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2G HTS Wire and High Field Magnet Demonstration

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SuperPower, Inc.

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MAGNET LAB
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY - LOS ALAMOS NATIONAL LABORATORY - UNIVERSITY OF FLORIDA

Providing HTS Solutions for a New Dimension in Power – TODAY!

Acknowledgements

SuperPower

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- …and the rest of the SuperPower Team
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National High Magnetic Field Laboratory / FSU

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2G wire program goals for U.S. industry have been established through the Title III program

A primary source of funding for the 2G HTS Wire Program at SuperPower in 2007 came through the Title III office from DOE and DOD funding. The program is currently in Phase III, running from Jan. 2006 to June 2008.

Title III Program Milestones for June 2008

- Wire length ≥ 1000m
- Critical Current (Ic) ≥ 500A/cm width at 77K, self field
- (Je), without stabilizer ≥ 15,000 A/cm^2 at 65K, 3 Tesla,
- Comparable cost with 1G
- Annual Production Capacity ≥ 200,000 kA-m, i.e. 1000 km/year of 200 A tape in 4 mm width

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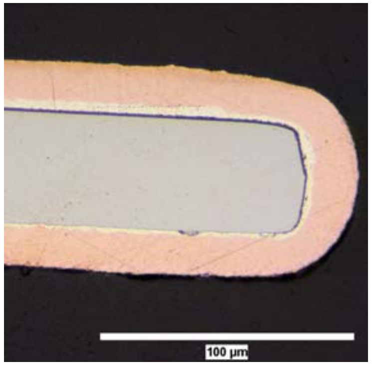
SuperPower’s 2G HTS wire utilizes high strength substrates coupled with high throughput processing

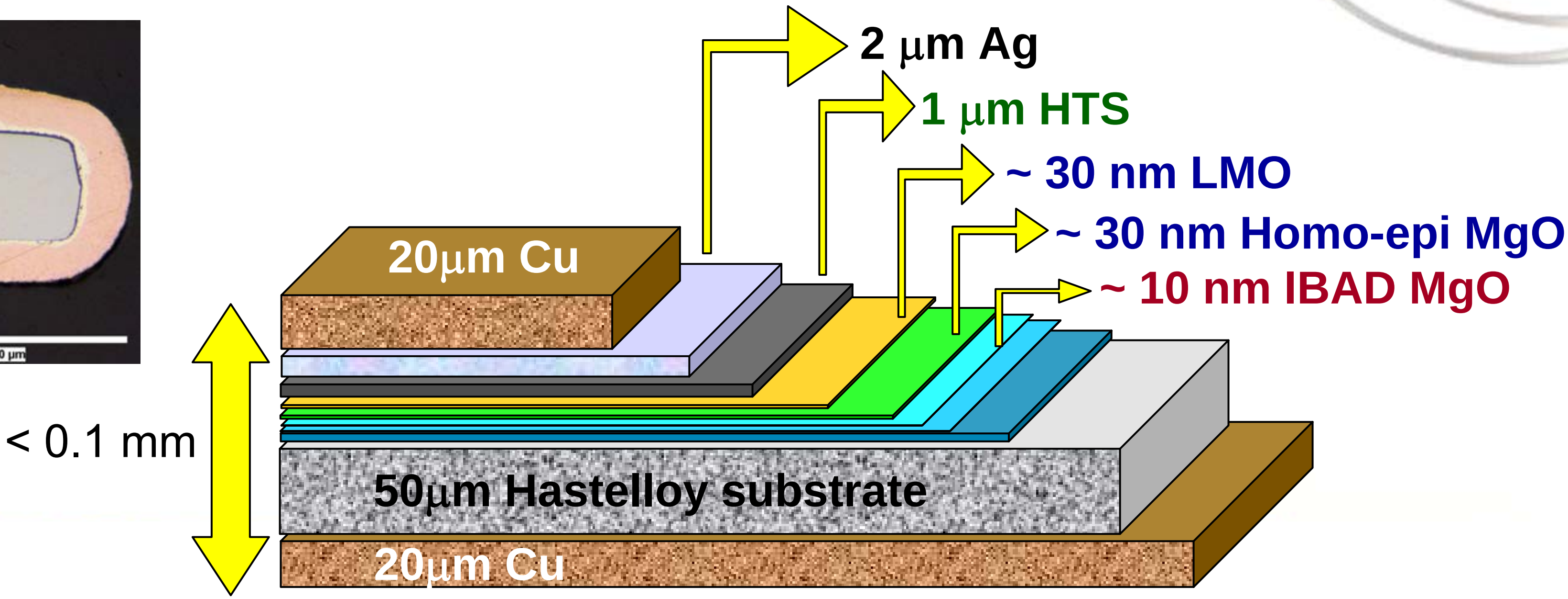
SuperPower’s 2G HTS wire is based on high throughput IBAD MgO and MOCVD processes.

Use of IBAD as buffer template provides us choice of any substrate.

- Advantages of IBAD are high strength, low ac loss (non-magnetic, high resistivity substrates) and high engineering current density (ultra-thin substrates)

High throughput is critical for low cost 2G wire and to minimize capital investment.





