SuperPower Inc.

superior performance.
powerful technology.

Progress in Scale-up of 2G HTS Wire at SuperPower – Part IV

V. Selvamanickam & Y. Xie

Y. Chen, X. Xiong, M. Martchevski, Y. Qiao, A. Rar,
B. Gogia, R. Schmidt, A. Knoll, and K. Lenseth

DOE funding through Title III Program & UT-Battelle
Leveraged funding from AFRL. Supported by CRADAs with Los Alamos, Oak Ridge, & Argonne National Laboratories

FY2008 Superconductivity for Electric Systems Peer Review, Arlington, VA, July 29 – 31, 2008

Actual production capacity metric: Ensuring availability of 2G wire for device projects

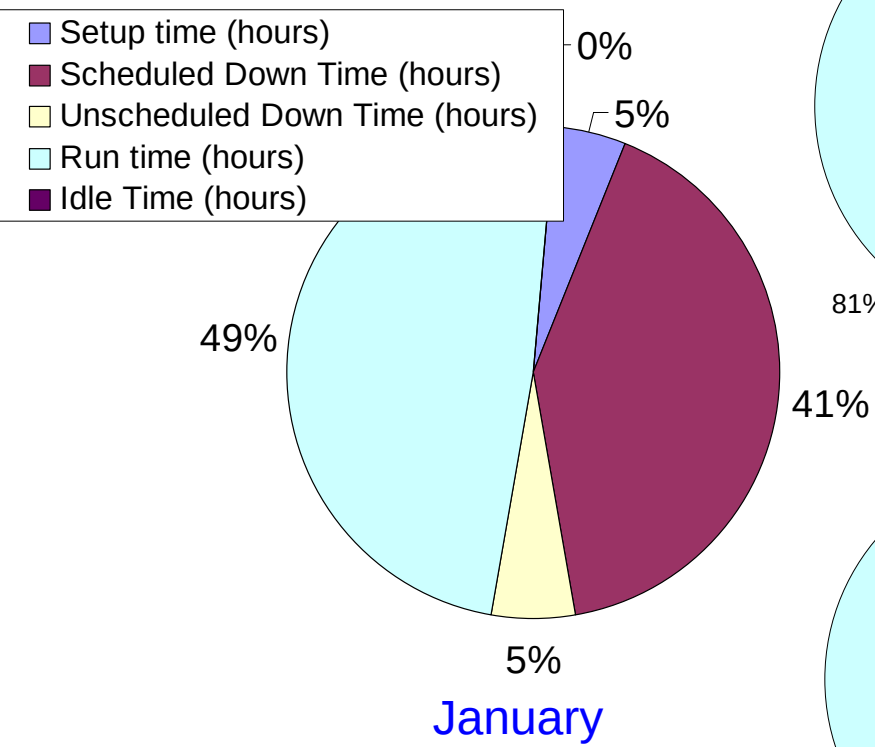
Process	Linear tape speed* (m/h)	Theoretical annual capacity (km)
IBAD MgO	360	3,145
Buffer	345	3,000
MOCVD	180	1,570

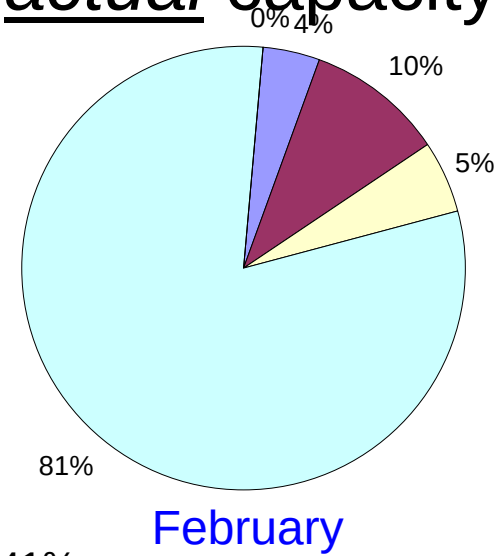
- Theoretical annual capacity does not take into account preparation time for deposition system, preparation time for tape, scheduled equipment maintenance, unscheduled down time and idle time
- In the first half of FY08, our *actual* capacity was only 5,000 m a week i.e. 250 km/year

