

High Performance 2G wires : From R&D to Pilot-scale Manufacturing

V. Selvamanickam, Y. Chen, X. Xiong, Y.Y. Xie, M. Martchevski, A. Rar, Y. Qiao,
R.M. Schmidt, A. Knoll, K.P. Lenseth, and C.S. Weber

Abstract—Tremendous progress has been accomplished in 2008 in key metrics of $\text{YBa}_2\text{Cu}_3\text{O}_x$ (YBCO) second-generation (2G) HTS wires at SuperPower. Using improved precursor chemistry in our Metal Organic Chemical Vapor Deposition (MOCVD) process, critical currents (I_c) as high as 813 A/cm were reached over meter-long lengths, representing the highest reported I_c in meter long 2G HTS. By use of Zr doping of $(\text{Gd,Y})\text{Ba}_2\text{Cu}_3\text{O}_x$, strong enhancements were achieved in in-field performance over a wide angular range. A I_c of 229 A/cm was achieved at 77 K and 1 T perpendicular to the wire which is about a factor of 2.5 times better than that of standard MOCVD-derived films. At 65 K and 3 T, a I_c of 340 A/cm was demonstrated perpendicular to the wire. Kilometer lengths of 2G HTS have been demonstrated for the first time. Over 35 tapes 1,000 to 1,500 m in length with a complete 5-layer buffer stack have been routinely produced in our pilot-scale manufacturing facilities. An excellent in-plane texture of 6 to 7 degrees with a uniformity of about 2% was reproducibly achieved in the kilometer-long fully-buffered tapes. Using these high-quality buffers, the longest 2G wire length to date of 1,311 m was produced with a minimum I_c of 153 A/cm corresponding to a $I_c \times \text{length}$ value of 200,580 m. Also, an 1,030 m long complete 2G HTS wire has been demonstrated with a minimum I_c of 227 A/cm corresponding to a record $I_c \times \text{length}$ value of 233,810 A-m. Further, a 630 m long segment of the wire sustained a minimum I_c of 302 A/cm, the longest 2G wire reported to date with a I_c over 300 A/cm. Also, a I_c of 337 A/cm was achieved over a 540 m long segment. All these values represent a 2 to 3 fold improvement in length and I_c of 2G wires compared to our achievements in 2007. In 2008, a 30 m long 2G cable made with nearly 10,000 m of 2G wire previously delivered by SuperPower was successfully installed and energized in the grid of National Grid in downtown Albany, marking the world's first of 2G HTS device in the power grid.

Index Terms—second-generation HTS, IBAD, MOCVD, cable, long length, critical current, BZO, Zr

I. INTRODUCTION

In the last two years, $\text{YBa}_2\text{Cu}_3\text{O}_x$ (YBCO) second-generation (2G) High Temperature Superconducting (HTS) wires have been rapidly scaled up to routine pilot-scale

Manuscript submitted on August 26, 2008. The work at SuperPower was supported in part by contracts with the U.S. Department of Defense, U.S. Department of Energy, and U.S. Air Force Research Laboratory. Part of the work was done under Cooperative Research & Development Agreements with Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL), and Argonne National Laboratory (ANL).

All authors are with SuperPower, 450 Duane Ave., Schenectady, NY 12304, U.S.A. (corresponding author : Venkat Selvamanickam, now with the University of Houston, phone : 713-743-4044; fax : 713-743-4514 ; e-mail : selva@uh.edu)

manufacturing and are now available in quantities sufficient for prototype device demonstrations. The key metrics that SuperPower has focused on in the past few years to commercialize 2G HTS wire have been long lengths, high currents and high production capacity. In addition, SuperPower has concentrated on developing 2G HTS wires suitable for device applications with superior properties in-field performance, low ac losses, and high-quality joints.

SuperPower's 2G HTS wire is based on biaxially-textured buffers based on ion beam assisted deposition (IBAD) of MgO [1] on high-strength Hastelloy substrates followed by YBCO deposition by metal organic chemical vapor deposition (MOCVD) [2]. A main advantage of these techniques is high throughput that enables large production capacity. In 2007, 2G HTS wires were fabricated with critical currents (I_c) of nearly 600 A/cm over 1 m, and in lengths of 500+ m with a minimum critical current of nearly 200 A/cm [3]. In this paper, we will present an overview of the progress in 2008 in R&D and pilot-scale manufacturing of high-performance 2G HTS wires.

II. HIGH CRITICAL CURRENTS IN 1 M LENGTHS

Since 2006, we have employed a multipass technique to fabricate thick films of YBCO by MOCVD. In this technique, multiple layers of YBCO are deposited one atop each other in individual passes to build a thick film. Using a composition of $(\text{GdY})\text{BCO}$ instead of $(\text{YSm})\text{BCO}$, we had improved critical currents in thick films made in 2007. In 2008, we added 5% Zr to the precursor chemistry of $(\text{GdY})\text{BCO}$ and also doubled the number of passes i.e. reduced thickness of the film in each pass by half. With these modifications, higher critical currents were achieved in films of up to 3 micrometers in thickness as shown in Figure 1. As shown in the Figure, a critical current level of 803 A/cm was achieved in a 3.5 μm thick film. All self-field critical current measurements reported in this paper were conducted using continuous dc currents over the entire tape width of 12 mm without patterning.