SuperPower’s 2G pilot manufacturing facilities have been *operational* since 2006

Majority of investment already made for 1000 km/year capability

Pilot Substrate Electropolishing

Pilot Buffer

Pilot IBAD

Pilot HTS

Substantial improvements made in 2007 in all key metrics: Ic, processing speed and piece lengths of 2G wire

Metric	2005	Aug. 2006	Aug. 2007	Improvement in 2007
Ic (A/cm) – short, reel-to-reel processed	407	557	**740**	30%
Ic (A/cm) over 1 m	236	470	**595**	27%
Ic (A/cm) over 10 m	215	276	**484**	75%
IBAD speed* (m/h)	3	195	**360**	85%
Buffer speed* (m/h)	n/a	120	**345 to 360**	185 to 200%
MOCVD speed* (m/h)	15	90	**180**	100%
Ic over 200 m at stated speed	106	246	**227**	**Same Ic level with much higher speeds in all processes**
Buffered tape piece length (m)	210	550	**1,375**	150%
Completed 2G wire Piece Length (m)	207	322	**595**	85%
Ic × L (A-m)	22,000	70,520	**102,935**	46%

*4 mm wide tape equivalent, single pass

Advancements in key Title III Program metrics resulted in significant 2G cost reduction in 2007

Process	Improvements already Made
IBAD	Throughput increased 100%
Buffer	Throughput increased up to 200%
Intermediate QC	Throughput increased 65%
MOCVD	Throughput increased 100% Precursor cost decreased 33%
Silver	Target cost decreased 70%
Electroplating	Cost reduced 15%; Yield increased 12%
Final QC	~ 4x increase in Transport Ic test speed ~ 3x increase in Non contact Ic speed
Several processes	Increase in yield of later-stage processes have *cumulative* impact on early-stage processes

Process	Cost Reduction
Substrate	20%
IBAD	43%
Buffer	29%
Inspection	47%
MOCVD	47%
Silver	45%
Slitting	39%
Electroplating	25%
Test	69%
Total	**44%**

Our internal conductor cost target for Sept. 07 was met in Jan. 07

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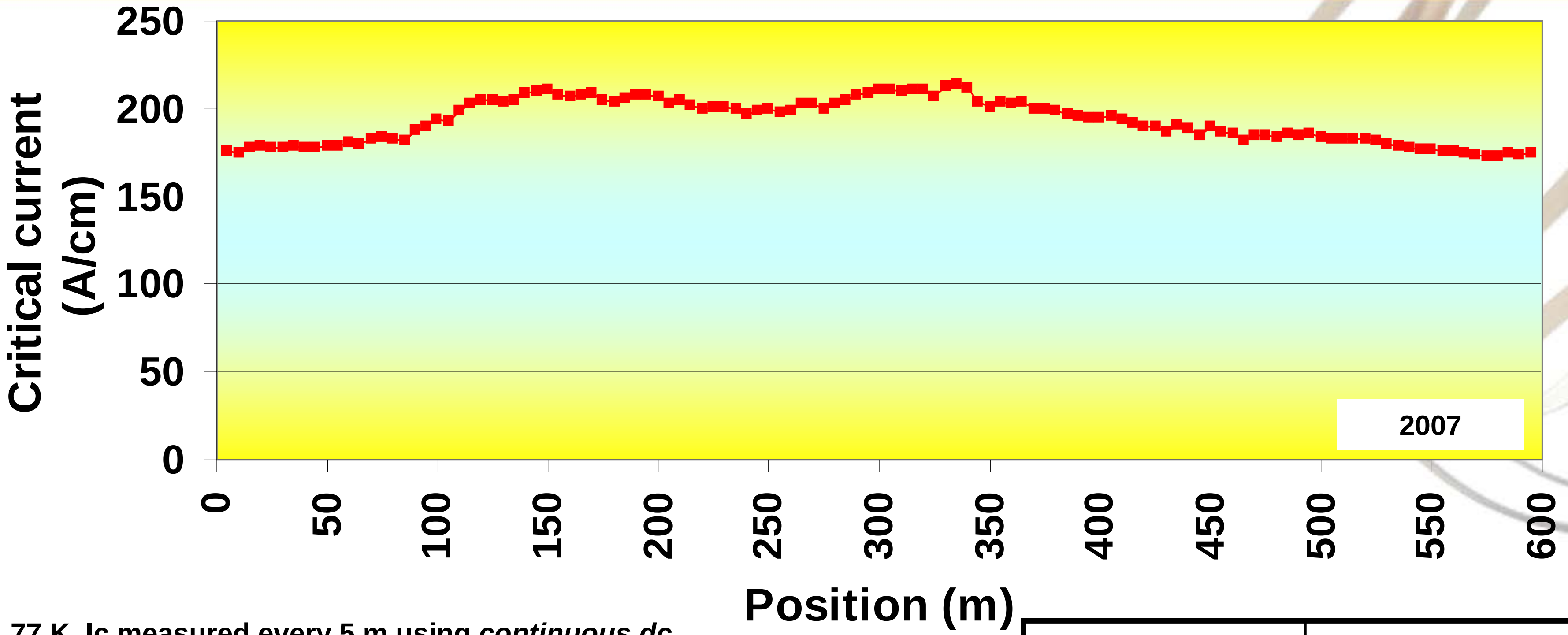
Long length processing of 2G wire demonstrated



