



# Testing of Single Phase Short Sample Cable Core Made with YBCO Conductors

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**Session # 4LW01**

*HTS Solutions for a New Dimension in Power*

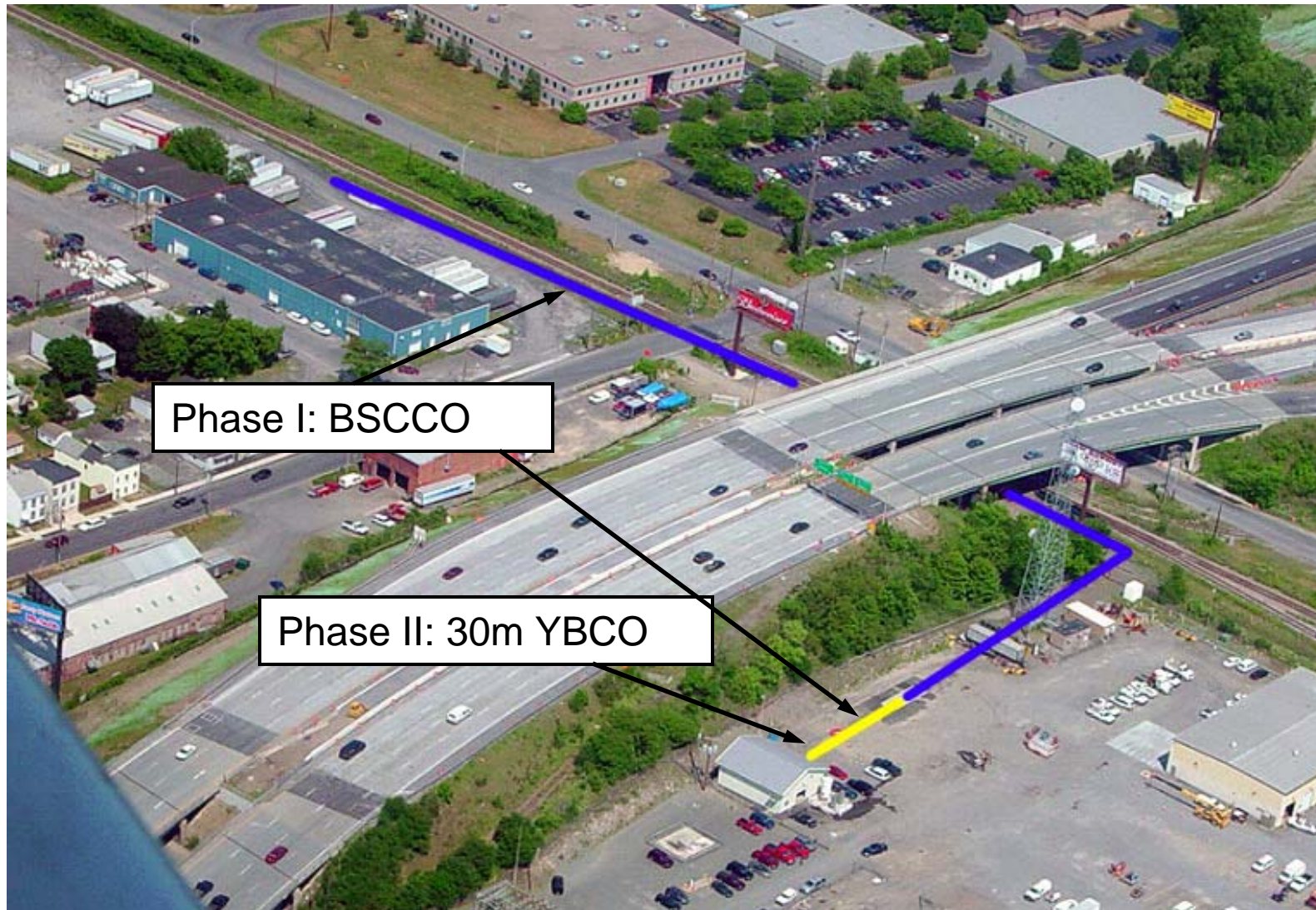
2006 Applied Superconductivity Conference — August 31, 2006

# Presentation Outline

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- **Process development of YBCO conductors for cable applications**
  - Width
  - Overcurrent Protection
  - Mechanical Properties
- **Testing of 1 $\Phi$  YBCO cable cores**
- **Benefits of thinner substrates**
- **Status of 10km wire delivery to SEI**

# Albany Cable Project Configuration



# Specifications for 2G Conductor



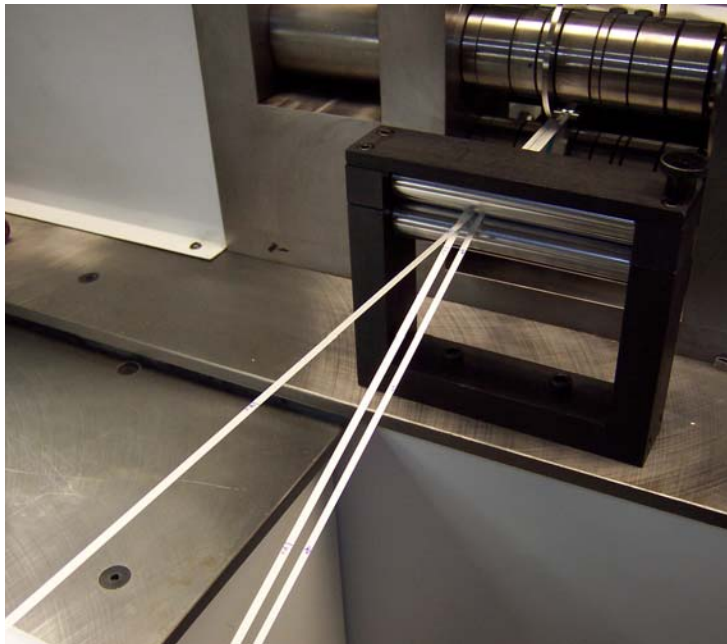
<b>Conductor Width</b>	4 mm
<b>Cable Former</b>	16 mm diameter
<b>Bend diameter</b>	100 mm
<b>Critical tensile stress</b>	150 MPa
<b>Hermetic test</b>	No $I_c$ & thickness change after 10 atm of $LN_2$ for 24 hours
<b>Spiral Winding</b>	95% $I_c$ retention after winding on 16 mm former with 130 mm pitch

Albany Cable is a very compact cable made with practical 4 mm wide conductor

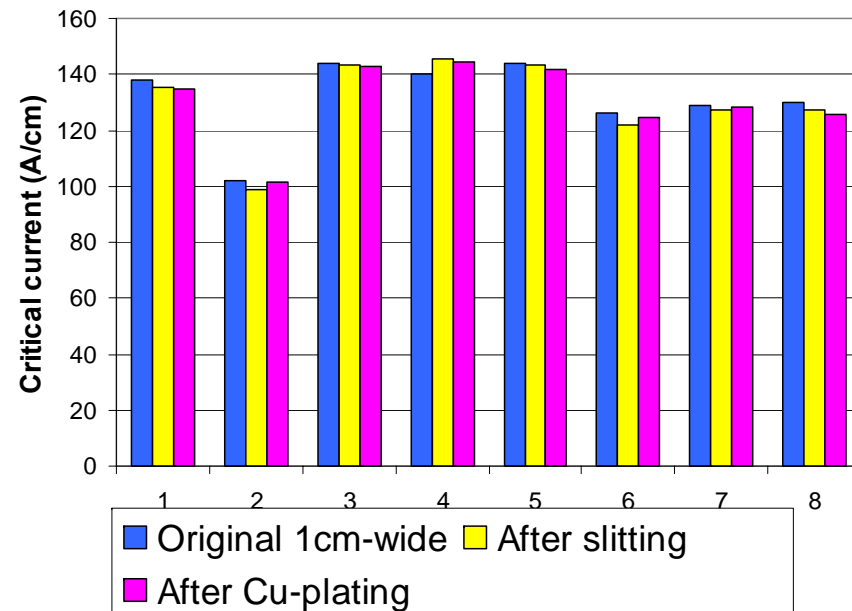
# Slitting to 4 mm width before copper stabilizer application



To use “Surround Stabilizer,” tapes have to be slit prior to copper plating i.e. directly on Ag overlayer.



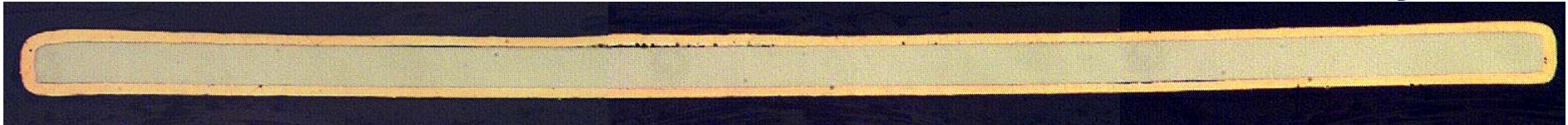
Two 4 mm wide tapes slit from a 1 cm wide, 8 m long tape.