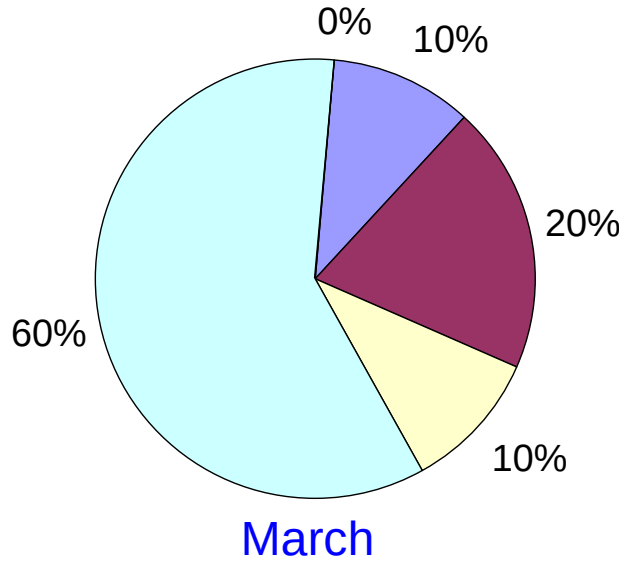
*4 mm equivalent

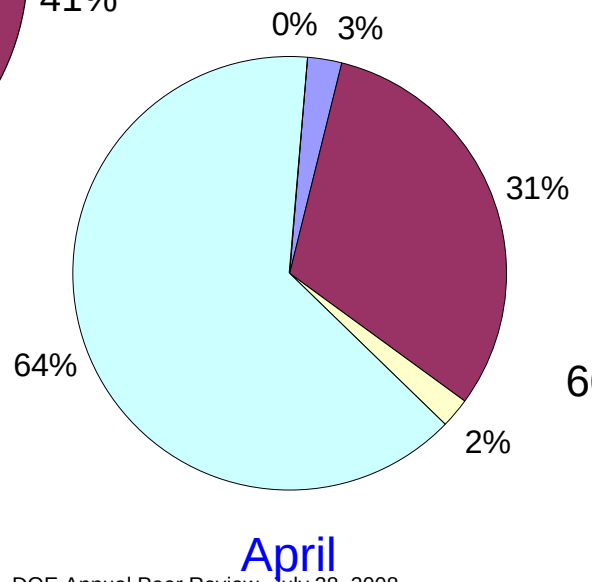
Equipment use time monitored on a monthly basis to accurately determine *actual* capacity

