SuperPower Inc.
A Subsidiary of Intermagnetics General Corporation

SuperPower's 2G HTS Conductor: Conductor Design & Properties

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This work was partially supported by AFRL, Title III, DOE, and AFOSR

HTS Solutions for a New Dimension in Power

DOE Wire Development Workshop, St. Petersburg, FL – January 2006

Focus: Key features of SuperPower's 2G conductor design & new data on properties

Thin-profile conductor using 50 micron substrates

- Higher Je – overall thickness < 0.1 mm
- Much less damage after slitting
- Better bend properties
- Higher tensile strength

Surround stabilizer

- Better overcurrent protection
- Better dielectric strength
- Lower ac losses

Joints & Splices

- Electrical & Mechanical Properties

Photolithographically Striated conductor for low ac losses

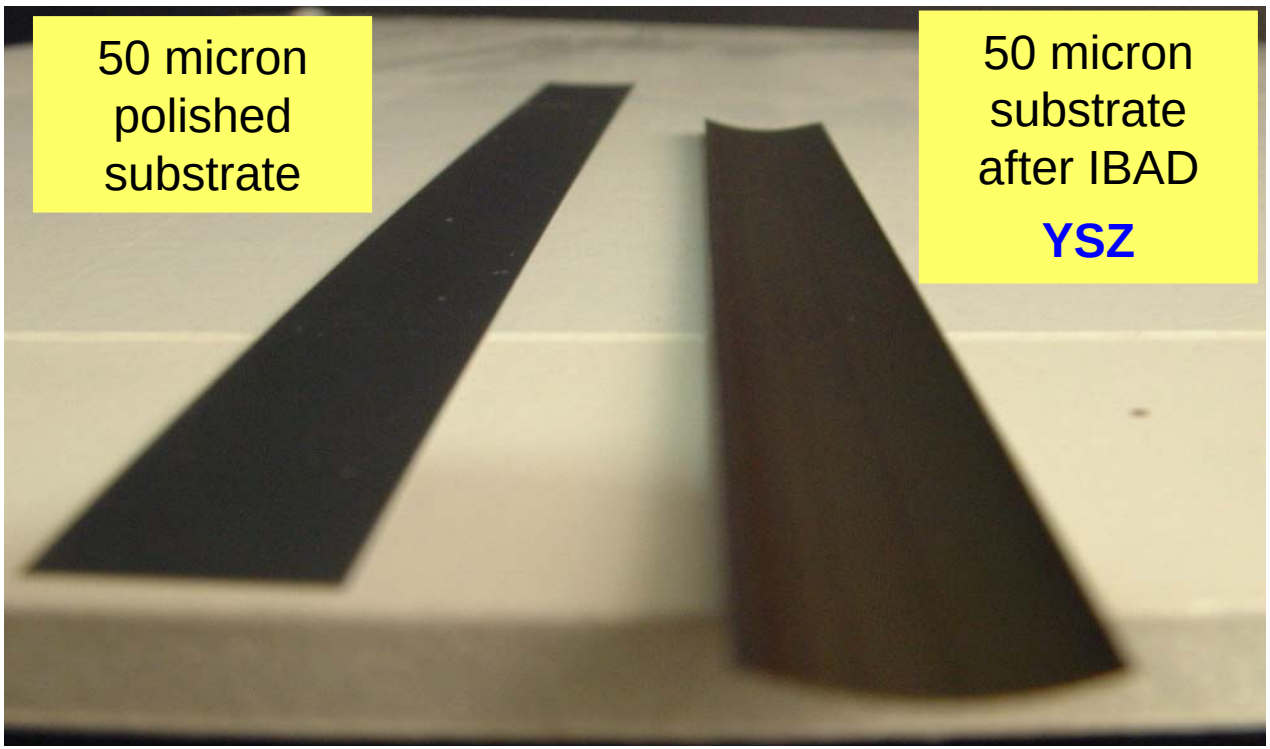
- First ac loss measurements on striated AND twisted conductor

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

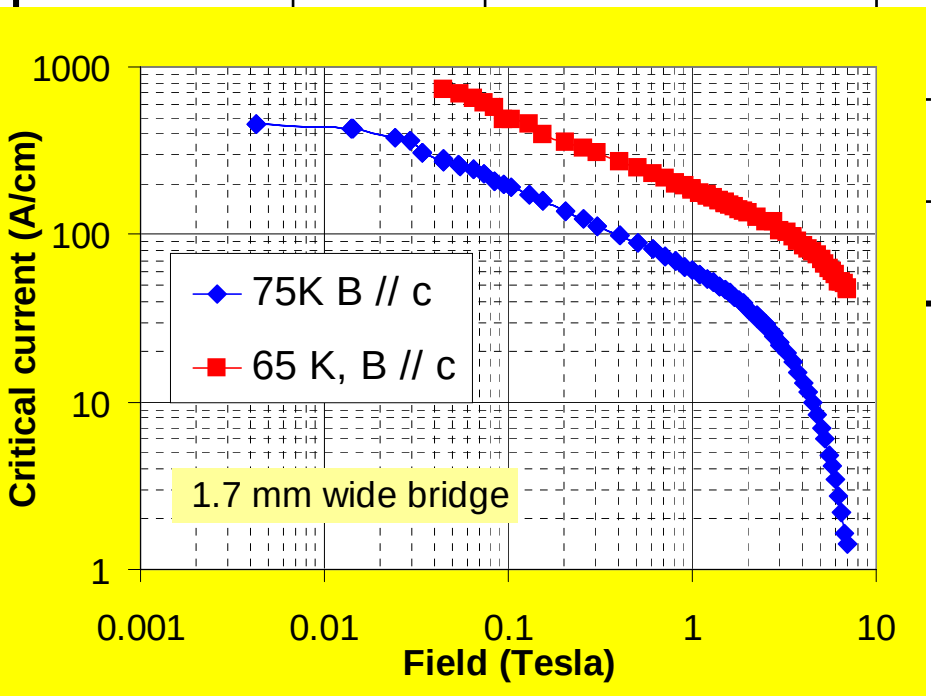
Transitioning to IBAD MgO provided the opportunity to use thin substrates (50 microns) for increased Je



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

SuperPower Inc.

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
50	MgO	1.1	0.01	77	0	220	40
50	MgO	3.0	0.01	**77**	**0**	**400**	**71.4**
			0.01	75	1	61	11
			0.01	**65**	**1**	**185**	**33**
			0.01	**65**	**3**	**105**	**18.8**

