SuperPower's 2G HTS Conductors for Power Applications

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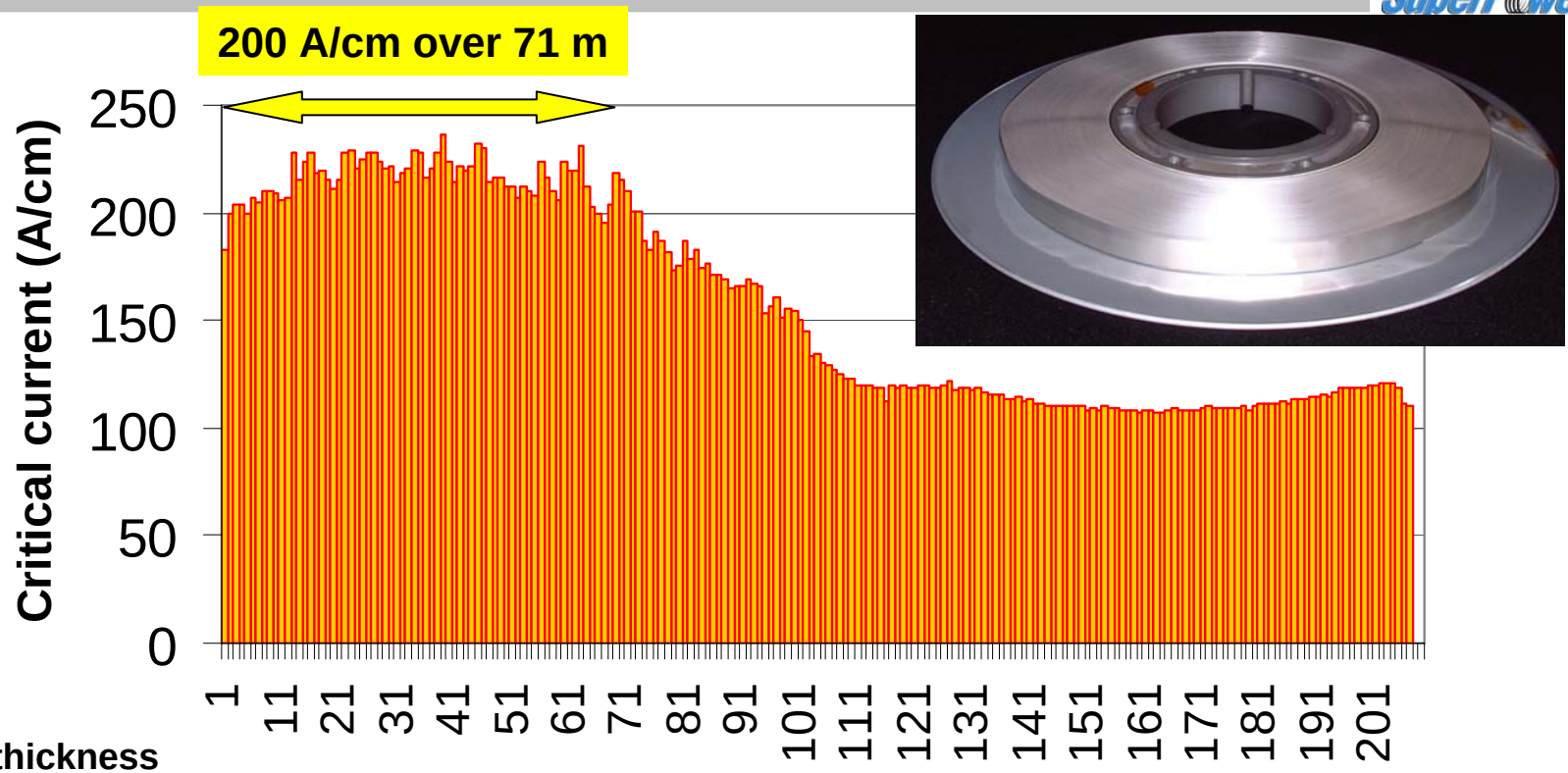
HTS Solutions for a New Dimension in Power

Coated Conductors for Applications Workshop, Santa Fe – December 2005

IBAD-MOCVD based conductors have been scaled to 200 m lengths



YBCO film thickness
1.47 microns @ start &
1.32 microns @ end

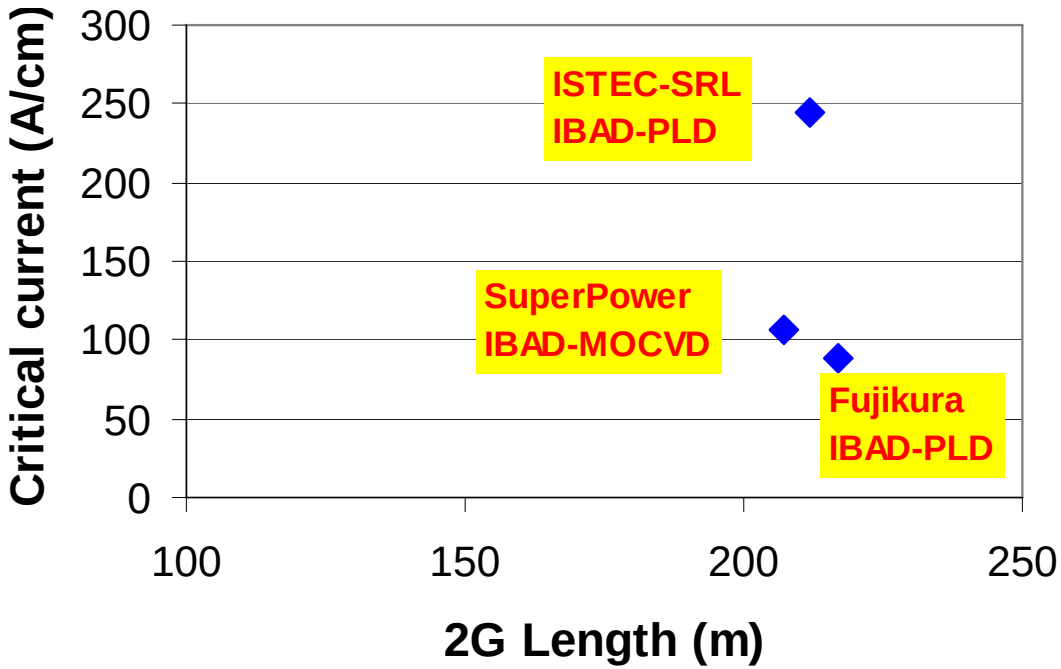
MOCVD 1st pass: 10 m/h
MOCVD 2nd pass: 10 m/h

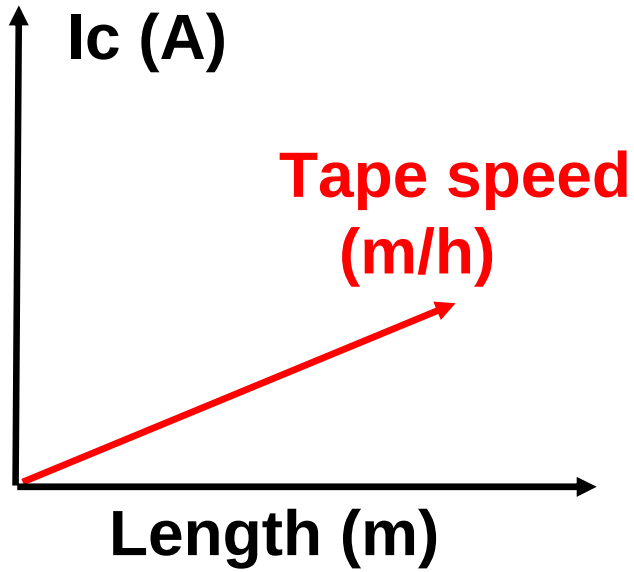
Minimum Ic of 106.7 A/cm over 206.7 m (22,030 A-m)