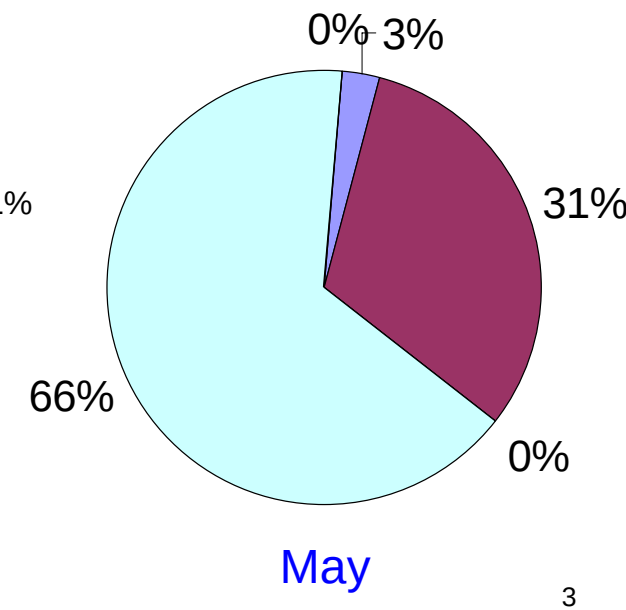
Electropolishing







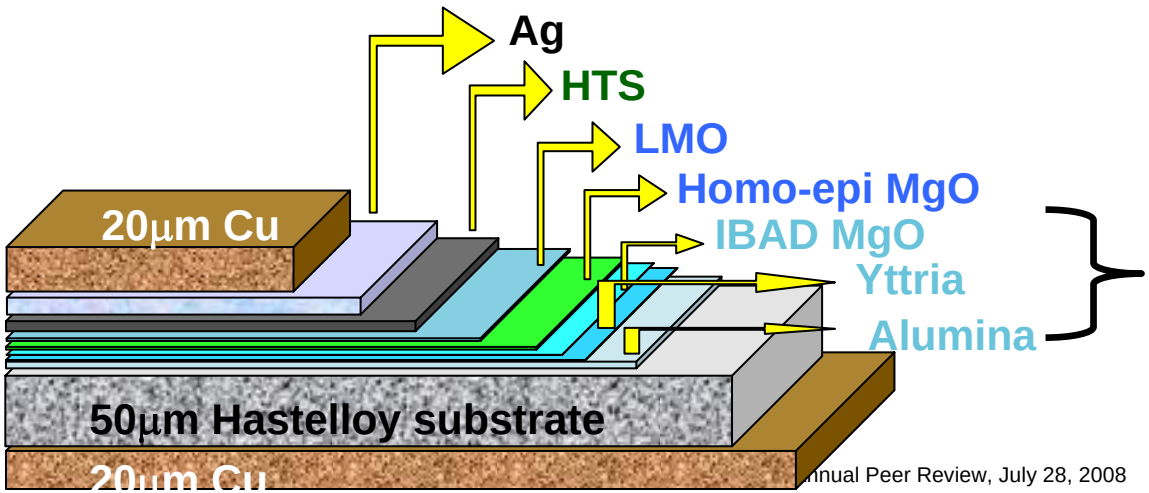




Our focus is to maximize *run time* to ensure high *actual* production capacity

Increasing run time in Pilot IBAD

- **Process speed of IBAD MgO is high: 360 m/h***
- **Need to reduce non-process time (set-up time)**
  - 3 layers (alumina, yttria, and IBAD MgO) were all deposited sequentially in Pilot IBAD system.
  - Since sputtering target needed to be changed between layers, system needed to be vented to atmosphere
  - Vacuum pump-down time turned to be a lot longer than deposition time
- **Solution was to move out alumina and yttria layer deposition out of the Pilot IBAD system.** So, we developed a change to deposition process for these layers - from ion beam sputtering a magnetron sputtering.

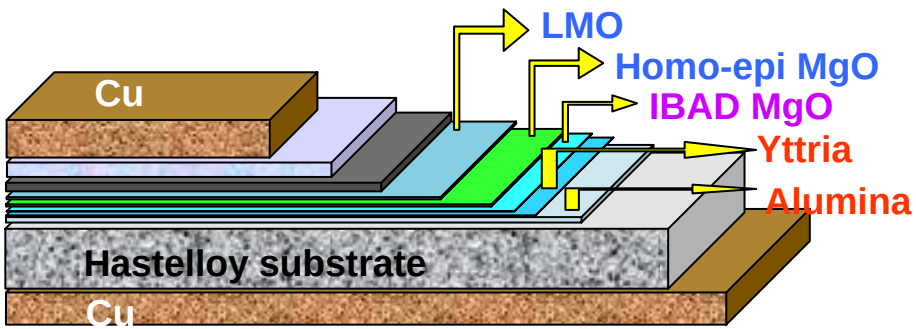


Each of the 3 layers deposited separately by ion beam sputtering

* 4 mm speed equivalent

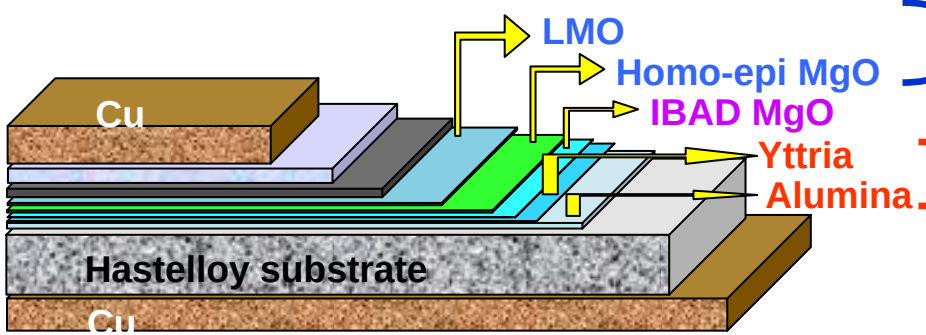
Transition of alumina & yttria layers and combining their processes boosted *actual* production capacity

- Buffered tape production capacity was limited by Pilot IBAD system – one tape a week (5,000 m); significant equipment time was available in Pilot Buffer system.
- Alumina & yttria processes were modified to magnetron sputtering & moved to Pilot Buffer system to avoid capital procurement
- ***Developed process for simultaneous deposition of alumina & yttria layers sequentially using 2-chambers available in Pilot Buffer system - combined two process steps into one, eliminating one set-up time.***
- Speed of **750 m/h** (limited only by hardware) of 4 mm wide tape to deposit both alumina & yttria; deposition time is only 6 hours!



