SuperPower Inc.

superior performance.
powerful technology.

Recent development of 2G HTS coils and quench detection methods

Yi-Yuan Xie, Maxim Marchevsky, Venkat Selvamanickam,
Drew Hazelton, and John Dackow

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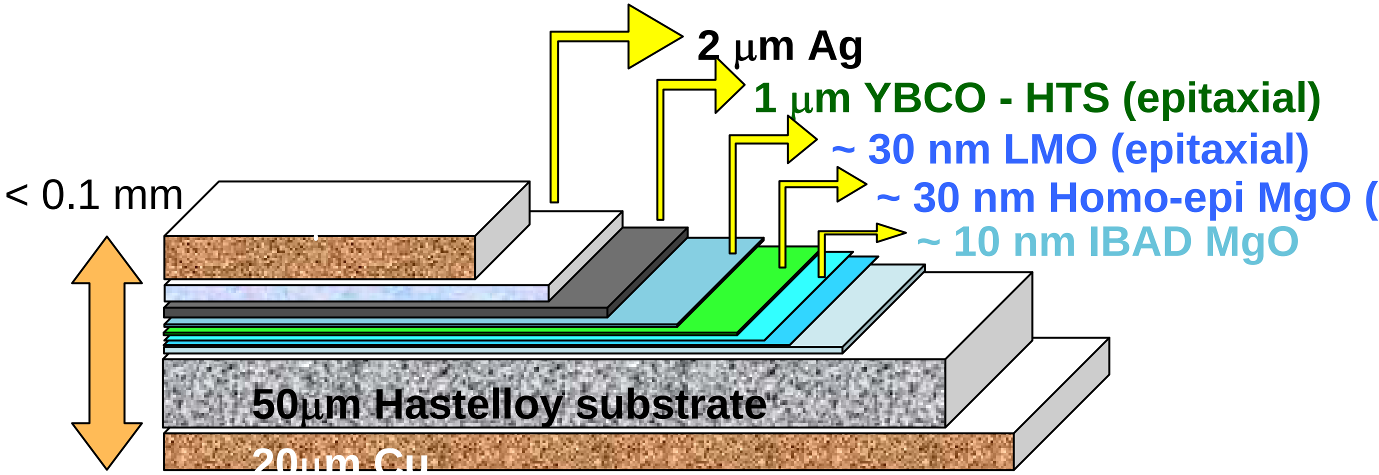
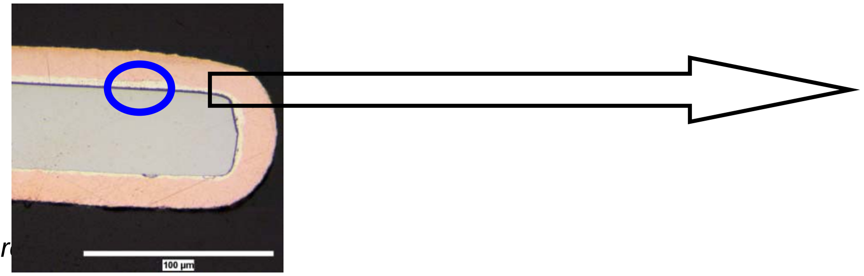
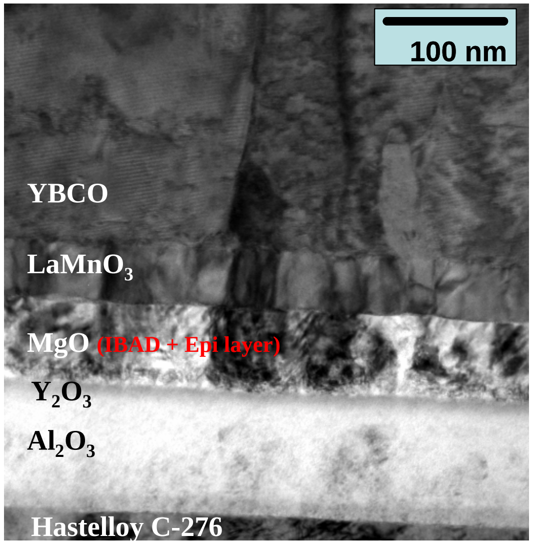
SuperPower's 2G HTS wire is based on high throughput processes & superior substrate