71 m with Ic of 200 A/cm with standard deviation of 4.3%

Standard deviation of 4.3% over the last 100 m

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





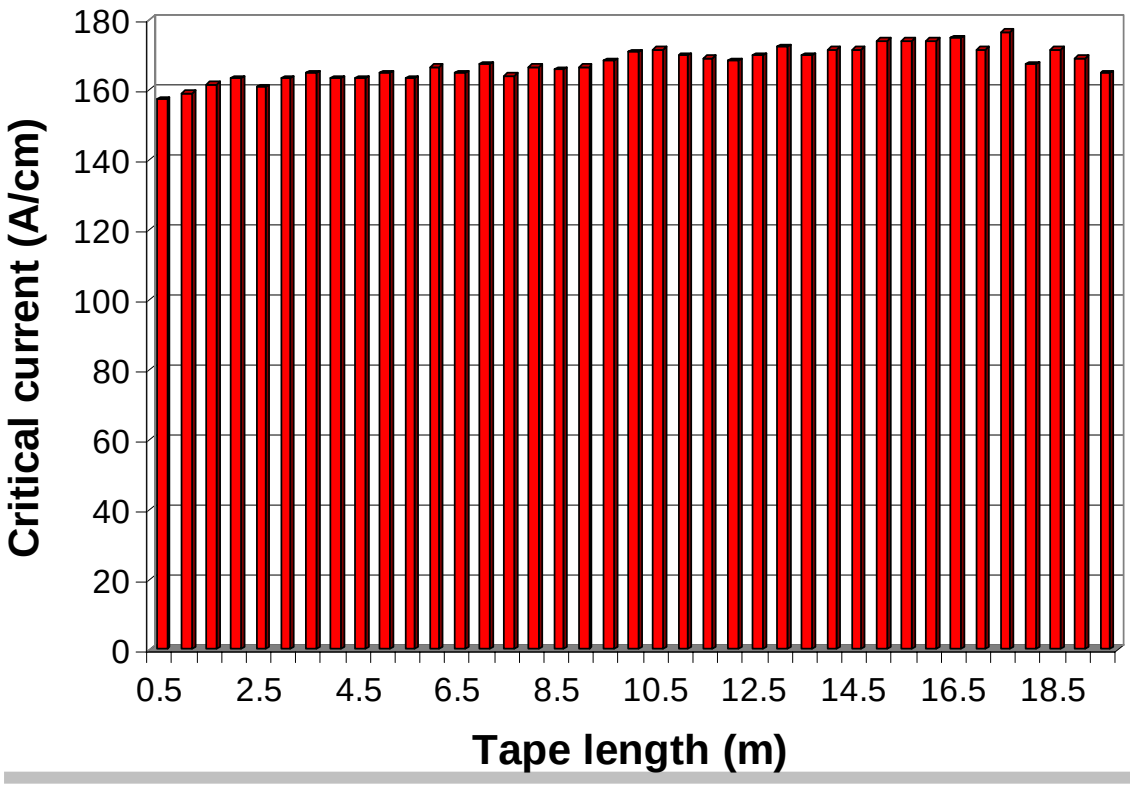
- Effective linear tape speed of PLD processes ~ 3 m/h
- Effective linear tape speed of MOCVD process = 5 m/h
- At 5 m/h of 12 mm wide tape, annual production would be less than 100 km/year of 4 mm wide conductor. This is far less than the current 1G market of ~ 700 km/year.

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

5-fold increase in linear tape speed demonstrated with MOCVD

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 single pass at 25 m/h.



160 A/cm over 20 m

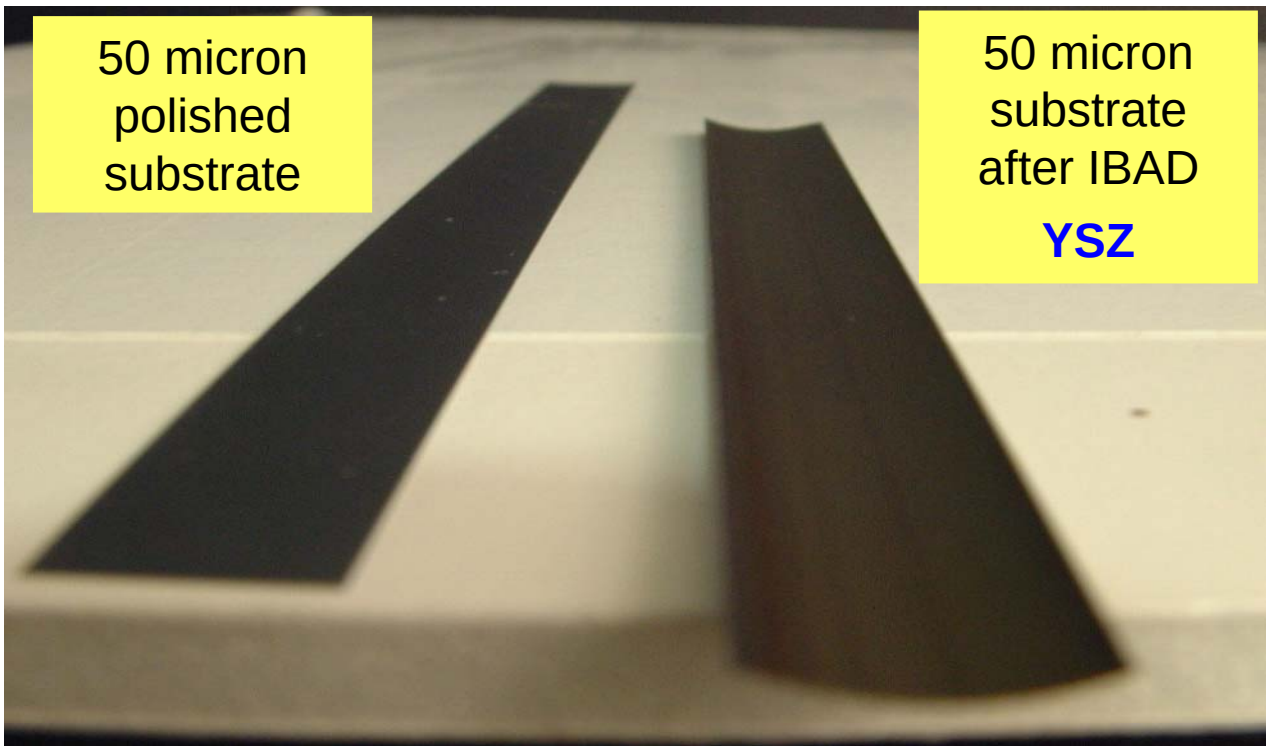
Standard deviation = 2.7%

Thinnest 2G conductor: High Je conductors by reducing substrate thickness in half

The substrate comprises the bulk of the material in the 2G conductor and so has a high impact on effective Je.

