SuperPower Inc.
A Subsidiary of Intermagnetics General Corporation

Superconductivity for Electric Systems
2006 Annual DOE Peer Review

July 25 – 27, 2006

HTS Solutions for a New Dimension in Power

Progress in Scale-up of 2G Conductor at SuperPower

- Venkat Selvamanickam
- Yi-Yuan Xie
- Jodi Reeves

Program funding from Title III and DOE through UT-Battelle

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FY06 was the year of transition to Pilot-scale manufacturing: *Goals were established accordingly*

Needed Feature in Commercial 2G	Stated goal for FY06 in FY05 presentation
High throughput	Helix tape handling in all processes; 30 m/h in every step to produce 100 m at 100 A/cm
Long lengths with excellent uniformity	250 m with Ic of 100 A/cm with 5% uniformity
High Ic in long lengths	300 A/cm over 100 m
Reproducibility	Produce 8000 m for Albany Cable project
Quality Control	High-speed XRD tool for IBAD MgO buffers
Higher Ic – thick films	500 A/cm in 2 micron films
Better in field properties	Je of 100 kA/cm^2 in self field and 25 kA/cm^2 at 1 T, 77 K, using chemical substitution
Better mechanical properties	Using thinner substrates, better joints*
Ac loss reduction in long lengths	Demonstrate patterned + twisted conductor
Overcurrent protection	Quench testing of coils
Better dielectric properties	Dielectric testing
2G Prototypes	3 T coil at 65 K, 2G for FCL

Our goal is to completely replace 1G in 2 - 3 yrs. Only 2G in the upcoming SPI projects !

*not specifically stated in FY'05 presentation

Outline

Long length scale up & high-throughput manufacturing of IBAD-MOCVD conductor	V. Selva
2G conductor delivery for the Albany Cable Project	V. Selva
Higher critical currents in MOCVD conductors	V. Selva
Properties of SuperPower's 2G conductor, New 2G Prototypes	Yi-Yuan Xie
Quality Control for Manufacturing Scale-up & Research Integration	Jodi Reeves
FY06 Performance & Results & FY07 Plans	Jodi Reeves

Long Length Scale-up & High-Throughput Manufacturing

In FY05, MOCVD process was scaled up to 200 m lengths

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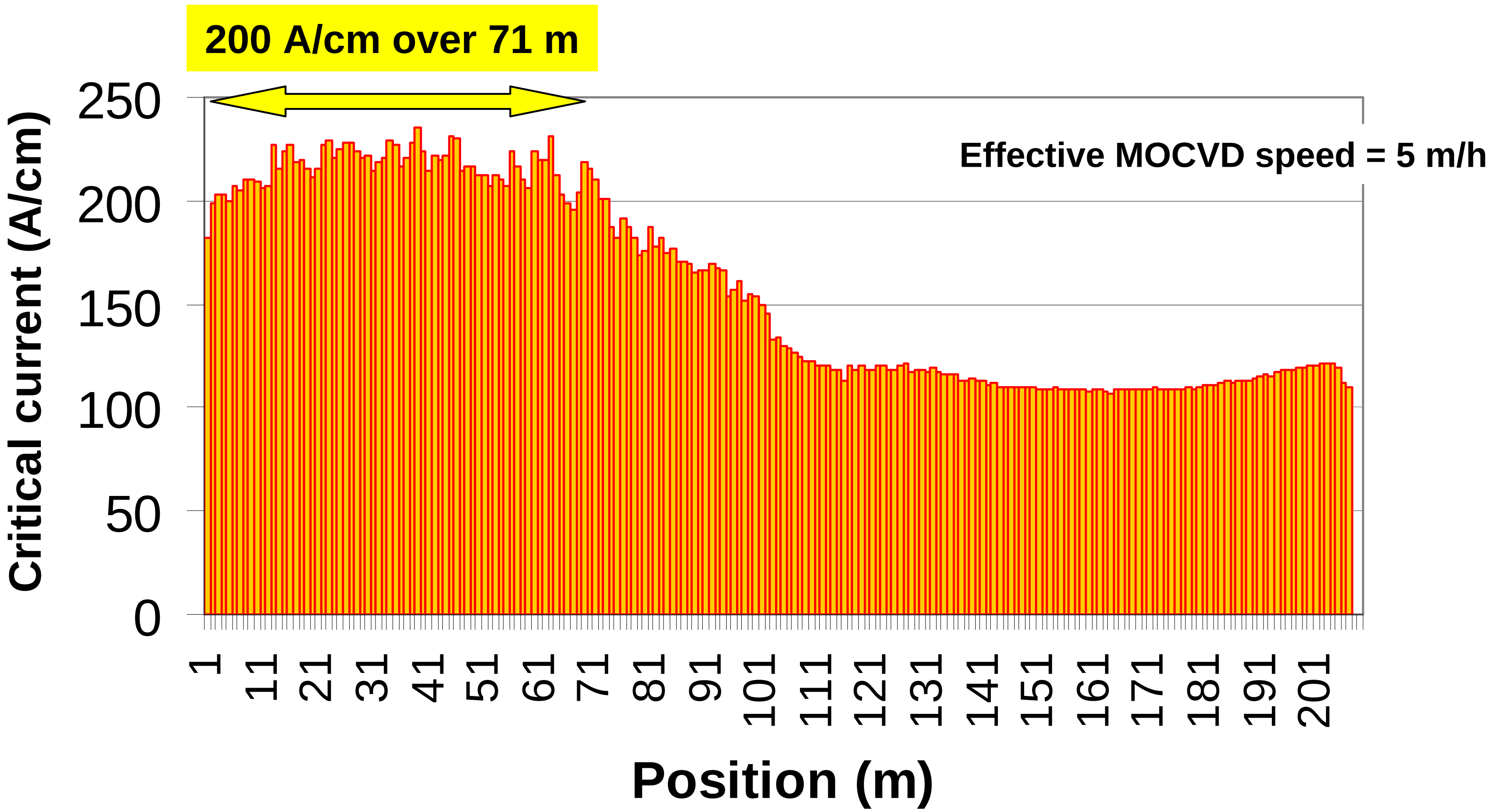


Minimum Ic of 106 A/cm over 206 m (22,030 A-m)

Standard deviation of 4.3% over the first 71 m with a Ic of 200 A/cm

Standard deviation of 4.3% over the last 100 m

Reviewers made it very clear that the non-uniformity issue beyond 70 m in long MOCVD tapes needed top priority

Comments from reviewers from FY05 Peer Review :

"I found the induction period and degradation of film properties after a period of time *disconcerting*….I think a high priority should be placed on why the process degrades after a period of time".

"… the long-length stable processing needs to be solved with high priority. "

"Although this was a characteristic of the system being operated, it sounds like a problem that is solvable, and bodes well for a rather high critical current over much longer lengths".

"The process seems capable of producing coated conductors at a high rate, although there are problems at the moment in coating long lengths with uniform properties. If the process drift problems can be solved, it should be successful at meeting DOE targets for the 2G wire program"

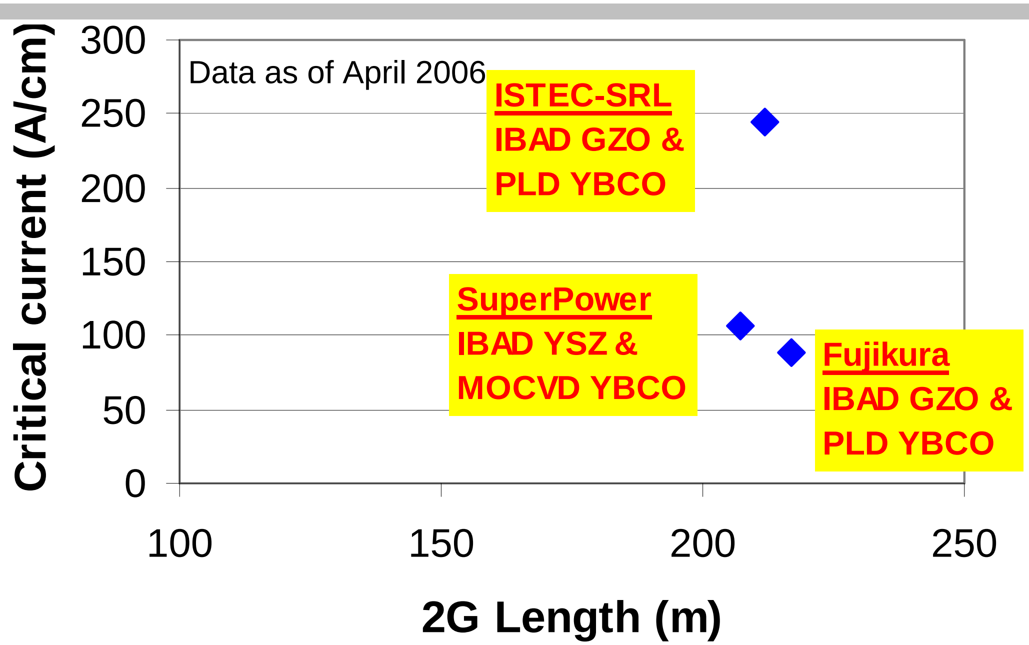
In FY'05: 2 passes at 10 m/h: effective speed is 5 m/h.