Critical current densities of the films described in Figure 1 are shown in Figure 2. As displayed in the Figure, starting with a critical current density (J_c) of 6.6 MA/cm² in a 0.35 μm thick film, J_c values of 3.68 MA/cm² and 2.06 MA/cm² have been achieved in a 2.1 μm and 3.3 μm thick films respectively. The I_c value of 803 A/cm in the 3.3 μm film was achieved actually over a length of 1.2 m. The high current result was repeated over another 1 m long tape made with the same MOCVD precursor chemistry and thickness of 3.3 μm . The current-voltage characteristic of the meter long wire is

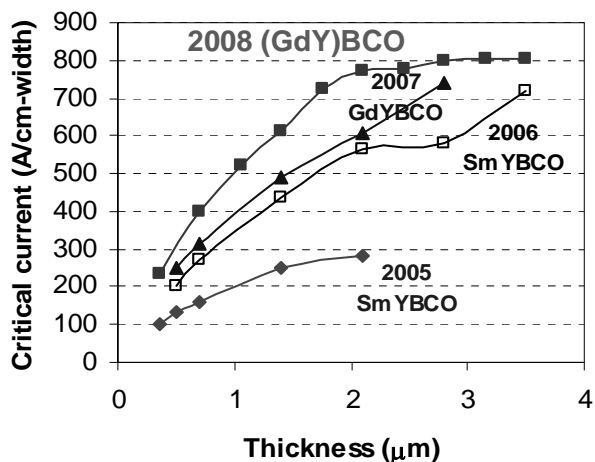


Fig.1. Progress in critical current levels of thick films fabricated by MOCVD on IBAD MgO-based substrates from 2005 - 2008.

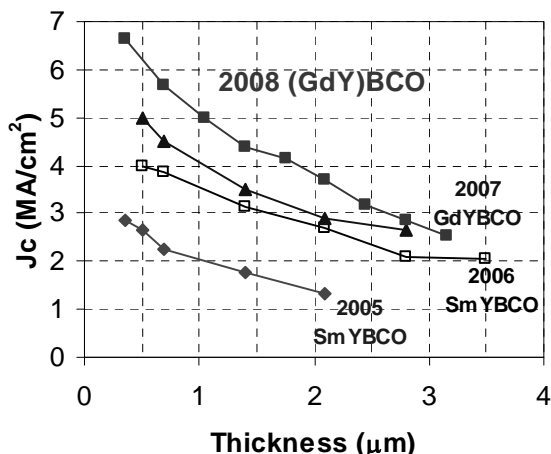


Fig.2. Progress in critical current density levels of thick films fabricated by MOCVD on IBAD MgO-based substrates from 2005 - 2008.

shown in Figure 3. A sharp transition was observed at a critical current of 976 A (=813 A/cm) at a voltage criterion of 1 μV/cm.

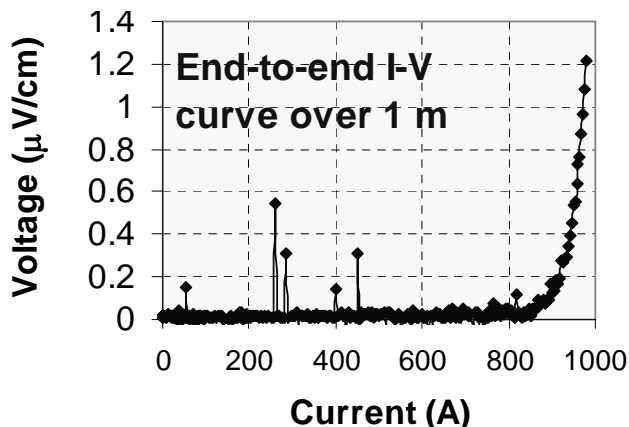


Fig.3. Current-Voltage characteristics obtained on a 1 m long wire with a HTS film 3.3 μm in thickness, made by a multipass MOCVD process.

