

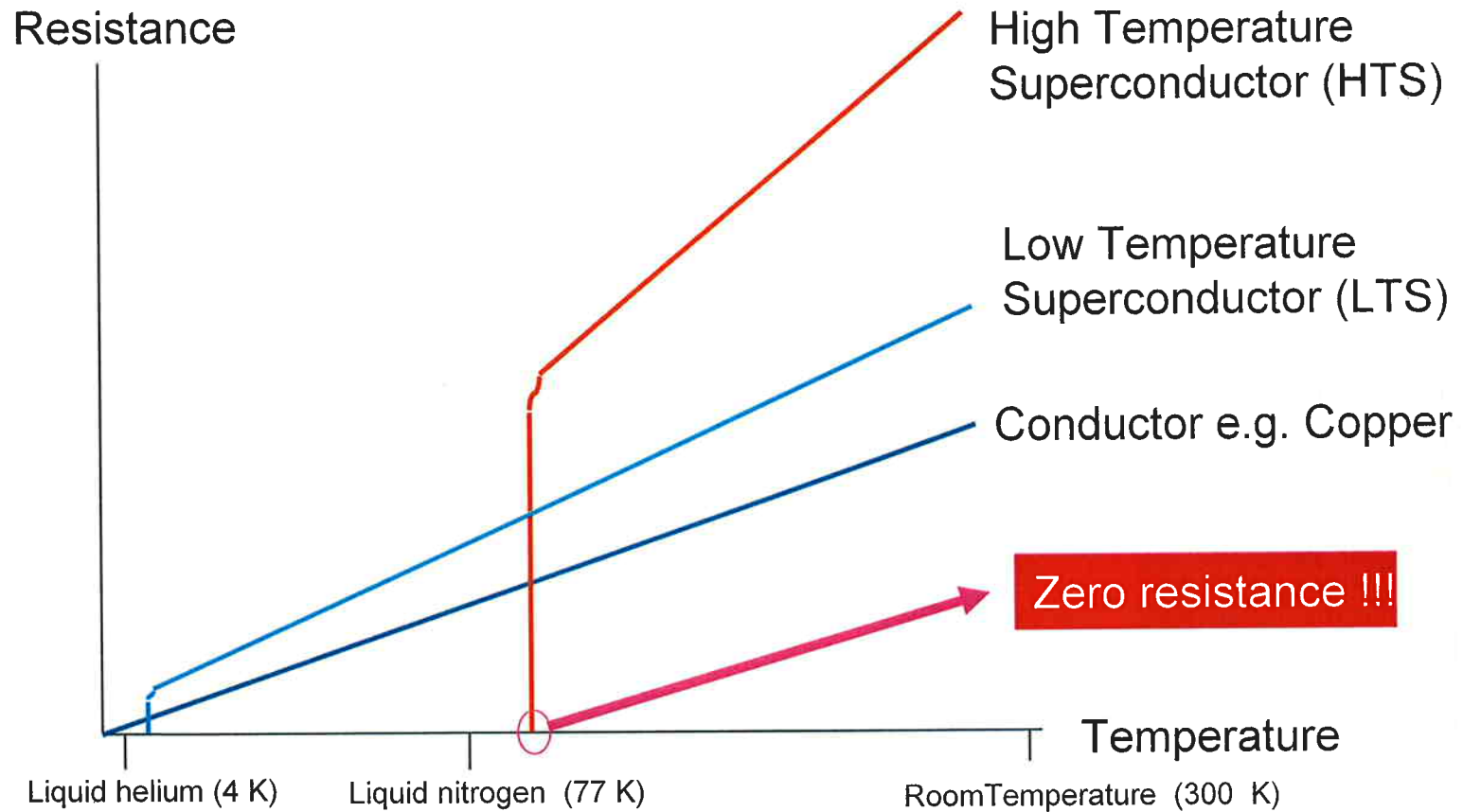


## **Fabrication of Long Lengths of Flexible High-temperature Superconductor Thin Film Tapes for Electric Power Applications**

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- ▶ **X. Xiong, Y. Chen, P. Hou, T. Salagaj, Y. Xie, M. Gardner, J. Reeves, Y. Qiao, Y. Li, K. Lenseth, and V. Selvamanickam**

# High Temperature Superconductors (HTS) can carry much higher current than copper

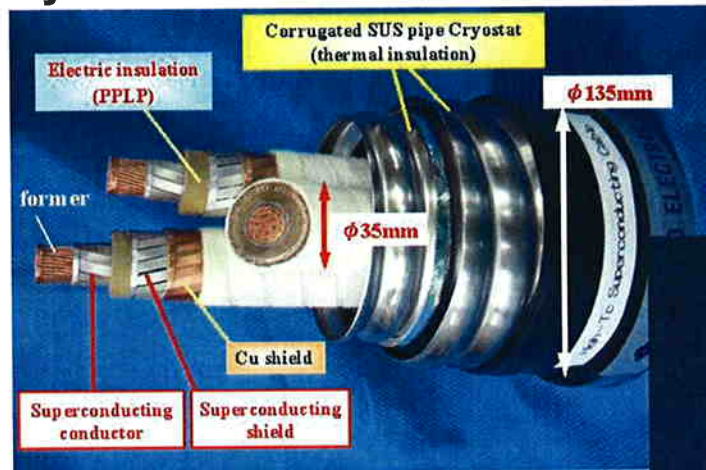


**Current carrying capability of copper ~ 100 A/cm<sup>2</sup>**

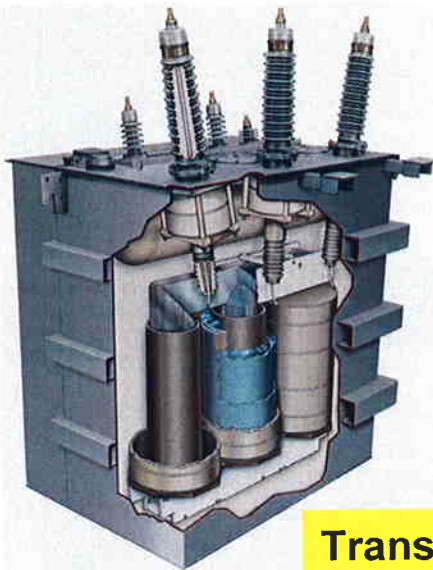
**Current carrying capability of superconductor ~ 1,000,000 A/cm<sup>2</sup>**