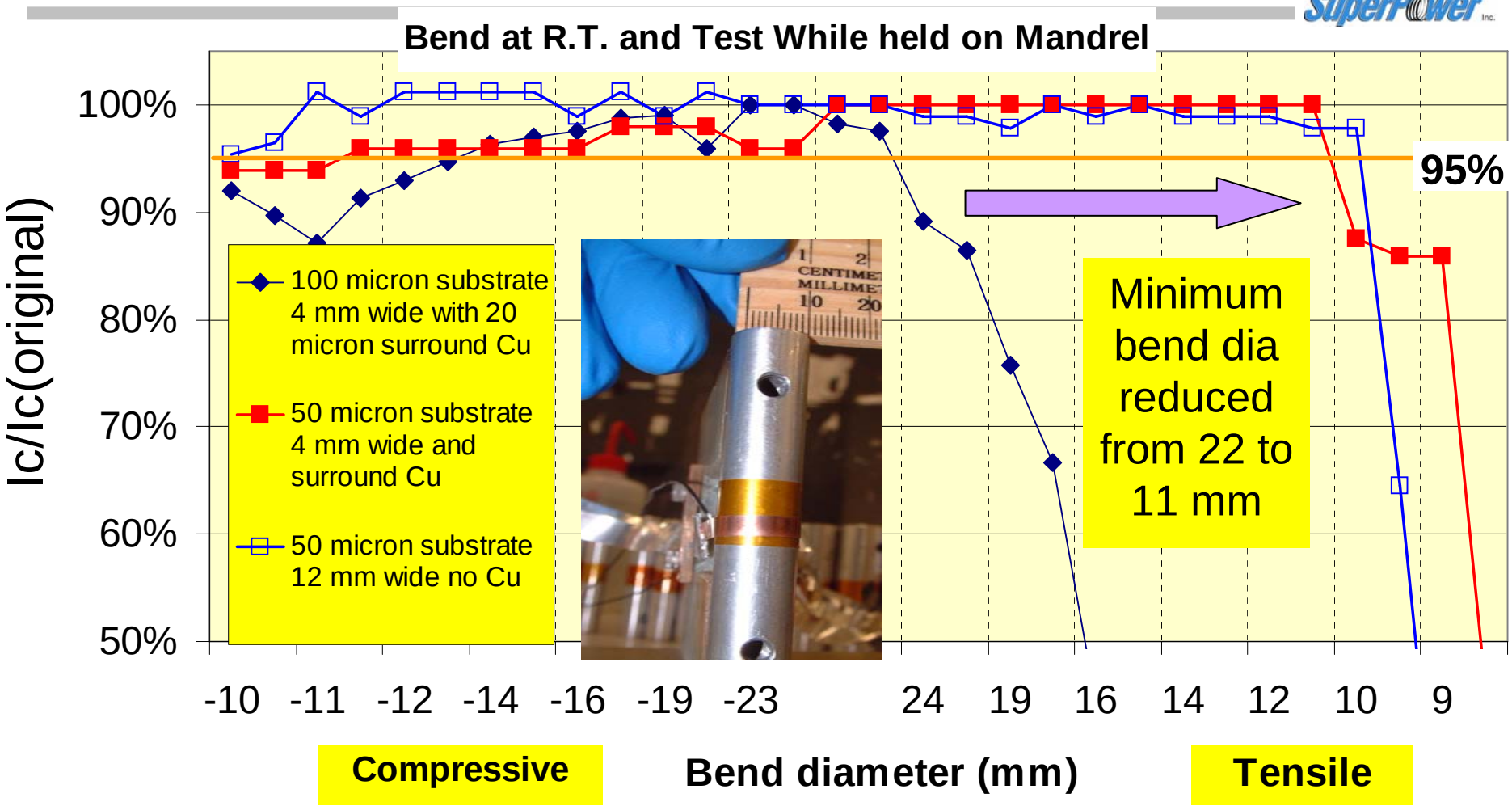


Title III program Je goals:

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

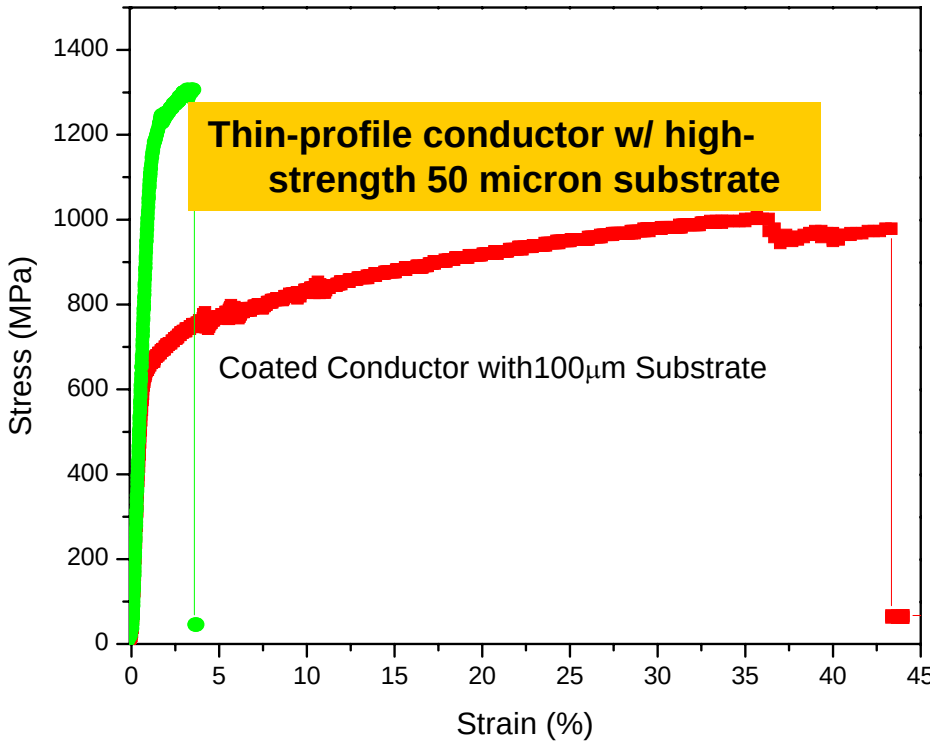
15 kA/cm^2 @ 65 K, 3 T by 2008

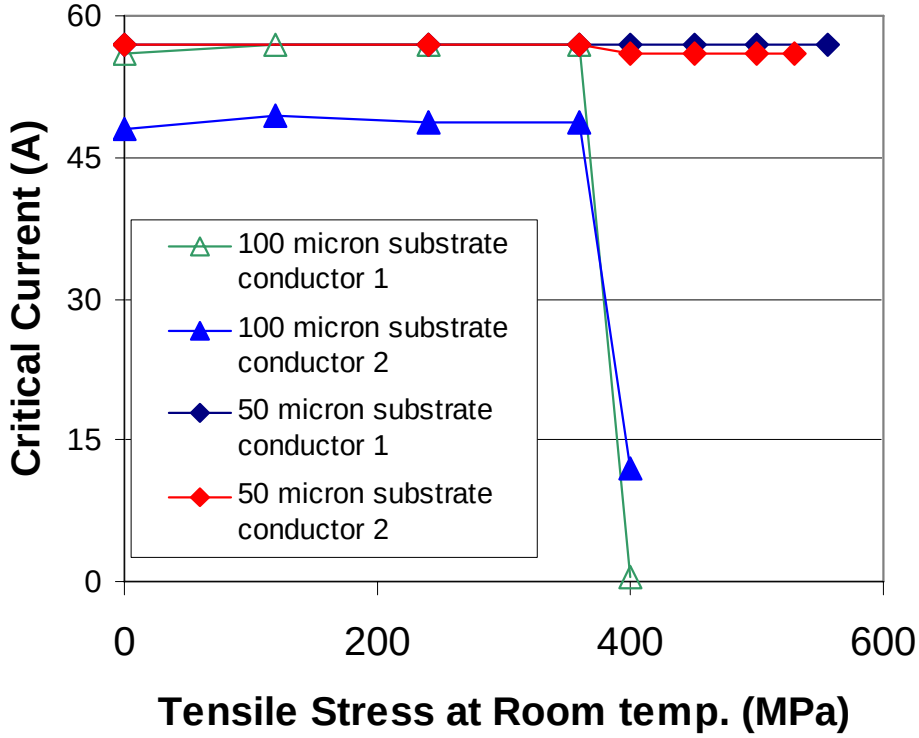
Bend performance significantly improved using thin-profile 2G conductors



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

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





Yield strength (at 77 K) of 2G conductor*:

with 100 micron substrate = 650 MPa

with high-strength 50 micron substrate = **1200 MPa**

Critical tensile stress of 2G conductor:

with 100 micron substrate = 350 MPa

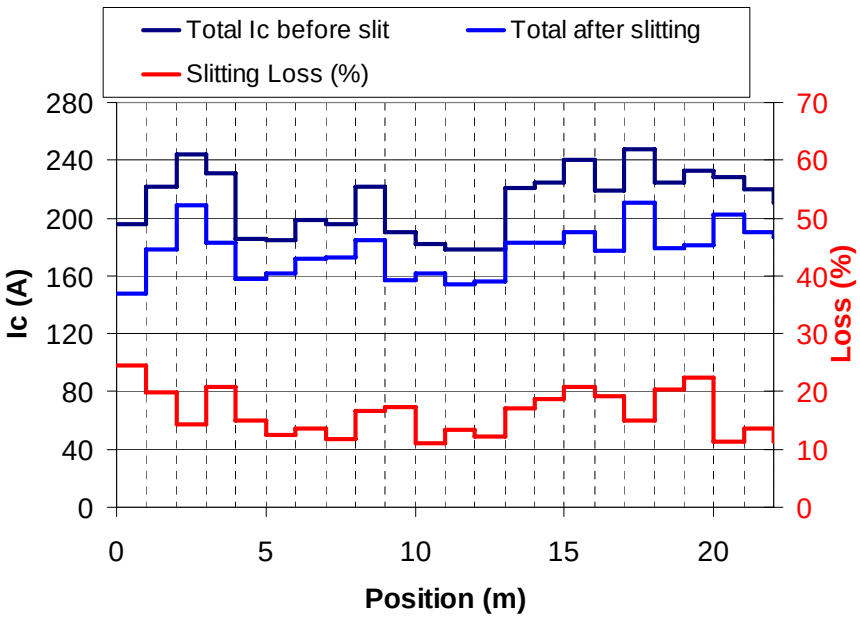
with high-strength 50 micron substrate **> 550 MPa**

