SuperPower's 2G HTS Conductors: Status & Outlook

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HTS Solutions for a New Dimension in Power

DOE Wire Development Workshop – January 2006

Questions from session chairs

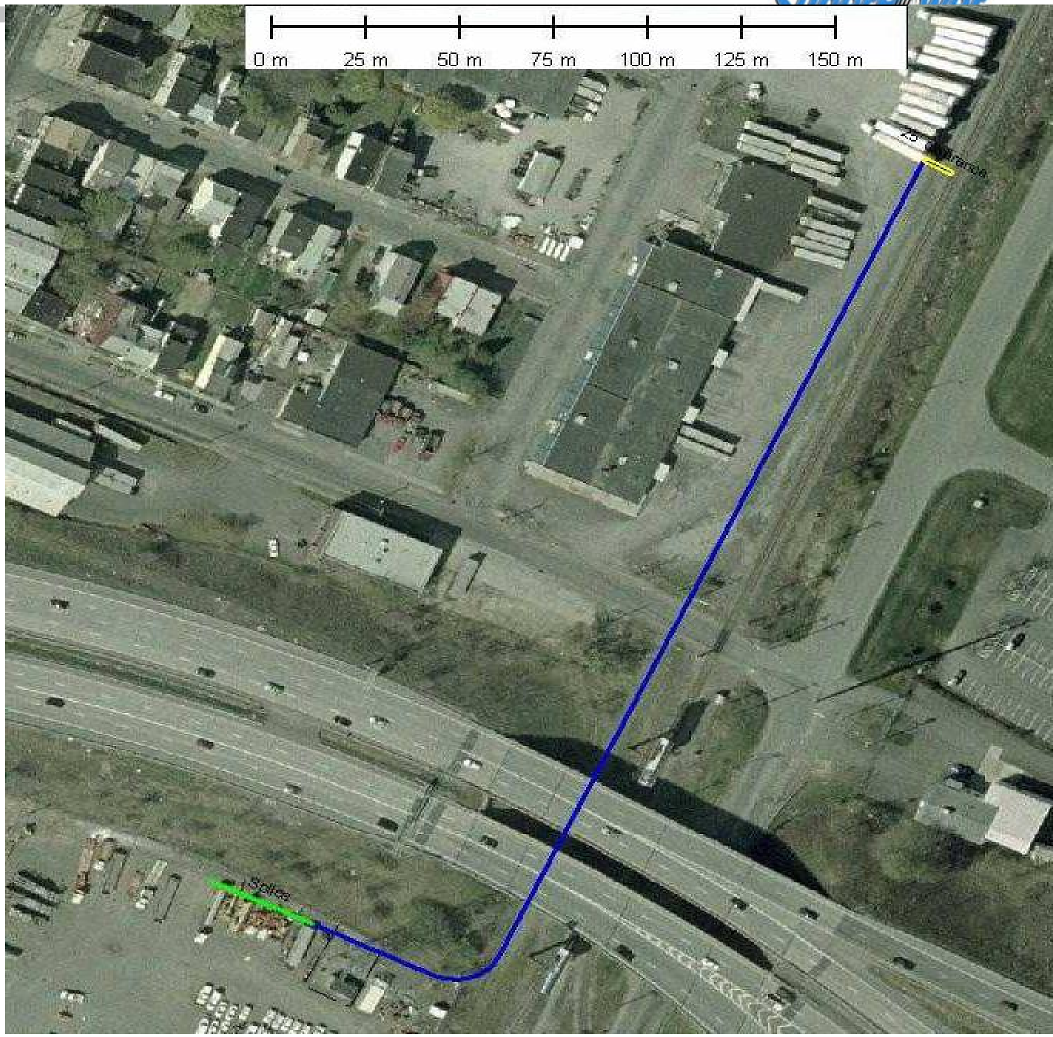
1. What is the production rate of the slowest step? What is the fastest production rate you anticipate for your present fabrication facility without significant reduction in wire properties/characteristics?
2. What is the most expensive step ? What can be done to reduce the cost of the more expensive steps?
3. Have you identified the origins of reduction in Ic from short to long lengths? What steps have you taken to address/remove any deficiencies?
4. What are the top five ***technical*** advances for realizing long-lengths with high Ic's and with a price/performance ratio of less than $10 kAm? On which of these would you like the national laboratories to focus?
5. What ***fundamental*** research would you like the national laboratories to conduct in order to increase the likelihood of realizing practical applications?
6. If the National Labs were to ***stop*** working with you right now because of reduced DOE investment in HTS materials R&D, how would that modify your strategy and the cost of needed R&D at your company?

2G HTS is at the threshold of being implemented in commercial electric power devices

We have come a long way in the last 4 years from centimeter sized tapes to 200 m long practical 2G HTS conductors

Full-fledged pilot-scale manufacturing of 2G conductors in 2006

SuperPower will provide nearly 10 km of 2G HTS conductor in 2006 to build a 30 m long cable for the Albany Cable project, which will be the world's first 2G device.



<u>Albany Cable project</u>: National Grid, 350 m long cable. World's first in-grid cable, first underground cable, first cable-to-cable joint. World's first 2G device (30 m)

Title III Phase 3 program underway to promote manufacturing of higher performance conductor in even longer piece lengths at high throughput

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Phase 3 duration: January 2006 – June 2008

Phase 3 Program goals:

Conductor length ≥ 1000 m

Critical Current (Ic) ≥ 500A/cm width at 77K, self field,

Je, without stabilizer, 15,000 A/cm^2 at 65K, 3 Tesla,

Annual Production Capacity ≥ 200,000 kA-m.

