# Fast Growth Process of Long-Length YBCO Coated Conductor with High Critical Current Density

Yijie Li, J. Reeves, X. Xiong, Y. Qiao, Y. Xie, P. Hou, A. Knoll, K. Lenseth, and V. Selvamanickam

***Abstract*—On the basis of previously reported 10 m long YBCO tape with over 100 A/cm performance, we are working towards scaling up the YBCO coating process to 100 m lengths. We are using a high tape speed of 15 m/h for fabrication of long lengths. To understand the mechanism of high growth rates of $YBa_2Cu_3O_{7-x}$ (YBCO) on buffered metal substrates, the relationship between critical current density and YBCO film thickness has been systematically investigated. When YBCO thickness was below one micrometer, the critical current density ($J_c$) was over 2 MA/cm$^2$. As YBCO thickness was increased, $J_c$ decreased gradually. However, $J_c$ still remained 0.91 MA/cm$^2$ at a YBCO thickness of 4.2 μm. Critical current ($I_c$) was 380 A across 1 cm wide tape at 77 K. To scale up YBCO coating process, the deposition rate was increased to a growth rate of 70 nm/s, corresponding to a tape speed of 15 m/h. The average phi-scan rocking curve of YBCO films was ~3° on 11° buffered metal tape. The omega scan rocking curve (FWHM) was just 1.5°. $J_c$ of 2 MA/cm$^2$ at 77 K and self-field was achieved at a high deposition rate of 70 nm/s and a tape speed of 15 m/h by optimizing deposition parameters. The high rate process has been transferred to long lengths and results will be discussed in this manuscript.**

***Index Terms*—Coated conductors, microstructural analysis, pulsed laser deposition, superconducting materials, in-plane texture, YBCO thick films.**

## I. Introduction

SINCE the first meter-long YBCO coated conductor with over 100 A/cm was demonstrated [1], great progress has been made to scale up YBCO coated conductor fabrication in the range of kilometer length for practical electric power applications. The essential prerequisite for various large scale practical applications of coated conductors is the cost goal of \$10/kAm set by the U.S. Department of Energy for the superconducting wires to replace traditional copper wires. The critical current carrying capability is a major factor in achieving a low-cost conductor. To develop coated conductor with very high performance, one approach is to improve superconducting critical current density $J_c$. However, this will be limited by the buffer epitaxial quality or substrate texture. The other approach is to increase superconducting layer thickness. Unfortunately, previous studies showed that $J_c$ decreased with increase in YBCO thickness [2], [3]. Ion mill thinning experiments demonstrated that the top layer of thick YBCO films (>2μm) had much less and even no contribution to superconducting current carrying capability. In order to achieve high currents with thick films, it is necessary to understand the relationship between the YBCO thick film microstructure and the critical current $I_c$.

In this work, we deposited a series of YBCO films with different thicknesses. The superconducting critical current $I_c$ and microstructure of these YBCO films was investigated. The high rate reel-to-reel process has been transferred to pilot line for over 100m long length fabrication. In this paper, we also report our latest progress on scale-up of the YBCO coated conductor process.

## II. Experimental

### A. Short YBCO film deposition

Different thickness YBCO films were deposited on IBAD substrates using pulsed laser deposition (PLD). YBCO thickness change experiments were completed in our reel-to-reel prototype PLD system. The sample length was 10 cm. Short YBCO tapes (10 cm) were grown with KrF eximer laser (LPX200i). A base pressure of $5\times10^{-5}$ Torr was used. Laser pulse energy was 500-650 mJ. The incident angle of laser beam was 45°. High density YBCO targets were used for ablation. During deposition, in order to uniformly ablate the surface area of the YBCO target, computer-controlled target manipulation was applied for rapid rotation and rastering. The oxygen pressure was 200 mTorr. Laser pulse repetition rate was 100 Hz. The thickness of YBCO films varied from 0.5-4.2 μm. During YBCO thickness experiments, YBCO deposition conditions were fixed. Different YBCO thickness was achieved by using different tape moving speed. Film thickness was measured with a Dektak IID step-profilometer. Critical current $I_c$ was measured by a conventional four probe method using a criterion of 1 μV/cm. For $I_c$ and $J_c$ measurements, both

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wet-etched samples with 0.4-0.6 mm wide bridge and 1.0 cm wide unetched samples were used for comparison.