III. ENHANCED IN-FIELD PERFORMANCE

A number of researchers have demonstrated enhanced performance in magnetic field in HTS films using BaZrO₃ (BZO) additions [4-6]. However, there has not been any report of high critical currents at high magnetic fields in thick films made by MOCVD using BZO or Zr additions. Here, we report results on in-field performance of samples made with MOCVD precursor chemistry with Zr addition. Figure 4 exhibits the angular dependence of critical current at 77 K and 1 T of three films each 0.7 μm in thickness made with different compositions. It is seen that Gd substitution in YBCO consistently results in enhanced I_c in the orientation of field parallel to the a-b plane. Enhanced pinning in the orientation of field parallel to the a-b plane has been attributed to the abundance of (Gd,Y)₂O₃ precipitates that observed at a small angle to the a-b plane. The critical current in the perpendicular and intermediate orientations are not improved significantly with (Gd,Y)BCO composition compared to (Y,Sm)BCO composition. In the Zr-doped (Gd,Y)BCO sample however, a significant enhancement is observed in I_c over a wide angular range. The I_c in the orientation of field perpendicular to the a-b plane is a factor of about 2.5 times higher than that of the sample of standard (Y,Sm)BCO composition and 2 times higher than the sample of (Gd,Y)BCO composition. Even in intermediate angular range, the I_c of the Zr-doped sample is superior and is relatively constant compared to the undoped samples. The peak in the vicinity of the a-b plane is suppressed compared to the undoped (Gd,Y)BCO and could be due to some disruption to the oriented arrays of (Gd,Y)₂O₃ precipitates by BaZrO₃ columns that will be shown in next page.

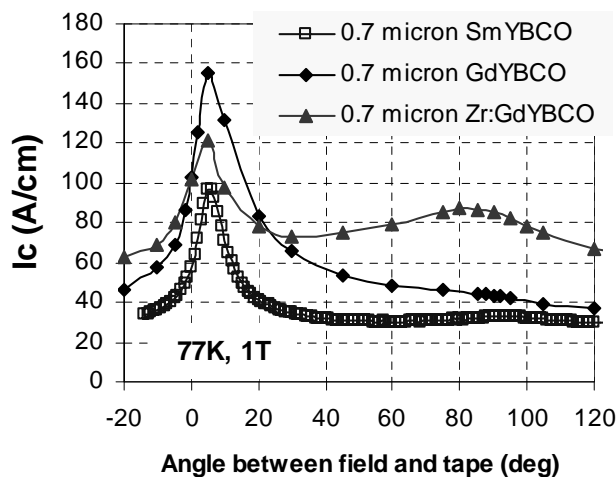


Fig.4 Angular dependence of critical current at 77 K and 1 T for three 0.7 μm thick films made by MOCVD with different precursor chemistries.

Next, films in the range of about 3 μm in thickness were fabricated using the same compositions described in Figure 4 and the results are shown in Figure 5. As seen in the figure, similar performance characteristics were found in the thick films too. The 2.8 μm film with (Gd,Y)BCO composition exhibited a substantial peak in I_c near a-b plane. The 3.3 μm film with Zr-doped (Gd,Y)BCO showed excellent performance over the entire angular range. At 77 K and 1 T, a

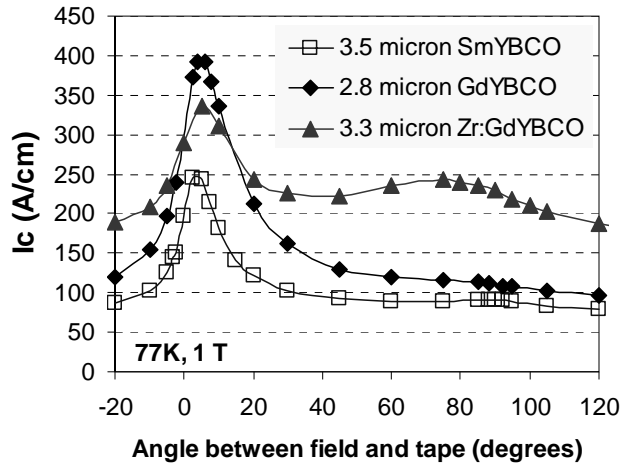


Fig.5. Angular dependence of critical current at 77 K and 1 T for three 3 μm thick films made by MOCVD with different precursor chemistries.

critical current value of 229 A/cm was measured in the orientation of field perpendicular to the a-b plane which is 2.5 times as high as that in a film of a standard, undoped composition. Also, a minimum I_c of 186 A/cm was measured which is also more than twice as high as the minimum I_c observed in film of undoped composition. The improvement in in-field performance was found to persist over fields up to 8 T as shown in Figure 6. At 65 K and 3 T, a critical current as high as 340 A/cm was achieved in the orientation of field perpendicular to the wire and a minimum I_c of 267 A/cm was obtained, as shown in Figure 7. These values are 88% and 67% respectively higher than the performance levels that we had obtained in 2007.

