FY06 Performance & Results and FY07 Plans

HTS Solutions for a New Dimension in Power

Superconductivity for Electric Systems – 2006 Annual DOE Peer Review

Scoring Criterion: FY06 Plans & Performance – Scale-up

2GFeature	Stated goal for FY06 in FY05 presentation
High throughput	Demonstrate Helix tape handling in all processes Achieve 30 m/h in every step to produce 100 m at 100 A/cm
	• New Pilot Buffer system with helix tape handling up to 12 tape wraps in two process chambers was set up. Speeds up of **40 m/h** routinely used for producing homo-epi MgO & LMO by sputtering processes with uniform texture of 6 to 8 degrees in single piece lengths up to 570 m.
	• Pilot MOCVD was retrofitted with helix tape handling system with 6 tape wraps and 2x longer deposition zone to achieve speeds up to 30 m/h
	• IBAD MgO was transitioned to Pilot IBAD system. Speeds of **65 m/h** routinely used to fabricate single piece tapes up to 570 m in length with uniform texture.
Long lengths with high uniformity	250 m with Ic of 100 A/cm with 5% uniformity
	• **322 m** long tape produced with **Ic of 219 A/cm (70,520 A-m – a new world record) with a uniformity of 4.3%** at a MOCVD speed of **30 m/h**
	• Achieved **uniformity better than 5% over 300 m and better than 3% over 200 m in several tapes,** all processed at 30 m/h in a single pass.
	• **100 A demonstrated in 4 mm wide, 270 m long conductor. Ic in the realm of 1G. Je = 26.3 kA/cm^2, up to 2 times that of 1G.**

Scoring Criterion: FY06 Plans & Performance – Quality

2G Feature	Stated goal for FY06 in FY05 presentation						
High Ic	Demonstrate 500 A/cm in 2 micron films Demonstrate 300 A/cm over 100 m						
	Length	5 cm	1 m	52 m	157 m	227 m	322 m
	Ic (A/cm)	557	470	272	263	246	219
	Thickness (μm)	2.1	2.1	1.0	1.2	1.2	1.2
	Jc (MA/cm^2)	2.65	2.24	2.72	2.19	2.05	1.83
Better in-field properties	Demonstrate Je of 100 kA/cm^2 in self field and 25 kA/cm^2 at 1 T, 77 K, using chemical substitution						
	Je of 100 kA/cm^2 in self-field & 21.1 kA/cm^2 at 1 T, 75 K achieved using chemical substitution & thicker (2.1 microns) MOCVD films.						
Quality Control	High-speed XRD tool for IBAD MgO buffers						
	Modified reel-to-reel XRD system for texture analysis of YBCO, LMO, and MgO (underneath YBCO !) In-plane, theta-2theta measurements can all be done on any material on long tapes in reel-to-reel moving mode or stop-and-go stationary mode. Cycle time for complete pole figure (±15º) = 30 seconds						

Scoring Criterion: FY06 Plans & Performance – Manufacturing

2G Feature	Stated goal for FY'06 in FY'05 presentation				
Reproducibility	Produce 8000 m for Albany Cable project				
Process	**# Production runs**	**Total Production (4 mm equivalent)**	**# Runs with process lengths greater than**		
			100 m	**200 m**	**300 m**
IBAD MgO	25	43,980 m	25	23	22
Homo-epi MgO+ LMO Buffers	37	37,560 m	37	27	24
MOCVD YBCO	31	17,160 m	31	24	11
		Inventory	**Piece lengths**		
			> 50 m	**> 100 m**	**> 200 m**
4 mm wide qualified conductor exceeding length spec (43 m) & Ic spec (100 A/cm)		**12,470 m**	**93**	**52 (55%)**	**25 (27%)**

Scoring Criterion: FY06 Plans & Performance – Conductor Properties

2G Feature	Stated goal for FY06 in FY05 presentation
Better mechanical properties	Improve mechanical properties using thinner substrates
	• Using high-strength 50 micron substrates, achieved **yield stress of 1200 MPa** in final conductor compared to 550 MPa last year and typical performance of other IBAD-based 2G. Also, using these high-strength substrates, achieved **critical tensile stress levels over 550 MPa** compared to 350 MPa last year. • Fabricated & tested thermo-electro-mechanical properties of *joints & splices* made with thin-profile conductor. Total conductor thickness with copper stabilizer = 95 microns. ***Total thickness at joint or splice = 220 microns which is ½ thickness of joints & splices that could be made with 1G or other 2G.*** • *No degradation in Ic even when joint or splice was bent to a diameter of 1" & thermal cycled.* Joint or splice resistance = 50 nΩ cm^2, similar to or better than 1G.
Ac loss reduction in long lengths	Demonstrate patterned + twisted conductor
	• Patterned conductor 100 & 50 micron filaments with 10 micron & 5 micron spacings respectively. Factor of 73 reduction in ac losses achieved at 0.1 T & 150 Hz. • Demonstrated the very first patterned & twisted conductor & measured ac losses of such conductor

