Recent Progress in Second-Generation HTS Conductor Scale-Up at SuperPower

V. Selvamanickam, Y. Chen, X. Xiong, Y.Y. Xie, J.L. Reeves, X. Zhang, Y. Qiao, K.P. Lenseth, R.M. Schmidt, D. W. Hazelton, and K. Tekletsadik

Abstract--**$YBa_2Cu_3O_x$ (YBCO) second-generation (2G) HTS conductors have been produced in lengths over 300 m in pilot scale facilities established at SuperPower. High throughput pilot-scale manufacturing has been demonstrated with tape speeds at or above 30 m/h of 12 mm wide tape (corresponding to 90 m/h of 4 mm wide conductor) in all steps. A 322 m long conductor with a minimum critical current value of 219 A/cm has been produced, which corresponds to a critical current × length value of 70,520 A-m. A 270 m long, 4 mm wide conductor with an end-to-end critical value of 100 A has also been demonstrated. In a campaign to manufacture 2G conductor for the Albany cable project, SuperPower has produced 12,470 m of conductor that meets or exceeds the specification for piece length (42.4 m) and critical current (100 A/cm). In fact, more than 55% of the conductor produced is at least 100 m in piece length and more than 27% greater than 200 m in piece length. In addition to scaling up 2G conductors to high-throughput pilot-scale manufacturing, we have demonstrated high critical currents in short samples produced by Metal Organic Chemical Vapor Deposition (MOCVD). Critical current values of 557 A/cm have been achieved in 2.1 micron thick films in 12 mm wide, 10 cm long tapes. These samples exhibit a critical current value of 116 A/cm at 1 T and 76 K, in the orientation of field parallel to the c-axis. We have also constructed a 4-pancake coil that generated a magnetic field of 1.1 T at 77 K and 2.4 T at 64 K. A Fault Current Limiter (FCL) assembly has been successfully constructed and tested at high power levels. A prospective current of 90 kA was successfully limited to 32 kA within 1 ms without any HTS element failure.**

Index Terms—**scale-up, coated conductor, second-generation HTS, coil, IBAD, MOCVD, FCL**

I. INTRODUCTION

Rapid progress has been made in the last year in scaling up $YBa_2Cu_3O_x$ (YBCO) coated conductors to long lengths. A key requirement in addition to long lengths with high critical currents is high-throughput processing. In 2005, all world-wide demonstrations of long-length coated conductors used tape speeds of less than 5 m/h for both YBCO and buffer layer deposition [1-3]. This linear tape speed of 10 – 12 mm wide tape would correspond to an annual production capacity far less than 100 km/year. In the second half of 2005, SuperPower focused on upgrading and modifying our Pilot production equipment to realize much higher linear tape speeds. For this purpose, we completely switched over to the much faster Ion Beam Assisted Deposition (IBAD) of MgO [4] as well used helical tape handling systems in all our Pilot production equipment. In this paper, we will present results on the outcome of high-throughput manufacturing of coated conductors. This paper also includes progress made with new prototypes made with 2G conductor.

II. SCALE UP TO 300+ M LENGTHS

In 2005, we hade demonstrated fabrication of IBAD YSZ buffered tape in 200 m lengths [2]. In 2006, we modified our Pilot IBAD equipment for MgO processing. Reflection High Energy Electron Diffraction (RHEED) was installed in this facility for on-line monitoring of the IBAD MgO layer over each of the 6 tape tracks in our helical tape handling system. Using only 0.42 m of the available deposition zone length of 0.6 m, we achieved linear tape speeds of 65 m/h of 12 mm wide tape in the IBAD MgO process. Up to 570 m single piece length of IBAD MgO tapes were produced at this tape speed with uniform, excellent RHEED patterns over the entire length [4]. In addition, we routinely produced up to 800 m lengths of IBAD MgO in each run using two single-pieces joined together.