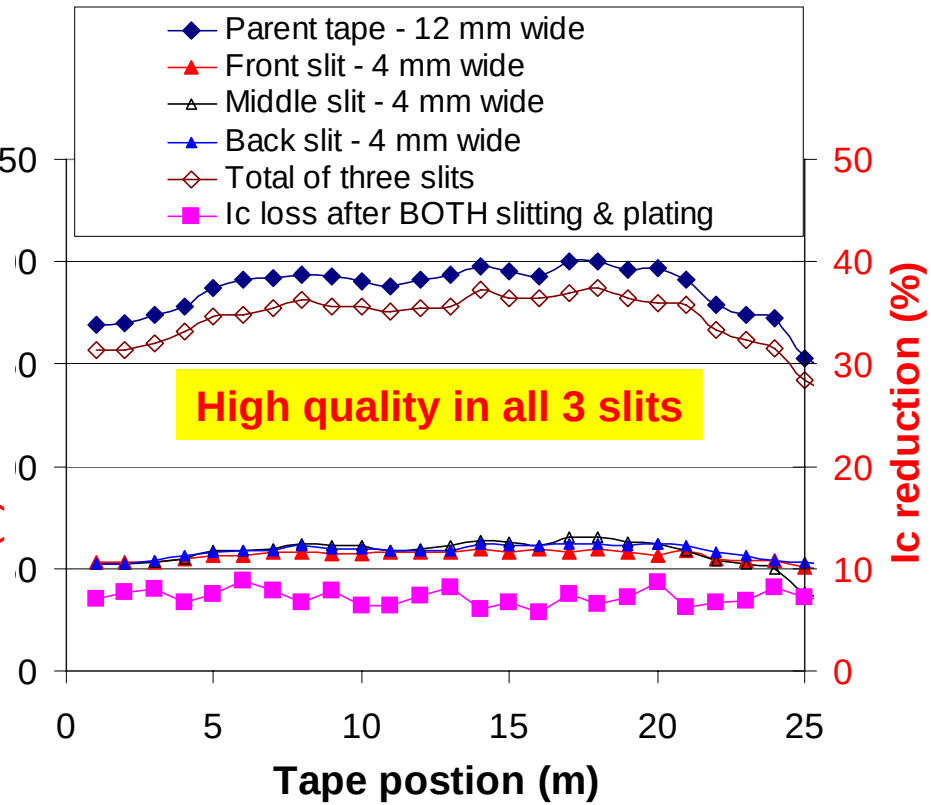
*77 K tensile testing measurements by Y. Zhou and K. Salama

Ic loss from slitting reduced by 50% in long lengths with thin-profile 2G conductors

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

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





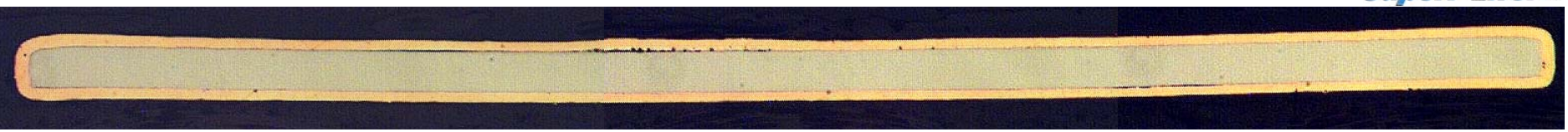
2G conductor with 50 micron substrate

2G conductor with 100 micron substrate

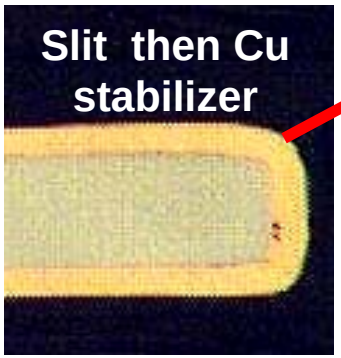
In 25 m lengths, average Ic loss in total of all 3 slits = 15%

In 25 m lengths, average Ic loss in total of all 3 slits: 7% with 50 micron substrates

Surround Stabilizer: Slit first & then stabilizer applied

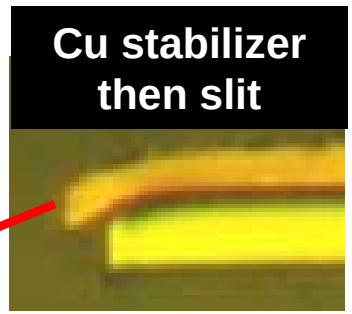


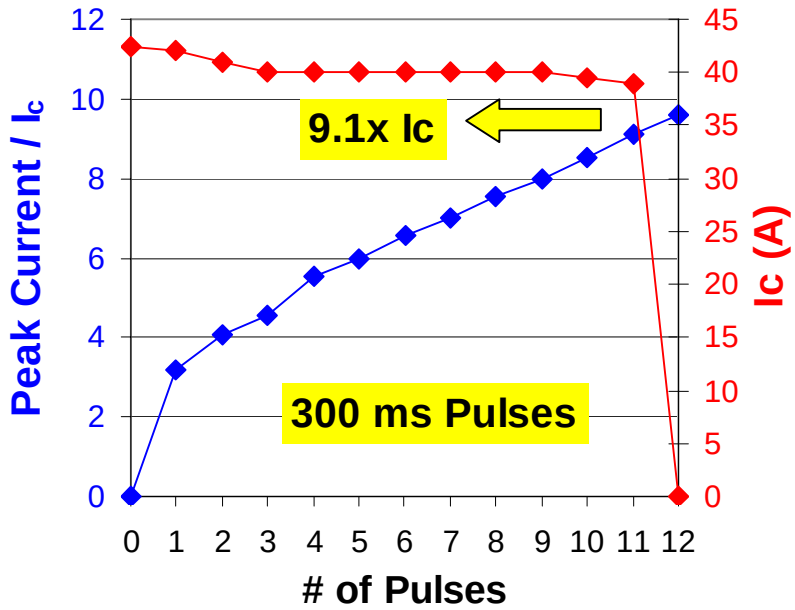
- An advantage of electroplating is "Surround Stabilizer" application, i.e. copper on all sides in 1 step.
- HTS is completely encased and protected
- Rounded edges – could be important for high-voltage applications



rounded edges

Sharp edges





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

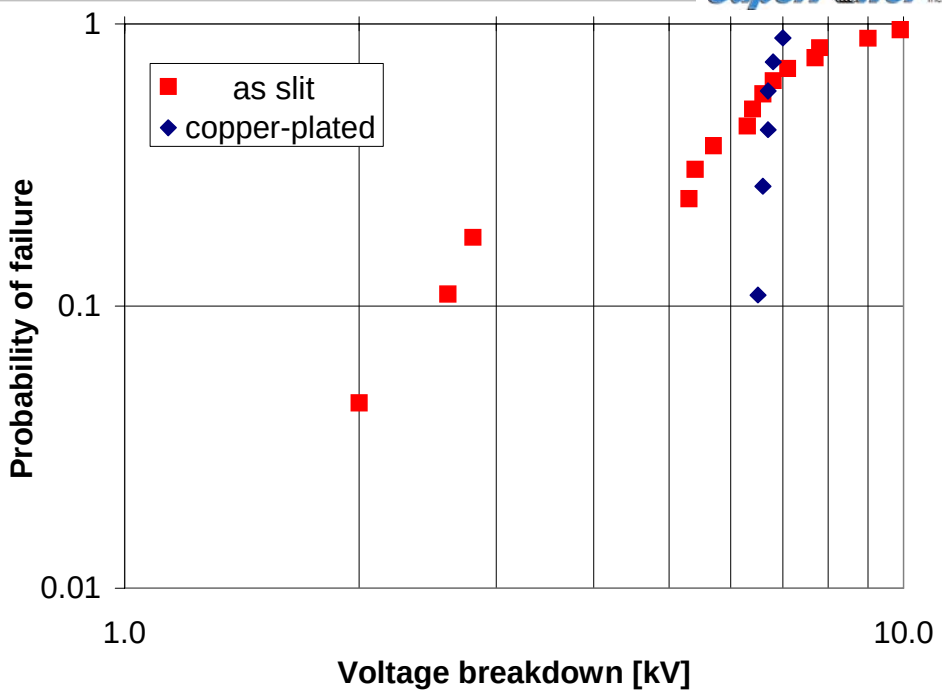
"Surround Copper Stabilizer" has been successfully implemented & tested on several hundred meters of conductor

*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 *.