# Significant benefits of HTS for electric power industry

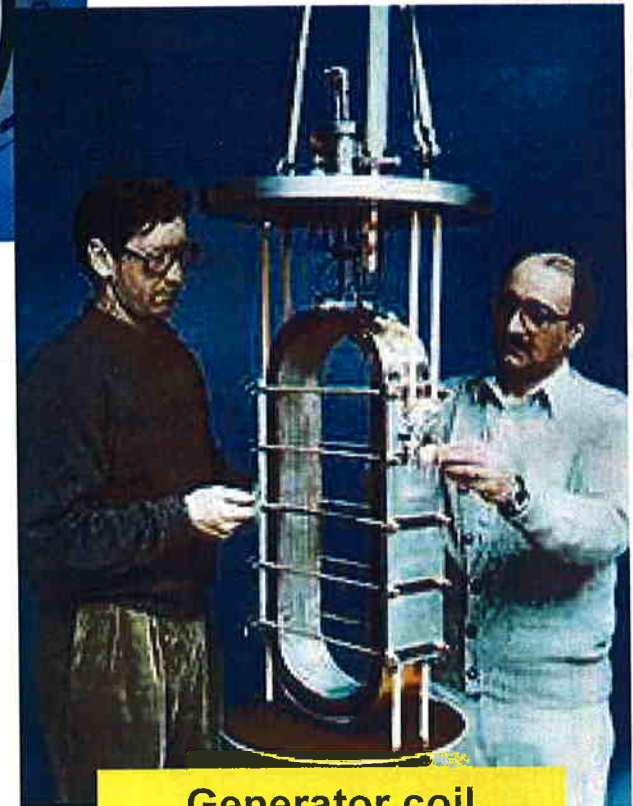
- Environmentally friendly
- More efficient
- Safer
- Smaller footprint
- Lighter
- Security benefits



HTS Cable



Transformer coil set



Generator coil

# HTS can provide premium power for military applications

**SuperPower** Inc.

High current density of HTS can enable devices that are

- High power
- Lightweight
- Compact

Suitable for military applications that require premium power without interference in battlefield mobility

## Long Duration High Power Microwave (HPM)



- Airborne Active Denial
- Large Aircraft Self-Protect

## High Peak Power Pulsed HPM

- Small Aircraft Self-Protect
- UCAV DEW Applications



## Solid State Laser



- Diode Pumped Solid State High Energy Laser (HEL)

All are electrically driven systems!



## Challenge is to produce HTS in form of a flexible wire

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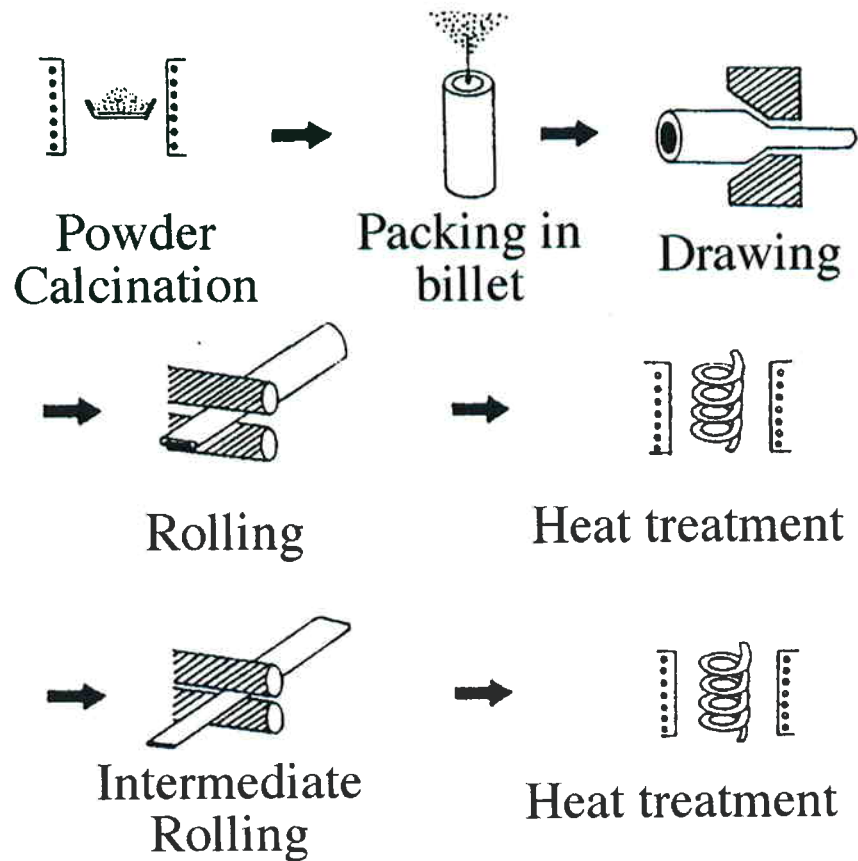
High-temperature superconductors are ceramic materials and are inherently brittle. Challenge is to produce them in a flexible wire form in lengths of kilometers

Two approaches to produce HTS in flexible wire form:

- First-generation (1G) HTS - HTS is encapsulated as filaments in a silver sheath
- Second-generation (2G) HTS- HTS is deposited as a thin film by semiconductor-type coating processes on a flexible nickel alloy substrate

# 1G HTS Technology - ready today, but expensive!

## 1G HTS Process Scheme



Monofilament

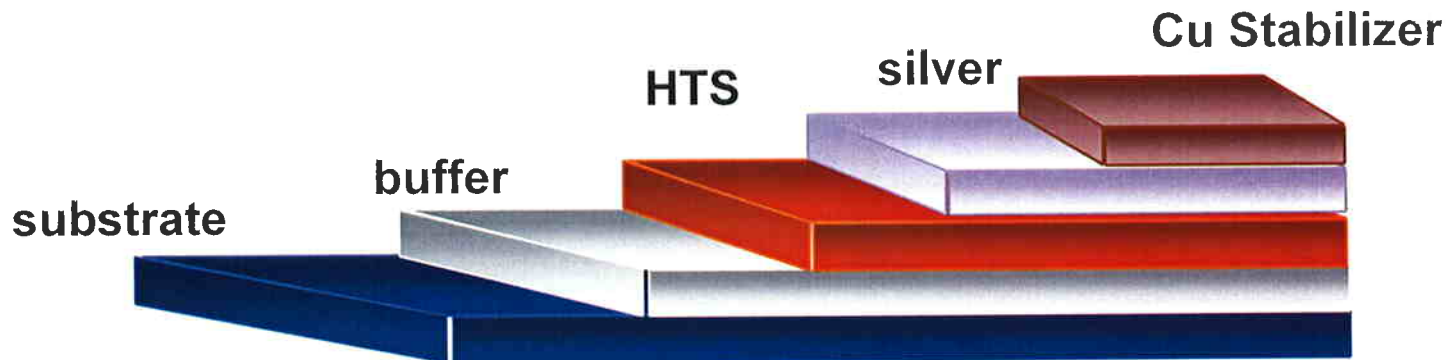


Multifilament

- ▶ Labor Intensive
- ▶ Long Processing cycle (6 to 8 weeks)
- ▶ Need 60 to 70% silver
- ▶ Difficult Process Control
- ▶ Best approach to make 100 m HTS