*B. Long YBCO coated conductor fabrication*

Long length YBCO tapes were fabricated with a Lambda Steel Industrial XeCl Laser. The details of YBCO tape fabrication have been published elsewhere [4], [5].

On the basis of previously reported 10 m long YBCO tape with over 100 A/cm performance, the process has been scaled up to 100 meter lengths. The current tape speed is 15 m/h corresponding to a 100 Hz of laser pulse repetition rate. For long tape fabrication, all processes from polishing, buffer deposition, YBCO deposition, and silver deposition were completed in a reel-to-reel mode. YBCO performance characterization of long tapes was completed with a reel-to-reel $I_c$ rig.

*C. Transport characterization and structural analysis*

The orientation and texture of YBCO films were analyzed by a general area detector diffraction system (Bruker Advanced X-ray Solutions, Inc.) with Cu Kα radiation operated at 20 mA and 40 kV, including θ-2θ scan, ϕ scan, and ω scan rocking curve measurements. The surface morphology of the films was observed using a high-resolution field emission scanning electron microscope (FESEM).

## III. Results and Discussions

*A. Superconducting properties of thick YBCO short samples*

The YBCO films with different thicknesses were deposited on 10 cm long and 1.0 cm wide buffered metal substrates. Because our earlier study showed that YBCO growth optimum temperature was strongly related with YBCO deposition rate [4], all YBCO samples in this work were deposited under the same growth rate. Differing YBCO thickness was controlled by changing the tape speed. Figure 1 shows the end-to-end $I_c$ values measured from different YBCO films. The thinnest YBCO film thickness is 0.6 μm. $I_c$ was 120 A at a criterion of 1 μV/cm. During $I_c$ measurements, for over 1.0 μm thick YBCO films, a very strict criterion of 2 μV per 10 cm was used to avoid burning samples. As shown in Figure 1, with increasing of YBCO thickness from 0.6 μm to 4.2 μm, $I_c$ also continuously increased from 120 A to 380 A although the increasing of $I_c$ was not linear.

Figure 2 shows the dependence of critical current density $J_c$ calculated with 1.0 cm full width and patterned 0.4-0.6 mm wide bridge. It was found that $J_c$ values measured from pattered samples were higher than those directly measured from full width samples. This difference possibly resulted from the thickness deviation across the tape width, especially for thinner YBCO films. When YBCO thickness was below one

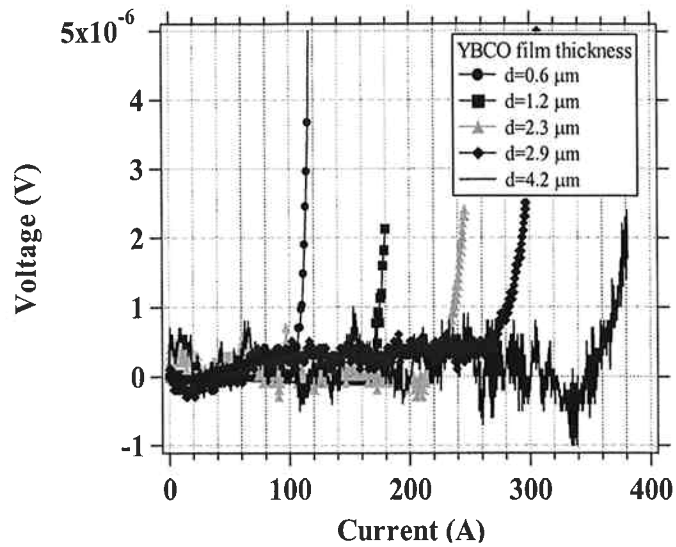


Fig. 1. I-V curves for different thick YBCO films deposited on buffered metal substrates. The YBCO tape width was 1.0 cm.

