



# Progress in Scale-up of 2G HTS Conductors at SuperPower

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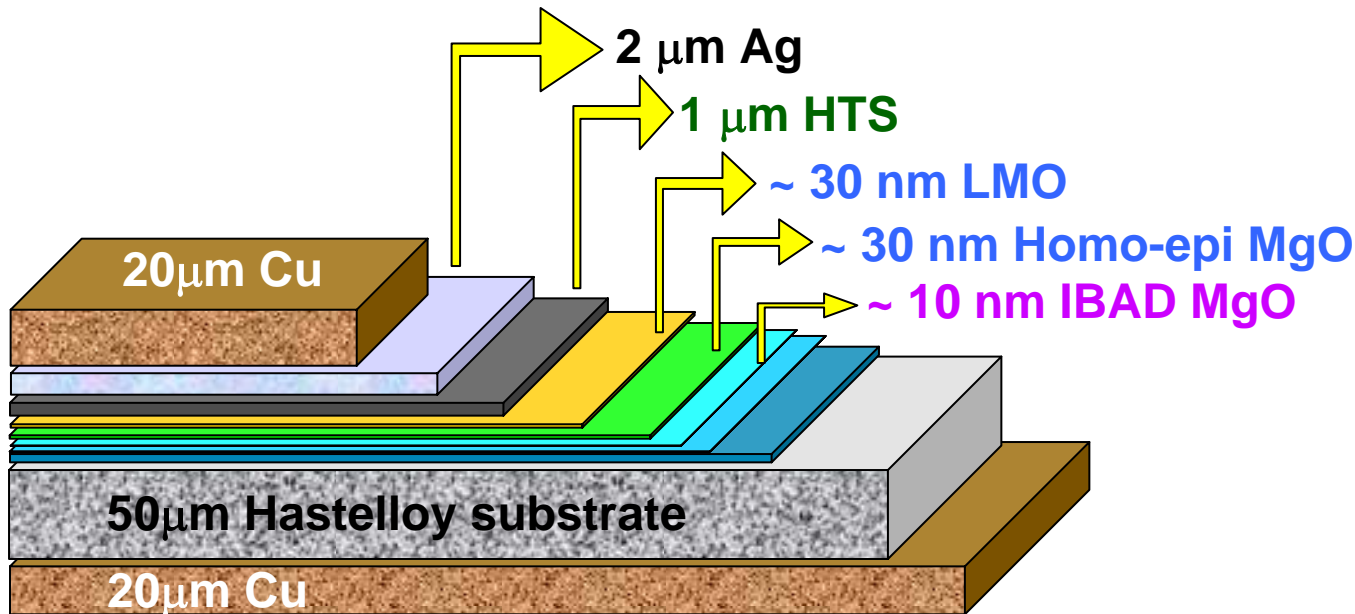
*HTS Solutions for a New Dimension in Power*

International Symposium on Superconductivity, Nagoya, October 30 – Nov. 1, 2006

# 2006 marked the first year of high-throughput Pilot Production of 2G conductor



	2005	Aug. 2006
IBAD	YSZ: 1 m/h	IBAD MgO: <b>65 m/h</b> of 12 mm wide tape
Buffer	n/a	Homo-epi MgO & LMO buffers: <b>40 m/h</b> of 12 mm tape
MOCVD	(Y,Sm)BCO: 5 m/h	(Y,Sm)BCO: <b>30 m/h</b> of 12 mm tape (single pass)



All layers produced at high throughput.

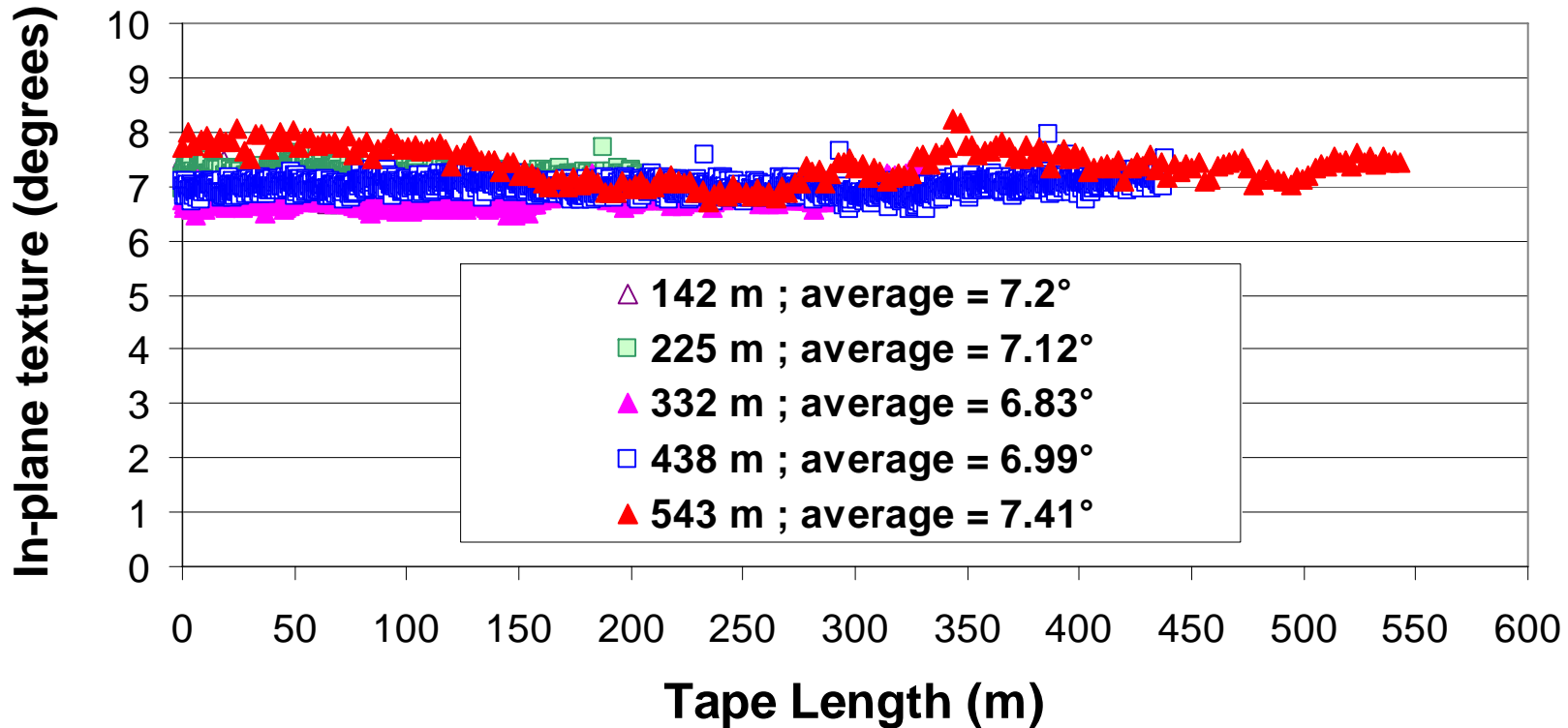
Minimum speed of 30 m/h corresponds to annual capacity of 350 km/year of 4 mm product.

# 550 m long tapes have been produced in Pilot IBAD & Pilot Buffer system at high linear speeds



Routine production of IBAD MgO in Pilot IBAD system at 65 m/h of 12 mm wide tape in piece lengths up to 570 m & process lengths up to 800 m (2 pieces)

Routine production of homo-epi MgO and LMO buffer layers in Pilot Buffer system at 40 m/h of 12 mm wide tape in piece lengths up to 550 m.



**In-plane texture of LMO over 550 m produced at 40 m/h = 7.4°**

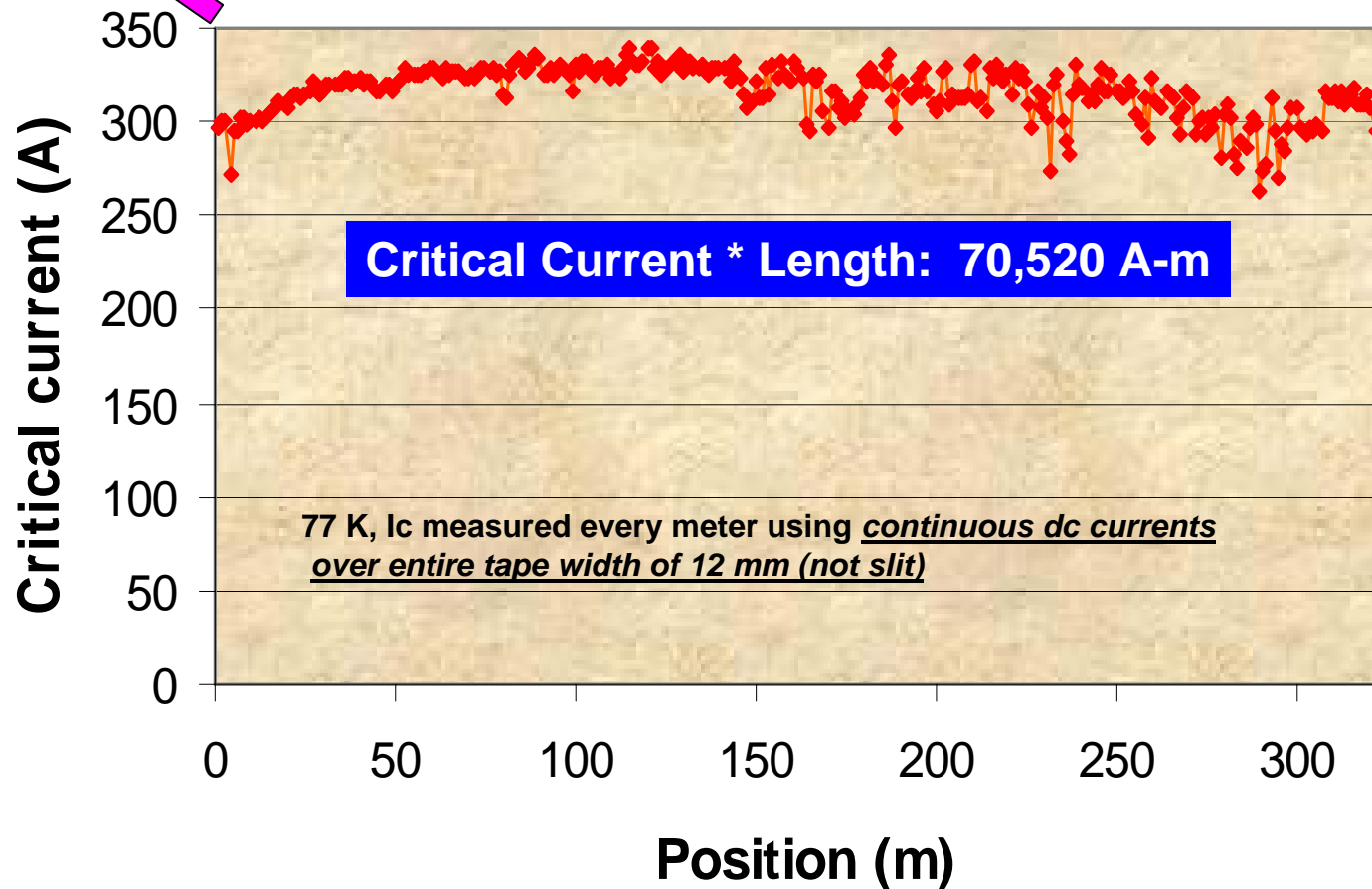
# High $I_c$ with excellent uniformity over 300 m by MOCVD in a *single pass at 30 m/h on IBAD MgO*

