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superior performance.
powerful technology.

Second-Generation HTS Wire for Magnet Applications

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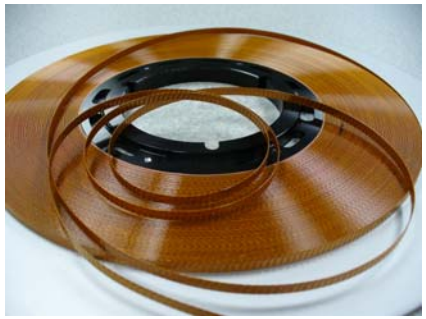
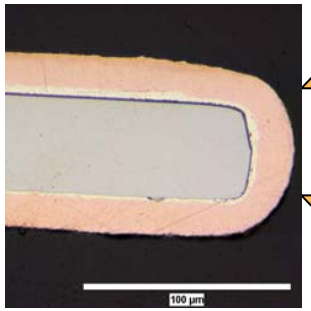
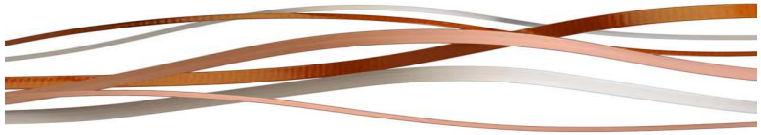
SuperPower develops advanced 2G HTS technology and manufactures commercial wire





v 0.1 mm

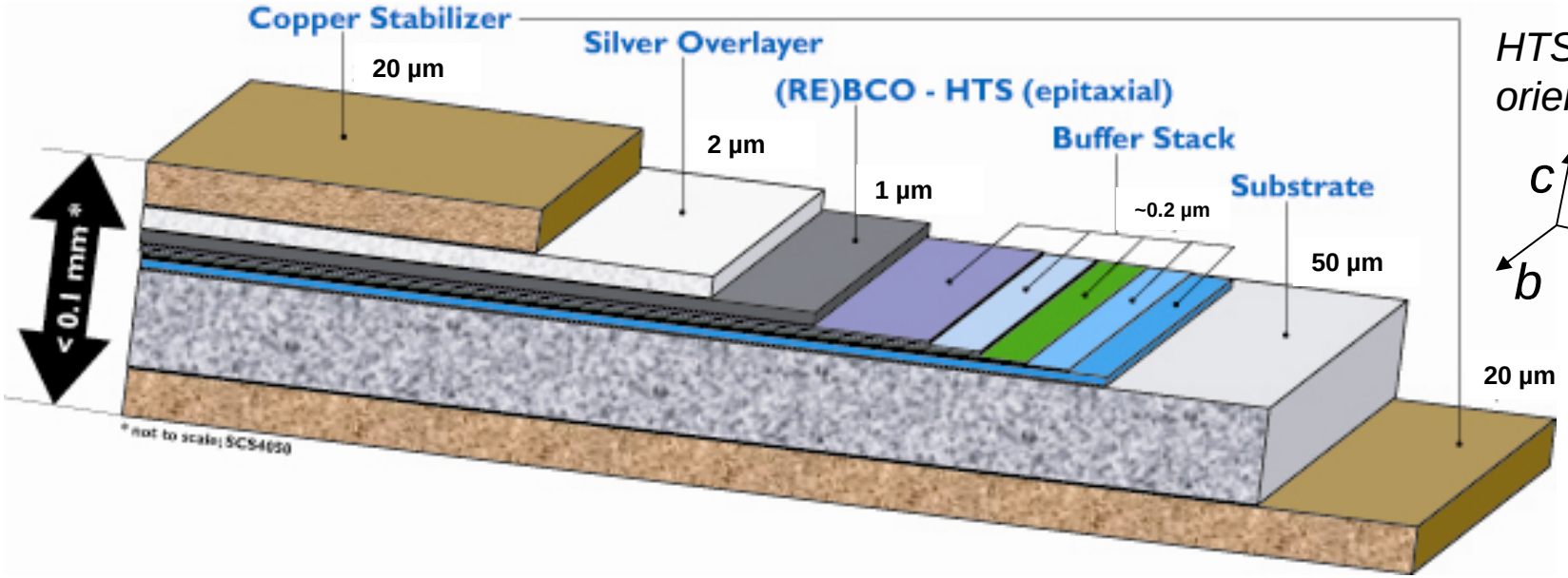


Surround Copper Stabilizer: by electroplating; electric stability, hermetic seal and solder temp. up to 250°C

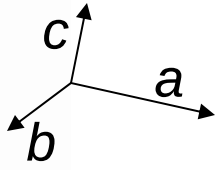
HTS layer (biaxially aligned): by *MOCVD*, high dep. rate + large dep. zone area ➔ high throughput

Buffer stack: IBAD-MgO based, biaxial texture formation with ~10 nm film ➔ high throughput; wide range of substrate options;