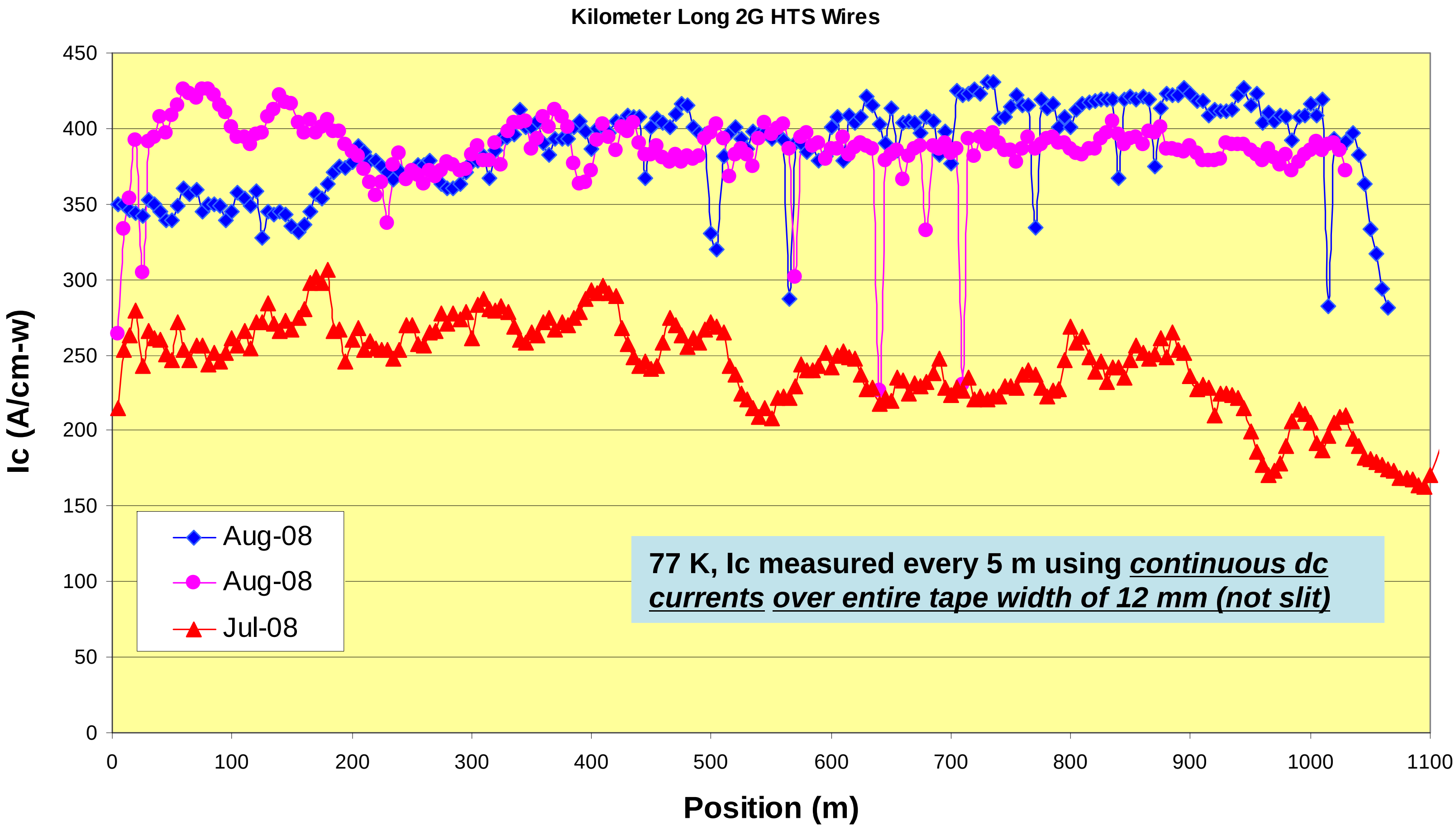
- High throughput is critical for low-cost 2G wire and to minimize capital investment
- SuperPower's 2G wire is based on high throughput IBAD MgO and MOCVD processes
- Use of IBAD as buffer template provides the choice of any substrate
- Advantages of IBAD are high strength, low ac loss (non-magnetic, high resistive substrates) and high engineering current density (ultra-thin substrates)