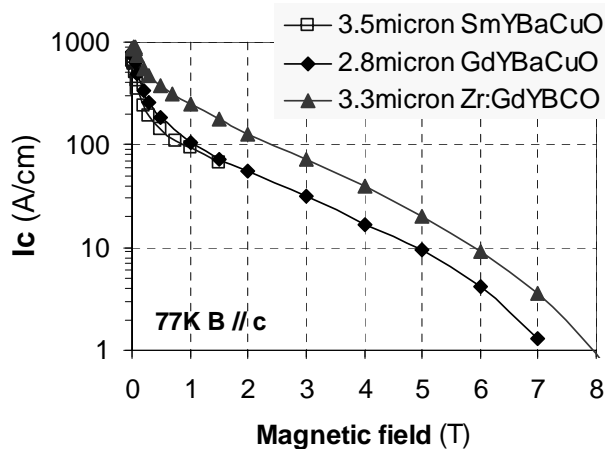


Fig.6. Field dependence of critical current at 77 K with field applied perpendicular to the wire for three 3 μm thick films made by MOCVD with different precursor chemistries.

The Zr-doped samples reveal an abundance of vertically oriented BZO columns throughout the microstructure as seen in Figure 8. Therefore, a combination of $(\text{Gd,Y})_2\text{O}_3$ precipitates along the a-b plane direction and BZO columns perpendicular to the a-b plane direction result in excellent performance over a wide angular range of magnetic field. While Zr is added in MOCVD (rather than BZO as in the case of physical vapor deposition techniques in ref. 4-6), it has been confirmed by X-ray Absorption Fluorescence

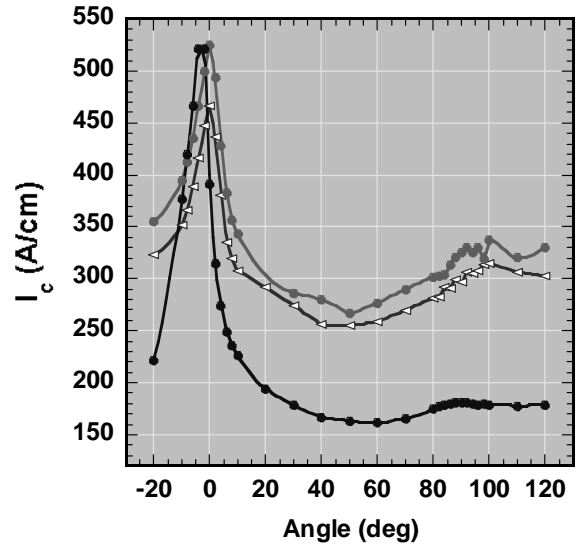


Fig.7. Angular dependence of critical current at 65 K and 3 T for three 3 μm thick films made by MOCVD with different precursor chemistries.

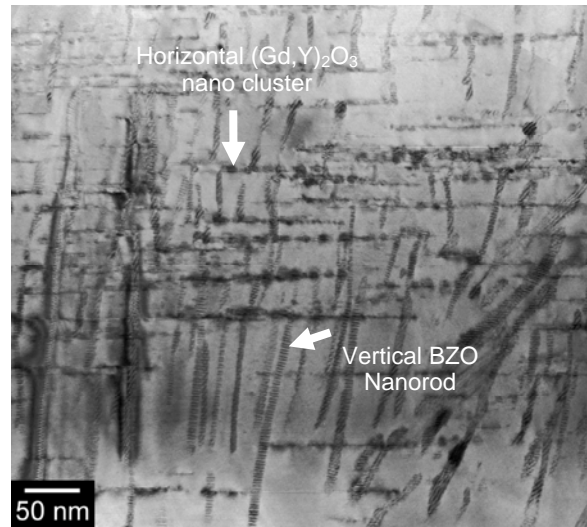


Fig.8. Cross sectional TEM analysis on a thick $(\text{Gd,Y})\text{BCO}$ film with Zr doping made by MOCVD.

Spectroscopy (XAFS) that the Zr is in form of BZO in the final film [7].

The enhanced performance in Zr-doped samples has been successfully transitioned to our pilot MOCVD system. We have observed a factor of 2.4 increase in I_c in the orientation of field perpendicular to the wire by Zr-doping to $(\text{Y,Sm})\text{BCO}$ composition and a factor of 1.8 increase in I_c by Zr-doping to $(\text{Gd,Y})\text{BCO}$ composition. Long-length 2G HTS wires are also now made by Zr-doped precursor chemistries.

IV. KILOMETER LENGTHS OF 2G WIRES

In 2007, we reported routine fabrication of kilometer lengths of tapes with a complete 5-layer buffer stack of alumina, yttria, IBAD MgO, homo-epi MgO, and LaMnO_3 (LMO) [3]. The total thickness of the stack is only 160 nm. In 2008, we continued pilot-scale manufacturing of 1,300 to 1,500 m lengths of tapes with complete 5-layer buffer stack.

Results from in-plane texture measurements obtained on several long tapes with complete 5-layer buffer stack are shown in Figure 9. As shown in the Figure, an excellent in-plane texture value of 6 to 7 degrees has been achieved with uniformity of about 2% over the entire lengths of 1,300 to 1,500 meters. Over 35 tapes each over a kilometer in length with a 5-layer buffer stack have been routinely and reproducibly made with uniform and excellent texture [8].