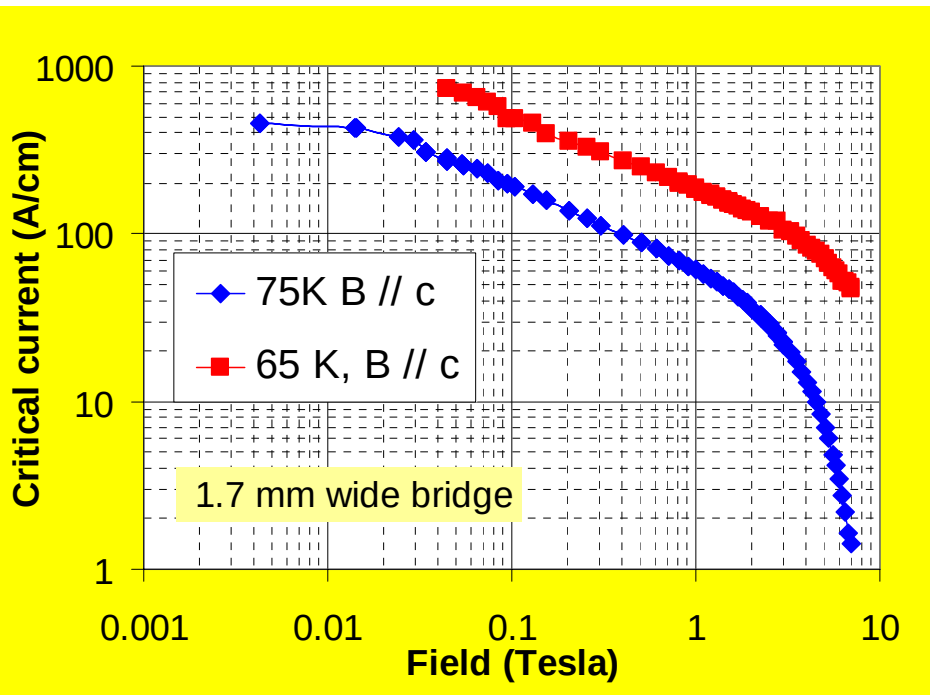
Previously, 100 micron thick substrates were used for IBAD YSZ because of transverse tape bowing issue with 50 micron substrates

Transitioning to IBAD MgO provided the opportunity to use thin substrates (50 microns) for increased Je



High Je conductor for coil applications achieved using 50 micron thin substrates & 3 μm thick YBCO

Substrate (μm)	Buffer	YBCO thickness (μm)	Length (m)	Temp (K)	Field (T)	Ic (A/cm)	Je (kA/cm^2)
100	YSZ	1.1	0.01	77	0	220	21



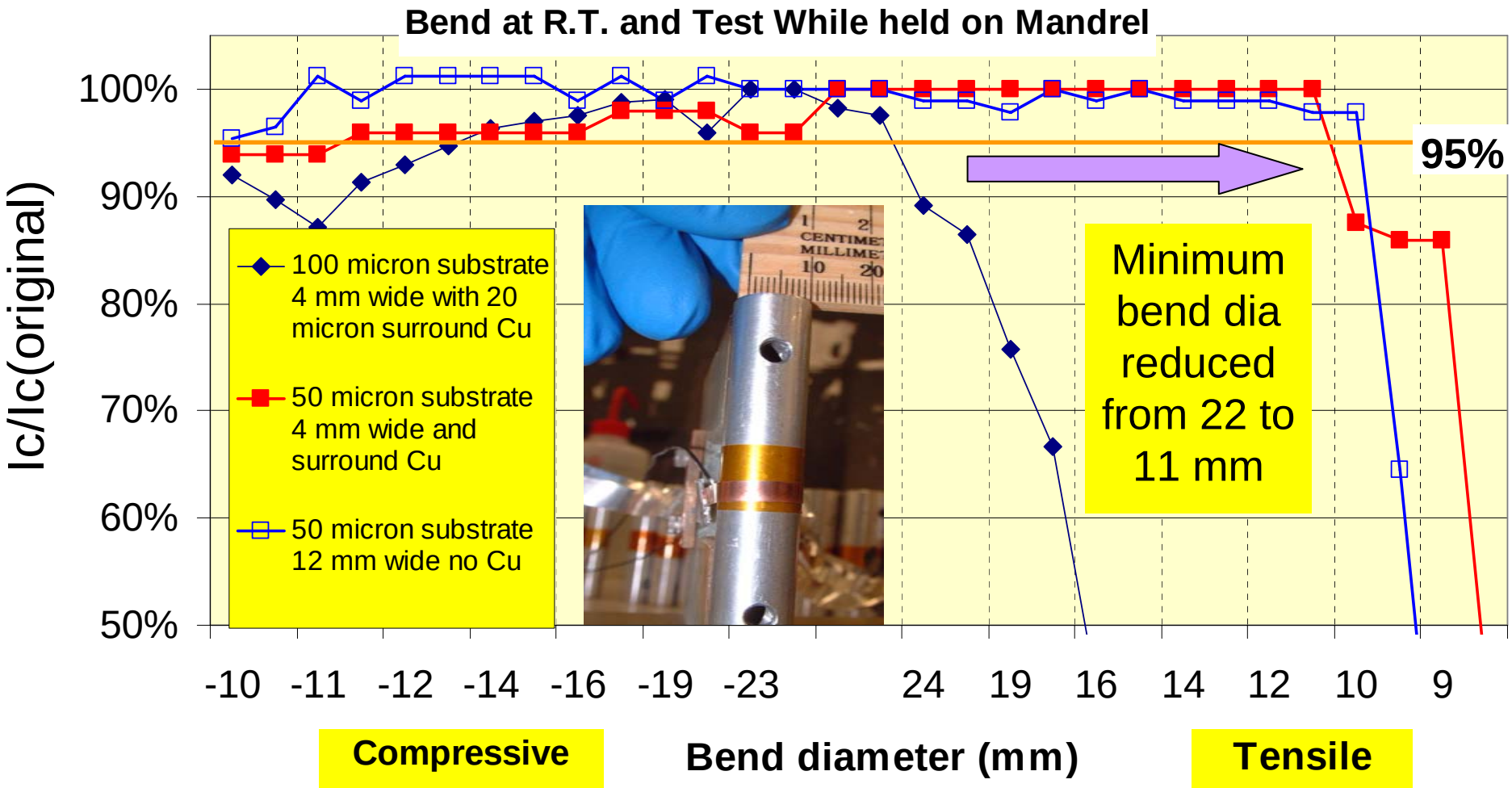
Title III program Je goals:

10 kA/cm^2 @ 65 K, 2 T by Dec05

15 kA/cm^2 @ 65 K, 3 T by 2008

In-field measurements by L. Civale & B. Maiorov

Bend performance significantly improved using 50 micron substrate-based conductors



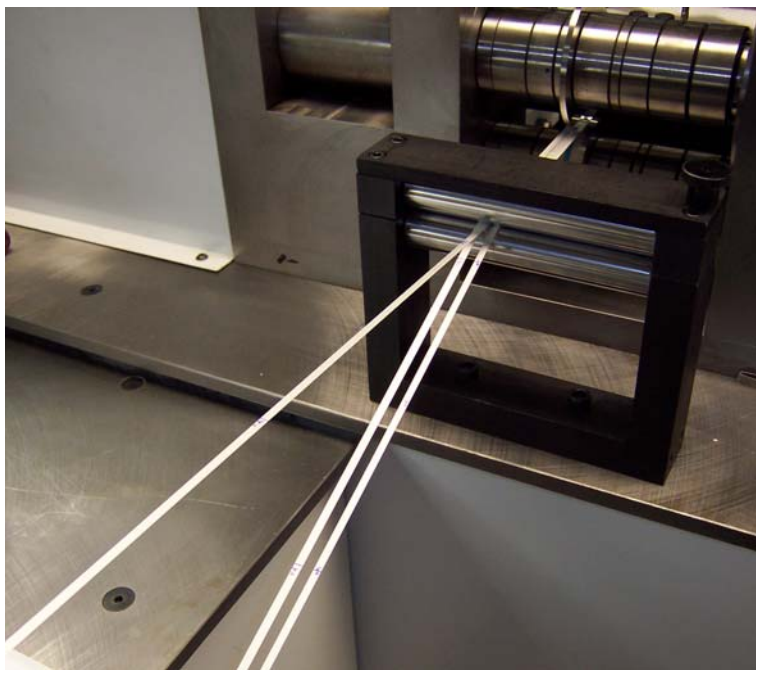
2x reduction in bend diameter using conductors with 50 micron substrates