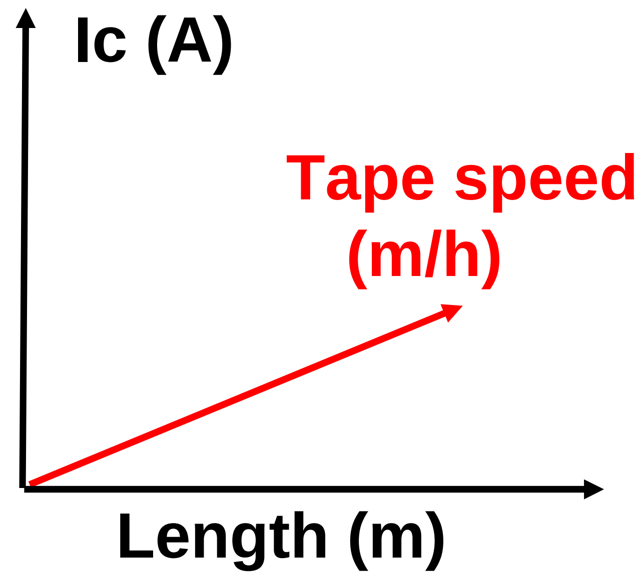
Ic is uniform over the 1st 71 m ~ 8 hours of processing

If speed can be increased to ~ 30 m/h, then 240 m can be produced in 8 hours.

Our first plan of attack was to increase speed from 5 m/h to 30 m/h

Tape speed needed to be substantially increased for 2G to be commercially viable





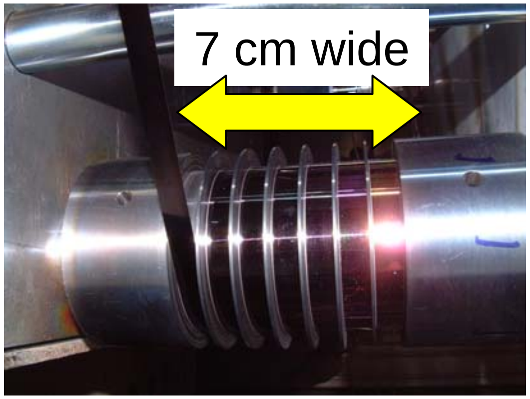
- All 200+m long demonstrations last year used low speeds in buffer & YBCO processes
- Speed of IBAD YSZ & IBAD GZO processes ~ 1 m/h of 10 or 12 mm wide tape
- Effective linear tape speed of PLD processes ~ 3 m/h of 10 mm wide tape
- Effective linear tape speed of MOCVD process = 5 m/h of 12 mm wide tape
- 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

Objective set to extend helix tape handling system 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 multi-pass process.

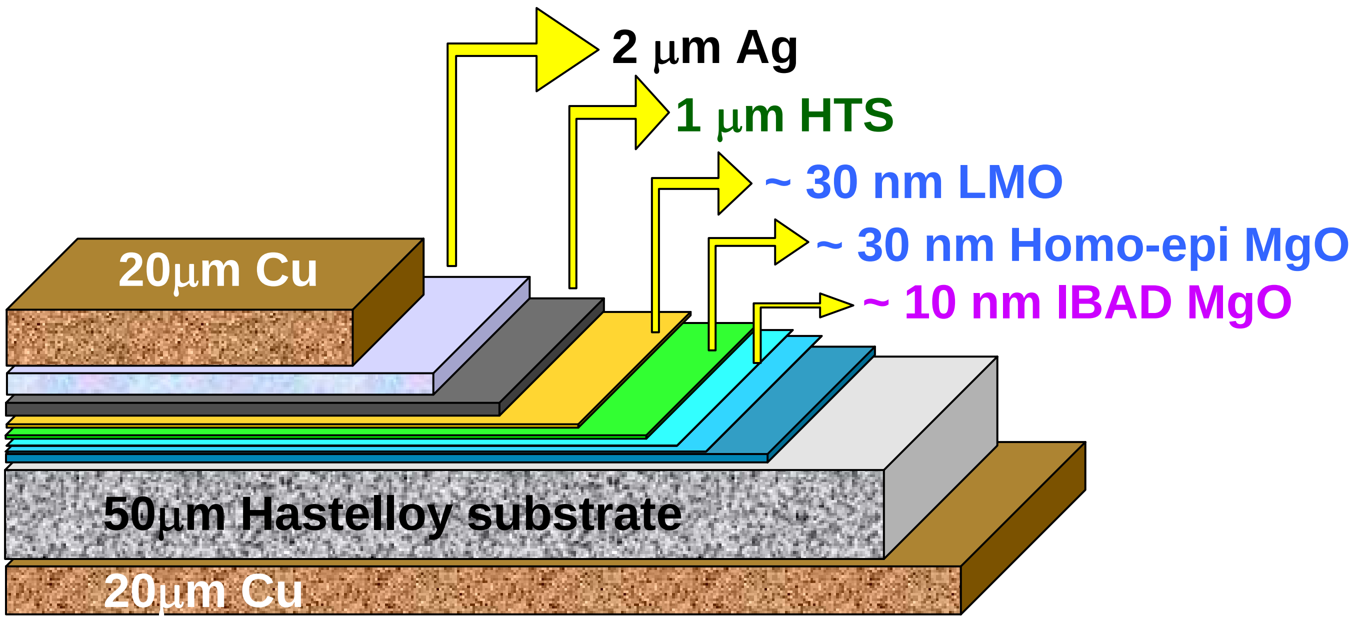


Comp3.mov

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

In FY06 Pilot Production Equipment was upgraded for high throughput processing of all layers

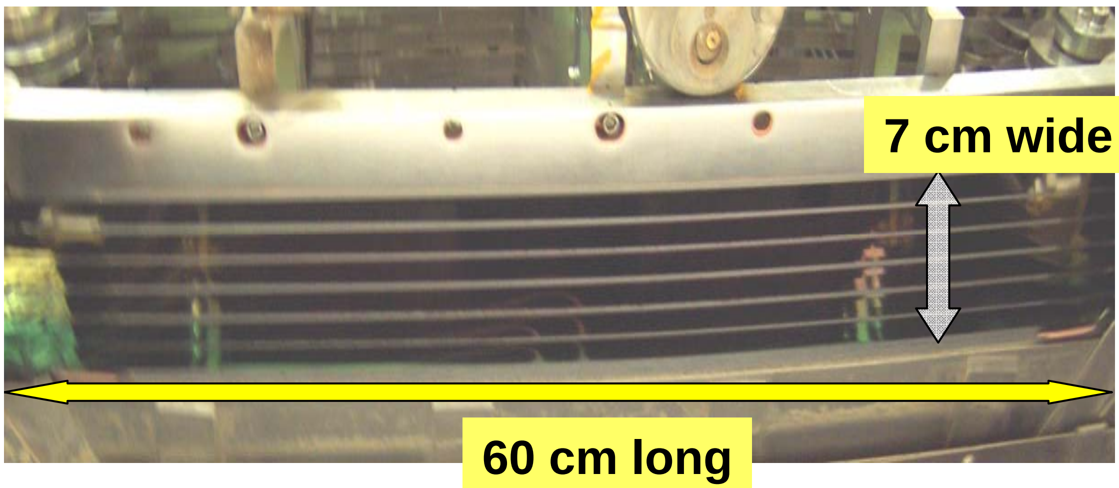
	FY'05 status	FY'06 plan
IBAD	Helix tape handling YSZ: 1 m/h	Transition to IBAD MgO in Pilot IBAD. Modify hardware accordingly.
Buffer	n/a	New Pilot Buffer system with helix tape handling
MOCVD	Single tape; 5 m/h	Retrofit with helix tape handling; Increase deposition zone length & width

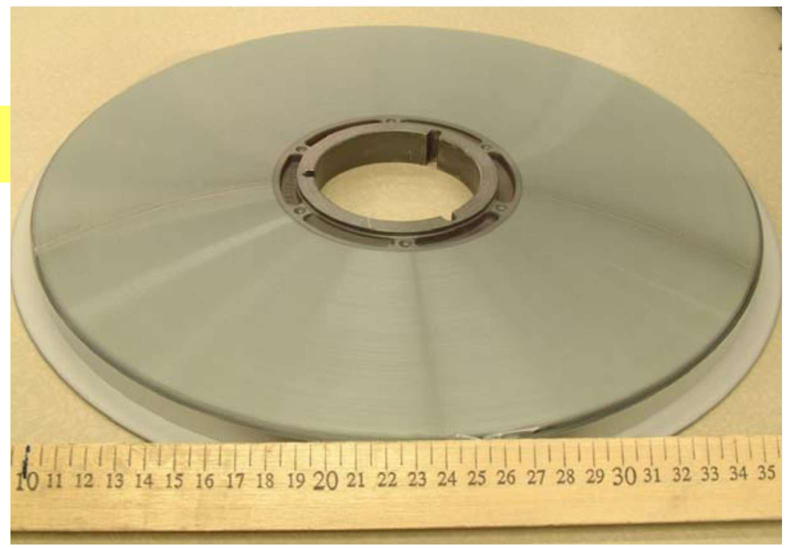


Tremendous challenge to successfully implement modifications in *three* critical pieces of equipment *simultaneously* & then routinely produce *10,000 m* of conductor for delivery to Albany Cable project

