



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

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HTS Solutions for a New Dimension in Power

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



Thin-profile conductor using 50 micron substrates

-  Higher J_e – 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

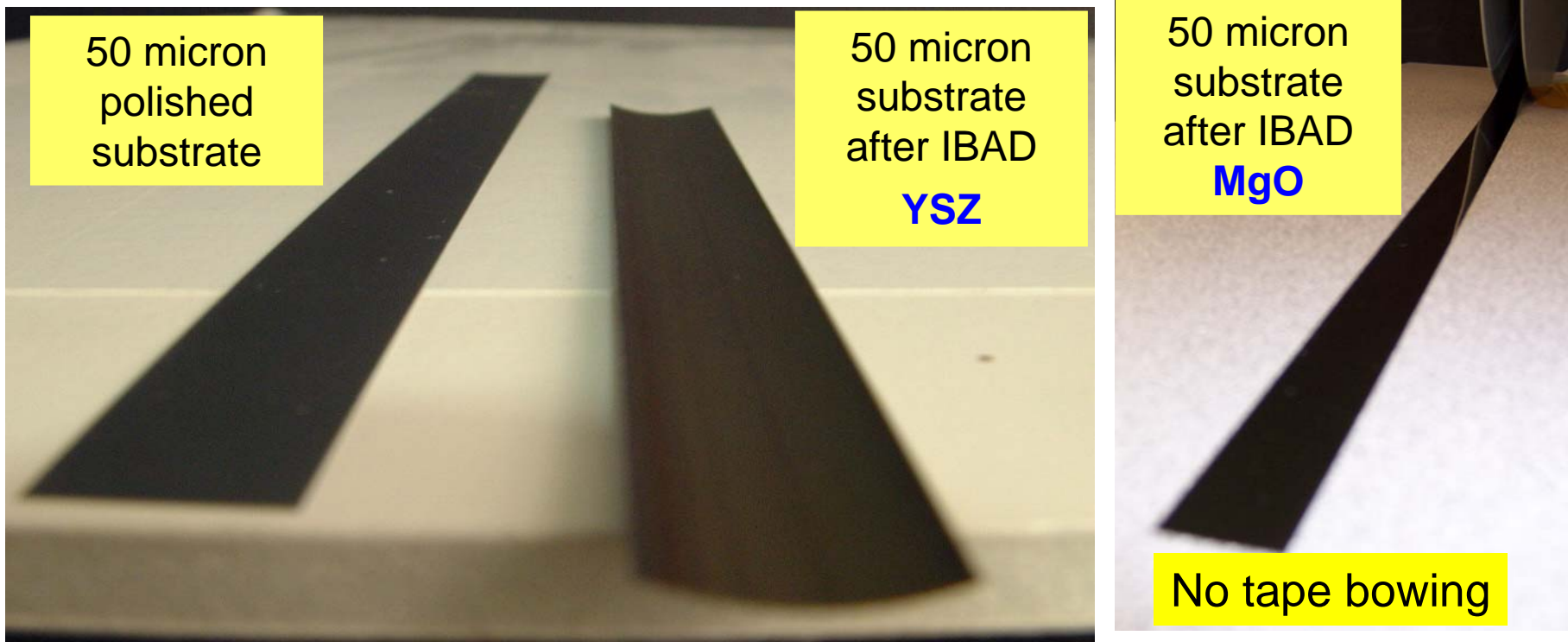
-  First ac loss measurements on striated AND twisted conductor

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

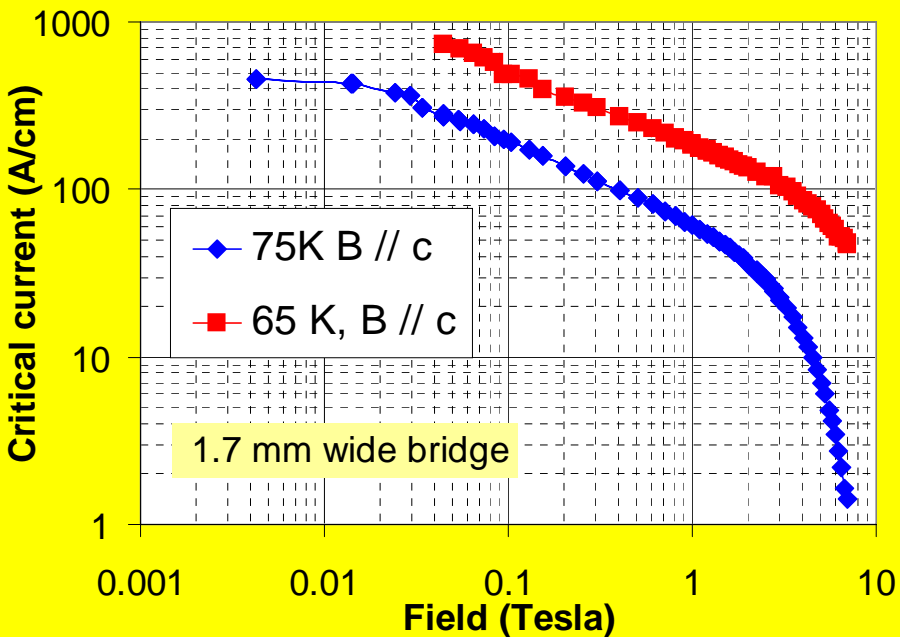
Transitioning to IBAD MgO provided the opportunity to use thin substrates (50 microns) for increased Je



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



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



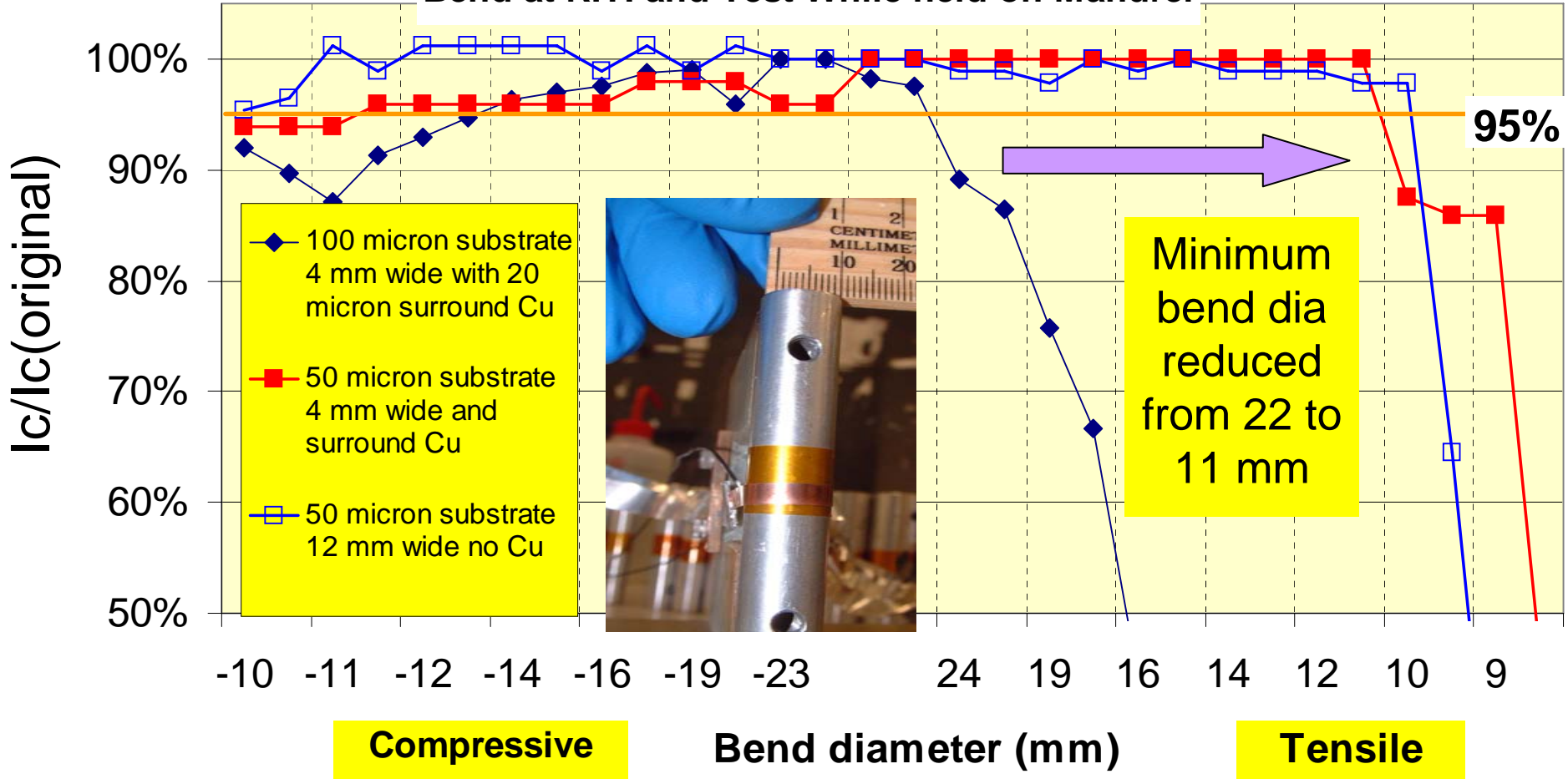
Title III program Je goals:

10 kA/cm² @ 65 K, 2 T by Dec05

15 kA/cm² @ 65 K, 3 T by 2008

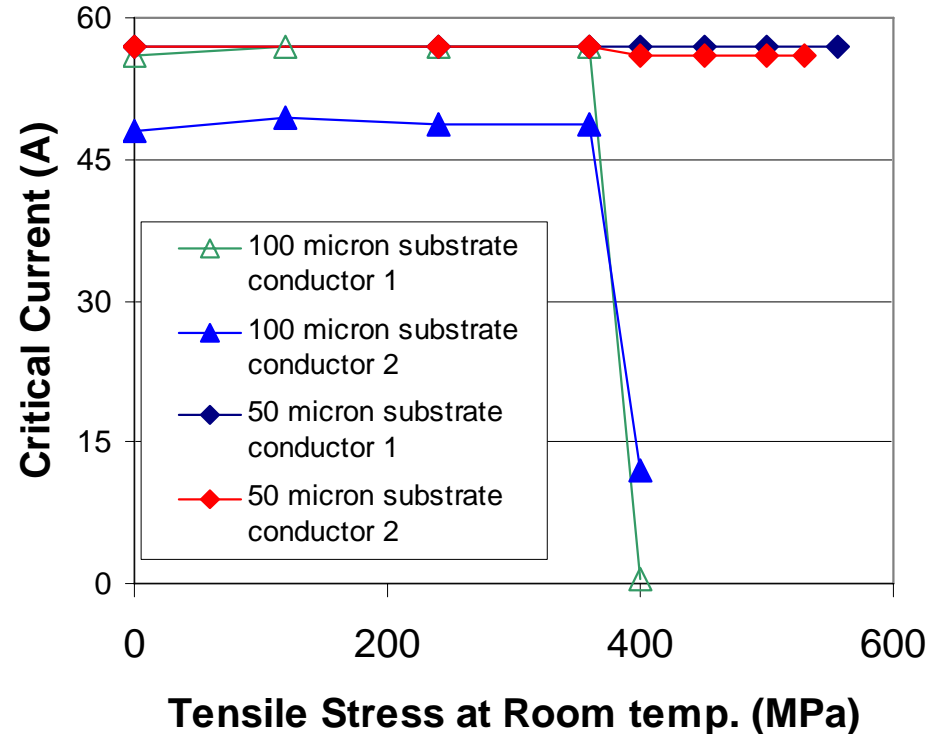
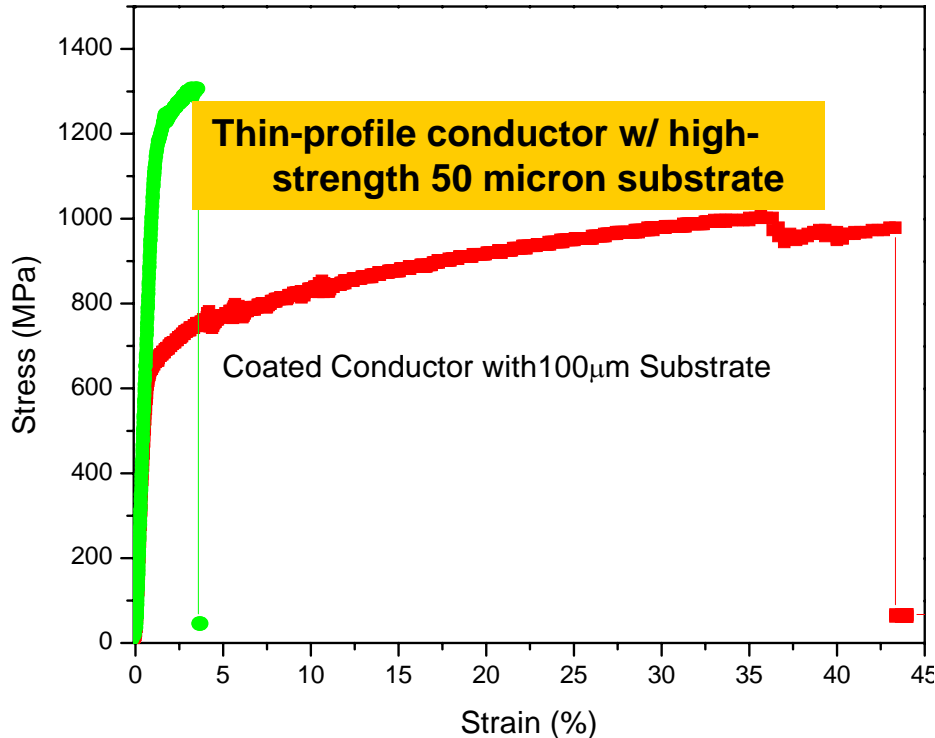
Bend performance significantly improved using thin-profile 2G conductors