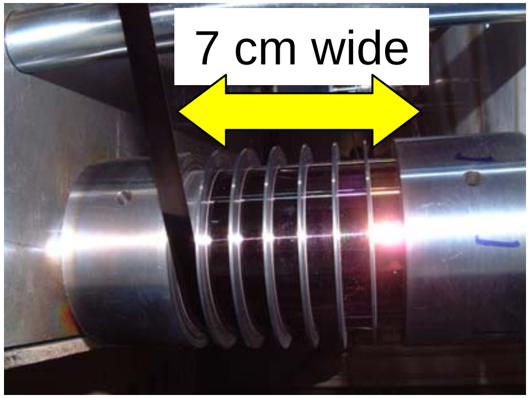
- Corresponds to 1000 km/year of 200 A conductor

Long piece lengths & high throughput are essential for high-volume manufacturing of low-cost conductor

Helix tape handling system extended to all processes to enable long piece lengths & high throughput

Since we use in-situ processes, we have a choice between processing a wide tape or a narrow tape with helix tape handling

We chose helix tape handling because of the immense advantages it provides and the demonstrated benefits of a multipass process.



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- ☑ Much longer (>5x) single piece lengths - important for wire customers who are already used to several 100 m to 1000 m of 1G
- ☑ Much shorter (>5x) process times for the same piece length
- ☑ Less concern with uniformity across width (5x narrower)

Pilot production equipment upgraded for delivery of ~10 km for Albany Cable Project

Since the 2005 Peer review, we have made key pilot production equipment additions & changes for long piece lengths & high throughput

- Conversion of Pilot IBAD system for MgO ~ enables 100x speed increase
- Pilot Buffer system for sputtering of buffer layers on IBAD MgO buffers ~ enables 160x speed increase
- Helix addition to Pilot MOCVD + deposition zone extension ~ enables 20x speed increase

Status of IBAD tape manufacturing in August 2005

Pilot IBAD facility

Used to produce IBAD YSZ tapes up to 230 m piece lengths

Routinely produced more than forty 100+ m long IBAD YSZ tapes

Fully automated, robust operation extending more than 60 hours of non-stop processing.

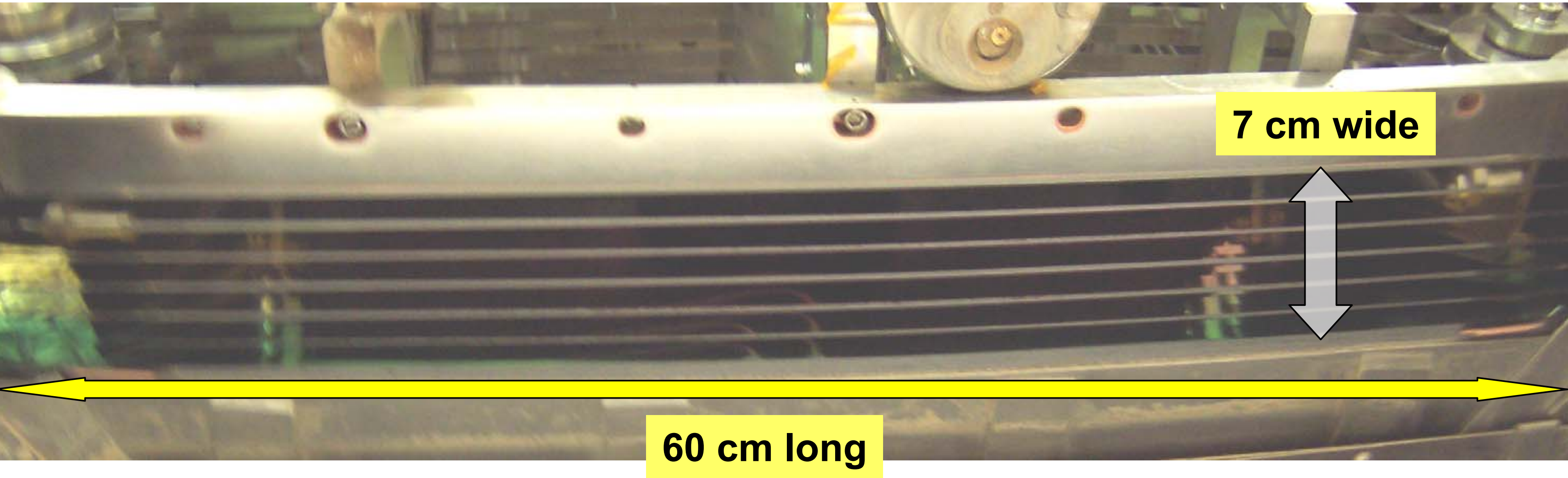
Prototype IBAD facility

Used to produce IBAD MgO tapes up to 140 m piece lengths

Routinely produced more than forty 140 m long IBAD MgO tapes to date.

High throughput IBAD MgO has been transitioned to Pilot IBAD system

- Proto IBAD system: Deposition zone length = 8 cm, 4 tape wraps, 10 m/h
- Pilot IBAD system: Deposition zone length of 60 cm, 6 tape wraps
  - Would enable linear tape speeds > 100 m/h (or a throughput > 300 m/h of 4 mm wide tape)