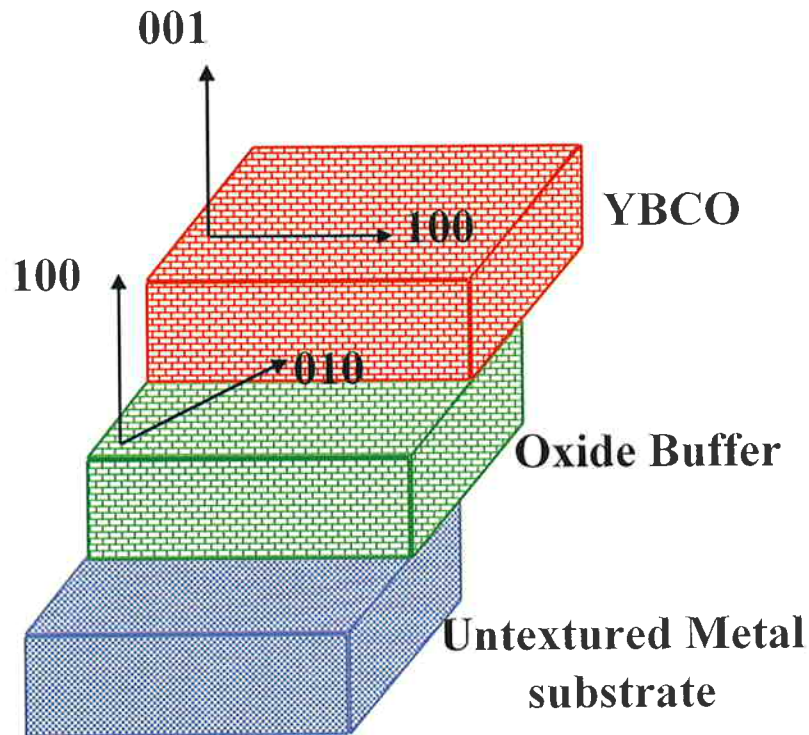
# 2G HTS is inherently a low-cost HTS conductor manufacturing approach

*SuperPower*™

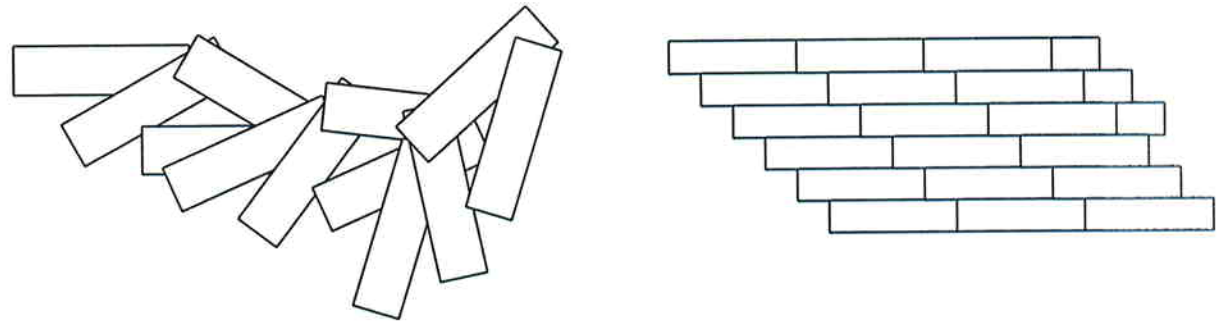


- ✓ **Much lower labor costs:** 2G can be produced in an automated continuous process compared to elaborated drawing and rolling procedures in 1G
- ✓ **Much lower materials costs:**
  - 95% of the structure of 2G is comprised of inexpensive nickel alloy substrate and copper
  - Only 3% of 2G is made of silver compared to 70% in 1G
  - About 40 times less HTS in 2G than in 1G.
- ✓ **Much less operational costs:**  
Hours to produce kilometer lengths of 2G instead of weeks for 1G
- ✓ **Much lower capital costs:** \$ 15 to \$ 20 M compared to \$ 100 M for 1G

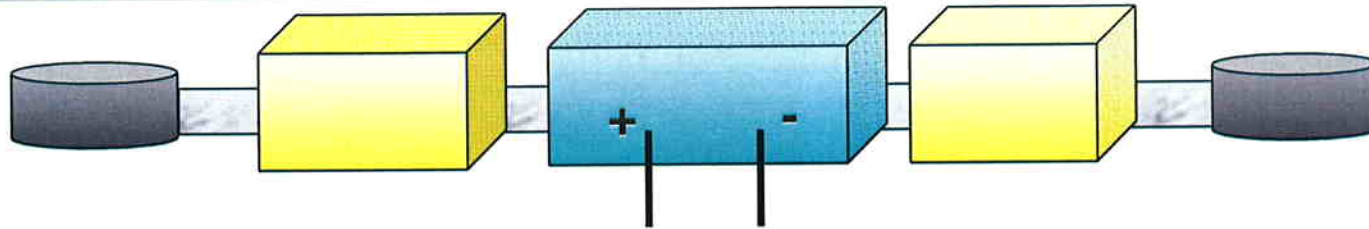
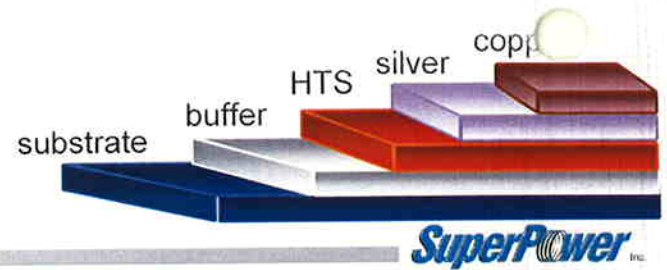
# Challenges in scaling up 2G HTS conductor



