Recent Progress in Second-generation HTS Wires at SuperPower

V. Selvamanickam, Y. Chen, X. Xiong, Y. Xie, X. Zhang, A. Rar, K. Lenseth, R. Schmidt, M. Martchevskii, and J. Herrin

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Providing HTS Solutions for a New Dimension in Power – TODAY!

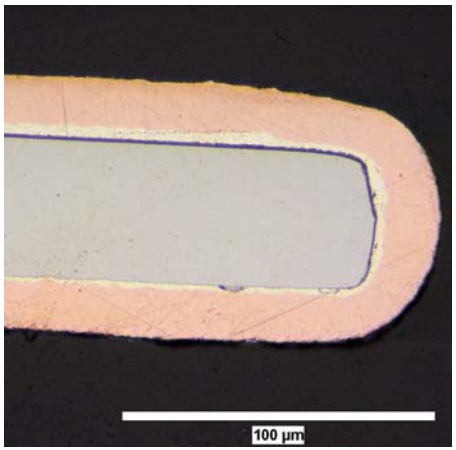
SuperPower's 2G wire is based on high throughput processes & superior substrate

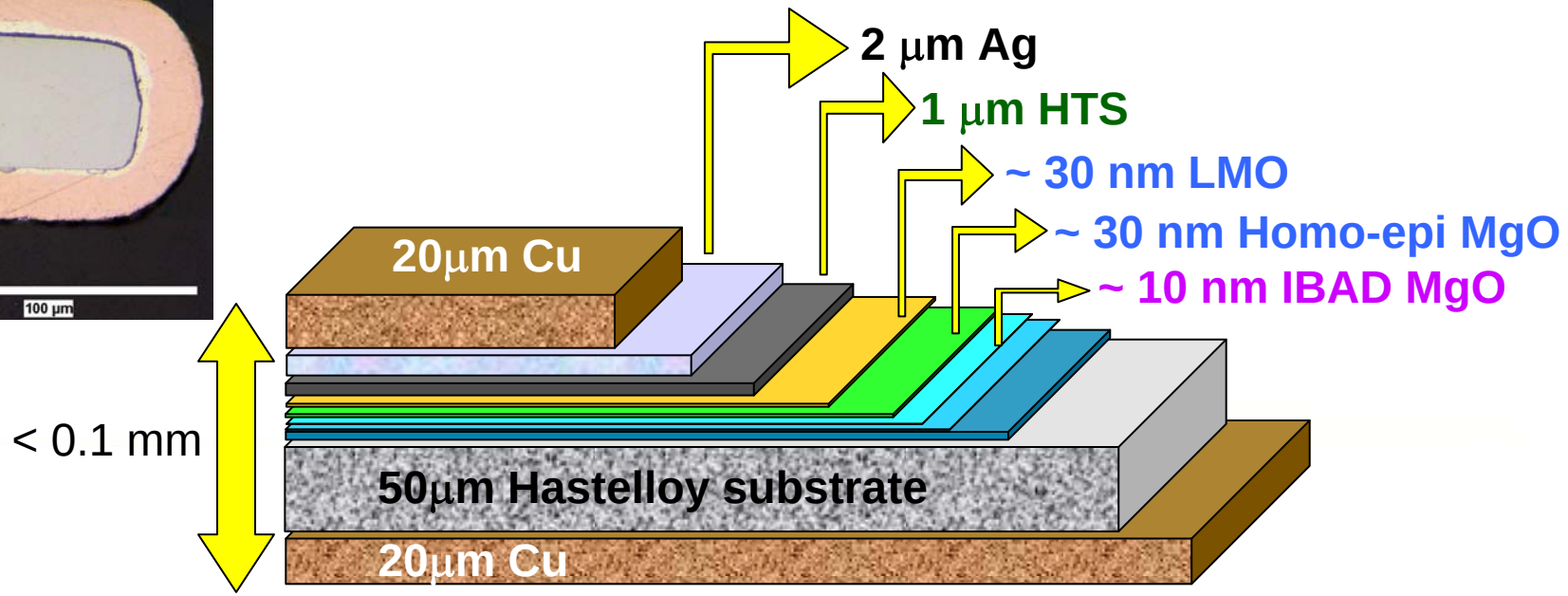
High throughput is critical for low cost 2G wire and to minimize capital investment.

SuperPower's 2G conductor is based on high throughput IBAD MgO and MOCVD processes.

Use of IBAD as buffer template provides us choice of any substrate.

- Advantages of IBAD are high strength, low a.c. loss (non magnetic, high resistive substrates) and high engineering current density (ultra thin substrates)

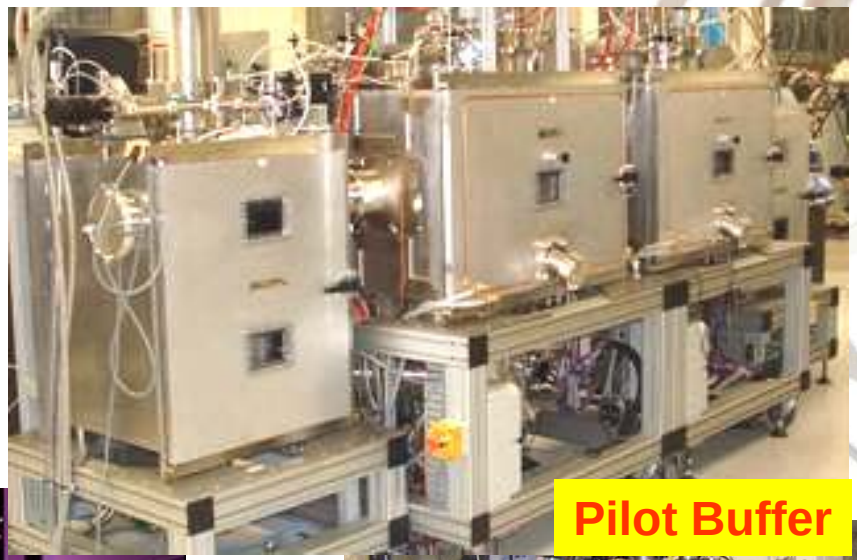




SuperPower's 2G Pilot Manufacturing facilities have been *operational* since 2006

Majority of investment already made for 1000 km/year capability

Pilot Substrate Electropolishing



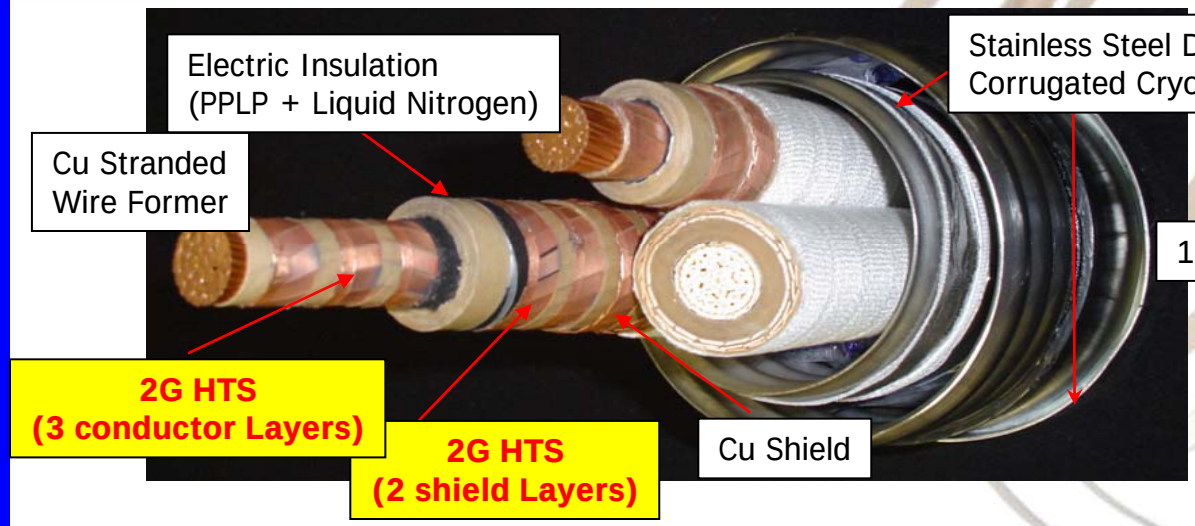
Pilot Buffer

Pilot IBAD

Pilot HTS

30 m 2G-Cable has been manufactured & tested by Sumitomo with ~ 10,000 m of our 2G wire