YBCO thickness

1.2  $\mu\text{m}$

Min  $I_c = 263 \text{ A} = 219 \text{ A/cm}$  over 322 m  
Uniformity of 4.3% over 322 m

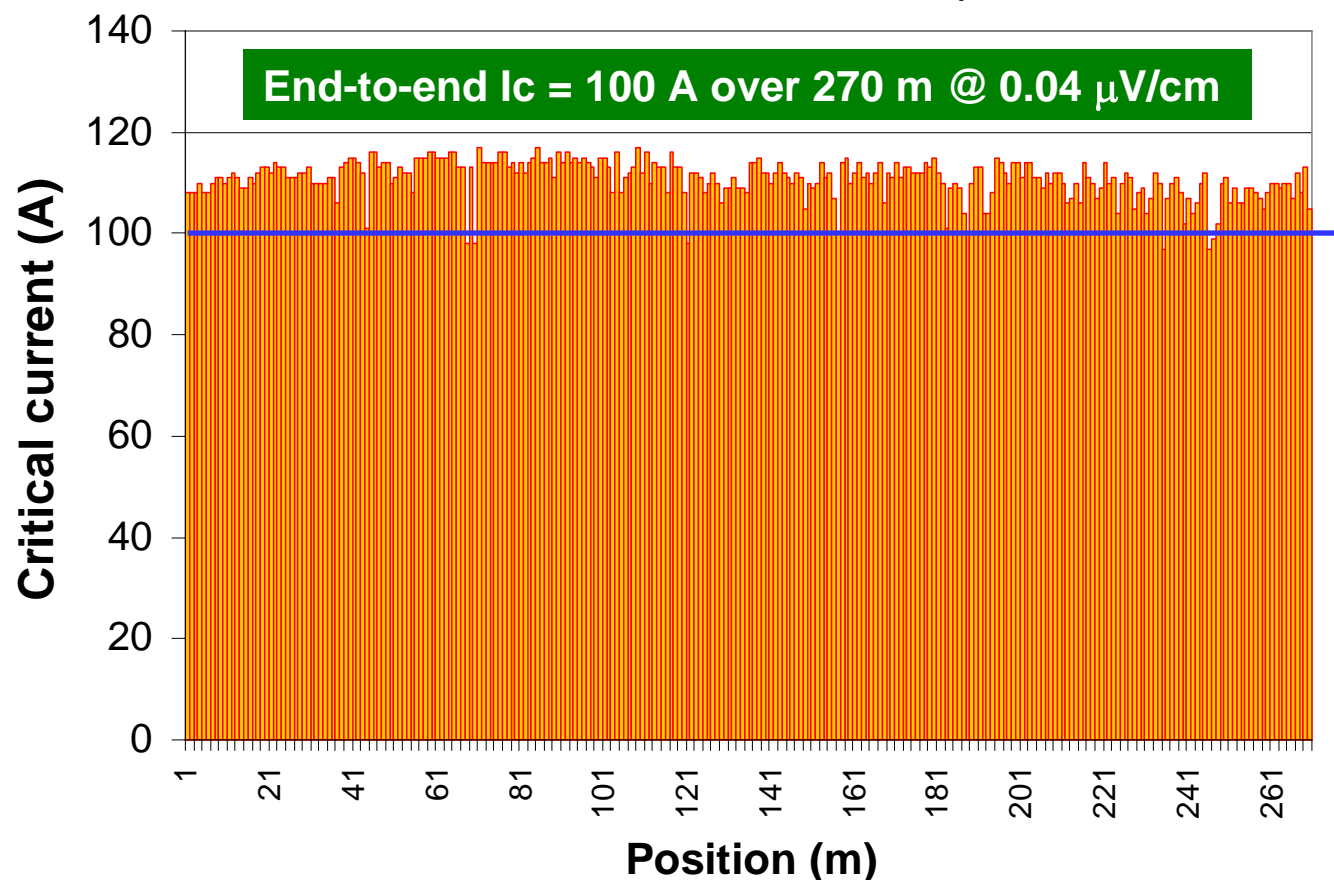
1.2  $\mu\text{m}$



# 2G conductor now available in long lengths with $I_c$ comparable to 1G & $J_e$ about 2x better than 1G



End-to-end critical current of 4 mm wide 2G conductor slit from 12 mm wide tape

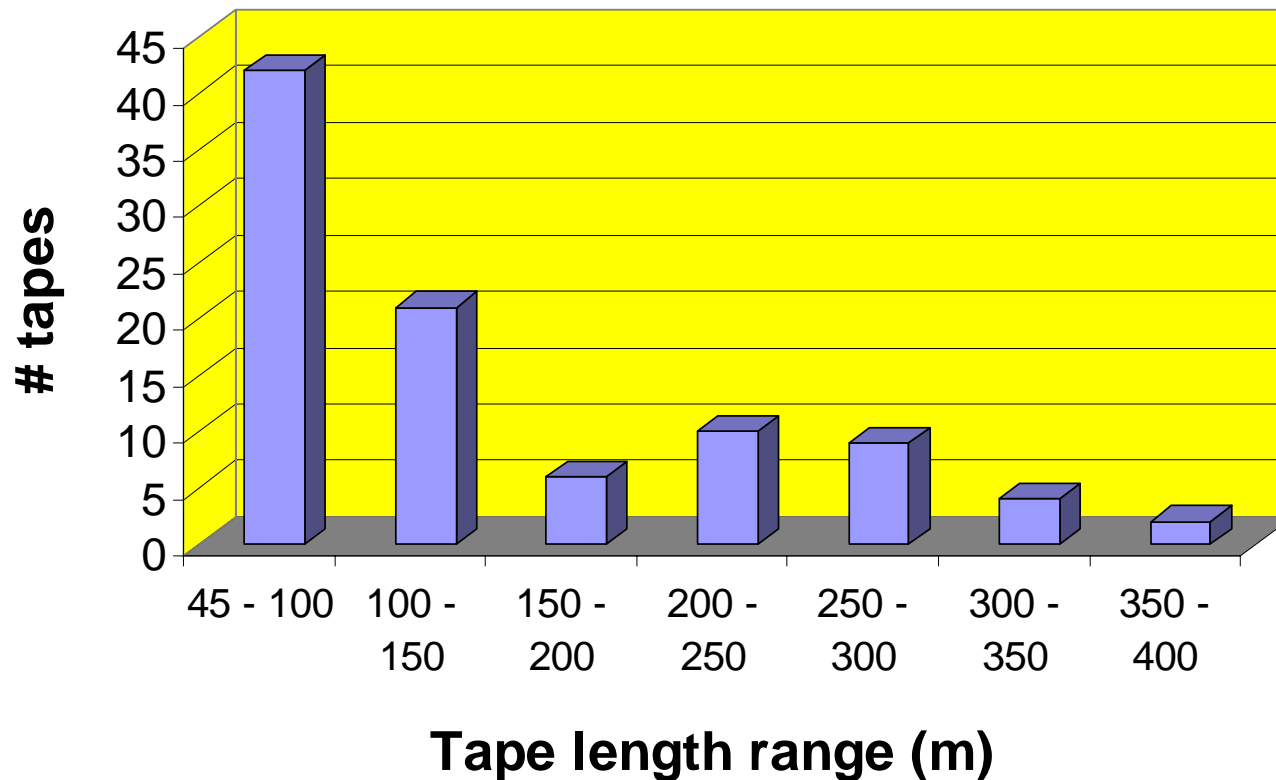


**$I_c = 100$  A in a 4 mm wide 2G conductor over 270 m !**  
 **$J_e = 26.3 \text{ kA}/\text{cm}^2$  (for a 20 micron surround stabilizer i.e. 40 micron total)**  
**compared to a 1G  $J_e$  of  $13 \text{ kA}/\text{cm}^2$  to  $17 \text{ kA}/\text{cm}^2$**