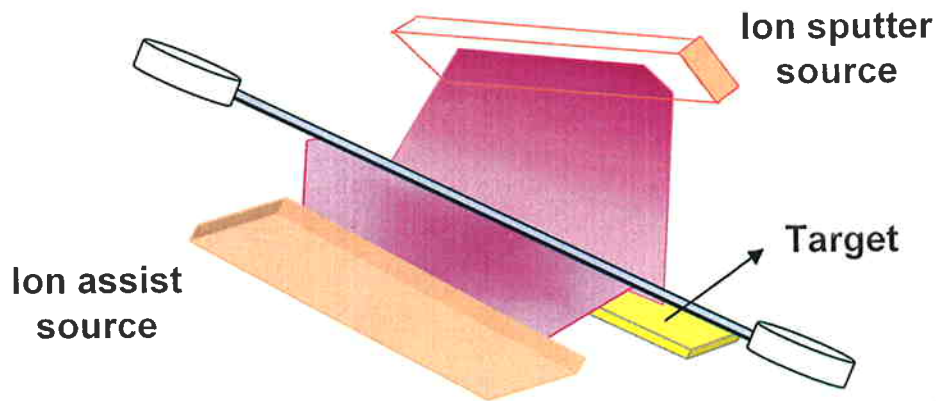
- Highly polished metal substrates
- Robust buffer layer(s) that is biaxially-textured
- High current carrying superconductor layer
- All of the above with very uniform quality in kilometer lengths
- and more....



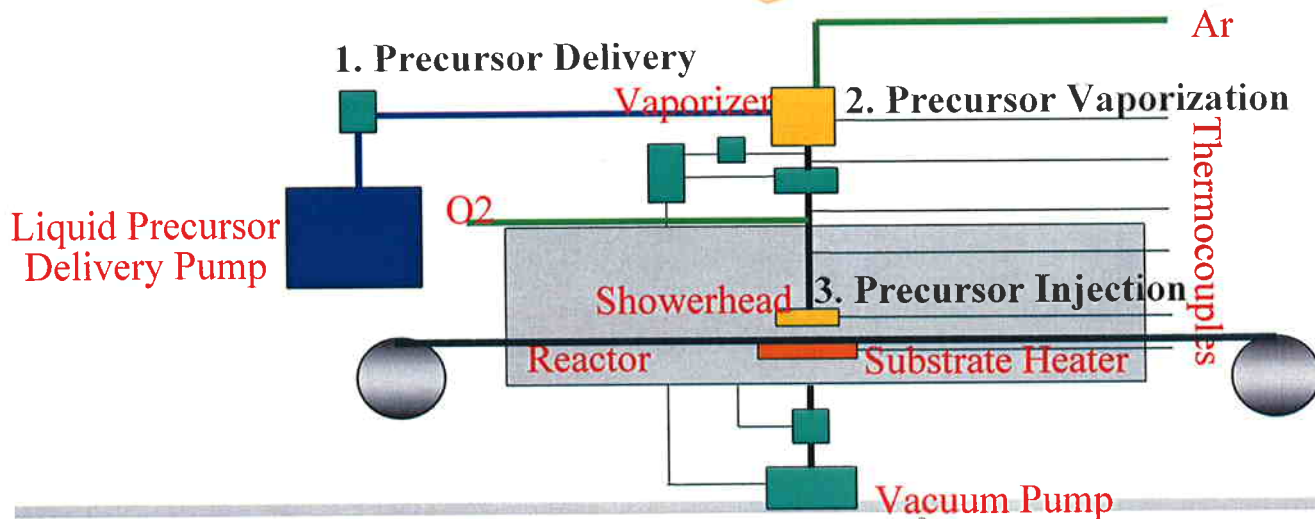
# 2G HTS Conductor Manufacturing at SuperPower: Steps 1 - 3



Metal Substrate  
Electropolishing



Buffer Layer by Ion  
Beam Assisted  
Deposition



HTS Layer by Metal  
Organic Chemical  
Vapor Deposition

# Superiority of IBAD technology



## Virtually any substrate could be used

- High-strength substrates
- Non magnetic substrates
- Low cost, off-the shelf substrates (Inconel, Hastelloy, Stainless Steel)
- Very thin substrates
- Resistive substrates – for low a.c. losses
- Easy to handle – less possibility of defects

## Small grain size – sub micron range

- No issues with percolation
- Can pattern conductor to very narrow filaments for low ac loss conductor



**Pilot IBAD**

# MOCVD provides advantages of high throughput & single-piece lengths

SuperPower<sup>INC.</sup>

For a low-cost conductor, high throughput is a major requirement.

Throughput =

Deposition Rate × Deposition zone length  
× Deposition zone width

Single-piece length =

Deposition Rate × Deposition zone length



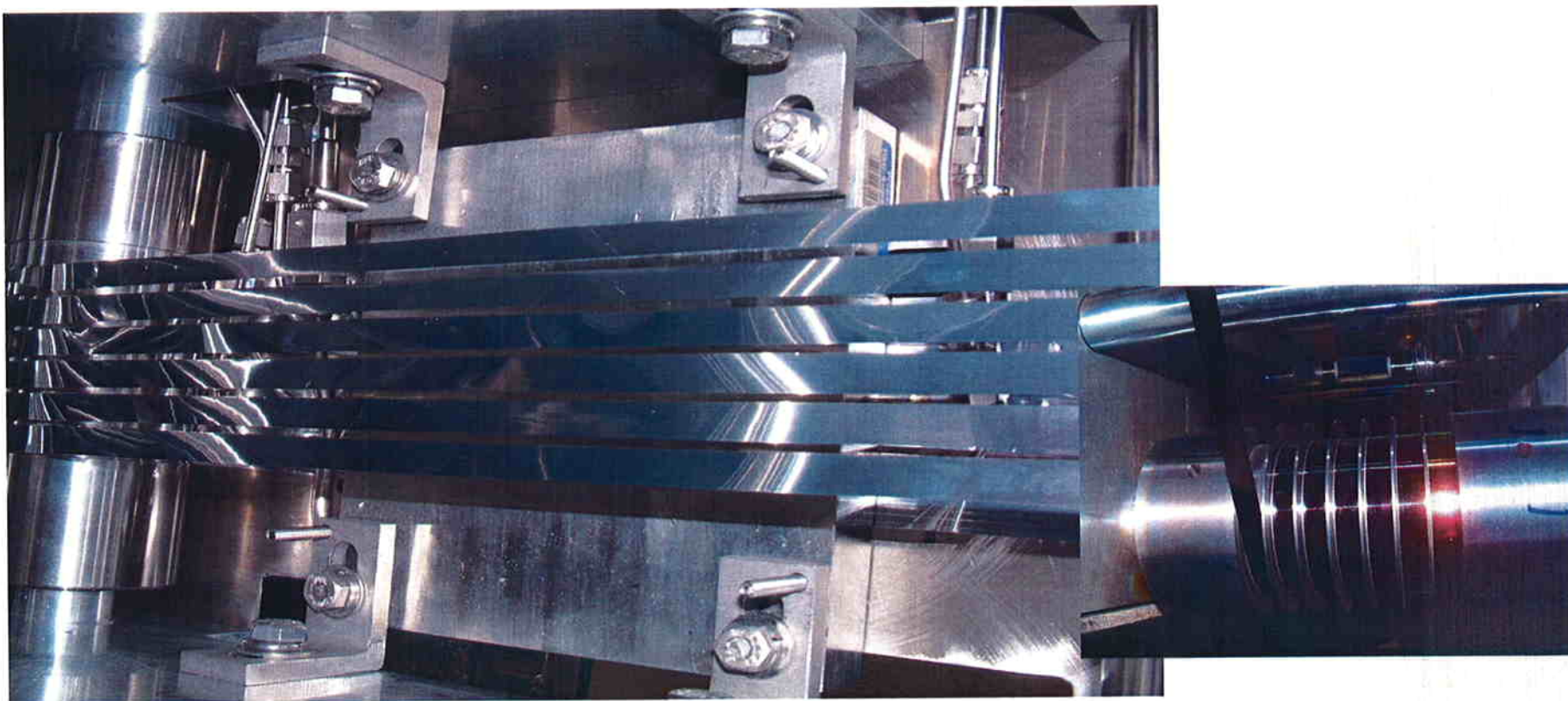
Only MOCVD offers the advantage of high deposition rates (150 Angstroms/s) as well as long and wide deposition zone