Bend at R.T. and Test While held on Mandrel



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

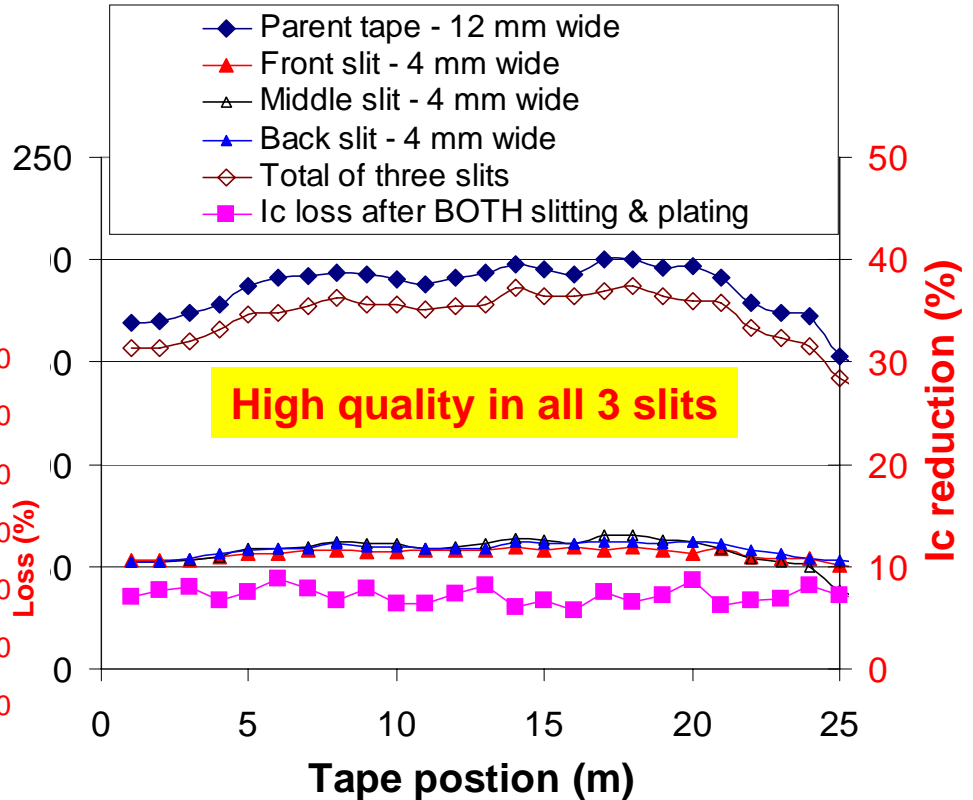
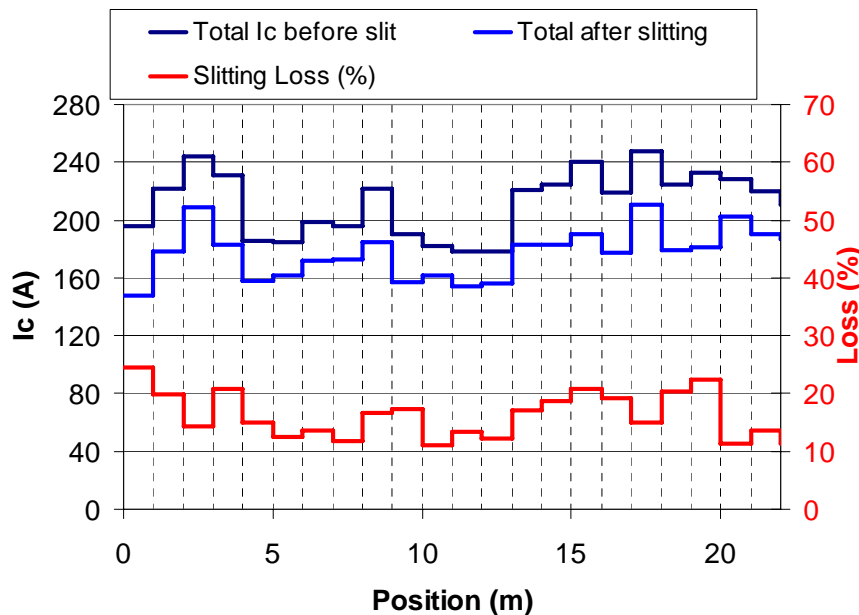
> **550 MPa**

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



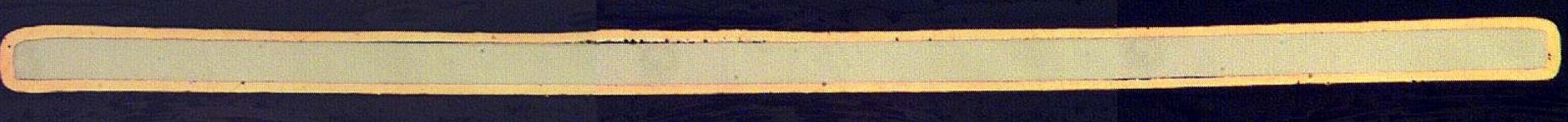
2G conductor with 50 micron substrate

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

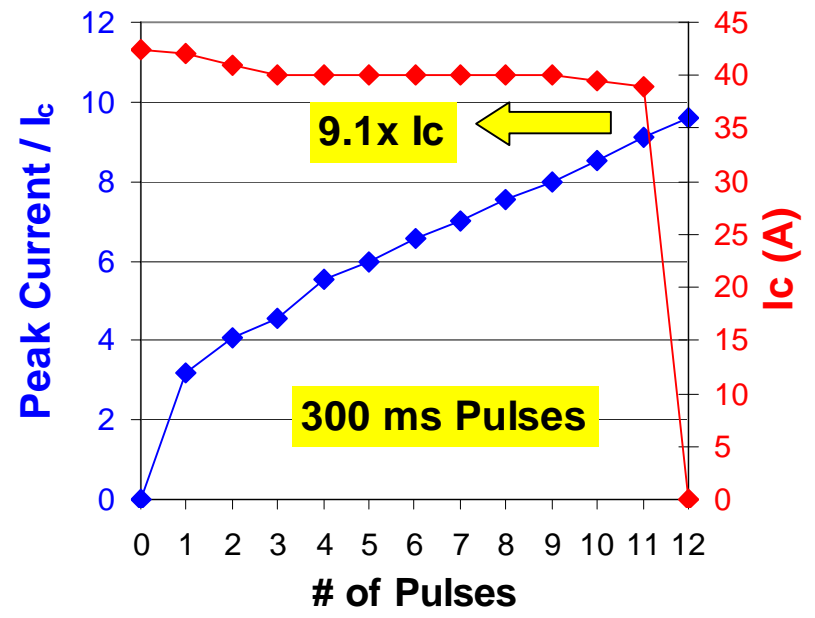
2G conductor with 100 micron substrate

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

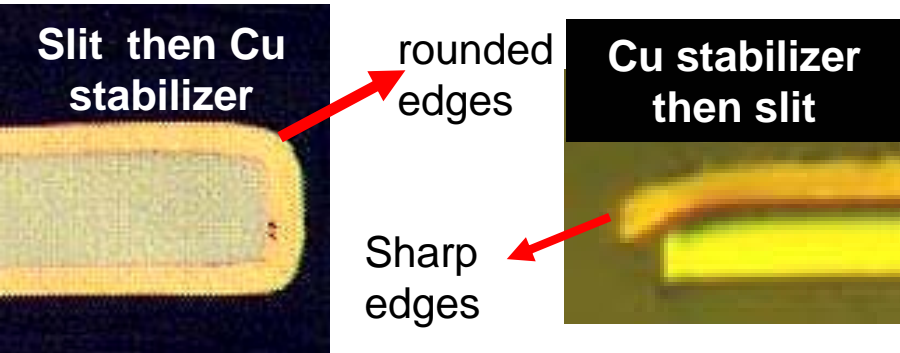
Surround Stabilizer: Slit first & then stabilizer applied



- 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



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



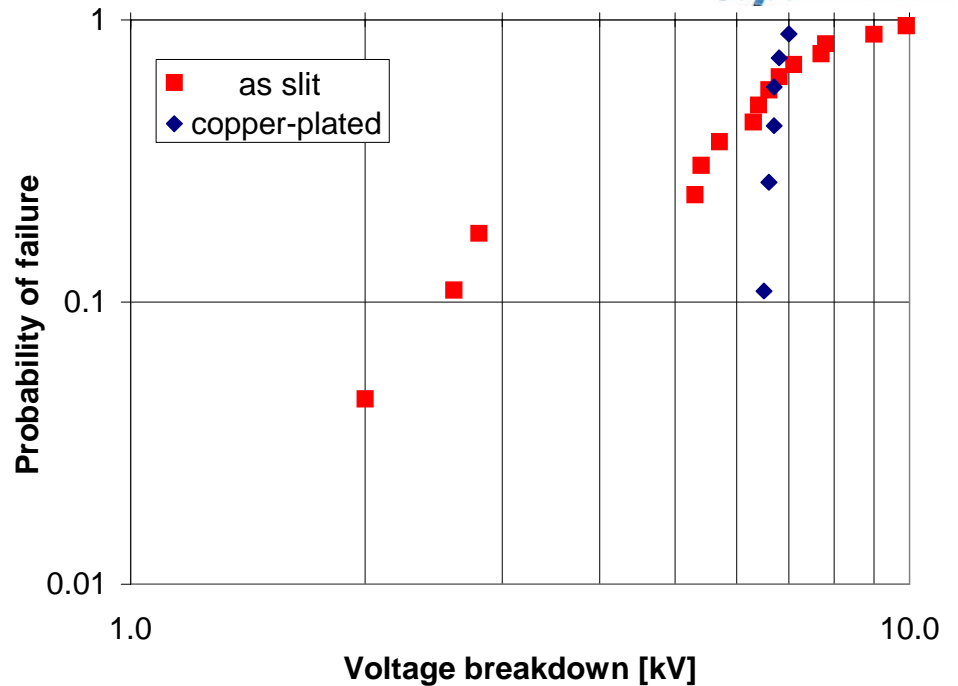
“Surround Copper Stabilizer” has been successfully implemented & tested on several hundred meters of conductor