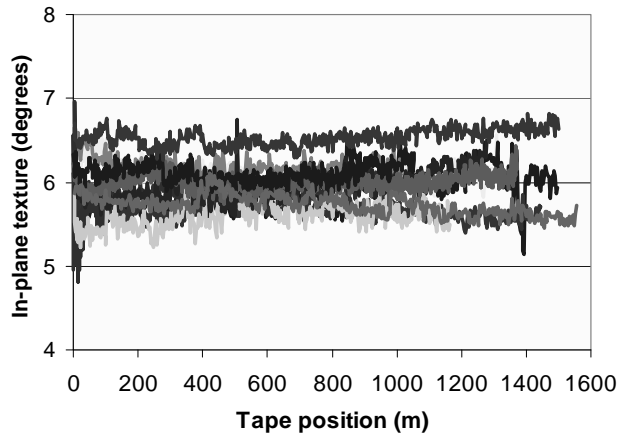


Fig.9. In-plane texture measurements obtained on several tapes with a complete 5 layer buffer stack based on IBAD MgO tape, all in lengths of 1,300 to 1,500 m.

Kilometer lengths of complete 2G HTS wire have been sought after ever since the demonstration of this technology in centimeter lengths in the early 1990s. The challenge of achieving high quality, epitaxial, nearly-single crystalline films with uniform properties over a kilometer in length without defects has been significant. Having established a robust manufacturing operation to fabricate kilometer lengths of fully-buffered tape, we were able to focus on undertaking this challenge. Several kilometer lengths of complete 2G HTS wire were made with good and uniform I_c levels of 200 A/cm, but a very few sporadic drops in I_c limited the I_c over the entire kilometer length. Some drops were traced to z-bends caused by sudden increase in tension in reel-to-reel tape handling systems. Other drops were traced to momentary fluctuations in the MOCVD process. After diligently working through the issues, we were able to demonstrate a 935 m long complete 2G wire with a minimum I_c of 170 A/cm in December 2007 which corresponds to a $I_c \times$ length value of 158,950 A-m.

In July 2008, we successfully crossed the kilometer threshold as shown in the results in Figure 10. As with other kilometer lengths, this wire was made with high tape speeds in all processes : 750 m/h in magnetron sputtering of alumina and yttria, 360 m/h in IBAD MgO, 345 m/h in magnetron sputtering of homo-epi MgO and LMO, and 90 m/h in MOCVD of YBCO ; all values provided are for equivalent wire width of 4 mm. Figure 10 shows the critical current distribution over an 1,311 m long complete 2G wire, measured every 5 m. Continuous dc transport current measurements over the entire 12 mm wire width and a 0.2 microvolt/cm criterion were used to measure I_c . As shown in

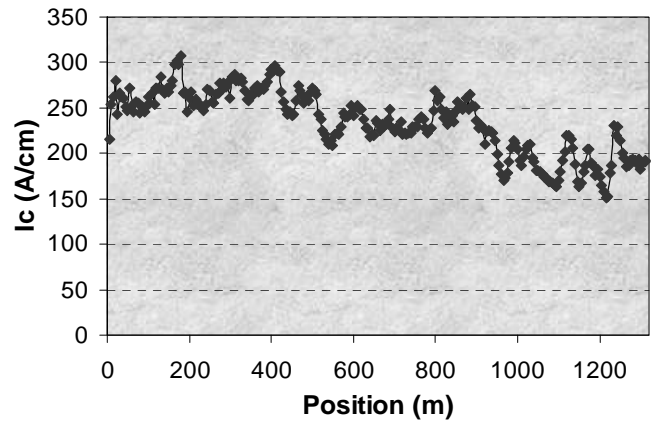


Fig.10. Critical current distribution over an 1,311 m long 2G HTS wire measured using continuous dc transport currents over entire wire width of 12 mm and using a voltage criterion of 0.2 μ V/cm.

the Figure, a I_c of 200 A/cm was achieved over 945 m. Also the minimum I_c over 1,210 m was 163 A/cm and the minimum I_c over 1,311 m was 153 A/cm. The latter corresponds to a $I_c \times$ length value of 200,580 A-m, which is the first demonstration of crossing the threshold of 200,000 A-m. N-values are always measured along with I_c every 5 m. Results from the 1,311 m long wire is shown in Figure 11. As shown in the Figure, a uniform n-value distribution was found over the entire length with an average value of 31 and a range of 21 to 37 and a uniformity of 10%. The high n-values observed over the entire length confirm the high quality of the kilometer long 2G HTS wire.