## # Hours to produce 1 km of coated conductor

<i>1 micron thick HTS</i>	Deposition Zone	
	1 m	10 m
<b>Deposition Rate</b>		
<b>150 Angstroms/s</b>	<b>18</b>	<b>2</b>
1 Angstrom/s	2,778	278
10 Angstrom/s	278	28

A helix-based tape handling system is used in all our thin film deposition processes

**SuperPower** INC.

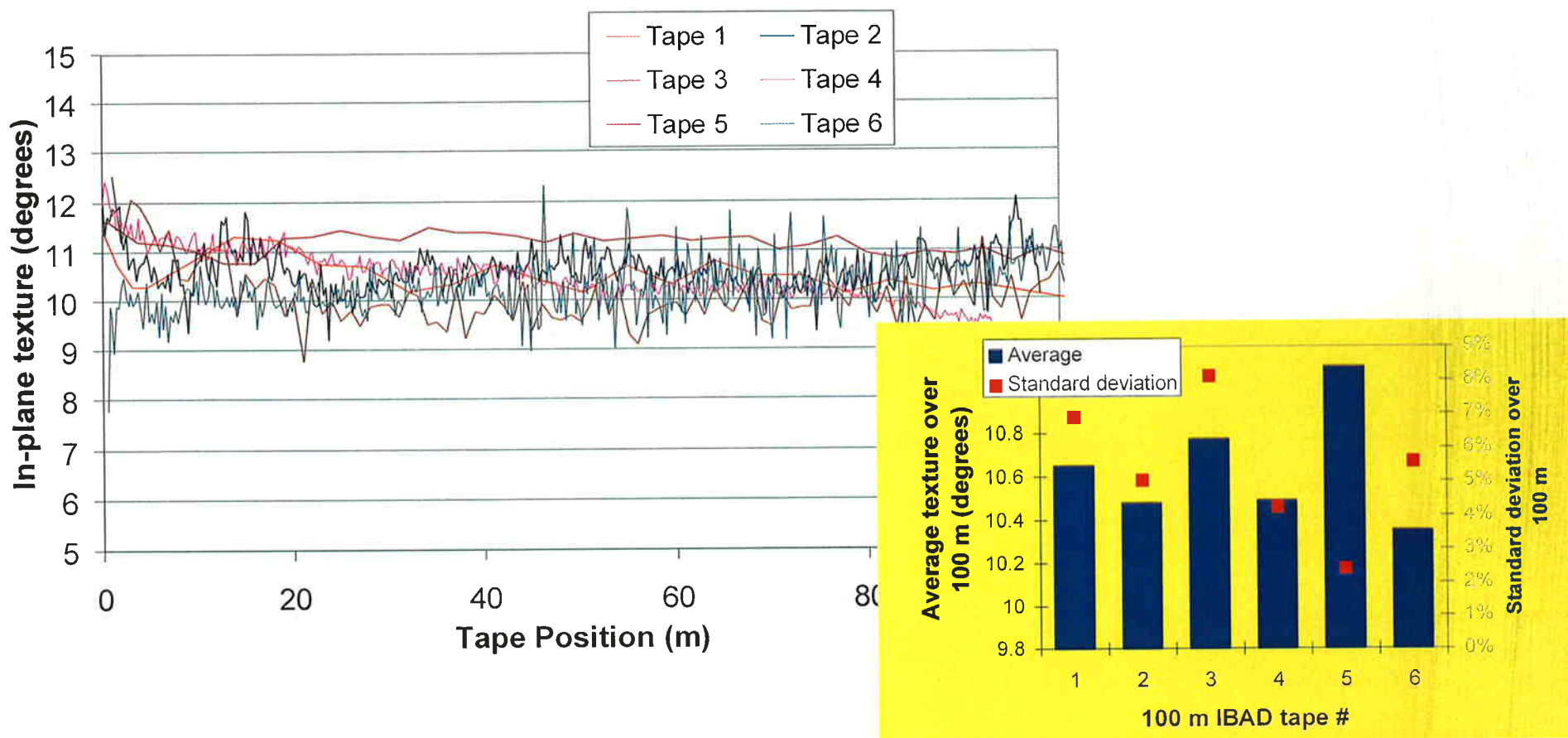


Helix enables very long single piece lengths & high throughput

# Highly biaxially textured buffer layers have been produced in long lengths



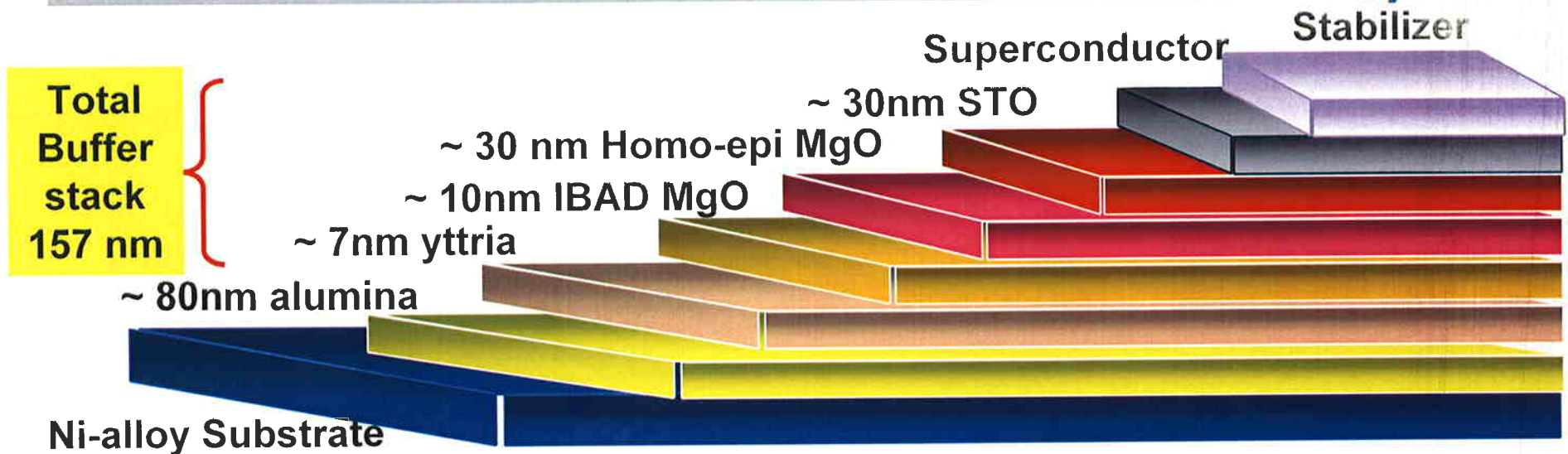
Over 20, 100 m IBAD tapes produced with same process



**Average of average texture over 100 m of all 6 tapes = 10.6 degrees**  
**Standard deviation of average texture over 100 m of all 6 tapes = 2.5%**