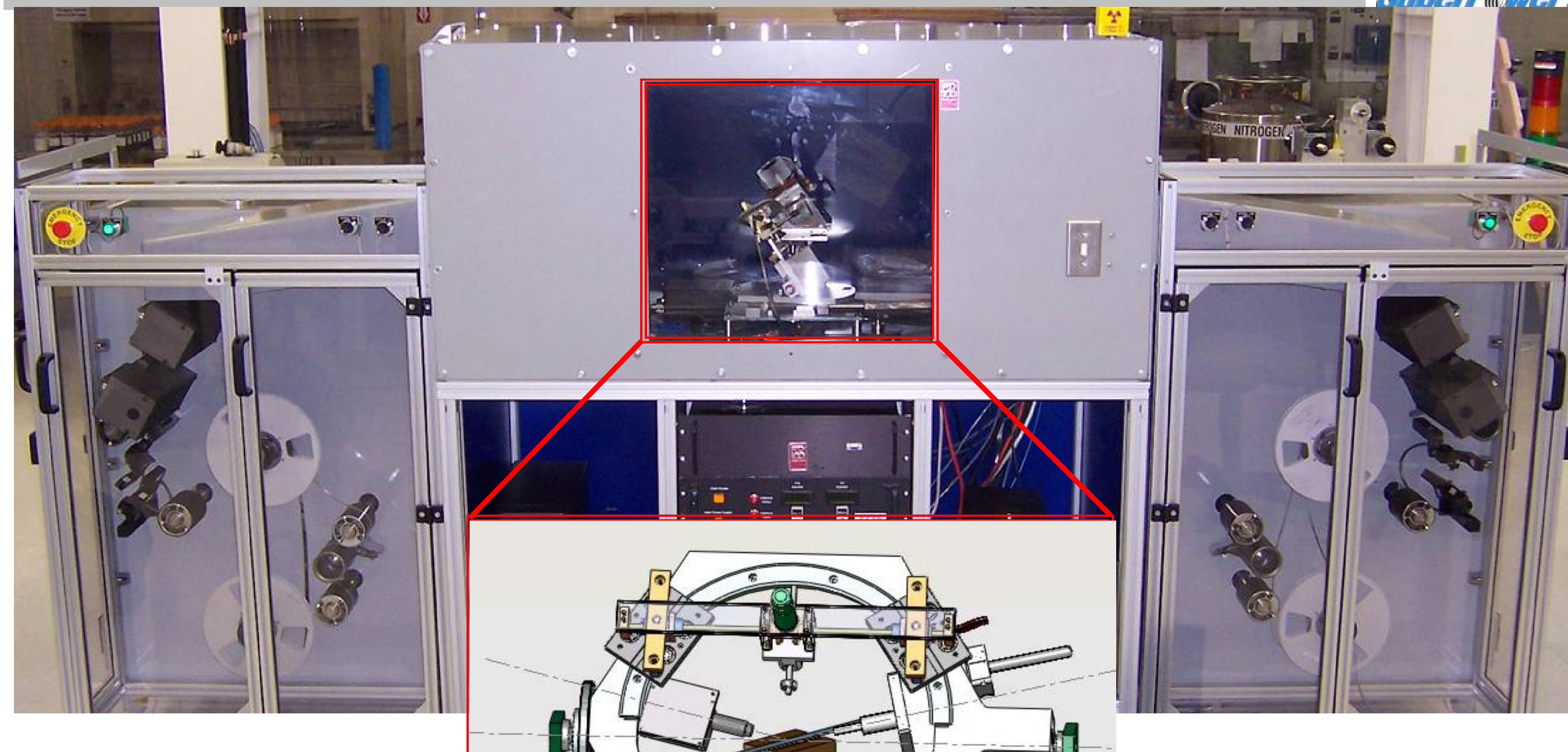
- **Several 250 m long IBAD MgO tapes have been produced with a deposition zone of 42 cm & a speed of 65 m/h of 12 mm wide tape i.e. 195 m/h of 4 mm wide tape**

Pilot Buffer System has been established for long length, high throughput buffer layers for IBAD MgO

- Two chambers for sequential deposition of 2 buffer layers on IBAD MgO
- Helix tape handling in both chambers, each with 12 tape wraps. Deposition zone length in each chamber = 0.3 m
- Spool boxes for 1 km single-piece lengths

Expected tape speed for sputtering of both layers simultaneously = 160 m/h of 12 mm wide tape i.e. 480 m/h of 4 mm wide tape

Reel-to-reel XRD system has been upgraded for rapid texture measurements of up to 1 km of any material