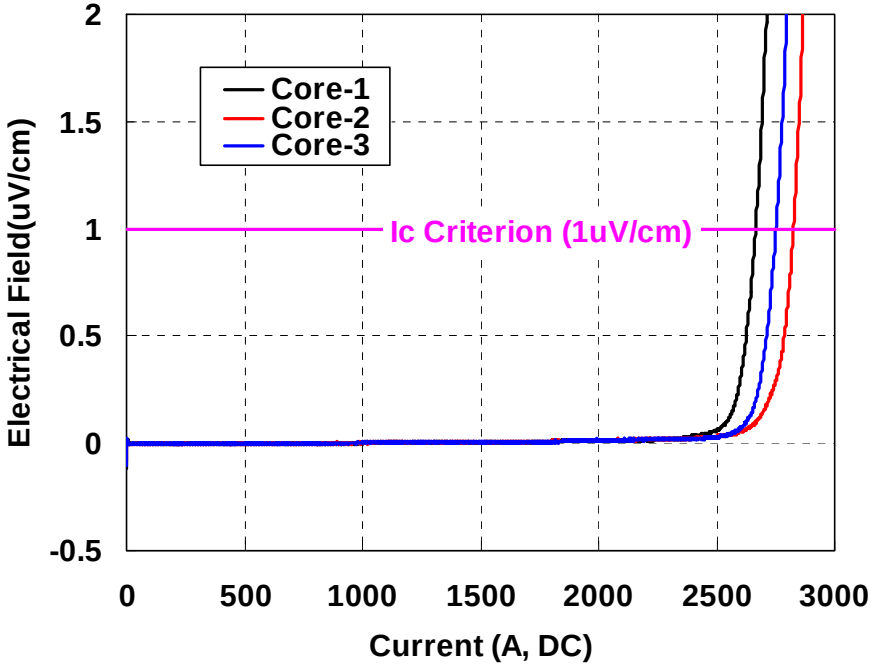
Nearly 10,000 m of 2G wire in 43 m piece lengths and minimum Ic over 70 A was delivered by SuperPower in Dec. 2006, marking the single largest delivery of 2G wire

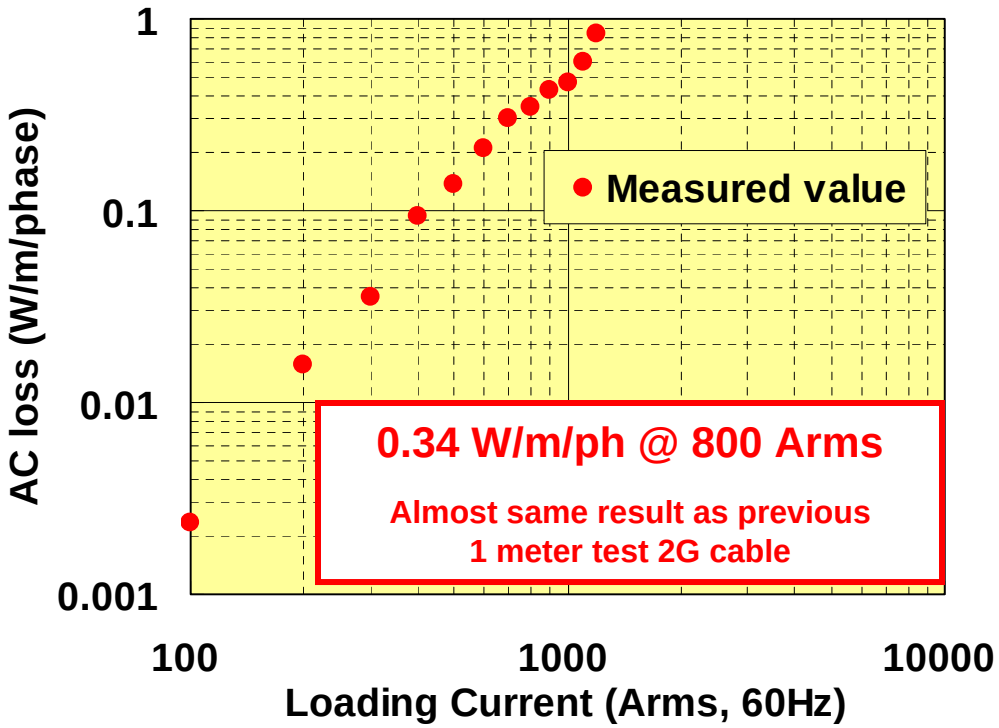


SUMITOMO ELECTRIC

Ingenious Dynamics

Excellent overall performance obtained in 2G cable





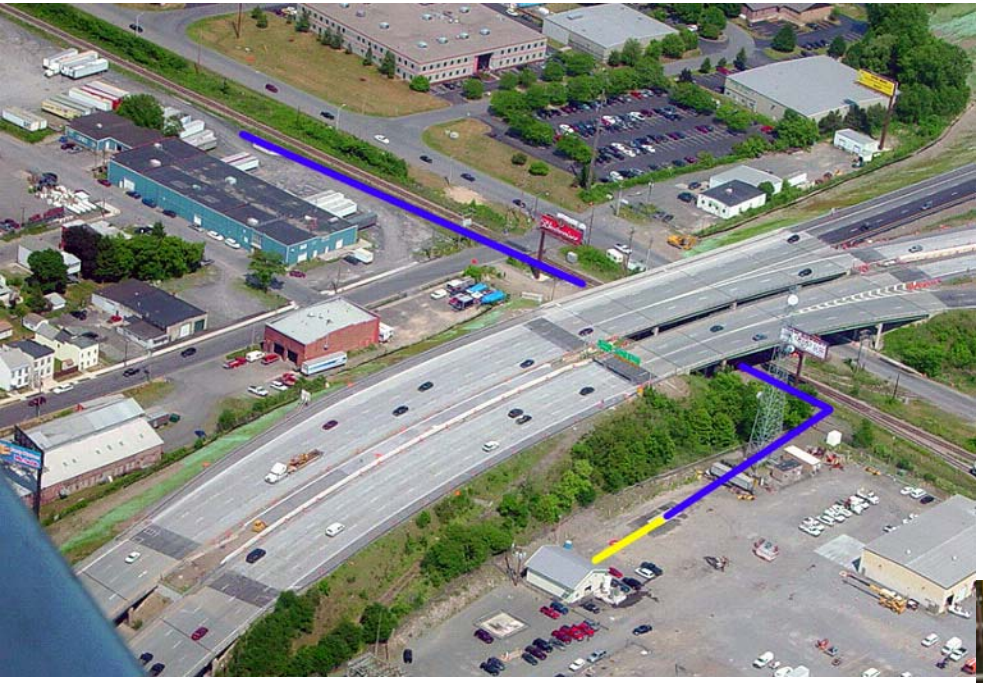
Ic of conductor layers ~ 2660 – 2820A
(DC, 77K, 1μV/cm)

Ic of shield layers ~ 2400 – 2500A
(DC, 77K, 1μV/cm)

No Ic degradation and No defect was found at dismantling inspection when bend to a diameter of 2.4 m

Cable withstood AC 69kV for 10 minutes and Impulse ±200kV, 10 times

2G cable has been installed in grid of Albany Cable site



Installation at Albany Cable site (Aug. 5, 2007)

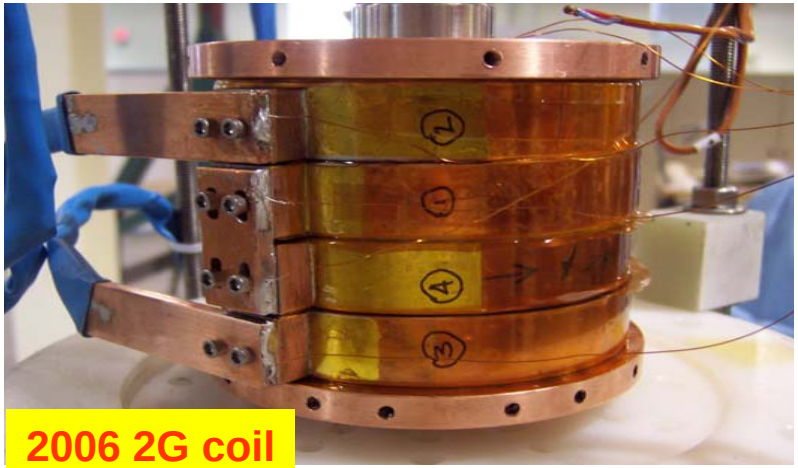
- World's first in-grid cable, first underground HTS cable, first cable-to-cable joint, 350 m long
- On-Grid Operations Began July 20, 2006
- 30 m segment of 1G cable replaced by 2G cable which is world's first 2G device

2G cable cool-down begins late Nov. 2007 and will be energized soon thereafter

New high field coil constructed with 2G wire

Total thickness of our 2G wire including copper stabilizer is only 0.095 mm which is ½ the thickness of 1G and other 2G wires. This is very useful for coil applications where higher number of amp-turns can be obtained.