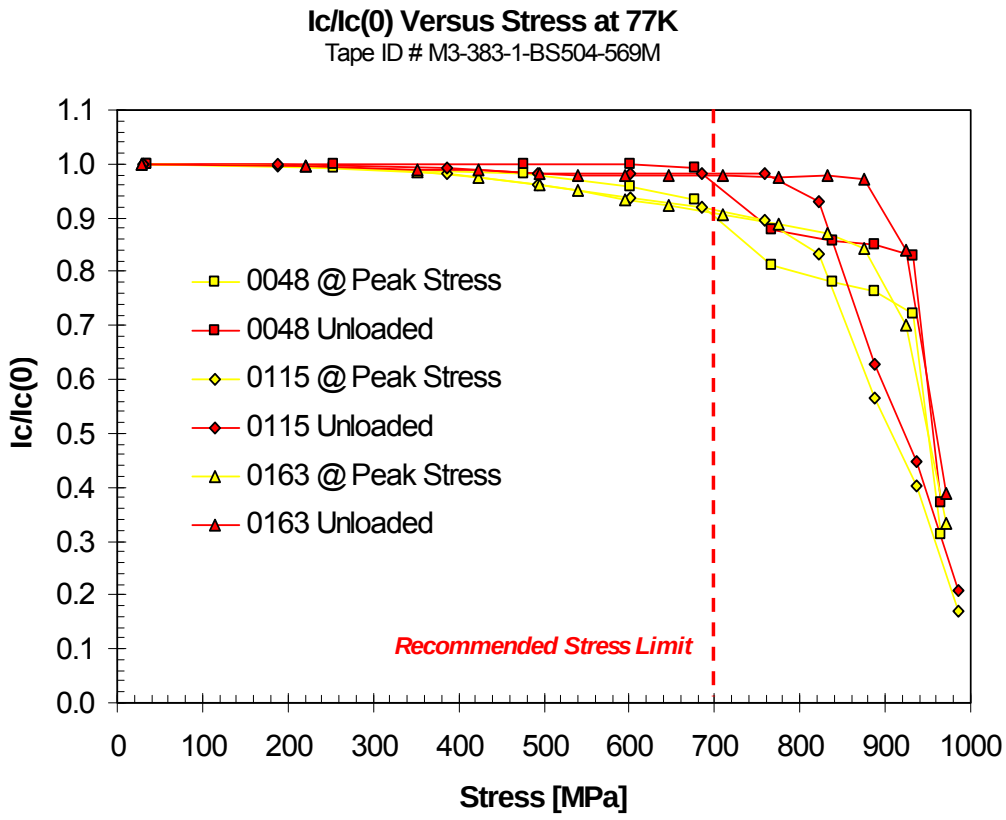
Substrate: High strength, thin and highly resistive ➔ high J_e and low ac loss



HTS grain orientation



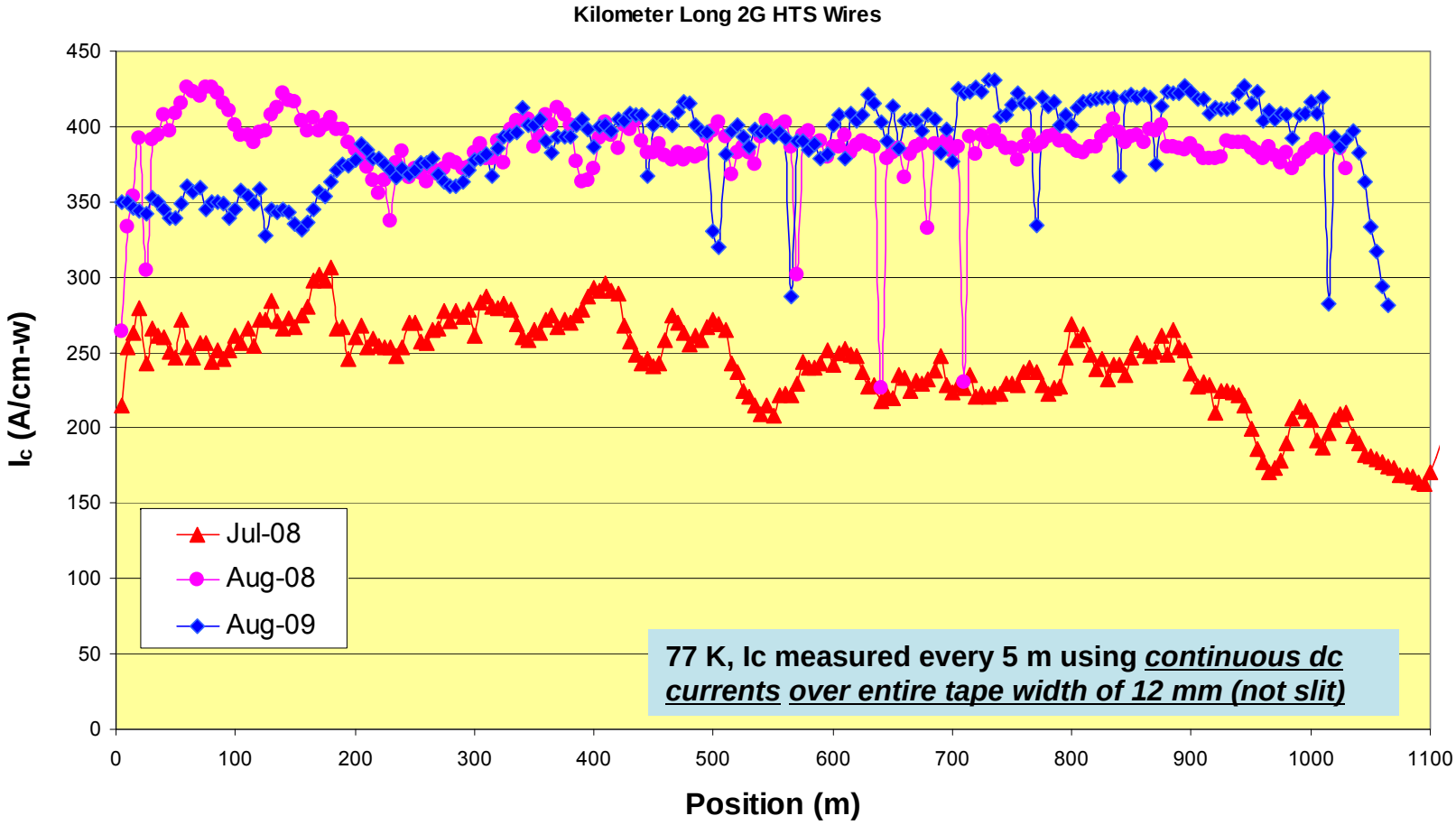
SuperPower® 2G HTS wire tolerates high axial stress ~700 MPa