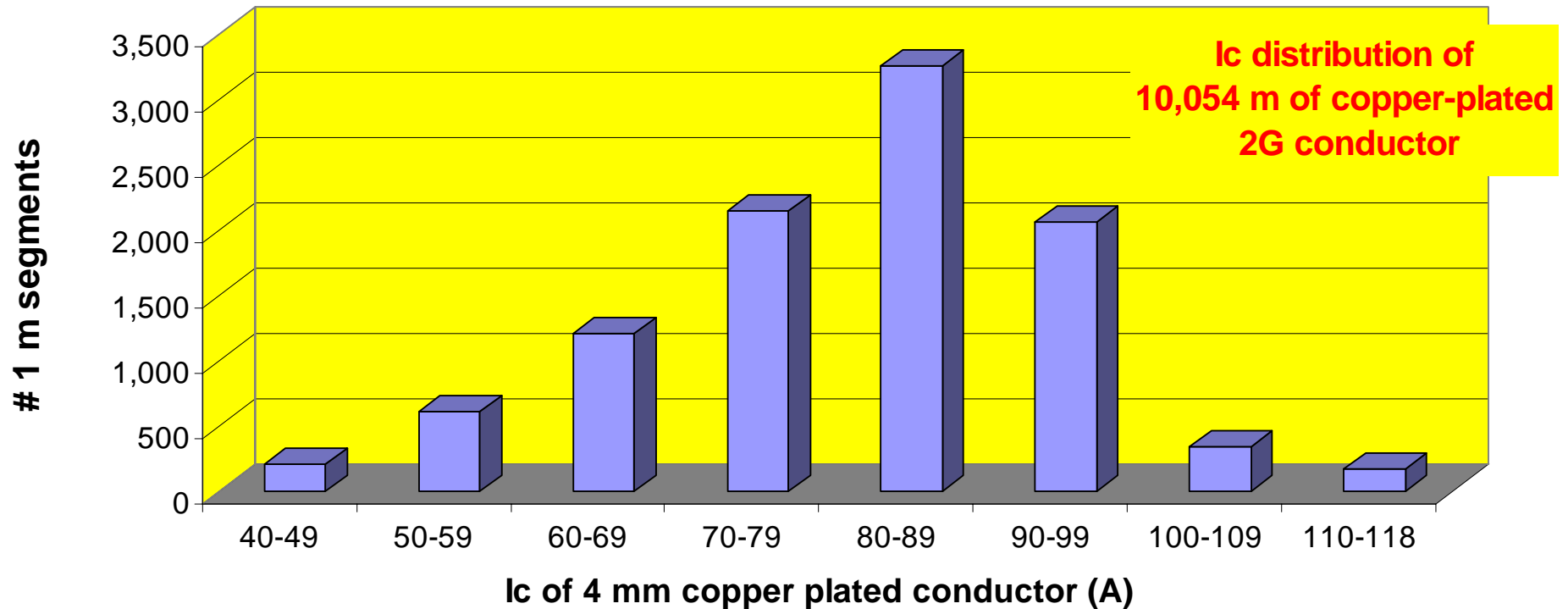
# More than **12,000 m** of qualified 4 mm slit tape produced by end of July for Albany Cable Project



- 🌀 Piece length required = 42.4 m; Total length required = 9,700 m
- 🌀 55% of tapes in inventory > 100 m piece length
- 🌀 27% of tapes in inventory > 200 m piece length



## **Oct. 06: Completed electroplating of copper stabilizer on 12,000 m and subsequent Ic testing\***



**Average transport critical current of final product = 81 A**

**80 % of segments have Ic > 70 A, 58% have Ic > 80 A, 26% have Ic > 90 A**

- Hermeticity tests on 10,000 m of final product are underway
- Tapes are being prepared for shipment of 225 individual spools each with ~ 43 m to Sumitomo Electric to construct a 35 m 2G cable

# Next goal: Price competitiveness of 2G



2G conductors have been produced in long lengths with excellent performance and delivery of 10,000 m from the first volume Pilot Production is very imminent.

*However, at ~ \$ 600 to \$1,200/kA-m, the price of 2G conductor is still at least 5 times higher than that of 1G*

2G has to be cost competitive with 1G within the next 2 years in order to be used in the next round of various device prototype projects.

- 👤 Manufacturing improvements
  - Yield: Reliability of Equipment
  - Raw material cost
  - Effective labor use: 3 shift operation can yield 2 times output as 2-shift operation
- 👤 Technology improvements

Attribute	1G	2G (Aug 06)	2G goal (June 08)
Piece length (m)	1,500	300	1,000
Ic (A) in 4 mm over long lengths	200	100	200
Capacity (km/year)	< 1,000	350	1,000

**Our focus since August 06 has been to further increase *Ic*, throughput, & piece lengths**



# ***Goal 1: Higher Currents***

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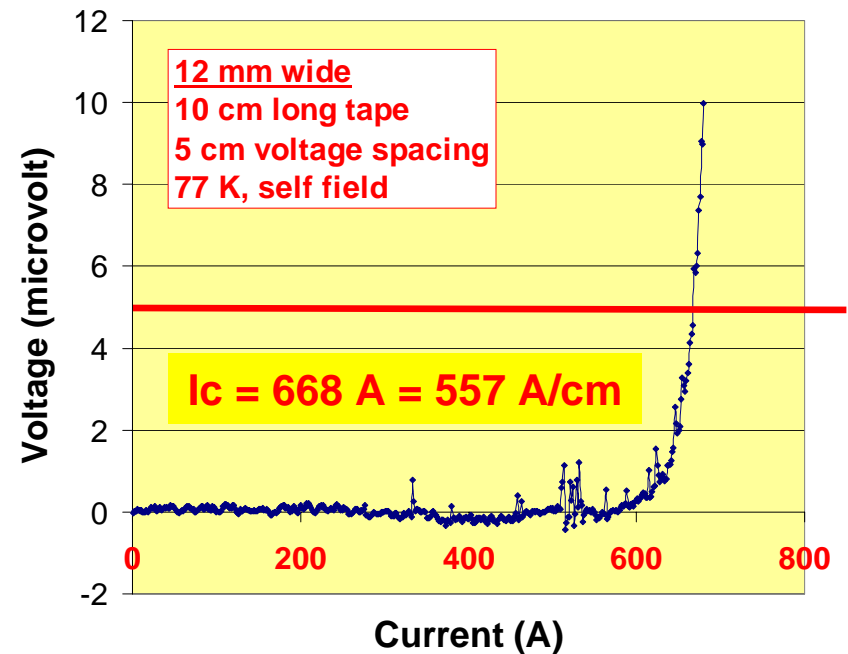
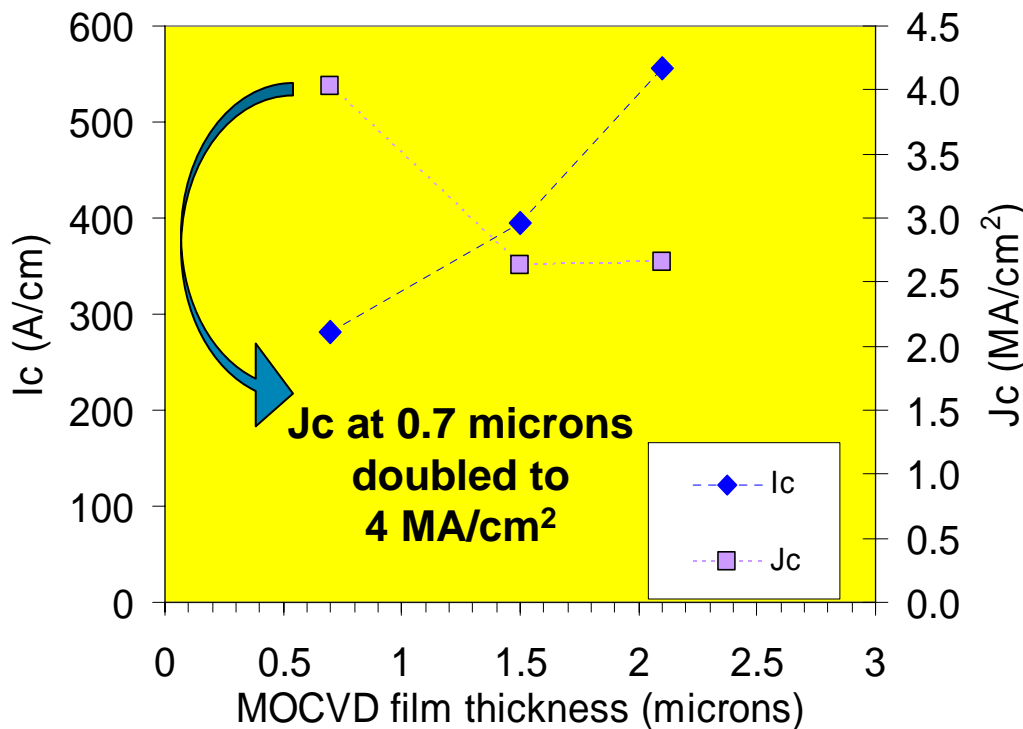
***Pathway to lower cost 2G***