High throughput IBAD MgO has been transitioned to Pilot IBAD system

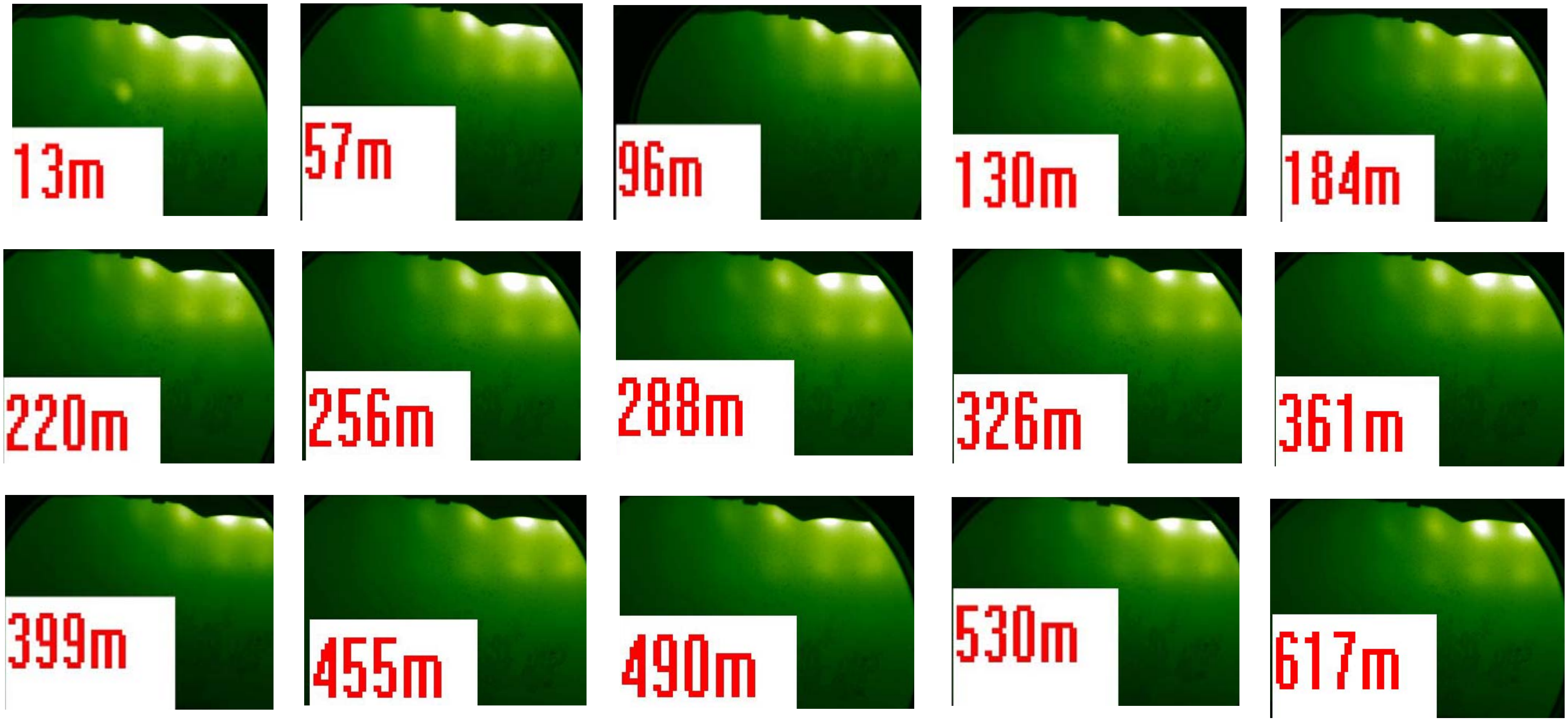
- Pilot IBAD system: Helix tape handling with a deposition zone length of 60 cm, 6 tape wraps. With IBAD YSZ, yielded ~ 1 m/h.
  - With IBAD MgO would enable linear tape speeds > 100 m/h (or a throughput > 300 m/h of 4 mm wide tape)





- **Up to 570 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**

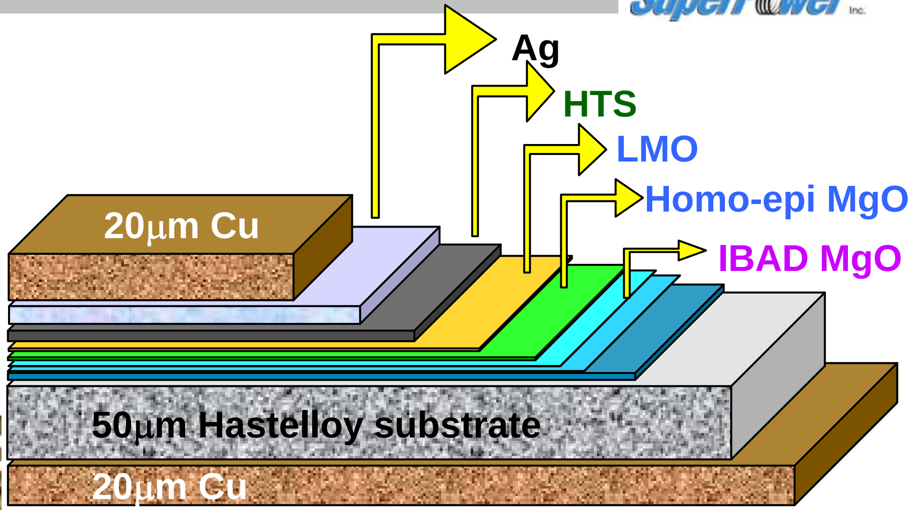
Up to <u>570 m long single-piece</u> IBAD MgO tapes routinely processed in Pilot IBAD with good & uniform texture

