superconducting layer succeeded first-generation BSCCO-based tapes. This architectural shift, achieved after years of development, was driven by the demand for superior mechanical properties and production scalability while maintaining high critical current densities.

Currently, CC based on *RE*BCO-superconducting layer have become even more significant. Due to rapid development of the IBAD-MgO bi-axially textured templates [1] replacing the former more time-consuming IBAD templates based on Y-stabilized zirconia (YSZ) as well as the RABiTS process with issues in delamination properties and grain boundary transparencies, the production of CCs rose on an industrial scale [2], [3], [4], especially for ultra-high-field applications [5], [6] and to transfer large amounts of current without losses [7]. Additionally, advancements in CC technologies allowed many research groups around the world to develop better and more efficient cables, motors, generators and especially magnets. Within last couple of years many fusion start-ups like Proxima Fusion and Commonwealth Fusion Systems have emerged with the goal of using HTS CCs to build magnets for their magnetic-field-based confinement concepts [8] to maintain a compact plasma and produce vast amounts of clean energy. This leads to an increased demand for CCs.

Even though the CC industry is rapidly advancing with new start-ups [9], challenges on bridging the gap between material research institutes and large-scale CC manufacturers remain. Innovative material development approaches of small-scale research labs often cannot be tested in demonstrator systems due to the unavailability of necessary tape length and hence it may take years until producers take up these developments. For this reason, the KIT-CERN Collaboration on Coated Conductors (KC^4) was founded. Despite significant progress in km-long production, REBCO CC manufacturers largely restrict the tapes to standard widths of 4 and 12 mm [10], [11], particularly due to demand from high-field applications [12]. Nevertheless, wider HTS CC tapes have huge potential for several applications, including novel magnet architectures such as DUDA [13], RF cavities [14] and undulators [15]. Seeing the innumerous benefits of wide CCs, REBCO deposition on 30 mm CC wide IBAD-MgO templates were carried out at the KC^4 facility with the possibility to upscale the width even further and investigate various novel magnet designs and tailored pinning landscapes.

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Fig. 1. PLD 600 deposition line view (top left), the plasma plume inside the PLD 600 chamber (bottom left), tape winding machine and a drum (right).

II. KC^4: KIT-CERN Joint Open Collaboration on HTS Coated Conductors

A. The KC^4 Facility

Within the High Field Magnets R&D Initiative of CERN [16] KIT and CERN started a joint project in 2021 to take over the industrial pilot CC facilities of Bruker (Fig. 1, top left), which were located at that time in Alzenau, Germany and developed by Bruker using their proprietary ABAD textured tapes concept in combination with HTS deposition using Pulsed Laser Deposition (PLD, Fig. 1 bottom left) [17]. These tapes showed very good low temperature, high field critical current properties and Bruker demonstrated tape length depositions up to 600 m [18]. The unique aspects of the Bruker CC approach were to use ABAD textured YSZ buffer layers and a PLD deposition system, which covers not a simple reel-to-reel tape transportation. Instead, a long rotating cylinder surface covering the textured metal tape is coated (Fig. 1, right). This approach enables the use of a completely radiation-based substrate heating and the possibility to coat tapes of various width and even wide foils under identical deposition conditions. Core deposition facilities covering reel-to-reel substrate cleaning, ABAD buffer deposition, HTS deposition by PLD, Ag- coating, O-loading and Cu-plating were moved to, installed and commissioned at the Institute for Technical Physics at KIT.

Since 2023 first deposition runs were performed, and since 2024 regular research-based CC coating operations are running.

The basic concept of KC^4 is to realize a research-oriented CC pilot production facility, which is able to deposit special, not commercially available, high quality CC architectures in sufficiently long tape lengths, enabling the realization of special research focused demonstrator systems in the magnet and power application area. Equally important will be the development of new high performance CC architectures for various application fields. Currently, high quality doped and undoped YBCO thin films with a typical film thickness of 1 µm are deposited onto commercially available IBAD-MgO templates instead of using the BRUKER ABAD templates. We obtained and tested high quality IBAD-MgO templates up to a tape width of 16 mm from several commercial Coated Conductor producers like Faraday Factory, Sunam, Shanghai Superconductor Technologies SSCT, Shanghai Creative Superconductors SCSC and High-Temperature Superconductors HIT. Our approach to realize also wide CCs larger than 20 mm tape width is so far strongly limited since no IBAD MgO templates wider than 16 mm are currently available from commercial suppliers. Therefore, we started our own wide IBAD MgO tape development task together with iBeam Inc. and the results shown in this paper on 30 mm wide IBAD tapes are based on these templates. Standard 12 mm wide IBAD tapes coated with 1 µm HTS were used for process optimization and show the following typical properties.