In FY'06, we demonstrated a 2G coil that generated 1.1 T at 77 K and 2.4 T at 64 K



2006 2G coil

2007 2G coil

- In FY'07, we constructed a coil with 6 double pancakes using 462 m of 2G wire.
- The coil was tested in the National High Magnetic Field Lab at FSU

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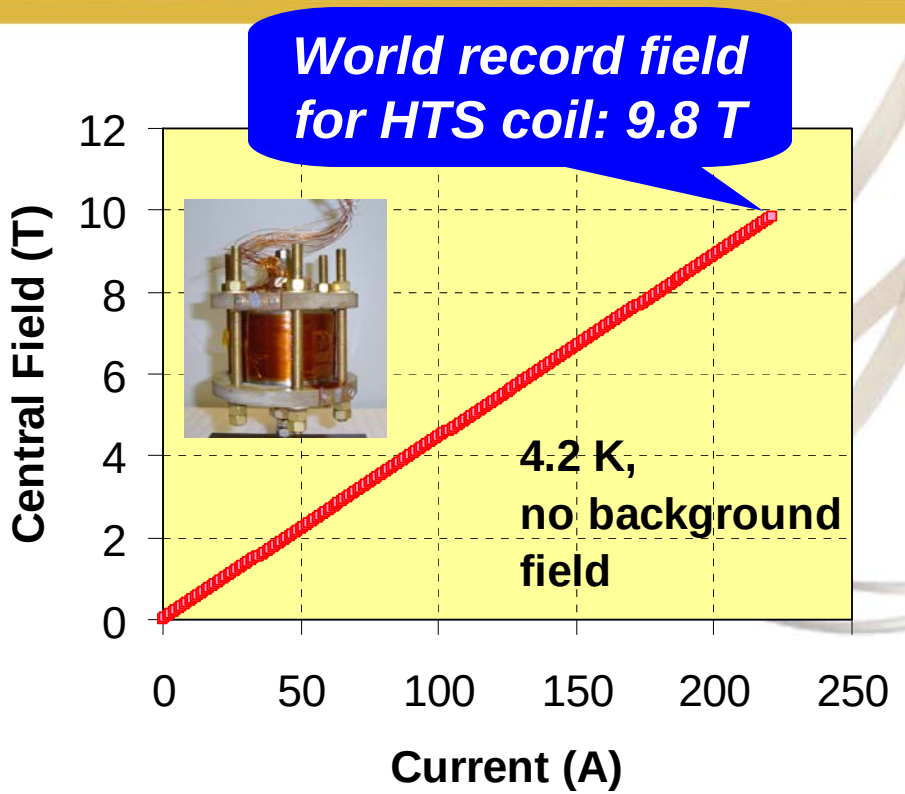
World record performance achieved with 2G coil

Coil ID	9.5 mm (clear)
Winding ID	19.1 mm
Winding OD	~ 87 mm
Coil Height	~ 51.6 mm
# of Pancakes	12 (6 x double)
2G tape used	~ 462 m
Average Ic of tapes in coil	78 A in 4 mm width (77 K, self field)
# of turns	~ 2772
Coil Je	~1.569 A/mm^2 per A
Coil constant	~ 44.46 mT/A



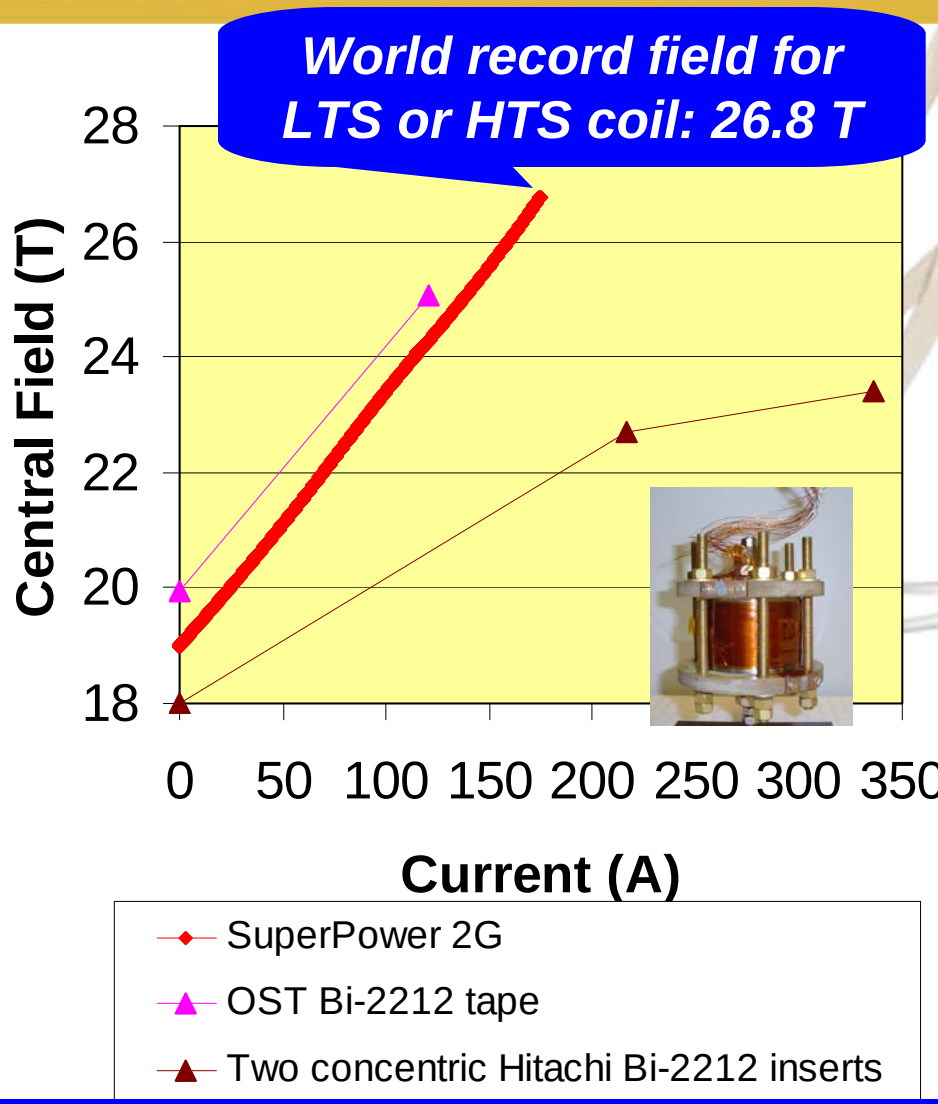
4.2 K Coil Ic - self field	221 A
4.2 K Amp Turns @ Ic - self field	612,612
4.2 K Central field – self field	9.81 T

Coil tested by H. Weijers, D. Markewicz, & D. Larbalestier, NHMFL, FSU

World record performance achieved with 2G coil

4.2 K Coil Ic – 19 T background (axial)	175 A
4.2 K Amp Turns @ Ic – 19 T background (axial)	485,100
4.2K Central Field – 19 T background (axial)	26.8 T

	2007 SP	2003 OST	1999 Hitachi 2- insert
Conductor length (km)	0.46	2.1	1.0
Winding Je (A/mm^2)	275	86	125/112
Additional field generated (T)	7.8	5.1	5.4
Total field achieved (T)	26.8	25.1	23.4



This demonstration extends the potential of 2G over a wider application range

Coil tested by H. Weijers, D. Markewicz, & D. Larbalestier, NHMFL, FSU

Key Milestones to be met in order for 2G to replace 1G in 2008

There are key areas where 2G needs to be competitive with 1G by 2008 in order to be used in the next round of various device prototype projects.