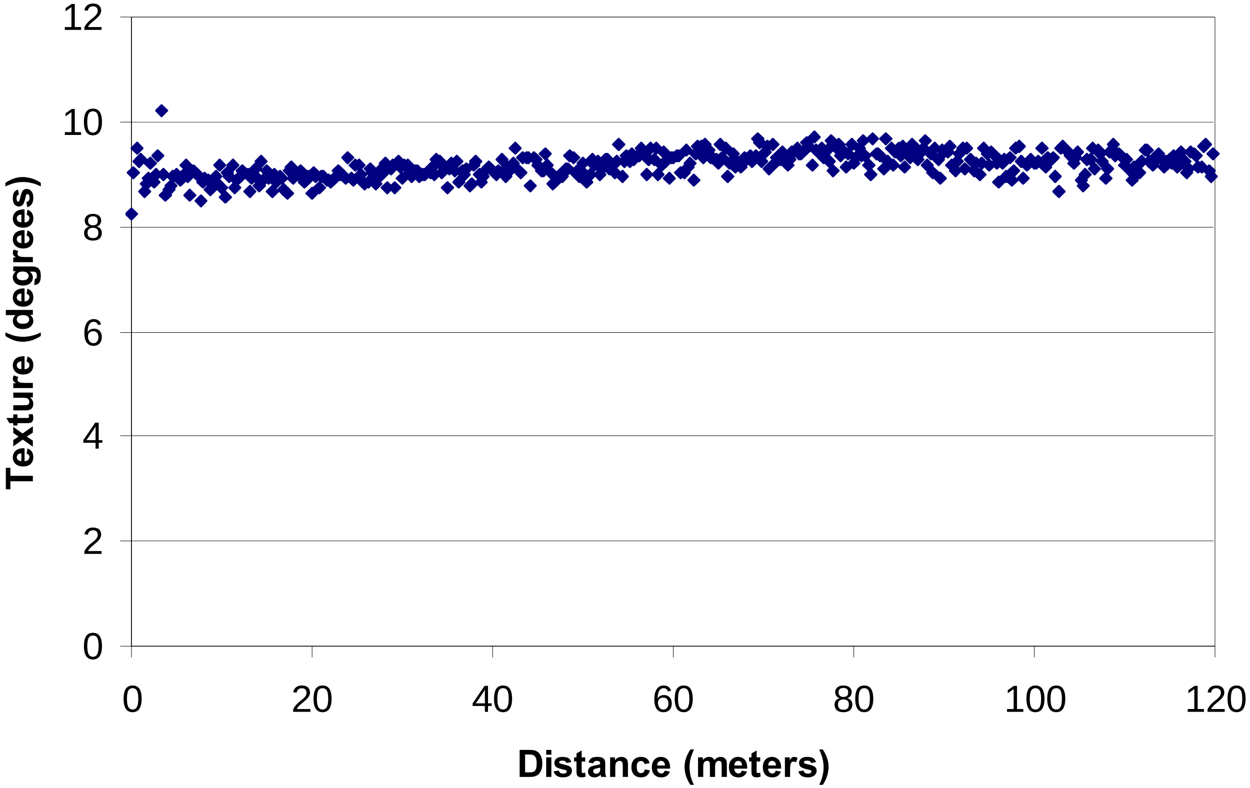


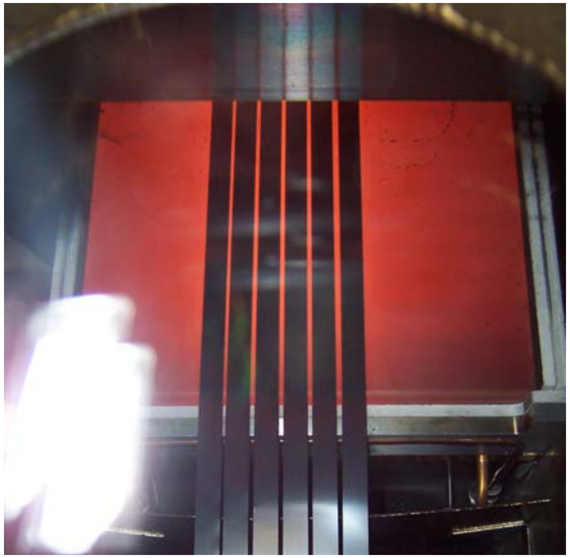
Fully automated system

Out-of-plane, in-plane, theta-2theta measurements can all be done on any material on long tapes

250 m long tapes have been produced in Pilot Buffer system at linear speeds of 80 m/h

Using only 6 of the 12 tape tracks in helix tape handling in Pilot Buffer system, 80 m/h tape speed has been achieved with each of the 2 buffer layers on IBAD MgO





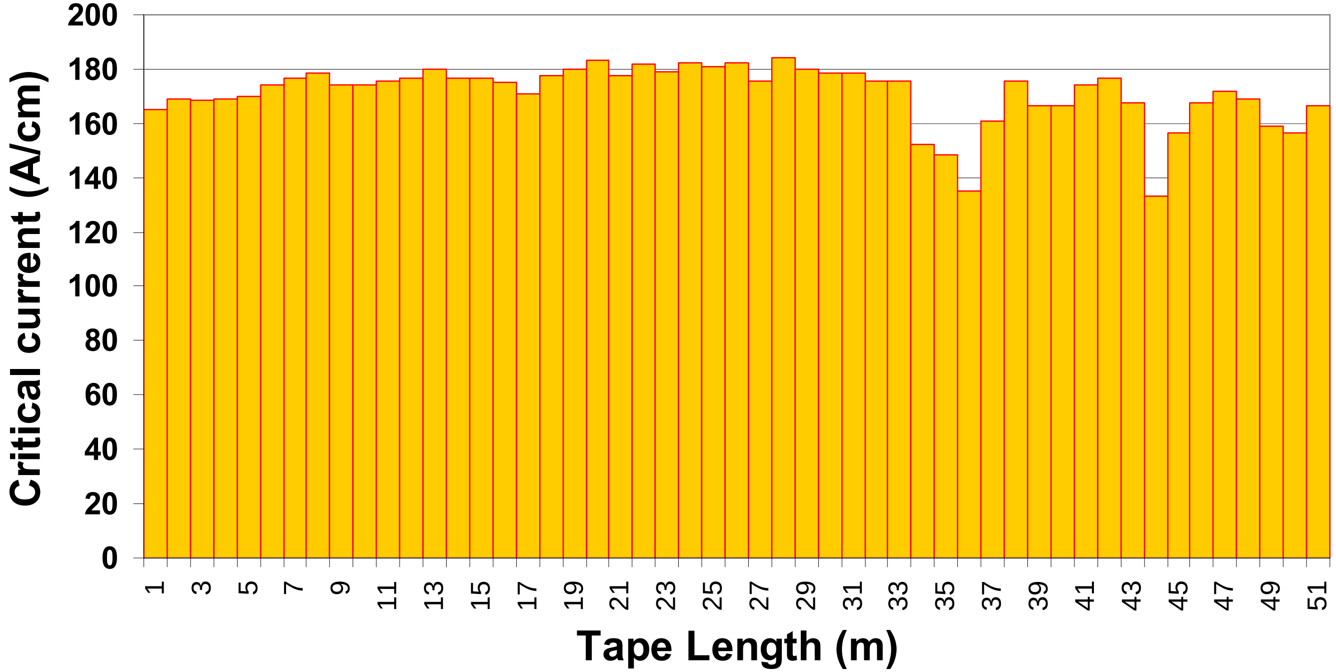
In-plane texture of LMO over 120 m produced at 80 m/h = 9.2º ± 0.24º

High current achieved by MOCVD on high speed IBAD MgO & LMO buffers

IBAD MgO @ 65 m/h of 12 mm wide tape (195 m/h of 4 mm wide tape)

LMO @ 40 m/h of 12 mm wide tape (240 m/h of 4 mm wide tape)