B. Experimental Procedures

Pristine YBCO films were deposited on 12 mm wide tapes from Shanghai Superconductors Inc. with CeO_2 terminating layer, and on IBAD-MgO 30 mm wide tapes with $(La,Sr)MnO_3$ (LSMO) buffer layer in one run. To deposit a 1 µm thick YBCO layer, the deposition temperature was set to 770°C, the repetition rate of the XeCl excimer laser (LEAP Coherent, $\lambda = 308$ nm) was set to 190 Hz, the oxygen partial pressure to 0.4 mbar and the laser energy to 455 mJ. The growth rate was 0.24 nm/s, and to achieve a 1 µm thick YBCO layer, 800000 pulses were required. After the deposition, all tapes were coated with a 3 µm thick silver protective layer by thermal evaporation followed by oxygen annealing in a tubular furnace for 2 hours at 450°C.

The phase purity and possible presence of secondary phases as well as pole figures were measured at a Bruker XRD D8 and a Rigaku Smartlab 3 kW device. The uniformity of coating for the 30 mm wide tapes were acquired by inductive J_c measurement on a CryoScan, THEVA GmbH (criterion 50 mV corresponding to 1µV/cm in transport measurements). Critical temperatures (T_c) were measured inductively on a 14 T Physical Properties Measurement System (PPMS) with an in-house-made mutual induction set-up. To measure the transport properties, pieces of 1×1 cm were laser cut from the middle of the 12 mm and the 30 mm wide tapes and structured into 1 mm long and 20 µm wide bridges by using a Nd:YAG pico-second laser. The transport properties were measured at the PPMS in 4-point geometry with magnetic fields up to 14 T. To calculate J_c, a 1 µV/cm criterion was used.

C. Results on 12 mm Wide IBAD-MgO Tapes

The KC^4 HTS-pilot line, even though being an industrial type of deposition line, is primarily used as a research facility at ITEP-KIT being able to coat up to 200 m of 12 mm wide CCs. Like small-scale pulsed laser deposition setups, it requires systematic depositions to see the limits of its capabilities as well as to show the performance and upscaling of HTS tapes produced. Therefore, the PLD deposition system needed to be optimized and tested on 12 mm wide tapes prior to the deposition on 30 mm wide IBAD-MgO tapes. For this, many deposition runs were done starting from 60 cm long pieces up to 30 m long pieces. Since different IBAD-MgO templates require different deposition parameters we are currently focusing our experiments deposition of pristine YBCO on CeO_2 terminated IBAD-MgO tapes from Shanghai Superconductors Inc.

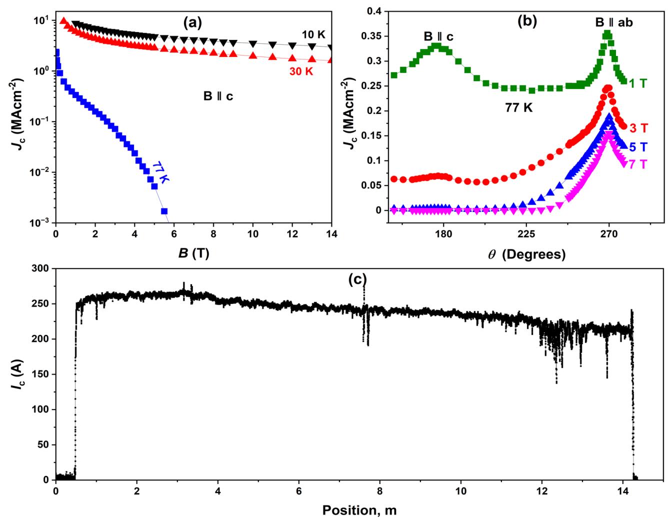

Fig. 2. Critical current densities of 1 µm thick YBCO superconducting thin film deposited on 12 mm wide IBAD-MgO template from Shanghai Superconductors Inc. (a) Field dependence of J_c at 77, 30 and 10 K; (b) Angular dependence of J_c at 77 K; (c) Critical current I_c vs. length for 15 m long tape.

Fig. 2(a) shows the field dependence of J_c at 77, 30 and 10 K. At 77 K and self-field, 1 µm thick YBCO superconducting film shows 2.4 MAcm^{-2}. This value is rather common for YBCO films on single crystals and on commercially available tapes and lies in the typical range of 2–6 MAcm^2 [19]. Compared to low-field J_c, the tape shows a strong dependence on magnetic fields at 77 K. At 30 K and 3 T, J_c is 3.6 MAcm^2 and at 10 K and 10 T tape also shows 3.5 MAcm^2.