Scoring Criterion: FY06 Plans & Performance – Prototypes & properties

2G Feature	Stated goal for FY06 in FY05 presentation
Over-current protection	Quench testing of coils
	• Detailed stability tests done on our conductor by ORNL (will be presented in CRADA presentation). High-field coil will be shipped to ORNL for stability tests.
Better dielectric properties	Dielectric testing of our 2G conductor with ORNL.
	• Extended dielectric tests on our surround stabilized 2G to a winding geometry at ORNL. Surround stabilized 2G shows higher breakdown voltage & lower probability of failure than as-slit tapes.
2G Prototypes	• Fabricate coils with high Je conductor to achieve field of 3 T at 65 K • Modify 2G conductor to meet specific customer requirements such as fault current
	• **Fabricated a coil that generated 1.1 T at 77 K** (best with any superconductor ?). **This coil generated 2.4 T at 64 K** • Demonstrated the viability of 2G as FCL elements. Rapid response time of 1 ms, fast quench of ~ 3 times Ic, fast recovery ~ 5 seconds & uniform current sharing in parallel operation. • High-power tests conducted with a 2G SFCL assembly at KEMA. **Prospective currents of 90 kA limited to 39 kA with only 3 kA through 2G.** *Response time within 1 ms. No element failure. Better in all respects than FCL with melt-cast BSCCO in similar high-power tests.*

Scoring Criterion: FY06 Results –

Substantial progress in FY06 in Length, Throughput, Critical Current, & Uniformity

		FY05	FY06
IBAD	IBAD YSZ	140 m, 1 m/h	Stopped YSZ
	IBAD MgO length	140 m	**570 m single piece** **750 m process length**
	IBAD MgO speed	10 m/h	65 m/h of 12 mm wide tape (= 195 m/h of 4mm wide tape)
MgO + LMO Buffers	Length	125 m	**570 m**
	Speed	10 m/h	40 m/h of 12 mm wide tape
MOCVD Ic (A/cm)	5 cm (no bridges)	250	**557** on IBAD MgO
	1 m	235	**470** on IBAD MgO
	Over 50 m	206 on IBAD YSZ	272 on IBAD MgO
	Over 100 m	152 on IBAD YSZ	263 on IBAD MgO
	Over 200 m	107 on IBAD YSZ	**246** on IBAD MgO
	Over 300 m		**219** on IBAD MgO
Uniformity in MOCVD Ic	Over 100 m	4.2% on IBAD YSZ	**1.7%** on IBAD MgO
	Over 200 m	30.0% on IBAD YSZ	**2.6%** on IBAD MgO
	Over 300 m		**4.3%** on IBAD MgO
MOCVD speed	To produce 1 micron YBCO film	5 m/h	**30 m/h** of 12 mm wide tape (= 90 m/h of 4mm wide tape)

Scoring Criterion: FY06 Results –

Substantial progress in FY06 in & wire production, coil performance, QC & new 2G prototypes

	FY05	FY06
Wire Produced for Albany Cable project	320 m	**12,470 m**
HTS coil	0.8 T at 64 K	**1.1 T at 77 K, 2.4 T at 64 K**
2G Prototypes	World's 1st & 2nd 1 m cables with 4 mm conductor ac loss of 0.36 W/kA-m World's 1st rotating machine – 7.5 h.p.	Viability of 2G in FCL demonstrated. 2G FCL assembly built & tested to high power levels. Performance of 2G FCL met AEP's requirement of 26 kA rms (70 kA peak) fault condition
QC	Characterization of texture, buffer thickness, composition & depth profiling using advanced analytical tools at labs & Universities	Quality control of texture, buffer thickness, YBCO composition, & depth profiling using new in house tools : Reel-to-reel XRD, spectroscopic ellipsometer, ICP, Glow Discharge Optical Emission Spectroscopy