Next, we procured, installed and brought into operation new Pilot buffer equipment. This equipment consists of two process chambers each with a deposition zone length of 0.3 m and fitted with a helix tape handling system capable of processing over 12 tape tracks [4]. The two chambers are in-line with each other and so, the two buffer layers atop the IBAD MgO, namely homo-epi MgO and $LaMnO_3$ (LMO) can processed simultaneously. Using only 6 of the 12 tape tracks in the two process chambers, we achieved linear tape speeds of 40 m/h in each of the two processes. Up to 550 m single piece lengths of tape with homo-epi MgO and LMO buffers have been produced reproducibly with an in-plane texture value of about 7 degrees. Figure 1 displays in-plane texture measurements obtained every 2.7 m of a 543 m long IBAD MgO tape with homo-epi MgO and LMO buffers. This tape showed an average in-plane texture value of 7.4 degrees over the entire length of 543 m.

Manuscript submitted on August 28, 2006. The work at SuperPower was supported in part by contracts with the U.S. Department of Defense, U.S Department of Energy, U.S. Air Force Research Laboratory, and the U.S. Air Force Office of Scientific Research. Part of the work was done under Cooperative Research & Development Agreements with Los Alamos National Laboratory (LANL) and Oak Ridge National Laboratory (ORNL).

All authors are with SuperPower, 450 Duane Ave., Schenectady, NY 12304, U.S.A. (corresponding author : Venkat Selvamanickam, phone : 518-346-1414 ; fax : 518-346-6080 ; e-mail : selva@igc.com)

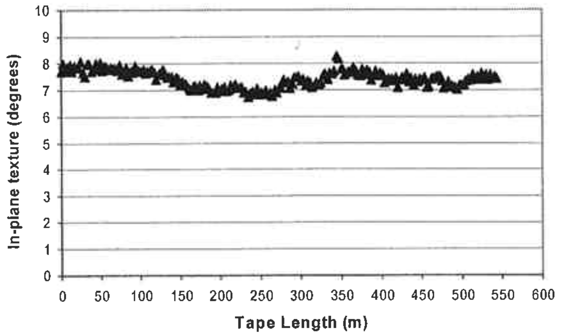

Fig.1. In-plane texture measurements obtained on a 543 m long IBAD MgO tape with homo-epi MgO and LMO buffer layers. The average texture of the tape over 543 m is 7.4 degrees.

In 2005, we had used an overall tape speed of 5 m/h to produce 206 m long coated conductor MOCVD in our Pilot MOCVD system with a minimum critical current value of 106 A/cm [2]. In 2006, we retrofitted our Pilot MOCVD equipment with helical tape handling with 6 tape tracks. Additionally, we extended the heater and the showerhead to enlarge the length and the width of the deposition zone. Critical current (I_c) values exceeding 250 A/cm have been routinely achieved in long tape lengths with the upgraded MOCVD system. Tape lengths over 300 m have been routinely produced by MOCVD. Recently, we achieved a minimum critical current value of 219 A/cm over a 322 m long conductor. This result is shown in figure 2. As shown in the figure, an excellent uniformity of 4.3% was measured over the entire length of 322 m. This result corresponds to a critical current × length value of 70,520 A-m.

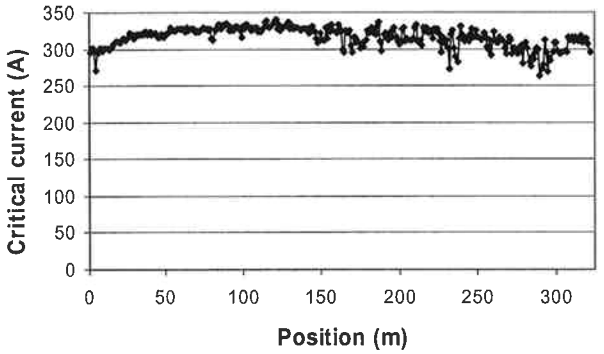

Fig.2. Meter-by-meter transport critical current measurement on a 322 m long, 12 mm wide tape produced by MOCVD in a single pass at 30 m/h. The minimum critical current value is 269 A or 219 A/cm.