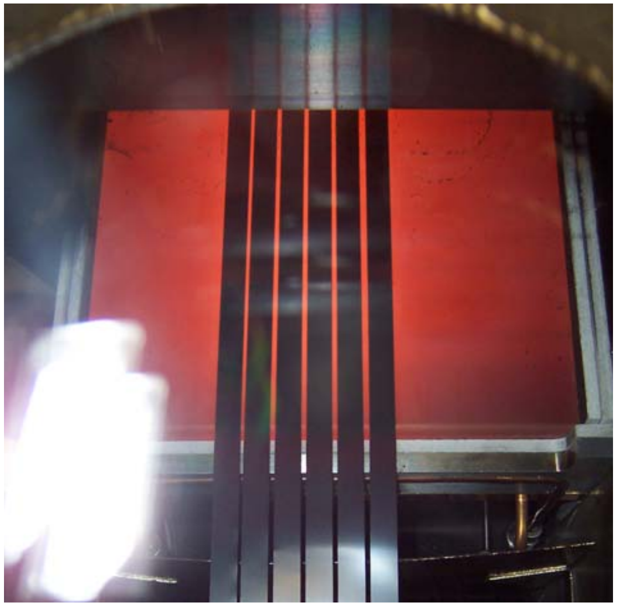


Uniform RHEED patterns obtained over process lengths up to 800 m

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

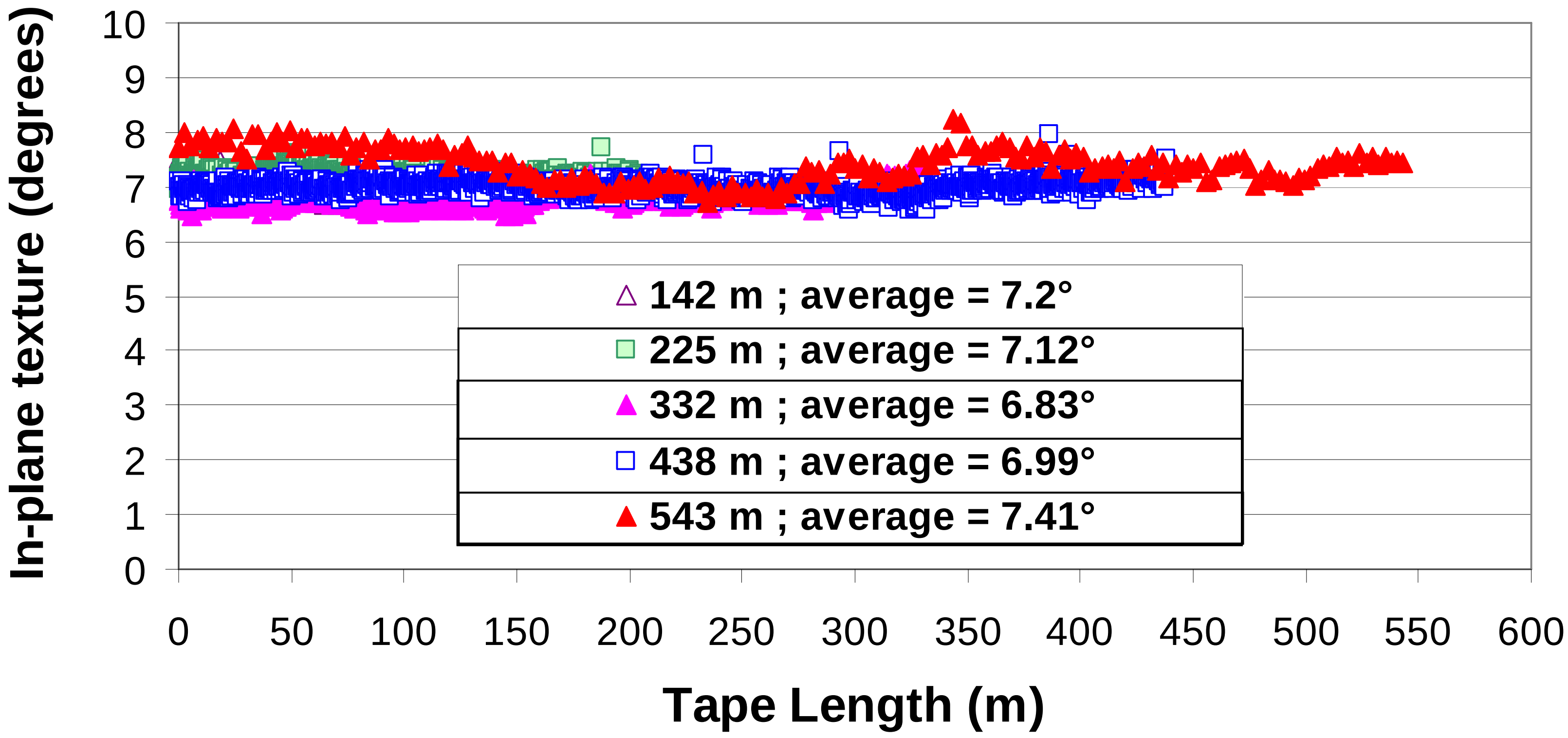
- Two chambers for sequential deposition of 2 buffers (homo-epi MgO & LMO) on IBAD MgO
- Helix tape handling in both chambers, each with 12 tape wraps. Deposition zone length in each chamber = 0.3 m
- Spool boxes for 1 km single-piece lengths





550 m long tapes have been produced in Pilot Buffer system at linear speeds of 40 m/h

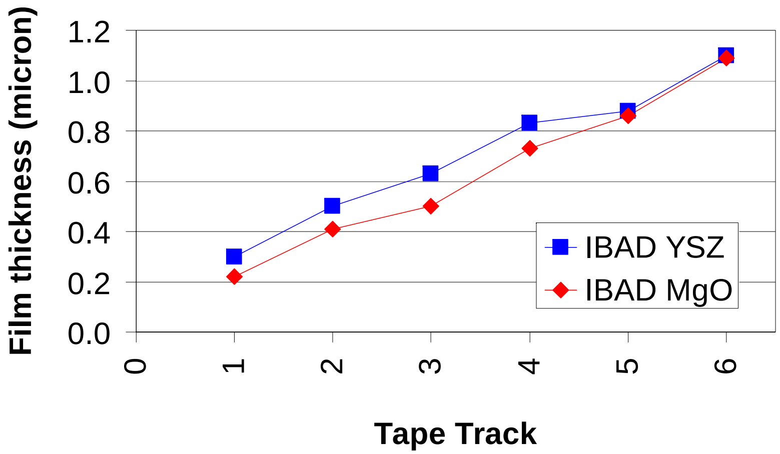
Using only 6 of the 12 tape tracks in helix tape handling in Pilot Buffer system, 40 m/h tape speed is routinely used to produce up to 550 m lengths of homo-epi MgO and LMO on IBAD MgO.

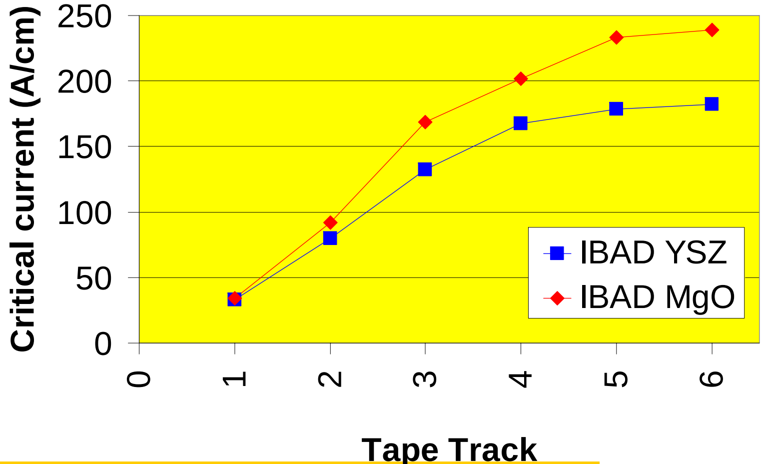


In-plane texture of LMO over 550 m produced at 40 m/h = 7.4º

6-fold increase in linear tape speed demonstrated with MOCVD

Helix tape handling with 6 tape tracks was added to our Pilot MOCVD system for higher line speeds. **Tapes processed with helix in a <u>single</u> pass at 30 m/h.**





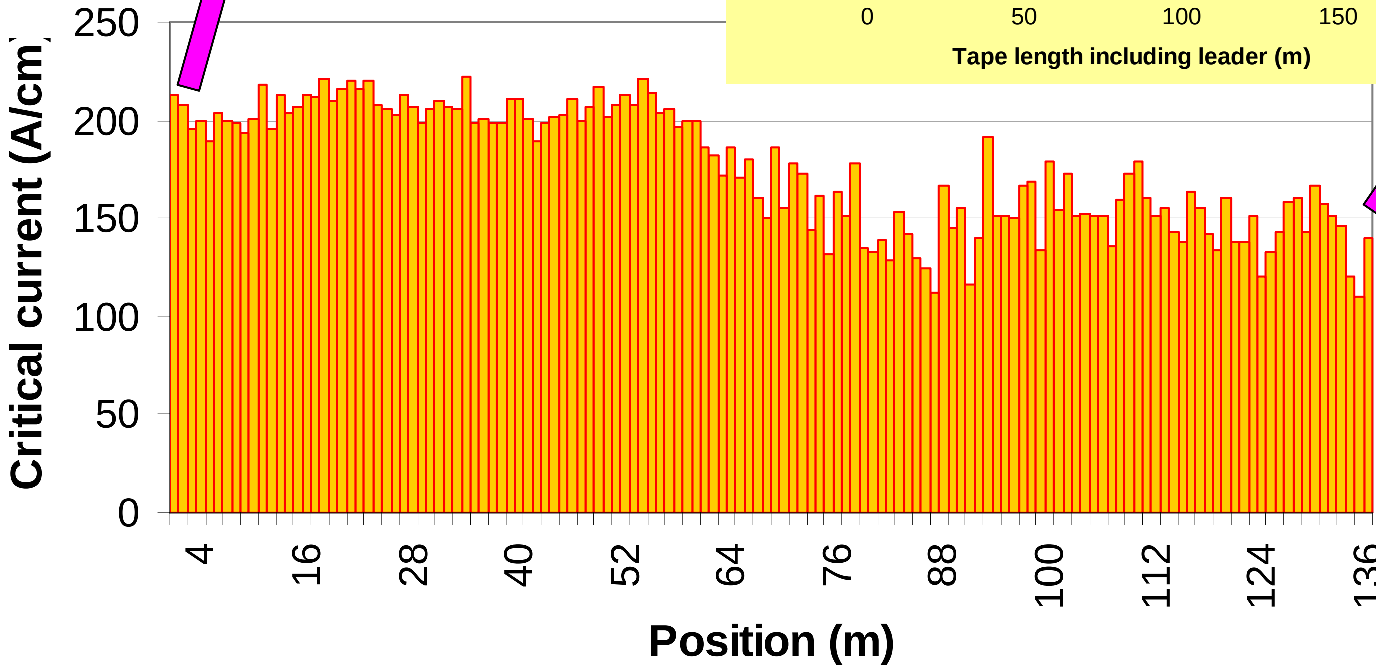
Ic ~ 250 A/cm achieved in 1.1 micron thick film at 30 m/h (single pass) by MOCVD on IBAD MgO buffers

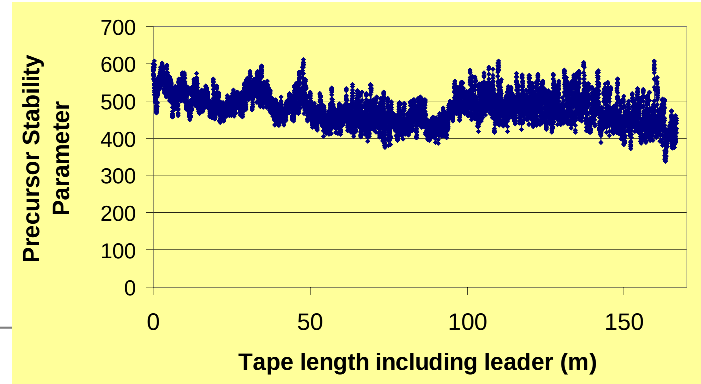
Began MOCVD processing 100+ m lengths at 30 m/h on IBAD MgO tapes: *Déjà vu all over again!*

