# DEVELOPMENT OF BIAXIALLY TEXTURED $YBa_2Cu_3O_7$ COATED CONDUCTORS IN THE U.S.

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**Abstract:** Two new processes have been under development since 1991 that promise a new, cost-effective way to manufacture flexible, high current density wires made from $YBa_2Cu_3O_7$ (YBCO). The key is to prepare a textured substrate, or "template," on which the YBCO may be deposited as a biaxially aligned thick film. Ion beam assisted deposition (IBAD) of yttria stabilized zirconia or magnesium oxide on alloy tapes enables a final superconducting layer with grain-to-grain, in-plane alignment to within 3-5 degrees. Similar results are achieved on rolling-assisted, biaxially textured substrates (RABiTS) using a variety of oxide layers on textured nickel tapes. The performance of research lengths of prototype wires in strong magnetic fields at 65 K already exceeds that of NbTi and $Nb_3Sn$ in liquid helium. A scalable, *ex-situ* process for the YBCO coating has been demonstrated on both types of substrates. Consistent values of critical current density ($J_c$) greater than $1 \times 10^6$ A/cm$^2$ are now obtained on RABiTS, and $J_c$'s in excess of $2 \times 10^6$ A/cm$^2$ have been obtained on both substrates. A nonmagnetic variation of RABiTS (Ni-13% Cr) has also been shown to yield $J_c$ greater than $1.5 \times 10^6$ A/cm$^2$. Six private companies in the U.S. are scaling up YBCO coated conductors for power and physics applications.

**Keywords:** High temperature superconductors, YBCO, coated conductors, ion beam assisted deposition, RABiTS, biaxial texture, electron beam evaporation, sol gel, pulsed laser deposition

## INTRODUCTION

The U.S. Department of Energy (DOE) leads the U.S. national effort to develop high-temperature superconductor (HTS) wires and to demonstrate prototype electric power applications using the best wires available today. With a year 2000 budget of nearly $32 million, the DOE is sponsoring perhaps the largest single national effort toward research and development of HTS wires.

Due in part to this government-national laboratory-university-industry partnership, long lengths of "first generation" BSCCO-2223 and -2212 HTS tapes are now commercially available. Since 1991 the performance of BSCCO-2223 tapes has increased by an order of magnitude while the price of the tapes has decreased dramatically. According to Riley [1], in 1999 kilometer lengths of BSCCO-2223 tapes were available from at least one U.S. company at a price of approximately $300/kA-m. This price represents a substantial reduction from that quoted just one year ago of $1,000/kA-m [2]. Yet it may still be said that the BSCCO-2223 tapes are in the "precommercial" stage, based upon production quantities alone. In 1998, the total annual U.S. production capability for BSCCO-2223 tapes was approximately 350 kilometers. For comparison, a number of companies worldwide each can produce nearly 20,000 km per year of NbTi for magnetic resonance imaging and research applications.

The use of BSCCO tapes at liquid nitrogen temperatures is presently limited by thermally activated flux motion to those applications involving low magnetic fields. For this reason, most of the field tests of transformers, motors, generators, and current limiters have been conducted at or below 30 K. Previously, the utility of the YBCO compound was constrained to current leads and other "short" applications of HTS due to the lack of technology to produce biaxially textured films on practical metal-based substrates. This situation changed with the development of ion beam assisted deposition (IBAD) substrates pioneered first in Japan [3] for HTS tapes and subsequently refined significantly in 1995 by the Los Alamos group [4]. Also, in 1996 the Oak Ridge National Laboratory (ORNL) presented the first results using a template called rolling-assisted, biaxially textured substrates (RABiTS) [5,6].

The RABiTS template is formed from high-purity nickel and certain alloys using thermomechanical processing and recrystallization to form highly cube-textured tape. Appropriate buffer layers and the superconductor coating are then deposited epitaxially on the RABiTS tape. The high critical current densities obtained using this substrate may be attributed to the strong biaxial texture leading to a preponderance of low-angle grain boundaries in the structure, starting with the metal tape and ending with the superconducting film [7].