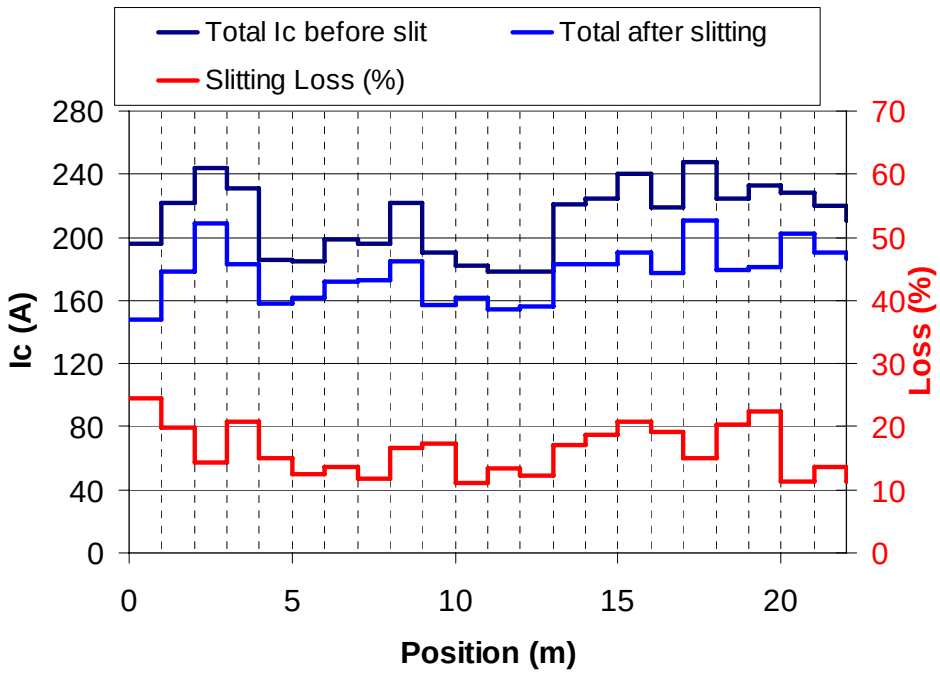
Slitting used to fabricate tapes with application driven widths (i.e. 4 mm wide for HTS cable)

Tapes are slit ***prior*** to copper stabilizer plating

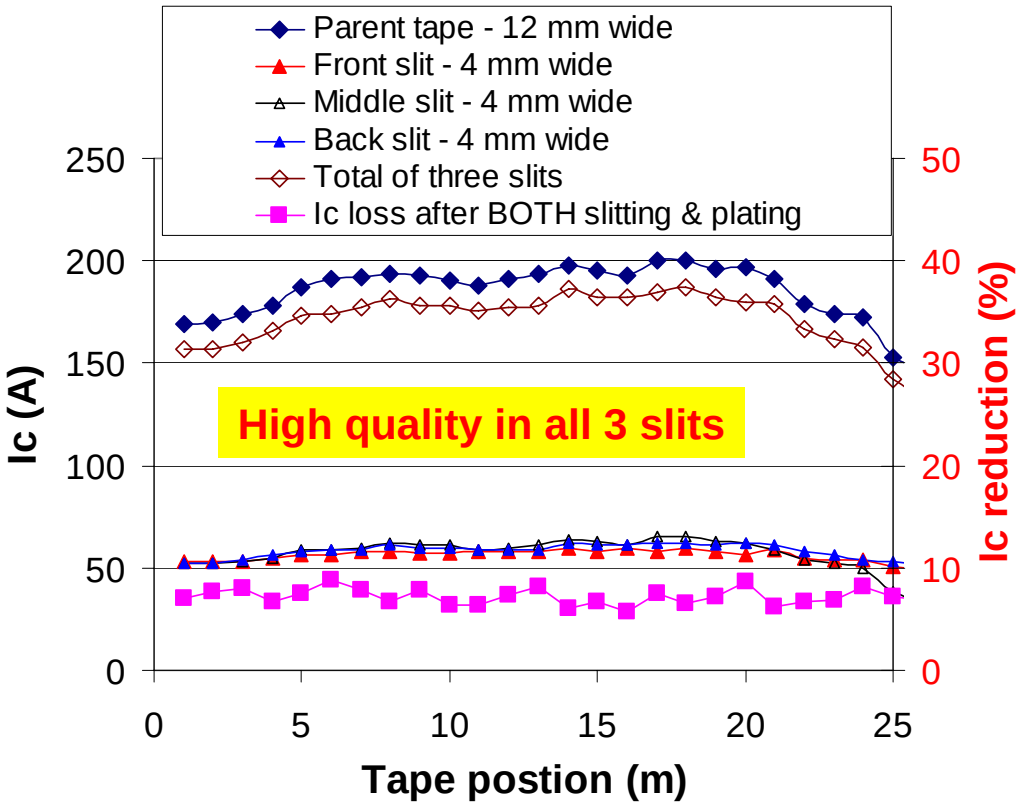
Currently, we slit 3 x 4 mm tapes from a 12 mm wide tape – No scrap

Nominal Ic reduction after slitting conductors with 100 micron thick substrates





Ic loss from slitting reduced by 50% in long lengths with 50 micron substrates (IBAD MgO)



160 m slit & plated conductor

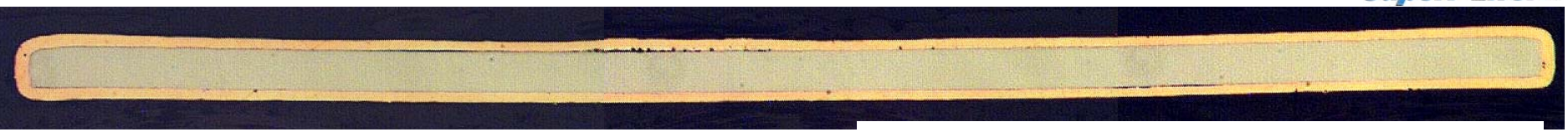
In 25 m lengths, average Ic loss in <u>total of all 3 slits</u>:

7% with 50 micron substrates

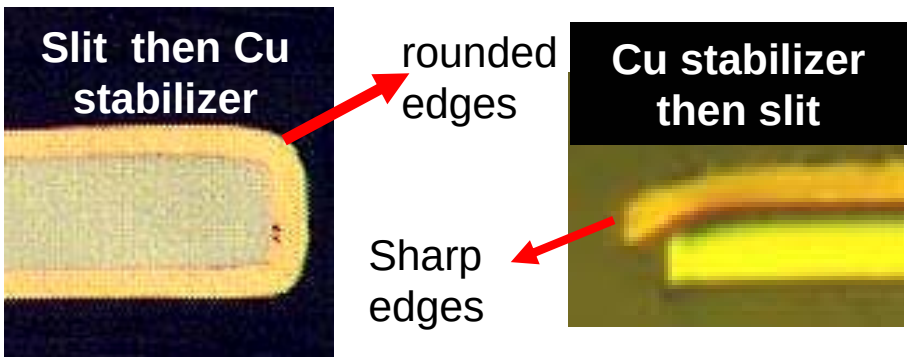
15% with 100 micron substrates

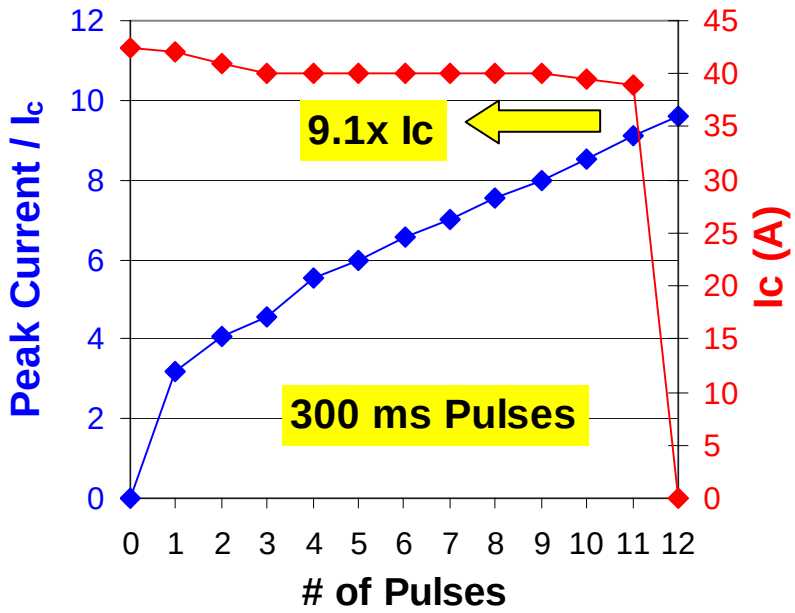
Zero-scrap slitting followed by surround stabilizer Cu plating is now routine & has been scaled up to 100+ m.

2G conductor for cable: slit to 4 mm width followed by Surround Copper Stabilizer



- 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





Minimal Ic degradation and no tape burn out at over-current levels of 9 times Ic with 300 ms pulses*

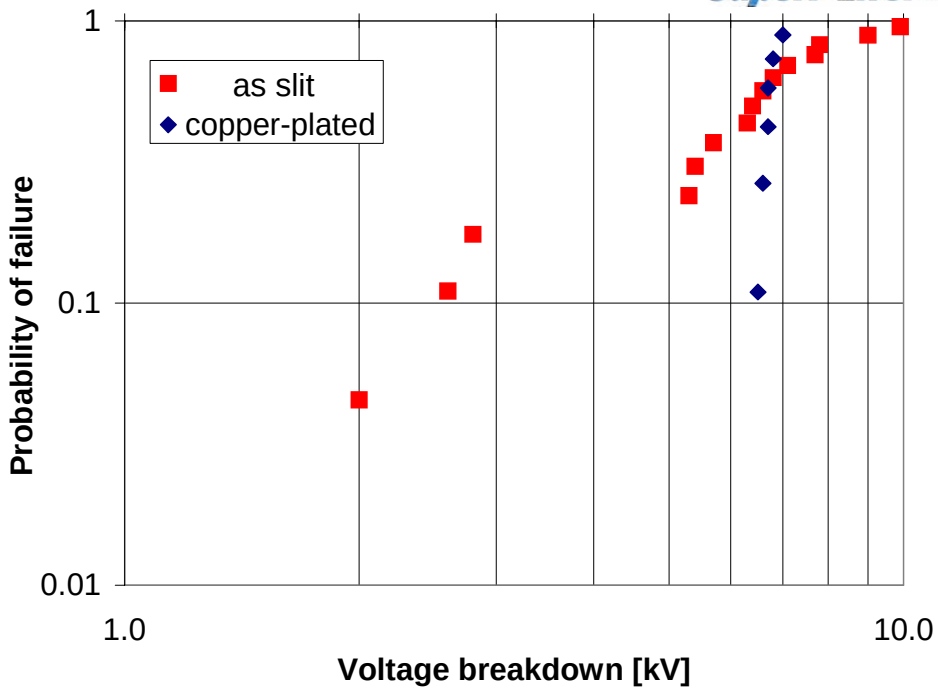
"Surround Copper Stabilizer" has been successfully implemented & tested on several hundred meters of conductor

*Measurements by Jankowski & Iwasa, MIT

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

Of the four DOE-SPI projects that suffered HTS coil failures, 3 were due to insulation and 1 due to quench *.

This year, ORNL compared the dielectric strength of conductors with rounded edges in surround stabilized conductor, compared to slit tapes with sharp edges



Data from Robert Duckworth

Sample	As-slit	Slit & surround stabilizer
Avg. Breakdown voltage	6.1 +/- 2.2 kV	6.7 +/- 0.2 kV
10% probability breakdown	2.1 kV	6.5 kV

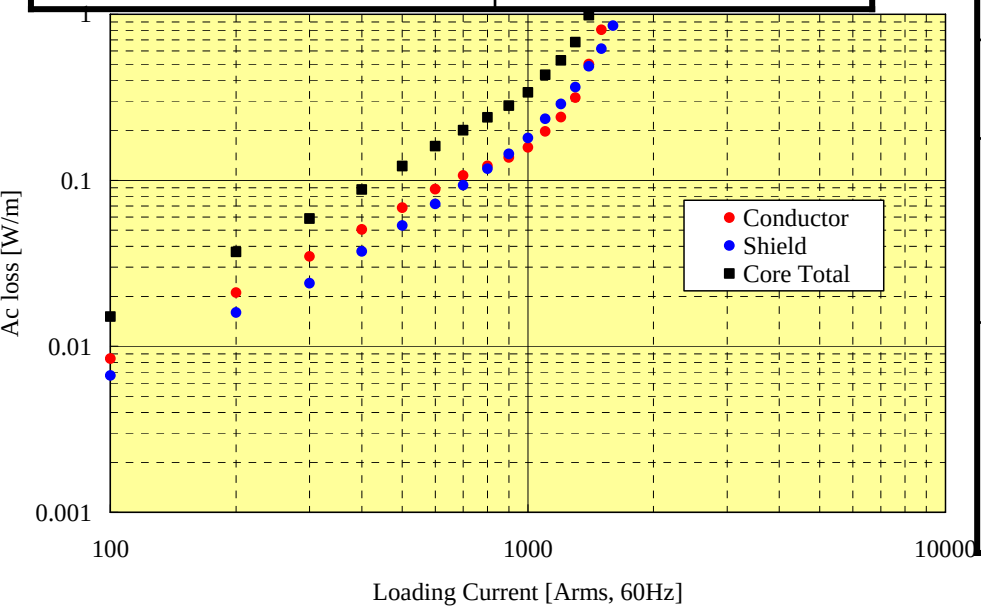
Probability of failure at low voltages is much reduced in conductors with surround stabilizer

*C. Rey, DOE Wire Workshop, January 2005

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

Conductor delivery	06/04	03/05
Total length (m)	61	113
Average Ic (A/cm)	122	160
Conductor details	0.145 mm thick 4 mm Surround Cu	