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

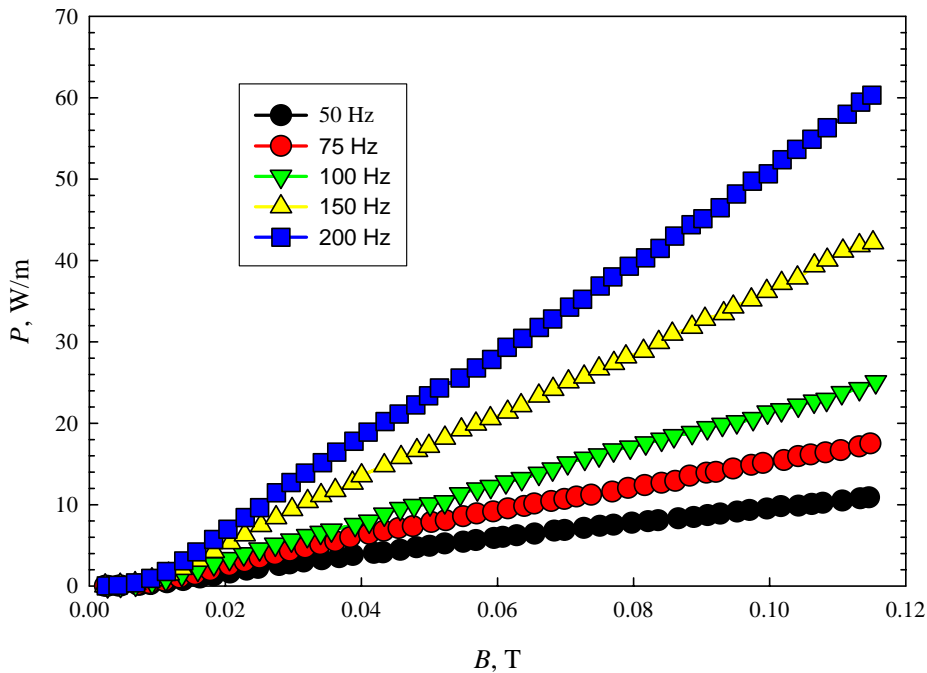
Sample	As-slit	Slit & surround stabilizer
Avg. Breakdown voltage	6.1 +/- 2.2 kV	6.7 +/- 0.2 kV
10% probability breakdown	2.1 kV	6.5 kV

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

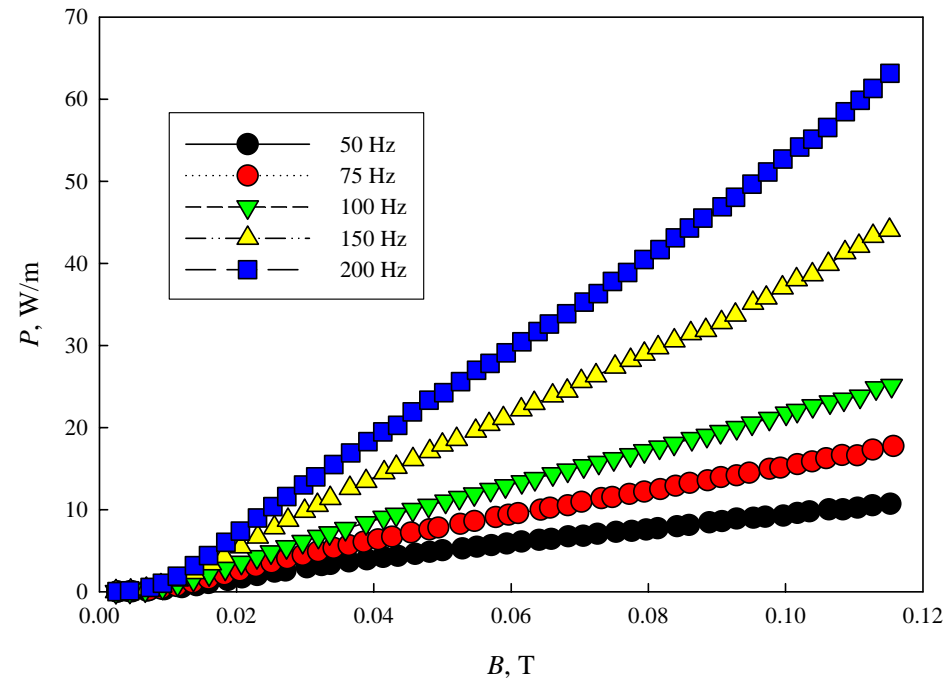
Surround stabilization of conductor is advantageous for ac tolerance too

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)



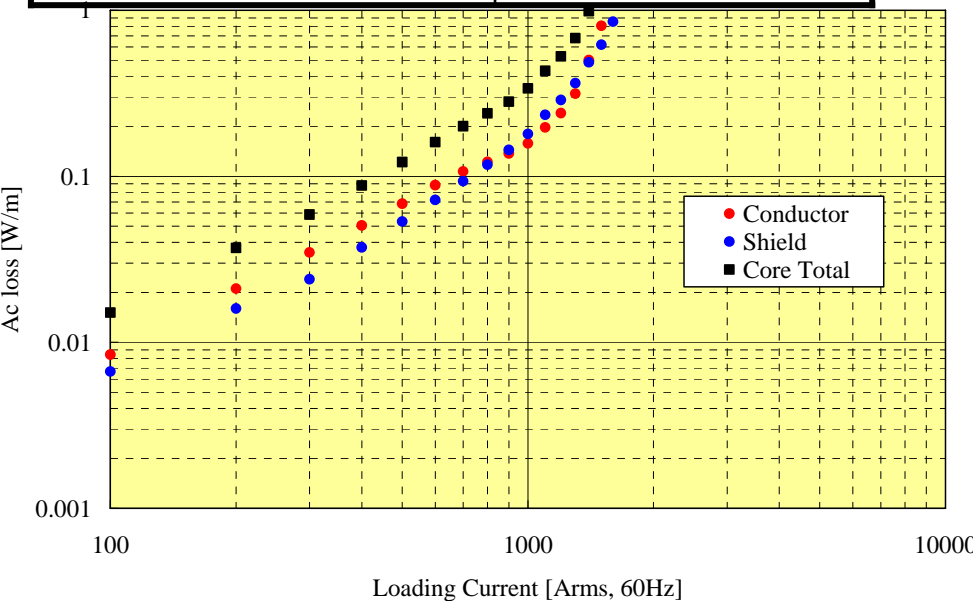
No additional ac losses from 20 microns of copper on substrate side!

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 I_c (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 I_c (A)	2150	2350 (c) 2240 (s)
AC loss in conductor + copper former (W/m) @ 1000 A rms	0.4	0.16