The IBAD technique starts with a polycrystalline nickel-based superalloy tape and generates a highly in-plane oriented template through deposition of yttria stabilized zirconia (YSZ) or MgO in the presence of a well-collimated "assisting" ion beam directed at an appropriate angle to the substrate. After epitaxial deposition of a thin cap layer (often $CeO_2$ in the case of YSZ), the template may then be used for superconductor deposition by a variety of techniques, yielding high $J_c$'s.

## HIGH CRITICAL CURRENTS

High $J_c$'s have been produced on both IBAD and RABiTS substrates using a number of techniques for superconductor deposition. The research workhorse, pulsed laser deposition (PLD), frequently yields $J_c$'s in excess of $2 \times 10^6$ A/cm$^2$ on either substrate at 77 K and in self-field, with champion numbers over $3 \times 10^6$ A/cm$^2$. Los Alamos can now routinely obtain critical currents of 200 A for 1-cm-wide short (<5-cm) tapes. Another method for YBCO growth has recently attracted attention. The *ex-situ*, or "$BaF_2$" process involves the room-temperature deposition of yttrium, barium fluoride, and copper onto RABiTS or IBAD substrates, followed by a batch post-anneal at elevated temperature in the presence of water vapor and oxygen to form the superconducting phase. Using this process, high-$J_c$ films were grown for the first time on metal substrates by the Oak Ridge group [7,8] in 1998. A summary of the typical $J_c$ versus temperature obtained using RABiTS/YBCO(PLD) is shown in Fig. 1 [9, 10]. Recent results for the field dependance of $J_c$ in RABiTS/YBCO (*ex-situ*) are shown in Fig. 2 [8].

Using the *ex-situ* approach, typical results for 0.3-μm YBCO on RABiTS are 1.0-1.7 × $10^6$ A/cm$^2$ (77 K, H=0) with the best value now $2.3 \times 10^6$ A/cm$^2$ [8]. This process works equally well for the IBAD/YSZ substrates produced by Los Alamos. For a 15-cm section of tape processed in 1-cm pieces, $J_c$ exceeded $1 \times 10^6$ A/cm$^2$ over the entire section and $J_c$ exceeded $2.5 \times 10^6$ A/cm$^2$ over the central 10-cm section with the best texture [8]. It is generally observed that $J_c$'s in the best films on both RABiTS and IBAD substrates are substantially higher than would be expected from their texture as derived from x-ray diffraction (XRD). An explanation for this is found from grain orientation maps obtained from electron backscatter diffraction patterns which indicate that local or grain-to-grain misorientations are smaller than global variations determined from XRD [7,8].

The overall, or engineering current density, calculated using the critical current divided by the entire cross sectional area of the coated conductor, is also of interest for applications. The highest numbers to date have been achieved by the Los Alamos group on a 1-cm x 5-cm IBAD/YSZ substrate that was just 40-µm thick. According to Foltyn [1], a 1.5-µm YBCO film grown on this template conducted 176 A (75 K) and had an engineering current density of nearly 42,000 A/cm$^2$. The highest engineering current density on RABiTS using the *ex-situ* process was reported by Feenstra [1] as 28,000 A/cm$^2$.

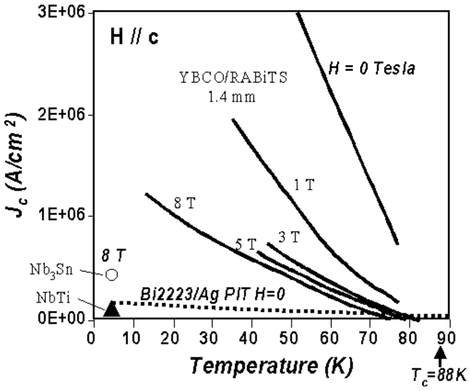


Fig. 1. Temperature dependance of the $J_c$ of YBCO (PLD) on RABiTS as a function of applied magnetic field.

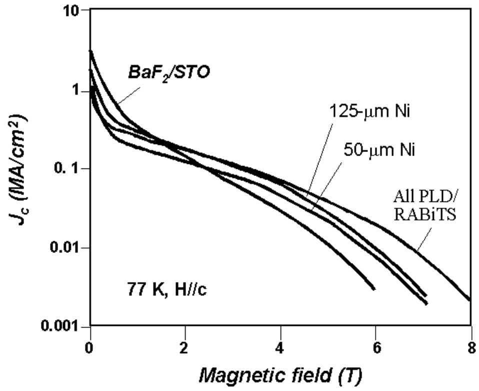


Fig. 2. Magnetic field dependance of the $J_c$ of RABiTS/YBCO (*ex-situ)* compared with STO/YBCO (*ex-situ*) and RABiTS/YBCO (PLD).