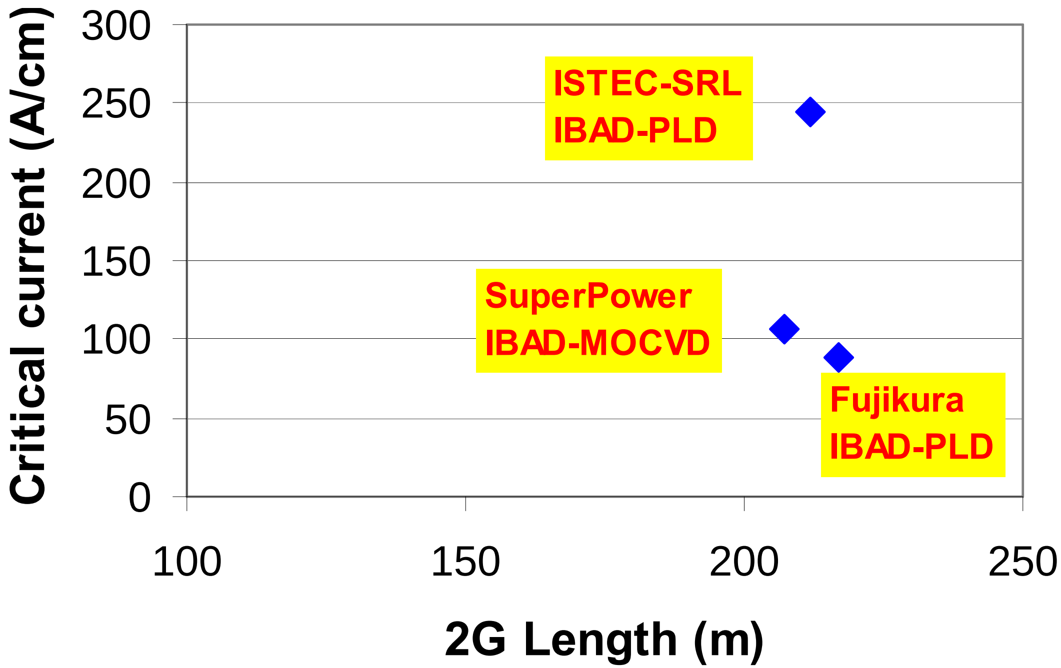
MOCVD @ 10 m/h 1st pass, 10 m/h 2nd pass

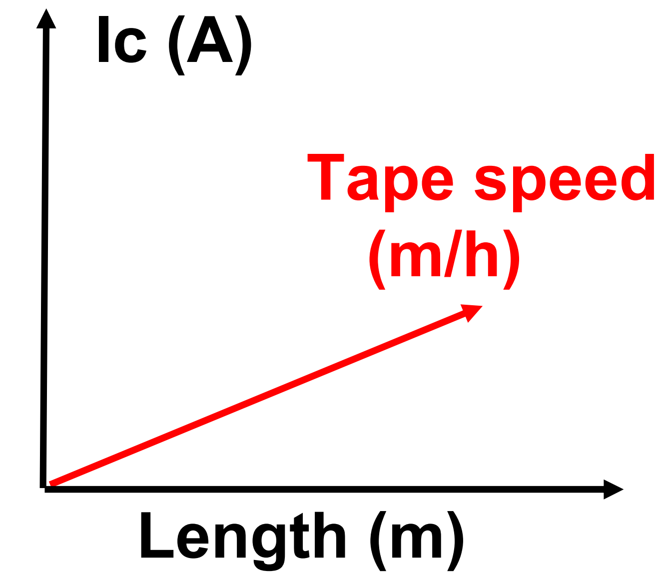


Critical current > 134 A/cm over 51 m

Standard deviation over 51 m = 6.4%

Good Ic & length demonstrated by PLD & MOCVD, but a ***third dimension*** needs to be addressed





- **Effective linear tape speed of PLD processes ~ 3 m/h**
- **Effective linear tape speed of MOCVD process = 5 m/h**
- **At 5 m/h of 12 mm wide tape, annual production would be less than 100 km/year of 4 mm wide conductor. This is far less than the current 1G market of ~ 700 km/year.**

In addition to Ic & Length, high linear tape speed has to be demonstrated in YBCO processes