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

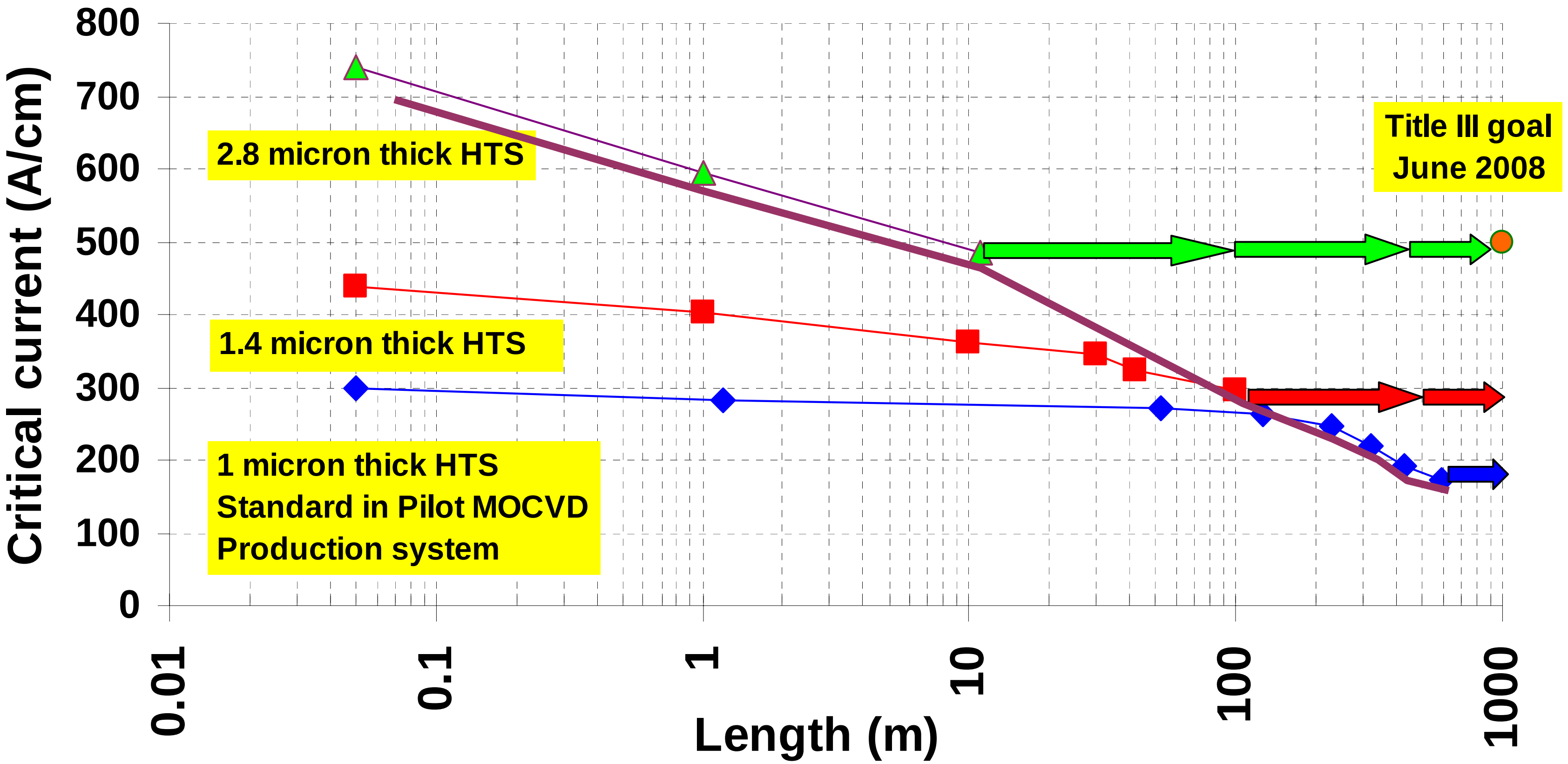
Minimum Ic = 173 A/cm over 595 m

Ic × Length = 102,935 A-m

Uniformity over 595 m = 6.4%

Process (single pass)	Speed of 4 mm tape (m/h)
IBAD MgO	360
Homo-epi MgO	213
LMO	360
MOCVD	135

Progress being made both in Pilot Manufacturing of long lengths & technology development with shorter lengths