# Multifunctional oxide layers are used in our 2G HTS conductor

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Alumina --- barrier layer to prevent diffusion of metal element into superconductor

Yttria – seed layer to provide good nucleation surface for IBAD MgO

IBAD MgO – template layer introduce biaxial texture

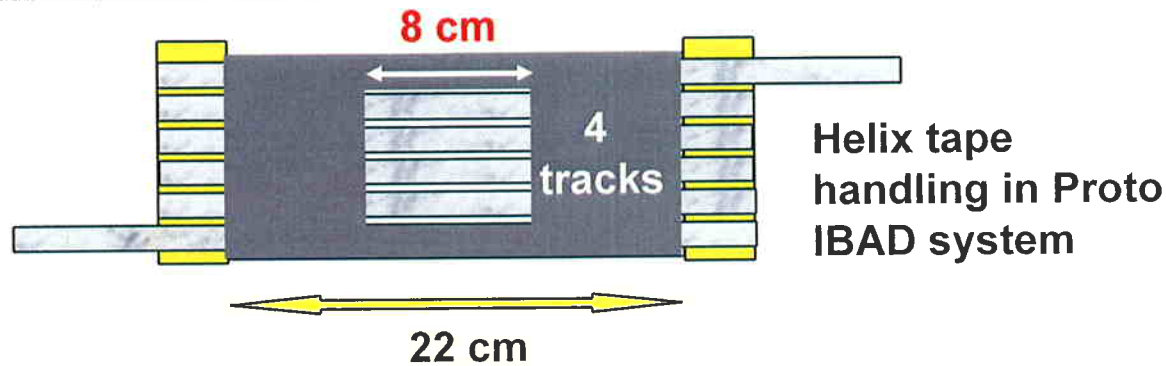
Homo-epitaxial MgO --- buffer layer to improve biaxial texture

STO --- cap layer, to provide lattice match between MgO and YBCO and good chemical compatibility.

High process throughput enabled by thin buffer layer stack based on IBAD MgO

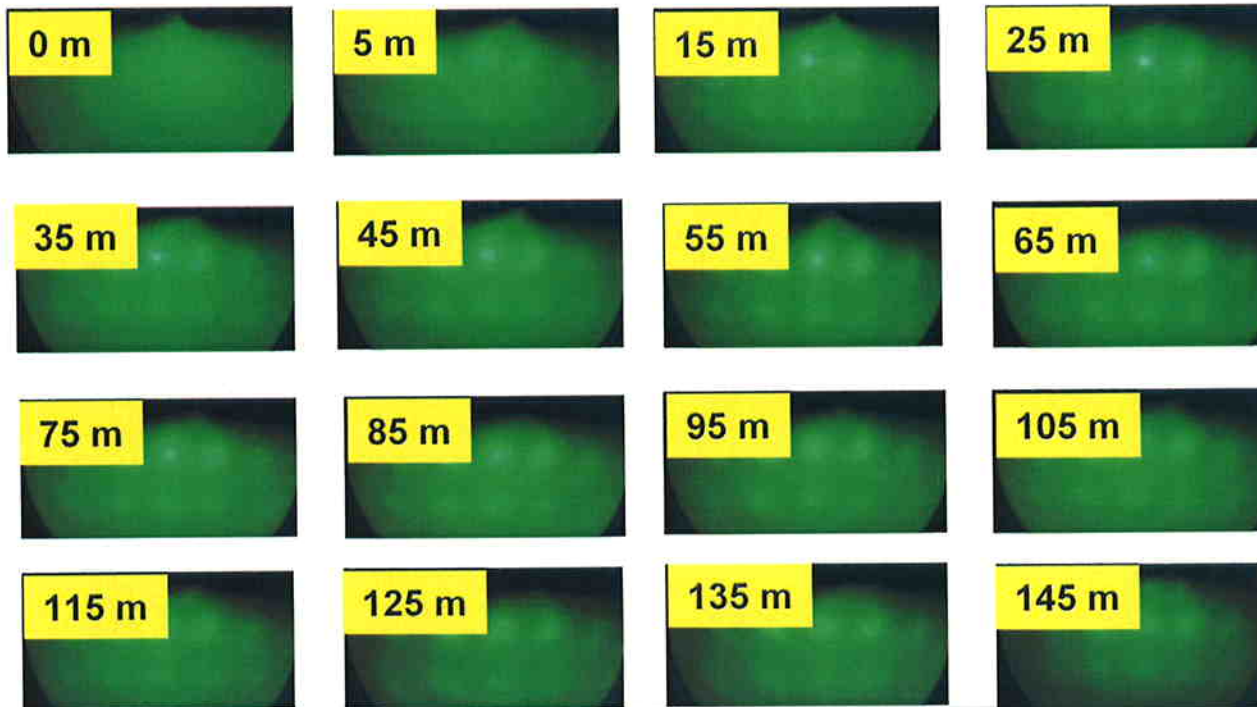
# IBAD MgO is being routinely fabricated in 135 m lengths at 10 m/h even in a Prototype IBAD system