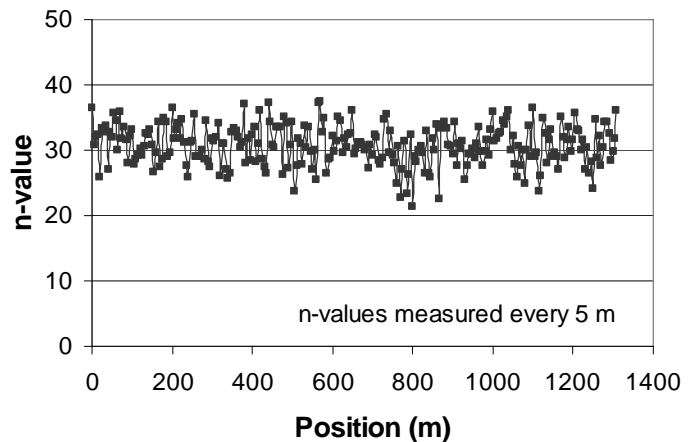


Fig.11. N-value distribution over an 1,311 m long 2G HTS wire measured using continuous dc transport currents over entire wire width of 12 mm.

On the heels of this achievement, in August 2008, we made yet another advancement in kilometer-long 2G wire manufacturing. An 1,030 m long 2G wire was produced and the results from this wire are shown in Figure 12. As shown in the Figure, except for only three locations, the rest of the wire showed I_c values above 300 A/cm. A minimum I_c of 227 A/cm was measured corresponding to a new world record $I_c \times$ length value of 233,810 A-m. Furthermore, a 630 m segment of this wire showed a minimum I_c of 302 A/cm, the longest 2G wire length demonstrated to date with I_c over 300 A/cm.

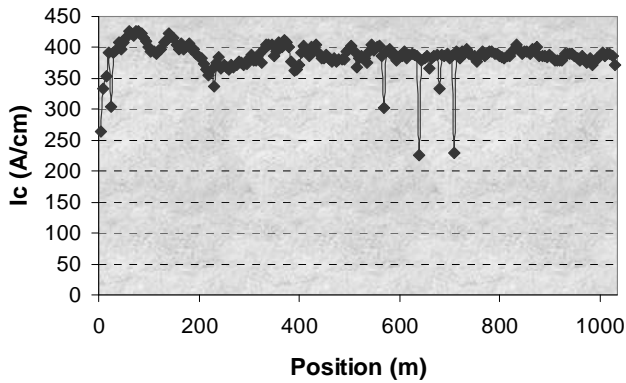


Fig.12. Critical current distribution over an 1,030 m long 2G HTS wire measured using continuous dc transport currents over entire wire width of 12 mm and using a voltage criterion of 0.2 μ V/cm.

A 540 m segment showed a minimum I_c of 337 A/cm and a 325 m segment displayed a minimum I_c of 372 A/cm. Over a 55 m segment, a minimum I_c of 401 A/cm was measured.

The performance achievements in our long-length 2G wires in summarized in Figure 13 which includes a comparison with the performance levels in 2007. As shown in the Figure, substantial progress was made in achieving kilometer lengths with good I_c of 200+ A/cm as well as in intermediate lengths of 600+m with an excellent I_c of 300+ A/cm. The overall progress of $I_c \times$ Length metric of our 2G wires over the last 6 years is shown in Figure 14. It can be seen that a 10-fold increase occurred in the last 3 years and more than a 2-fold improvement in the last year.

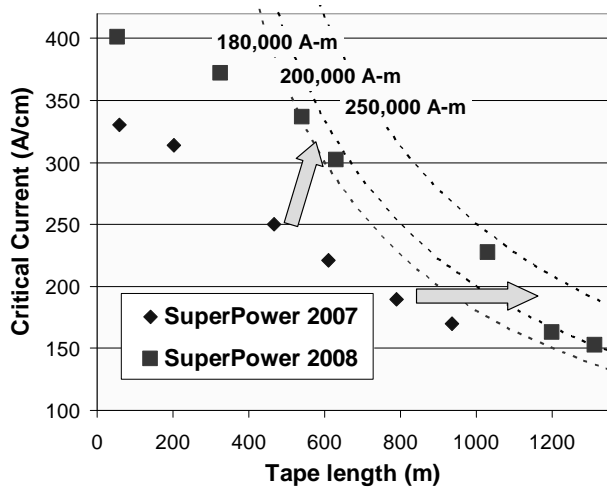


Fig.13. Progress in performance levels of long-length 2G wire at SuperPower in 2008 compared to 2007. Advancements made in 2008 led to achievement of 200+ A/cm in kilometer lengths and 300+A/cm in 600+ m lengths.

A summary of the progress in the various 2G HTS wire metrics is shown in Table I. It can be seen from the Table that an excellent progress occurred in all key metrics in 2008 and that the improvement trend continues year over year.