Data from R. Holtz, NRL

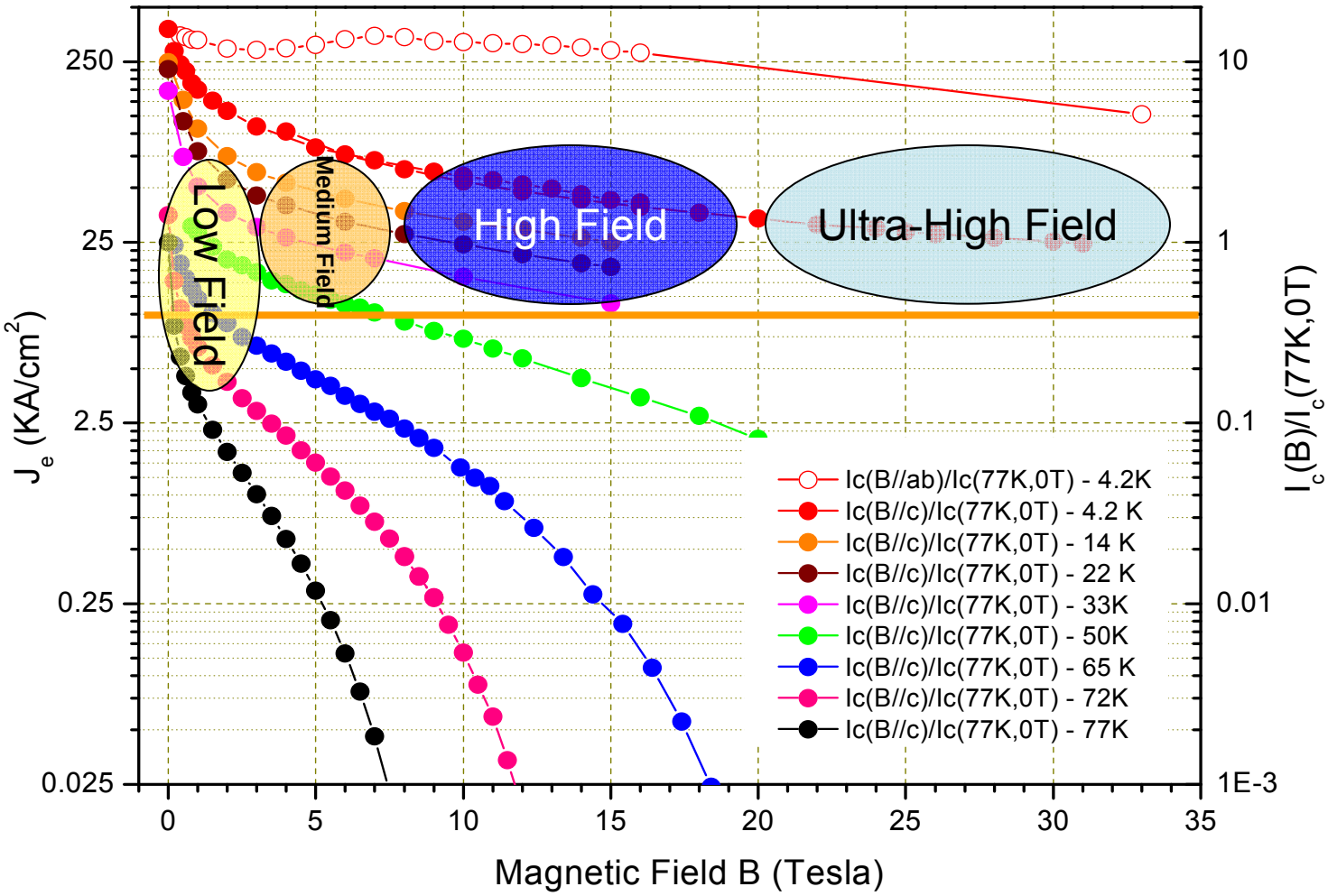
- I_c drops by up to 10% <u>reversibly</u> under peak stress up to 700 MPa (about 0.6% strain)
- Above 700 MPa (0.6% strain) Ic degrades <u>irreversibly</u>
- N-value does not change with peak stress up to 700 MPa
- N-value degrades irreversibly coincident with irreversible Ic degradation
- Define σ_{IcRL} (ε_{IcRL}) = "I_c Reversiblity Limit" = Peak monotonic stress (strain) for >98% reversibility of I_c
- σ_{IcRL} (ε_{IcRL}) = 700 MPa (0.6%)

IBAD-MgO-based MOCVD 2G HTS wire is produced in kilometer lengths



- **Minimum current (I_c) = 282 A/cm-w over 1065 m**
- **New world record: I_c × Length = 300,330 A-m**

Excellent in-field performance makes a wide range of real-world applications possible