5-fold increase in linear tape speed demonstrated with MOCVD

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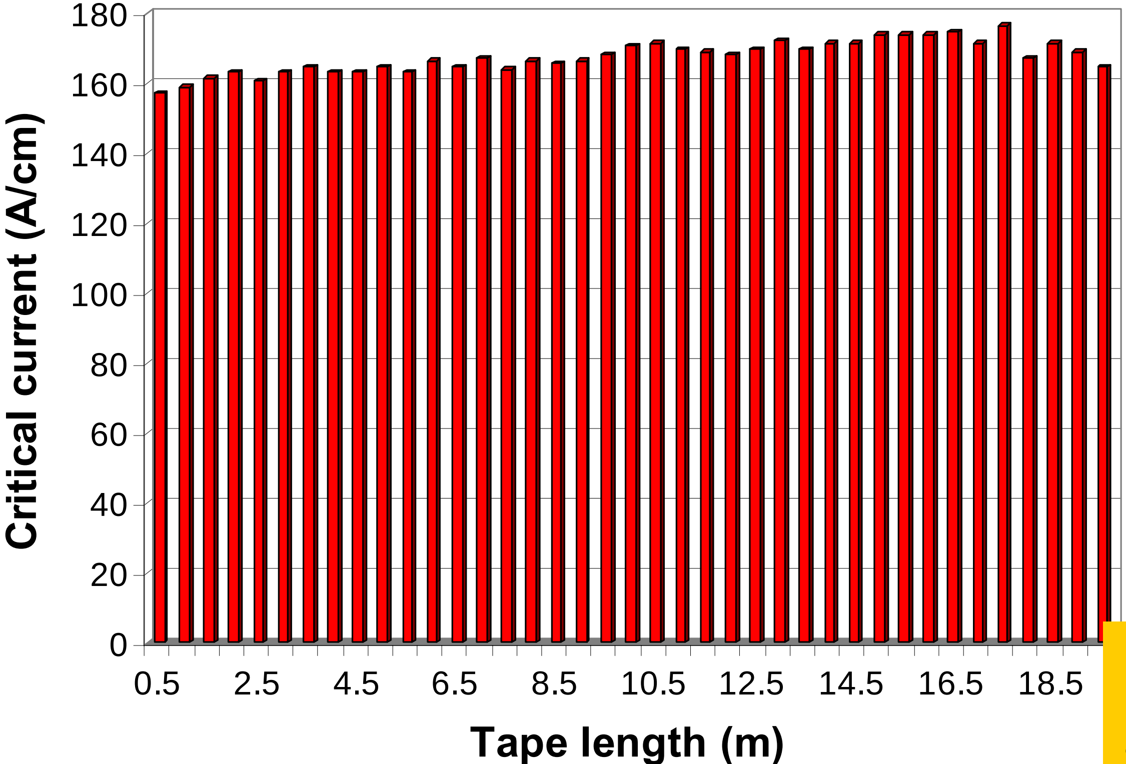
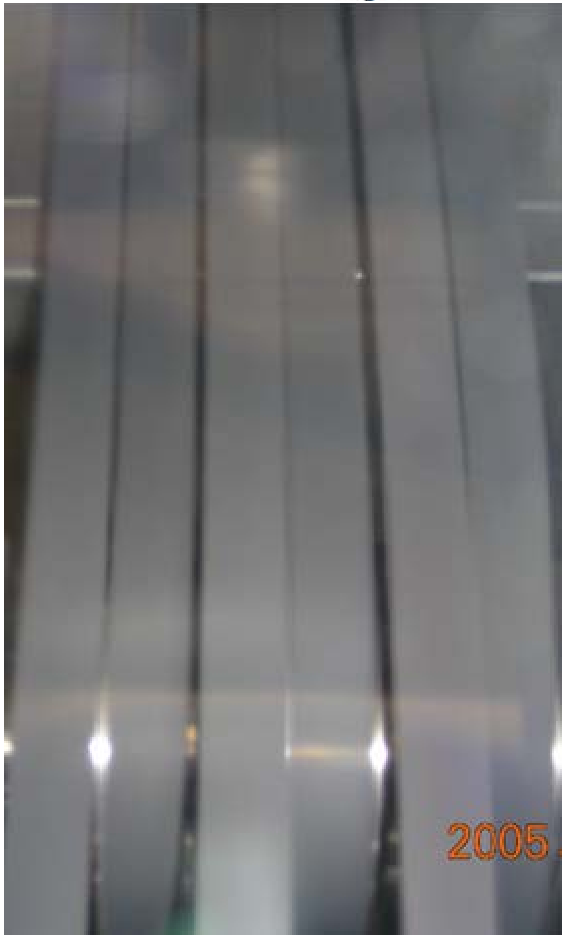
In August 2005, we used a tape speed of 5 m/h to produce 200 m long tape in Pilot MOCVD system.

Helix tape handling was added to our Pilot MOCVD system for higher line speeds.

20 m long tape processed using 6 tracks in helix in a





160 A/cm over 20 m

Standard deviation = 2.7%

High linear tape speed in our existing pilot-scale facilities enable large production capacity & long piece lengths

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Process	Demonstrated linear tape speed (m/h of 4 mm wide tape)	Linear tape speed expected in 2006 with same system* (m/h of 4 mm wide tape)
Electropolishing	180	900
IBAD	195	300
Buffer	240	480
MOCVD (160 A/cm over 20 m)	75	270
Slitting	540	540
Metallization*	90	270

Based on the throughput of each process, production capacity of 1000 km/year can be expected in 2006 with our existing pilot-scale facilities.

With approximately 10 hours of continuous processing, piece lengths of 1000 m will be possible in 2006 with our existing pilot-scale facilities

*New Pilot-scale metallization system will be set up in ‘06.

Conductor cost components & impact

Direct labor and overhead costs are significantly reduced with high throughput processes.

- Less labor time to produce a unit length of conductor
- Less capital equipment investment to produce a unit length of conductor & so, less depreciation costs

Materials costs:

We use off-the-shelf Hastelloy substrates – ***very inexpensive substrate***

IBAD + Buffer layer thickness < 0.2 micron. ***Insignificant buffer cost***

HTS layer is now 1 micron thick. Could be up to 5 microns thick in future for high current, low ac loss conductor

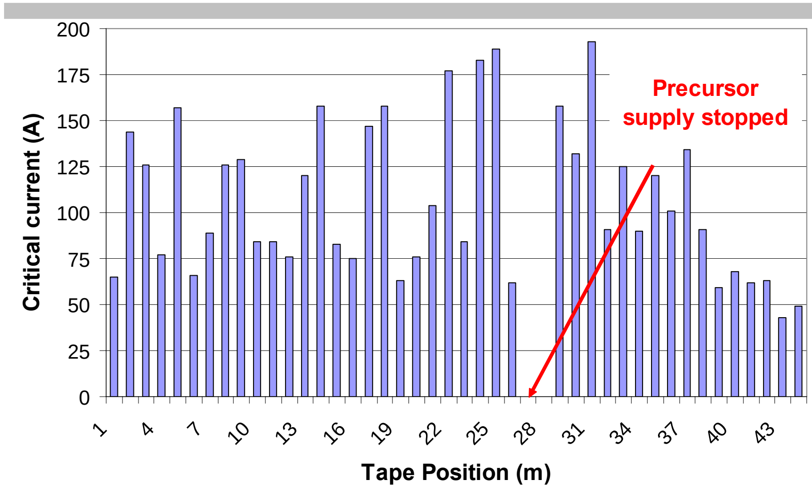
HTS layer is the most complex in all types of 2G conductors. Yield will be primarily determined by the HTS layer. So, focus on reduction in cost of processing the HTS layer is most appropriate

We have already attained a 10-fold reduction in MOCVD precursor cost in 1 year even with only 10 kg batch sizes. Only a factor of 4 reduction in precursor cost is needed even for a 1000-fold more precursor volume to meet the price target of $ 10/kA-m