YBCO film thickness | 0.93 µm

YBCO composition | Y+Sm 1.15, Ba 1.70, Cu 3.15

0.98 µm | Y+Sm 1.11, Ba 1.82, Cu 3.07

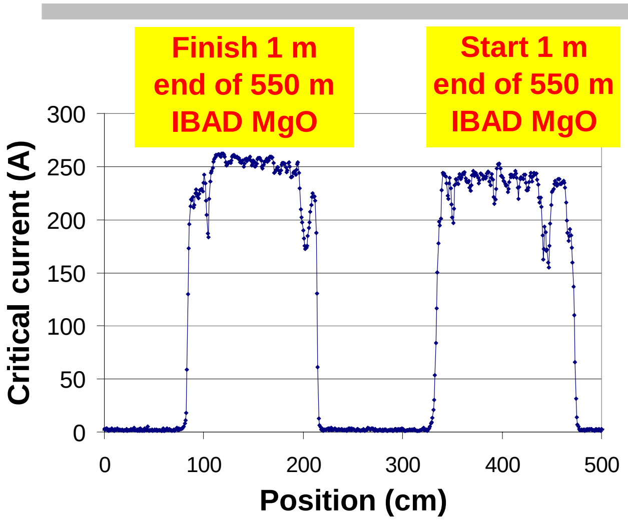


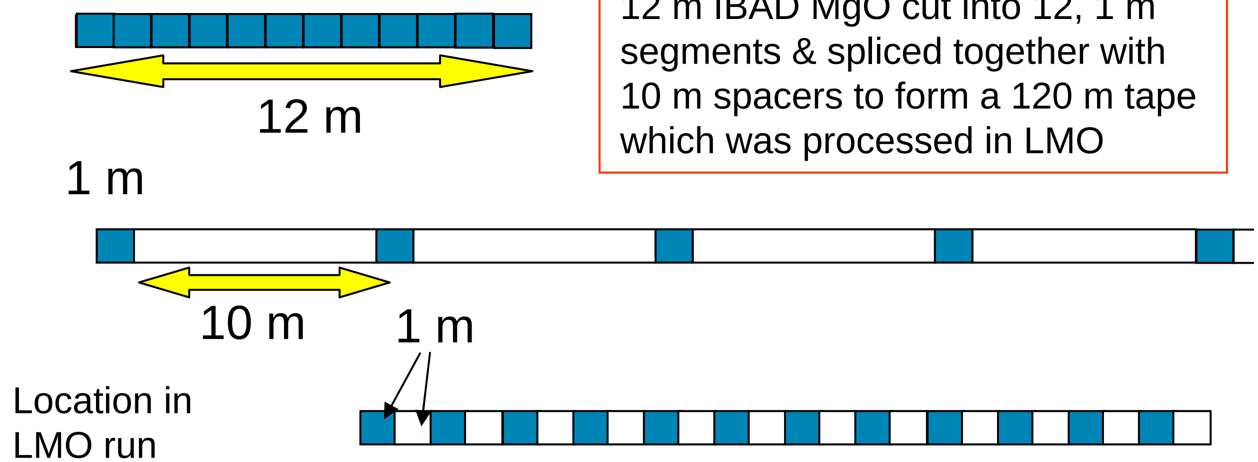


Film thickness & composition are not the reason for the drop in Ic after ~ 50 m

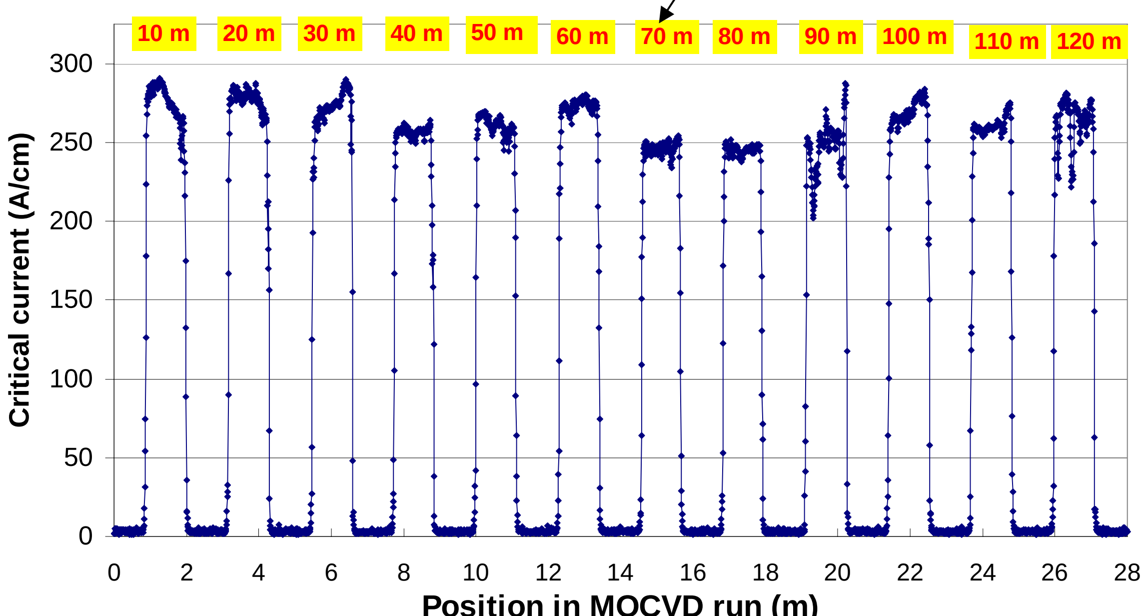
Precursor stability is not the reason for the drop either

Next, checked whether non uniformity in IBAD MgO or buffer quality could be reasons for the drop in Ic after 50 m





12 m IBAD MgO cut into 12, 1 m segments & spliced together with 10 m spacers to form a 120 m tape which was processed in LMO



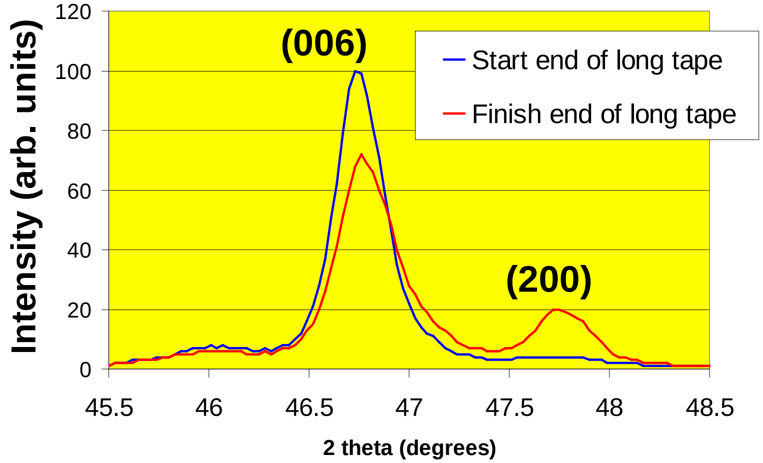
12 segments of 1 m LMO were then cut out and spliced together with 1 m spacers to form a 24 m long tape & processed in MOCVD

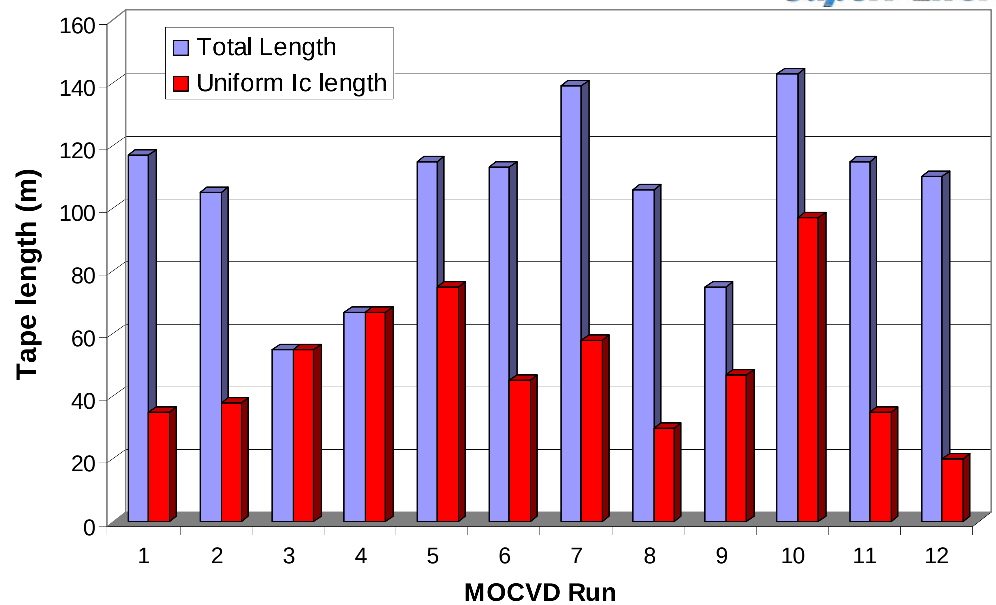
No uniformity problems with long IBAD MgO tapes