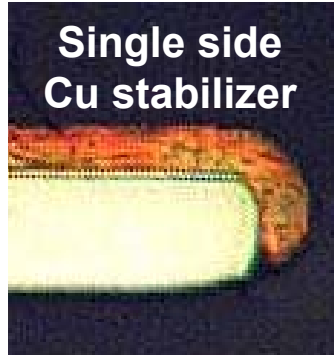
- Only 1% average reduction in  $I_c$  (sum of both 4 mm tapes) after slitting
- No degradation in  $I_c$  after electroplating copper stabilizer

Slitting directly on silver overlayer shows the robustness of our coated conductor and enables “Surround Cu Stabilizer” application

# Electroplating process demonstrated for copper stabilizer application on coated conductors



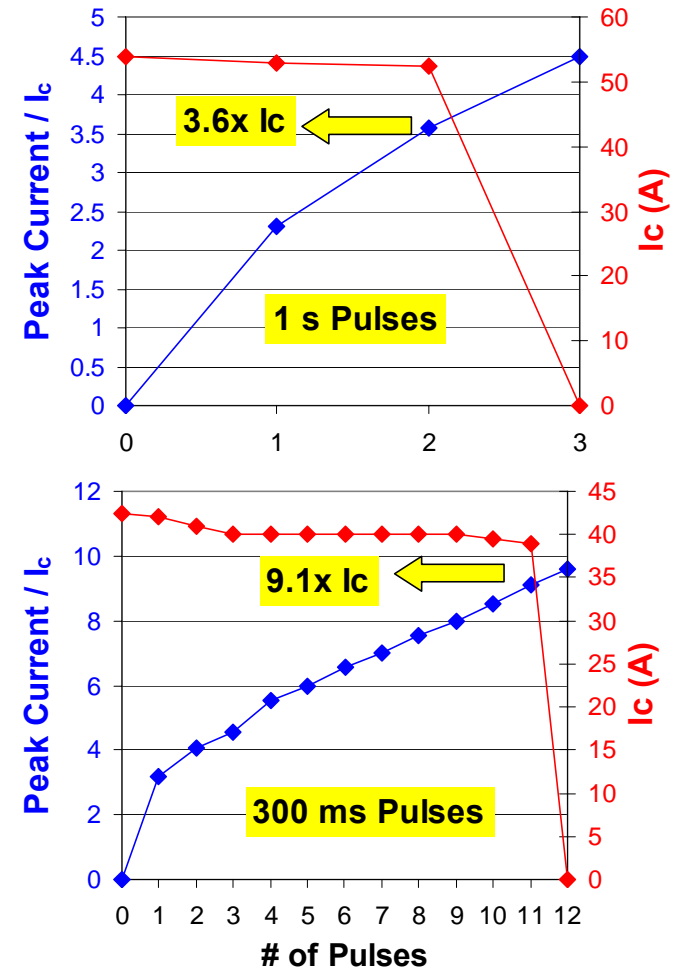
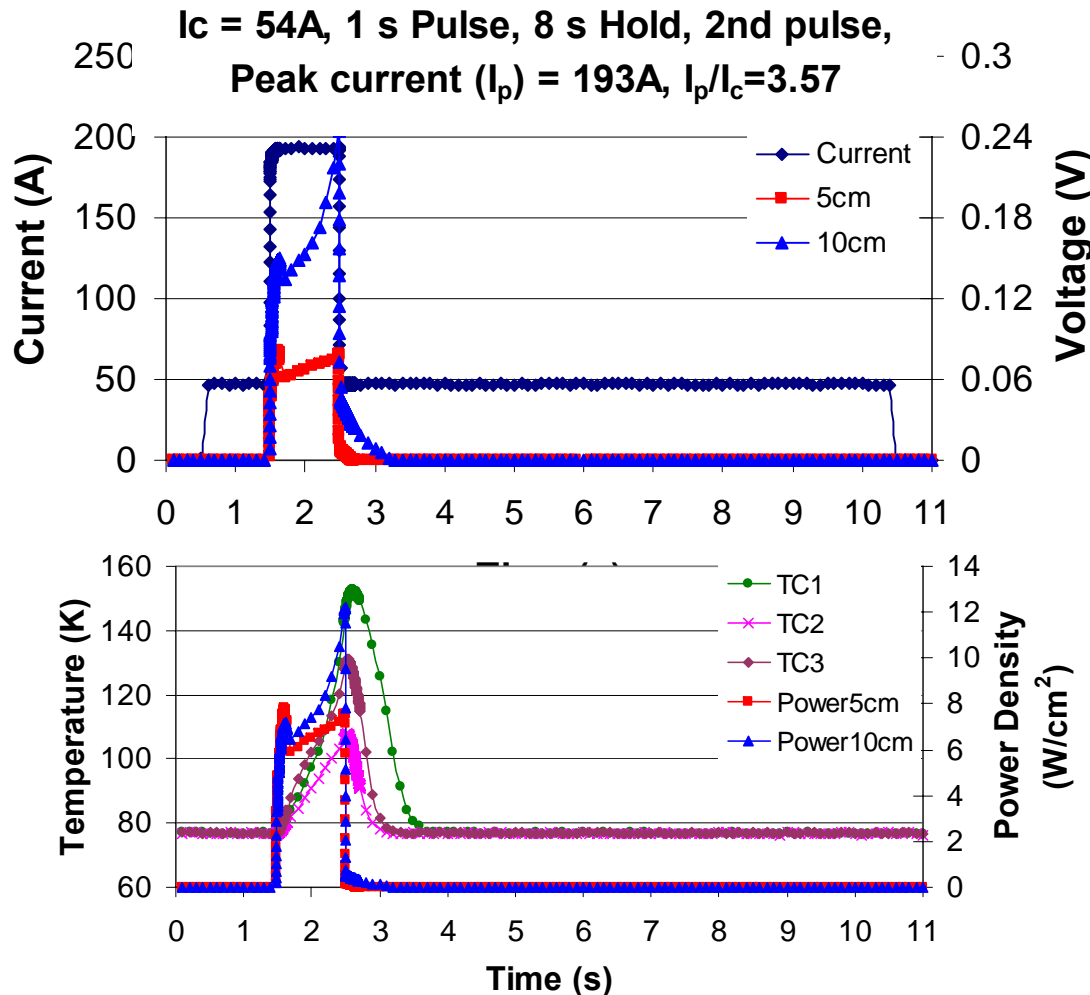
- An advantage of electroplating is “Surround Stabilizer” application i.e. copper on all sides in 1 step.
- HTS is completely encased and protected
- Rounded edges – could be important for high-voltage applications



	Current & Power required to burnout conductor	
Conductor Type	Conductor 1	Conductor 2
<b>Single side Cu (40 microns)</b>	233A – 18.6W/cm <sup>2</sup>	205A – 18.1W/cm <sup>2</sup>
<b>“Surround Stabilizer” Cu (20 microns all sides)</b>	279A – 33.3W/cm <sup>2</sup>	277A – 27W/cm <sup>2</sup>

**“Surround Copper Stabilizer” provides higher over current handling capability for coated conductors**

# Overcurrent handling capability of “surround stabilizer” structure verified with pulsed currents

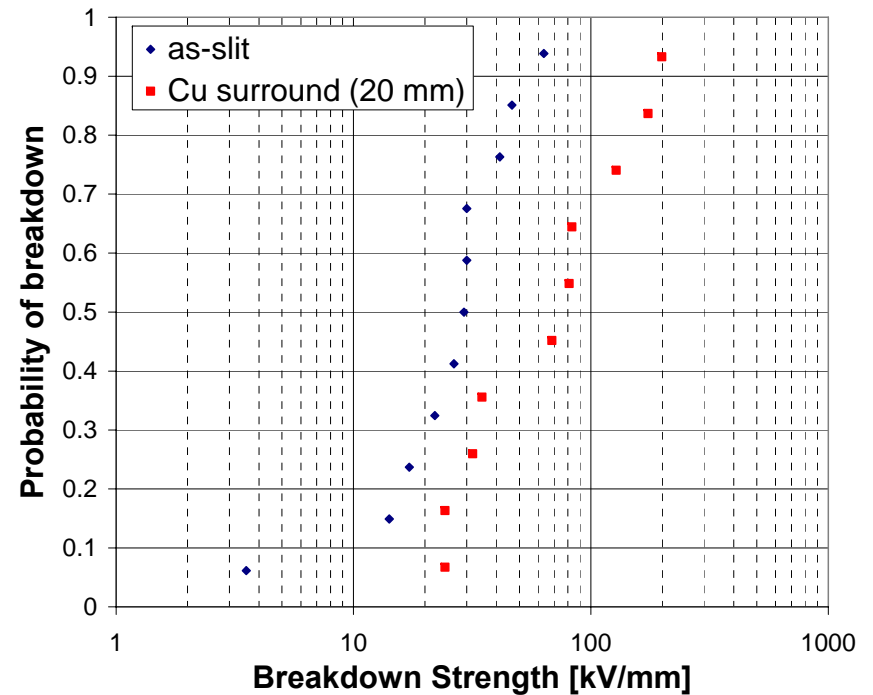
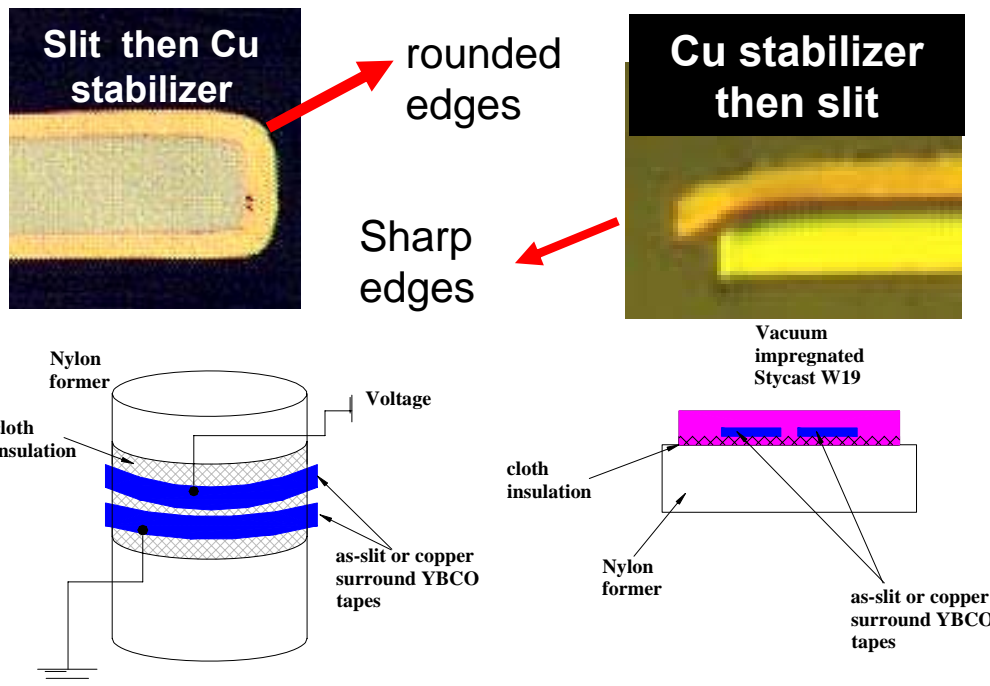