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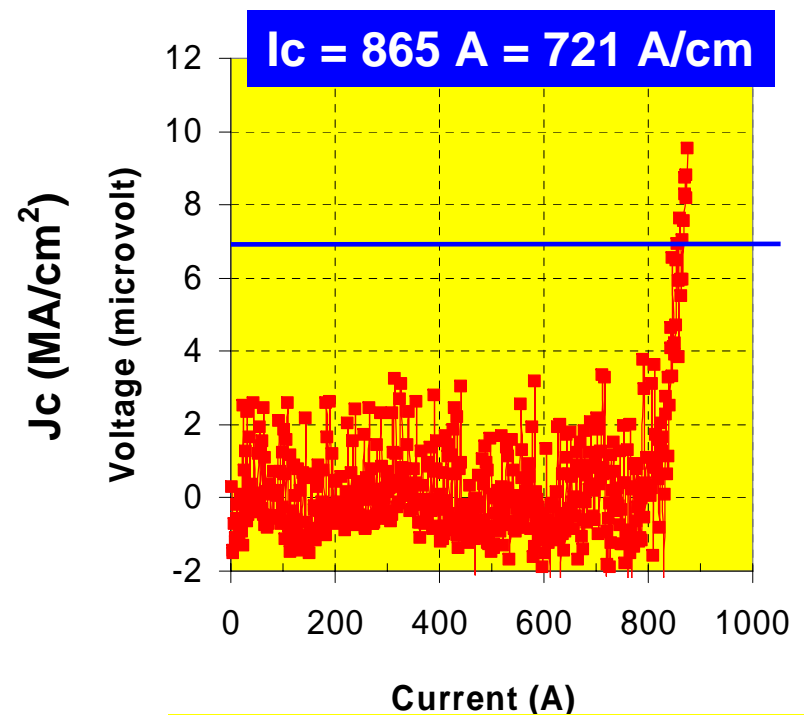
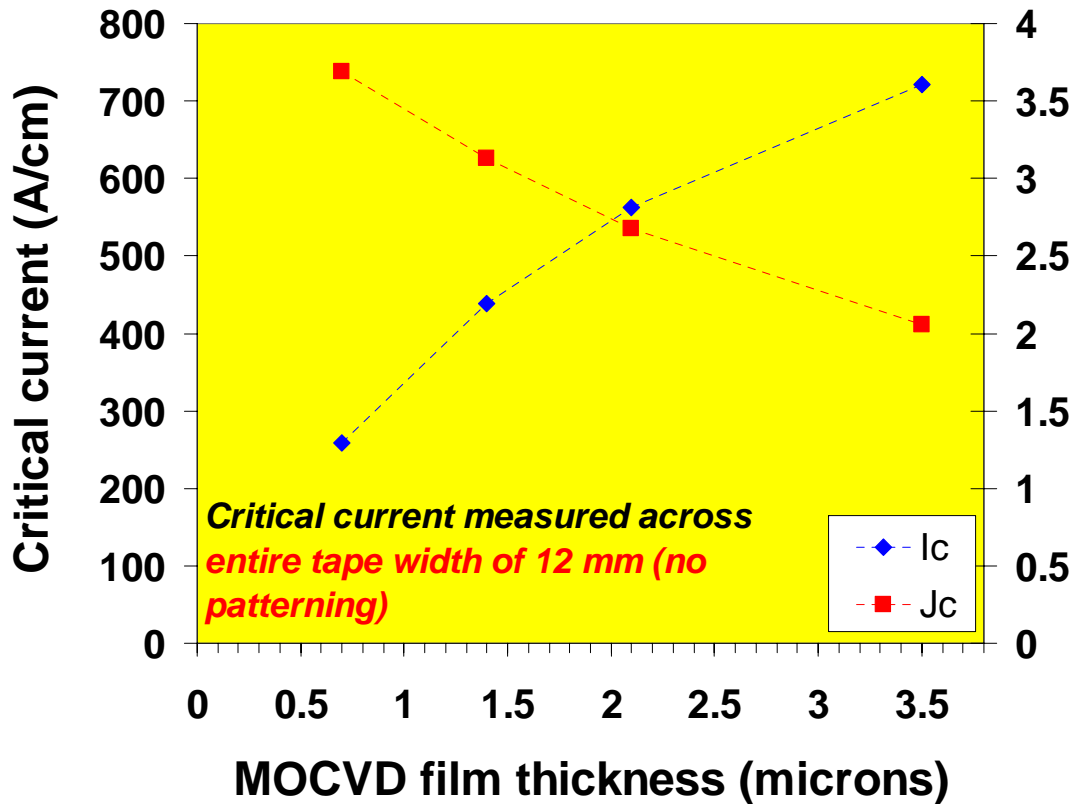
# May 2006: 550+ A/cm demonstrated in *continuous, reel-to-reel processed MOCVD conductor*

Thick films are fabricated in a multipass approach by MOCVD, i.e. layers of HTS films are deposited one over other in distinct runs



In a 2.1 micron film made in 3 passes, achieved  $I_c$  of **557 A/cm** ( $J_c = 2.65 \text{ MA/cm}^2$ ) over 12 mm wide, 10 cm long tape.

**Oct. 2006: Critical current of **721 A/cm** achieved over 7 cm of continuous, reel-to-reel processed MOCVD conductor**



**Ic measurement using continuous dc current (no pulsed current) across entire tape width of 12 mm No patterning**

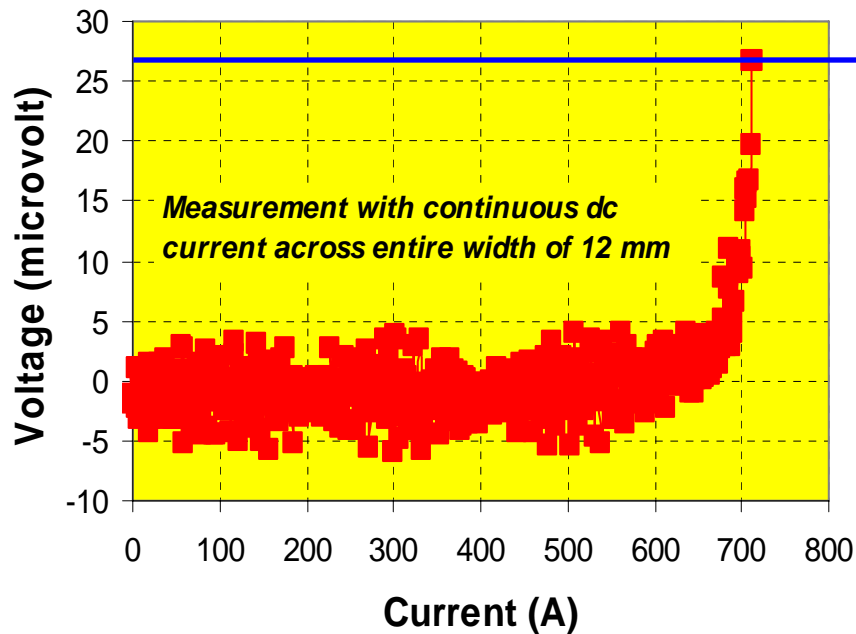
**In a 3.5 micron film made in 5 passes, achieved Ic of **721 A/cm** (Jc = 2.06 MA/cm<sup>2</sup>) over 12 mm wide, 7 cm long tape.**

# Oct. 2006: Scaled up thick film MOCVD process to longer lengths with high currents

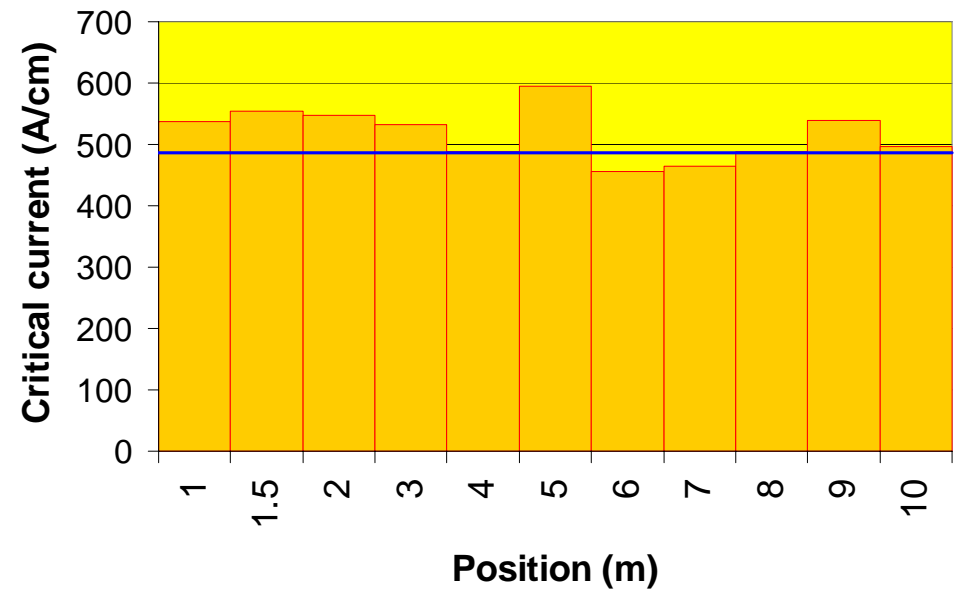


4-pass MOCVD process for a total HTS film thickness of 2.8 microns

Over 1 m length,  
714 A at  $0.27 \mu\text{V}/\text{cm}$  = 595 A/cm



Over 11.1 m length,  
End-to-end  $I_c$  of 583 A at  $1 \mu\text{V}/\text{cm}$   
= 486 A/cm