IBAD-MgO based MOCVD-2G HTS wires produced in kilometer length



77 K, Ic measured every 5 m using ***continuous dc currents over entire tape width of 12 mm (not slit)***

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

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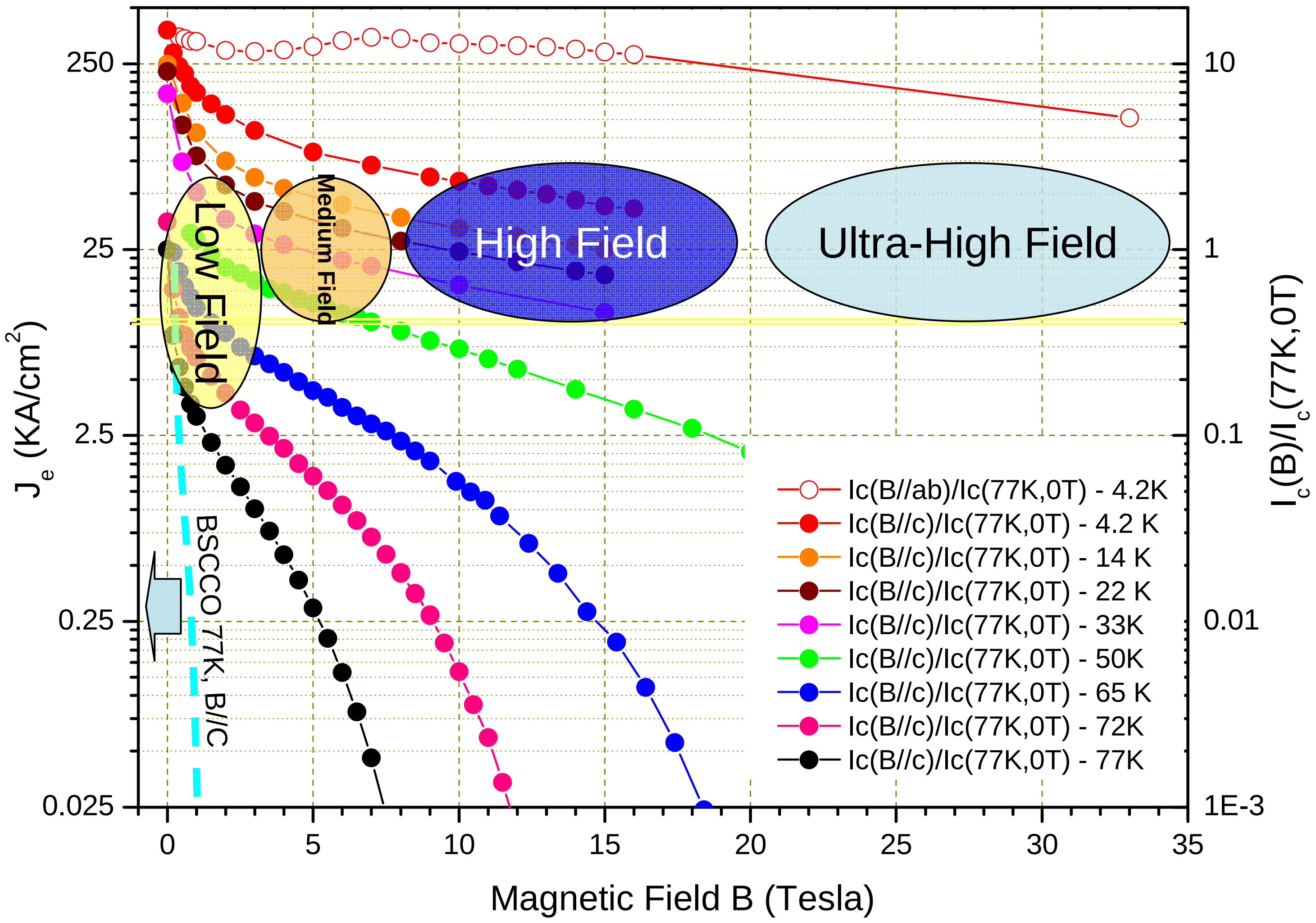
Excellent in-field performance make a wide range of real-world applications possible



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
- 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. Cu stabilized) and scaling factors measured by D. Larbalestier, *et al* at FSU and E. Barzi, *et al*. of Fermi Lab.

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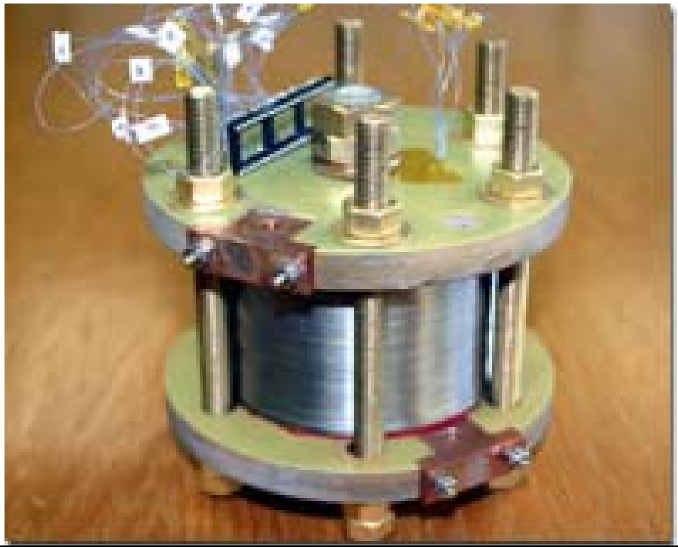
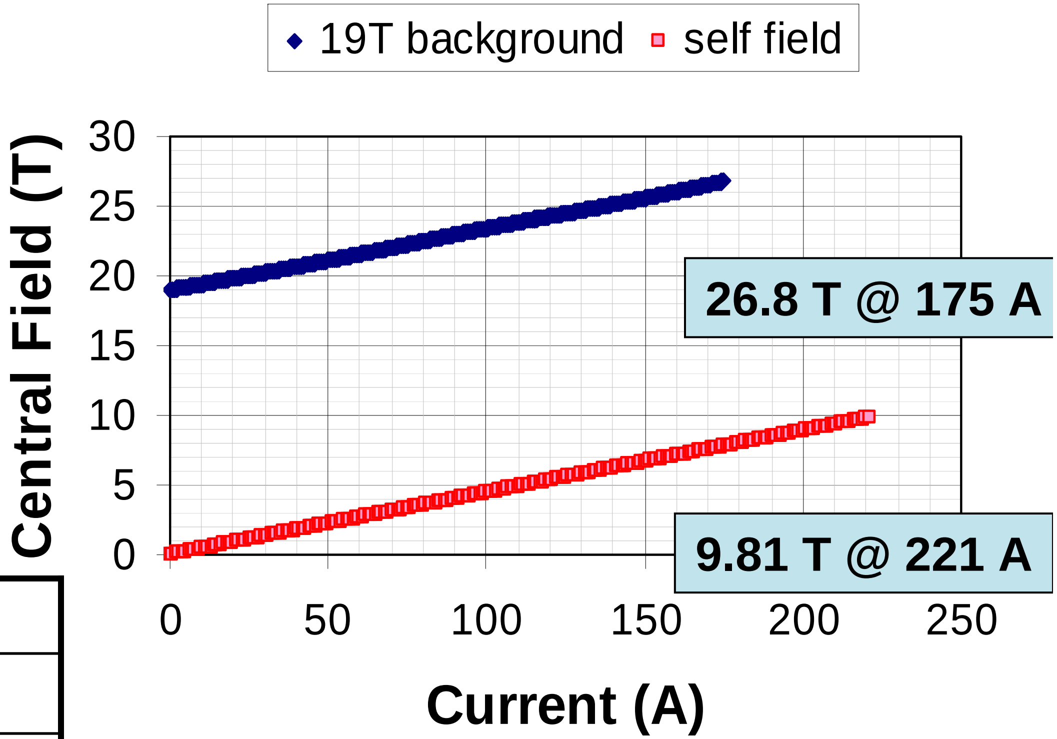
In 2007, we demonstrated a world record high-field magnet