Figure 3 exhibits the progress in critical current × length parameter in MOCVD-based conductors produced at SuperPower. It can be seen that a logarithmic enhancement in the ampere-meter value has been demonstrated over the last 4 years.

Critical currents have been measured end-to-end over long lengths of selected tapes after slitting to 4 mm width. Figure 4 displays both meter-by-meter measurement and end-to-end critical current value obtained over a 270 m long tape after slit to 4 mm width. It can bee seen that an end-to-end critical current of 100 A has been achieved over 270 m in the 4 mm wide tape, as measured at a voltage criterion of 0.04 microvolts/cm.

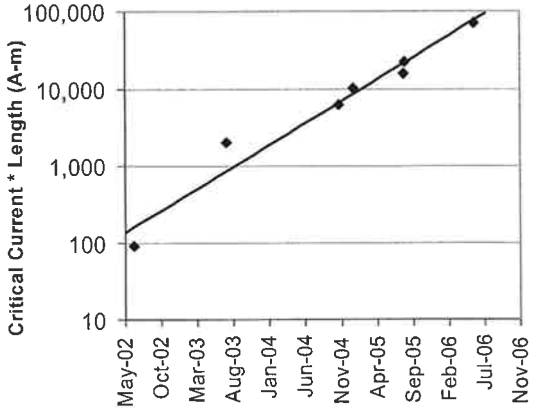

Fig.3. Progress in the performance and length of 2G conductors produced by IBAD-MOCVD at SuperPower in the last 4 years.

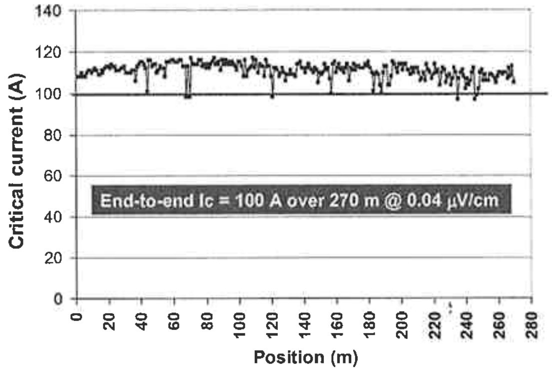

Fig.4. Meter-by-meter critical current measurement of a 270 m long, 4 mm wide tape. End-to-end critical current was 100 A over 270 m.

Using the high-throughput manufacturing conditions, we have routinely produced long-length conductors in a manufacturing campaign to deliver 2G conductor to Sumitomo Electric Indusries to build a 30 m 2G cable for the Albany Cable project. This would the world's first 2G device when completed. To date, we have produced and qualified 12,470 m of conductor all exceeding the specs of 42.4 m piece length and 100 A/cm critical current. Figure 5 shows a histogram of the tapes that are in inventory for the Albany Cable project.

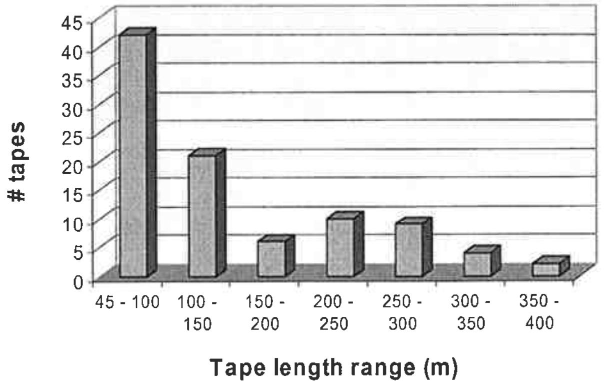

Fig.5. Histogram of 4 mm wide tapes produced at SuperPower for the Albany cable project that meets or exceeds the spec of 100 A/cm.

As shown in the figure more than 55% of the tapes are over 100 m in piece length and over 27% over 200 m in piece length.