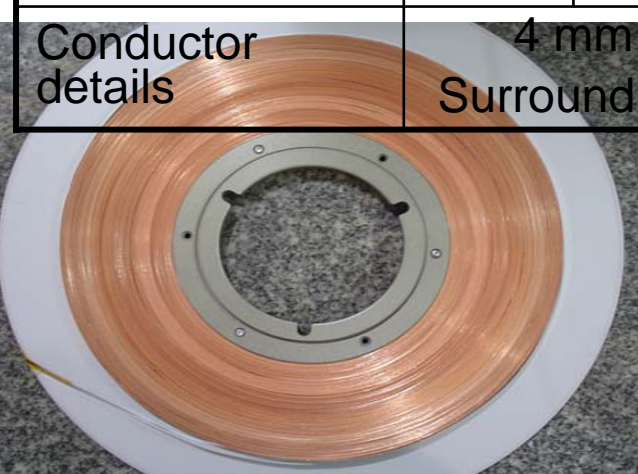
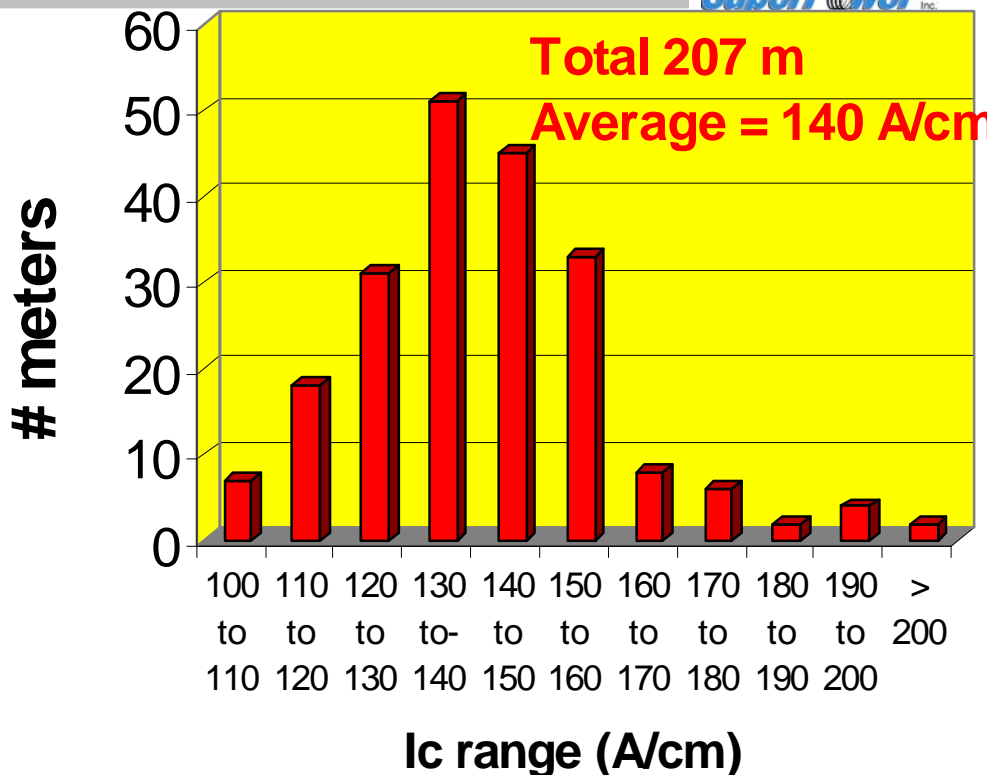


AC losses in conductor + copper former is 2.5 times less in the new 2G cable with a complete structure (shield layers)

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	

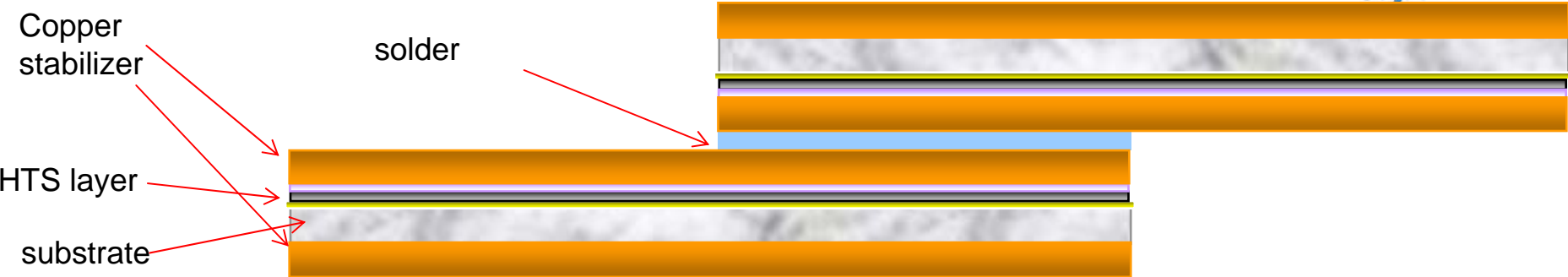


Thin-profile conductors were successfully qualified by hermeticity and bend, tensile & spiral winding tests

No Ic loss in the following bend tests:

- Condition 1: Tensile @ 2" → Compressive @ 2" → Compressive @ 1" → Tensile @ 1"
- Condition 2: 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

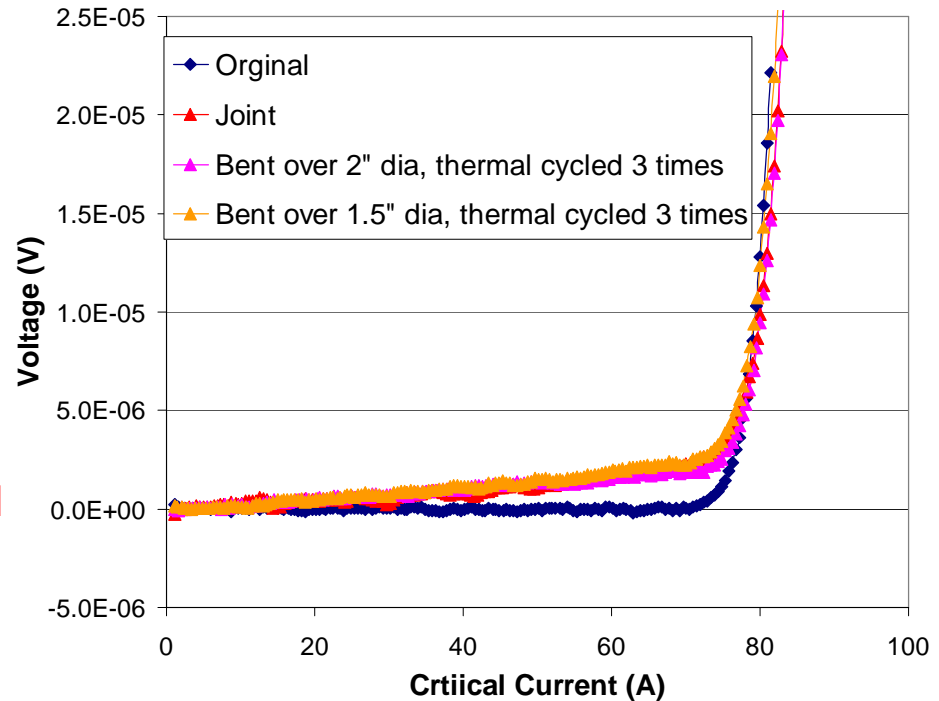
Thickness at joint = 0.32 mm

No degradation in I_c (1 $\mu\text{V}/\text{cm}$) over the joint

Resistivity over the joint is 38 $\text{n}\Omega\text{-cm}^2$

No degradation in I_c and resistivity when bent over down to 1.5" diameter and thermal cycled three times. I_c 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