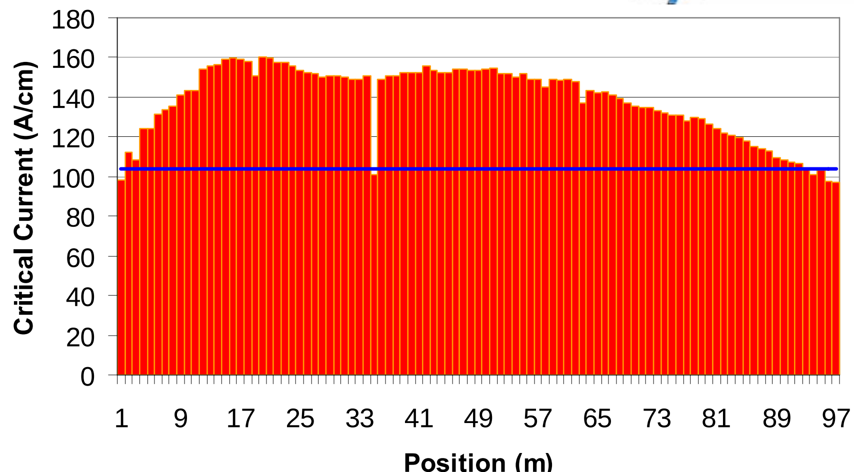
Further cost reduction strategies:

- Manufacturing: Yield and equipment up-time are important
- R&D: Higher Precursor use efficiencies both by equipment design as well as techniques to enhance reaction kinetics even further

Improvements in the MOCVD process in last 2 years have enabled Ic over long lengths similar to Ic in short lengths



July 2004 – Ic of long lengths limited by short-range fluctuations in precursor supply



Dec 2004 – Eliminated short-range fluctuations in precursor supply, local defect & long range variation

August 2005:
Uniform Ic of 200 A/cm over 70 m.

Essentially same Ic as that typically achieved in short tapes

Drop beyond 70 m needs to be addressed

Expect to solve with upgraded MOCVD system that enables high linear speeds (with helix)

On-line monitoring of precursor delivery status would be valuable

Our top 5 focus areas for widespread commercial use of 2G conductor

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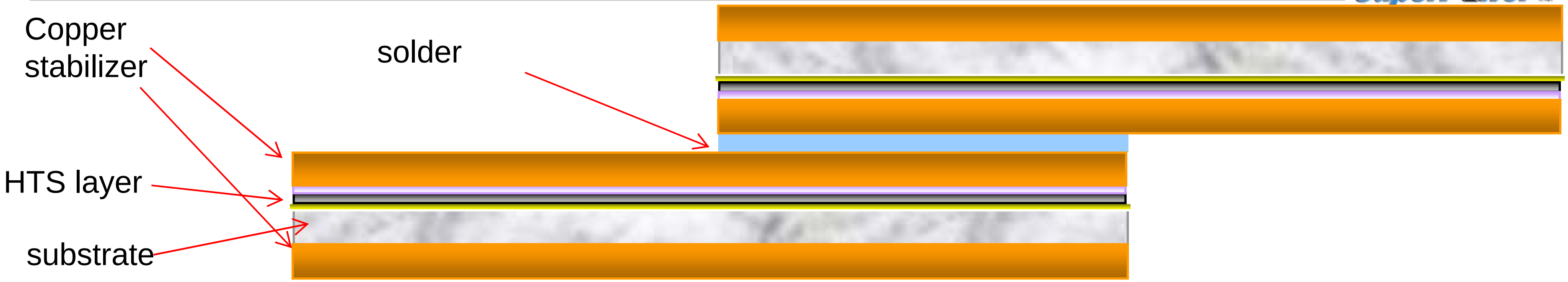
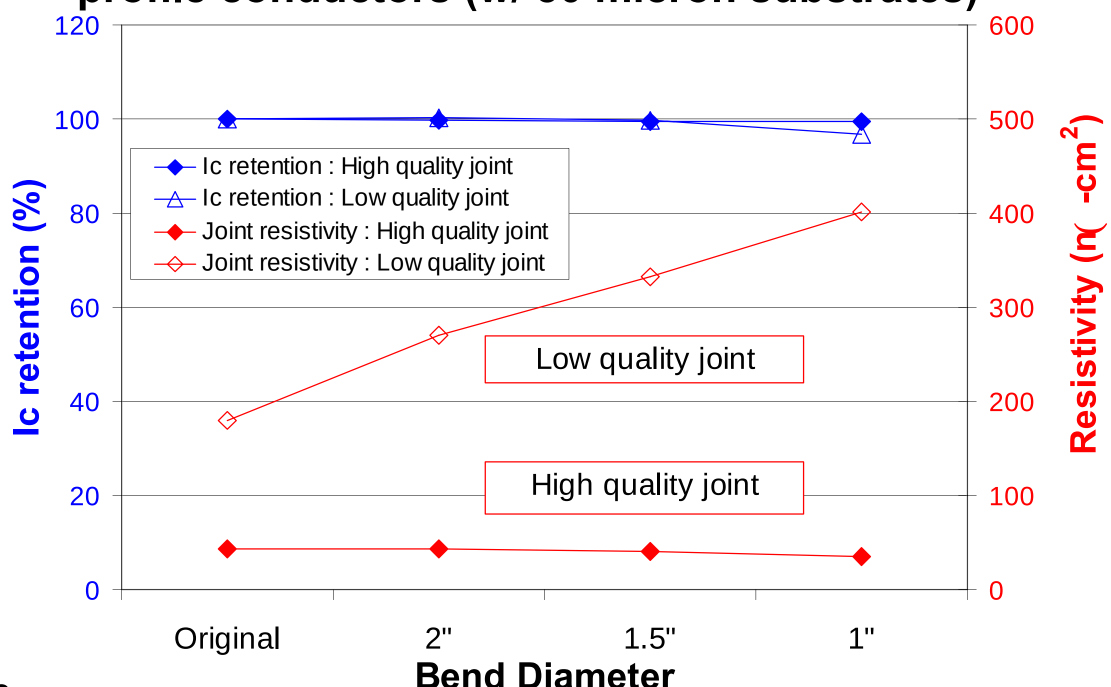
- **Yield - reproducibility**
  - On-line QC with feedback control
  - Manufacturing protocols
- **Equipment reliability - throughput, yield**
  - Preventive maintenance
  - Equipment design
- **Critical current magnitude in long lengths**
  - Thicker films
  - Higher current density
- **Conductor designed for application needs**
  - Ac tolerant conductor
  - Conductor for FCL
  - Mechanically robust, low resistance joints & splices
- **MOCVD precursor utilization efficiency**