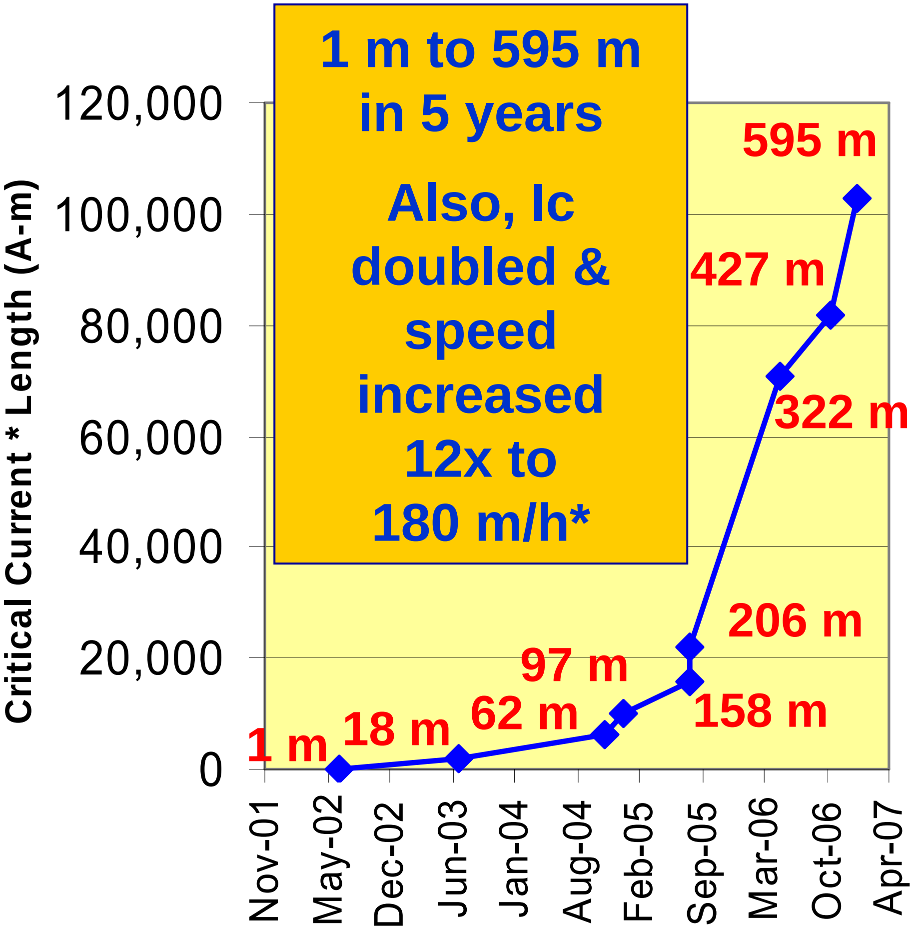
Next Steps:

Manufacturing scale-up to reach 1000 m with Ic > 200 A/cm

Manufacturing improvements to raise Ic level of 500+m Production lengths to that of short lengths of same film thickness i.e. 500 m and then 1000 m with Ic > 300 A/cm

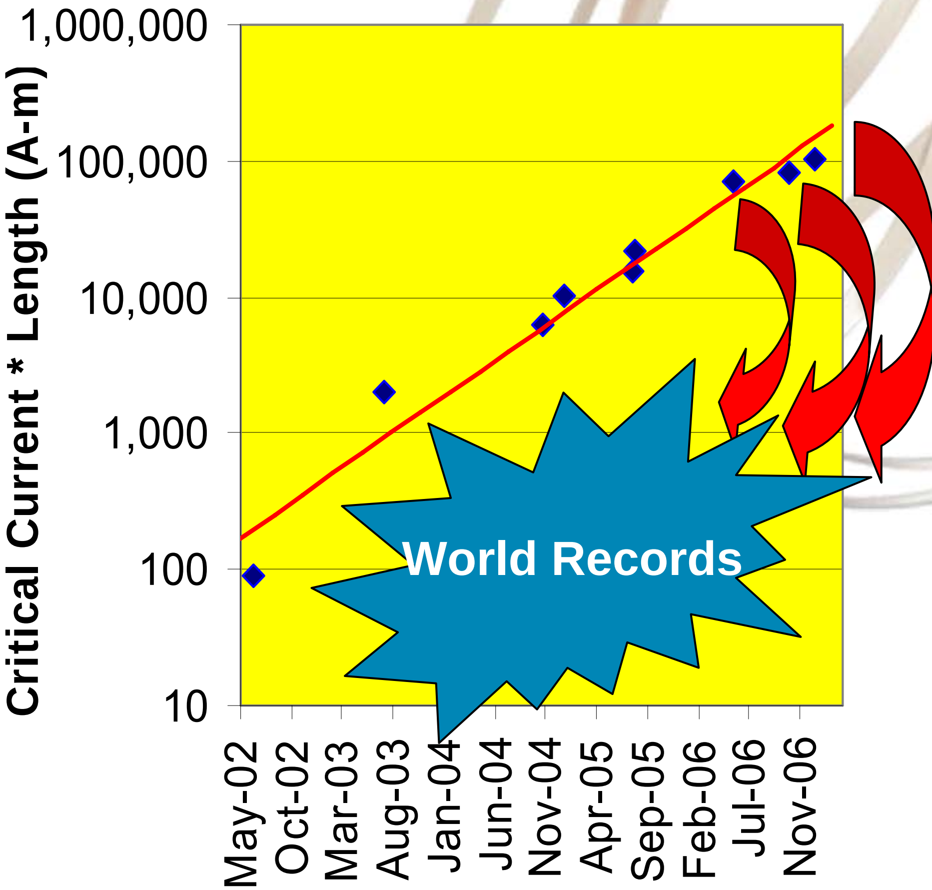
Technology transition of higher-current conductors to Pilot manufacturing i.e. 100 m, then 500 m and then 1000 m with Ic of 500 A/cm