Key metrics that need to be demonstrated with 2G are :

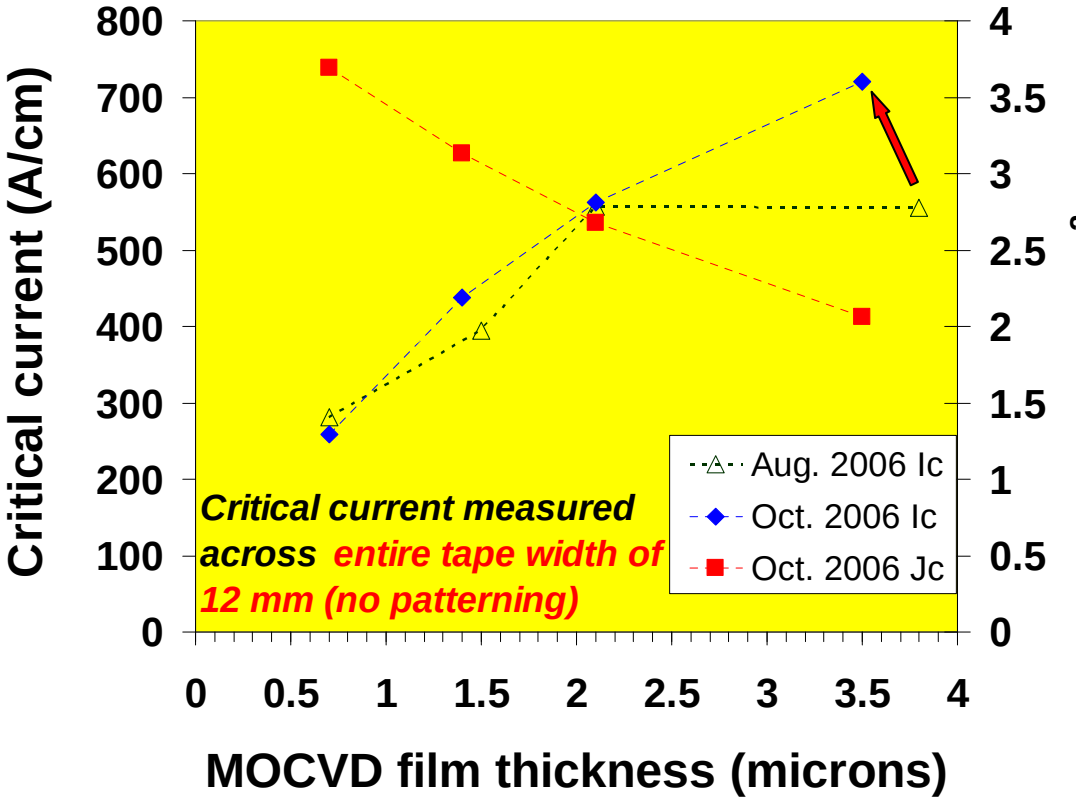
- Long piece lengths
- Critical Current over long lengths
- Availability
  - High throughput (= production volume/year)
  - Demonstrate large deliveries from Pilot-scale production
- Comparable cost with 1G

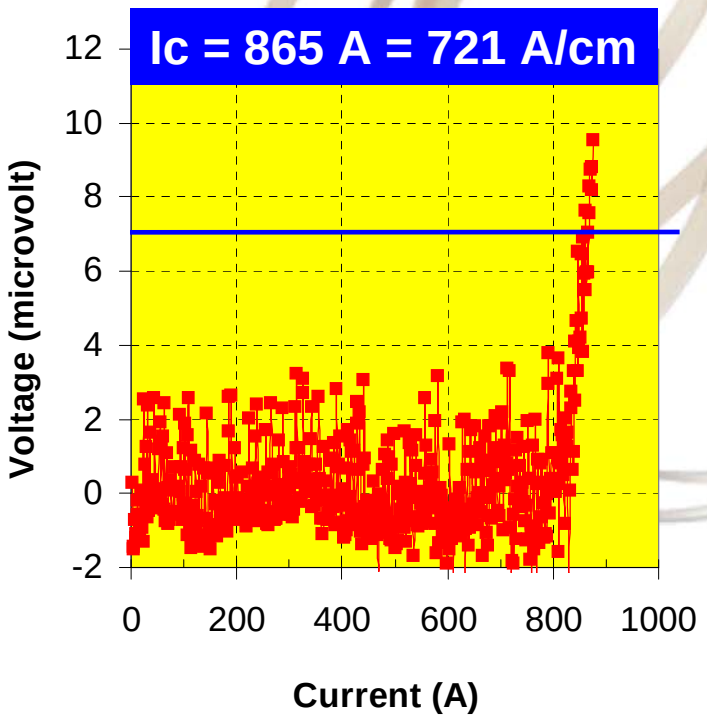
Metric	1G	2G (2006)	Title III 2G goals (June '08)
Piece length (m)	1,500	400	1,000
Ic (A) in 4 mm over long lengths	200	100	200
Capacity (km/year)	< 1,000	350	1,000*

Our focus in 2007 has been to make significant progress in all key metrics

*1000 km/year at the specified length & Ic

Pathway to commercialization of 2G
Metric 1 : Higher Currents





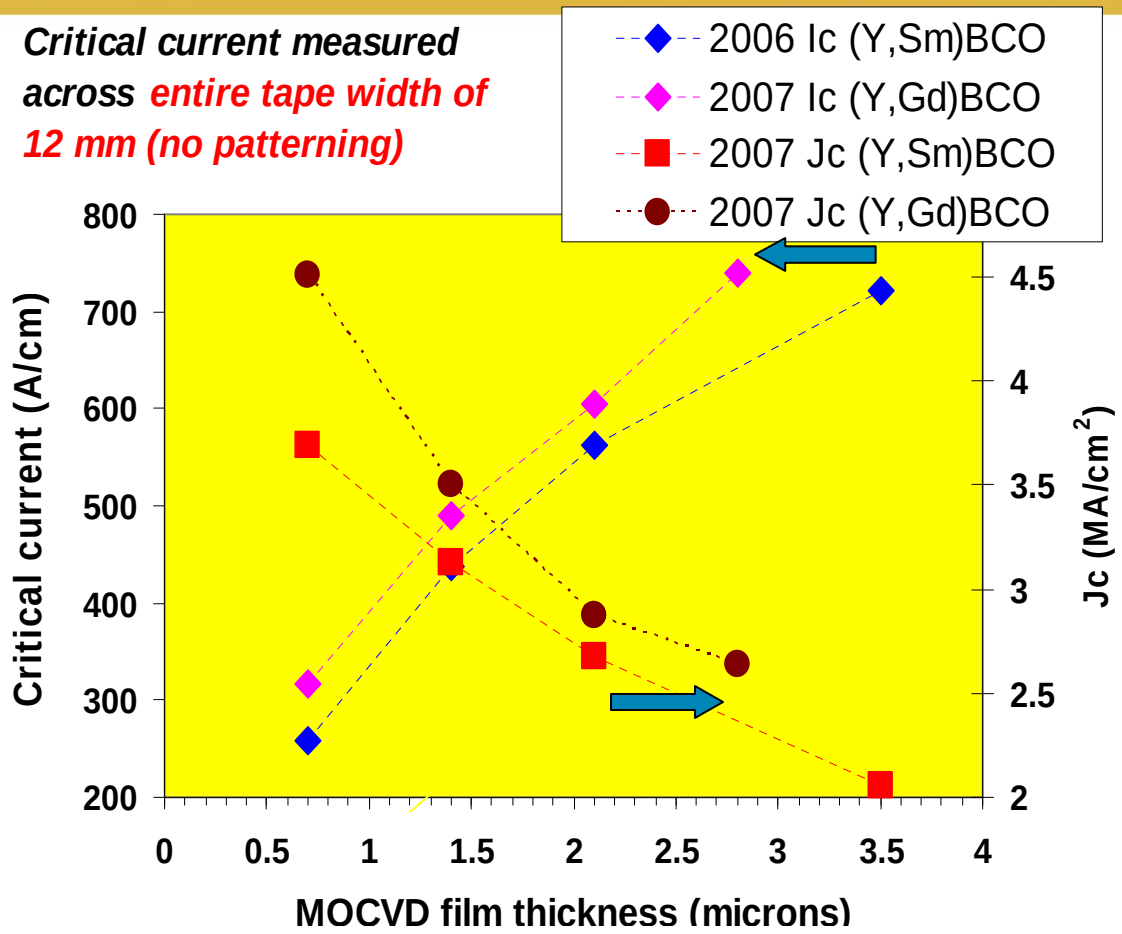
Ic measurement using continuous dc current (no pulsed current) across entire tape width of 12 mm No patterning

Oct. 2006 : In a 3.5 micron film made in 5 passes, achieved Ic of **721 A/cm (Jc = 2.06 MA/cm²)** over reel-to-reel processed 12 mm wide, 7 cm long tape.

Thick film MOCVD technology continues to be advanced by improving microstructure to achieve higher currents

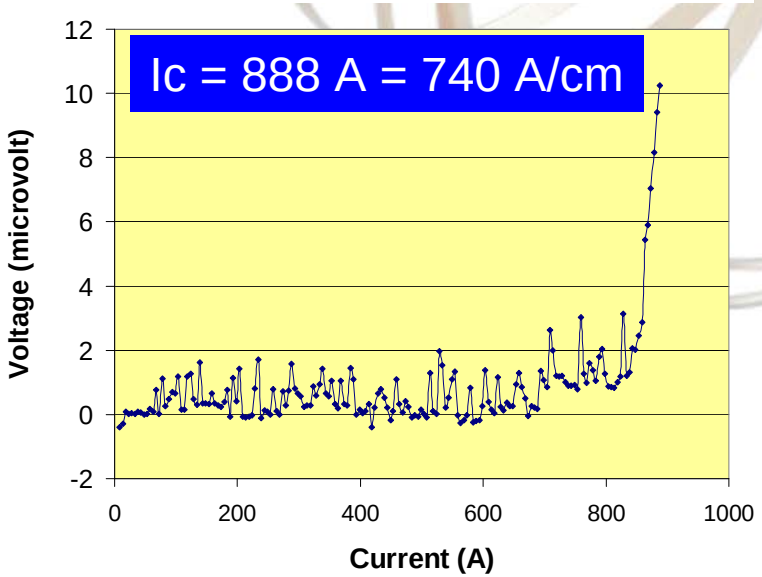
Modified MOCVD film composition (Gd-YBCO) yielded higher currents in thinner films

Critical current measured across entire tape width of 12 mm (no patterning)



Microstructural problems increase with increasing film thickness.