Electrical & mechanical properties of joints & splices are being qualified



- 4 mm wide conductors each with 20 µm surround stabilizer
- Joint length = 3 cm
- Original tape thickness = **0.095 mm**
- Thickness at joint = **0.22 mm**

Thickness at joint can be reduced by using thin-profile conductors (w/ 50 micron substrates)



Joint resistivity = 40 nΩcm²

Ic across joint & resistivity of joint are not affected down to a bend diameter of 1"

Quality of joint primarily determines electrical & mechanical performance

More details in session 4 presentation

Promising results obtained on SFCL elements using 2G conductors

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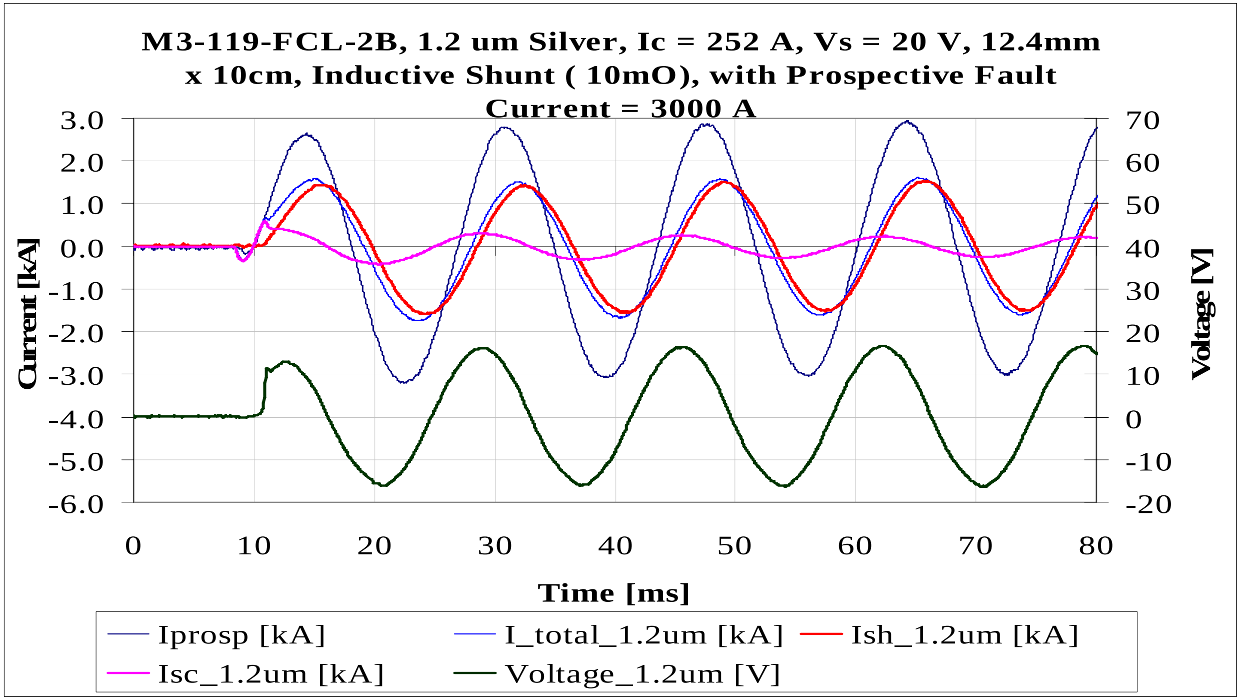
Advantage of IBAD-based conductor for FCL is use of highly resistive substrate

Used a typical 2G conductor as SFCL element :

- 12 mm wide
- Ic = 252 A
- 1.2 μm metal overlayer
- Subject to a 8 cycle fault current
- Voltage = 20 V on the circuit



- **Demonstrated including 1st peak limitation, fast response time (within 1 ms) and low quench current (1.8 to 3 times Ic)**
- **Uniform current sharing when conductors were tested in parallel**
- **Successful tests on recovery under no load conditions up to 6 repetitive faults of 12 cycles**
- **More details in presentation by Yi-Yuan Xie in session 4**

Fundamental research support needed from labs & universities

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1. High Ic: thick film, high Jc

- Now film thickness is 1 – 1.5 microns, Jc ~ 2 MA/cm^2
- Goal is to increase Jc to 3 MA/cm^2 at 1 micron & 2 MA/cm^2 at 2.5 microns

2. Better In-field properties

- Now Ic drops by 4 – 5 at 1 T, 77 K (field perpendicular to tape). Goal is to reduce it to 2.

3. Conductor design for low ac losses, stability, FCL

- Now, 100-fold reduction in ac losses achieved. Need to demonstrate in long lengths

4. Simpler architectures – fewer (multifunctional) layers

- Now 5 intermediate layers. Goal is to reduce it to 3.

5. Reaction kinetics of MOCVD process

- Now, deposition rate is 120 Angstroms/s. Goal is to increase to 500 Angstroms/s

6. On-line monitoring tools – Yield

- Need tools for on-line monitoring of precursor composition, film composition, and flow distribution in MOCVD process, & various film properties in buffer processes

National lab support is absolutely necessary for continuous materials & process improvements to reach the target of $ 10/kA-m