Remarkable progress in 2G wire scale-up over the last 5 years



1 m to 595 m in 5 years

Also, Ic doubled & speed increased 12x to 180 m/h*



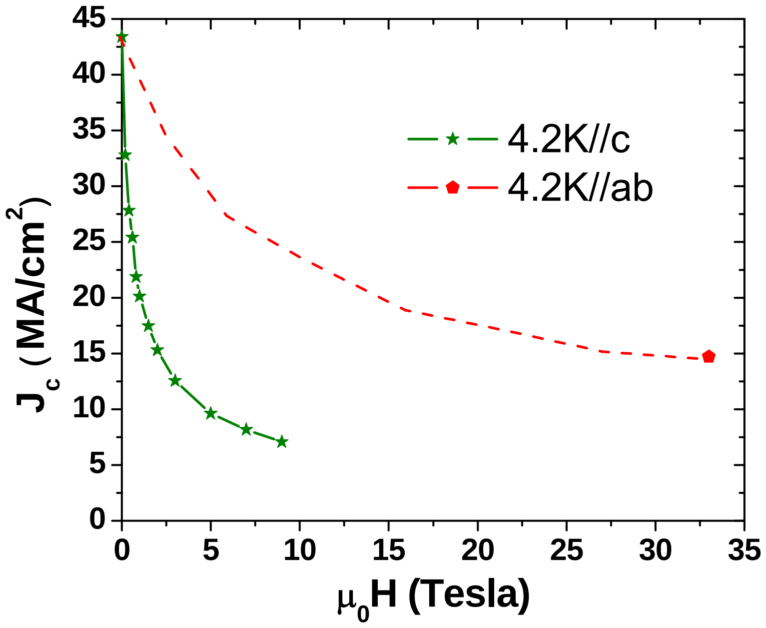
World Records

*4 mm speed equivalent

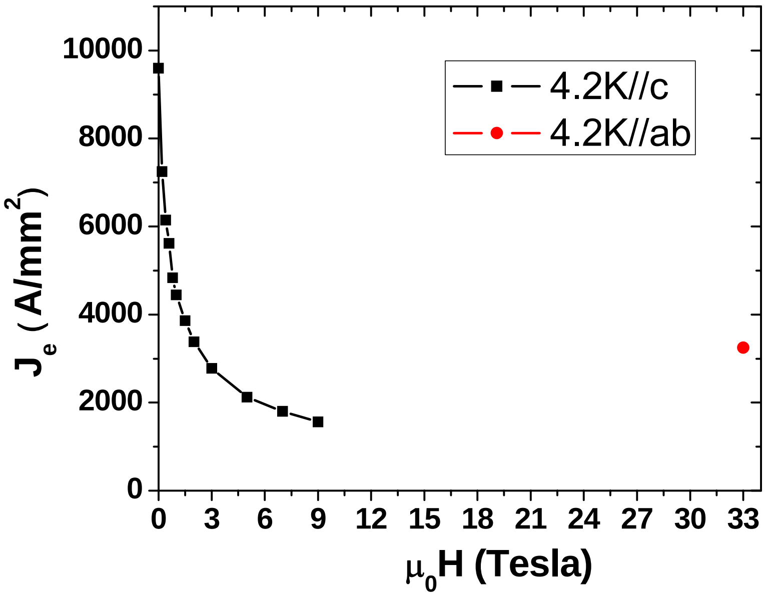
Critical current properties of the 2G wire make it ideal for lower temperature, high field applications

Data (solid figures) taken on bridge sample.

Dashed red line is hypothetical curve.