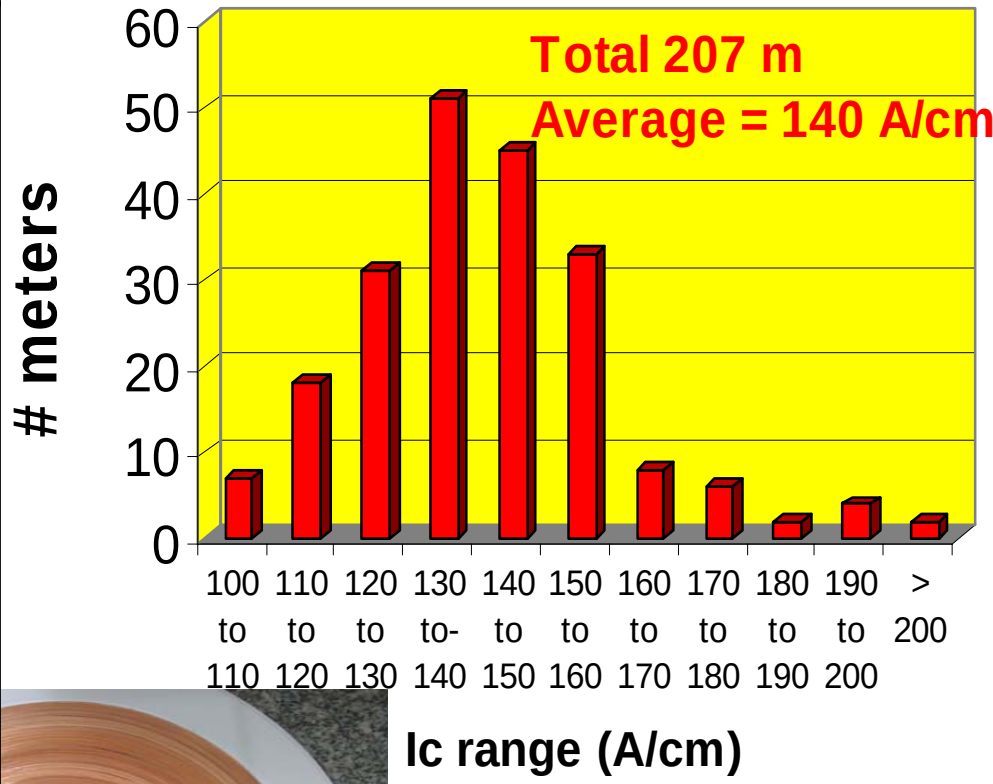
Cable features	06/04	07/05
# conductor layers	4	4
# shield layers	0	2
Total # 2G tapes used	48	88
Cable Ic (A)	2150	2350 (c) 2240 (s)
AC loss in conductor + copper former (W/m) @1000 A rms	0.4	0.16

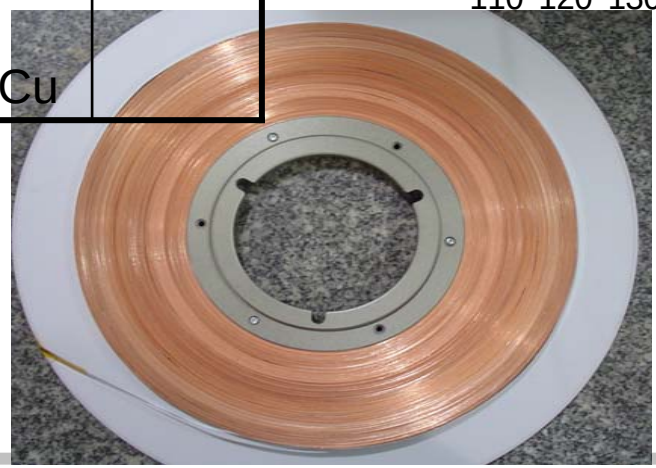


AC losses in conductor + copper former is 2.5 times less in the new 2G cable with a complete structure (shield layers)

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

Conductor delivery	06/04	03/05	07/05
Total length (m)	61	113	**207**
Average Ic (A/cm)	122	160	**140**
IBAD Buffer	YSZ	YSZ	**MgO**
Substrate thickness (μm)	100	100	**50**
Total conductor thickness (μm)	145	145	**50**
Conductor details	4 mm Surround Cu		





2G coils for rotating machinery: Significant improvement in 2005

Four 2G Racetrack coils supplied to Rockwell in June 2004 & the world's first 2G-based rotating machine was constructed & tested

Motor tested at 1800 rpm, 1.2 hp
800 Amp-turns/coil @ 82 K in June 2004

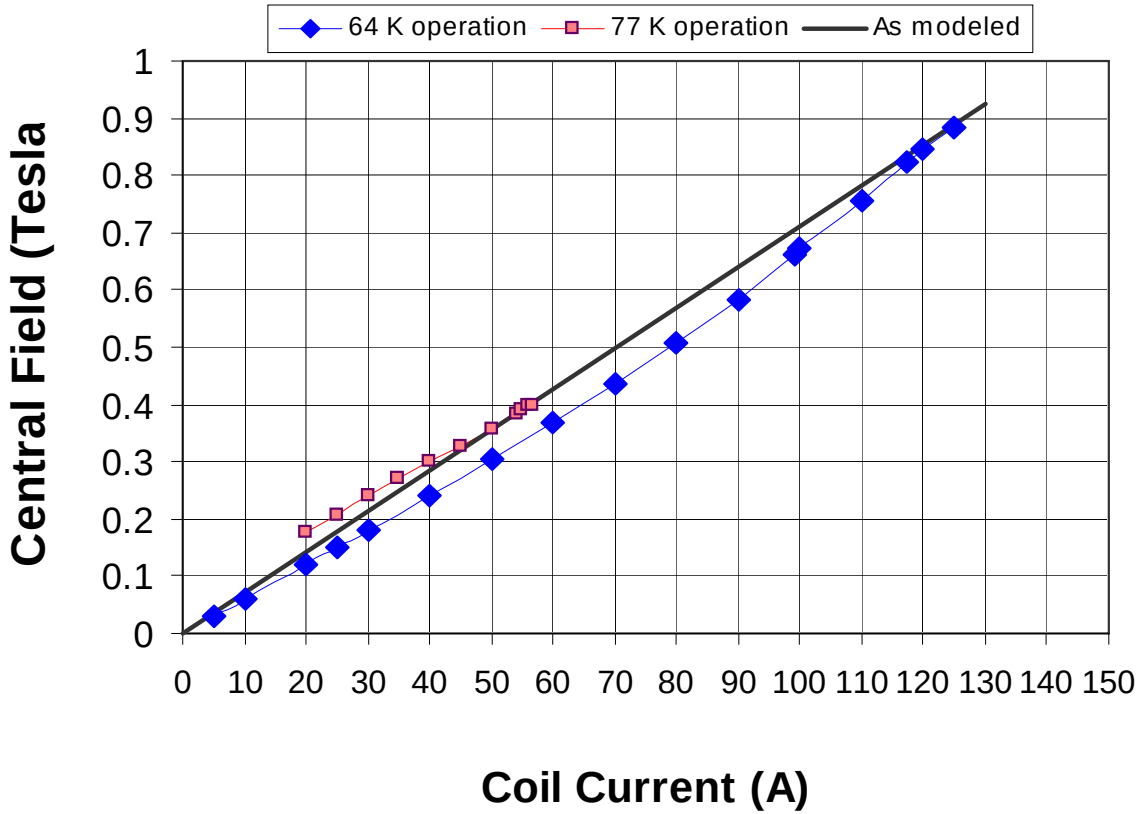
4 new race track coils provided to Rockwell in 2005 – with better performing conductor and improved coil design