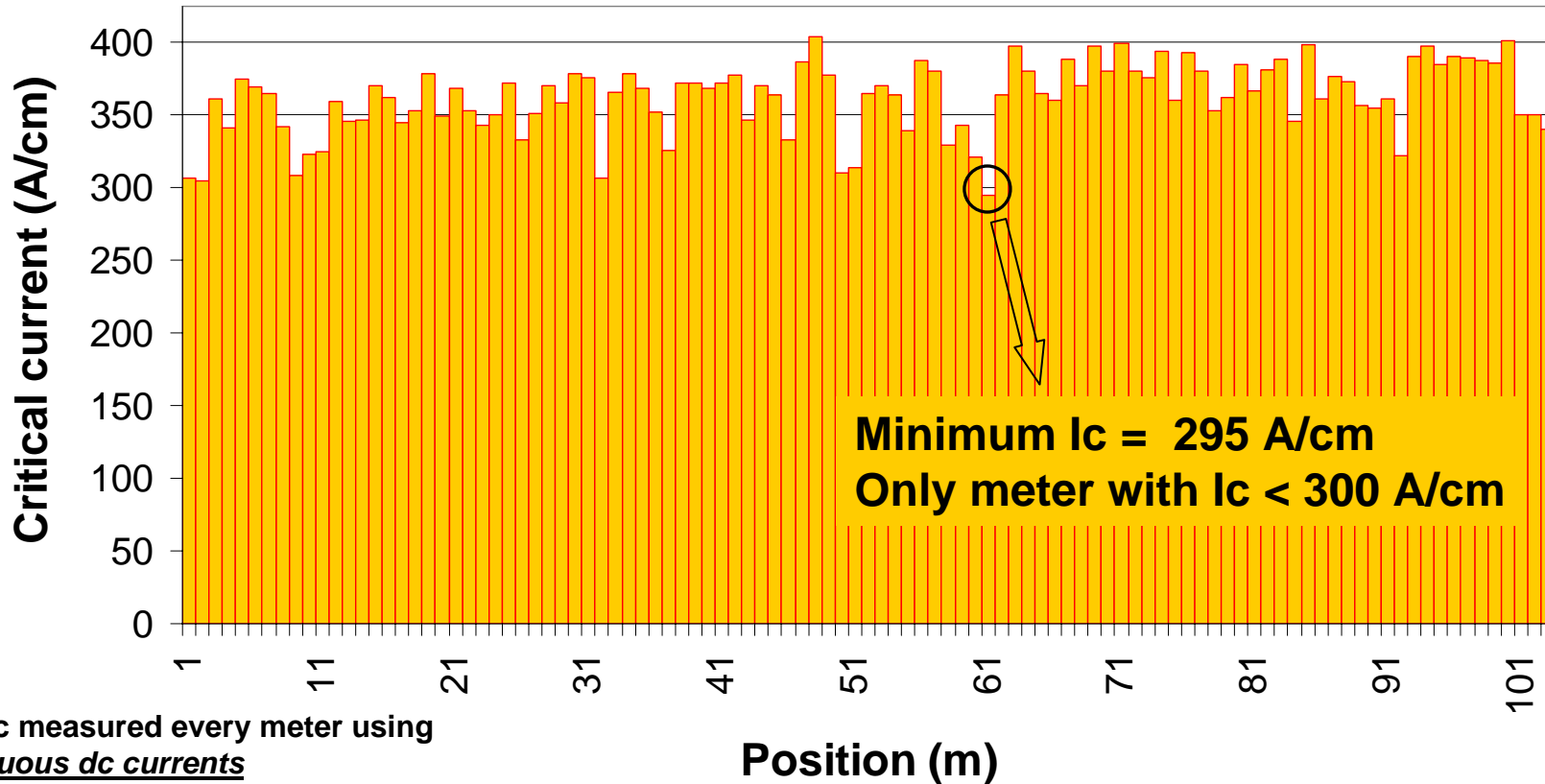


Demonstration of the feasibility of 200 A in a 4 mm wide tape in 10+ m lengths

# Oct. 2006: 300 A/cm class conductor produced in 100+m lengths



1.4 micron thick HTS film produced in Research MOCVD system



77 K,  $I_c$  measured every meter using continuous dc currents over entire tape width of 12 mm (not slit)

**Minimum  $I_c$  over 103 m = 295 A/cm**

**(End-to-end  $I_c$  over 103 m will be > 300 A/cm)**

**Standard deviation = 6.8%**

**Average  $I_c$  = 362 A/cm**

**Maximum  $I_c$  = 404 A/cm**

# ***Goal 2: Higher Speeds***

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***Pathway to lower cost 2G***

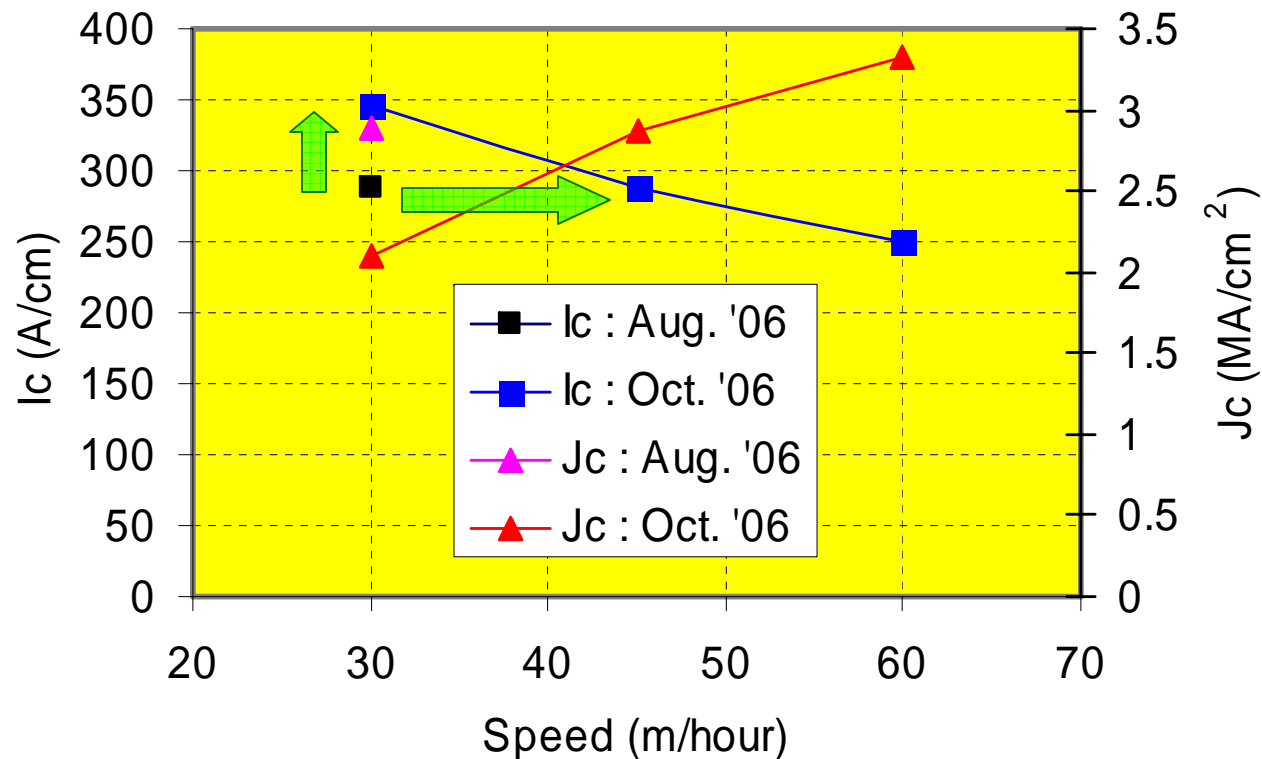
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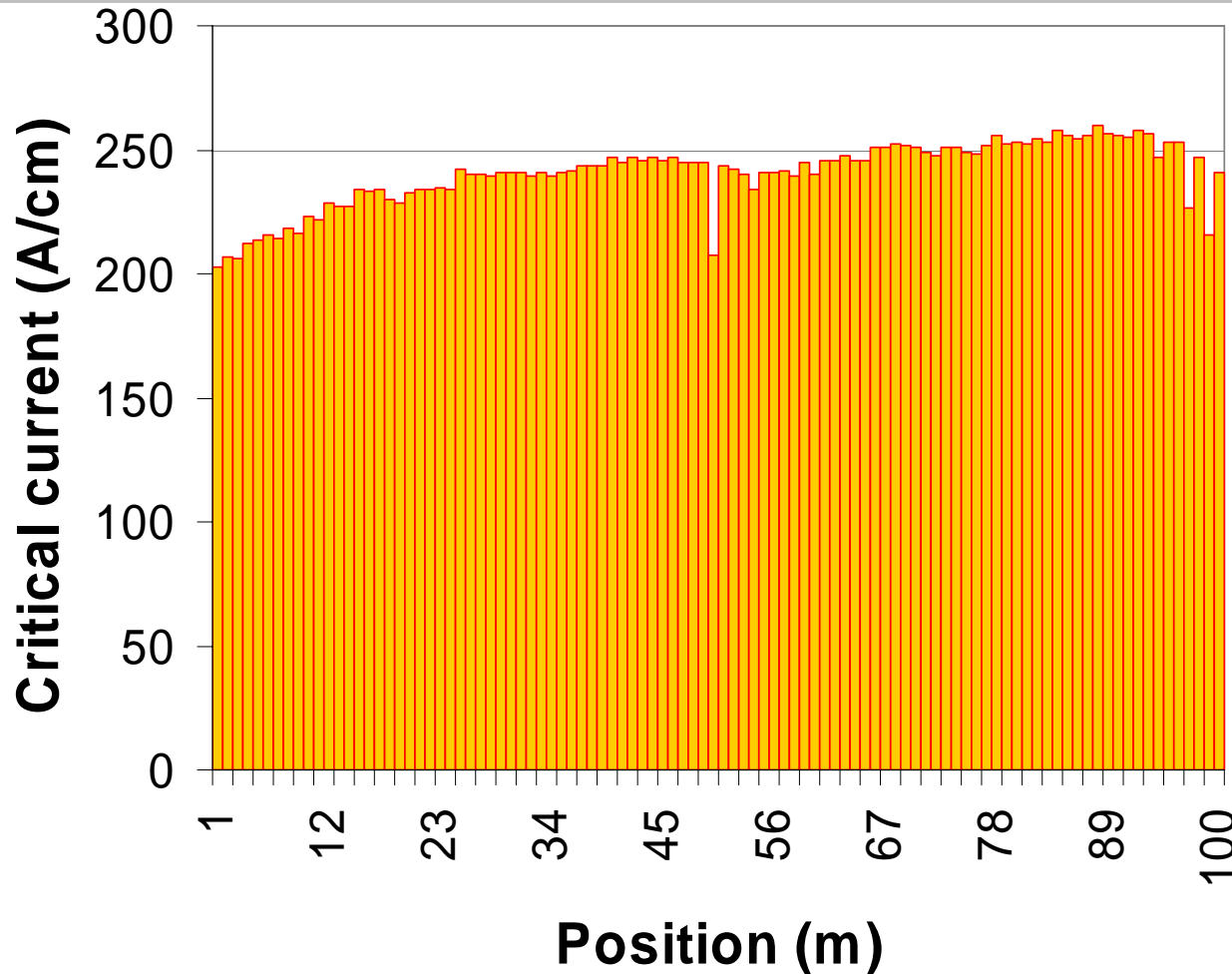
## Oct. 06: MOCVD tape speed increased by 50% to 45 m/h of 12 mm wide tape (single pass)

MOCVD precursor flow increased by **33%** to achieve 1 micron thick YBCO films at 45 m/h compared to at 30 m/h in Aug 06. *Same  $I_c$  of ~ 285 A/cm achieved at 45 m/h compared to 30 m/h in Aug 06.*

With higher precursor flow, 1.65 micron thick films produced at 30 m/h to achieve a higher  $I_c$  of 340 A/cm.