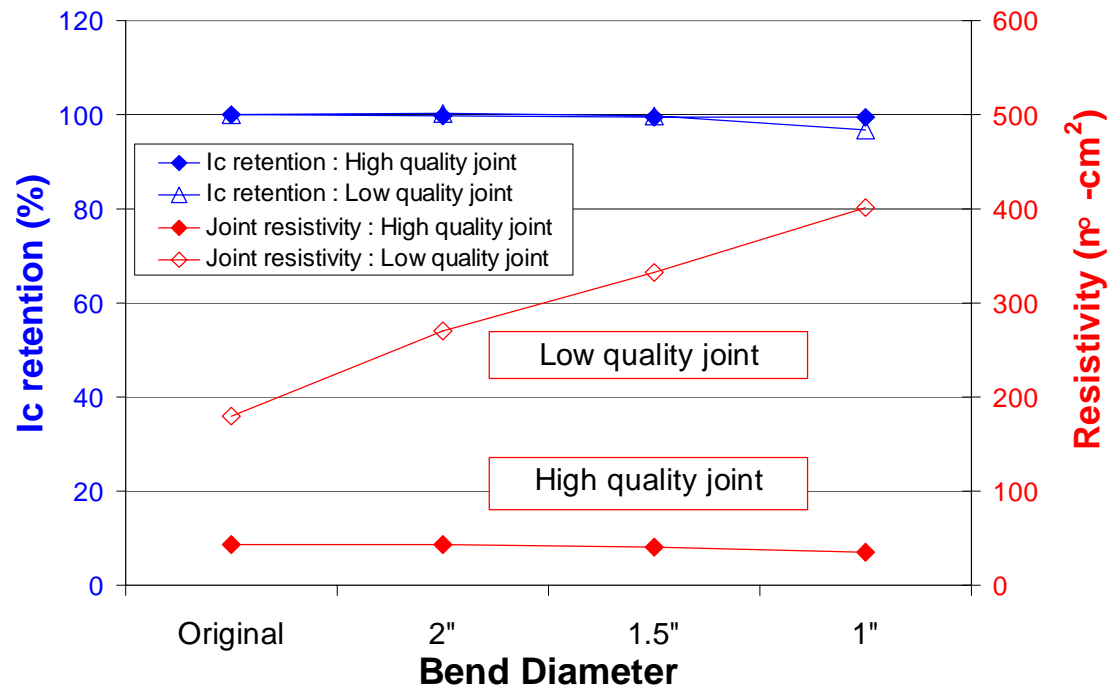
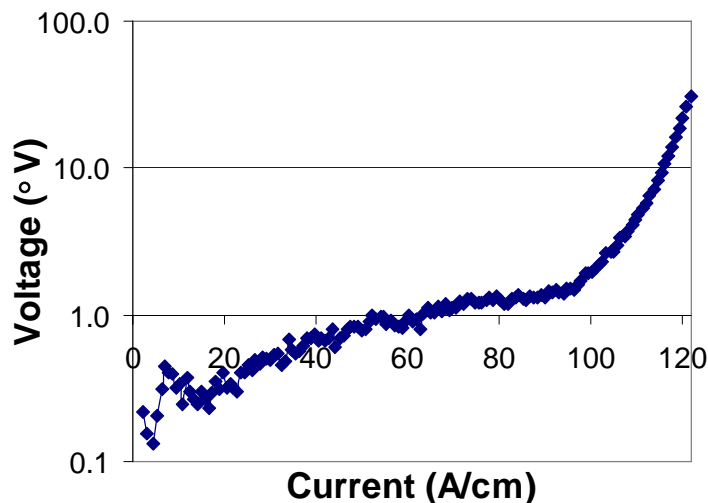
Thickness at joint can be reduced from 0.32 mm to 0.22 mm by using thin-profile conductors (w/ 50 micron substrates)

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**

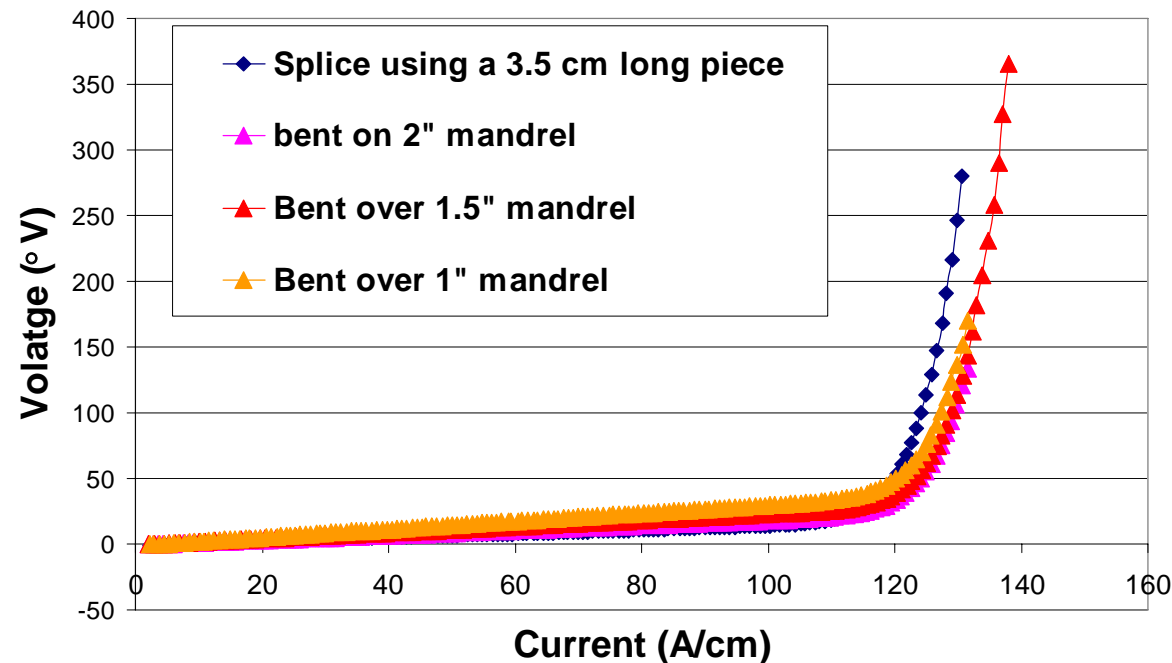
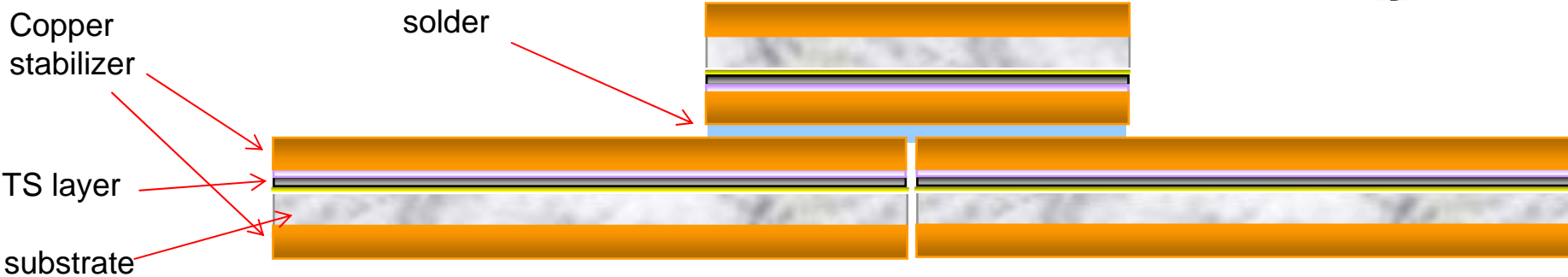


Joint resistivity = **40 $\text{n}\Omega\text{cm}^2$**

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 nΩcm²**

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

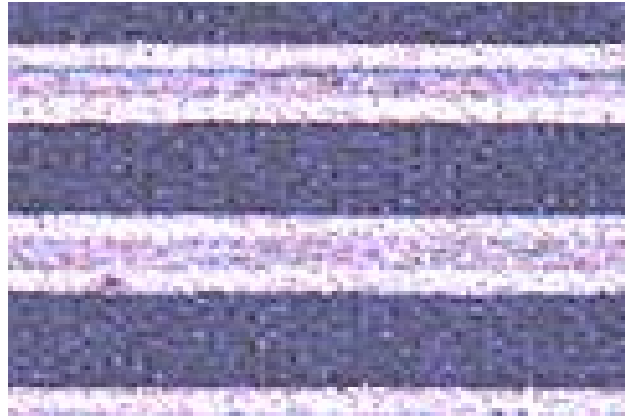
AC tolerant conductors with fine line widths & spacings created by photolithographic patterning

SuperPower

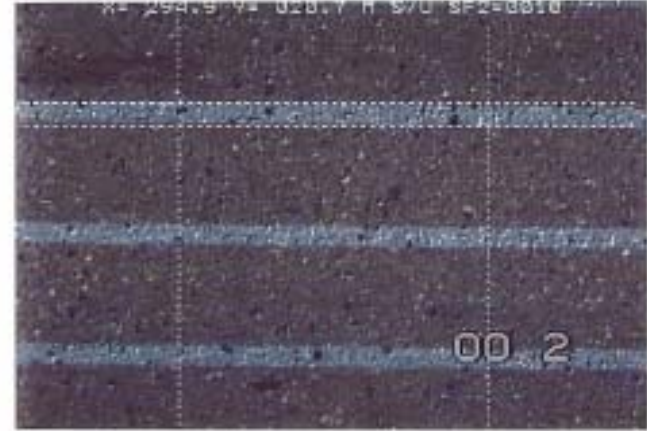
Narrow line widths are preferred for low ac loss.