III. HIGHER CRITICAL CURRENTS

Previously, the typical critical current density (J_c) of our MOCVD-based conductors has been in the range of 2 to 2.5 MA/cm^2 for 1 micron thick YBCO films. Microstructural analysis of our tapes showed the presence of Ba-Cu-rich amorphous phases constituting to nearly 20% of the tape thickness [5]. Such amorphous phases could have impeded the flow of current in the film. In 2006, we optimized our MOCVD process conditions to eliminate these secondary phases from the bulk of the YBCO films. As a result, J_c values of 3 to 3.5 MA/cm^2 were achieved in 0.7 micron films. Microstructure analysis of the higher current tapes revealed that the Ba-Cu-rich phases were eliminated from the bulk of the film and relegated to the surface. While this is a positive development, such secondary phases at the surface would limit the performance of additional YBCO layers deposited on the first layer by the multi-pass approach used by SuperPower. Further refinement of the MOCVD process yielded clean films with only spotty presence of CuO phases on the surface. J_c of up to 4.8 MA/cm^2 was achieved in such films that are 0.7 micron thick. Using this improved structure as the first layer, we deposited two additional layers of YBCO by MOCVD. Results from this work are summarized in figure 6. As shown in the figure, a J_c of 2.65 MA/cm^2 was achieved in a 2.1 micron film. This corresponds to a critical current value of 557 A/cm measured over the entire width of a 12 mm wide tape that is 10 cm long. Without a copper stabilizer, this value corresponds to a engineering current density of 100,000 A/cm^2 at self-field and 77 K.

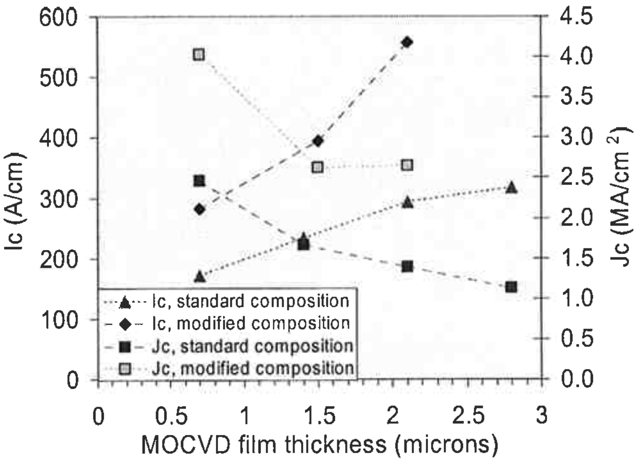

Fig.6. Critical current and J_c of MOCVD films on IBAD MgO buffered tapes as a function of film thickness. The measurements were conducted across the entire tape width of 12 mm (no bridges).

TABLE I
CRITICAL CURRENT PERFORMANCE OF IBAD-MOCVD-BASED 2G CONDUCTORS PRODUCED AT SUPERPOWER

Length (m)	0.05	1.2	52	127	227	322
I_c (A/cm)	557	470	272	263	246	219
Thickness (micron)	2.1	2.1	1.0	1.2	1.2	1.2
J_c (MA/cm^2)	2.65	2.24	2.72	2.19	2.05	1.83
I_c uniformity (%)			1.0	1.8	3.1	4.3

High critical currents have been achieved over a range of tape lengths as shown in Table I. As displayed in the Table, we have achieved critical currents over 470 A/cm in 1.2 m lengths and well over 200 A/cm in longer tapes. The Table also shows the uniformity in I_c over the long tapes. It can be seen that uniformity of better than 2% and 3% have been demonstrated in 100 and 200 m lengths respectively.

In-field measurements were conducted at 75.5 K at Los Alamos National Laboratory on the tape described in Figure 6. Table II summarizes the performance of the tape at 1 T, in the orientations of magnetic field perpendicular and parallel to the c-axis. It can be seen from the Table that critical currents over 100 A/cm have been achieved even in the orientation of field parallel to the c-axis at 75.5 K. The corresponding engineering current density (J_e) (with 3 microns of silver overlayer and without a copper stabilizer) is 21.1 kA/cm^2. In the orientation of field perpendicular to the c-axis, a critical current of 294 A/cm and a J_e of 50.5 kA/cm^2 have been achieved at 1 T.