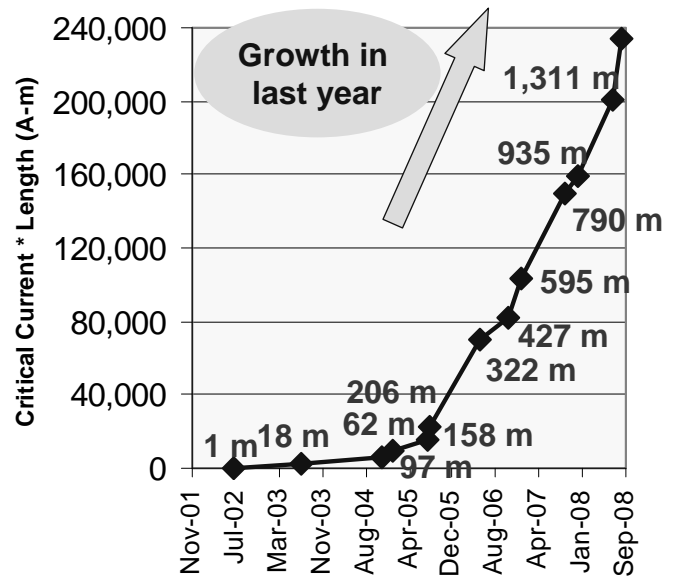


Fig.14. Progress in 2G HTS wire scale up at SuperPower since 2002. A rapid growth in $I_c \times$ Length metric has been demonstrated in the last 3 years.

TABLE I
PROGRESS IN SEVERAL KEY METRICS OF 2G HTS WIRES PRODUCED AT SUPERPOWER

Metric	2006	2007	2008	Improvement in last year
I_c (A/cm) over 1 m	470	595	813	37%
I_c (A/cm) - 77 K, 1 T		116	229	97%
I_c (A/cm) - 65 K, 3 T		181	340	88%
I_c over 200 m (A/cm)	246	227*	378*	67%
Length with $I_c > 200$ A/cm (m)	322	322	1030	220%
I_c over 500 m (A/cm)		170	337	98%
Length with $I_c > 300$ A/cm (m)	103	202	630	212%
Completed 2G wire Piece Length (m)	322	595	1,311	120%
$I_c \times L$ (A-m)	70,520	102,935	233,810	127%

* at 100 to 200% higher speed than in 2006

V. WORLD'S FIRST 2G DEVICE IN THE POWER GRID

In December 2006, SuperPower delivered nearly 10,000 meters of 2G HTS wire to Sumitomo Electric in 225 segments, each 43 to 44 m in length and with average minimum I_c of 70 A in 4 mm widths. Sumitomo Electric fabricated a 30 m long cable section with the wire for the Albany Cable project. The cable was tested to have a I_c of 2660 A to 2820 A in the conductor layers and 2400 A to 2500 A in the shield layers. The ac loss of the cable was found to be 0.34 W/m/phase at 800 A_{rms} . No I_c degradation and no defect were found at dismantling inspection when bend to a diameter of 2.4 m. The cable withstood AC 69kV for 10 minutes and an impulse voltage of ± 200 kV, applied 10 times.

In August 2007, the 2G HTS cable was installed in the Albany cable site in the grid of National Grid in downtown

Albany, New York as shown in Figure 15. A joint was made between an existing 320 m segment of 1G HTS cable and the 30 m 2G HTS cable and the entire 350 m cable was tested in December 2007. Current-voltage characteristics obtained from the 350 m cable are shown in Figure 16. As shown in the Figure a I_c of 2300 A was measured at 73 K and a I_c of 2750 A was measured at 69 K. No significant loss was found in the performance of the 2G cable after installation in the underground duct in the power grid.



Fig.15. Installation of the 30 m long cable made by Sumitomo Electric with nearly 10,000 m of SuperPower's 2G HTS wire.

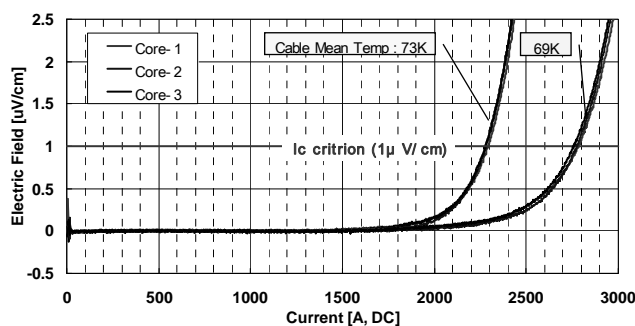


Fig.16. Current-voltage characteristics of the 350 m long cable including a 30 m long 2G HTS cable segment as laid in the underground duct in the power grid of National Grid in Albany, New York.

Finally, on January 8, 2008, the cable was energized in the power grid marking this as the first in-grid device of any kind made with 2G HTS wire. The cable transmitted electricity in the grid powering 25,000 households in the Albany area without any problems as shown in Figure 17.