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

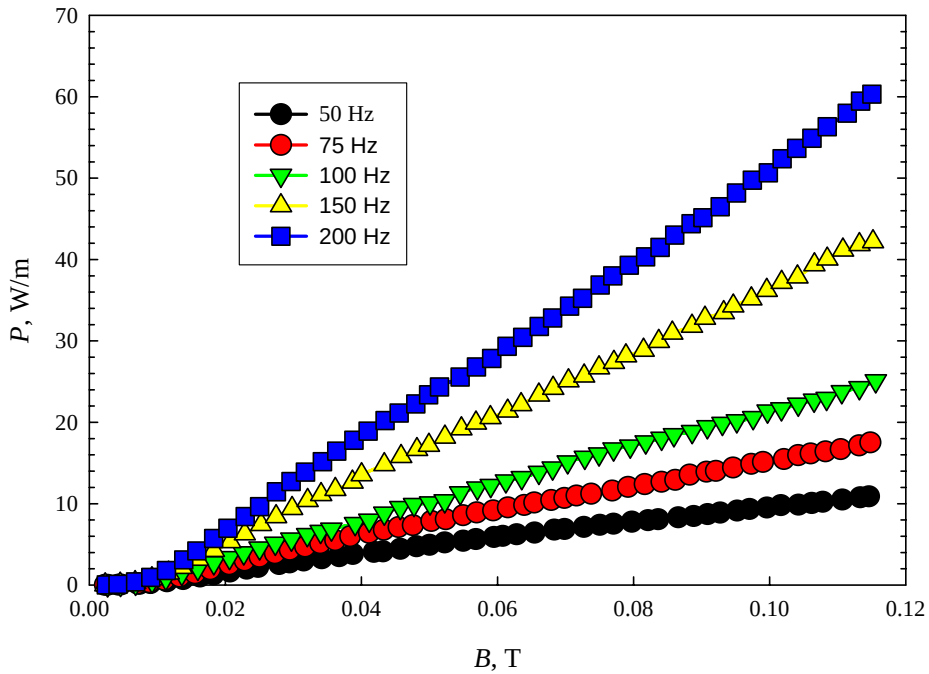
Probability of failure at low voltages is <u>much reduced</u> in conductors with surround stabilizer

*C. Rey, DOE Wire Workshop, January 2005

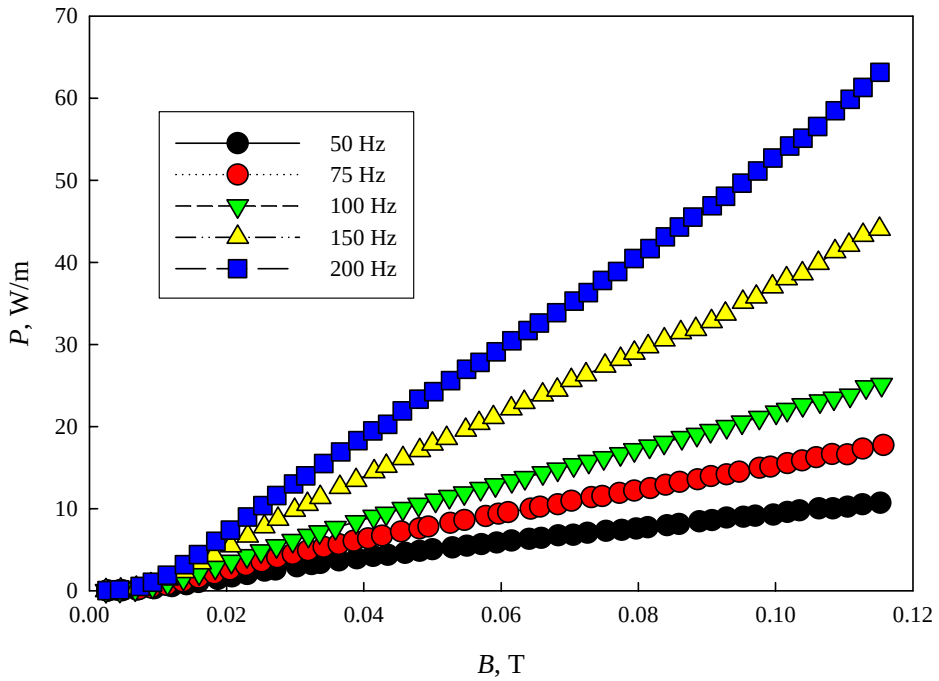
Surround stabilization of conductor is advantageous for ac tolerance too

Previous concern about effect of additional copper for stability on ac losses

Conductor w/ 20 μm Cu on YBCO side only



Conductor w/ 20 μm Cu on all sides (Surround stabilizer)



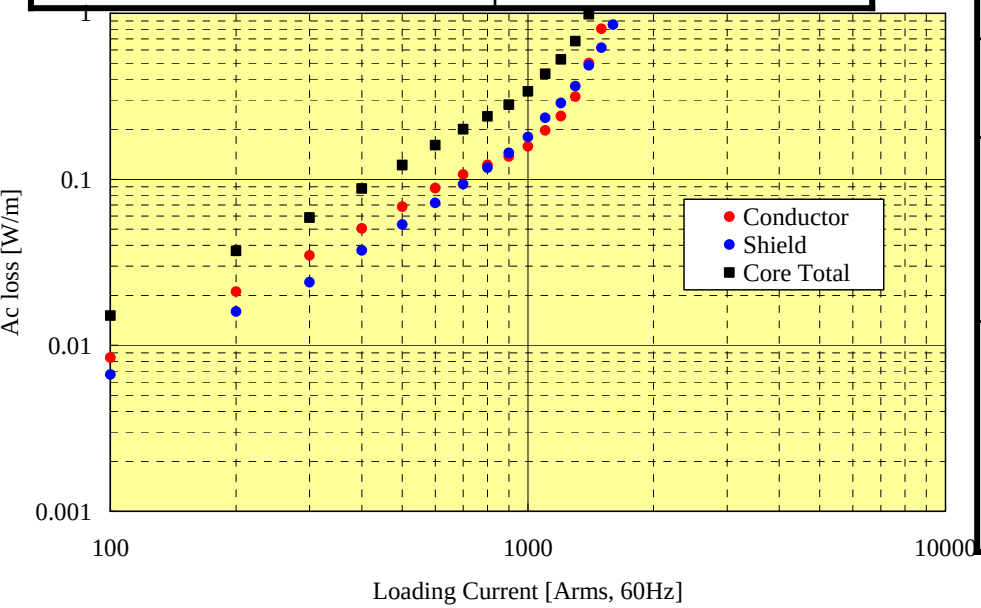
No additional ac losses from 20 microns of copper on substrate side!