Combining homo-epi MgO/LMO processes completed effort in doubling *actual* capacity

- **Process speeds of homo-epi MgO & LMO are high: 345 m/h*.**
- But homo-epi MgO & LMO processes were done separately, so set-up time turned out to be longer than deposition time.
- **Now simultaneous deposition of homo-epi MgO & LMO processes - combined two process steps into one, eliminating 1 set-up time.**
- *Modus operandi* in Pilot Buffer: one week to produce 4 alumina-yttria tapes, following week, switch targets to produce 4 homo-epi MgO/LMO tapes. Hence, effective actual capacity of Pilot Buffer = two tapes a week
- With the transfer of alumina & yttria out of Pilot IBAD, actual capacity of IBAD MgO is also doubled to two tapes a week.



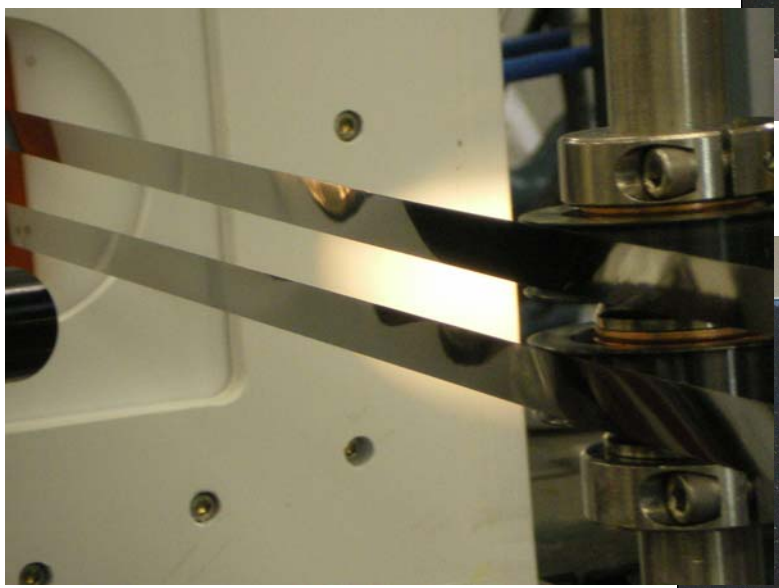
Now these 2 layers deposited simultaneously in Pilot Buffer

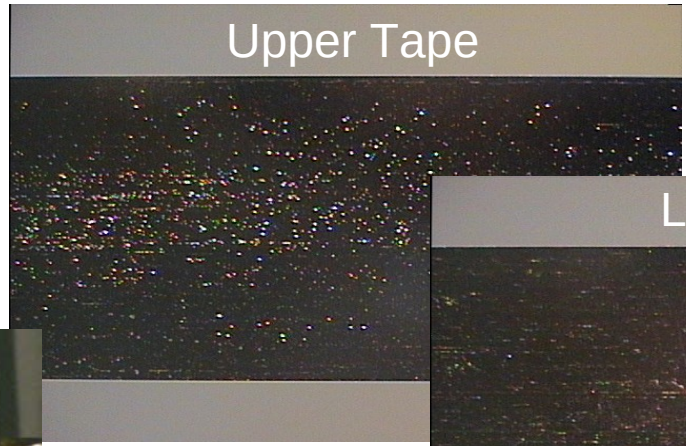
Now these 2 layers are deposited simultaneously in Pilot Buffer

*Through changes in alumina & yttria deposition processes and simultaneously deposition, as well as simultaneous deposition of homo-epi MgO & LMO, **actual production capacity has been doubled to 10,000 m per week i.e. 500 km/year***

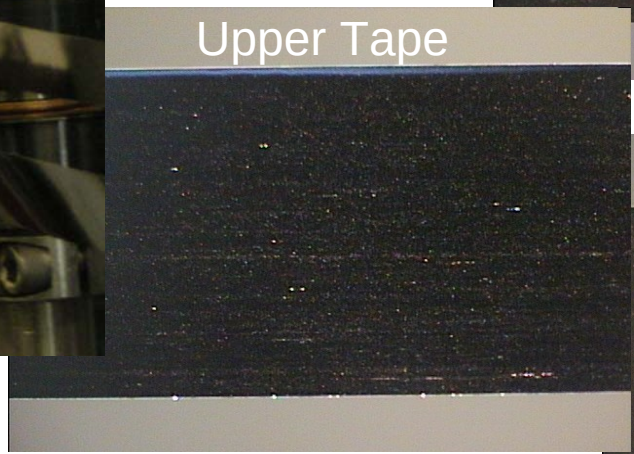
Doubling tape throughput in electropolishing: polishing 2 tapes simultaneously