Minimal  $I_c$  degradation and no tape burn out even at overcurrent levels of 9 times  $I_c$  with 300 ms pulses and 3.5 times  $I_c$  with 1 s pulses

# Conductor with surround stabilizer has been found to exhibit superior dielectric strength

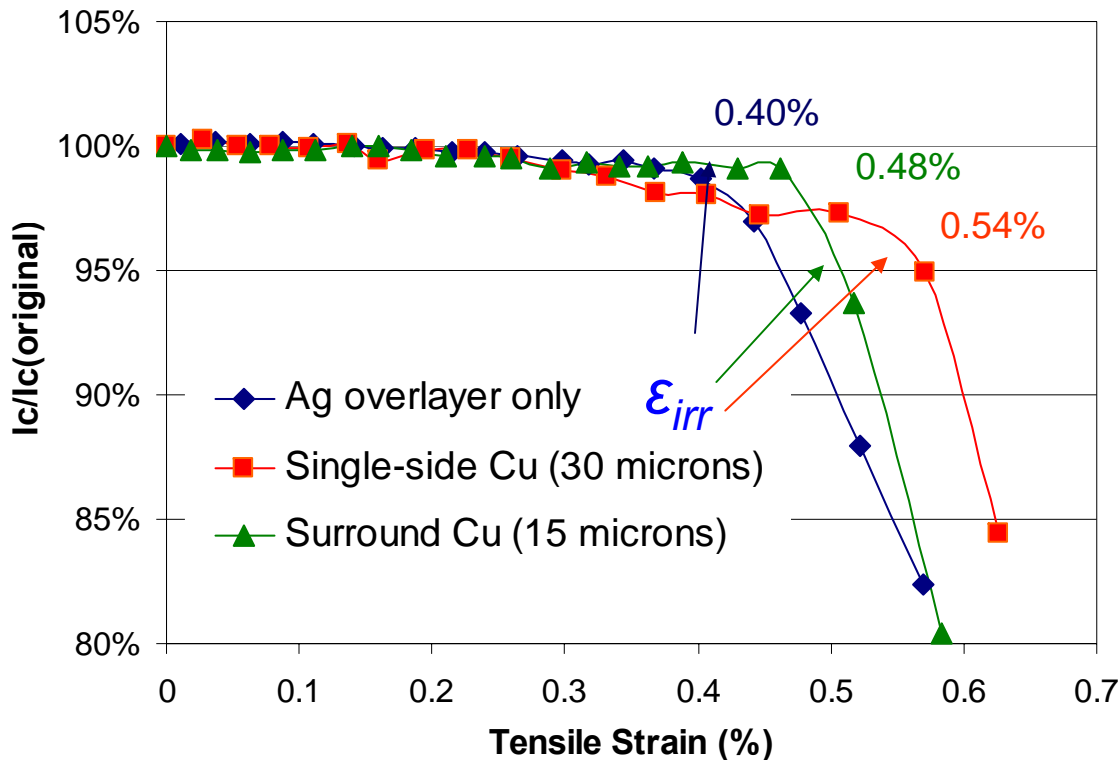


Testing compared the dielectric breakdown of the two types in a winding geometry.



Sample	As-slit	Slit & surround stabilizer
Average breakdown voltage	29.4 kV/mm	84.9 kV/mm
10% probability breakdown	10 kV/mm	19 kV/mm

# 4 mm wide, Cu stabilized conductor shows excellent irreversible axial strain and yield strength\*

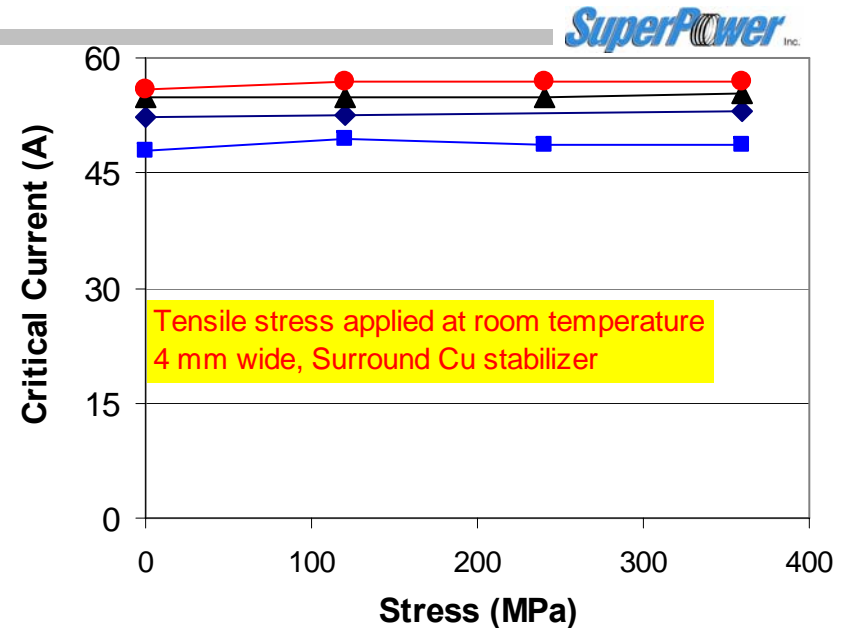
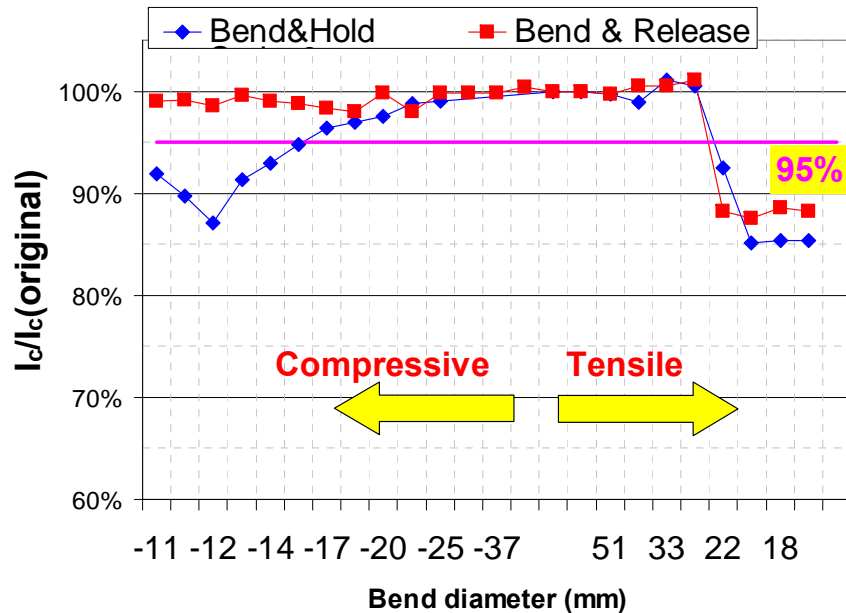


Wire design	Yield Stress (MPa) at 0.2%
Bare Metal Sub.	455 (295K) 690 (76K)
2G w/ Ag overlayer only	693 (76K)
2G w/ surround Cu 15 μm)	454 (295K) 640 (76K)

Axial-strain performance of the prototype practical conductor “comfortably meet the most severe benchmarks for applications” – NIST.