Can high currents be achieved in thinner films ?

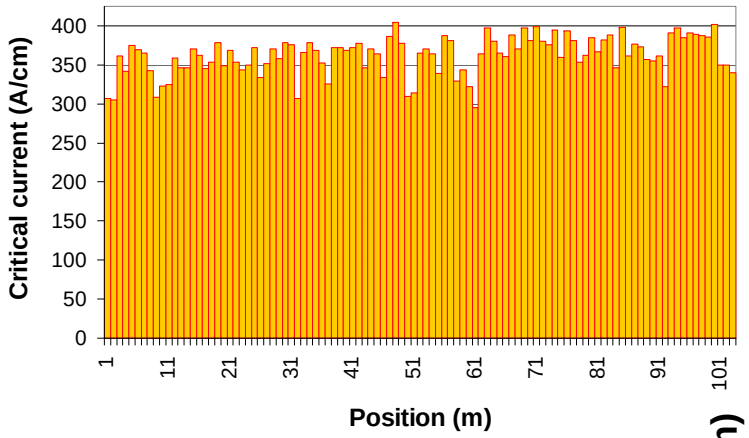


In a 2.8 micron film made in 4 passes, achieved Ic of **740 A/cm (Jc = 2.64 MA/cm²)** over reel-to-reel processed 12 mm wide, 10 cm long tape.

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

This demonstration of 300 A conductor in 4 mm width is 50% better performance than the best 1G available today

Higher currents in > 100 m lengths at higher speeds



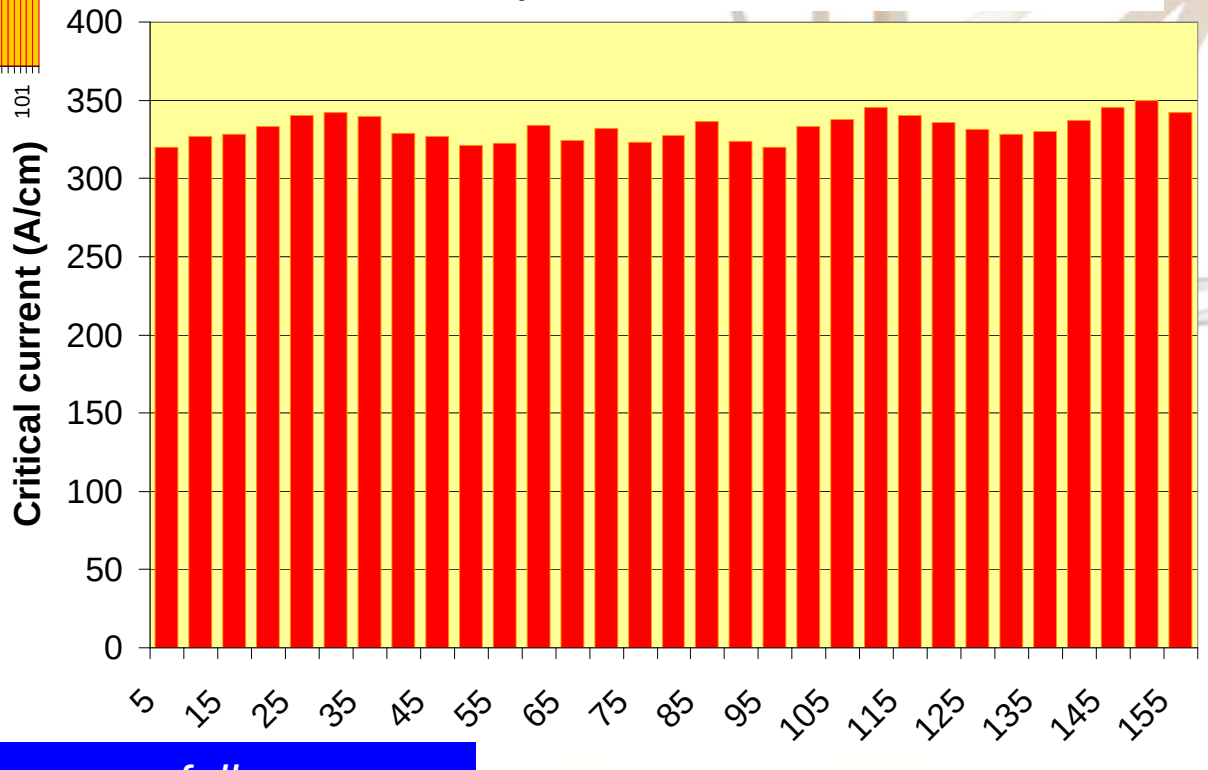
In 2006, we demonstrated Ic ~ 300 A/cm over 100 m in MOCVD tape processed in Research MOCVD system.
Tape speed = 15 m/h*
Uniformity over 103 m = 6.8%

In Oct. 2007, produced 155 m long tape in Pilot MOCVD system

Tape speed ~ 70 m/h*

Minimum Ic over 155 m = 320 A/cm

Uniformity over 155 m = 2.5%



Thicker film MOCVD technology successfully transitioned to Pilot system to produce long high current tapes at ~ 5x higher speeds

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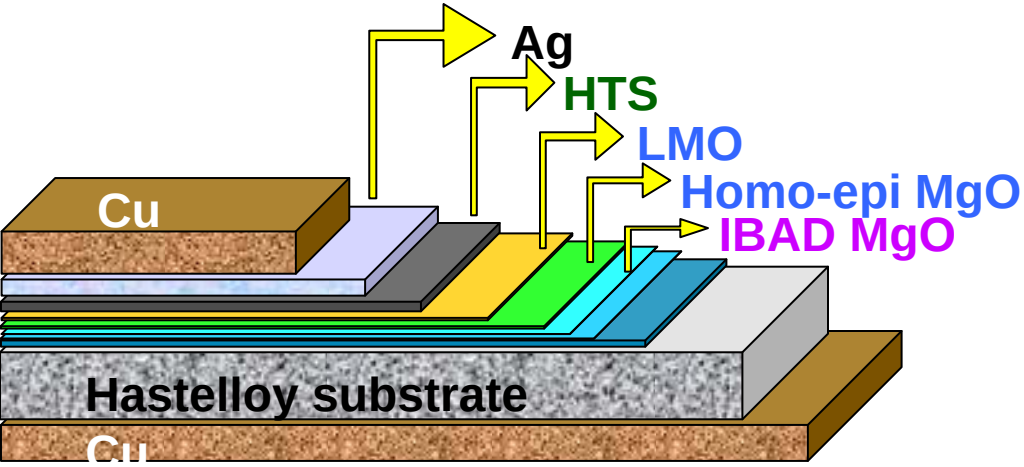
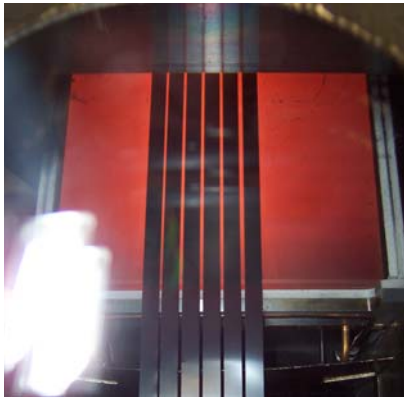
* 4 mm wide tape equivalent

Pathway to commercialization of 2G
Metric 2 : Higher Throughput

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 195 m/h to 360 m/h for 4 mm wide tape.**

Higher power levels, more tape tracks in helix system were used in reactive sputtering of **homo-epi MgO to increase speed from 120 m/h to 345 m/h of 4 mm wide tape.**