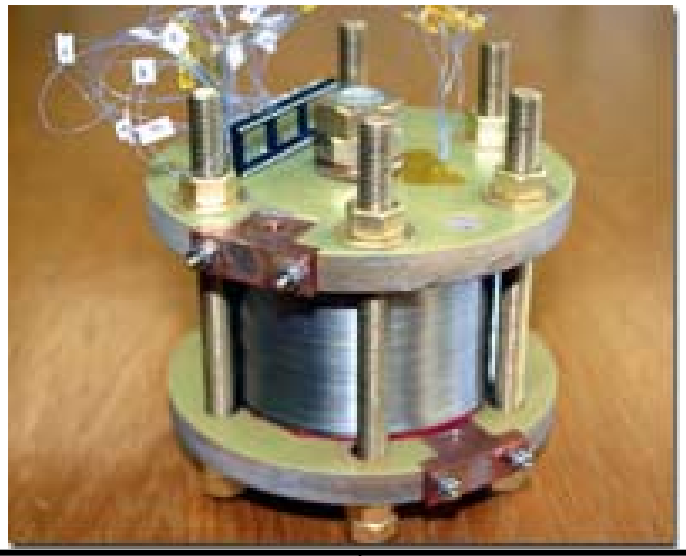
High Temp, Low Fields:
- Cable
- SFCL
- Transformer
- Motor/generator
- Plasma Confinement
- Xal growth magnet
- Magnetic separation

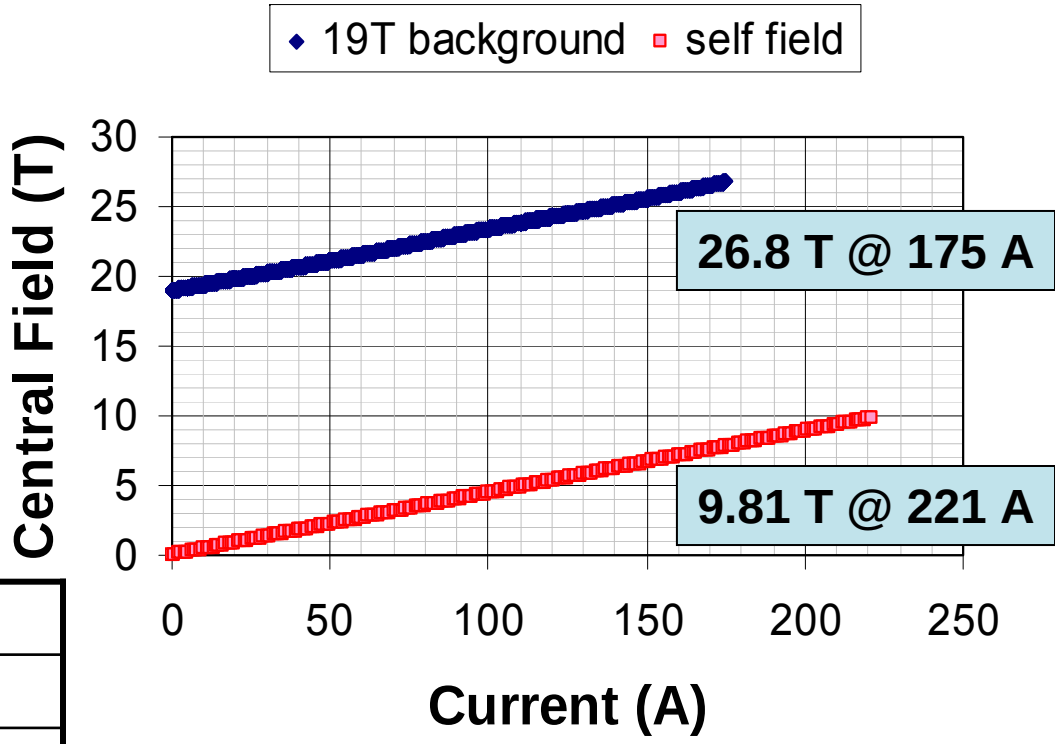
Medium Temp, Medium Fields:
- Motor/generator
- Plasma Confinement
- Xal Growth Magnet
- Magnetic separation
- Maglev
- SMES

Low Temp, High Fields:
- SMES
- High-Field MRI
- High-Field Insert
- NMR

* J_e is calculated based on I_c (77 K, 0T) = 100 A/4 mm (surr. copper stabilized) and scaling factors measured by D. Larbalestier, *et al* at FSU and E. Barzi, *et al*. of Fermi Lab.