Measurements by M. Sumption, OSU

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	

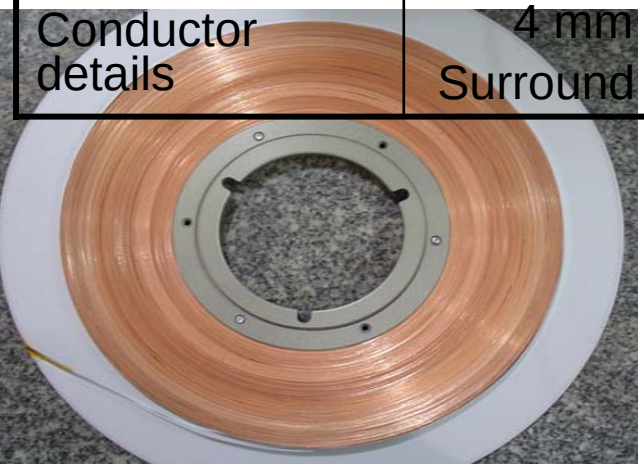
Cable features	06/04	07/05
# conductor layers	4	4
# shield layers	0	2
Total # 2G tapes used	48	88
Cable Ic (A)	2150	2350 (c) 2240 (s)
AC loss in conductor + copper former (W/m) @1000 A rms	0.4	0.16

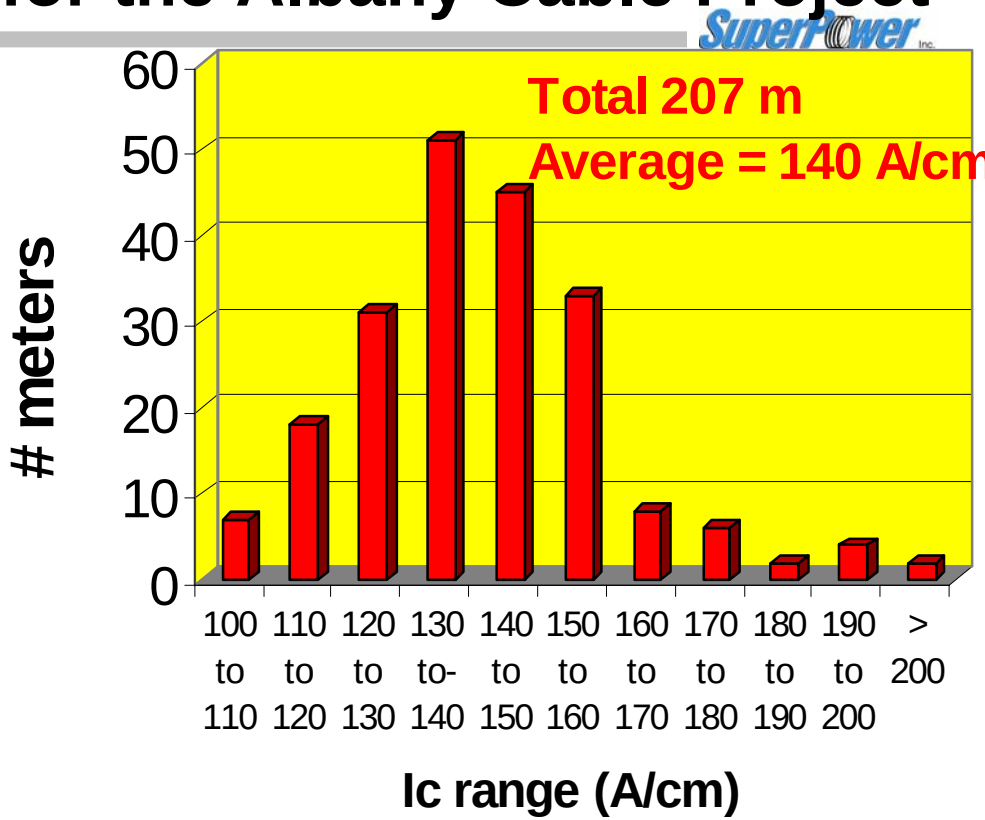


AC losses in conductor + copper former is 2.5 times less in the new 2G cable with a complete structure (shield layers)

Surround stabilized thin profile 2G conductor have been qualified & delivered 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	**95**
Conductor details	4 mm Surround Cu		



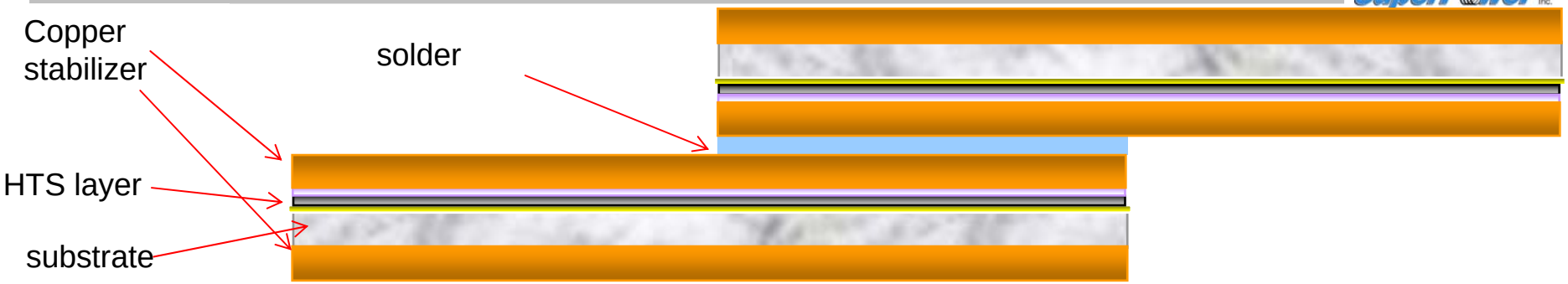


Thin-profile conductors were successfully qualified by hermeticity and bend, tensile &spiral winding tests

<u>No Ic loss in the following bend tests</u>:

- <u>Condition 1</u>: Tensile @ 2" → Compressive @ 2" → Compressive @ 1" → Tensile @ 1"
- <u>Condition 2</u>: Compressive @ 2" → Tensile @ 2" → Tensile @ 1" → Compressive @ 1".