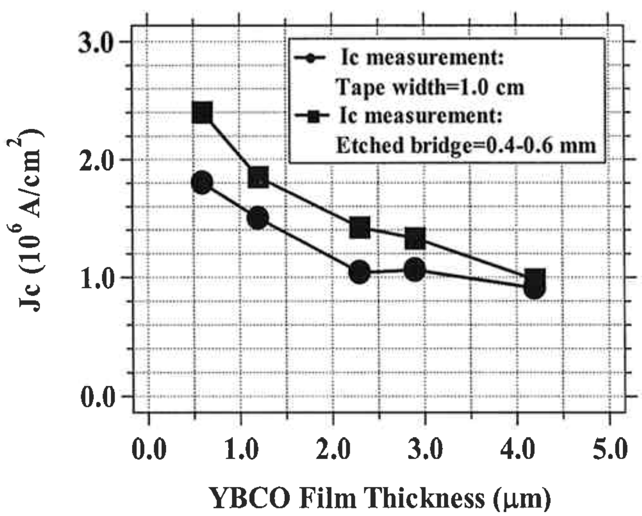


Fig. 2. Critical current density $J_c$ versus YBCO film thickness measured from full 1.0 cm width and etched 0.4-0.6 mm wide bridge, respectively.

micrometer, $J_c$ was over 2.0 $MA/cm^2$. As YBCO thickness was increased, $J_c$ decreased gradually. However, $J_c$ still remained 0.91 $MA/cm^2$ at a YBCO thickness of 4.2 μm. $I_c$ was 380 A across 1.0 cm wide tape at 77 K.

To investigate the structure of YBCO films with different thicknesses, X-ray diffraction (XRD) including θ-2θ scan, ω scan, and ϕ scan measurements was done for orientation and in-plane texture analysis. XRD θ−2θ measurements proved that all YBCO films with different thicknesses had pure c-axis orientation. In the whole thickness range, only (00*l*) reflections were observed, as shown in Figure 3 for a 4.2 μm thick YBCO film. However, ω scan and ϕ scan XRD measurements showed that 4.2 μm thick YBCO film had slightly broad out-plane and in-plane textures. For 1.0 μm thick YBCO films, the ω scan rocking curve (FWHM) Δω was 1.5° degree. The average ϕ scan rocking curve $\Delta\phi$ was $3^{\circ}$ on $11^{\circ}$ buffered metal tapes. The values of $\Delta\omega$ and $\Delta\phi$ for 4.2 mm thick YBCO films were $1.9^{\circ}$ and $4.8^{\circ}$ respectively, as shown in Figures. 3 and 4. Both XRD and SEM observations showed that the YBCO orientation was sensitive to substrate temperature and the deposition rate. By optimizing substrate temperature and temperature profile along the deposition zone, pure c-axis oriented YBCO films could be obtained in the whole range of YBCO thickness up to 4.2 μm. Our experiments showed that pure c-axis orientation was very critical to maintain high $J_c$ ($>10^6$ A/cm$^2$) for thick YBCO films. With increasing YBCO thickness, it was easy to form a-axis and c-axis mixed orientations probably due to YBCO

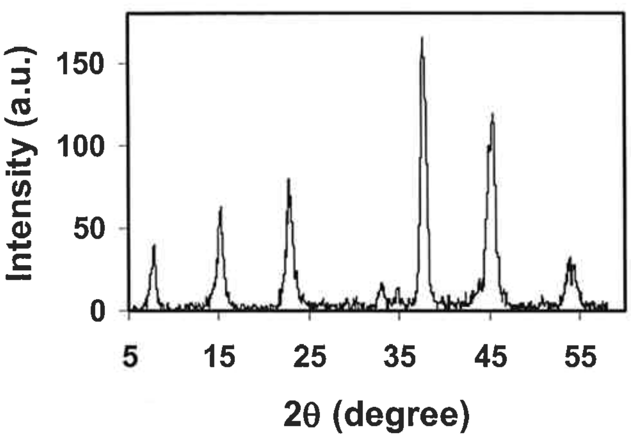


Fig. 3. θ-2θ scan XRD pattern of a thick YBCO film deposited on buffered metal substrates. Only (00*l*) reflections from YBCO film were observed.