# Oct. 06: 100 m lengths demonstrated with good Ic at 50% higher MOCVD tape speed



Process	Speed of 12 mm tape (m/h)
IBAD MgO	65
Homo-epi MgO	34
LMO	40
<b>MOCVD</b>	<b>45</b>

**Minimum Ic of 202 A/cm over 100 m in MOCVD tape processed at 45 m/h in a single pass (film thickness of 1 micron)**

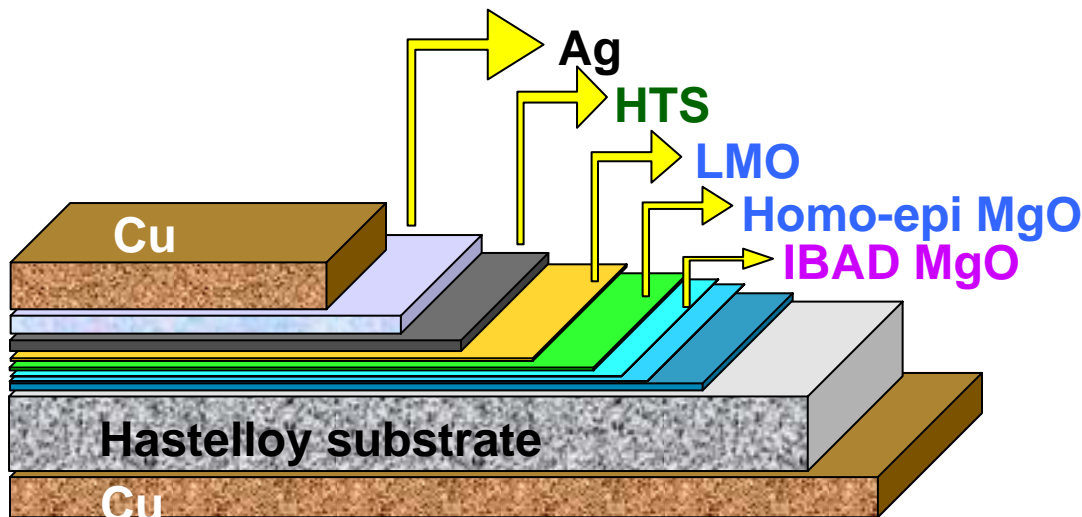


# IBAD MgO & Buffer processing speeds were doubled in the last two months

Using reactive sputtering of metal Mg target instead of an oxide target, deposition rate in IBAD MgO process was increased by 55%. Assist-ion beam profile was re-optimized to match the higher deposition rate profile.

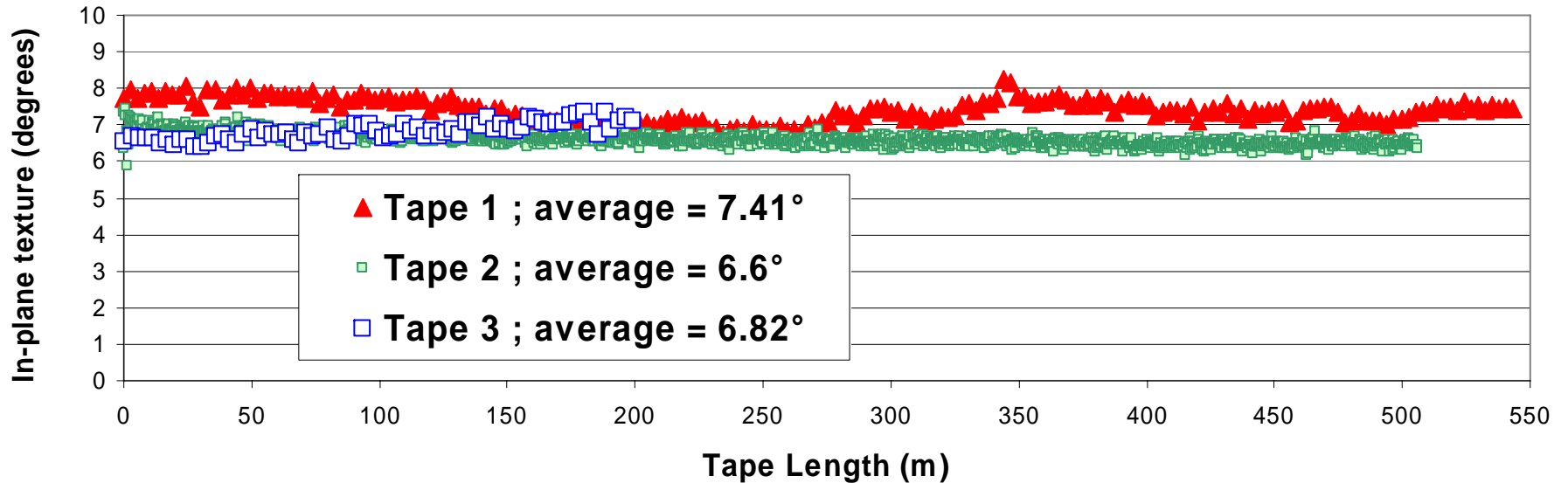
Speed of IBAD MgO process was increased from **65 m/h** to **120 m/h** for 12 mm wide tape.

Higher power levels was used in reactive sputtering of homo-epi MgO to increase speed from **34 - 40 m/h** to **80 m/h** of 12 mm wide tape.



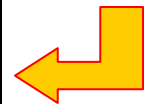
# Tape tracks used in helix tape handling system was increased and film thickness was decreased by 25% to increase speed of LMO process from **40 m/h** to **80 m/h**.

# Excellent texture achieved in IBAD MgO & Buffer tapes produced at 2x processing speeds

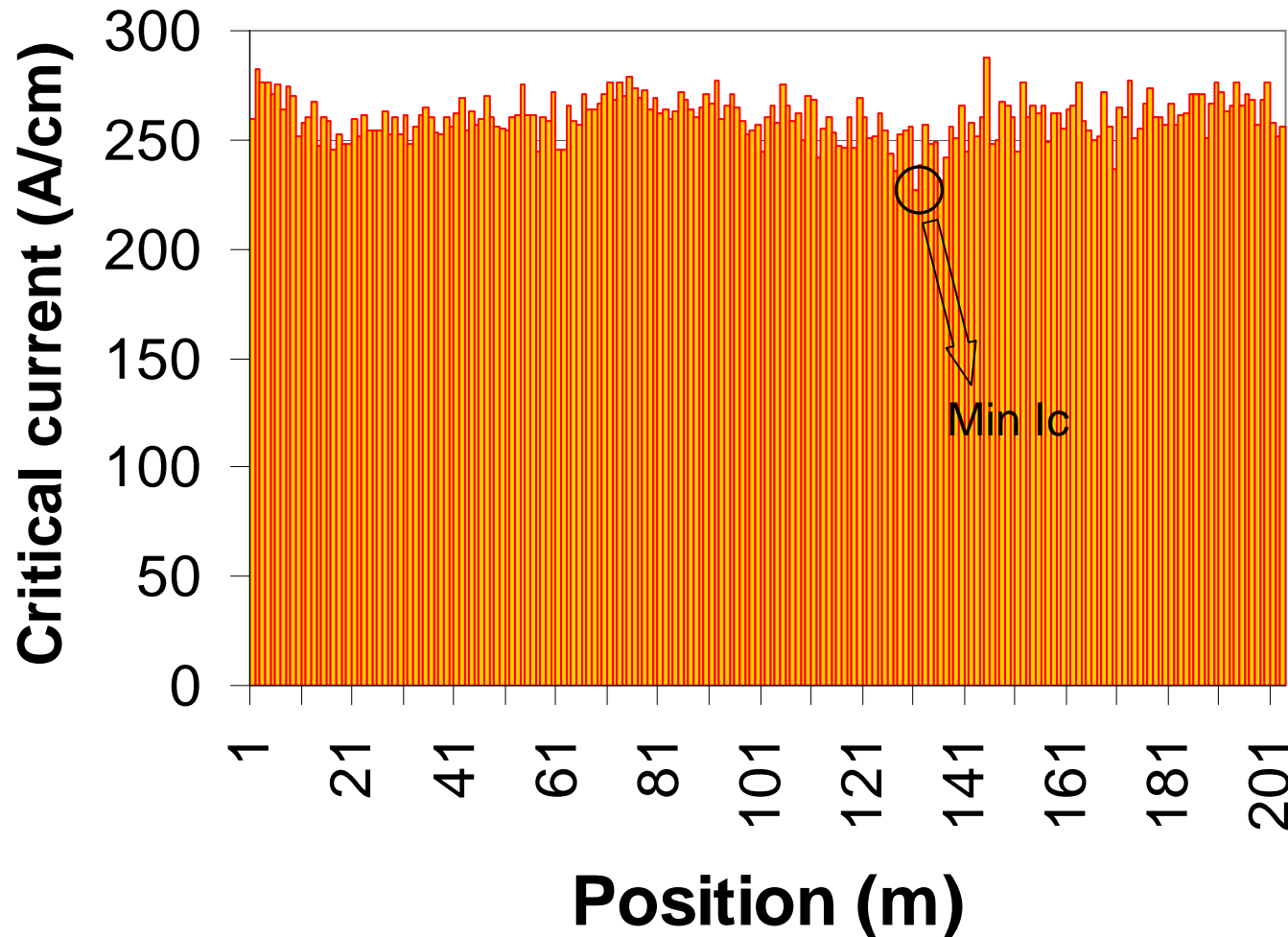


Tape	Length (m)	Production date	Linear Tape Speed (m/h)		
			IBAD MgO	Homo-epi MgO	LMO
1	543	Jun. 06	65	34	40
2	506	Sept. 06	65	60	60
3	200	Oct. 06	120	80	80