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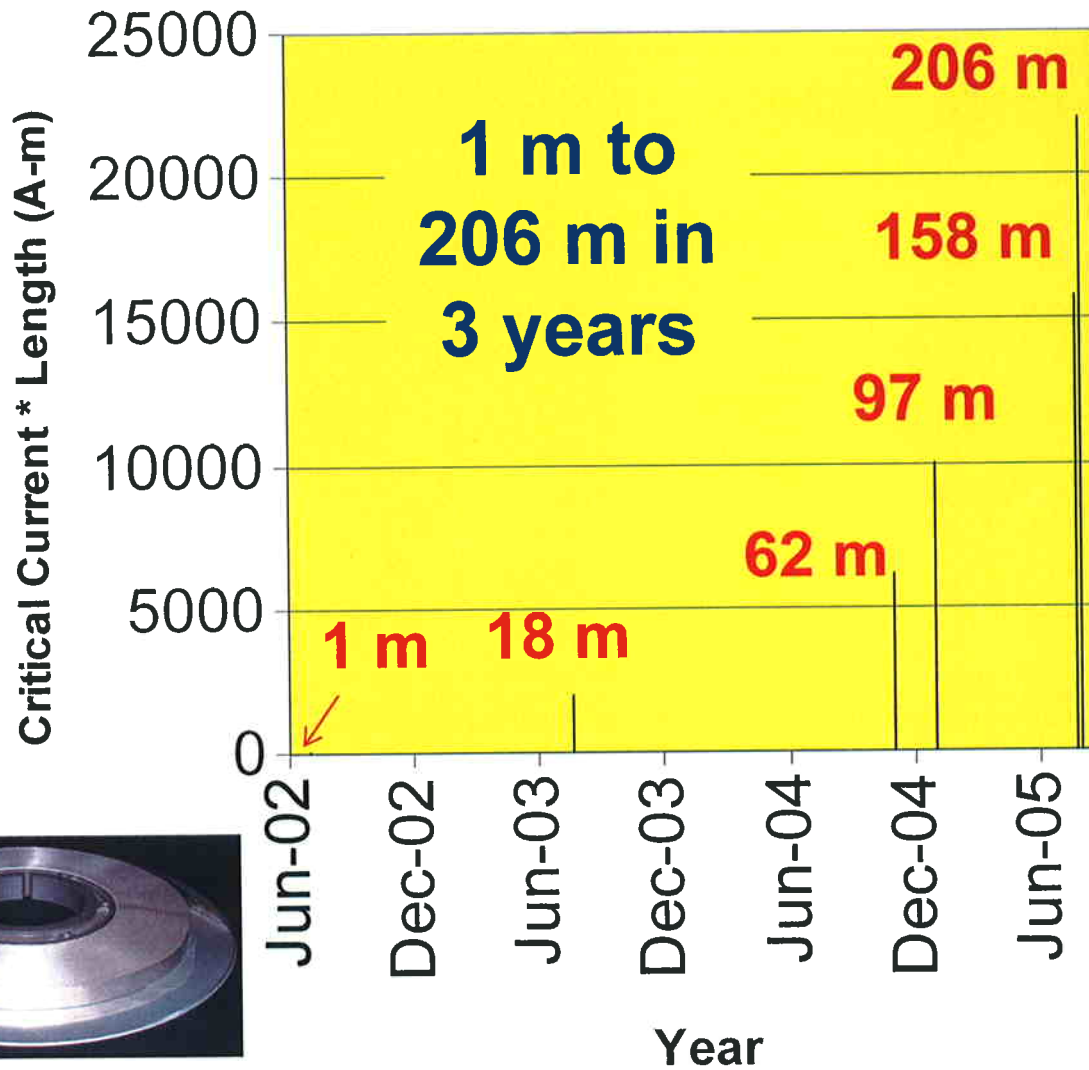
140mm

180mm



Over twelve 130 m long IBAD MgO tapes have been fabricated on 50 micron thick substrates at 10 m/h

# IBAD-MOCVD-based 2G HTS conductors have been scaled up to 200 m lengths



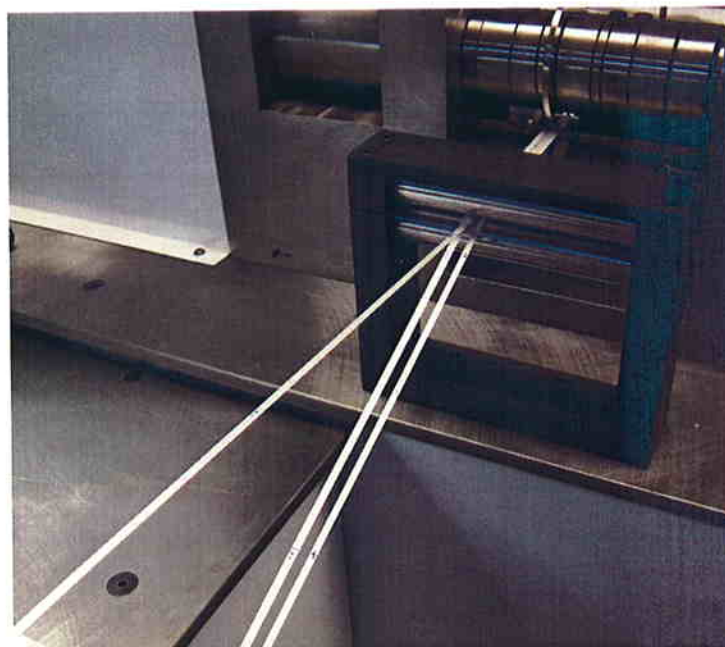
# Post MOCVD processing of 2G HTS conductors to address needs of power applications