2006
6 tape tracks

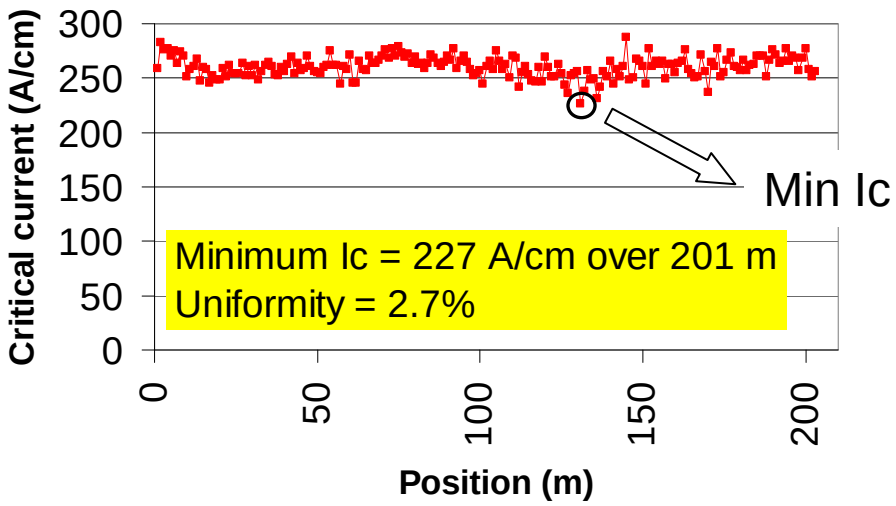
Tape tracks used in helix tape handling system was increased and film thickness was decreased by 25% to **increase speed of LMO process from 120 m/h to 360 m/h.**

2007
11 tape tracks

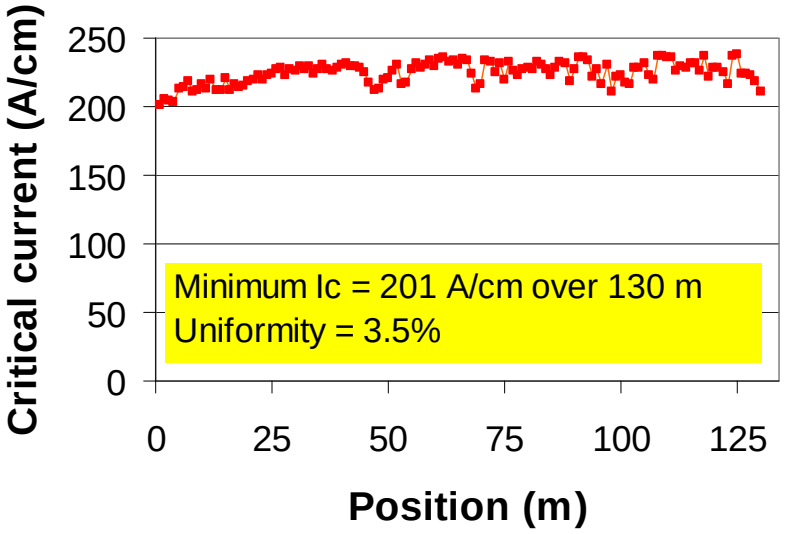
IBAD MgO & Buffer processing speeds have been increased by 100% to 200%

We have proven high throughput processes in all steps in our Pilot 2G manufacturing to produce high quality wire in long lengths

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



June '07 : High currents over 130+m with all processes at even higher speeds

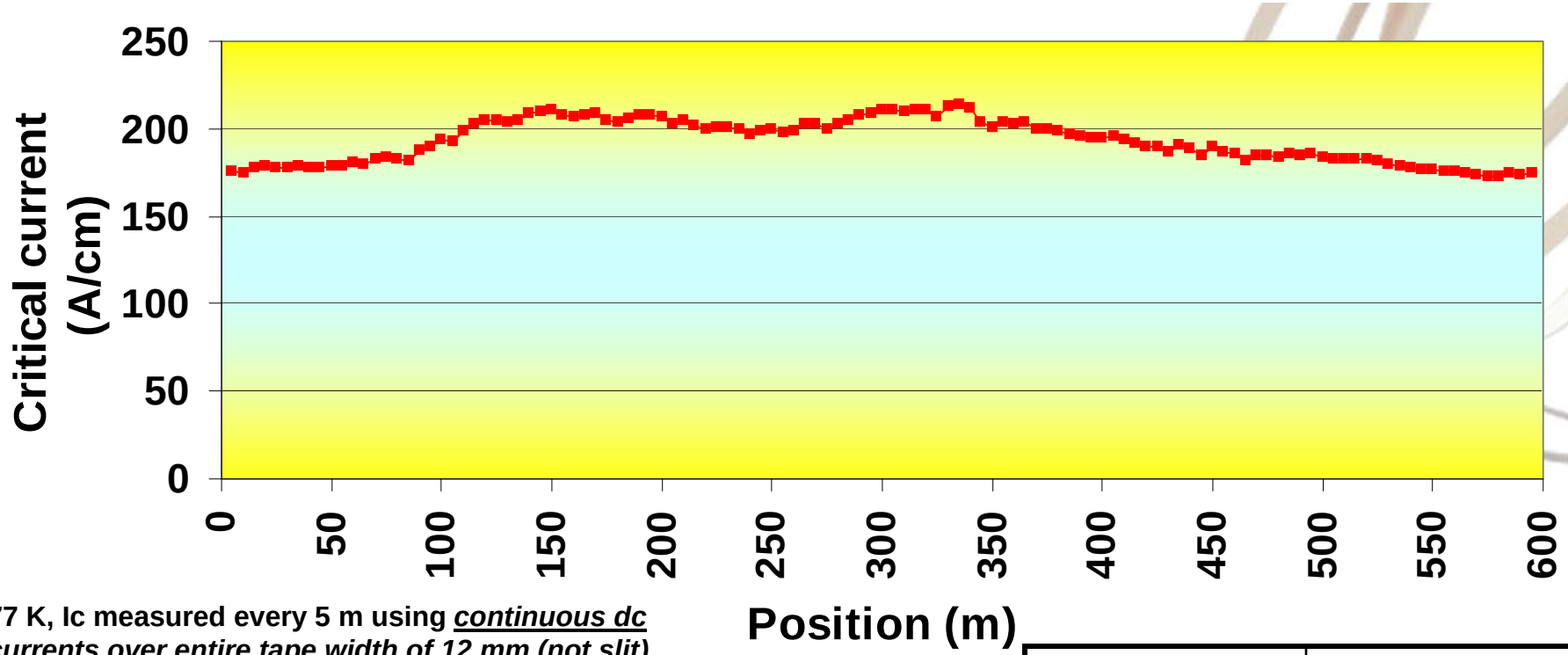


Process	Month	IBAD MgO	Homo-epi MgO	LMO	MOCVD YBCO
Speed of 4 mm wide tape (m/h)	Oct. '06	360	240	240	135
	June '07	360	345	345	180
Production capacity (km/yr) (if 45% of time/year is available for deposition)		1,440	1,380	1,380	720

Production capacity of 1,000 km/year already exceeded in IBAD MgO & Buffer processes is close to being achieved with MOCVD

Pathway to commercialization of 2G
Metric 3 : Long Lengths

In January 2007, we crossed an important milestone of 100,000 A-m.