Joints between 2G conductors show good electrical & thermo-mechanical properties

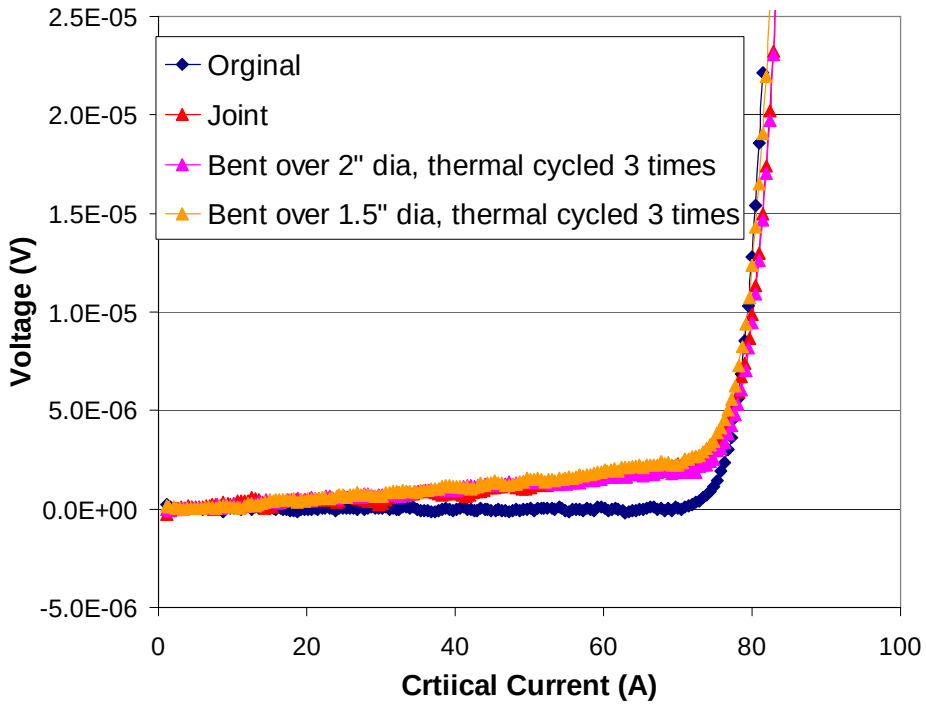


4 mm wide conductors each with 20 μm surround copper stabilizer

Joint length = 3 cm

Original tape thickness = 0.145 mm

Thickness at joint = 0.32 mm



No degradation in Ic (1 μV/cm) over the joint

Resistivity over the joint is 38 nohm-cm^2

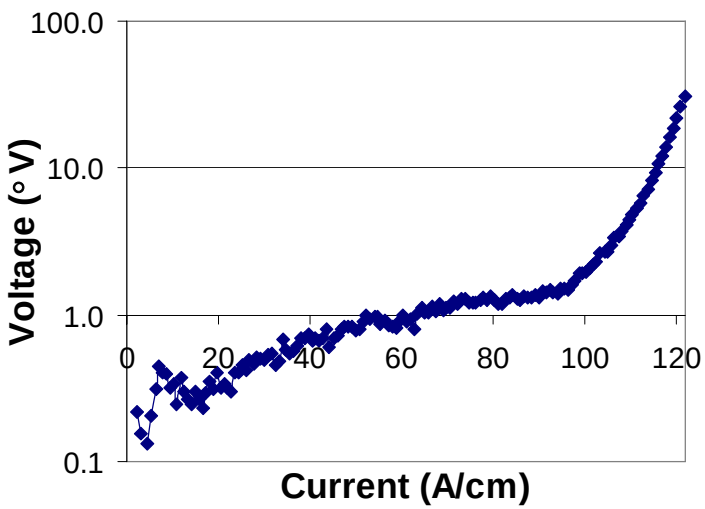
No degradation in Ic and resistivity when bent over down to 1.5" diameter and thermal cycled three times. Ic was tested at every thermal cycle

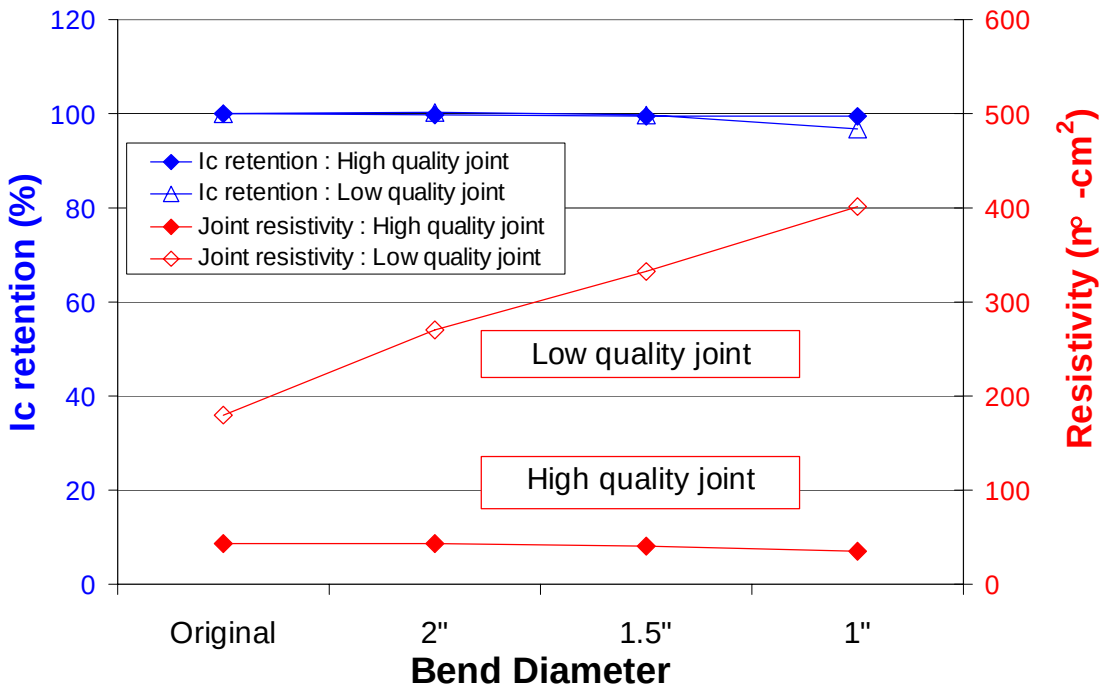
When further bent over 1" mandrel, solder material failed.

Joints between thin-profile conductors also shown excellent mechanical & electrical performance

Thickness at joint can be reduced from 0.32 mm to 0.22 mm by using thin-profile conductors (w/ 50 micron substrates)

- 4 mm wide conductors each with 20 μm surround copper stabilizer
- Joint length = 3 cm
- Original tape thickness = 0.095 mm
- Thickness at joint = 0.22 mm



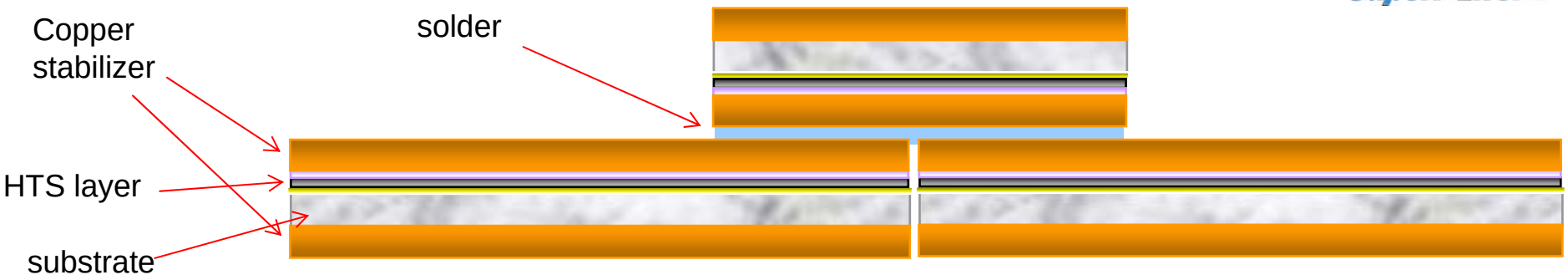


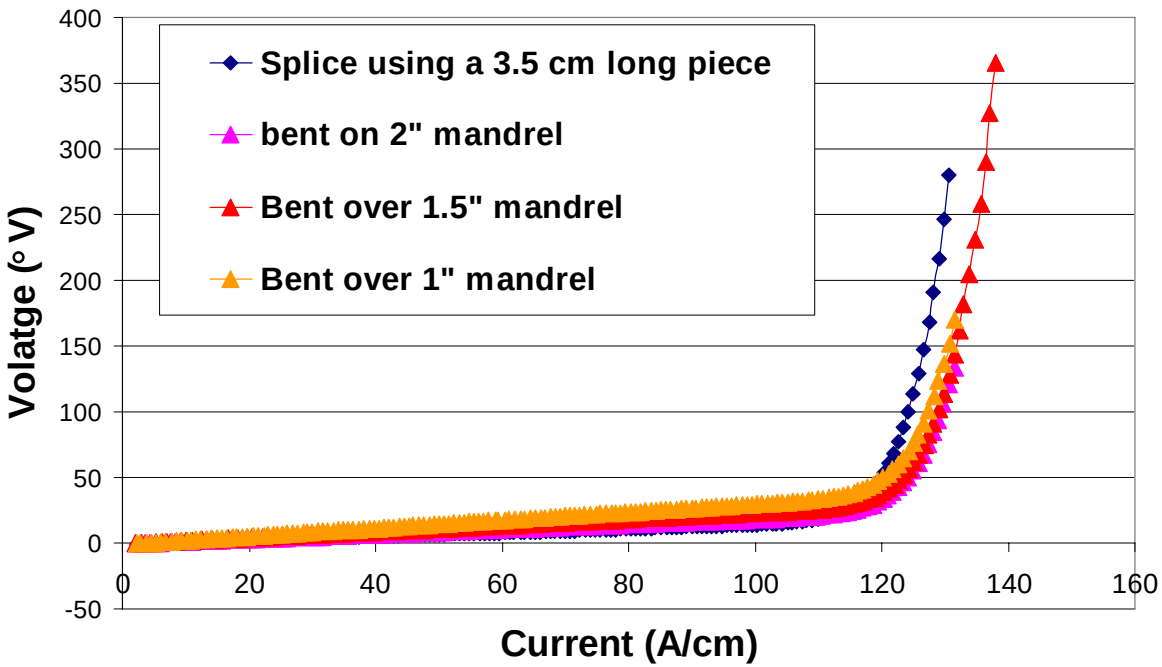
Joint resistivity = 40 nΩcm²

Ic across joint & resistivity of joint are not affected down to a bend diameter of 1”

Quality of joint primarily determines electrical & mechanical performance

Splices of thin-profile conductors also show excellent mechanical & electrical properties





Two 4 mm wide, 0.095 mm thick (50 micron substrate, 20 micron surround copper stabilizer spliced with a similar piece 3.5 cm long.