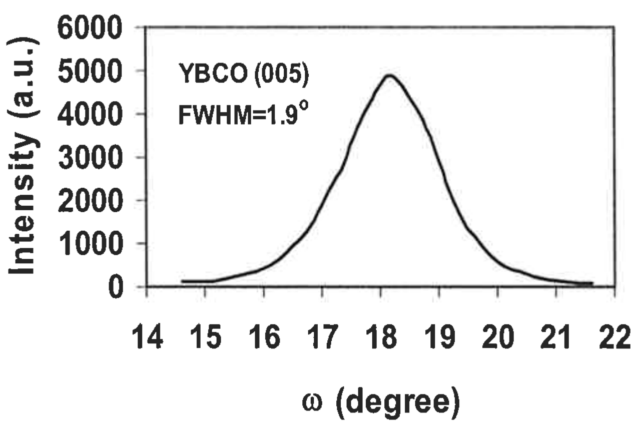


Fig. 4. ω scan YBCO (005) peak for a thick YBCO film. The FWHM value was only 1.9° indicating the film had a good out-plane texture.

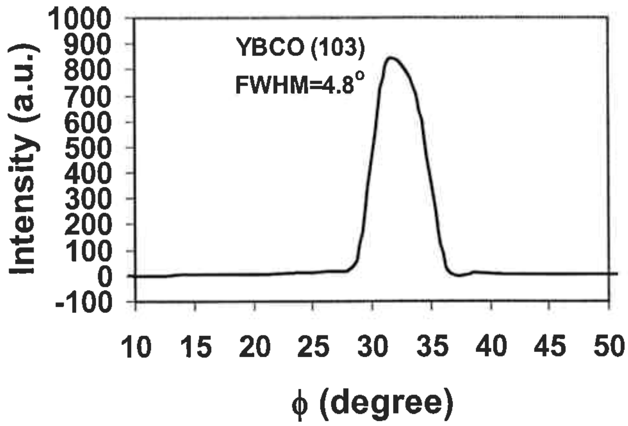


Fig. 5. ϕ scan rocking curve from a thick YBCO film shows the in-plane texture of YBCO (103) peak just slightly increased from 3.0° corresponding to 1.0 μm thick YBCO film to 4.8° corresponding to 4.2 μm thick YBCO film.

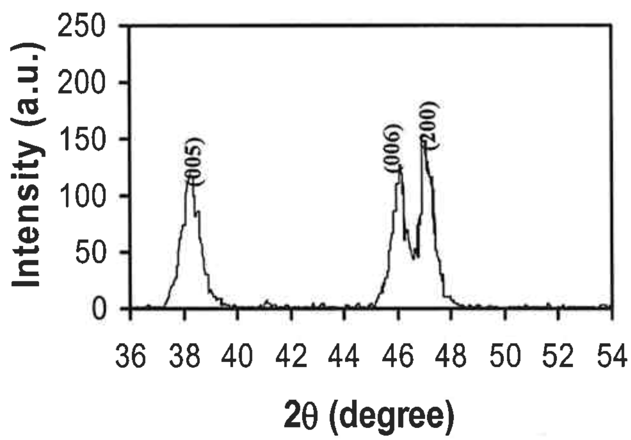


Fig. 6. θ-2θ scan XRD pattern of a thick YBCO film deposited at relatively lower substrate temperature. Both (200) and (006) reflections from YBCO film were observed, indicating that the thick YBCO film had a- and c-axis mixed orientations.

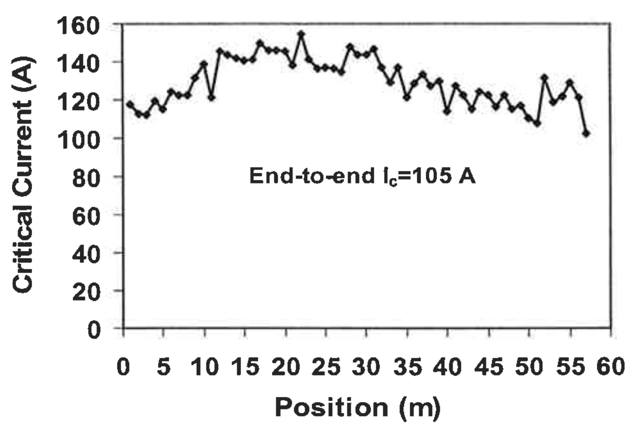


Fig. 7. Critical current $I_c$ distribution over a 57 m long YBCO tape. End-to-end $I_c$ was 105 A/cm measured at a criteria of 0.01 μV/cm.