TABLE II
PERFORMANCE DATA OF IBAD-MOCVD-BASED 2G CONDUCTORS IN A MAGNETIC FIELD OF 1 T AT 75.5 K

1 T, 75.5 K	I_c (A/cm)	J_c (MA/cm^2)	J_e (kA/cm^2)
B ~ ‖ a-b	294	1.4	50.5
B ‖ c	117	0.56	21.1

IV. HIGH FIELD COILS

In 2005, we demonstrated a coil made with our 2G conductor that generated a field of 0.4 T at 77 K. This year, we fabricated a larger coil with 4 pancake windings. The key parameters of the coil are shown in Table III. As shown in the Table, 160 m of conductor with an average I_c of 246 A was used to construct this coil. Since we use a thin-profile conductor with only 95 microns of total thickness which includes 40 microns of copper stabilizer, a coil with a small inner diameter of 10.92 mm could be fabricated without comprising the conductor quality. The maximum axial magnetic field generated in the coil was measured in its bore at 77 K and 64 K at both increasing and decreasing currents. The measurement at each temperature was repeated multiple times.

Figures 7 and 8 exhibit the performance characteristics of the coil at 77 K and 64 K respectively. As shown in the figures, a magnetic field of 1.1 T was generated in the coil at 77 K and a field of 2.4 T generated at 64 K. This is the first demonstration of a superconducting coil generating a field above 1 T at 77 K, to our knowledge.

TABLE III
PARAMETERS AND PERFORMANCE OF 2G COIL

Property	Specification
Coil I.D. (mm)	10.92
Winding I.D. (mm)	12.70
Winding O.D. (mm)	7.52
Height (mm)	57.2
2G conductor used (m)	159.6
# Turns	1,156
Average I_c of conductor in coil (A)	246
77 K coil I_c (A)	54
77 K Amp-turns @ I_c	62,000
64 K coil I_c (A)	113.7
64 K Amp-turns @ I_c	131,437

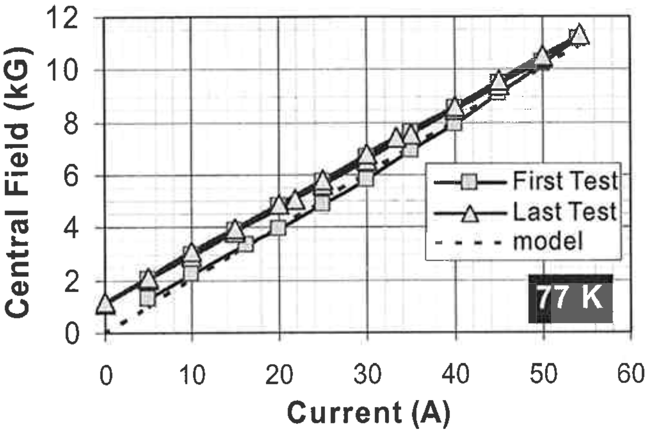

Fig.6. Axial field generated in the 2G coil described in Table III at 77 K with increasing and decreasing currents. The current-field characteristic predicted by a model is also shown.

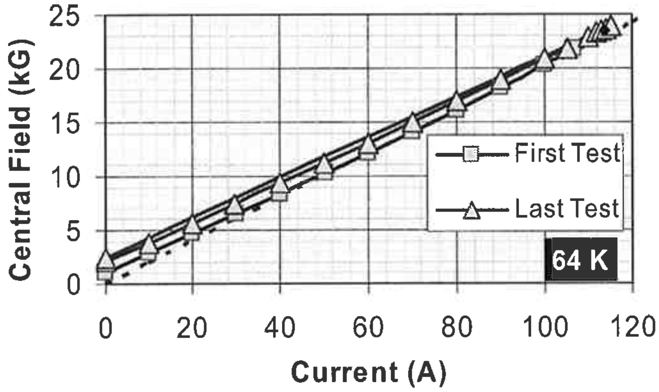

Fig.7. Axial field generated in the 2G coil described in Table III at 64 K with increasing and decreasing currents.