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**
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

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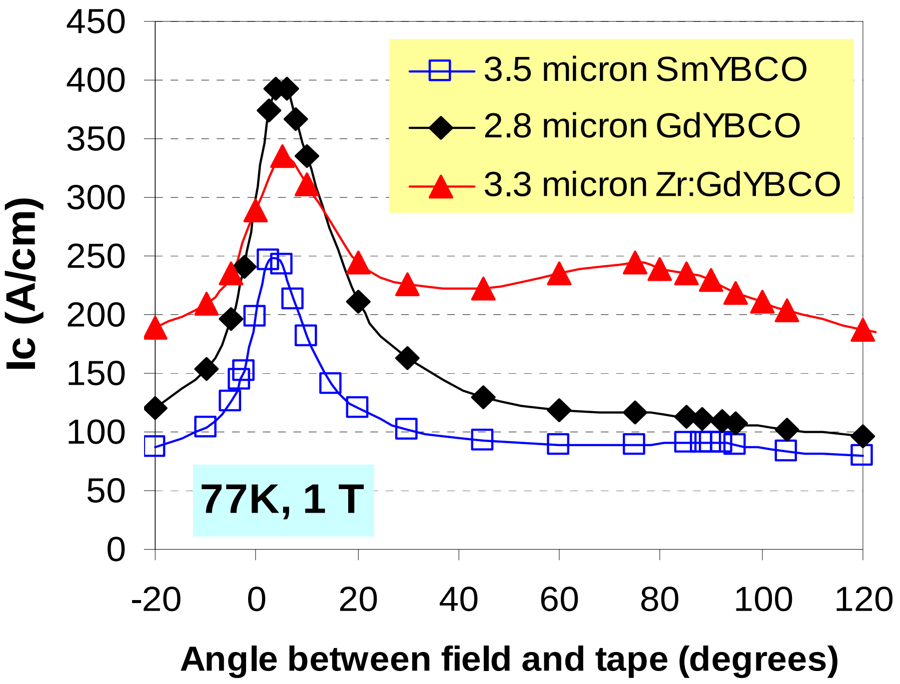
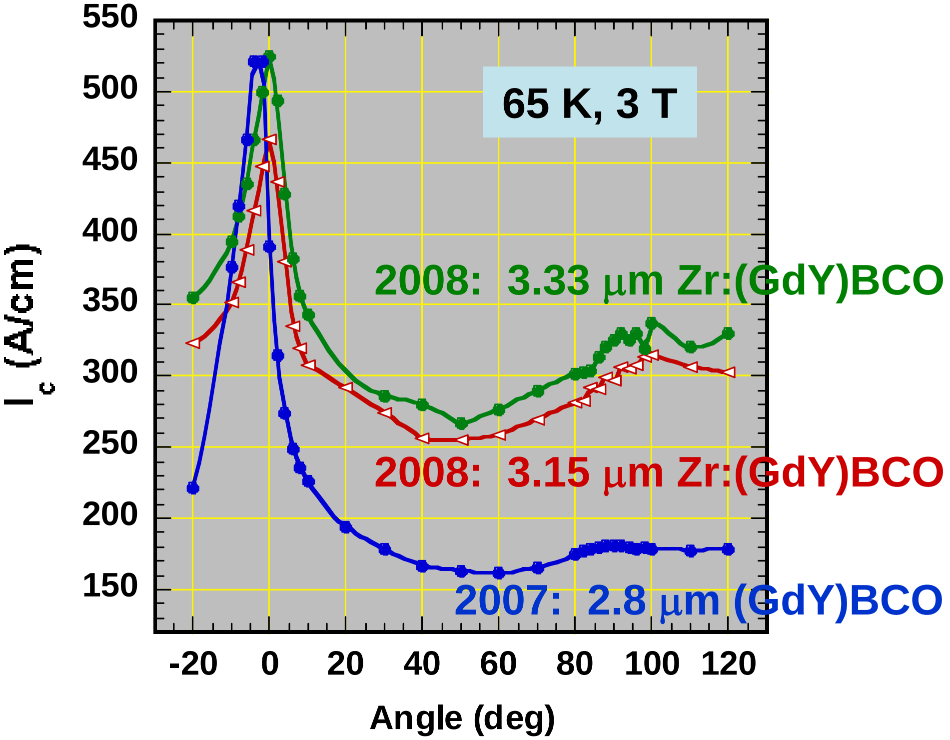
<u>2008</u>: Zr doping was demonstrated in MOCVD to achieve dramatic improvements in in-field performance