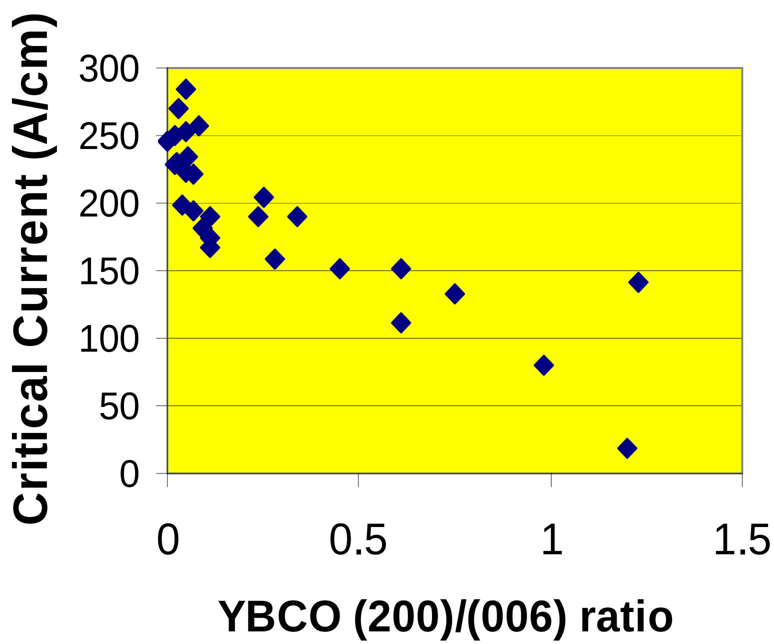
No uniformity problem with homo-epi MgO + LMO buffers

So, drop in Ic after 50 m should be an MOCVD problem !

Statistics from a series of 12 MOCVD runs provided a clear reason for the drop in Ic after ~ 50 m







Significantly higher (200)/(006) ratio at the end of long tape.

In a series of 12 MOCVD runs in lengths of 50 to 150 m, only the first 50 m on an average showed uniform Ic

XRD analysis on samples cut from the beginning and end of the long tapes showed a good correlation between the Ic and ratio of (200)/(006) peak intensities

Modification of MOCVD process based on XRD data yielded uniform Ic over 100 m

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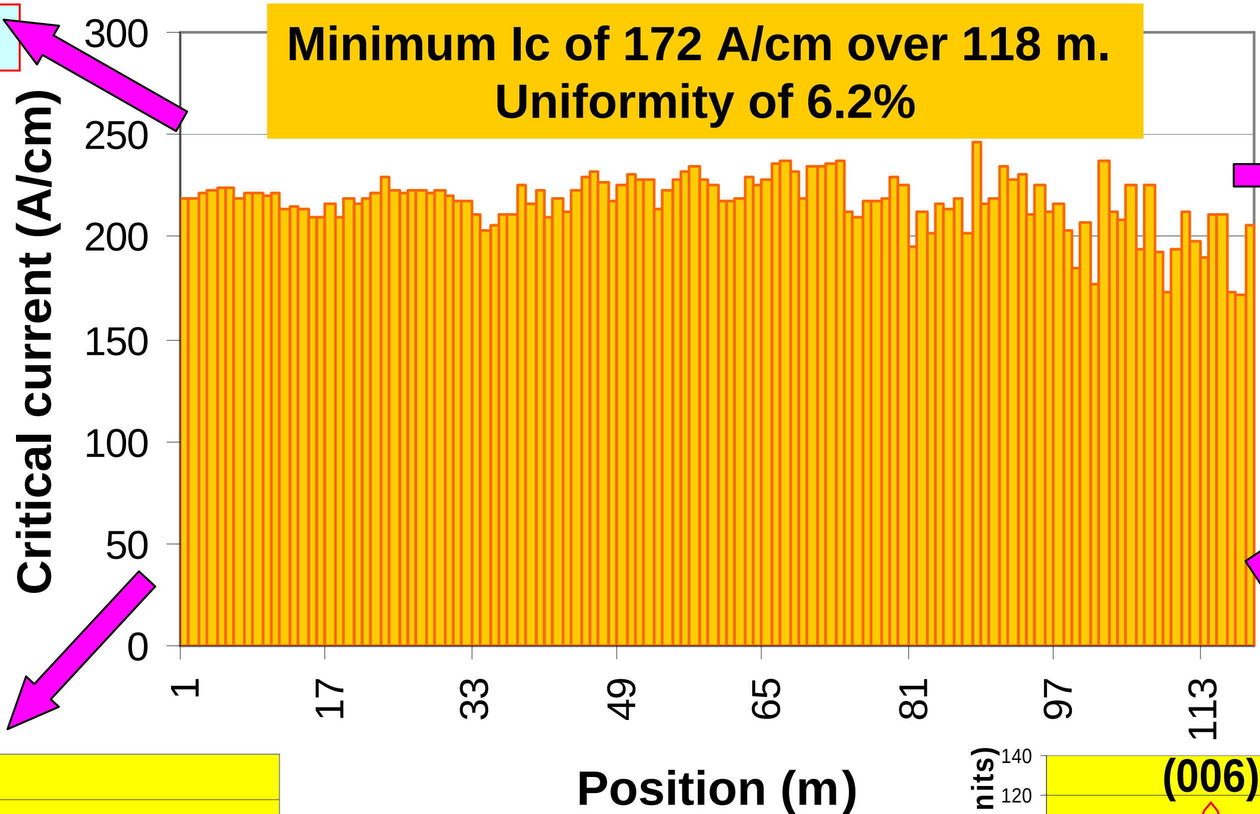
YBCO thickness