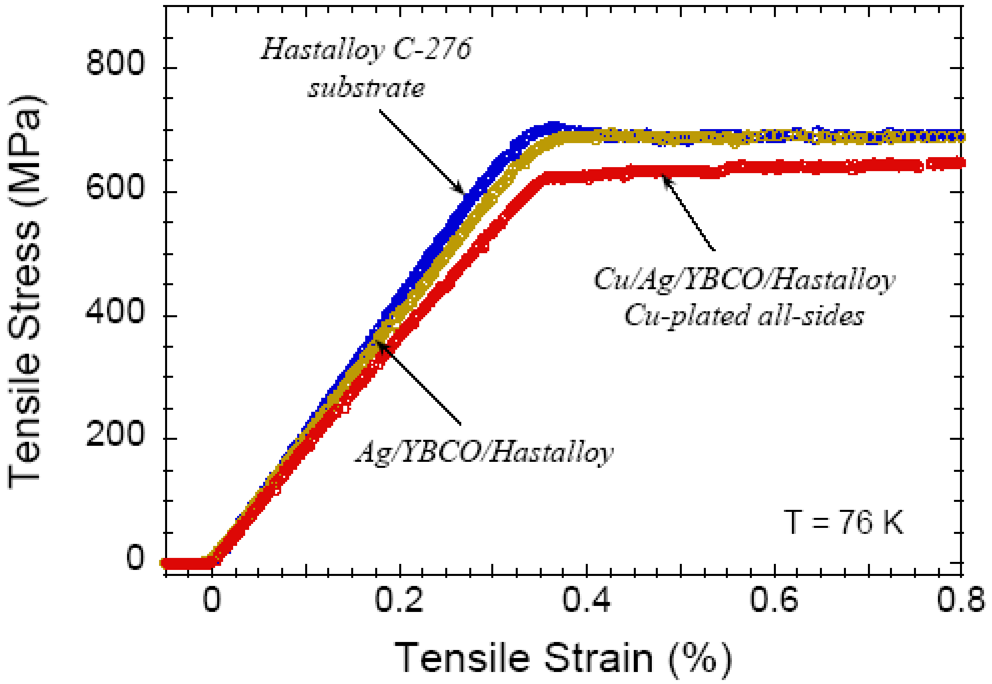
Superconductor critical current density



Conductor critical current density thickness ~ 95 µm

Data by Z. Chen at NHMFL / FSU (2007)

Mechanical properties of 2G wire are ideal for high stress applications

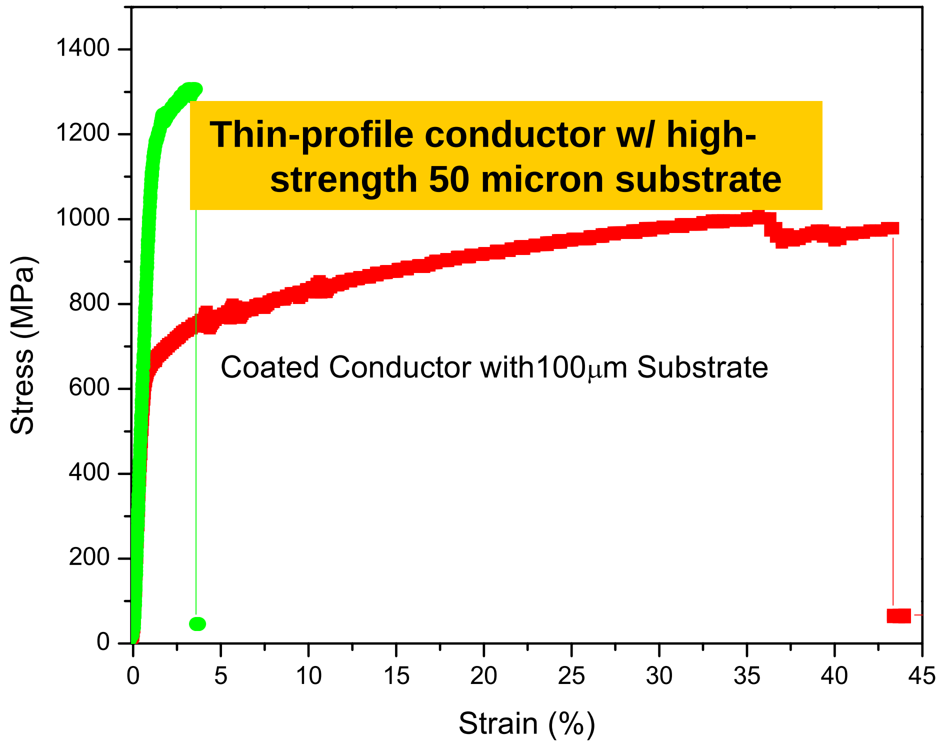


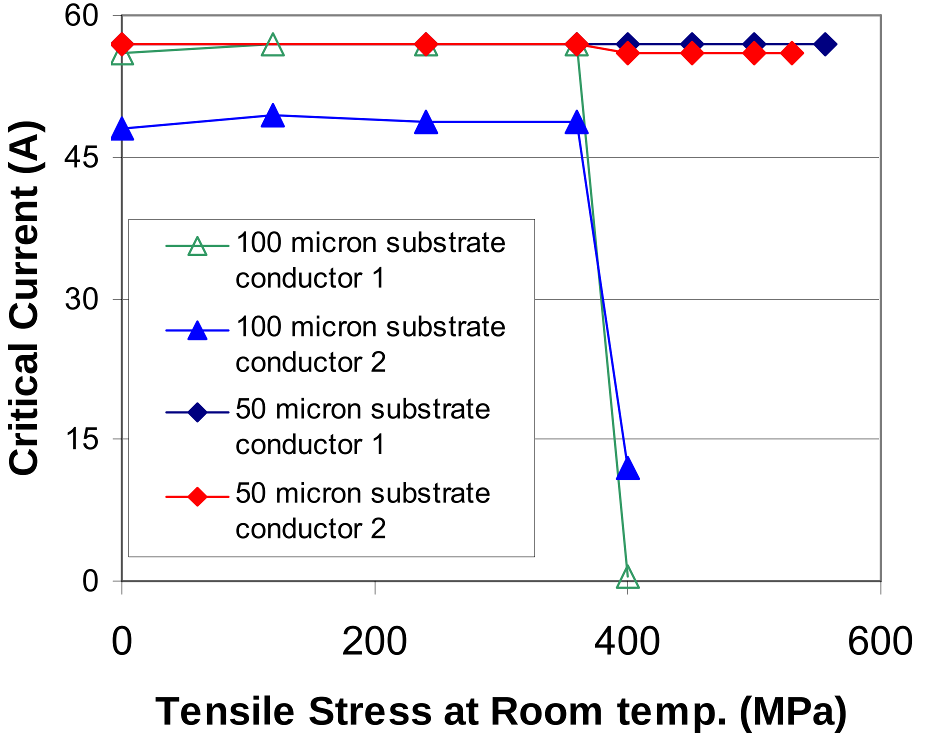
Stress-strain traces for SuperPower 2G YBCO at 76K. Included are a trace of the base substrate material, Hastelloy C276 which dominates the conductor mechanical properties. Note the impact of copper stabilizer which slightly lowers the overall composite strength.