VI. CONCLUSIONS

2008 has been a stellar year of progress for 2G HTS wire R&D and manufacturing. Kilometer lengths of 2G HTS wire which have been sought after for the last nearly 20 years have been finally demonstrated with excellent critical current performance levels of 227 A/cm over 1030 m. Additionally, high current levels of 302 A/cm have been achieved over 630 m. The potential of 2G HTS wire has been shown with repeated achievements of 800+A/cm over meter-long lengths. The use of Zr-doping has been shown for the first time in MOCVD process to significantly enhance critical current

performance in magnetic fields, reaching 229 A/cm at 77 K and 1 T and 340 A/cm at 65 K and 3 T. Finally, a device based 2G HTS wire has been energized in the electric power grid for the first time demonstrating the transition of this technology from laboratory to manufacturing to in-grid operation.

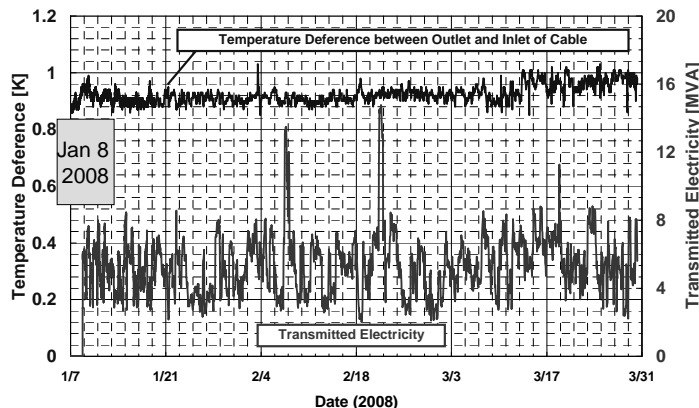


Fig.17. Electricity transmission by a 350 m long HTS cable including 30 m long 2G HTS cable segment made with SuperPower's 2G wire.

ACKNOWLEDGMENT

The authors would like to acknowledge the Dr. Parans Paranthaman, Dr. Goyal and Dr. Yifei Zhang of Oak Ridge National Laboratory for in-field measurements and Dr. Fumitake Kametani and Dr. David Larbalestier of Florida State University for Transmission Electron Microscopy and Mr. Hiro Yumura of Sumitomo Electric for providing data on the 2G cable operation.

REFERENCES

- [1] J.R. Groves, P.N. Arendt, H. Kung, S.R. Foltyn, R.F. DePaula, L.A. Emmert, and J.G. Stover, "Texture development in IBAD MgO films as a function of deposition thickness and rate", *IEEE Trans. Appl. Superconduct.* Vol. 11, 2822 (2001).
- [2] V. Selvamanickam, Y. Xie, J. Reeves, and Y. Chen, "MOCVD-Based YBCO-Coated Conductors," *Mater. Res. Soc. Bull.* Vol. 29, 579 (2004)
- [3] V. Selvamanickam, Y. Chen, X. Xiong, Y. Xie, X. Zhang, A. Rar, M. Martchevskii, R. Schmidt, K. Lenseth, J. Herrin, "Progress in Second-generation HTS Wire Development and Manufacturing," *Physica C*. (in print) doi:10.1016/j.physc.2008.05.063
- [4] J. L. Macmanus-Driscoll, S. R. Foltyn, Q. X. Jia, H. Wang, A. Serquis, L. Civale, B. Maiorov, M. E. Hawley, M. P. Maley, and D. E. Peterson, "Strongly enhanced current densities in superconducting coated conductors of $YBa_2Cu_3O_{7-x}+BaZrO_3$ " *Nature Materials* Vol. 3, 439 (2004).
- [5] S. Kang, A. Goyal, J. Li, A. A. Gapud, P. M. Martin, L. Heatherly, J. R. Thompson, D. K. Christen, F. A. List, M. Paranthaman, and D. F. Lee, "High-Performance High- T_c Superconducting Wires", *Science* Vol. 311, 1911 (2006)
- [6] Y. Yamada, K. Takahashi, H. Kobayashi, M. Konishi, T. Watanabe, A. Ibi, T. Muroga, S. Miyata, T. Kato, T. Hirayama, Y. Shiohara, "Epitaxial nanostructure and defects effective for pinning in $Y(RE)Ba_2Cu_3O_{7-x}$ coated conductors", *Appl. Phys. Lett.* Vol. 87, 132502 (2005).
- [7] V. Maroni, "ANL/SuperPower CRADA: Characterization of 2G Conductors", *Proc. DOE Annual Peer Review*, Arlington, VA, July 29 - 31, 2008.
- [8] X. Xiong, S. Kim, K. Zdun, S. Sambandam, A. Rar, K P. Lenseth, V. Selvamanickam, "Progress in High Throughput Processing of Long-Length, High quality and Low Cost IBAD MgO and Buffer Tapes at SuperPower", *IEEE Trans. Appl. Superconduct.* (this volume)