World record high-field magnet demonstrated in 2007





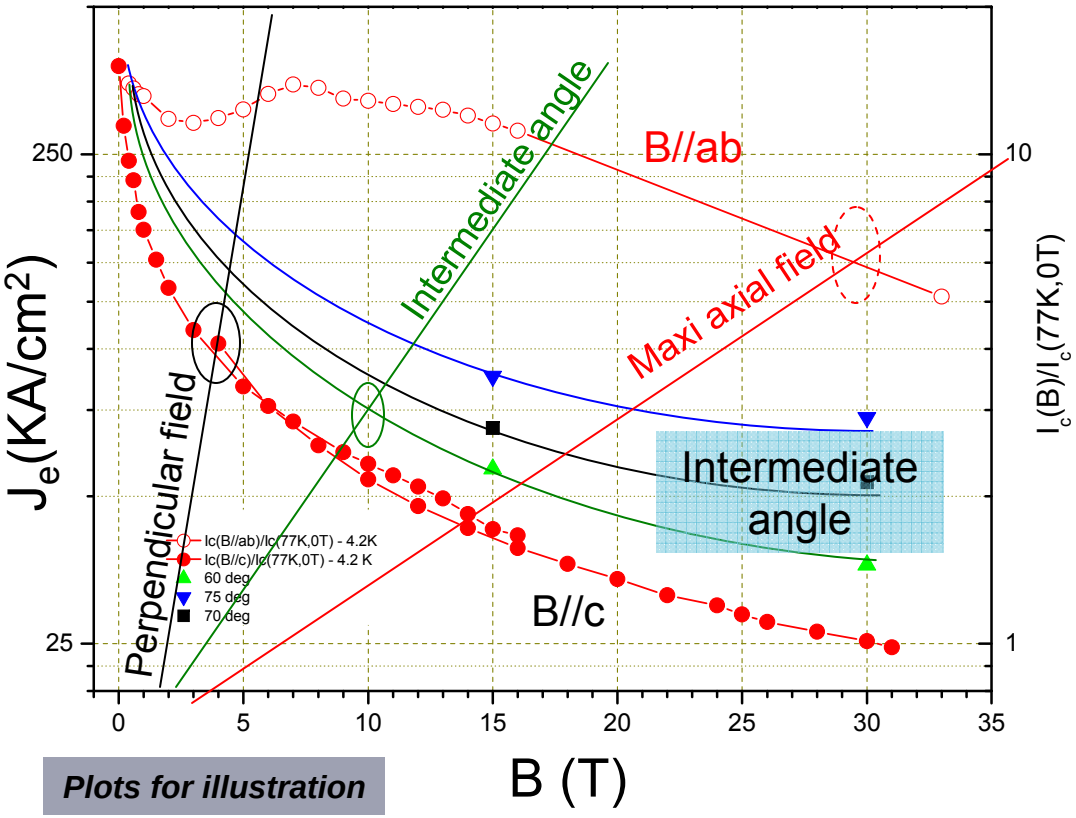
Coil ID	**9.5 mm (clear)**
Winding ID	**19.1 mm**
Winding OD	**~ 87 mm**
# of Pancakes	**12 (6 x double)**
2G wire length used	**~ 462 m**
Coil constant	**~ 44.4 mT/A**
Average Ic of wires in coil	**78 A in 4 mm width (77 K, self field)**

SuperPower coil tested in NHMFL's unique, 19-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet

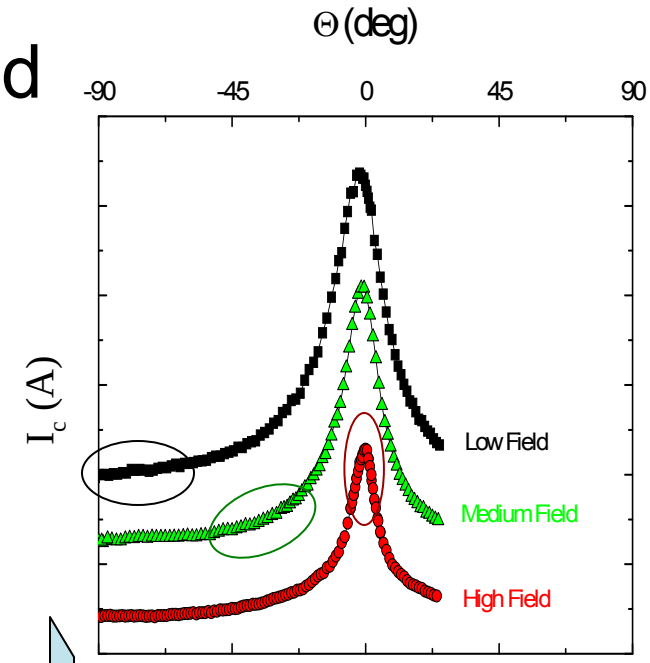
0.73 T generated by coil at 77 K

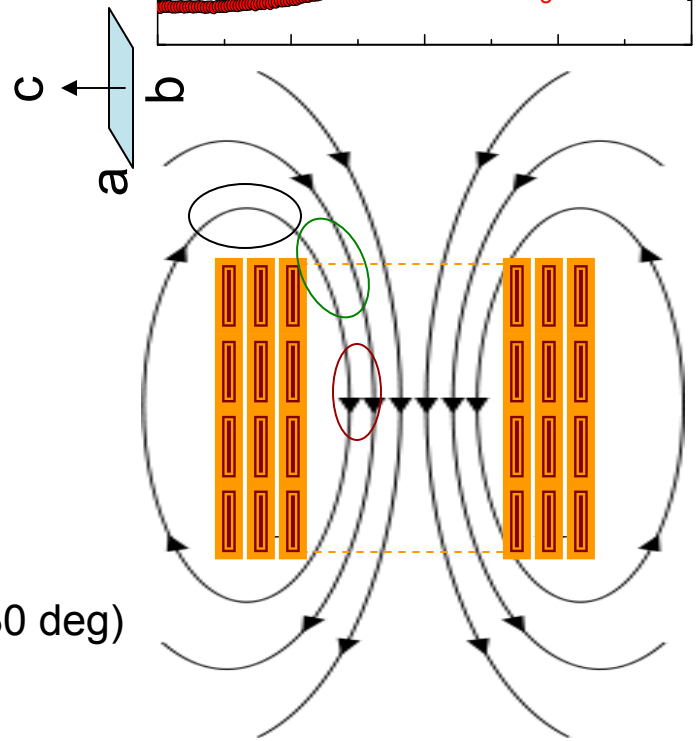
Coil tested by H. Weijers, D. Markewicz, & D. Larbalestier, NHMFL, FSU