- 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 Ic (B ⊥ tape) to 229 A/cm corresponds to J_e of 35,200 A/cm^2 (no copper)

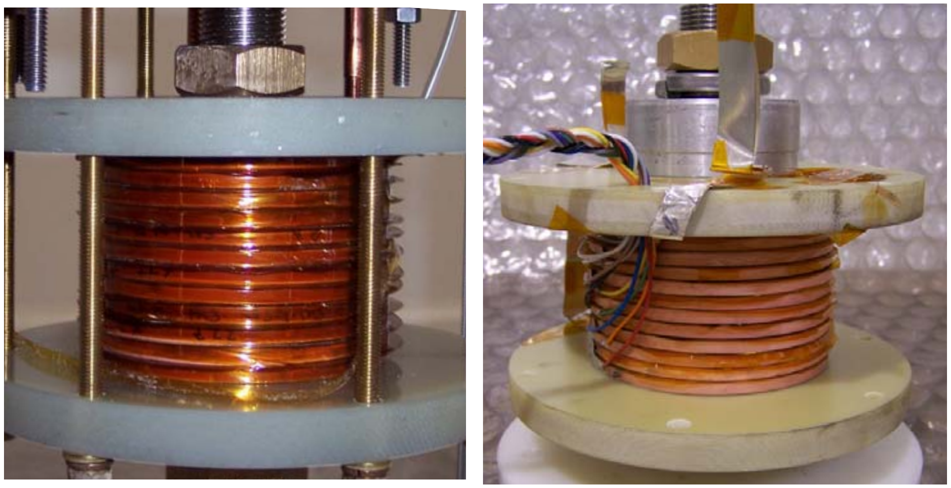
- 67% increase in minimum I_c to 267 A/cm corresponds to J_e of 41,000 A/cm^2 (no copper)
- 88% increase in Ic (B ⊥ tape) to 340 A/cm corresponds to J_e of 52,300 A/cm^2 (no copper)

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

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

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.

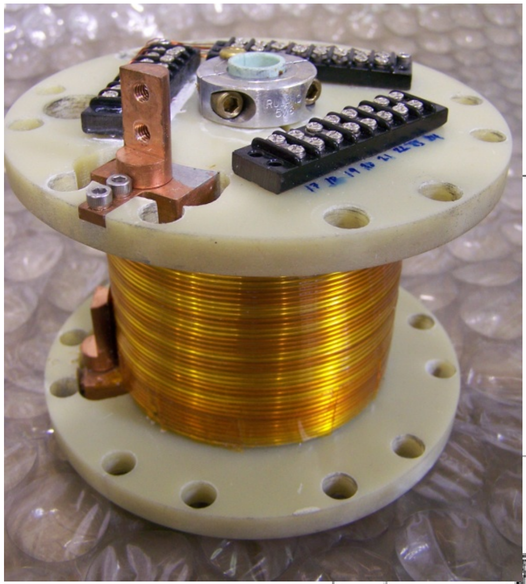


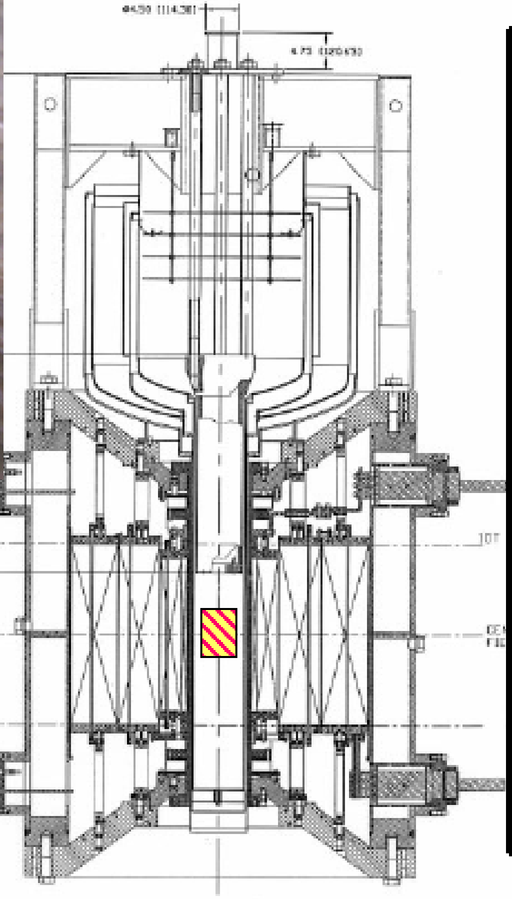
	Coil -1	**Coil - 2**
Field at 77 K	**0.97 T**	**1.09 T**
Field at 65 K	**2.39 T**	**2.5 T**
Field at 61 K		**3.0 T**