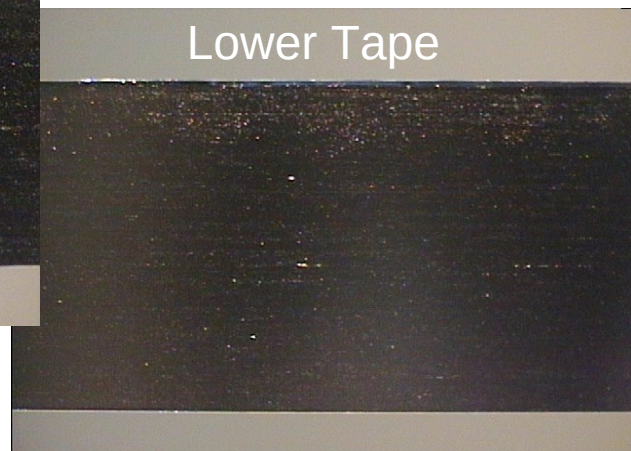
We have already begun effort to further increase actual production capacity, starting with electropolished substrate availability





1st trial

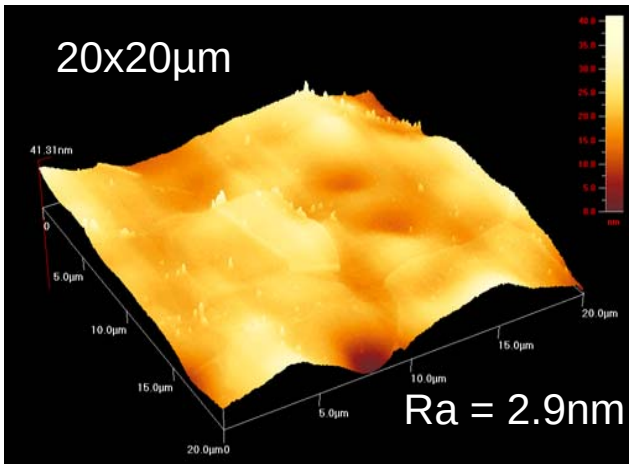


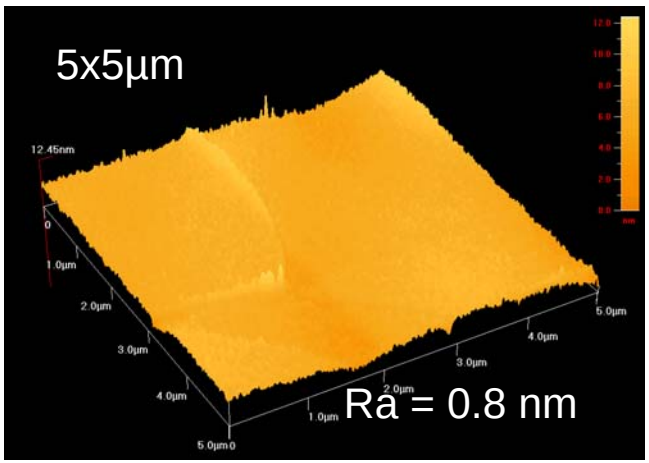


5th trial

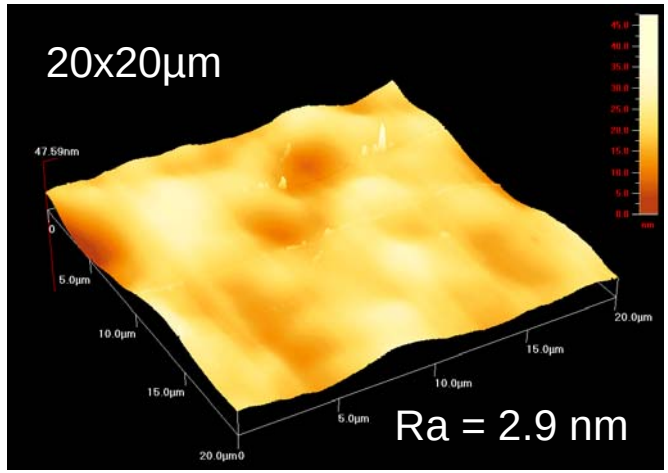
Good surface quality achieved in both electropolished tapes