Yield strength is much higher than that of other 2G conductors

# 4 mm wide, Cu stabilized conductor shows superior bend & tensile properties

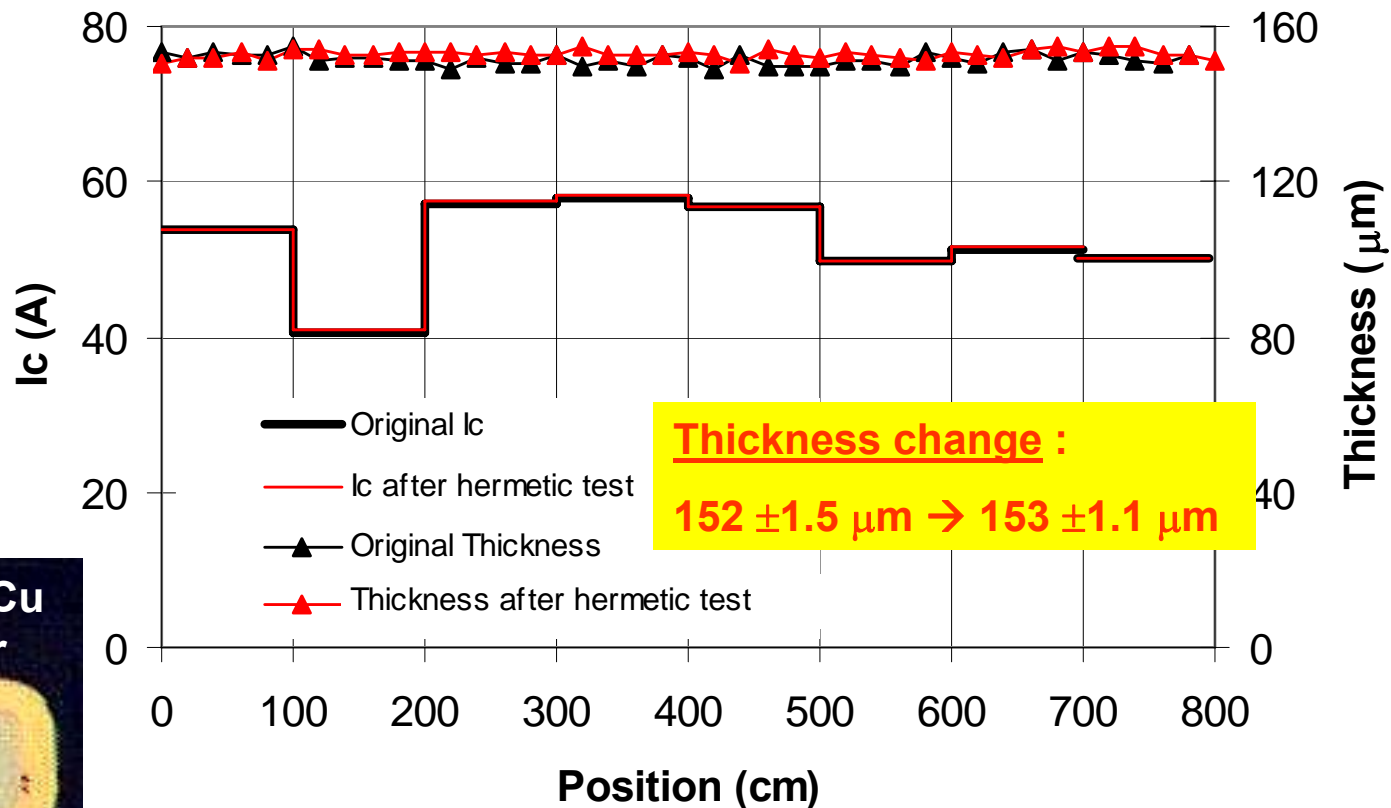


95 %  $I_c$  retention when bent :  
**Tension** - **25 mm diameter** both Bend & Hold and Bend & Release  
**Compression** –  
**< 11 mm diameter** - Bend & Release  
**~16 mm diameter** - Bend and Hold

Critical Tensile Stress of IBAD-based conductor > **350 MPa**  
 Critical Tensile Stress of 1-G conductor = **150 MPa**

**Nickel superalloy (IBAD)-based conductors are > twice as more robust than 1G**

# 4 mm wide, Cu stabilized conductor readily passes hermetic test with no change in $I_c$ or thickness



**“Surround Stabilizer” conductor structure completely encapsulates HTS & protects it from environment**

## Deliveries of slit & surround stabilized 2G conductor being made for the Albany Cable Project



June 2004: 61 m, 4 mm wide, surround copper stabilized, 100 micron substrates (IBAD YSZ), average  $I_c = 122 \text{ A/cm}$  delivered to SEI

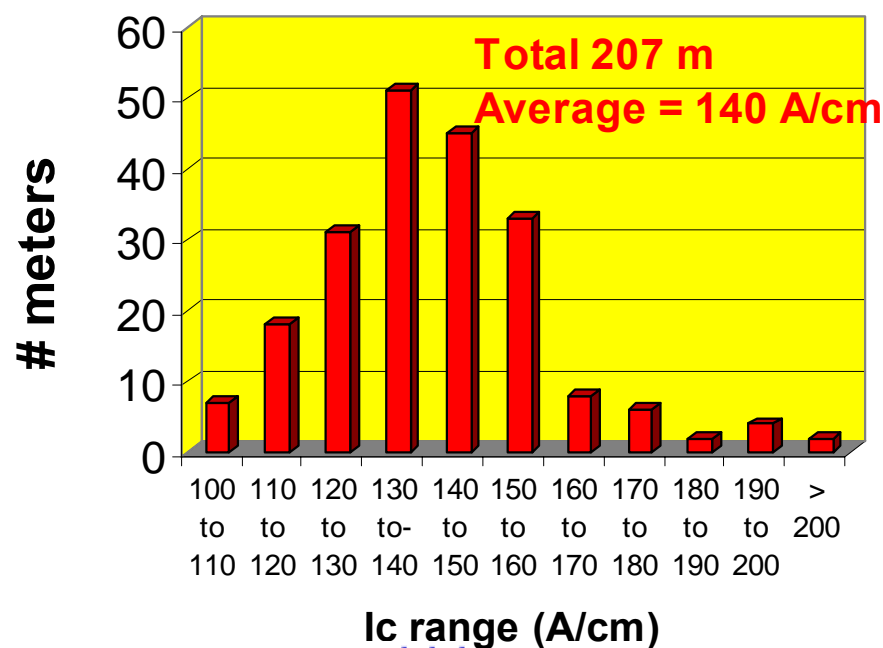
*First 2G cable with 4 mm conductor demonstrated*

1 m, 2150 A cable, ac losses 5 times less than previously made 2G cable

Cable core diameter is 16 mm – smallest demonstrated

March 2005: 113 m, 4 mm wide, 100 micron substrates (IBAD YSZ), average  $I_c = 160 \text{ A/cm}$ , delivered to SEI

July 2005: 207 m, 4 mm wide, 50 micron substrates (IBAD MgO), average  $I_c = 140 \text{ A/cm}$  (spec was 100 A/cm) shipped to SEI

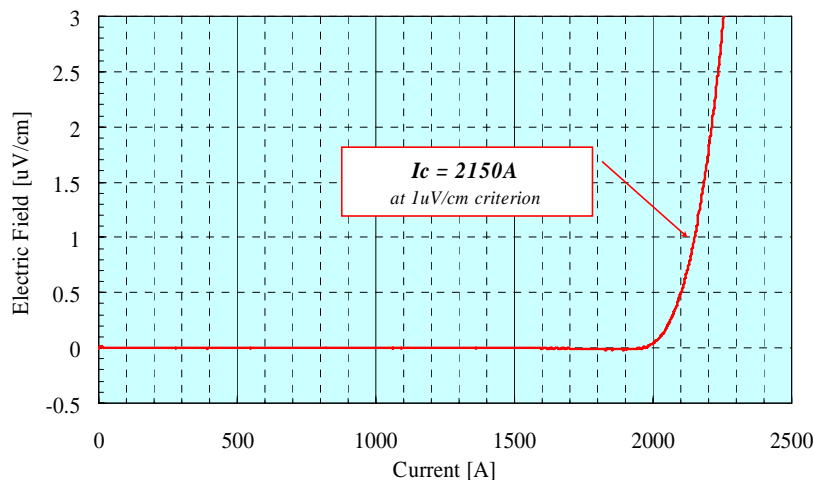


SEI Sumitomo Electric

# 1<sup>st</sup> 1-m 2G cable fabricated: Shows robustness of 4 mm 2G conductor



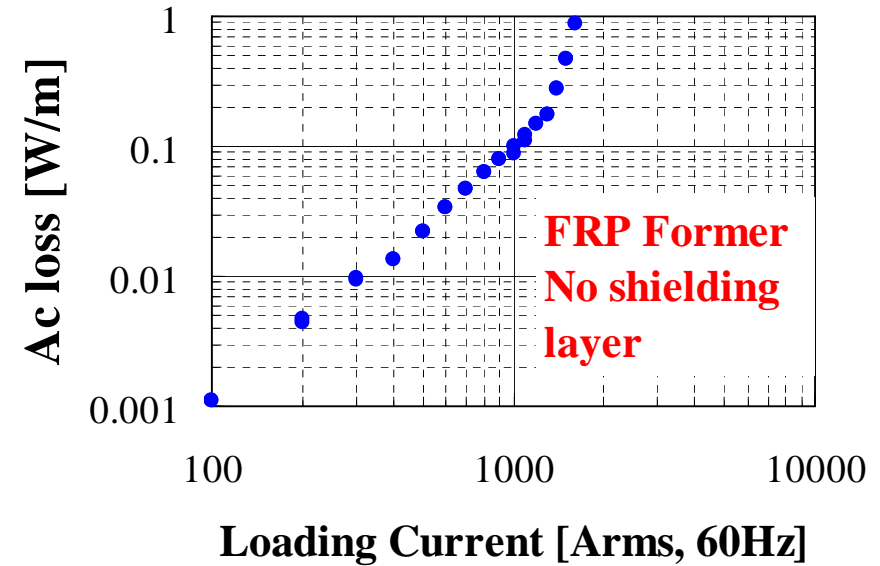
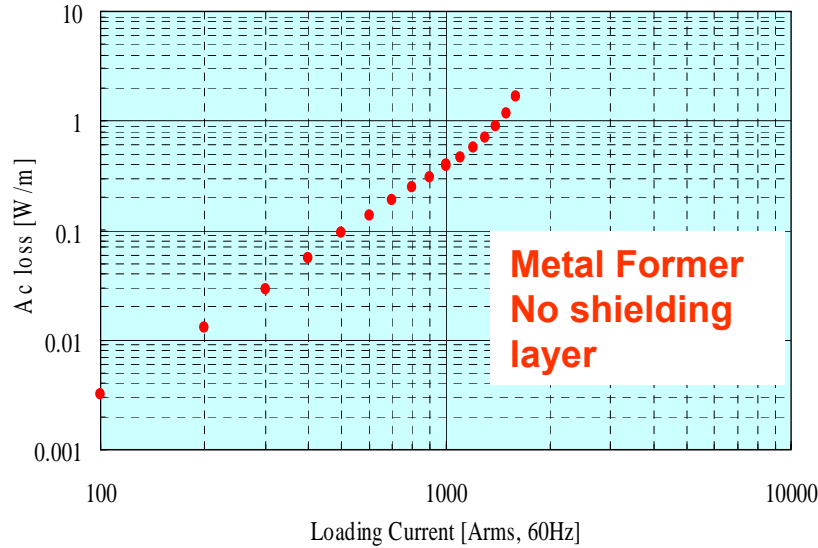
- 61 m of fully processed conductor i.e. slit to 4 mm width and plated with copper “Surround Stabilizer” shipped to SEI. Av. Ic of all tapes = 122 A/cm.