Measurements conducted at NIST by Ekin et al (2004)

Use of high-strength 50 micron substrates yield thin-profile 2G wire with enhanced tensile strain & critical tensile stress

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





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

with 100 micron substrate = 650 MPa

with high-strength 50 micron substrate
= 1200 MPa

Critical tensile stress of 2G wire:

with 100 micron substrate = 350 MPa

with high-strength 50 micron substrate
> 550 MPa

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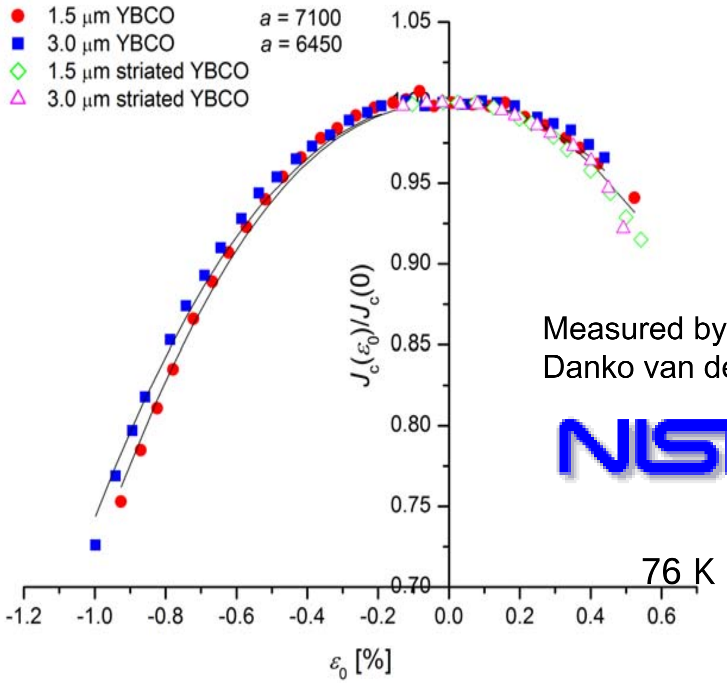
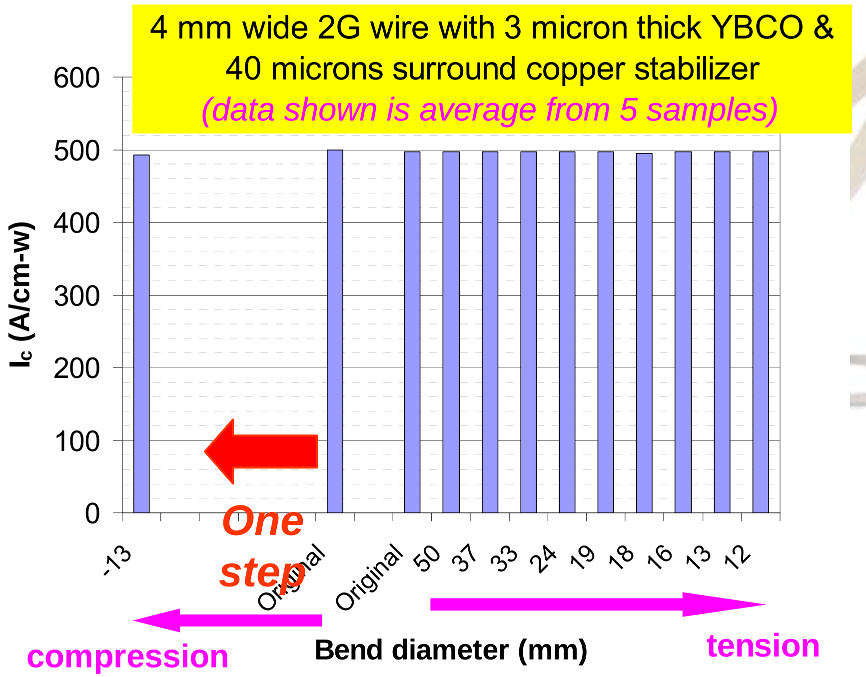
Excellent mechanical properties maintained even in 2G wire with 3 micron thick HTS films

In 2007, we started evaluation of mechanical properties of 2G wire with thick HTS films. Tapes were slit to 4 mm & copper plated with 40 microns of surround copper stabilizer & were tested in axial tension & compression at NIST and bending with YBCO in tension and compression at SuperPower.