0.93 µm

composition

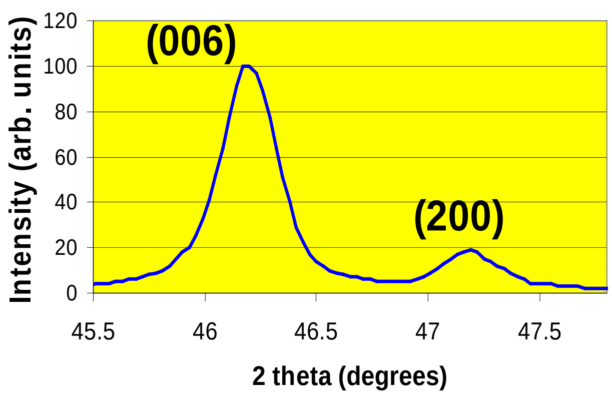
Y+Sm 1.16
Ba 1.72
Cu 3.13

Minimum Ic of 172 A/cm over 118 m.
Uniformity of 6.2%

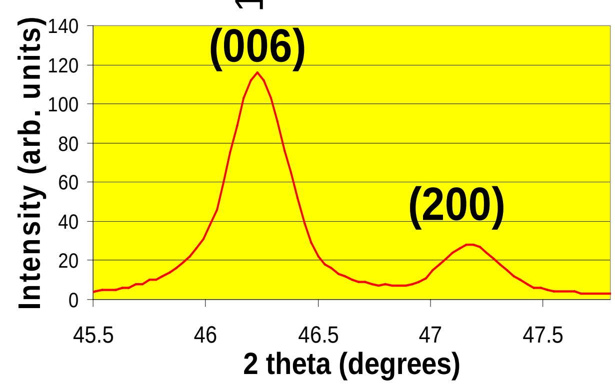


0.98 µm

Y+Sm 1.15
Ba 1.80
Cu 3.05



Similar (200)/(006) ratio, thickness & composition at 2 ends of long tape



Problem with drop in Ic recurred when MOCVD production length exceeded 100 m

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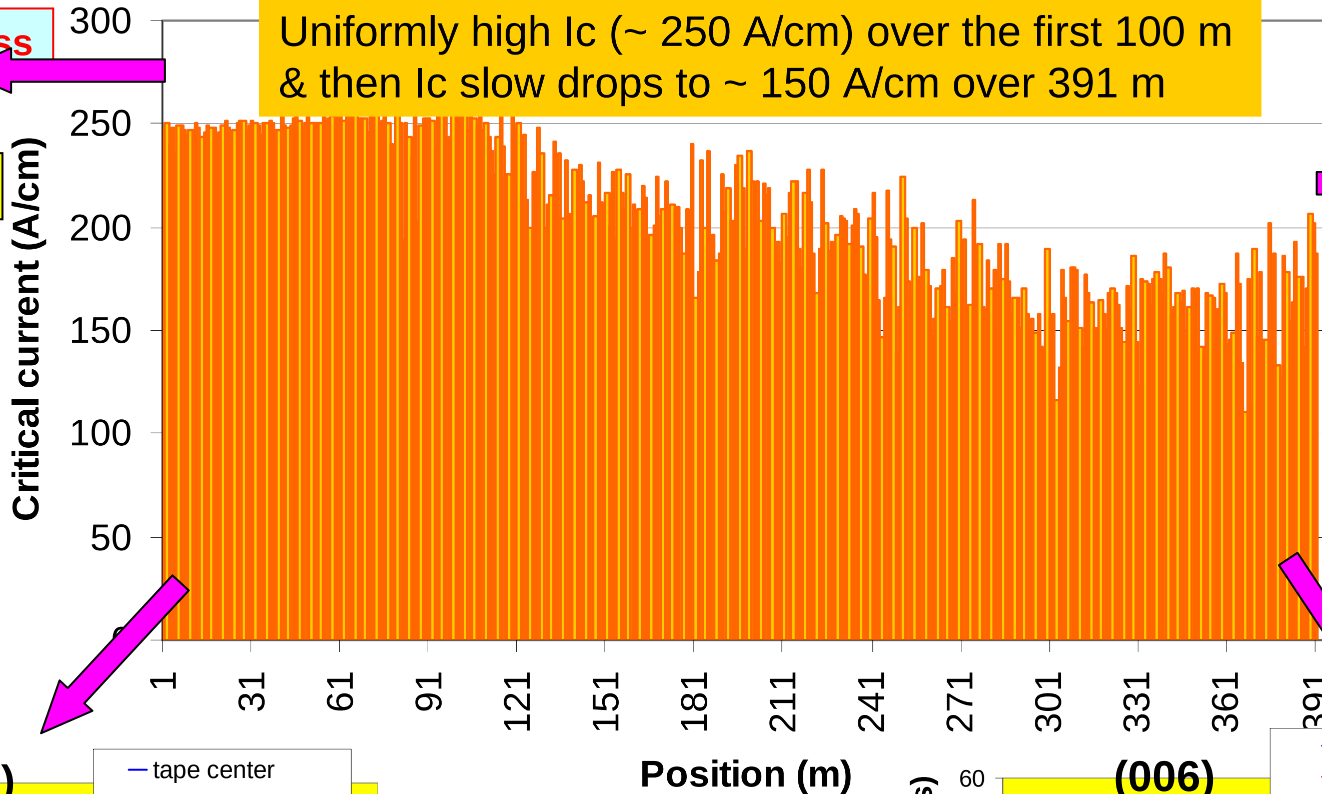
Uniformly high Ic (~ 250 A/cm) over the first 100 m & then Ic slow drops to ~ 150 A/cm over 391 m

YBCO thickness

1.0 μm

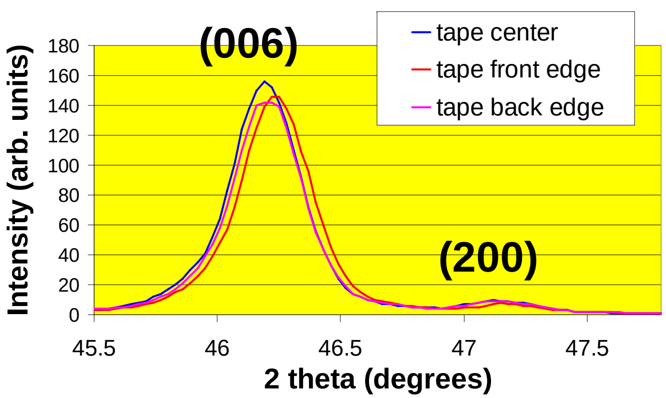
composition

Y+Sm 1.22
Ba 1.6
Cu 3.18

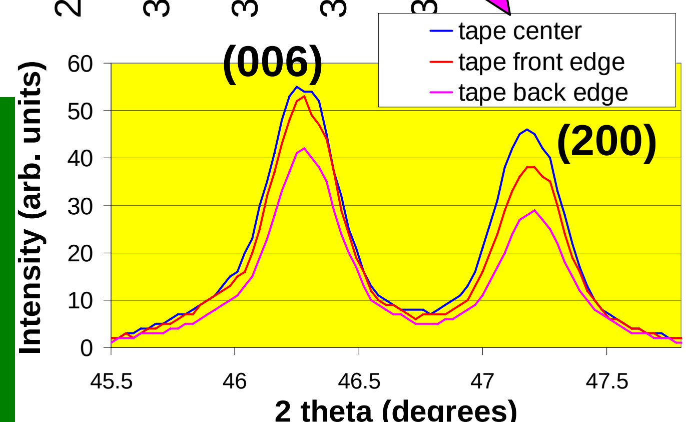


1.2 μm

Y+Sm 1.18
Ba 1.78
Cu 3.04



No significant differences in film thickness or composition at the 2 ends
But, substantially higher (200)/(006) peak ratio at finish end



Retuning of MOCVD process based on XRD data yielded high Ic over 300 m with excellent uniformity