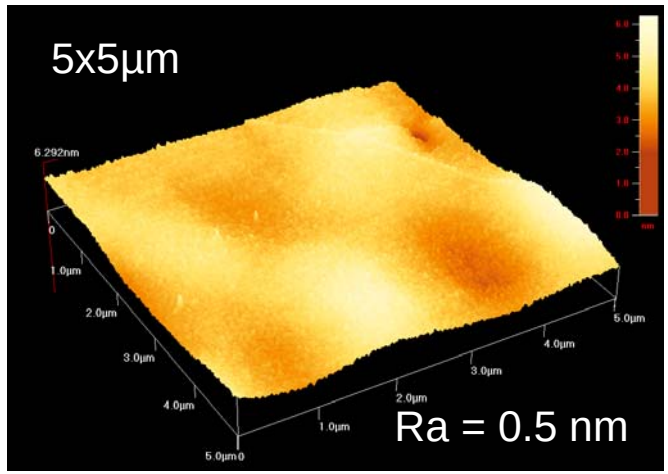
Top polished tape





Bottom polished tape





A wide range of Technology Transfer, Collaborations, and Partnerships with numerous institutions

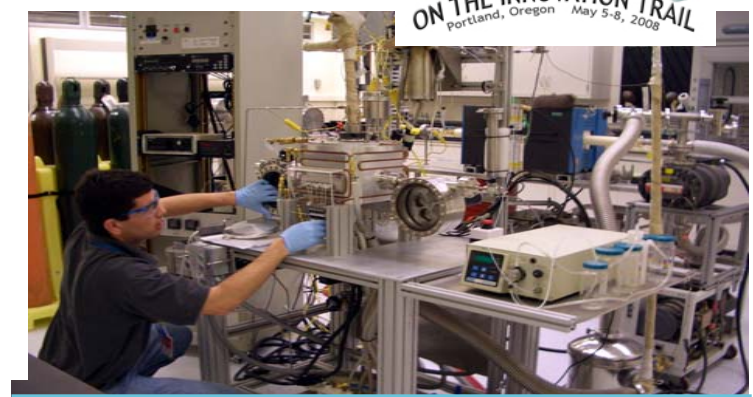
- **Customers & partners – 2G wire engineering to meet applications requirements**
- **National laboratories – Applied research for 2G wire performance improvements**
- **Universities – Basic research to understand 2G wire properties**

- LANL – CRADA in eighth year
  - Simplification of buffer structure for IBAD MgO, using Al-Y-O composite to combine alumina & yttria into a single layer
  - Position-dependent transport studies of Ic in long 2G wires
  - Ac loss measurements on coils
  - Additional patents licensed under existing License Agreement
  - **FLC award for successful transfer of IBAD MgO technology**
  - More details in LANL-SP CRADA presentation tomorrow
- ANL – CRADA in fourth year following a 5-year Pilot Center Agreement on 2G
  - Coordinated characterization to investigate development of YBCO growth in multi-track helix tape handling system in Pilot MOCVD
  - Understanding of Zr incorporation in MOCVD wires
  - More details in ANL-SP CRADA presentation tomorrow

Extensive collaborations with national laboratories for improving wire performance & wire testing

- ORNL – CRADA in sixth year.
  - Microstructural & in-field Jc studies to improve performance of MOCVD thick films and to improve in-field performance.
  - Joint development in Research MOCVD system to previously transferred to ORNL to directly support our process optimization work.
  - Simplification of buffer architecture by elimination of homo-epi MgO layer.
  - License Agreement executed and LMO technology licensed
  - ***FLC Award for LMO-enabled 2G HTS Wire (yes, two for SuperPower)***
  - More details in ORNL-SP CRADA presentation tomorrow

- **NRL**: Axial strain, transverse pull tests (R. Holtz)
- **NIST**: Axial strain measurements on 2G wire with thin substrates & thick HTS films (D. Laan)
- **AFRL**: AC tolerant conductor (P. Barnes)
- **NREL**: CRADA on electroplating copper (R. Bhattacharya)



SuperPower's MOCVD system at ORNL

Technology Transfer, Collaborations, and Partnerships ranging from Universities to device manufacturers