Narrow line spacings are needed to minimize loss of conductor.

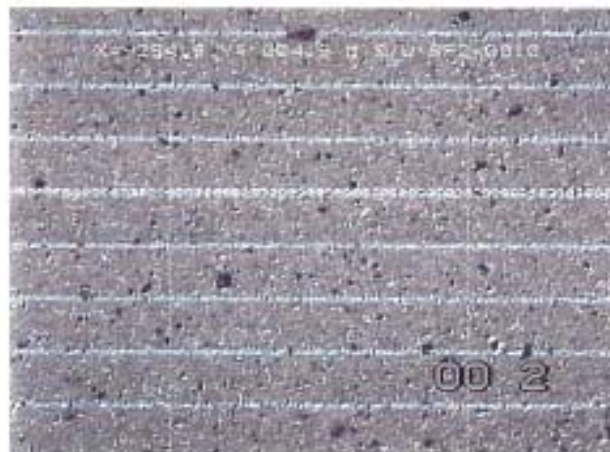
28 cm long conductors, 12 mm wide, 50 μm thick substrate, patterned *through YBCO & silver overlayer*



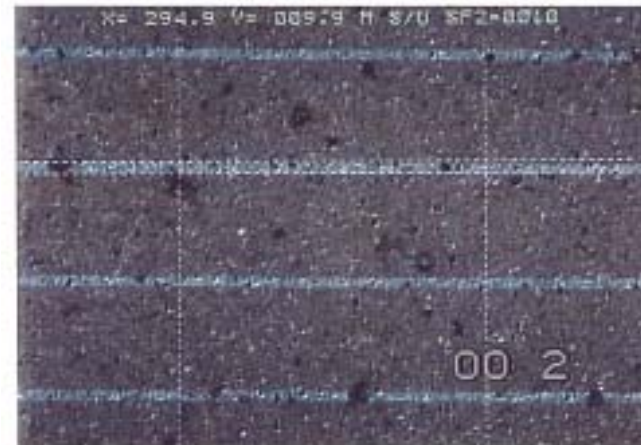
YBCO line width = 100 μm
Line spacing = 100 μm



YBCO line width = 100 μm
Line spacing = 20 μm



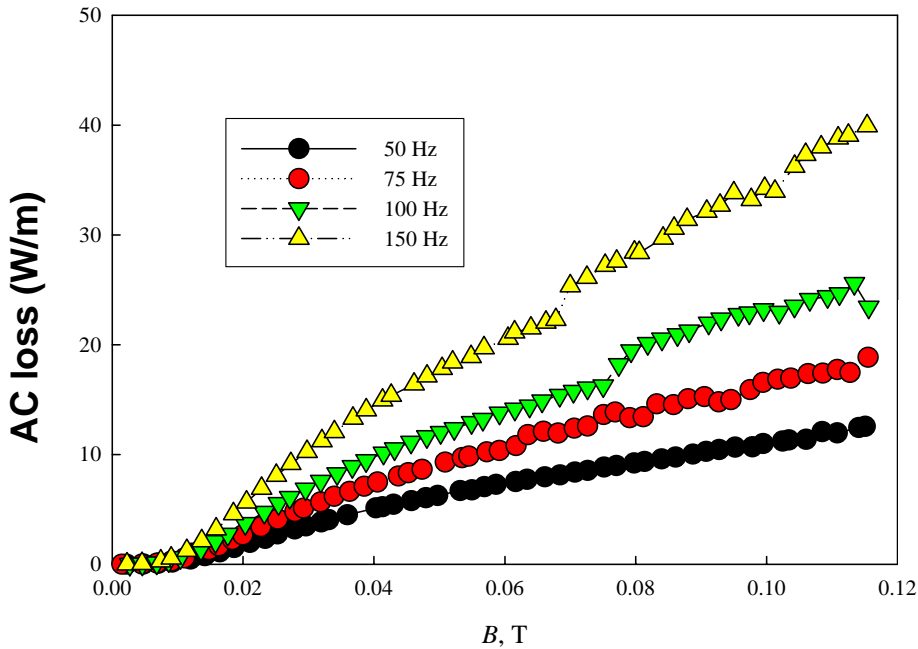
YBCO line width = 50 μm
Line spacing = 5 μm



YBCO line width = 100 μm
Line spacing = 10 μm

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

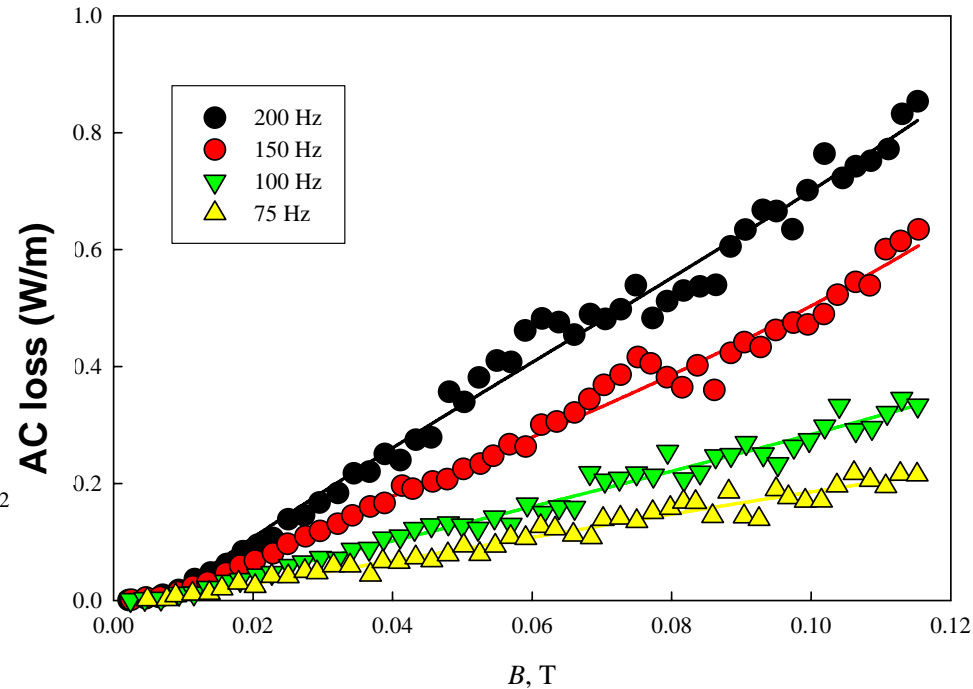
12 mm wide, 0.105 mm thick
Unstriated, 2 μm silver