	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

Third coil made with high amperage, undoped wire





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

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

Performance of all three coils exceeded 2T at 65 K

Performance parameter of third coil

Temperature	K	4.2	65	77
Coil I_c - self field	A	201.9	48.0	26.8
Amp Turns @ I_c- self field	A-turns	~ 746,222	~ 177,408	~ 99,052
J_e @ I_c, self field	A / mm^2	313.5	74.5	41.6
Central field – self field	T	**10.4**	**2.49**	**1.39**
Background field	T	19.89	3.0	1.0
Coil I_c in background axial field	A	144	31	18
Amp Turns @ I_c in background field	A-turns	~ 532,224	~ 114,576	~ 66,528
J_e @ I_c, in background axial field	A / mm^2	223.6	48.1	28.0
Total Central Field – in background field (axial)	T	27.4	4.60	1.93

- *At 65 K: 2.49 T in self field and 4.6 T in 3 T background field*
- *Achieved similar 65 K field with Zr-doped 2G wire even with substantially lower zero-field I_c, less wire and larger bore coil.*

Quench detection in 2G HTS coil

2G HTS high-field magnets is one of the most promising future applications. Effective prevention of quenches in these coils is crucial for their reliable operation.

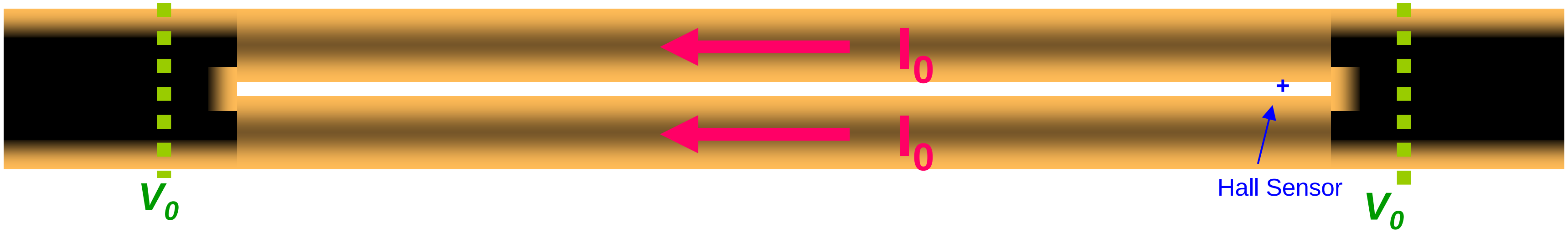
Quench detection in HTS wire is a serious engineering problem. This is due to a very slow (0.1 – 1 cm/s) normal phase propagation velocity (10^3-10^4 times less than in LTS!), resulting in a formation of the localized hotspots.

Traditionally, individual voltage monitoring in the magnet sub-sections is used to detect quenches. *Those hotspots are hard to detect: significant local heating occurs there prior to the surrounding region transitioning the normal state and becoming resistive.*

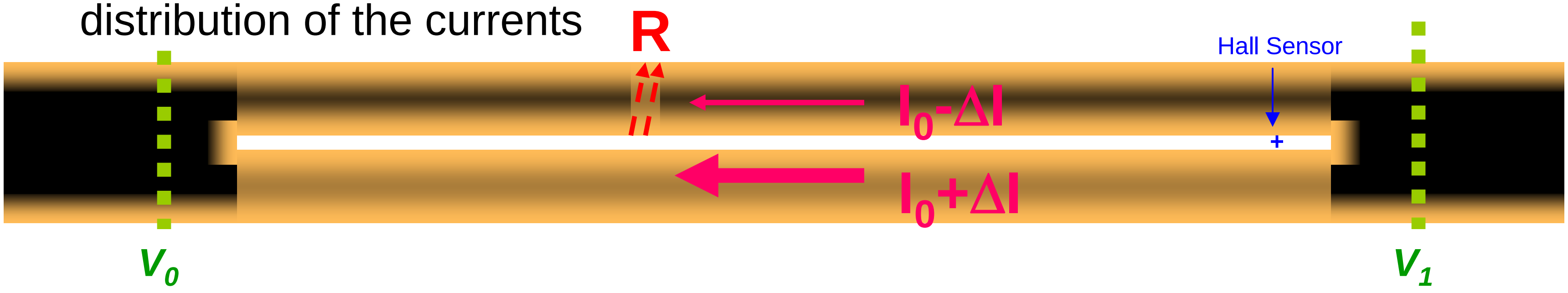
New method of quench detection

New wire configuration is proposed to be used to wind coils. The 2G wire is sub-divided in two parts of equal width along the entire length, except for the areas adjacent to the current leads

Zero resistance, same part geometry: equal distribution of the currents



Resistance onset in one of the parts (creep, flux jump, etc..) leads to re-distribution of the currents



Hall Sensor reading:

$$H_m = \frac{I_c}{4a\pi}\left[\ln\left(\frac{2(a^2-b_+^2)}{aw}\right)-\ln\left(\frac{2(a^2-b_-^2)}{aw}\right)\right]$$