- U. Houston: Mechanical property measurements, in-field performance (Kamel Salama, Goran Majkic)
- FSU: TEM, Flux pinning studies on MOCVD tapes, High-field coil (D. Larbalestier, Z. Chen, F. Kametani, D. Markewicz, H. Weijers), ac loss testing in tapes & coils (S. Pamidi, S. Dale)
- RPI: Process development & characterization of multifilamentary wires (Gopal Pethuraja, Partha Dutta)
- U.Albany: Advanced characterization with FIB, TEM, AFM, Auger, SIMS (Eric Lifshin, Brad Thiel, Kathleen Dunn)
- OSU: ac loss measurements on tapes with different Ic, multifilamentary geometries (Mike Sumption)
- Sumitomo Electric: 2G conductor testing for Albany Cable DOE-SPI project (Hiro Yumura)
- Reliance Electric: 2G conductor testing and engineering for Naval Generator program (Rich Schieferl)
- DOE Gridworks program: 2G conductor design & engineering for FCL DOE-SPI project (Juan Carlos Llambes, Drew Hazelton)
- Numerous customers: 2G conductor engineering for several applications FCL, magnets, ROEBEL cable, current leads, high-field coils

Scoring Criterion: FY08 Performance against **Goals** stated Last Year – Long-length metric

- **Piece lengths of 1000 m**
  - Routine manufacturing of 5-layer buffer stack in lengths of 1,300 to 1,500 m. Average in-plane texture of 7 degrees over entire length with excellent uniformity of ~ 2%. Over 35 tapes in lengths of 1,300+ m made with full 5-layer buffer stack.
  - Complete 2G wire demonstrated in kilometer lengths by control of every single process step
    - 945 m with Ic of 200 A/cm; Ic × Length = 189,000 A-m
    - 1,205 m with Ic of 163 A/cm; Ic × Length = 196,415 A-m
    - 1,311 m with Ic of 153 A/cm; Ic × Length = 200,580 A-m
    - All new world records
- **Critical current of 300 A/cm & then 500 A/cm**
  - 202 m with Ic of 314 A/cm with uniformity of 2.4%

Scoring Criterion: FY08 Performance against **Goals** stated Last Year – High current metric

- **Ic of 1000 A/cm in short lengths**
  - 813 A/cm over 1 meter using improved MOCVD process in thick films using production buffered tapes. Repeated achievement of 800+ A/cm over 1 meter.
  - 1007 A/cm measured on SuperPower 2G wire at ORNL (to be reported in SuperPower-ORNL CRADA talk tomorrow)
- **300 A/cm at 65 K & 3 T**
  - 340 A/cm at 65 K & 3 T (perpendicular field) and 267 A/cm (minimum Ic) using Zr-doped (Y,Gd)BCO.
  - 229 A/cm at 77 K & 1 T (perpendicular field) using Zr-doped (Y,Gd)BCO.
  - Zr-doped (Y,Gd)BCO process successfully transitioned to Pilot MOCVD. 2 to 3-fold improvement in Ic achieved at 77 K, 1 T
  - Long length (including world record kilometer length) 2G wires now produced with Zr-doped (Y,Gd)BCO

Scoring Criterion: FY08 Performance against **Goals** stated Last Year – Production capacity metric

- **Production capacity of 1000 km/year**
  - Based on line speeds, IBAD MgO and Buffer deposition theoretical production capacity exceeds 3,000 km/year and that of MOCVD exceeds 1,500 km/year
  - Our focus was on actual production capacity in FY08 to be comparable with 1G wire so that 2G wire can be made available in large quantities for large device projects.
    - Doubled IBAD MgO capacity to 10,000 meters a week by developing magnetron sputtering processes for alumina and yttria layers
    - Alumina and yttria layers routinely processed simultaneously at a speed of 750 m/h of 4 mm wide tape (4x increase in alumina process speed). Deposition time is only 6 hours for 5,000 m.
    - Homo-epi MgO and LMO layers routinely processed simultaneously, decreasing process time by ½
    - Doubling of electropolishing capacity demonstrated by polishing 2 tapes in parallel with good quality
    - **Together, our actual production capacity in FY08 was *doubled* from last year to 500 km/year**

Scoring Criterion: FY08 Performance against **Goals** stated Last Year – Cost metric

Cost reduction by improving manufacturing yield by QC and Process control and simplification of wire architecture