At 0.1 T, 150 Hz ac loss of
Standard tape: 34 W/m

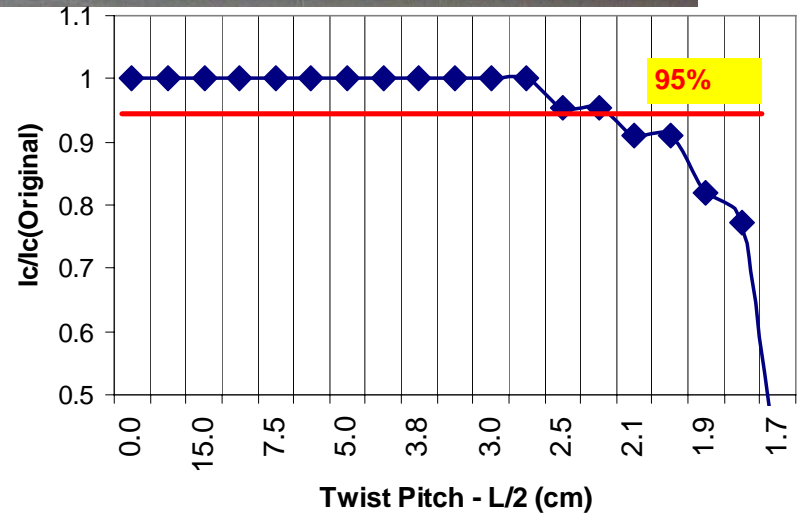
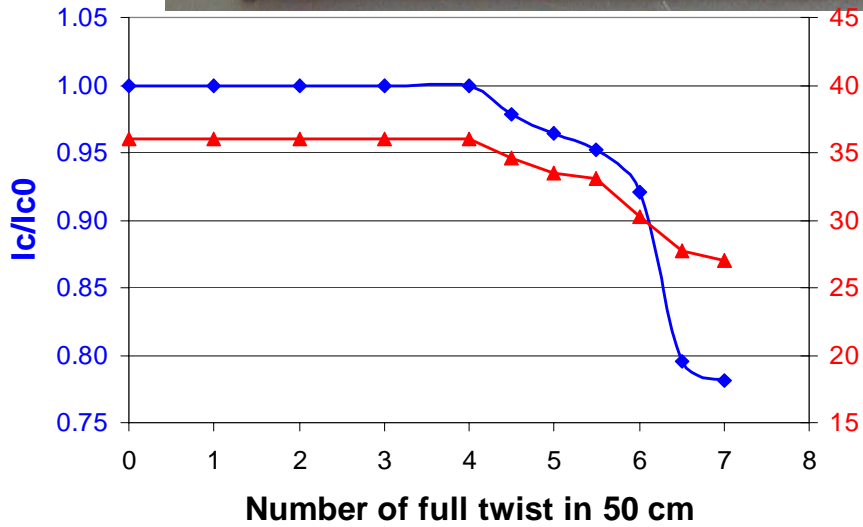
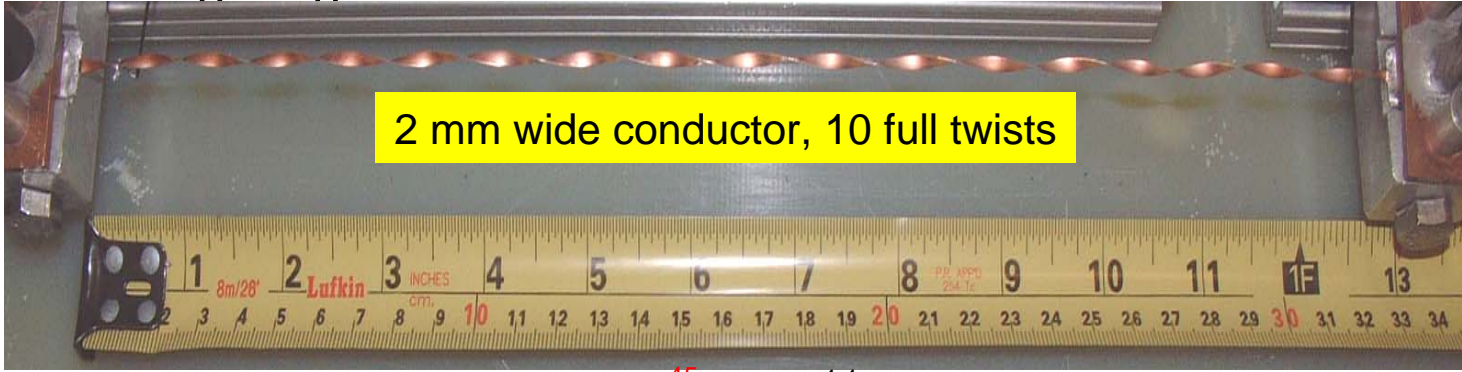
Tape striated with 100 micron filaments: 0.42 W/m (reduction of 73)

12 mm wide, 0.105 mm thick
**100 micron wide filaments, 25
micron spacing, 2 μm silver**



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

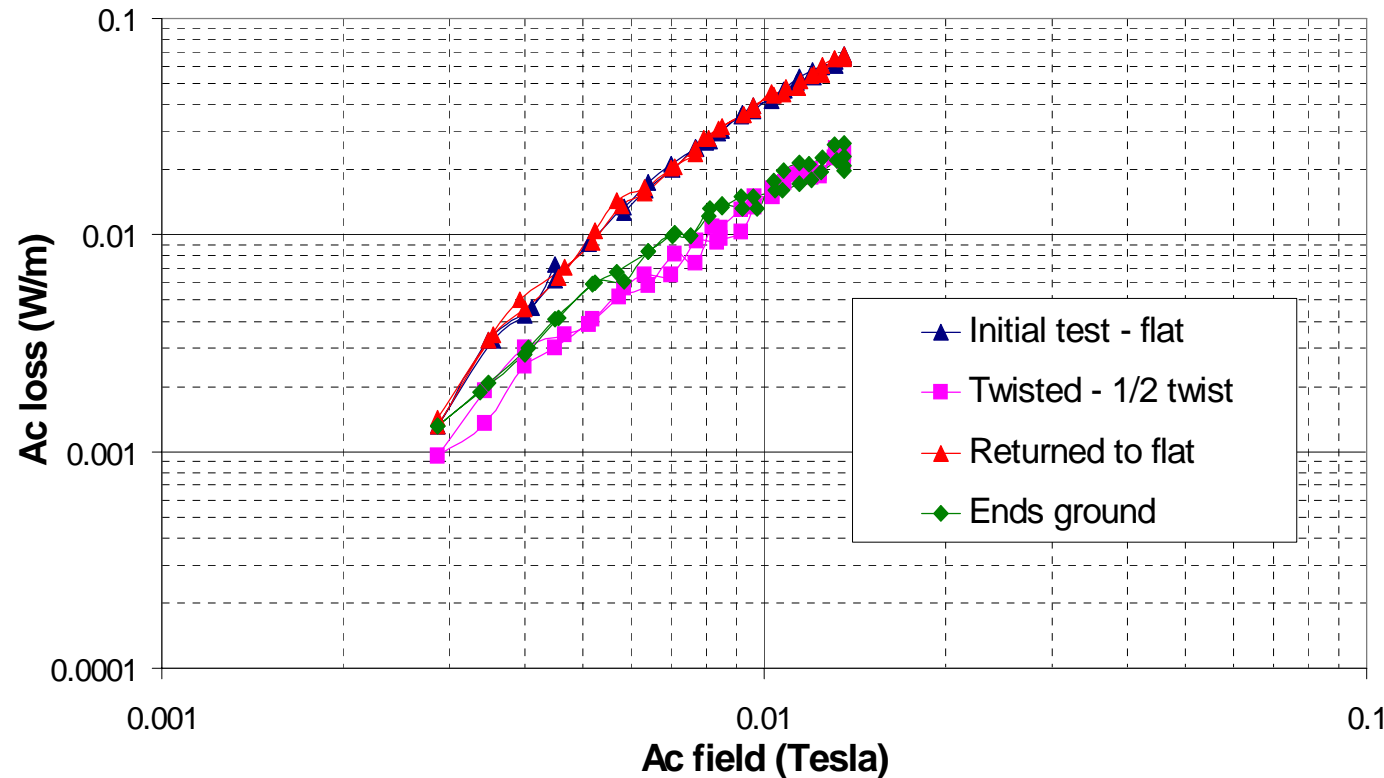
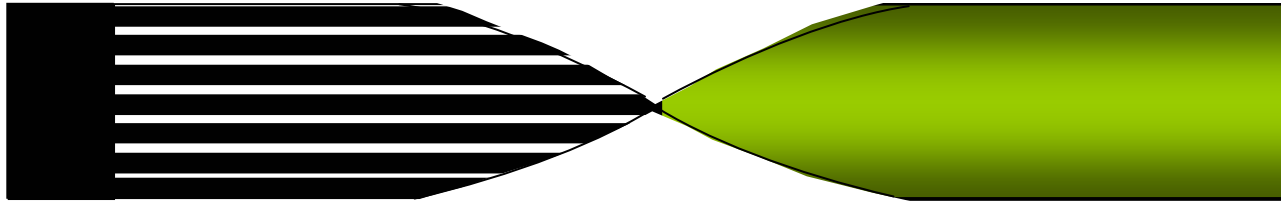
Twisting needs to be demonstrated in order for striated geometry to be fully effective in long lengths



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

95% original I_c 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 –
Photolithographic
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 nΩcm²
- 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