The dependence of J_c on magnetic field orientation ($J_c(\theta)$ characteristic, Fig. 2(b)) at 77 K shows a large peak in the *c*-axis direction at 1 T, and a large peak in *ab*-direction. At 3 T, the peak in *c*-axis direction is still visible; however, at 5 T and 7 T, it completely vanishes leaving a flat area around *c*-direction and large peaks in *ab*-direction. Such behavior is common for YBCO superconducting thin films, because during the deposition and island-type growth of the film, many low-angle grain boundaries are formed, which leads to the formation of a large density of threading dislocations that are able to pin magnetic flux lines along their length. The disappearance of the peak at 3 T suggests a matching effect. Considering that the density of threading dislocation may reach up to 10^{11} lines/cm^3, [20] this leads to a matching field of ∼1 T. Therefore, around 1 T, we observe a change in the pinning mechanism.

Fig. 2(c) shows the length dependence of I_c for a 15 m long tape. The tape shows values of 250-300 A for the first 10 m, which is followed by a gradual reduction over the last 5 m down to 220 A. This suggest that the deposition process still need to be optimized even further. In addition to the reduction of I_c, dropouts in I_c are visible. The reasons for this may be several factors such as tape handling, winding, instabilities of the deposition temperature and many others combined. Nevertheless, considering the results shown in this subsection, the HTS tapes from the KC^4 pilot line already satisfy certain performance levels starting at liquid nitrogen temperatures down to 10 K and at high magnetic fields, while the performance during the upscaling process is kept. Improved magnetic field performances could be obtained by using doped YBCO targets and will be reported elsewhere.

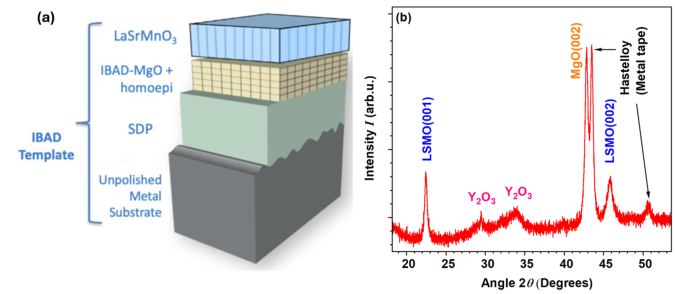

Fig. 3. (a) Schematic of the 30 mm wide IBAD-MgO template obtained from iBeam Materials, showing all the buffer layers; (b). θ-2θ XRD scans confirm the (100) orientation of the MgO and LSMO layer.

III. Successful Deposition of REBCO Films on 30mm Wide IBAD-MgO Tapes

The 30 mm wide IBAD-MgO template shown in Fig. 3(a) was developed at iBeam Materials, Santa Fe, USA, with the following configuration: IBAD-MgO/Epi-MgO/(La,Sr)MnO_3 (LSMO), deposited on solution-deposition planarized (SDP) Y_2O_3 (Yttria) coated Hastelloy C-276. The θ-2θ XRD scans in Fig. 3(b) confirmed the (100) orientation of the MgO and LSMO layers, and pole figure measurements indicate that the in-plane orientation is in the range 6.1°– 7.0° and 6.6° – 7.8° and the out-of-plane texture is in the range 2.8° – 4.8° and 3.4° – 4.9° respectively. The LSMO layer was deposited from a sputter target with the composition $La_{0.7}Sr_{0.3}MnO_3$ at iBeam Materials and has a nominal thickness of 40 nm. The thickness of the Hastelloy tape is within 40-50 µm and the thickness of the Yttria layer, used to planarize the Hastelloy is between 0.5 and 1.0 µm. The thickness of the IBAD-MgO layer is up to 15 nm (typically around 10 nm) and that of the homoepitaxial MgO layer is 60 nm. The conditions for PLD of YBCO on 12 mm and 30 mm wide tapes were identical.

The self-field critical current density (J_c) at 77 K of one of the produced tapes of width 30 mm and length 60 mm (Fig. 4) is highly uniform throughout the width and length, with a maximum value of 1.15 MA/cm^2. The θ-2θ XRD scan (Fig. 5(a)) shows that the YBCO film is phase pure with the desired *c*-axis orientation. The $R(T)$ measurements in Fig. 5(b) show a reasonably high T_c onset value of 88 K along with a sharp transition of ∼1 K.