HTS coil performance is determined by anisotropy in field dependence



Plots for illustration



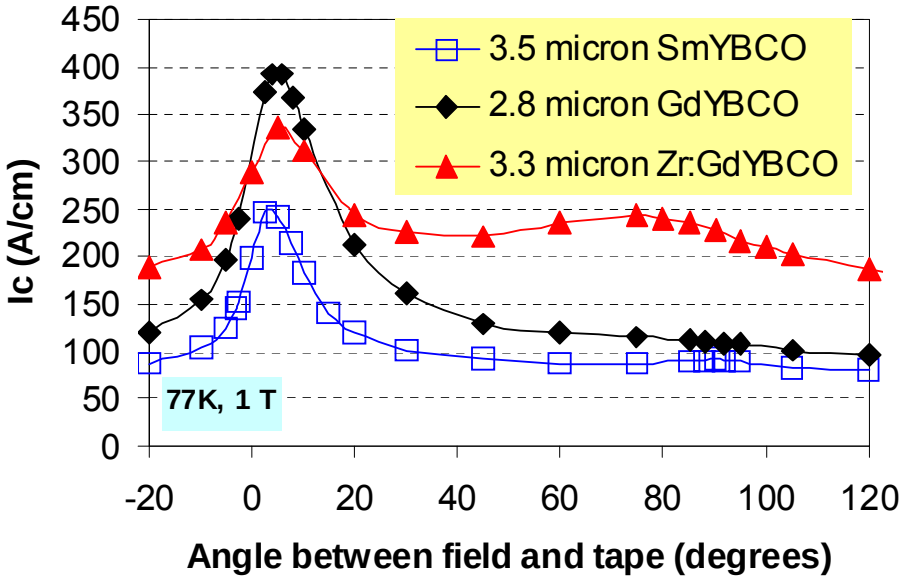


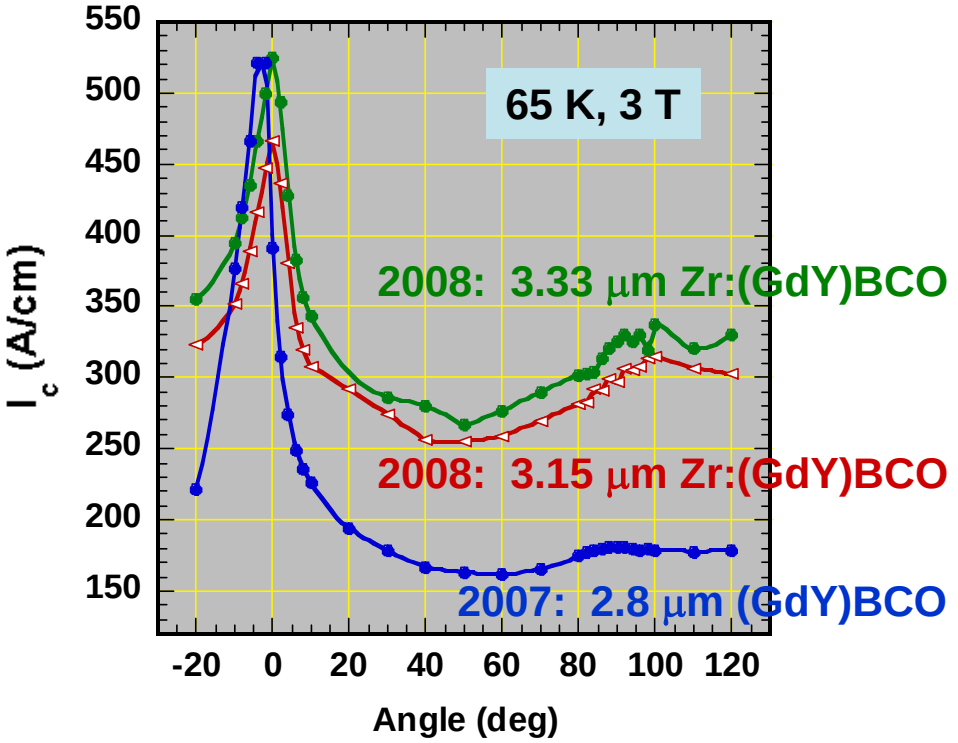
High flux density at small angles (Near B//ab)

Medium flux density at intermediate angle (20-30 deg)

Low flux density at high angle (B//c)

2008: Zr doping was demonstrated in MOCVD to achieve dramatic in-field performance improvements





- 97% increase in minimum I_c to 186 A/cm corresponds to J_e of 28,500 A/cm^2 (no copper)
- 85% increase in I_c (B ⊥ tape) to 229 A/cm corresponds to J_e of 35,200 A/cm^2 (no copper)

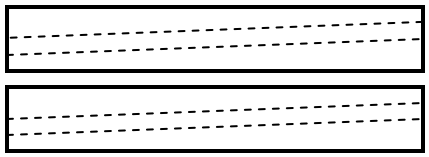
- 67% increase in minimum I_c to 267 A/cm corresponds to J_e of 41,000 A/cm^2 (no copper)
- 88% increase in Ic (B ⊥ tape) to 340 A/cm corresponds to J_e of 52,300 A/cm^2 (no copper)

In 2009, Zr-doping chemistry successfully transferred to production line

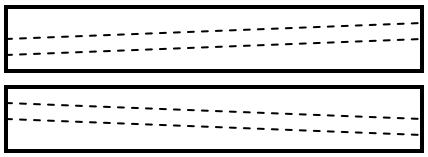
Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL

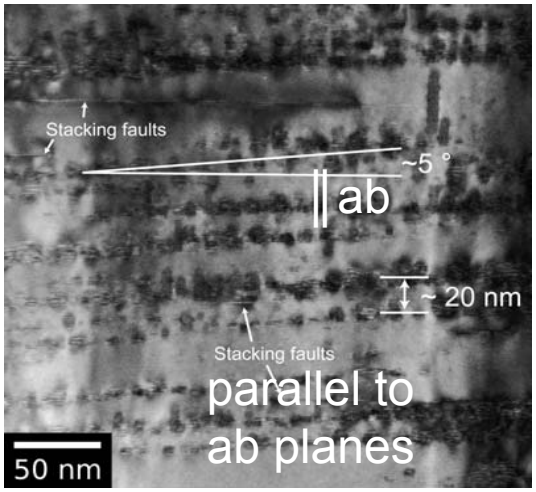
Asymmetry in Jc essentially eliminated by face-to-face stacking

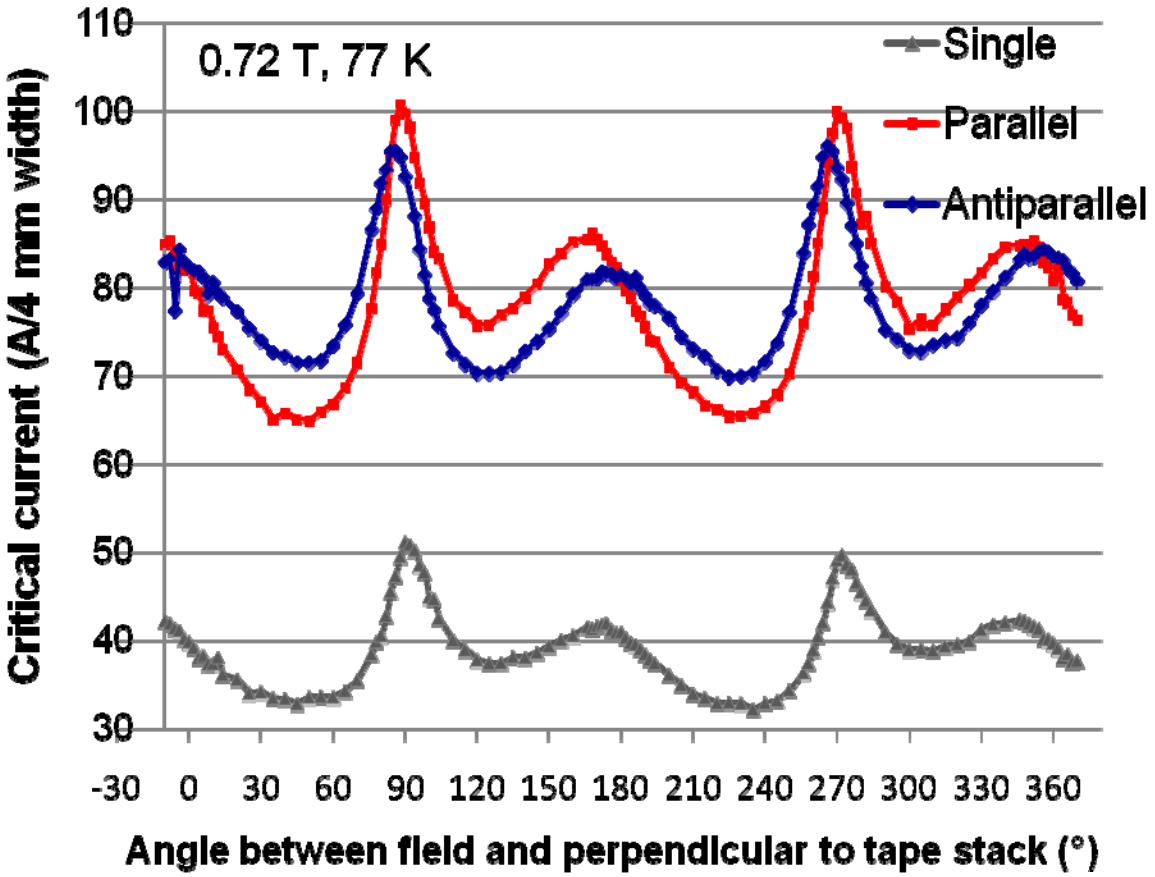
parallel



Antiparallel



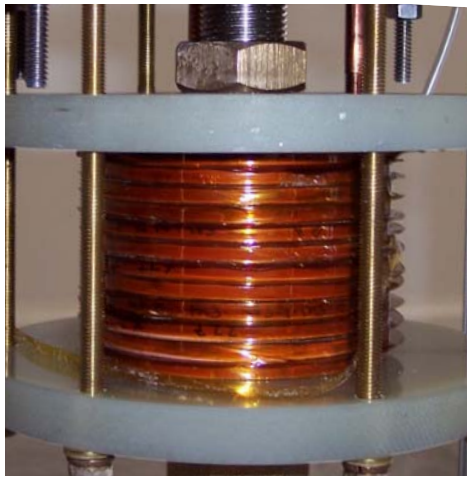


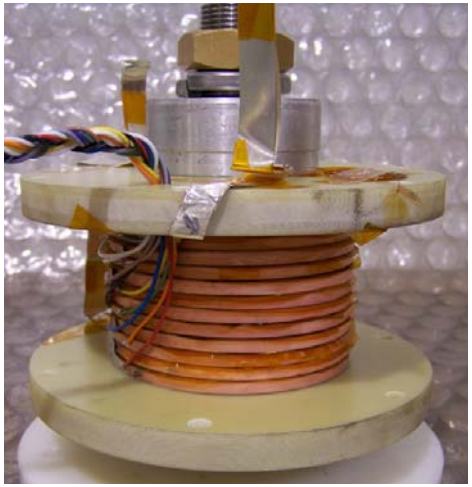


Antiparallel face-to-face stacking of wires results in 10% higher minimum Ic in field.