77 K, Ic measured every 5 m using *continuous dc currents* *over entire tape width of 12 mm (not slit)*

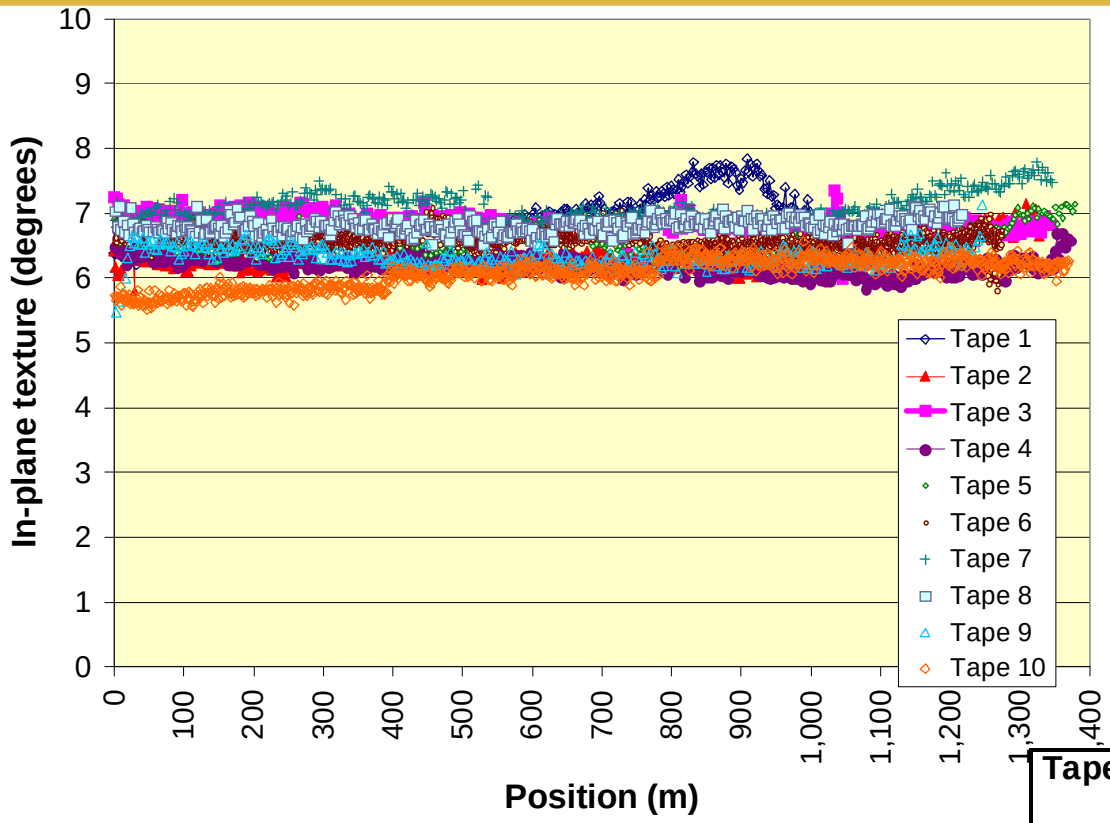
Minimum Ic = 173 A/cm over 595 m

Ic × Length = 102,935 A-m

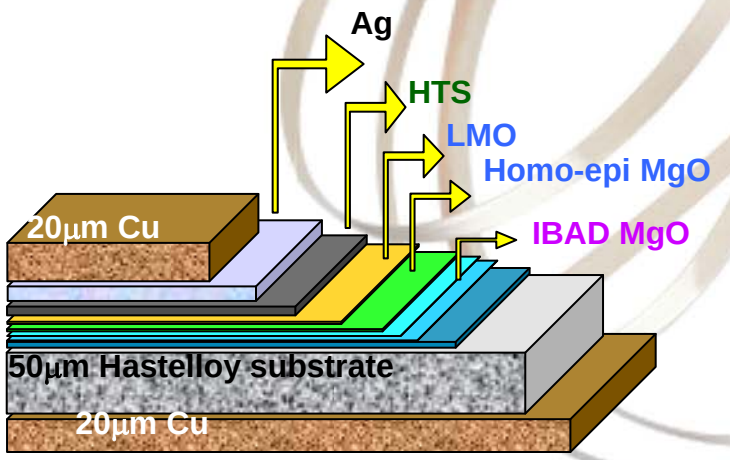
Uniformity over 595 m = 6.4%

Process (single pass)	Speed of 4 mm tape (m/h)
IBAD MgO	360
Homo-epi MgO	213
LMO	360
MOCVD	135

Kilometer lengths of fully buffered tape with excellent & uniform in-plane texture produced



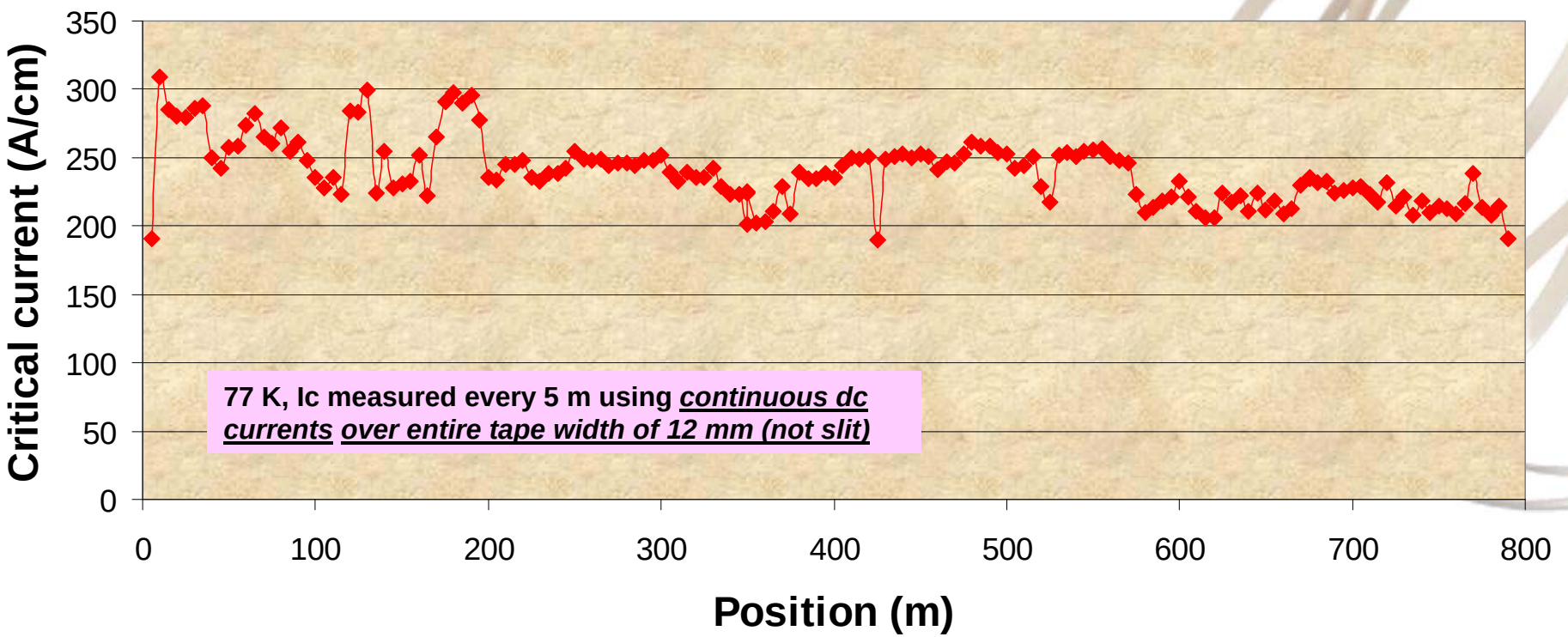
Next target : Kilometer lengths !



Tape	Length (m)	In-plane texture (°)			Uniformity
		Average	Min	Max	
1	1,001	6.79	6.20	7.84	6.2%
2	1,343	6.33	5.80	7.16	3.3%
3	1,346	6.85	6.00	7.35	2.1%
4	1,372	6.20	5.83	6.68	2.2%
5	1,375	6.58	6.23	7.14	2.5%
6	1,277	6.59	5.80	7.09	2.1%
7	1,346	7.09	6.66	7.79	2.9%
8	1,265	6.81	6.30	7.12	1.7%
9	1,246	6.33	5.47	7.13	2.4%
10	1,369	6.18	5.95	6.26	1.2%

Several tapes with complete 5-layer buffer stack produced in lengths of approximately 1,300 m with in-plane texture of 6 – 7 degrees and excellent uniformity of ~ 2%.

Sep. 2007 : New long length record !



Minimum Ic = 190 A/cm over 790 m

Ic × Length = 150,100 A-m

Uniformity over 790 m = 9.7%

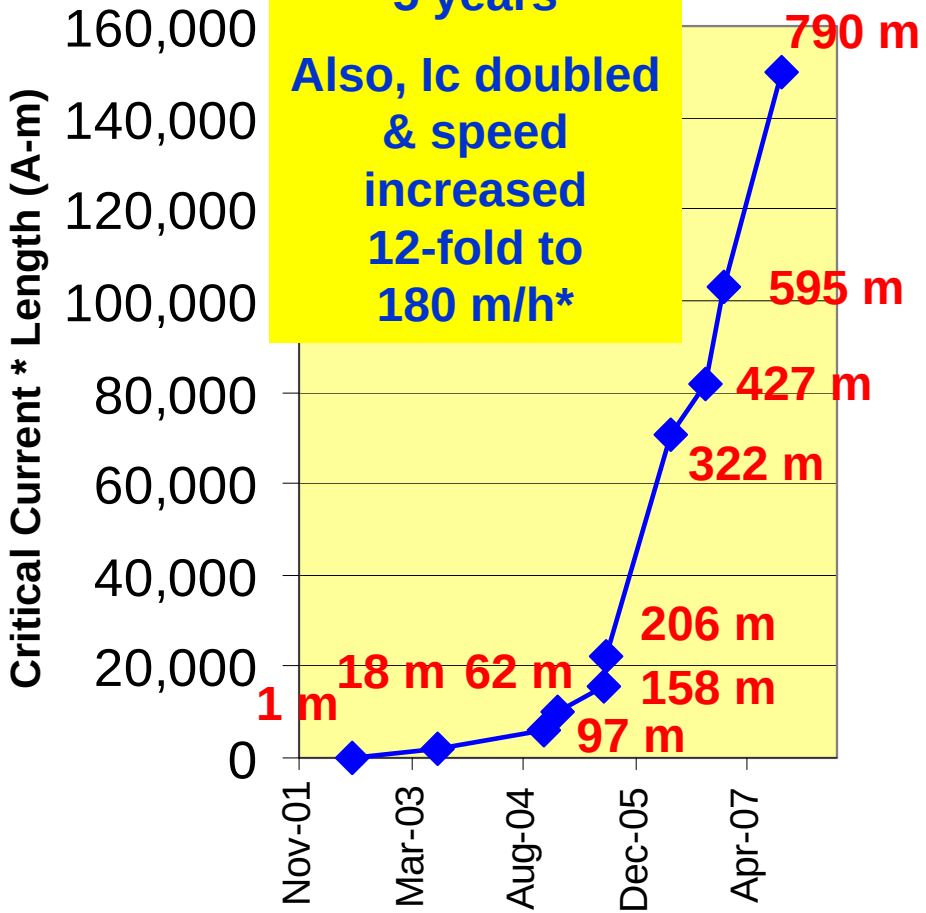
We are getting very close to kilometer long 2G wires !