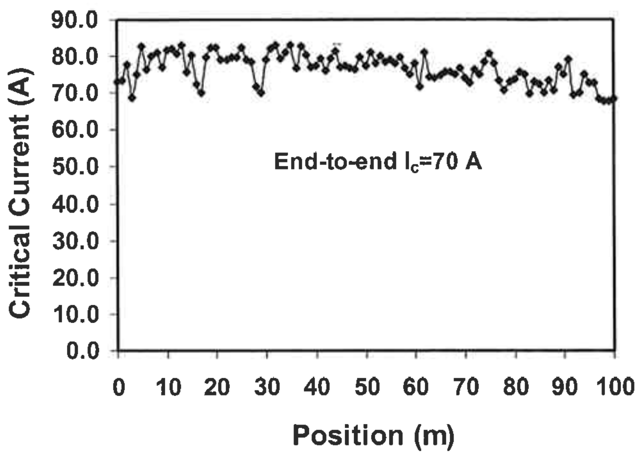


Fig. 8. Critical current $I_c$ distribution over a 100 m long YBCO tape. End-to-end $I_c$ was 70 A/cm. $I_c$ data were measured at 77 K, self-field, and at 1.0 m intervals.

emissivity changes, as shown in Figure 6. Pure c-axis oriented YBCO thick films could be fabricated at a relatively higher substrate temperature than the optimum substrate temperature for 1.0 μm thick YBCO films.

### B. *Performance of long YBCO tapes*

Long YBCO tapes were deposited with a Lambda Steel 670 industrial laser. On the basis of previously reported 10 m long YBCO tape with over 100 A/cm performance, we already scaled up the YBCO coating process to 100 m lengths. So far all of long YBCO tapes (30 m, 50 m, and 100 m) have been coated at a high tape speed of 15 m/h per pass and five passes. Figure 7 shows the $I_c$ profile for the first 57 m long tape. The end-to-end $I_c$ was 105 A/cm over 57 m at a very strict criteria of 0.01 μV/cm The n value was 36. $I_c$ data measured in 1 m intervals ranged from the minimum 103 A/cm to the maximum 155 A/cm at 1 μV/cm criteria. The end-to-end $I_c$ of 57 m long YBCO tape was very close to the values of $I_c$ obtained in 10 m runs and a 50 m simulation run. These results demonstrated the YBCO coating process was quite stable and reproducible. Figure 8 shows the $I_c$ profile for the first 100 m long YBCO tape. The end-to-end $I_c$ was 70 A/cm. $I_c$ measurements obtained in 1 m intervals showed an $I_c$ range of 68 A to 83 A. The standard deviation was 5.2% indicating good longitudinal homogeneity. Because the end-to-end $I_c$ values of long YBCO tapes were lower than those of short samples, there is still room to improve $I_c$ performance further for long YBCO tapes.

## IV. Conclusion

We have investigated the dependence of superconducting critical current density $J_c$ on YBCO film thickness. Under optimized YBCO coating conditions, thinner YBCO films (<1.0 μm) usually showed high $J_c$ of over 2 MA/cm$^2$. With increasing YBCO thickness, $J_c$ decreased gradually. However, $J_c$ still remained 0.91 MA/cm$^2$ at a YBCO thickness of 4.2 μm. $I_c$ was 380 A across 1.0 cm wide tape at 77 K. It was found that a- and c-axis mixed orientations were easily formed in thick YBCO films deposited at the optimum substrate temperature corresponding to thinner YBCO films. In order to maintain a high $J_c$ of over $1\times10^6$ A/cm$^2$ in thick YBCO films, thick YBCO films were deposited at a relatively higher substrate temperature to avoid a-axis orientation. In this work 4.2 μm thick YBCO film still had smooth surface. XRD measurements showed that YBCO thick films had pure c-axis orientation. The ω scan rocking curve was 1.9°. The FWHM value of ϕ-scan rocking curve was 4.8° on 11° buffered metal tape. To scale up YBCO coating process, the deposition rate was increased to a growth rate of 70 nm/s, corresponding to a tape speed of 15 m/h. End-to-end $I_c$ of 103 A/cm was achieved over a 57 m length. End-to-end $I_c$ of 70 A/cm was obtained from a 100 m long tape.

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