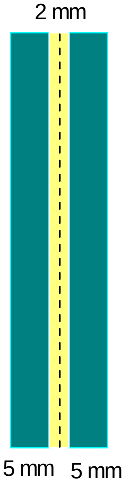
2a: strip width

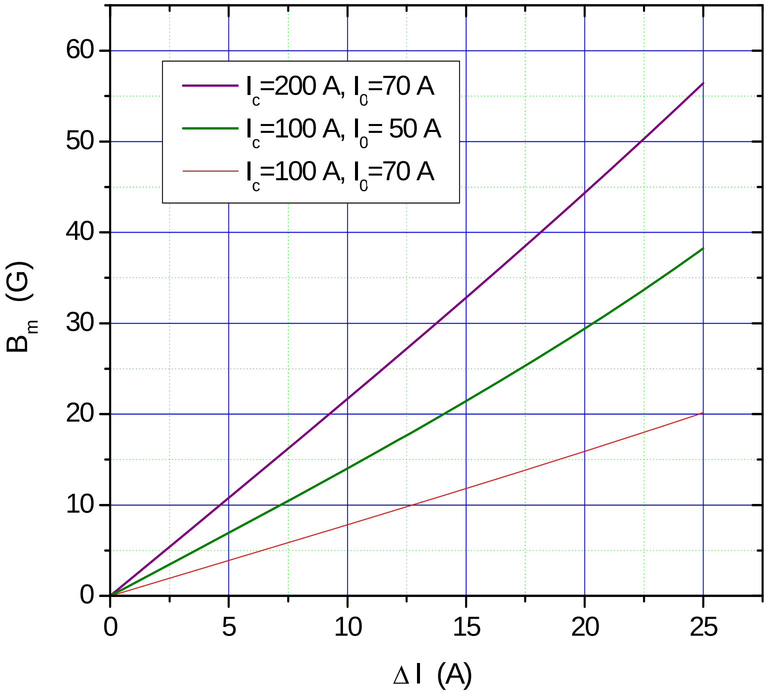
2w: gap width

$b_\pm = a\,(1-(I_0\pm\Delta I)^2/I_c^2)^{1/2}$

Calculation

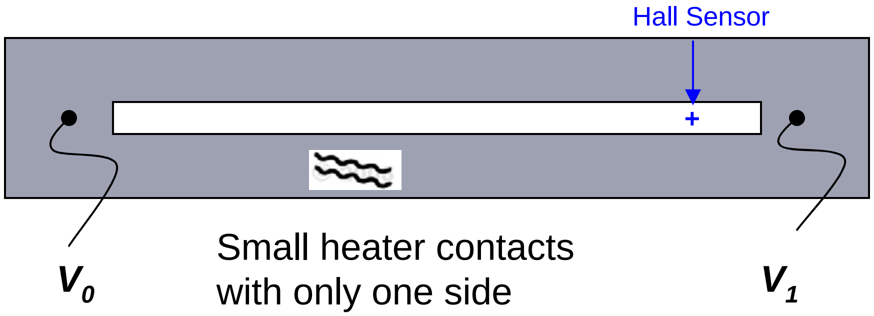
Theoretical result for the 12 mm-wide tape divided into two strips with various I_c and driving currents:



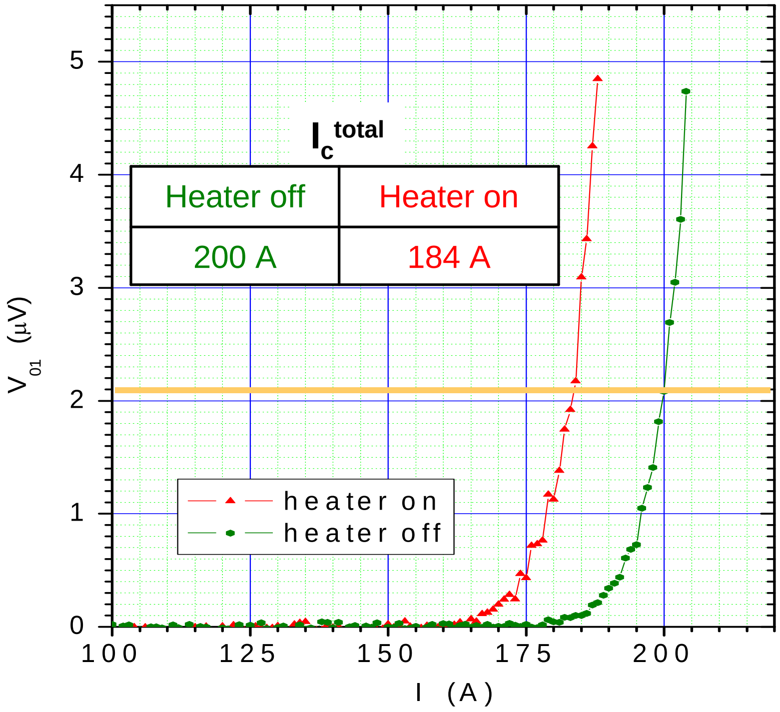


Readily detectable field of ~10 Gauss should appear in the gap region even for a small (~5-10 A) current imbalance;

Experiment



Small heater contacts with only one side



I_c^{total}

Heater off	Heater on
200 A	184 A

Heater on → decrease in I_c^{total} and redistribution of current less than I_c^{total}