## LENGTHS

The U.S. leader in demonstration of 1-m lengths of YBCO coated conductor is Los Alamos. A number of tapes made with IBAD/YSZ templates and YBCO (PLD) that are 1-m long have exceeded 100 A critical current over the entire length. For example, one tape reported recently by Foltyn [1] had a critical current of 122 A over a 97-cm measurement length, with a critical current of over 140 A along a 78-cm section. The most uniform tape produced by Los Alamos this year had cm-to-cm variations along the length of ±20%.

Oak Ridge has focused on developing the continuous processing parameters necessary for the *ex-situ* YBCO coated conductor approach. The work is at an early stage, with end-to-end $J_c > 5 \times 10^5$ A/cm$^2$ (77 K, H=0) reported by List [1] for 5-cm sections of tape where the buffer layers and YBCO were deposited with moving tape.

## PROCESS DEVELOPMENT

A number of critical issues that were identified at a 1998 workshop on coated conductor development are being addressed by the national laboratories [11]. Progress towards a completely nonmagnetic (77 K) stronger version of the RABiT substrate as reported by Goyal [1], for example, has enabled short samples of single-orientation, cube-textured Ni-Cr(13%) alloy with a $J_c$ of $1.4 \times 10^6$ A/cm$^2$ (77 K, H=0). In addition, a YBCO/RABiTS was recently demonstrated with totally conductive buffer layers

($SrRuO_3$ by PLD and $LaNiO_3$ by sputtering) with $J_c = 0.6 \times 10^6$ A/cm$^2$ (77 K, H=0) and $J_c = 1.4 \times 10^6$ A/cm$^2$ (64 K, H=0) [1]. Such a structure could be important for electrical stability of magnets and other devices during transients. In an effort to evaluate an alternative YBCO deposition approach, Balachandran [1] reported that the team of Argonne National Laboratory, Los Alamos, and Intermagnetics General (IGC) has demonstrated a $J_c$ in excess of $2 \times 10^6$ A/cm$^2$ ($I_c$>80 A) on a short sample of YBCO/IBAD tape using metal-organic chemical vapor deposition to grow the YBCO.

One of the interesting opportunities provided by the RABiTS approach is to apply all the layers on the metal tape by nonvacuum methods. Recently, the American Superconductor (ASC)/ORNL team announced progress towards this potentially low-cost way to make a coated conductor [12]. ORNL has developed a continuous dip-coating line and furnace with the capability of producing up to 3-m lengths of all-solution $Gd_2O_3$- buffered RABiTS [13,14]. ASC has developed an in-house *ex-situ* solution process for growing the YBCO using metal trifluoroacetate (TFA) precursor [15]. On a standard RABiT substrate with vapor-deposited buffer layers, a $J_c$ of $0.8 \times 10^6$ A/cm$^2$ (77 K, H=0) was achieved for a 0.4-μm-thick YBCO film. Should this team assemble an all-solution grown YBCO/RABiTS conductor with high current density, the prospects for scale-up at relatively low capital expenditure may be attractive.

## PRIVATE SECTOR INVOLVEMENT

There are six private companies and three major universities researching coated conductors in the U.S. The six companies, the selected YBCO deposition approach, and the selected substrate technology are shown in Table 1.

Table 1. U.S. companies developing YBCO coated conductors.

| Company | HTS Deposition Approach | Substrate |
|---|---|---|
| 3M | E-beam co-evaporation (*in-situ* and *ex-situ*) | IBAD, RABiTS |
| Oxford Superconducting Technology | PLD (research stage) | RABiTS |
| MicroCoating Technologies | CCVD (open atmosphere CVD), also TFA | RABiTS |
| EURUS Technologies | TFA others | RABiTS |
| American Superconductor | TFA | RABiTS |
| Intermagnetics General | PLD, MOCVD | IBAD |