Total # tapes ea. 1.2 m	48
Average $I_c$ of tapes	50.4 A
Average $I_c \times \#$ tapes	2421 A
Estimated $I_c$ of cable (accounting for field)	2140 A
<b>Measured <math>I_c</math> of cable</b>	<b>2150 A</b>

No degradation in  $I_c$  of cable even though the HTS layers were spiral wound in tension with a small diameter former (16 mm)

# First demonstration of a 2G cable with acceptable ac losses for practical HTS applications

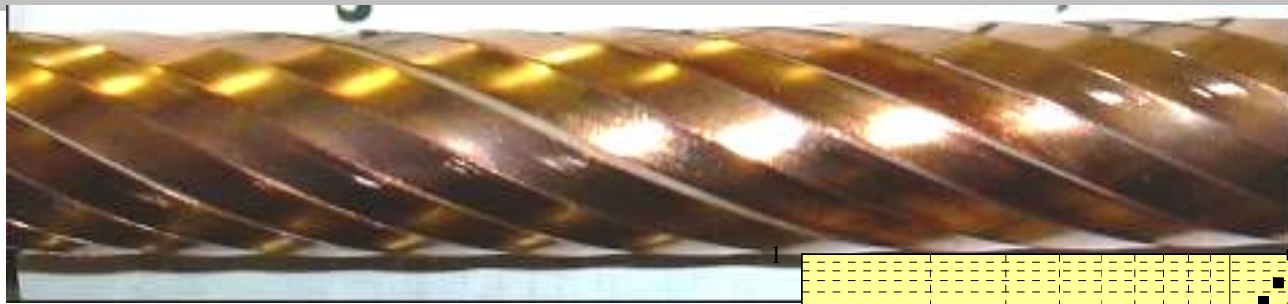


	Albany Cable SuperPower/SEI	AMSC-Southwire Cable* AMSC/Southwire/ORNL
AC loss @ $I_{peak}/I_c = 0.67$	<b>0.1 W/m – FRP former</b> <b>0.4 W/m – Metal former</b>	2 W/m <small>(*AMSC presentation DOE Peer review 2003)</small>

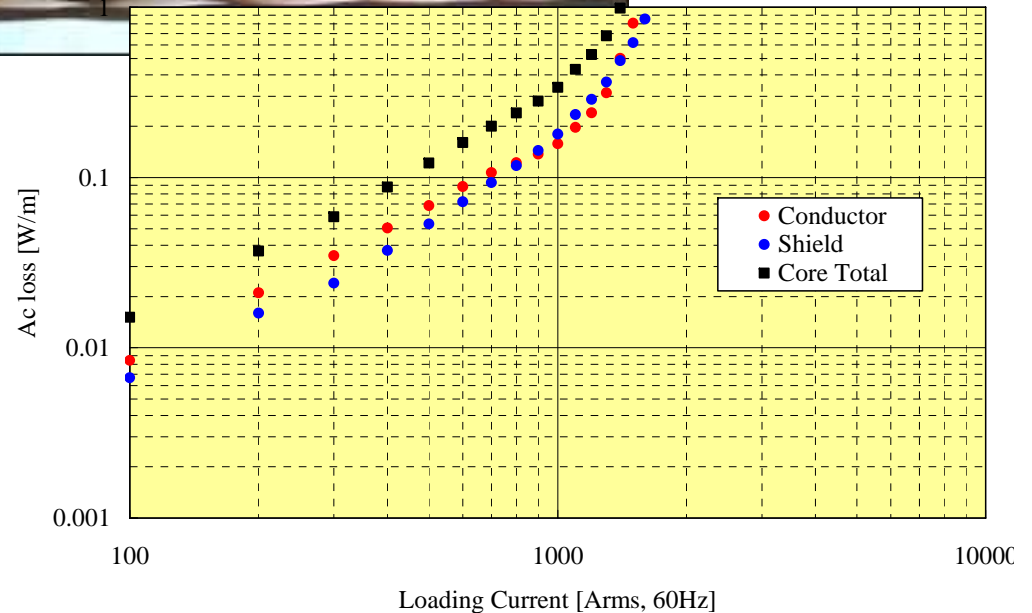
**AC losses of new 2G cable is 5 - 20 times less than that of 2G cable previously demonstrated**

## 2nd 1-m 2G cable built in 2005 with complete structure including shielding layers using new conductor

SuperPower Inc.



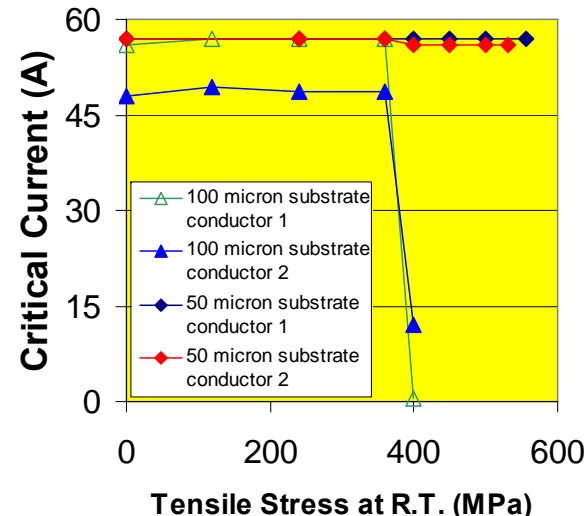
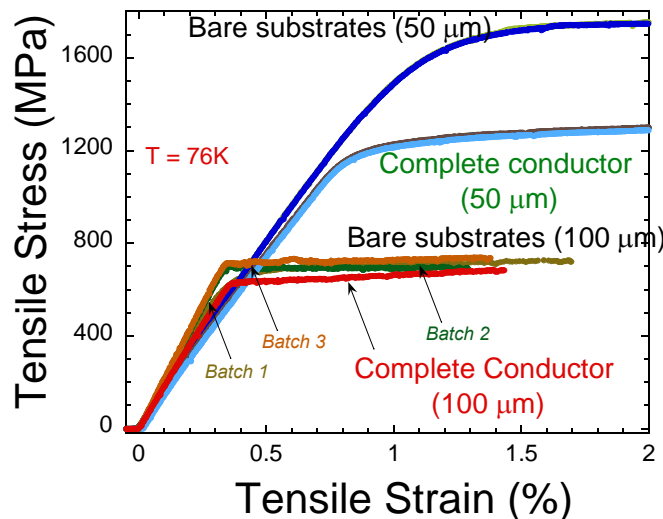
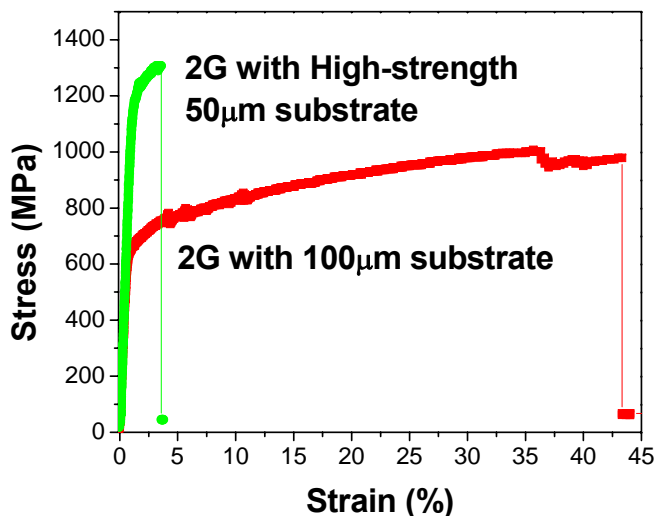
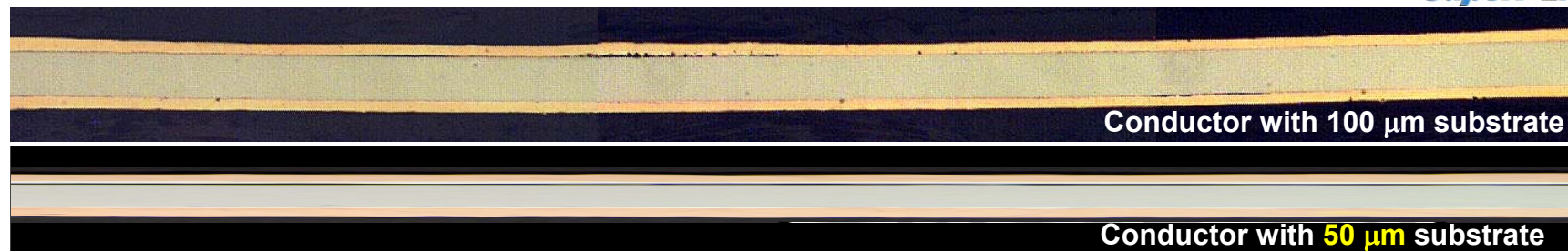
Cable features	FY04	FY05
# conductor layers	4	4
# shield layers	0	2
Total # 2G tapes used	48	88
Cable $I_c$ (A)	2150	2350 (c) 2240 (s)
AC loss in conductor + core (W/kA-m)	0.4	0.16



AC losses in conductor + core is 2.5 times less in the new 2G cable with a complete structure (shield layers)