Splice Resistivity = 50 $n\Omega cm^2$

No Ic degradation when splice was bent down to 1" diameter.

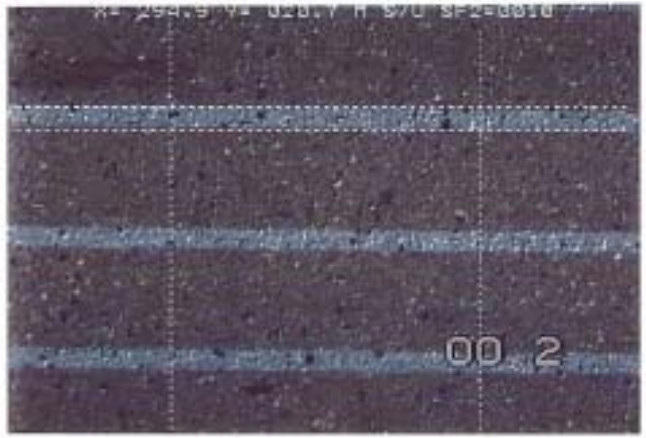
AC tolerant conductors with fine line widths & spacings created by photolithographic patterning

Narrow line widths are preferred for low ac loss.

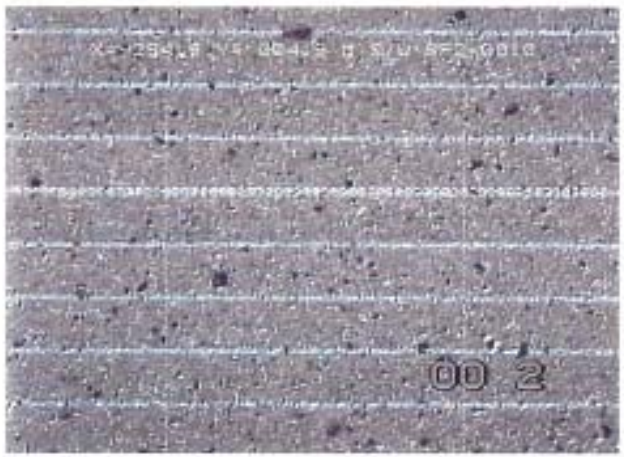
Narrow line spacings are needed to minimize loss of conductor.

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

YBCO line width = 100 μm
Line spacing = 100 μm



YBCO line width = 100 μm
Line spacing = 20 μm



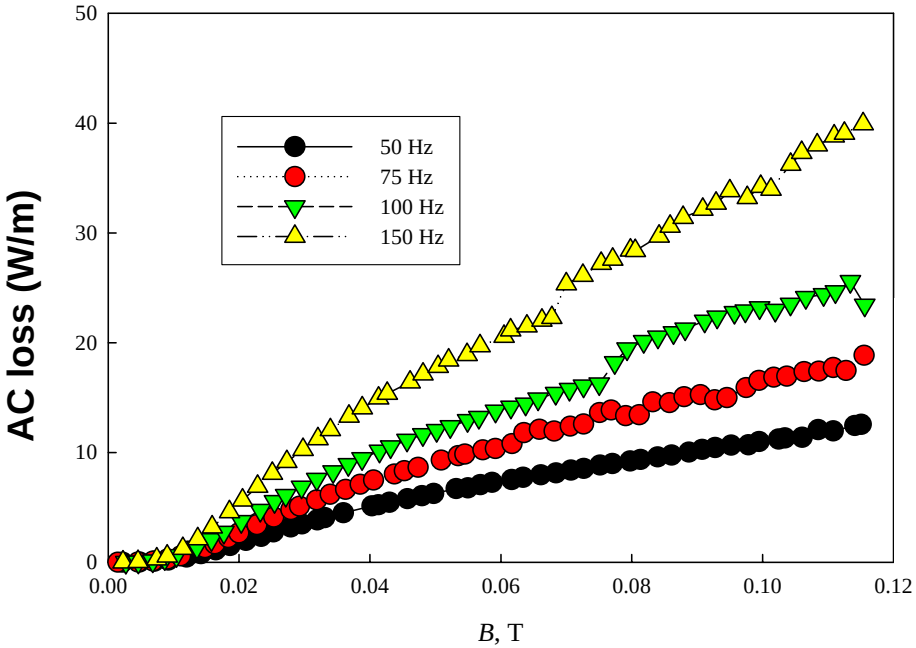
YBCO line width = 50 μm
Line spacing = 5 μm