The work of the ASC and IGC teams was discussed earlier. 3M Company is leveraging a number of resources, including internal funding, the U.S. DOE’s Superconductivity Program, and the Defense Advanced Research Project Agency to perform research that will lead to development of a continuous process for making lengths of coated conductor. They have been working with Los Alamos and Oak Ridge National Laboratories, as well as Southwire Company and Stanford University since 1997. 3M has succeeded in producing 100-m lengths of biaxially textured nickel tape compatible with buffer layer technology, including their own

$>10^6$ A/cm$^2$ has been obtained on this textured nickel. The 3M electron beam evaporation system has a 30-kW differentially pumped gun and a tape transport system capable of handling 4-cm-wide by 100-m long tape. According to O'Neill [1], short sample results obtained by 3M and ORNL using 3M nickel and $CeO_2$ vary in $J_c$ from 0.2 to 0.5 × $10^6$ A/cm$^2$ (77 K, H=0). Stanford University is conducting research for this team towards high-rate *in-situ* YBCO deposition.

Oxford Superconducting Technology (OST) has also succeeded in duplicating the highly textured nickel tape developed by Oak Ridge. Using Oxford Instruments buffer layers deposited by PLD, Brookhaven National Laboratory (BNL) deposited 2-μm-thick YBCO using the *ex-situ* approach with a resultant $J_c$ >0.8 × $10^6$ A/cm$^2$ (77 K, H=0) and 0.17 × $10^6$ A/cm$^2$ in a 1 Tesla background field [16]. OST has recently partnered with MicroCoating Technologies to scale up this technology and to research using MCT's open-atmosphere combustion chemical vapor deposition (CCVD) process for the oxide layer deposition. EURUS has also duplicated the biaxially textured nickel and has provided samples to a number of organizations worldwide. In one demonstration announced recently, the Air Force Research Laboratory used PLD to deposit buffer layers and YBCO on EURUS' nickel and measured a self-field $J_c$ of 1 × $10^6$ A/cm$^2$ [17].

## FUTURE TRENDS

There is intense research under way in the U.S. to complete development of continuous processes for fabrication of coated conductors. In fact, an estimated $16 million will be spent in the U.S. in 2000 on this research and development. Within the year 2000, it is likely that the first 5-10 meter lengths of YBCO conductor will be produced by industry, with scale up to 100-m lengths starting in 2001. As shown in Fig. 3, by the end of 2002, 10-100 meter lengths will begin to become available for construction of simple cables, magnets, and the like.

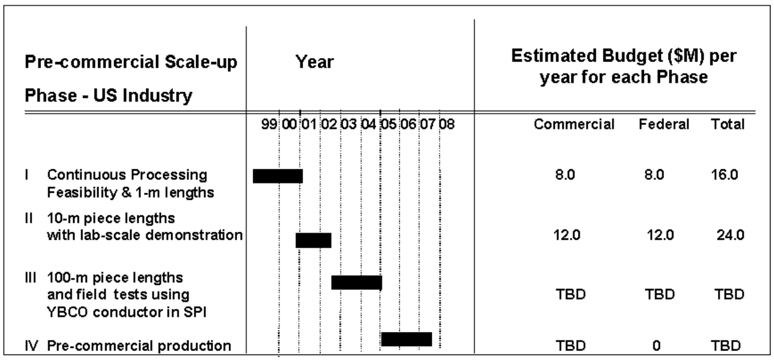


Fig. 3. Projected time line for coated conductor scale-up in the U.S.

## CONCLUSION

Moving tapes of YBCO(PLD)/IBAD-YSZ on nickel alloys consistently yield critical currents of the order 100 A/cm width, and short sample results on IBAD-MgO templates are very promising. High $J_c$'s (> 2 × $10^6$ A/cm$^2$) have been achieved on IBAD and RABiTS templates using the *ex-situ*, or "barium fluoride" approach. One company (ASC) has demonstrated nearly 1 × $10^6$ A/cm$^2$ (77 K, H=0) using a nonvacuum YBCO growth process on RABiTS. A total of five processes for deposition of buffer layers and YBCO on nickel tapes are being investigated by six U.S.-based companies. Given the investment by the government and private sectors, there is a high likelihood that 10-100 meter lengths of YBCO conductor will be available for applications by the end of 2001.

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