## **Benefits from switching to thinner substrate and status of the final wire delivery**

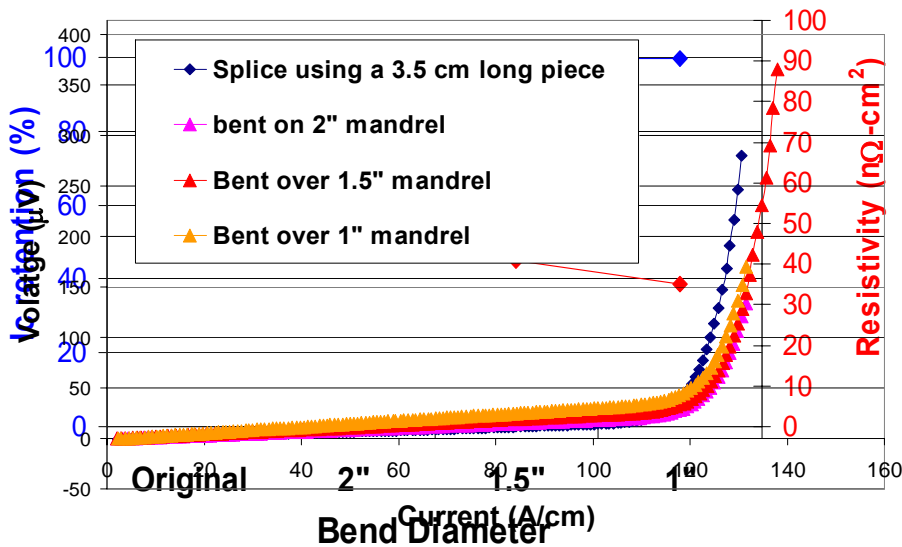
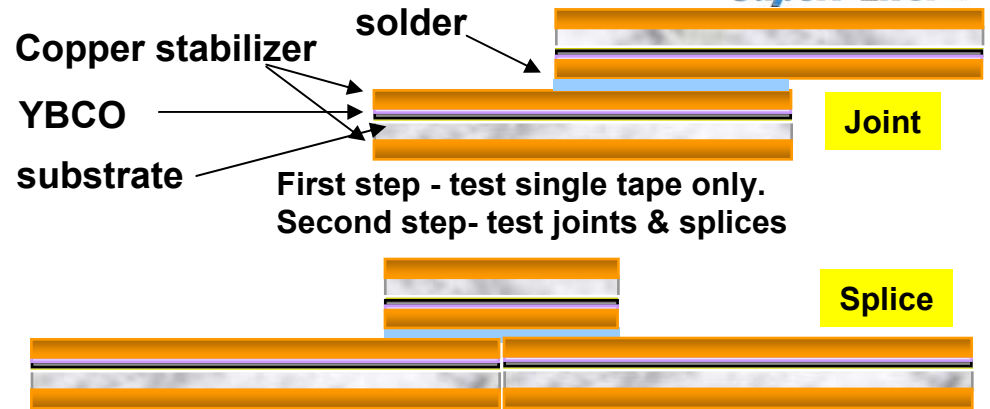
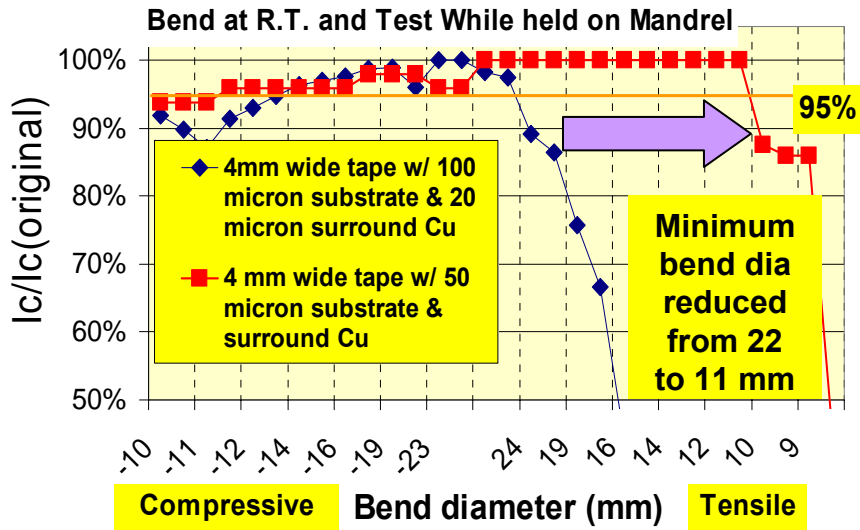
# Use of high-strength 50 micron substrates yielded thin-profile 2G conductors with much higher tensile strain & critical tensile stress



2G conductor made with	Yield strength at 77 K*
100 micron substrate	650 MPa
High-strength 50 micron substrate	1200 MPa



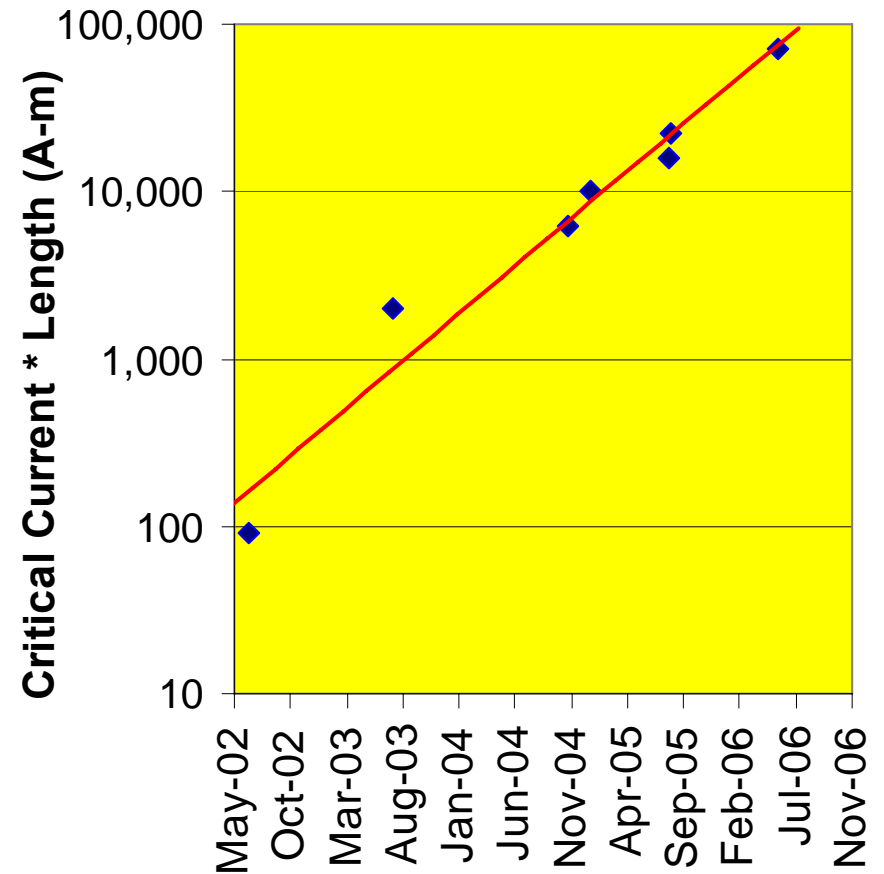
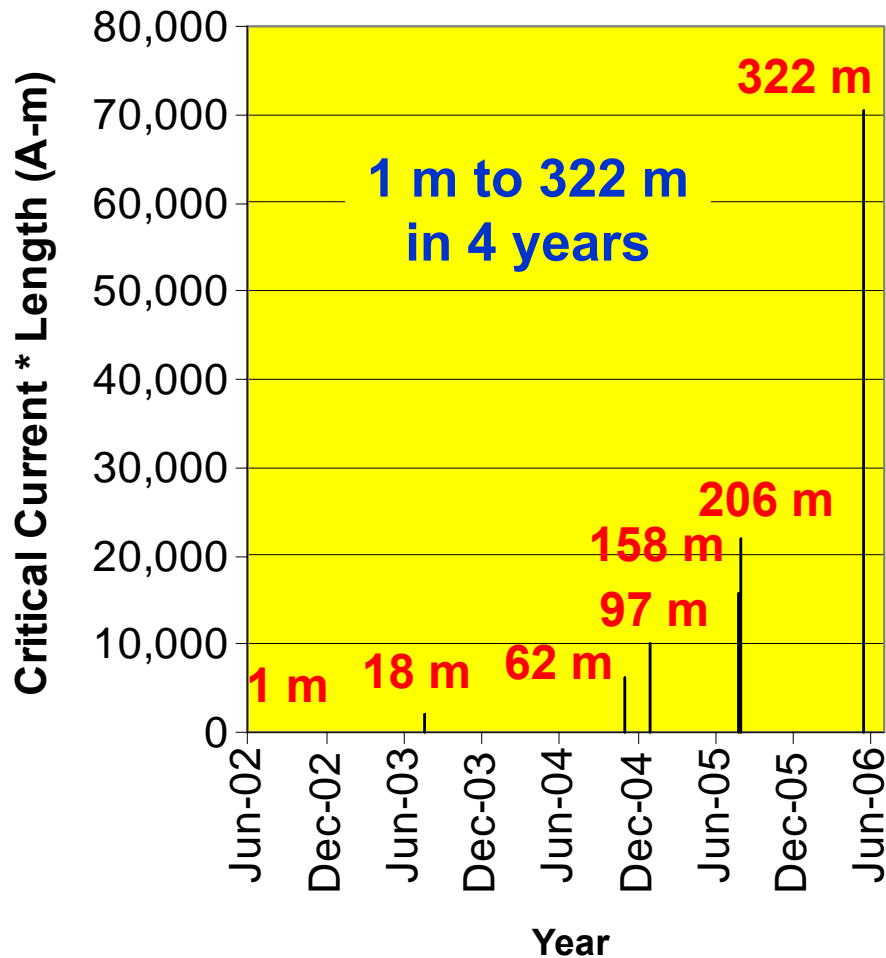
# Superior bend properties in joints & splices made with thin-profile conductors with 50 micron substrates