YBCO line width = 100 μm
Line spacing = 10 μm

Significant ac loss reduction over a range of frequencies & magnetic fields

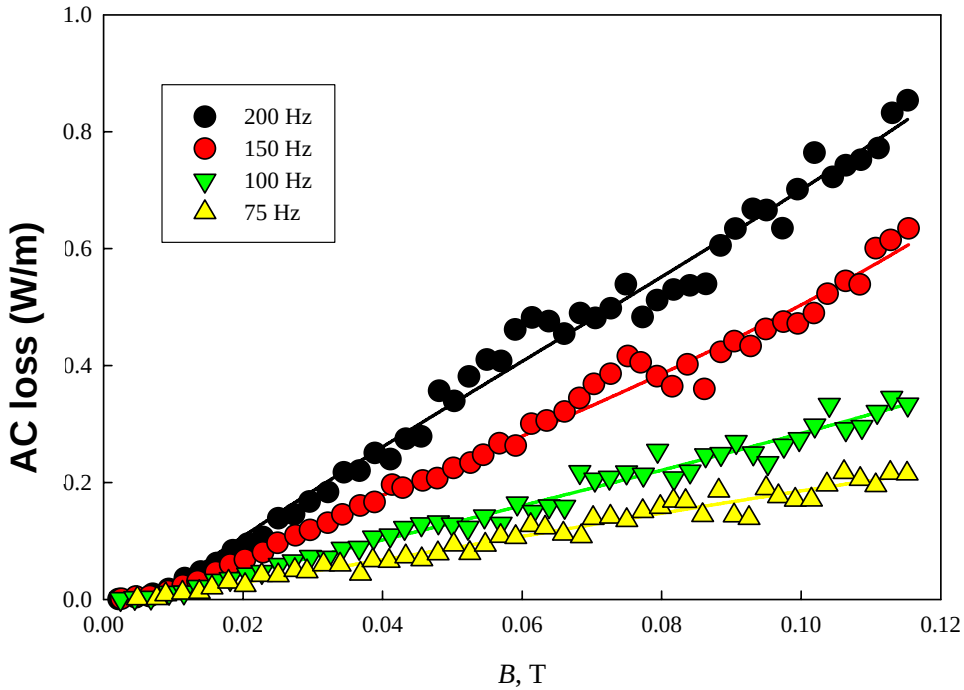
12 mm wide, 0.105 mm thick

Unstriated, 2 μm silver



12 mm wide, 0.105 mm thick

100 micron wide filaments, 25 micron spacing, 2 μm silver



At 0.1 T, 150 Hz ac loss of

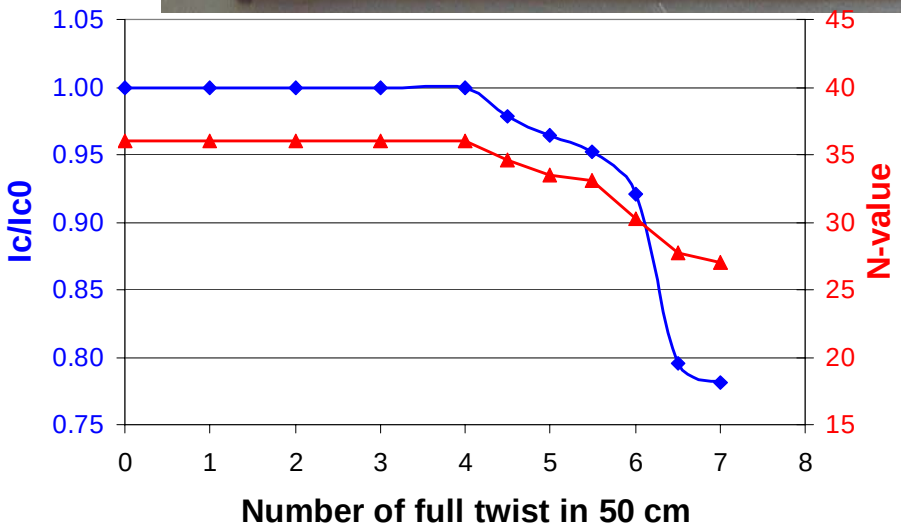
Standard tape: 34 W/m

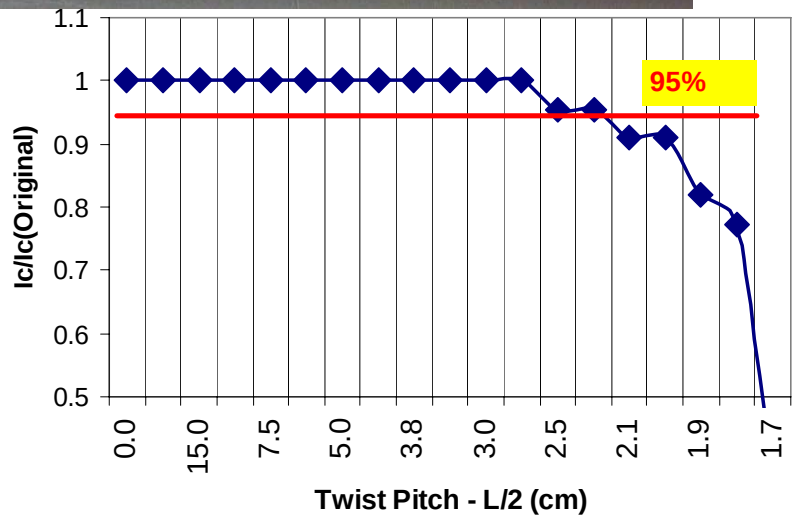
Tape striated with 100 micron filaments: 0.42 W/m (reduction of 73)

Measurements by M. Sumption, OSU

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

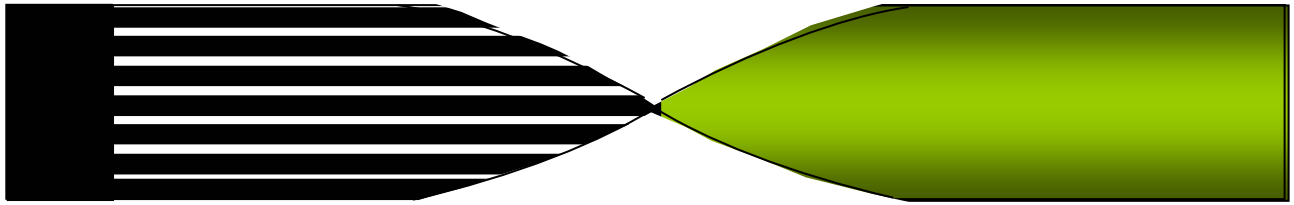


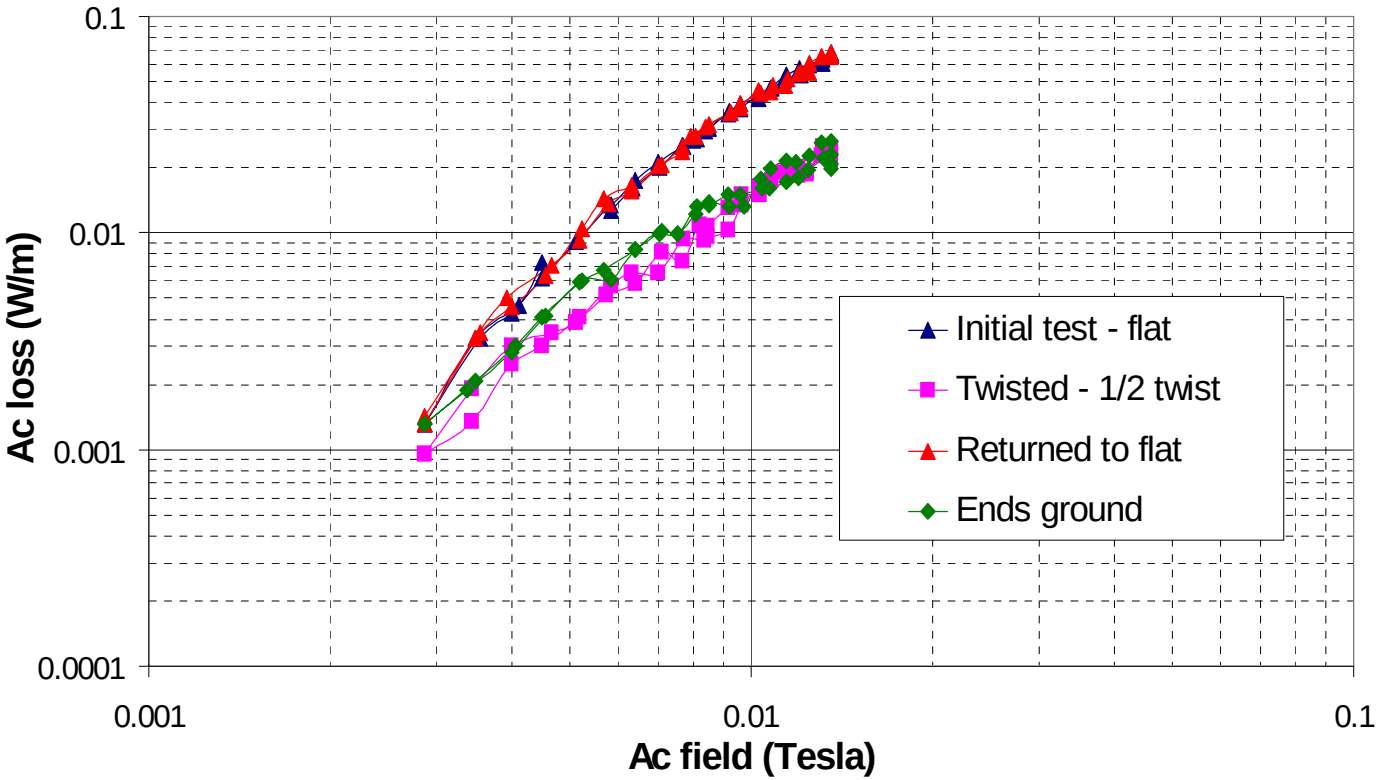


95% original Ic retained at 5.5 full twists (Twist pitch = 9.4 cm)

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

SuperPower's thin-profile 2G conductor specs

- **Width** = 4 mm
- **Thickness** = 75 to 95 microns (for stabilizer 20 to 40 microns)
  More than 2x times thinner than other 2G wires!
- **Surround stabilizer** = Customer specified (typical 40 microns total)
- **Critical tensile stress** > 550 MPa
- **Yield Strength** = 1200 MPa @ 76 K
- **Bend dia in tension** = 11 mm
- **Bend dia in compression** = 11 mm
- **Joint or Splice resistivity** = 50 $n\Omega cm^2$
- **Joint or Splice bend diameter** = 25 mm
- **Axial tensile strain** ~ 0.5%
- **Twist pitch** = 9.4 cm (4.6 cm for 2 mm wide wire)
- **Low AC loss in conductor because of nonmagnetic & resistive substrate. AC loss can be reduced 10 to 100 times after striation by photolithography**
- **Good dielectric strength because of rounded corners of stabilizer**

Several configurations of thin-profile 2G conductors available for various applications

Model	Width (mm)	Substrate thickness (mm)	Total thickness (mm)	Copper stabilizer thickness (mm)	Thickness at joint (mm)	Applications
SS 4050	**4**	**0.050**	**0.095**	**0.04**	**0.22**	**Cable & coils**

Various other conductor configurations (2 mm, 1 mm wide, etc.) are also available