Two coils made with Zr-doped 2G wire

Identical size, same quantity of Zr-doped wire with similar critical current performance at 77 K, zero field.





	Coil -1	Coil - 2
Field at 77 K	**0.97 T**	**1.09 T**
Field at 65 K	**2.39 T**	**2.5 T**
Field at 61 K		**3.0 T**

	Coil -1	Coil - 2
Coil ID	21 mm (clear)	21 mm (clear)
Winding ID	28.6 mm	28.6 mm
Winding OD	~ 87 mm	~ 84 mm
Coil Height	~ 56.7 mm	~ 57.8 mm
# of Pancakes	12 (6 x double)	12 (6 x double)
2G wire used	~ 480 m	~ 480 m
# of turns	~ 2664	~ 2688
Coil Je	~ 163.5 A/mm^2 @ 100A	~ 167.9 A/mm^2 @ 100A
Coil constant	41.9 mT/A	42.2 mT/A
Tape Ic (77 K, sf)	72 to 97 A	90 to 101 A

Repeatable enhanced coil performance demonstrated with Zr-doped 2G wire

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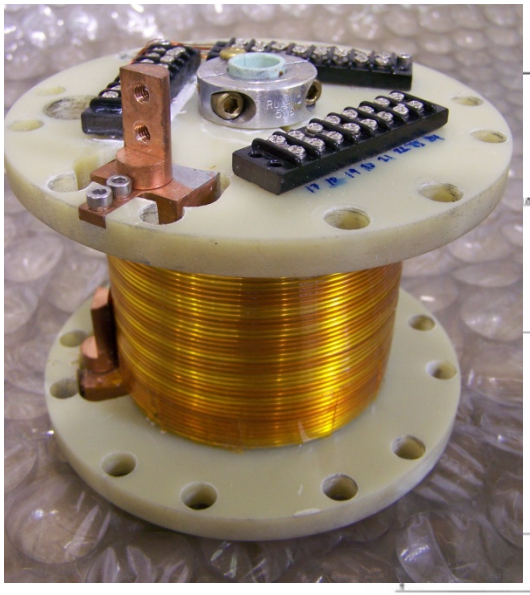
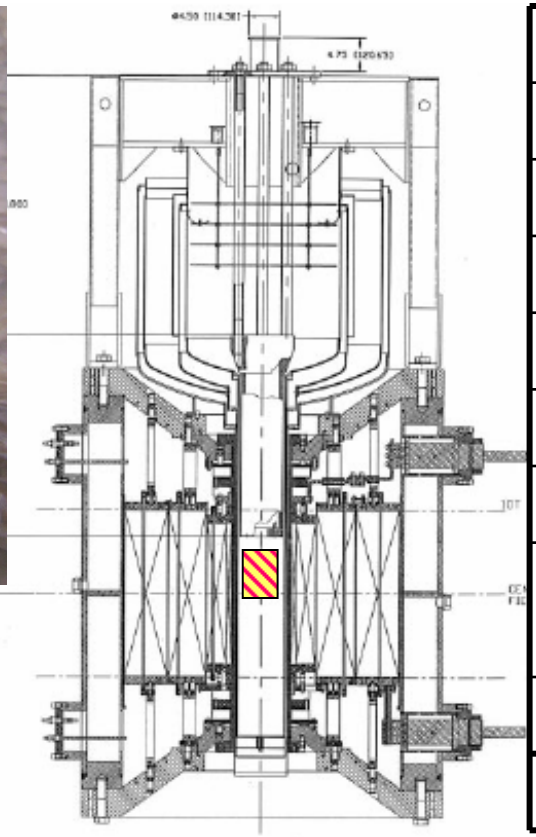
Third coil made with high amperage, undoped wire





Coil ID	12.7 mm (clear)
Winding ID	19.1 mm
Winding OD	~ 84 mm
Coil Height	~ 73.6 mm
# of Pancakes	16 (8 x double)
2G wire used	~ 600 m
# of turns	~ 3696
Coil J_e	~155.3 A/mm^2 @ 100A
Coil constant	~ 51.8 mT/A
Wire Ic (77 K, sf)	120 A – 180 A

Insert coil tested in NHMFL's unique, 20 T, 20 cm wide-bore, Bitter magnet

Temperature (K)	77	65	4.2
Central field – self field (T)	**1.39**	**2.49**	**10.4**
Total Central Field – in background field (axial) (T)	**1.93**	**4.60**	**27.4**
With Background field (T)	1.0	3.0	19.89

Patrick Noyes,
Ulf Trociewitz,
Huub Weijers,
Denis Markewicz,
David Larbalestier

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Summary

- SuperPower routinely produces 2G HTS wire in manufacturing line. New world record performance of $I_c \times L$ = 300,330 A-m achieved in km long wires.
- In-field performance enhancement at all field angles achieved *via* Zr-doping; technology has been transferred into production line.
- Asymmetry in angular dependence minimized *via* anti-parallel 2-stack conductor approach.
- High-field coils with consistently improved performance demonstrated with SuperPower® 2G wire. Self field was increased from 0.73 Tesla to above 1 T at 77 K and more than 2 T at 65 K. At 4.2 K, maximum fields of 10.4 T and 27.4 T were achieved in self-field and with 19.9 T background, respectively.

Thank you!
谢谢大家！

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