4 mm wide conductors each with 20  $\mu\text{m}$  surround copper stabilizer  
 Joint or splice length = 3 or 3.5 cm  
 Original tape thickness = 0.095 mm  
 Thickness at joint or splice = **0.22 mm (~ 2 times thinner that that with 1G or other 2G !)**

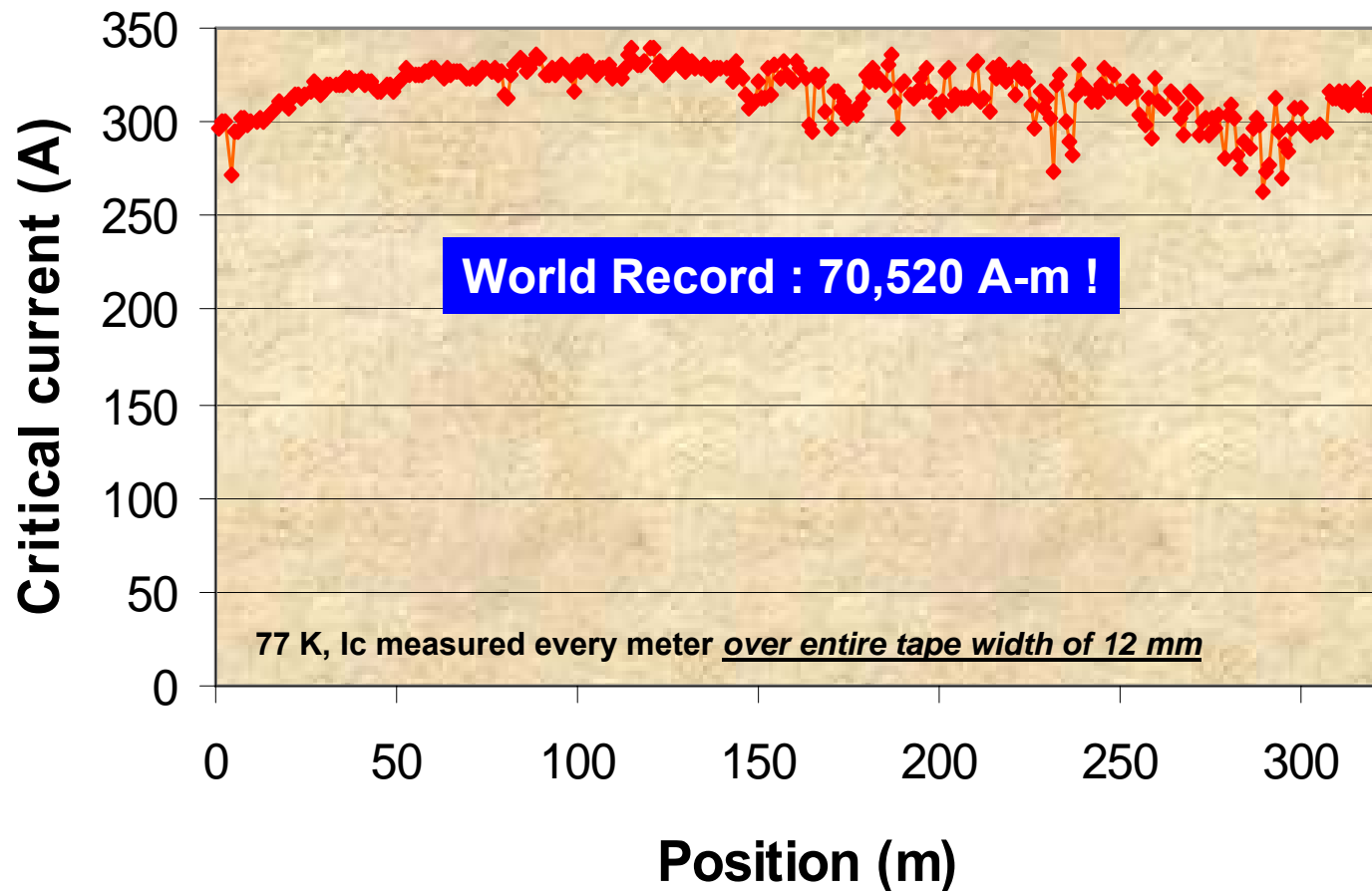
No degradation in Ic (1  $\mu\text{V}/\text{cm}$ ) over the joint or splice  
 Joint or splice resistivity = 40 to 50  $\text{n}\Omega\text{cm}^2$   
 No degradation in Ic and resistivity when **joint or splice is bent even down to 1" diameter and thermal cycled three times**. Ic was tested at every thermal cycle