Motor tested at 6 times higher power: 7.5 hp with new coils at 1800 rpm

7.5 hp achieved with 2G HTS coils in a 5 hp conventional motor frame

High field 2G coil demonstrated

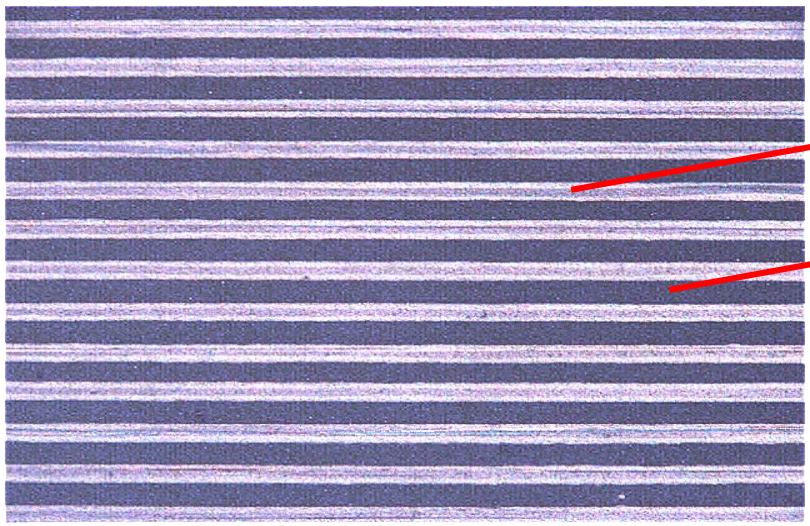
Double pancake coil using 20 m of 2G conductor tested at 64 K, 77 K



0.87 T achieved at coil current of 123 A
0.4 T achieved at coil current of 56 A

Photolithographic patterning of 2G conductor for ac loss reduction

- Photolithography process is used to striate conductor (YBCO & stabilizer) for reduced ac losses. Various patterning schemes are being evaluated.
- High throughput process: slowest step is 50 times faster than laser patterning



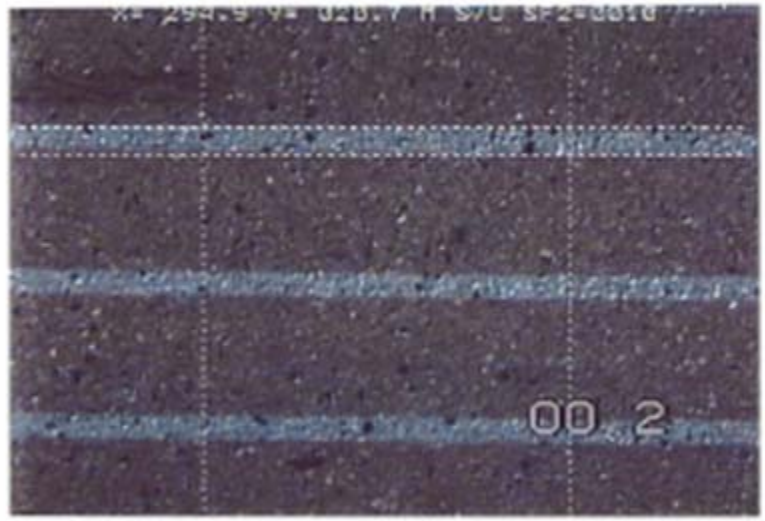
With 100 : 100 μm line width to spacing, ½ the YBCO is lost

Also, narrower line widths are preferred for lower ac loss

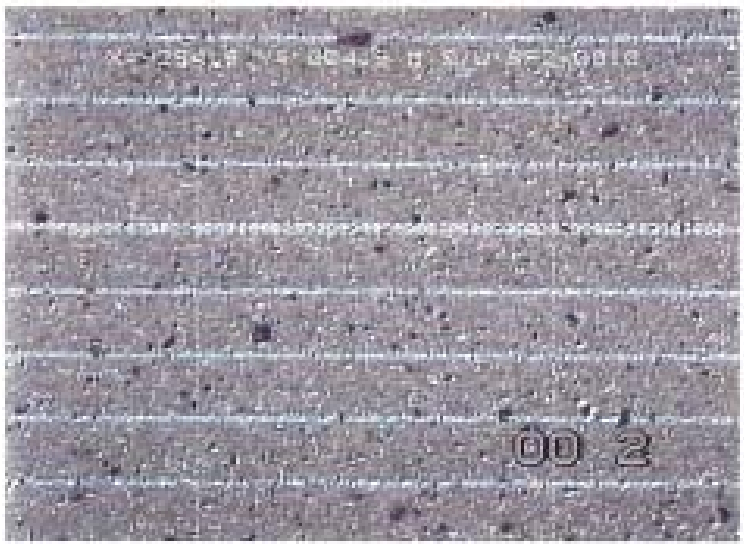
Conductors with even finer line widths & spacings created by photolithographic patterning

28 cm long conductors, 12 mm wide, 50 μm thick substrate, patterned through YBCO & silver overlayer

YBCO line width = 100 μm
Line spacing = 20 μm



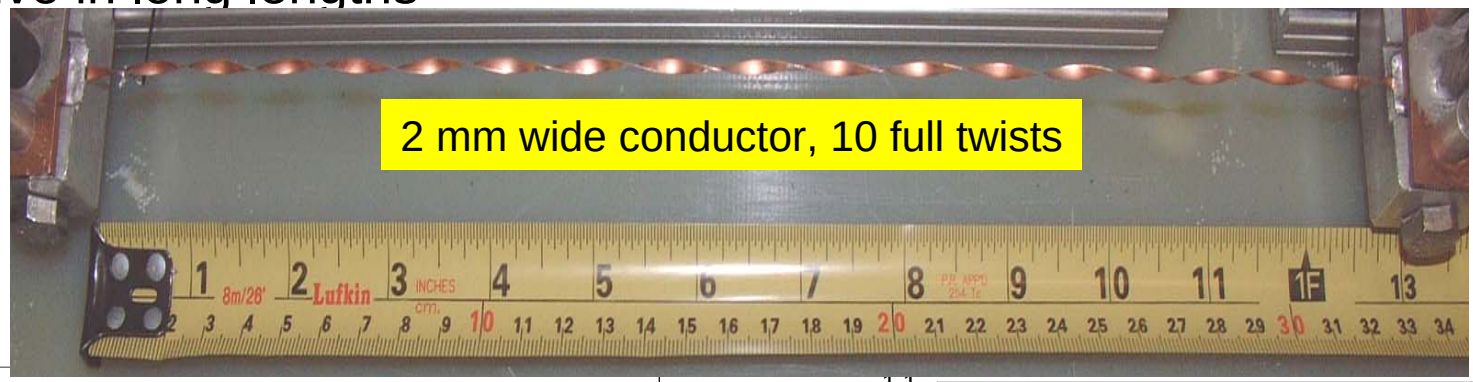
YBCO line width = 100 μm
Line spacing = 10 μm