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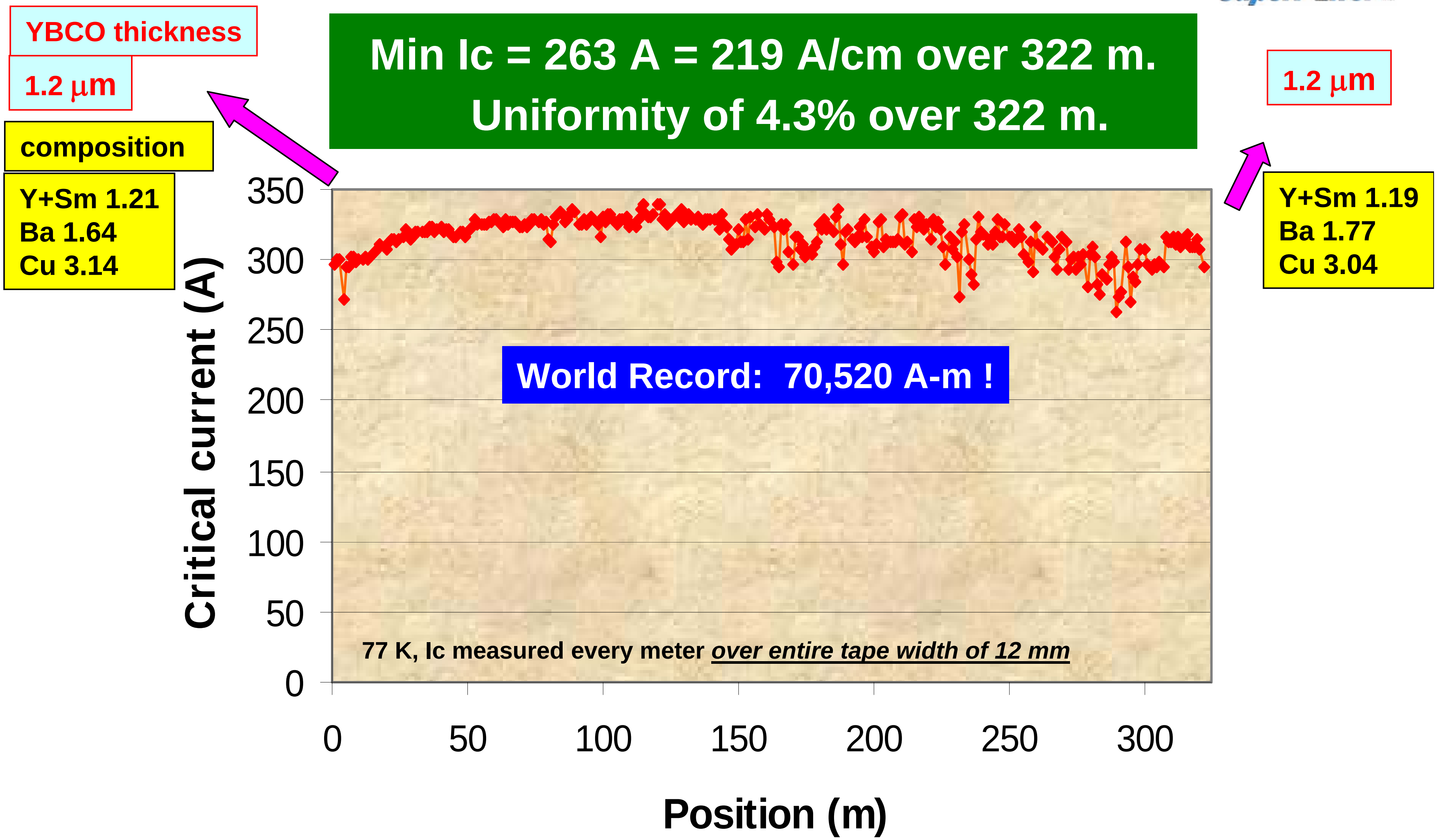
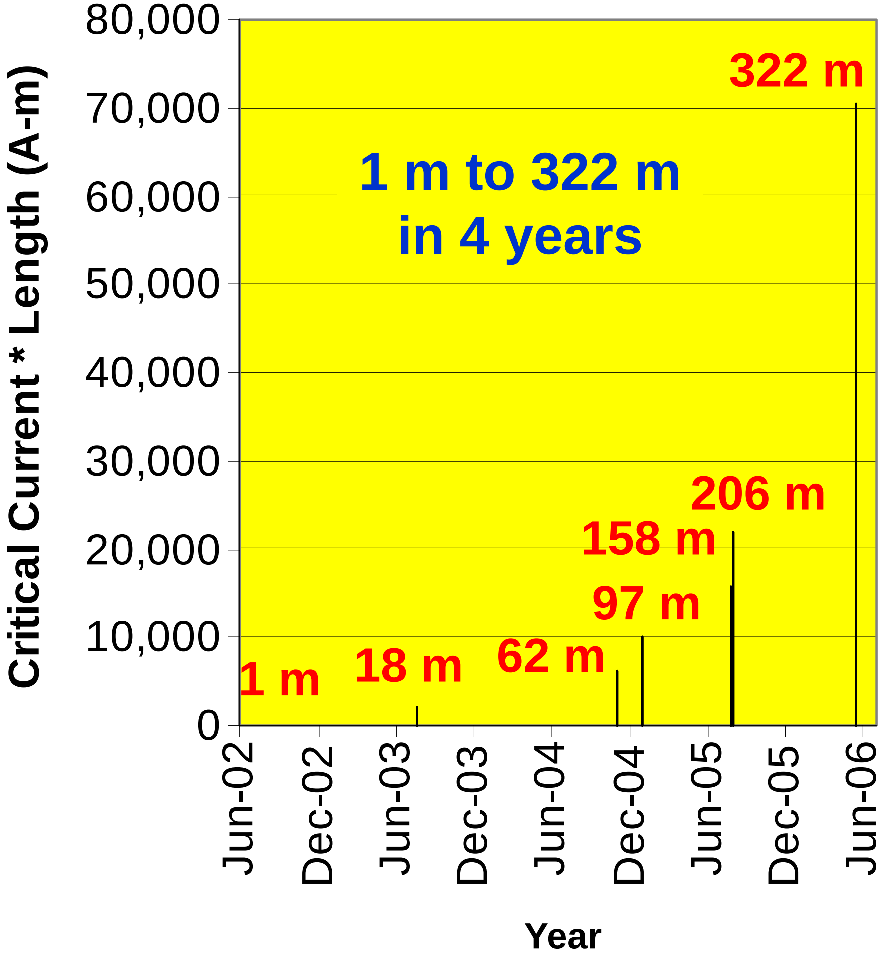
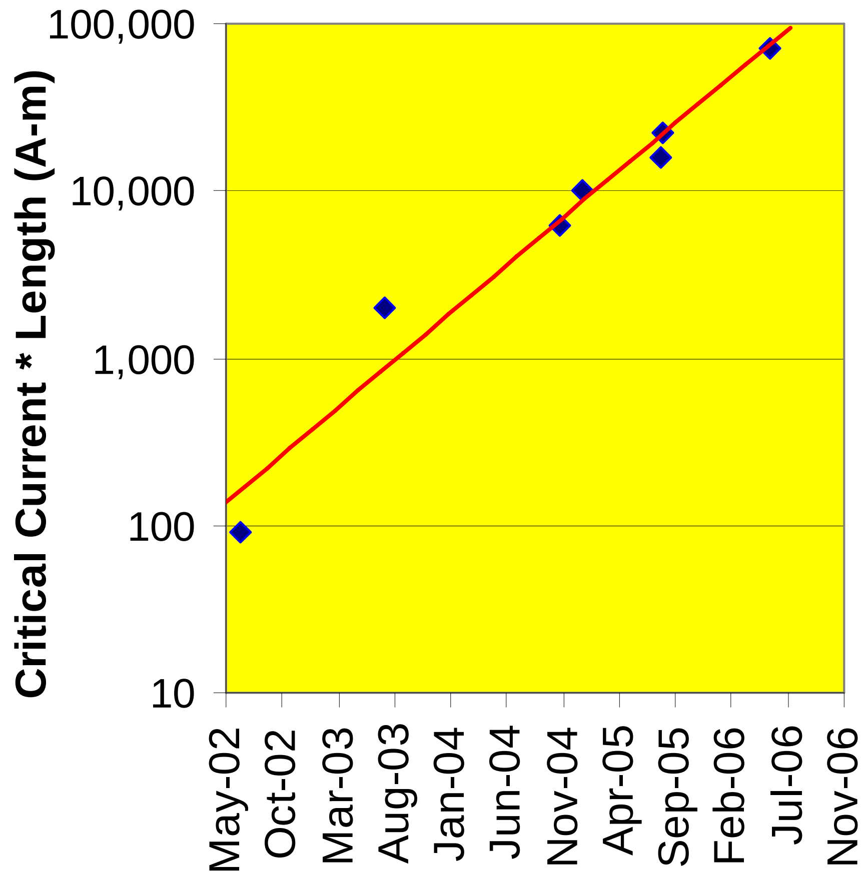
Min Ic = 263 A = 219 A/cm over 322 m.
Uniformity of 4.3% over 322 m.



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





2G conductor is now available in long lengths with Ic in the realm of 1G & Je about 2x better than 1G

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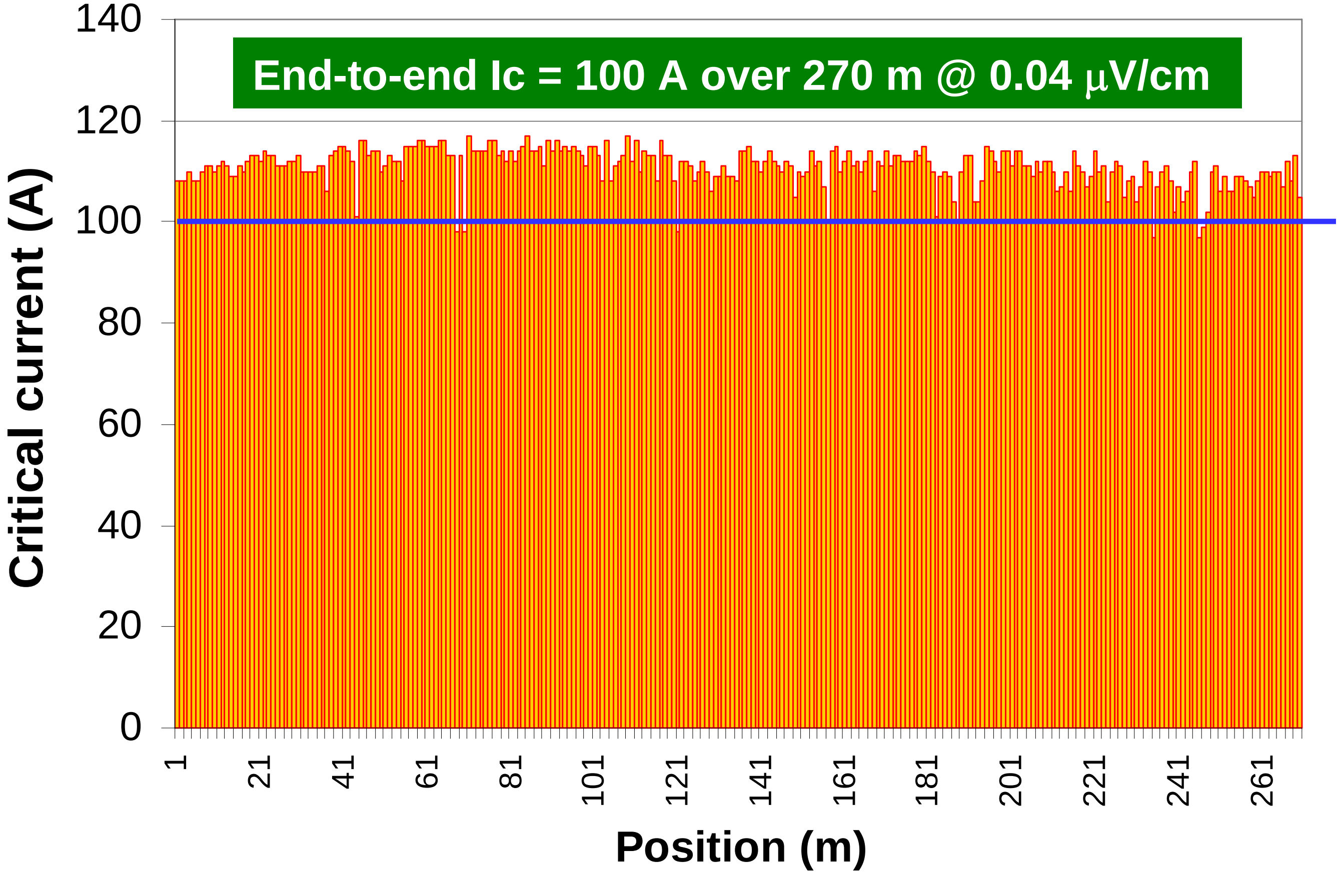
End-to-end critical current of 4 mm wide 2G conductor slit from 12 mm wide tape



Ic = 100 A in a 4 mm wide 2G conductor over 270 m!

Je = 26.3 kA/cm² (for a 20 micron surround stabilizer i.e. 40 micron total) compared to a **1G Je of 13 kA/cm² to 17 kA/cm²**