# Significant progress in 2G scale-up in the last 4 years

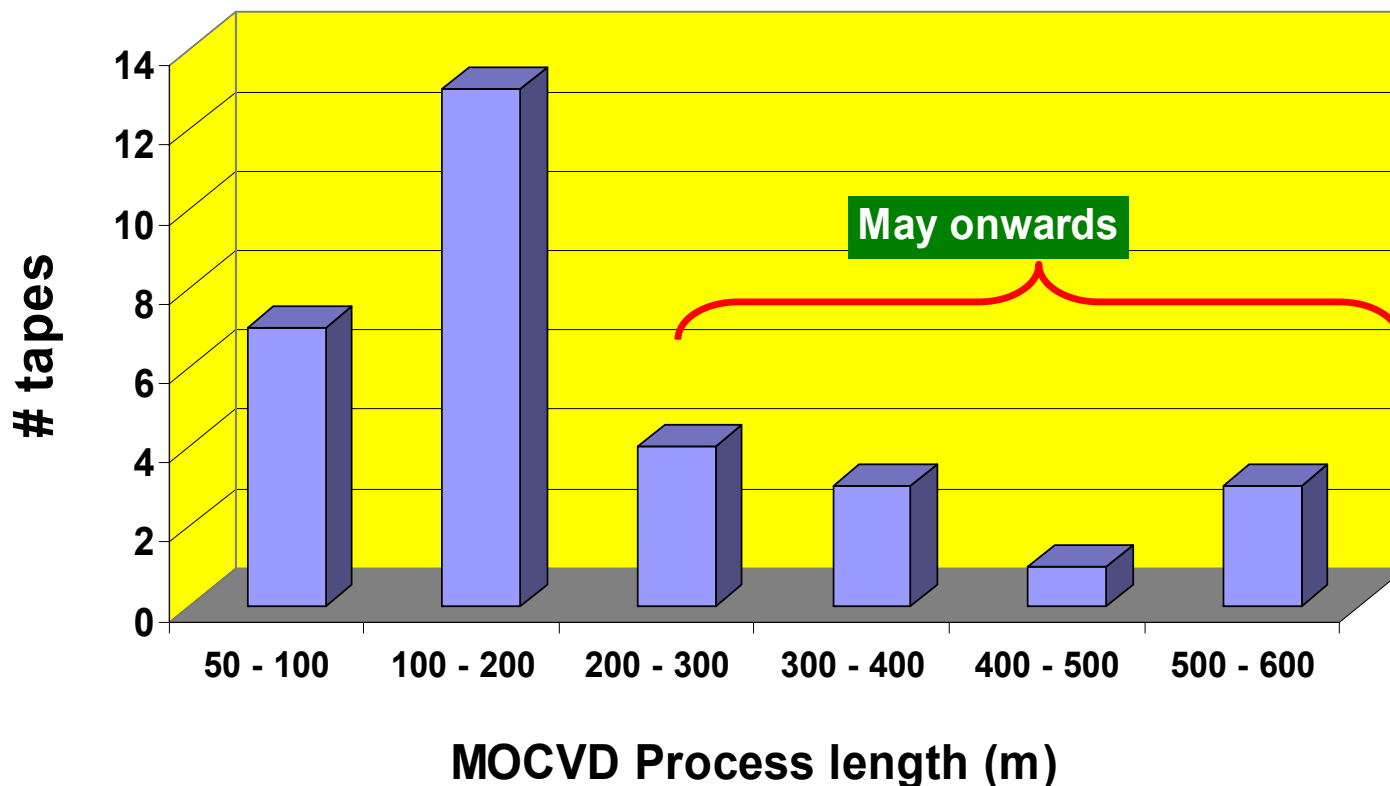


# 2G wire is produced in 300 m lengths with high $I_c$ & excellent uniformity

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



# We are now routinely processing MOCVD tapes in lengths over 300 m

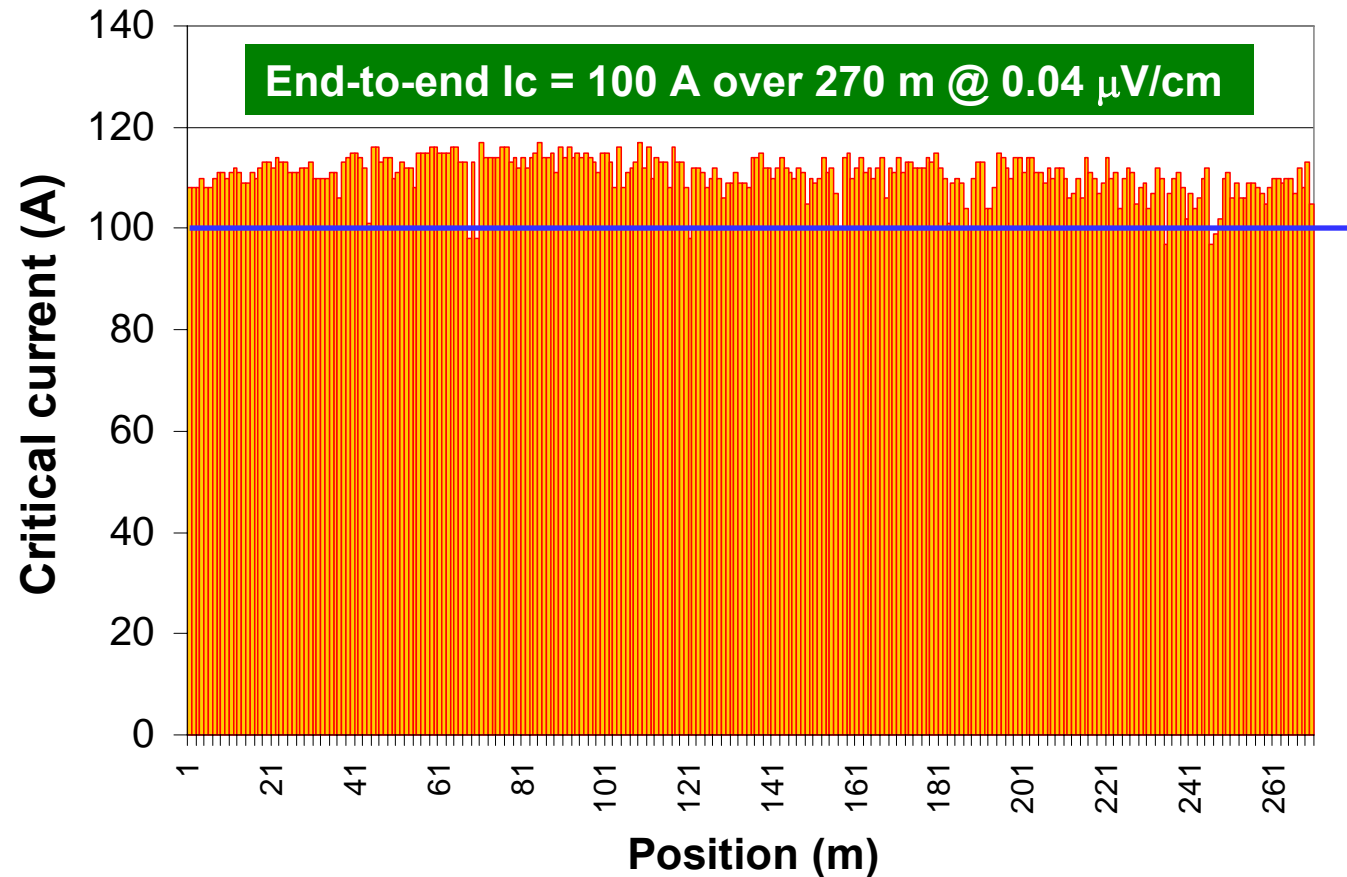


- 35% of tape produced by MOCVD are 200+m.
- 71% of tape produced since May are 200+ m and 43% are 300+ m
- 31 production runs yielding 5,720 m of 12 mm wide tape (= 17,160 m of 4 mm wide tape)

# 2G conductor is now available in long lengths with $I_c$ in the realm of 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

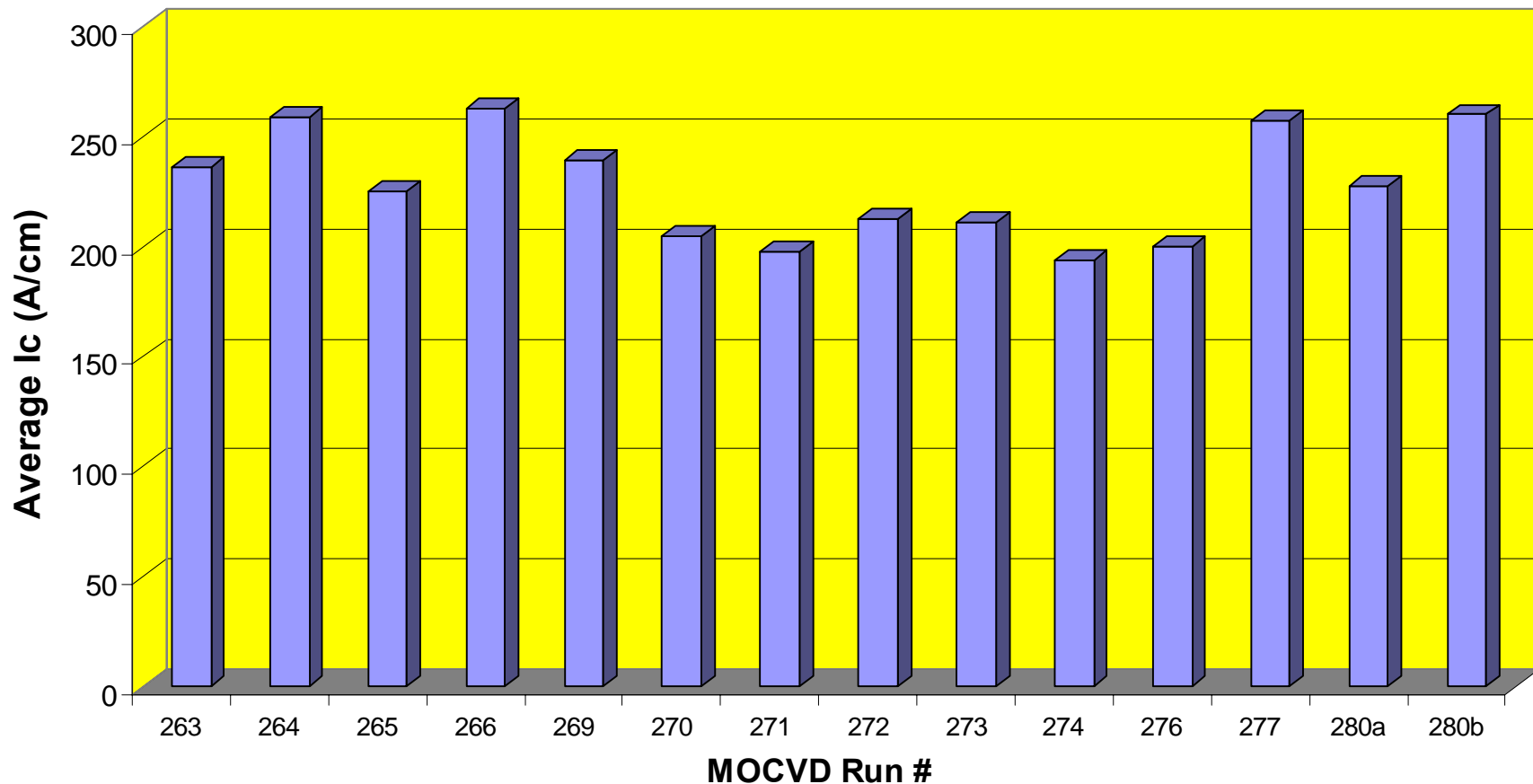


**$I_c = 100$  A in a 4 mm wide 2G conductor over 270 m !**

**$J_e = 26.3 \text{ kA}/\text{cm}^2$  (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  $17 \text{ kA}/\text{cm}^2$**

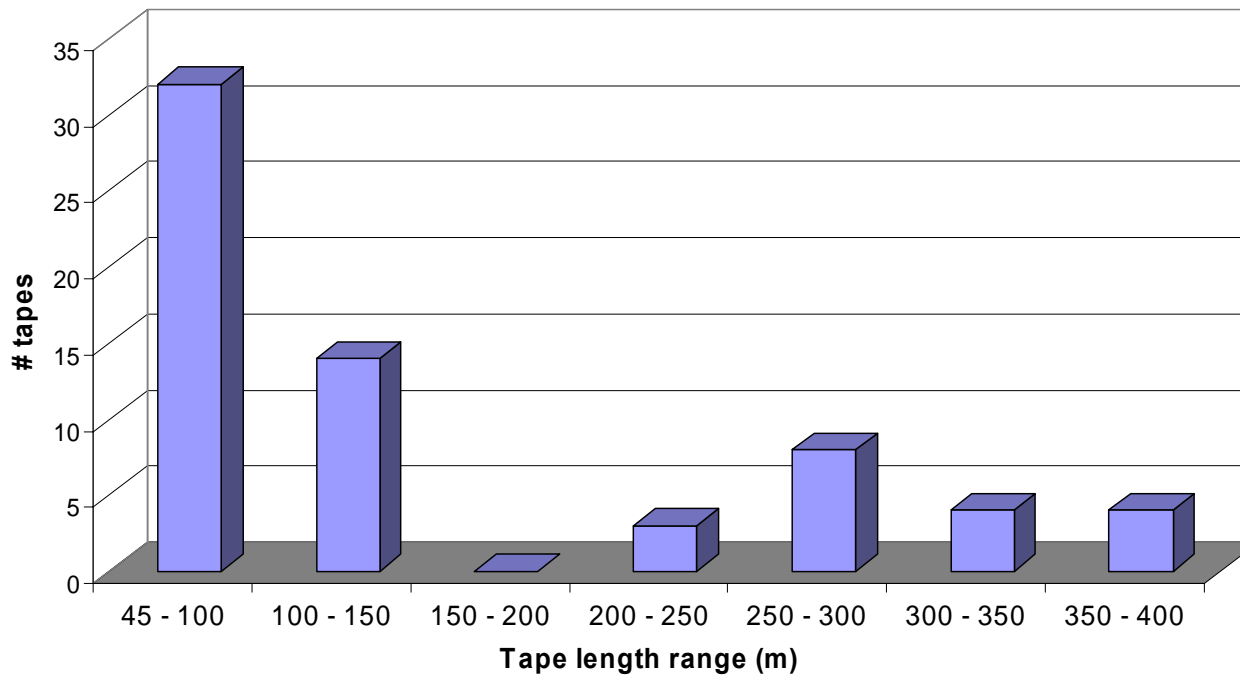
# Critical currents of 200 to 250 A/cm reproducibly achieved in long lengths from May onwards



#267 was damaged after MOCVD. #268 & # 275 were experimental runs  
Runs #278 & #279 were interrupted.

# More than 12,000 m of qualified tape in inventory for Albany Cable project

- 🕒 Piece length required = 42.4 m
- 🕒 50% of tapes > 100 m piece length
- 🕒 ~ 30% of tapes > 200 m piece length



**Thank You**