Albany Cable Project Production



**Oct. 06: High currents demonstrated over 200+m with  
all processes at higher speeds**



Process	Speed of 12 mm tape (m/h)
IBAD MgO	120
Homo-epi MgO	82
LMO	82
MOCVD	45

**Minimum  $I_c$  = 227 A/cm over 203 m**  
**Uniformity over 203 m = 3.7%**

# ***Goal 3: Longer Lengths***

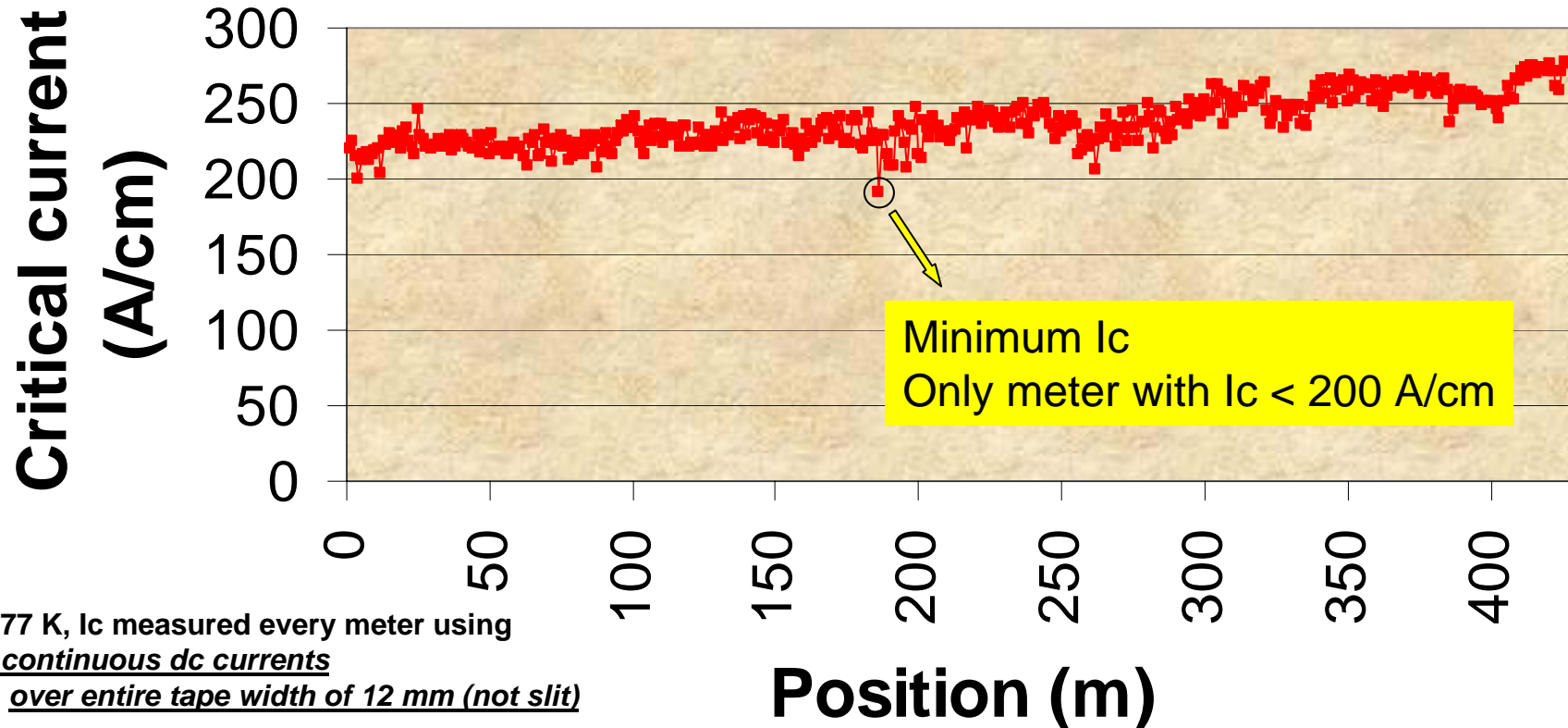
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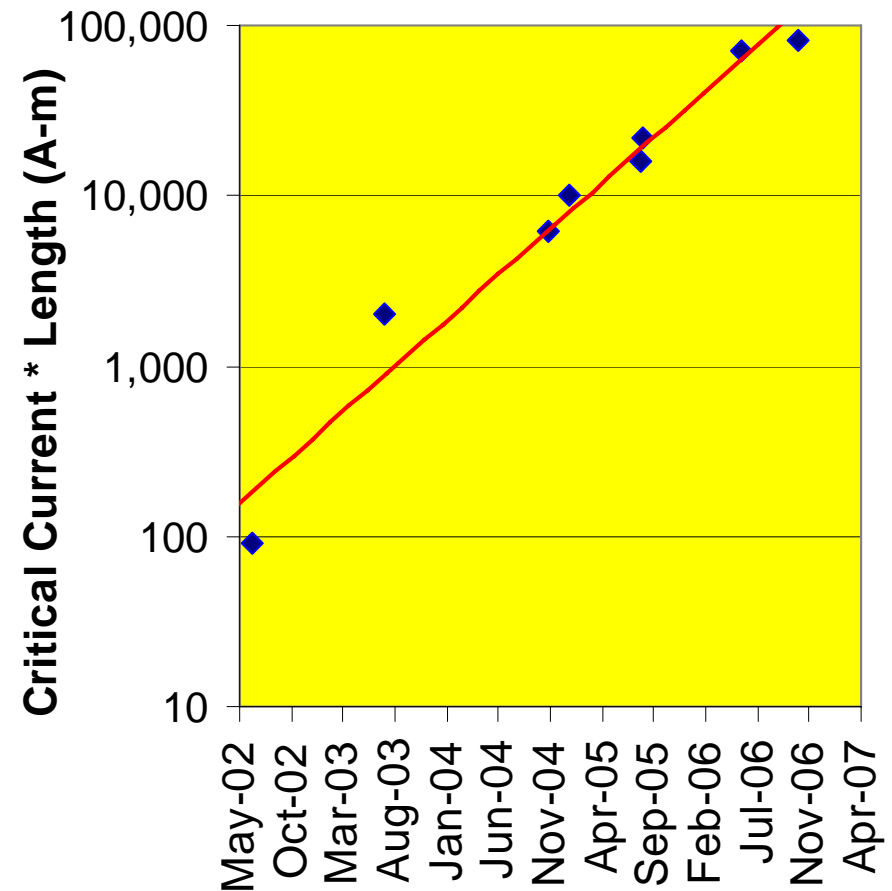
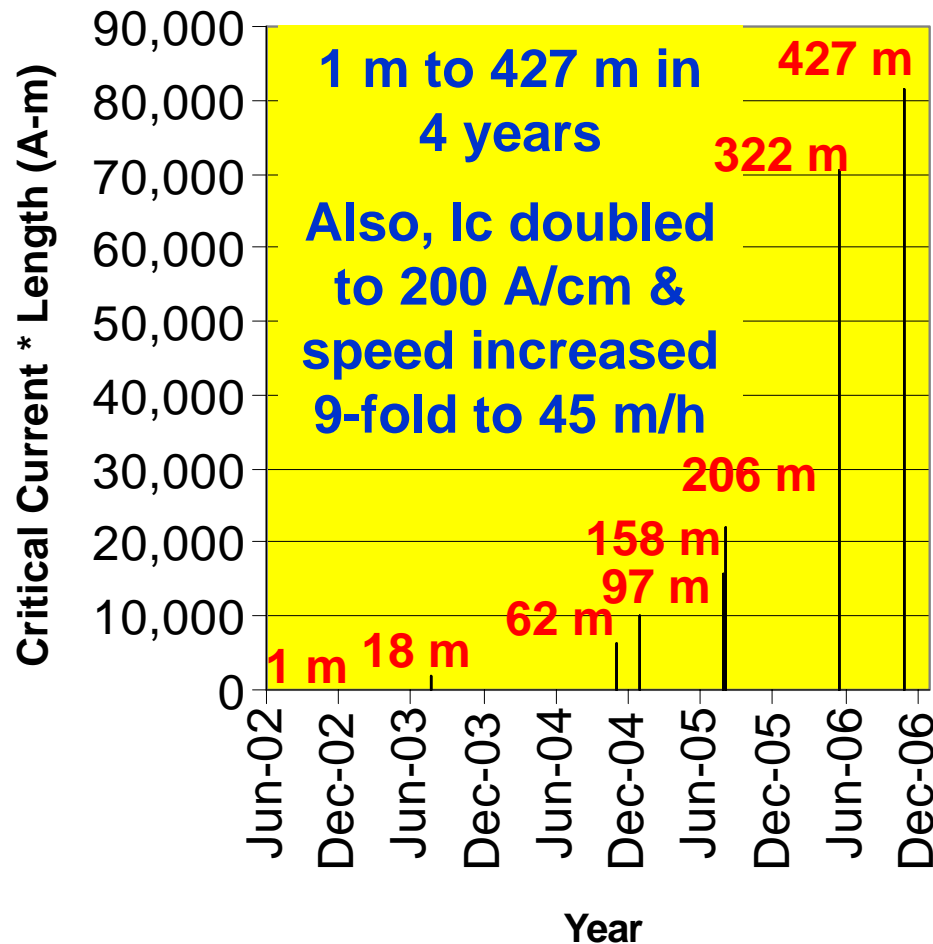
**Longer lengths (Oct. 06): 427 m produced by MOCVD at the higher speed of 45 m/h in 1 pass**