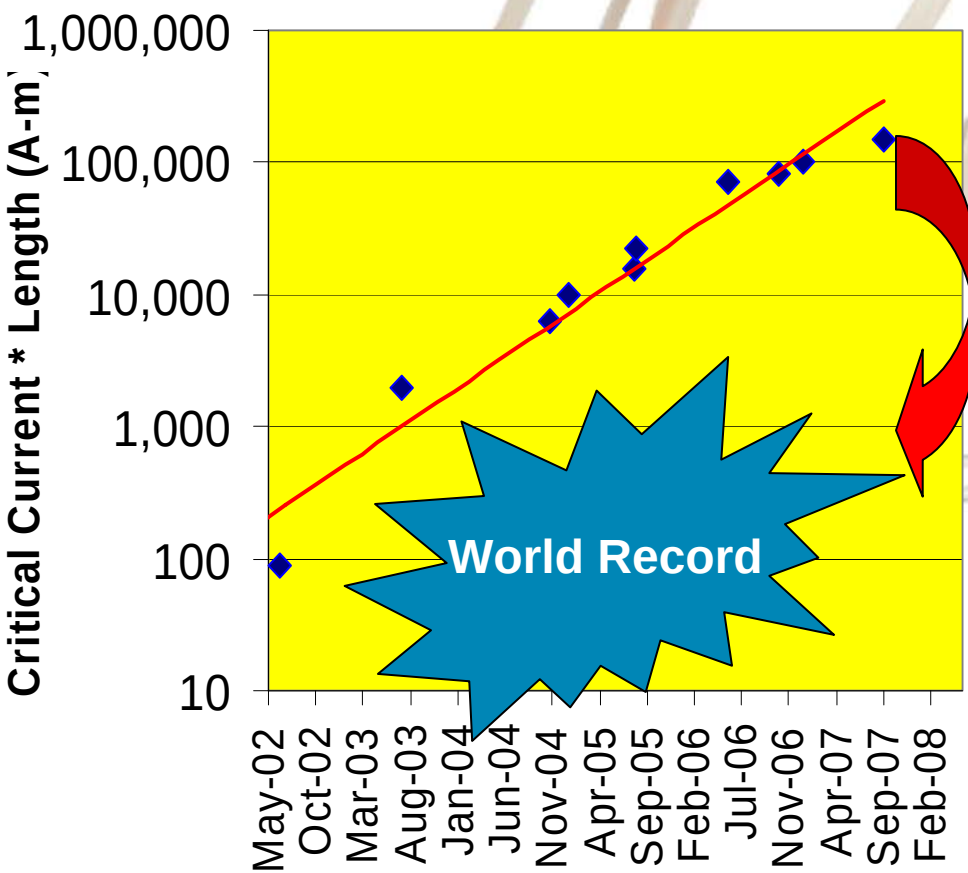
Process (single pass)	Speed of 4 mm tape (m/h)
IBAD MgO	360
Homo-epi MgO	345
LMO	345
MOCVD	~ 100

Remarkable progress in 2G wire scale-up over the last 5 years

1 m to 790 m in 5 years

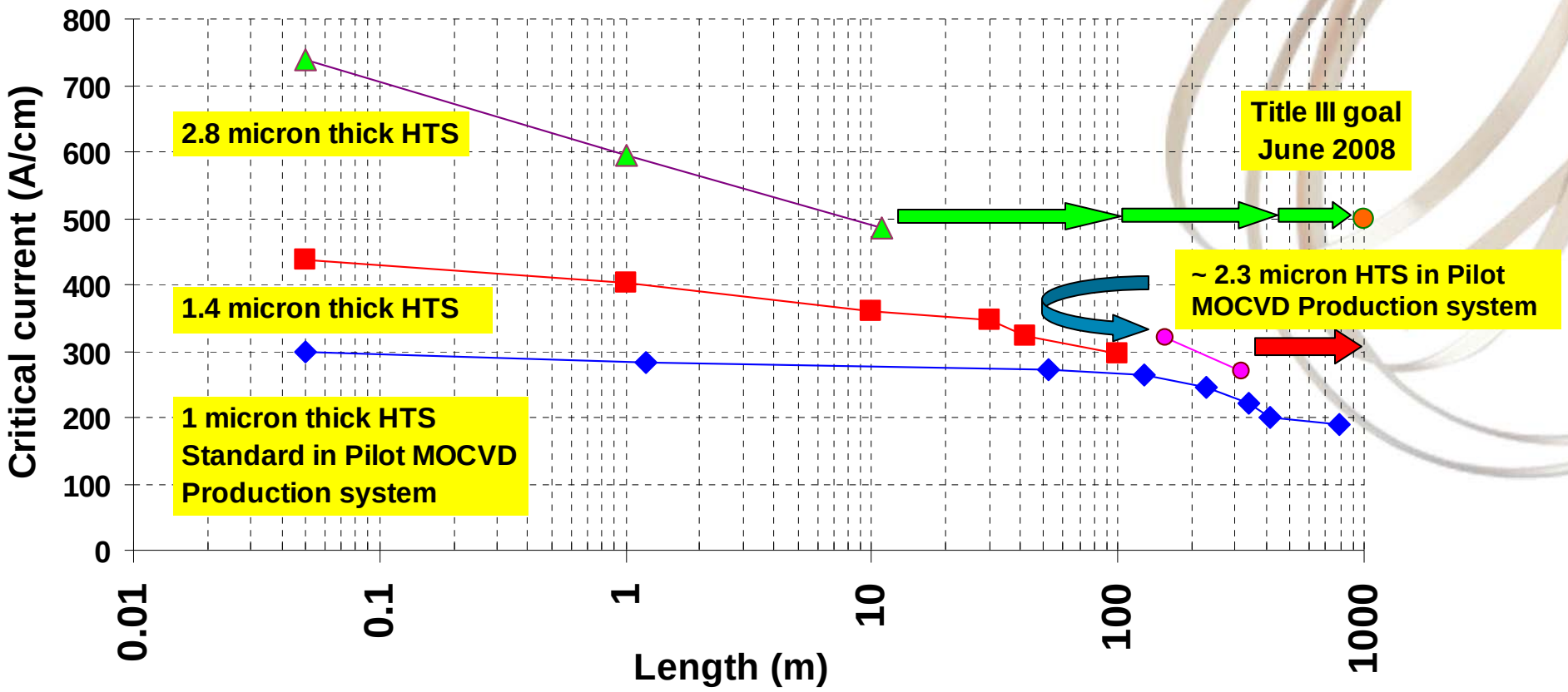
Also, Ic doubled & speed increased 12-fold to 180 m/h*





*4 mm speed equivalent

Progress being made both in Pilot Manufacturing of long lengths & technology development with shorter lengths



Next Steps:

Manufacturing scale-up to reach 1000 m with Ic > 200 A/cm (almost there !)

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

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

Substantial improvements made *since the last ISS* in all key metrics - Ic & speed, & piece lengths of 2G wire

Metric	2006 ISS	2007 ISS	Improvement in 2007
Ic (A/cm) – short, reel-to-reel processed	721 in 3.5 micron film	**740 in 2.8 micron film**	30% higher Jc
Buffer speed* (m/h)	240	**345 to 360**	40 to 50%
MOCVD speed* (m/h)	135	**180**	33%
Ic over 100 m at stated speeds of Buffer & MOCVD	227	**201**	**Same Ic level with much higher speeds in all processes**
Buffered tape piece length (m)	550	**1,375**	150%
Completed 2G wire Piece Length (m)	427	**790**	85%
Ic × L (A-m)	81,550	**150,100**	84%

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

*4 mm wide tape equivalent, single pass