The field and orientation dependence of J_c of the 30 mm wide sample are similar to the ones of the 12 mm wide tape. From the $J_c(B)$ measurements in Fig. 5(c), it can be seen that the J_c value in zero external field at 77 K is ∼1 MA/cm^2, corresponding to the inductively measured value, and at 30 K and 10 T external field, J_c is above 1 MA/cm^2 too. The angular dependence of J_c at 77 K, Fig. 5(d), shows high J_c values for $B \| c$ ($\theta = 0°$) in low-fields, and $B \| ab$ ($\theta = 90°$) in high-fields. Thus, the 30 mm wide REBCO tapes developed at the KC^4 facility have excellent properties considering the first-of-its-kind trials. The used cylinder-based deposition strategy will allow to extend this to coating of 60 cm

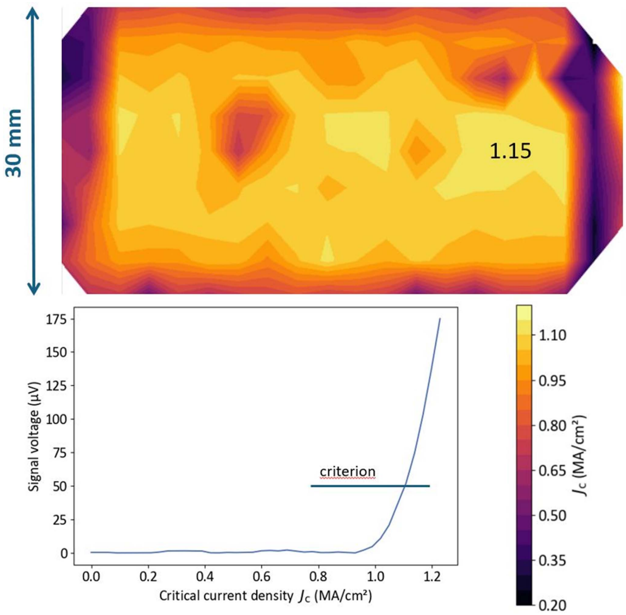

Fig. 4. Self-field inductive J_c measurement at 77 K, showing the J_c map (top) across the 30 mm × 60 mm sample, with *J*-*V* curve at the maximum J_c of 1.15 MA/cm^2 measured on the grid 3 mm × 3 mm. The J_c map and the sharp rise in the *J*-*V* curves indicate a uniform distribution across the width and length of the tape. Along the edges, fringe effects are observed due to partial placement of the measurement coil over the tape surface. .

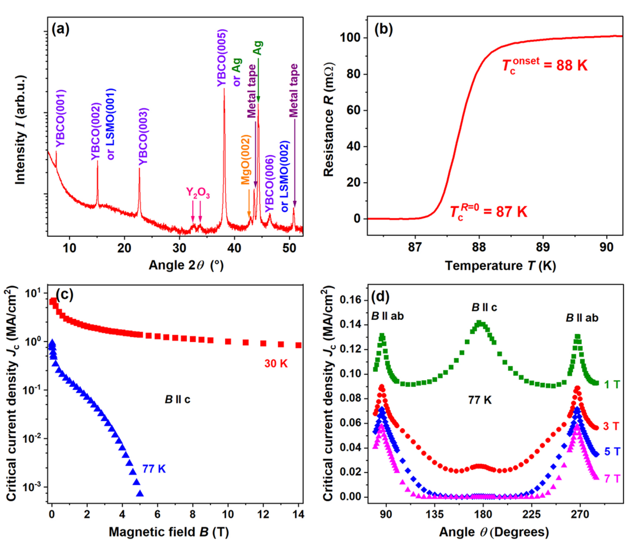

Fig. 5. *θ*-2*θ* XRD and transport measurements performed on the 30 mm wide REBCO tape: (a) good c-axis orientation and phase purity of the YBCO layer; (b) reasonably high T_c along with a reasonably sharp phase transition observed; (c) $J_c \geq 1$ MA/cm^2 in 10 T external field at 30 K; (d) high J_c values for *B* parallel to the c-axis in low magnetic fields and *B* parallel to the ab plane in high magnetic fields at 77 K.

wide and up to 5 m long HTS foils, provided the availability of such large area high quality IBAD-MgO templates.

IV. Outlook

From above results, we conclude that the 30 mm wide tapes developed at the KC^4 facility have the potential to be used in various high-field, low-temperature applications and with further optimization of the deposition parameters along with the inclusion of artificial pinning centers (APCs), they can pave the way for the advancement of wide HTS tapes. Since their width can be tailored for various applications, future plans involve upscaling to even wider tapes of 100 mm and longer lengths up to 10 m.

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