- **Add On-line QC tools such as on-line ellipsometry, on-line XRD, on-line tape inspection systems in Pilot systems**
  - Procured and tested on-line XRD system for Pilot MOCVD and on-line ellipsometry for Pilot IBAD. On-line tape inspection has been installed & used in long-length production in Pilot MOCVD.
  - High-yield operation achieved through robust QC and process control in every step. *Wire price decreased to $40/m from $65/m in FY07*
- **Work with LANL, ORNL, and ANL to evaluate modified buffers & substrate for IBAD MgO-based conductor to reduce # layers.**
  - Working with ORNL, eliminated homo-epi MgO buffer with direct deposition of LMO on IBAD MgO. Achieved high Ic in 2G wire fully made at SuperPower with 4-layer buffer stack (details in SP-ORNL CRADA presentation tomorrow)
  - Working with LANL, combined alumina and yttria layers into a single Al-Y-O composite (details in SP-LANL CRADA presentation tomorrow)

Scoring Criterion: FY08 Performance against **Goals** stated Last Year – Meeting customer requirements

Work with customers to engineer 2G wire to meet their requirements

- 2G cable made with nearly 10,000 of SuperPower's 2G wire brought into operation in grid in January. First 2G device energized in the power grid.
- Robustness of high-quality splices demonstrated in production mode. Supply of spliced wire with fully qualified joints to customer.
- Capability for insulated wire established in house. Delivery of insulated wire in 4 mm and 12 mm widths to customers.
- New industrial process developed and scaled up to produce up to15 m lengths of continuous multifilamentary wire with Ic up to 72 A in 4 mm widths and 5-fold ac loss reduction. Fabricated coils using lengths of multifilamentary wire. Lower ac losses and absence of coupling loss measured in coil made with multifilamentary wire.
- Recovery under load successfully achieved in high-power testing of FCL made with 2G wire.
- **33,000 meters procured in 77 wire orders at market price (5-fold increase from FY07) from 47 customers world wide. Customer base is 58 compared to 25 in FY07**.

Approach and Project Management: FY09 milestones

In FY09, we will continue steady progress toward our near-term goal of replacing 1G wire in prototype device projects and medium-term goal of challenging Cu wire in commercial projects

- **Long-length metric**
  - Achieve 300 A/cm first in 1000 m, then 1500 m.
- **High current metric**
  - Achieve 500 A/cm first in 500 m, then 1,000 m.
  - Improve Jc in 3 micron thick films to achieve 1000 A/cm (measured over entire width) in collaboration with ORNL
- **High in-field Ic metric**
  - Continue work with national laboratories to further improve in-field properties with Zr-doped chemistry and other chemical substitution. With ORNL specifically, optimize MOCVD precursor recipes using transferred Research MOCVD system.
  - Achieve a Ic of 400 A/cm at 65 K and 3 T using standard MOCVD processes

Approach and Project Management: FY09 milestones

- **Production capacity metric**
  - Bring a new pilot-scale MOCVD system on line to further increase capacity as well as work on scaling up our enhanced performance wire while continuing to meet customer deliveries of our standard wire
  - Continue to increase run time in all processes to further increase actual production capacity by at least 25%
- **Cost metric**
  - Focus on improving yield in all processes by tight process control and QC
  - Install & routinely use on-line QC tools such as on-line XRD in Pilot MOCVD, on-line tape inspection in Pilot Buffer system
  - Simplify substrate-buffer architecture jointly with ORNL, LANL, ANL and UH
- **Meeting customer requirements**
  - Continue our emphasis on working with customers to engineer 2G wire to meet their requirements for FCL, ac losses, mechanical properties, stability, in-field properties, conductor geometry and high-voltage requirements. Work with National lab & University partners to accomplish this task.
  - Continue to demonstrate 2G prototypes working with our partners & customers

Great strides made in FY08 in all key metrics and meeting customer requirements

Metric	2005 review	2006 review	2007 review	2008 review	Improvement in 2008
Ic (A/cm) over 1 m	236	470	595	813	37%
Ic (A/cm) at 77 K, 1 T			116	229	97%
Ic (A/cm) at 65 K, 3 T			181	340	88%
Ic over 200 m (A/cm)	106	246	227*	314*	38%
Length with Ic > 200 A/cm (m)		322	322	945	193%
Completed 2G wire piece length (m)	207	322	595	1,311	120%
Ic × L (A-m)	22,000	70,520	102,935	200,580	95%
2G wire price ($/m)	500	100	65	40	39%
2G wire orders (m)			6,400	33,000	415%

*at 100 to 200% higher speed than in 2006