V. HIGH POWER FAULT CURRENT LIMITER

Fault current limiters (FCL) of various designs have been evaluated over the years with HTS. The most problematic issue with HTS fault current limiters has been the failure of the HTS elements when a massive amount of energy is dumped in a very short duration. Since late 2005, SuperPower has been evaluating the use of 2G conductors as FCL elements. Since our conductor uses highly resistive Hastelloy substrate, no additional resistive stabilizer was found to be necessary. In low-power tests using single 2G elements about 10 – 20 cm in length, we repeatedly demonstrated first peak limitation, rapid response (1 to 3 ms), low quench current (1.8 to 3 times I_c), recovery under no-load conditions up to 6 repetitive faults of 12 cycles, and uniform current sharing when the elements were tested in parallel [6]. With single elements with a I_c of about 250 A, prospective currents of 3000 A were limited to 1500 A with only 500 A flowing through the HTS [6].

After successful low-power tests, we then constructed a FCL assembly using 12 elements, each 40 cm long with four 2G conductors per element [6]. High-power tests were conducted with this assembly at KEMA-Power Test Inc., Chaltont, PA. Figure 8 shows the FCL assembly performance in one of the multiple tests performed. It can be seen that a prospective current of 90 kA has been successfully limited to 32 kA within 1 ms with only 3 kA flowing through the HTS elements and *with no HTS element failure*. This test condition satisfies the requirement established by our partner American Electric Power, of 26 kA RMS, 70 kA peak limitation and is very promising for our program on constructing a alpha prototype FCL operating at 138 kV using 2G HTS elements.

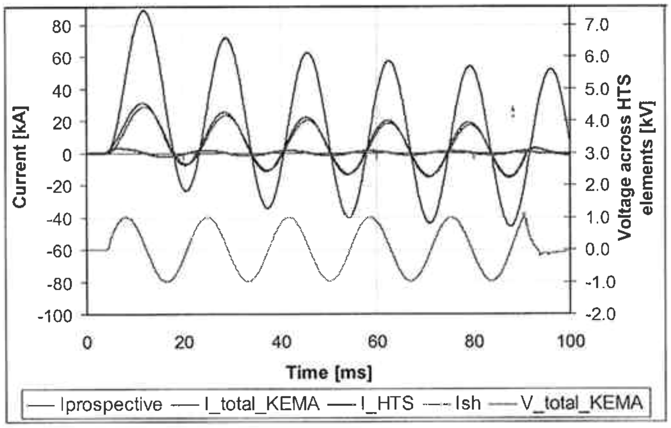

Fig. 8. Data from high-power tests conducted on a 2G HTS FCL assembly at the KEMA high voltage test facility.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Dr. Leonardo Civale and Dr. Boris Maiorov of LANL for magnetic field measurements.

REFERENCES

[1] V. Selvamanickam, J. Reeves, and D. E. Peterson, "Scale up of second-generation HTS wire at SuperPower" U.S. Dept. of Energy Annual Peer Review, Washington D.C., July 17-19, 2002.

[2] Y. Li, J. Reeves, X. Xiong, Y. Qiao, Y. Xie, P. Hou, A. Knoll, K. Lenseth, and V. Selvamanickam, *IEEE Trans. Appl. Superconductivity*(this volume)

[3] V. Selvamanickam, Y. Xie, J. Reeves, and Y. Chen, *MRS Bulletin*, Vol. 29, pp. 579 – 582 (2004).

[4] E. Specht, *Supercond. Sci. & Technol.* Vol. 13, 592 (2000).

[5] C. B. Cobb, P.N. Barnes, T. J. Haugan, J. Tolliver, E. Lee, M. Sumption, E. Collings, C. E. Oberly, *Physica C*.Vol.382, pp. 52-56, (2002).

[6] M. Suenaga, J. R. Clem, and S. R. Foltyn, *IEEE Trans. Appl. Superconductivity*(this volume)