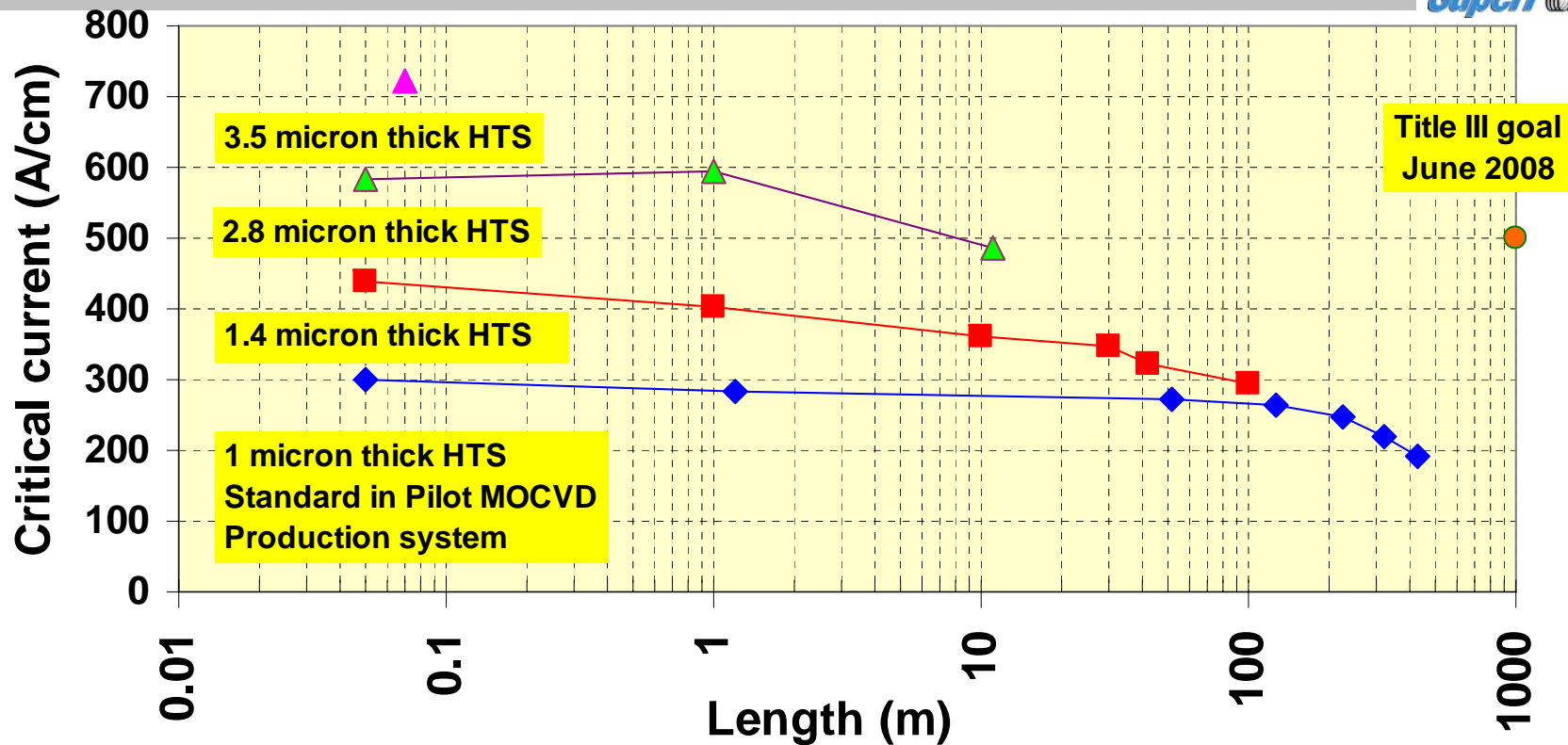
77 K,  $I_c$  measured every meter using continuous dc currents over entire tape width of 12 mm (not slit)

**Minimum  $I_c$  = 191 A/cm over 427 m**  
 **$I_c \times \text{Length} = 81,550 \text{ A-m}$**   
**Higher  $I_c \times \text{Length}$  achieved at 50% higher MOCVD speed**

# Significant progress in MOCVD scale-up in the last 4 years



# Ic vs. Length summary shows progress being made both in Pilot Manufacturing of long lengths & technology development with shorter lengths



## Next Steps:

Manufacturing scale up to reach 500 m threshold & then 1000 m with  $I_c > 200$  A/cm

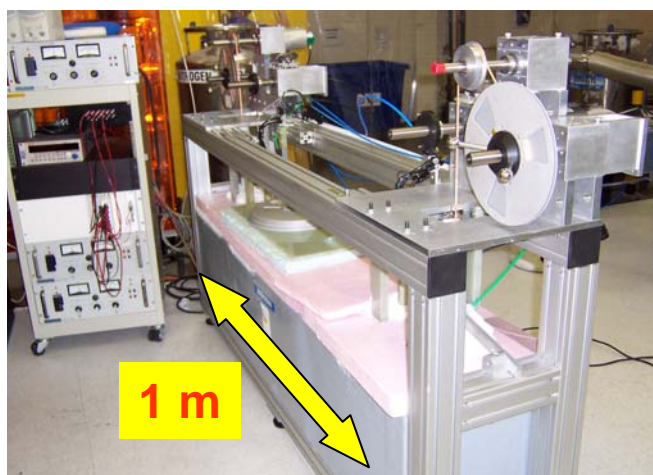
Manufacturing improvements to raise  $I_c$  level of 400+m Production lengths to that of short lengths of same film thickness i.e. 500 m and then 1000 m with  $I_c > 300$  A/cm

Technology transition of higher-current conductors to Pilot manufacturing i.e. 100 m, then 500 m and then 1000 m with  $I_c$  of 500 A/cm

# Testing speed enhanced to match speed of processing & longer production lengths

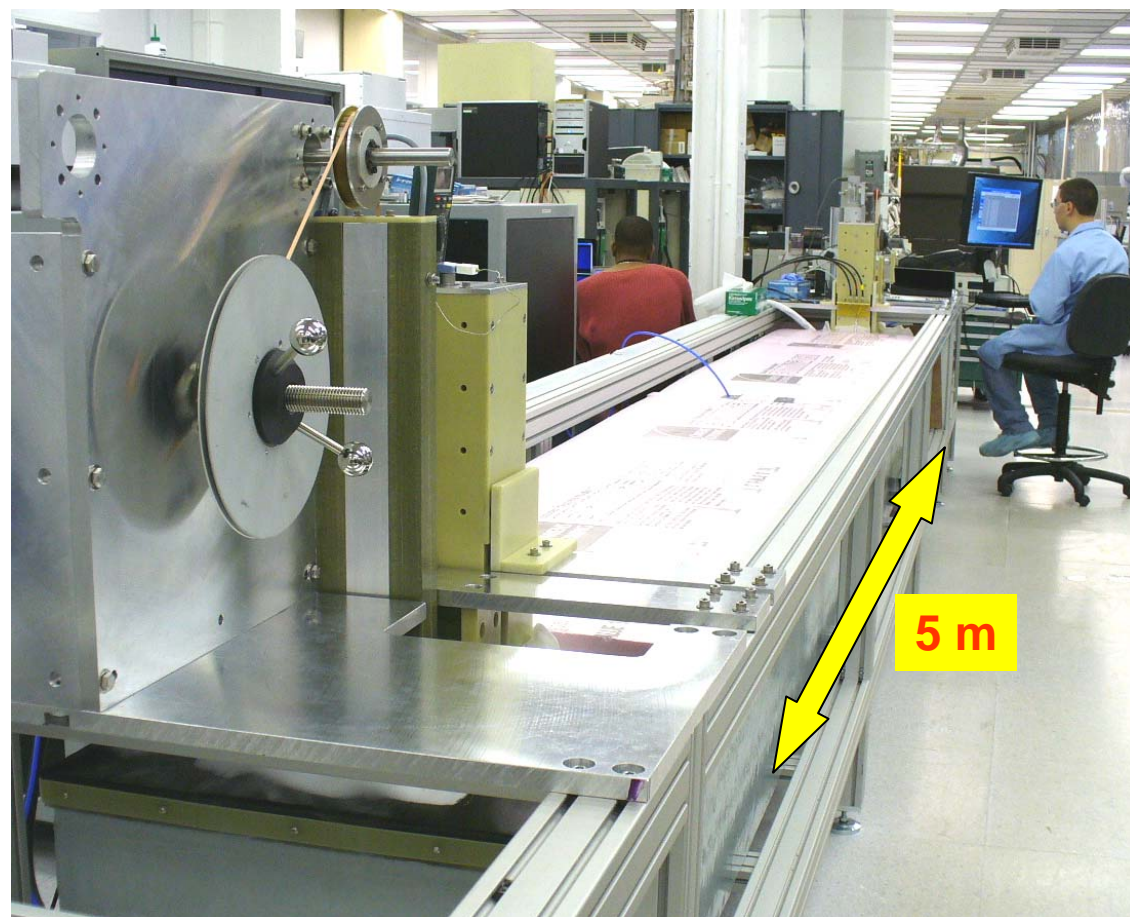


All our reported critical currents are by from I-V curve measurements using by standard transport technique with *continuous dc currents* which give *reliable*  $I_c$  and  $n$ -value data.



Meter-by-meter transport  $I_c$  measurements took 18 hours to completely test 427 m.

New 5 m transport  $I_c$  rig has been constructed. **Measurement time for a 427 m long tape can be reduced to just 4 hours.**





## Substantial improvements made in Ic & speed, & piece lengths of 2G conductors in the last 2 months

SuperPower

Attribute	2005	Aug 2006 (ASC)	Oct. 2006 (ISS)	Improvement after ASC 06
Ic (A/cm) – short, reel-to-reel processed	407	557	<b>721</b>	30%
Ic (A/cm) over 1 m	236	470	<b>595</b>	27%
Ic (A/cm) over 10 m	215	276	<b>484</b>	75%
IBAD speed* (m/h)	1	65	<b>120</b>	85%
Buffer speed* (m/h)	n/a	40	<b>80</b>	100%
MOCVD speed* (m/h)	5	30	<b>45</b>	50%
Ic over 200 m at stated speed	106	246	<b>227</b>	Same Ic level with 50 – 100% higher speeds in all processes
Ic × L (A-m)	22,000	70,520	<b>81,550</b>	100 m longer

**Rapid progress with higher currents, higher speeds, and longer lengths are all leading the way to a lower-cost 2G conductor**

# 2G conductor is now available in long lengths with excellent properties for prototype demonstrations



- 👤 Piece Lengths > 400 m
- 👤 Critical Current: 80 – 110 A in 4 mm widths
- 👤 Critical current uniformity: < 5%
- 👤 High throughput: IBAD – 120 m/h, Buffer – 80 m/h, YBCO – 45 m/h – all single pass of 12 mm wide tape
- 👤 Excellent joints, splices & solderability:
  - No degradation in  $I_c$  even when joint/splice was bend over 1" diameter and thermal cycled
  - Joint/splice resistance ~ 40 n $\Omega$ mcm<sup>2</sup>
  - No problem with soldering to our 2G conductor
- 👤 Excellent mechanical & in-field properties: 1.1 T coil at 77 K, 2.4 T at 64 K
- 👤 Tested in cable : Two 1 m cables demonstrated with 4 mm wide 2G conductor
- 👤 High Power FCL assembly demonstrated: 90 kA prospective fault current limitation demonstrated with our 2G conductor
- 👤 Price: \$ 600 – 1200/kA-m & dropping. Delivery of kilometers in 4 weeks