Scoring Criterion: FY06 Results

- *Successfully integrated IBAD MgO with MOCVD* – only all high throughput approach for 2G. Slowest process now is 30 m/h of 12 mm wide tape **(6x improvement from last year)**
- *Solved Ic degradation problem in MOCVD* (assigned a high priority by FY'05 reviewers). Achieved uniformly high Ic (> 200 A/cm) over 300 m lengths. Ic uniformity improved from 30% to 2.6% over 200 m
- In spite of a late start due to challenges in multiple simultaneous modifications to Pilot equipment, we have produced over 12,400 m of qualified 4 mm wide conductor for the Albany Cable project. Far exceeded the spec for piece length (42.4 m) and Ic (100 A/cm). 55% and 27% of tapes in inventory are over 100 m and 200 m respectively. 71% of tape produced by MOCVD since May is over 200 m and 43% over 300 m.
- Improved microstructure of MOCVD films to achieve up to 4.7 MA/cm^2 in 0.7 micron thick films – an 100% improvement from last year ! Using this template, achieved a Jc of 2.65 MA/cm^2 in 2.1 micron films (= 557 A/cm over 12 mm wide tape). This is a 90% improvement in Ic at this thickness ! Using a 2 mm wide bridge a Jc of 3 MA/cm^2 was measured in this 2.1 micron film (=630 A/cm). At 1 T, 75.5 K, B || c, a Ic of 117 A/cm (90% improvement from last year), Jc 0.56 MA/cm^2 (175% more) of & Je of 21.1 kA/cm^2 (82% more)
- Using rare-earth modification, achieved an improvement of 100% in Jc at B || a-b. Additional improvement at all field angles achieved with further foreign element doping. Peak at B || a-b was broadened by 5 to 6°
- Very first demonstration of *striated copper stabilizer* for ac loss reduction. Found that the copper stabilizer on the substrate does not add to the ac losses.
- Dielectric testing of 2G conductor with surround stabilizer tested in a wire geometry at ORNL. *Conductor with surround stabilizer withstood a higher breakdown voltage than as-slit conductor (85 kV/mm vs. 29 kV/mm) and a higher voltage at 10% probability of failure (19 kV/mm vs. 10 kV/mm)*

Scoring Criterion: FY07 Plans

Conductor Manufacturing & Commercialization

FY06 was the transition year to Pilot-scale manufacturing. FY07 will be the year to enhance the commercial viability of 2G and begin to compete head on with 1G.

- Complete delivery of 10,000 m of fully-tested 2G conductor to Sumitomo Electric to fabricate 30 m long 2G cable for the Albany Cable project.
- Increase throughput of Pilot IBAD MgO & Pilot Buffers to 100 m/h of 12 mm wide tape (= 300 m/h of 4 mm wide tape) while maintaining a texture of 6 to 8 degrees over 500 m.
- Achieve 3-fold increase in throughput in Pilot MOCVD to 90 m/h of 12 mm wide tape (= 270 m/h of 4 mm wide tape) while maintaining a Ic level of 200 A/cm

This throughput will enable a production capacity of 1000 km/year, on par with 1G

- Reach 1000 m single piece length milestone with electropolishing and IBAD MgO
- Reach 500 m single piece milestone of complete conductor with Ic of 200 A/cm

This single-piece length would be on par with typical 1G piece lengths

- Add new QC & test equipment to further support manufacturing & keep up with the throughput of conductor production
  - Add *on-line* QC tools in Process equipment – tape inspection, buffer thickness
  - Increase speed of critical current testing of long tapes by 4x.

Scoring Criterion: FY07 Plans – Conductor Improvement

- Extend thick film MOCVD technology with support of LANL, ORNL, & ANL to reach 750 A/cm in short tapes and 300 A/cm in lengths greater than 250 m.
- Work with LANL, ORNL, and ANL to evaluate modified buffers & substrate for IBAD MgO-based conductor to reduce # layers and problems with diffusion
- Work with ORNL & LANL to improve in-field properties by chemical substitution. With ORNL specifically, optimize MOCVD precursor recipes using transferred Research MOCVD system.
  - Achieve a Je of 125 kA/cm^2 at 77 K, self field & 30 kA/cm^2 at 77 K, 1 T
- Modify 2G conductor to meet specific customer requirements such as fault current, ac losses, high voltage, etc.
- Complete mechanical testing of conductor with 50 micron substrates (axial strain, fatigue) as well as with thick YBCO films with NIST, U. Houston, Florida State Univ.
- Stability testing of high-field 2G coils with ORNL & Rockwell.
- Embark on widespread sales & marketing of 2G to replace 1G (Title III program goal)

Answers to questions raised by reviewers in 2005

- "There is some indication of an exposure to vendor precursor supply quality".

  We have 2 fully qualified vendors that have supplying MOCVD precursors for 9 years & 3 years. Quality of precursors is very reproducible even in current purchase lots of tens of kg.

- "Assess the value of photon-assisted MOCVD, or at least be prepared to address the question by the next peer review".

  Our experiments several years ago showed PA-MOCVD as demonstrated with quartz lamps is not useful. Our growth rates in MOCVD without any assist is as high as that shown with PA-MOCVD. We are investigating alternate pathways to further increase growth rate.

- "AMSC is already taking orders for its Gen 2 tapes ... When will SP start?"

  We have been selling 2G wire for the last 2 years to several customers in several countries.

Piece lengths	~ 300 m
Ic	Typical 80 A, up to 100 A in 4 mm widths
Delivery time	Within **2 weeks** (just filled a 1000 m 4 mm equivalent wire order in 1 day ARO)
Price	10 m or less : No charge Longer lengths : Market price