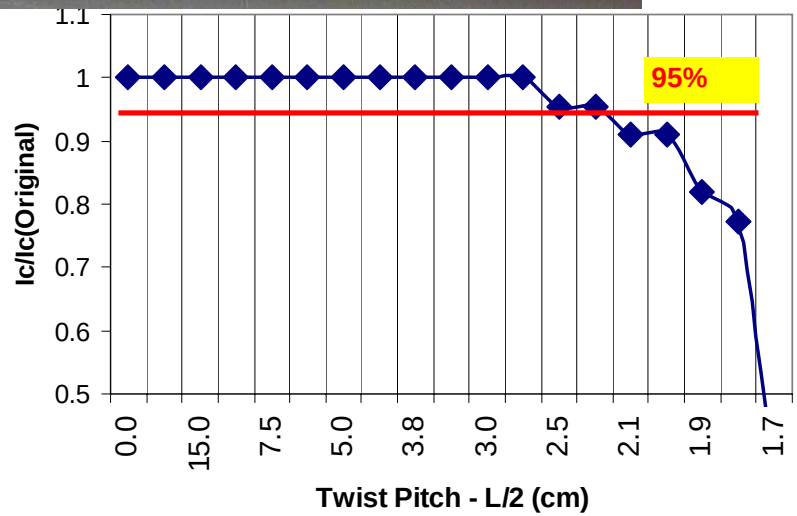


YBCO line width = 50 μm
Line spacing = 5 μm

Twisting of 4 mm & 2 mm wide conductors has been demonstrated

- Twisting needs to be demonstrated in order for striated geometry to be fully effective in long lengths

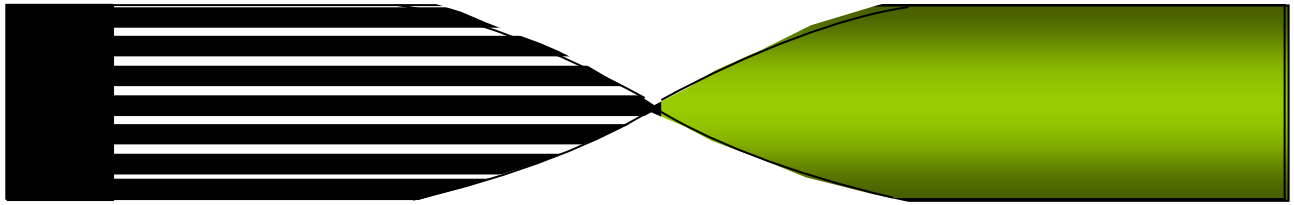


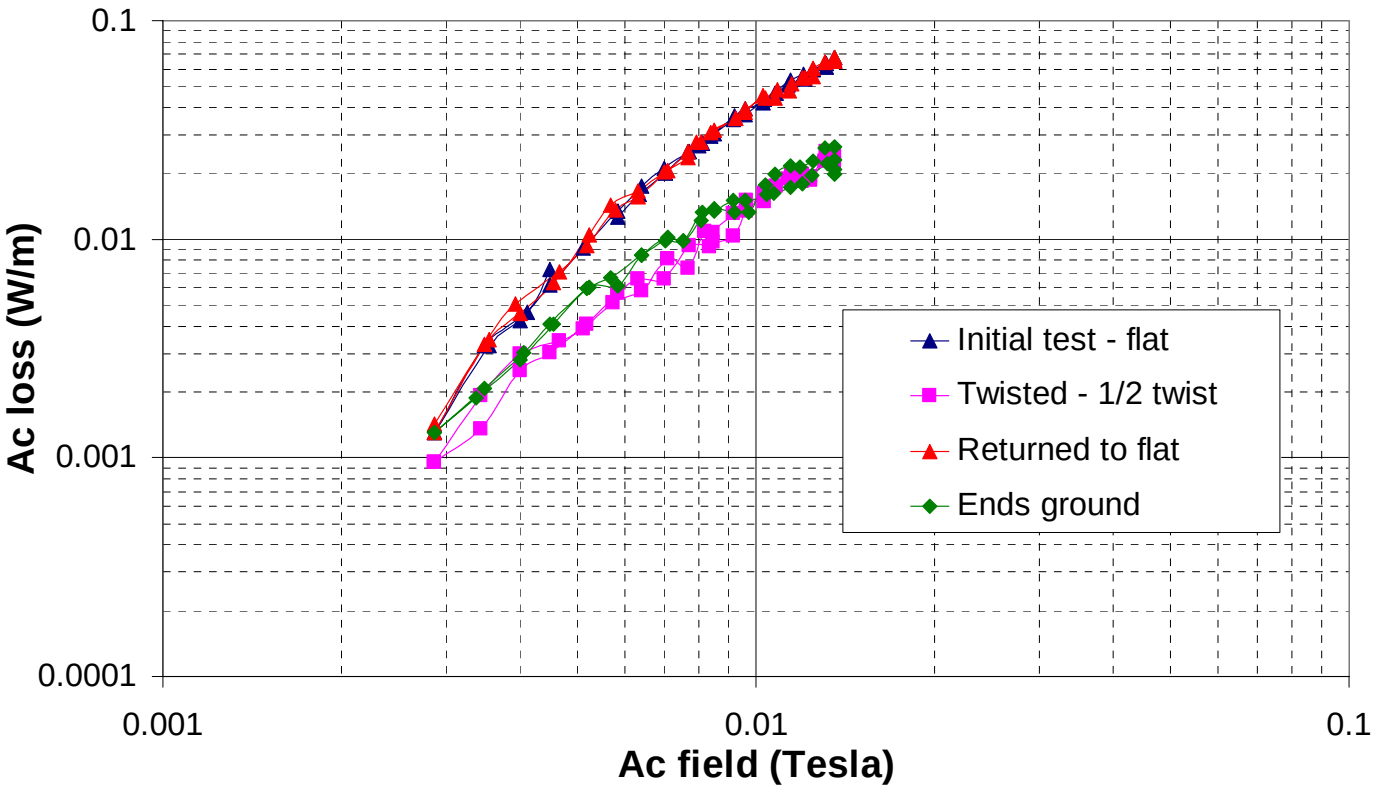


95% original Ic retained at 5.5 full twists (Twist pitch = 9.4 cm)

95% original Ic retained even at 10 full twists (Twist pitch = 4.6 cm)

First demonstration of AC loss reduction after twisting of patterned tapes





12 mm wide tape – Photolithograhic patterned to 100 micron line width & 25 line spacing & slit to 4 mm width.

Also patterned after slitting 12 mm wide tape to 4 mm and 2 mm widths

AC loss reduction after twisting is of same magnitude as after decoupling of filaments in a flat conductor

Summary

- A linear speed of **25 m/h** demonstrated (**single pass**) in MOCVD to achieve **160 A/cm over 20 m**. Conductor throughput needs to be addressed in addition to Ic & lengths.
- Thin conductor produced in lengths using 50 micron substrates & IBAD MgO
  - **Overall conductor thickness is reduced. Total conductor thickness with 40 micron Cu stabilizer < 0.1 mm**
  - **High Je enabled: 71 kA/cm^2 at 77 K, self field & 18.8 kA/cm^2 at 65 K, 3 T**
  - **Critical bend diameter in tension reduced by a factor of 2 to 11 mm**
  - **Reduced Ic loss after slitting; 7% loss in *sum of Ic of all slit tapes* over 25 m compared to 15% in conductor with 100 micron thick substrates**
- Photolithographic patterning of conductor with small filament width & spacing (**50 : 5 microns**)
  - **AC loss reduction verified for the 1st time by twisting of patterned tapes**
- Multiple deliveries totaling **381 m of cable conductor** (4 mm wide, copper stabilized) made to Sumitomo Electric for Albany Cable project.

Stay tuned for progress towards ~ 10 km 2G wire delivery for Albany Cable project in 2006