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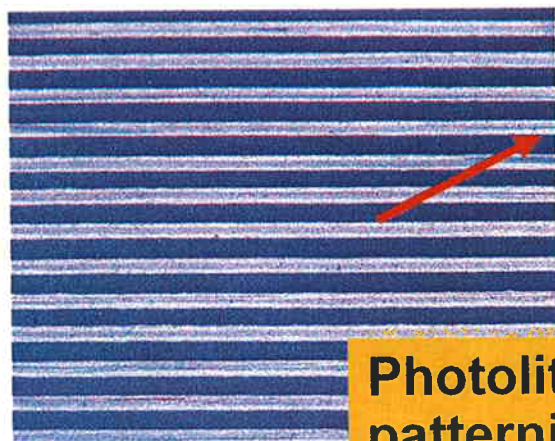


Surround Cu stabilizer

Electroplating of copper stabilizer for over-current protection



Slitting of conductor to produce practical 4 mm wide conductor



HTS + Ag

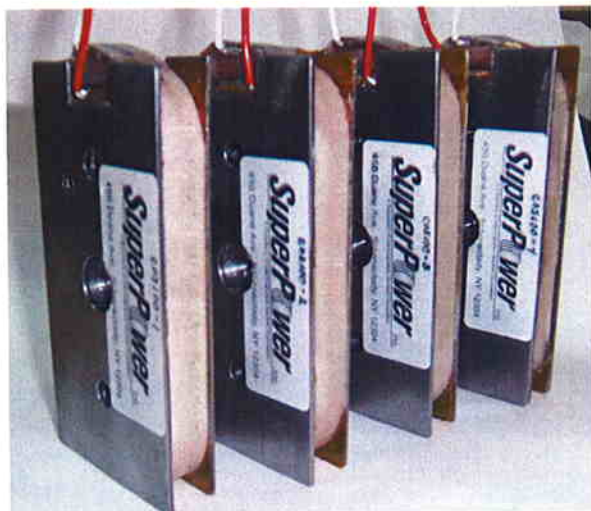
Photolithographic patterning for low ac losses

# Prototype electric power devices have been built and tested with 2G HTS conductor

SuperPower Inc.



World's only HTS cable made with practical 2G HTS conductor  
1 m long HTS cable with 4 mm wide conductor with surround copper stabilizer  
2350 A, ac loss of 0.16 W/kA-m in conductor layer and 0.36 W/kA-m in complete cable



World's only rotating machine (motor) with 2G HTS conductor

7.5 hp achieved in a conventional 5 h.p. motor frame

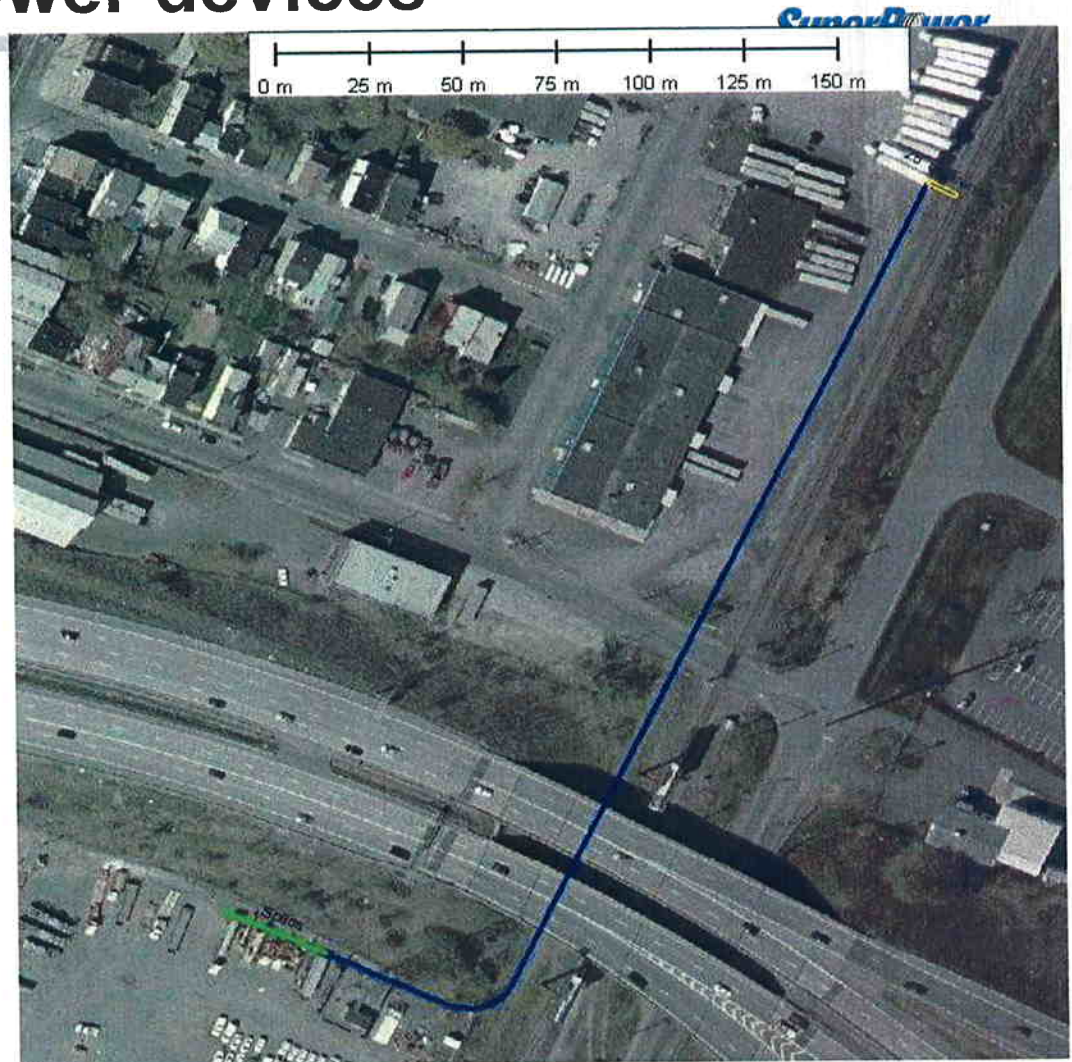
# 2G HTS is at the threshold of being implemented in commercial electric power devices

We have come a long way in the last 4 years from centimeter-sized tapes to 200m long practical 2G HTS conductors

Commercial manufacturing of 2G conductors will begin in 2006

We will provide nearly 10 km of 2G HTS conductor in summer 2006 to build a 30m long cable

Large electric power prototype devices with 2G conductors will begin appearing by late 2006/early 2007



**Albany Cable project:** National Grid, 350 m long cable. World's first in-grid cable, first underground cable, first cable-to-cable joint. World's first 2G device (30 m)