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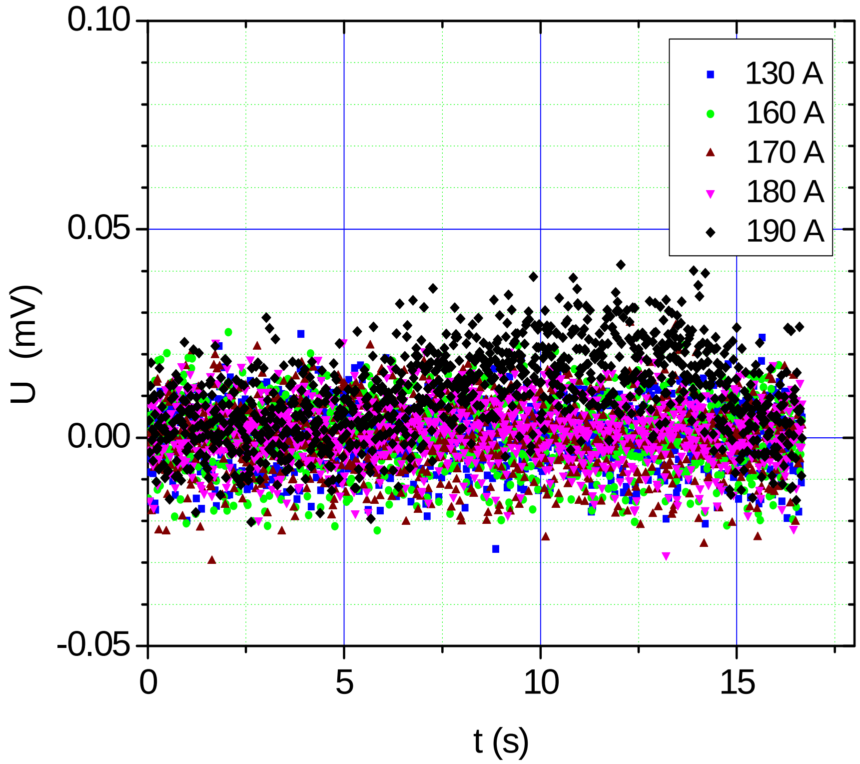
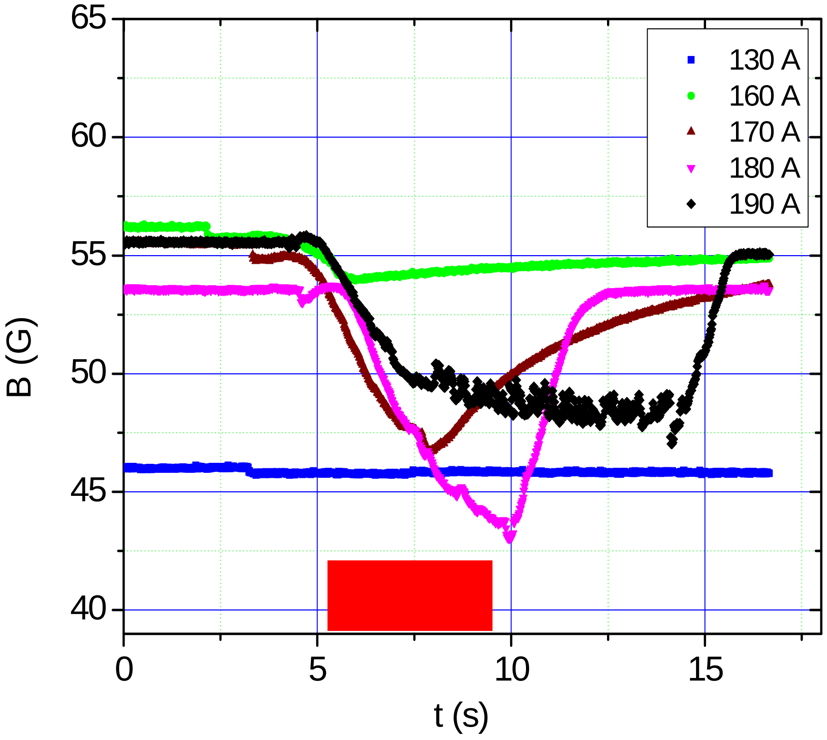
Response to heat pulse: Voltage *vs.* Hall sensor





Voltage due to heat pulse is unambiguously detected only when the transport current exceeds I_{c_heat}.

Magnetic field induction in the slit measured simultaneously during the heat pulse application (offset is due to electrical imbalance of the Hall sensor)

In this new method, the effect of local heating is clearly detected, even when current is well below I_c !

Summary

- 2G HTS wire is routinely produced in manufacturing line in SuperPower. New world record performances up to Ic × L = 300,330 A-m achieved in km long wires. Enhancement in in-field performance achieved *via* Zr-doping and the technology has been transferred into production line.
- More high-field coils with consistent and improvement performance demonstrated with SuperPower® 2G wires. Self field was increased from 0.73 Tesla to above 1 T at 77 K and more than 2 T at 65. 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.
- A novel technique for quench detection in 2G HTS conductors is proposed, based on the continuous tape modification (slitting) along the length and use of the Hall sensor as the field / current balance detector.
- Sensitivity of the technique is hundred times or more superior to the standard voltage detection scheme. The ability to detect the pre-quench condition due to a localized thermal degradation of the critical current or increase of the flux creep rate is a unique advantage of the proposed technique