Measured by
Danko van der Laan



4 mm wide 2G wire with 3 micron thick YBCO & 40 microns surround copper stabilizer
(data shown is average from 5 samples)

95% Ic retention measured in axial tension & compression up to <u>0.5%</u> even in wire with <u>3 micron</u> thick HTS layer

95% Ic retention measured in bending with YBCO in tension & compression down to a bend diameter of <u>13 mm</u> even in wire with <u>3 micron</u> thick HTS layer

High field insert coil construction

Wire:

Dimensions: 4 mm wide x 95 microns thick

Substrate: 50 micron Hastelloy

HTS: ~ 1 micron YBCO

Stabilizer: ~ 2 micron Ag on YBCO

~ 20 microns of surround copper stabilizer per side

Wire Ic: 72 – 82 A, 77 K, sf

Coil Winding:

Double Pancake Construction

Dry Wound (no epoxy)

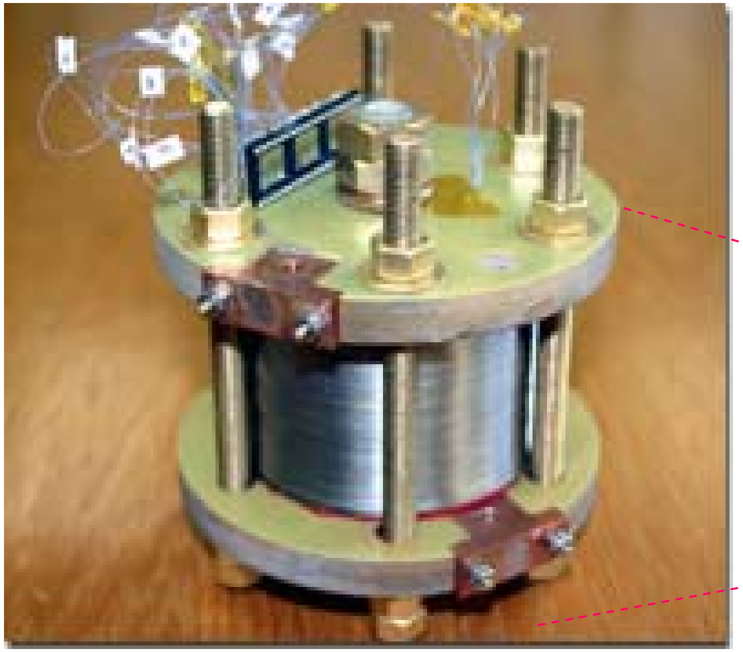
Kapton polyimide insulation (co-wound)

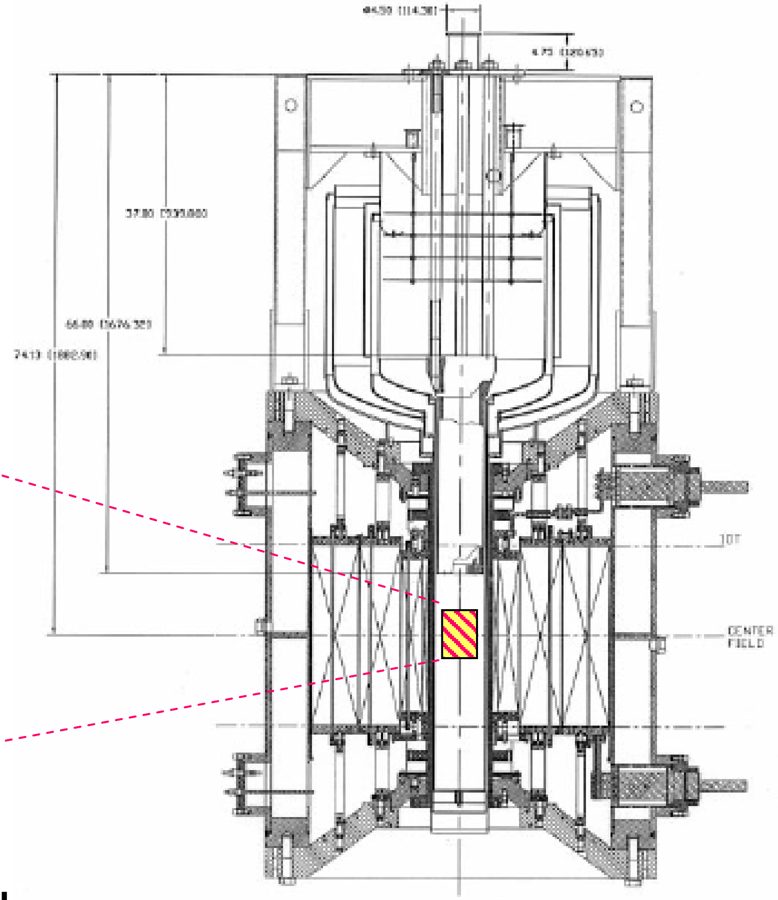
Overbanding: 316 Stainless Steel

Coil ID	9.5 mm (clear)
Winding ID	19.1 mm
Winding OD	~ 87 mm
Coil Height	~ 51.6 mm
# of Pancakes	12 (6 x double)
2G tape used	~ 462 m
# of turns	~ 2772
Coil Je	~1.569 A/mm^2 per A
Coil constant	~ 44.4 mT/A

NHMFL facilities provide 19T axial background field

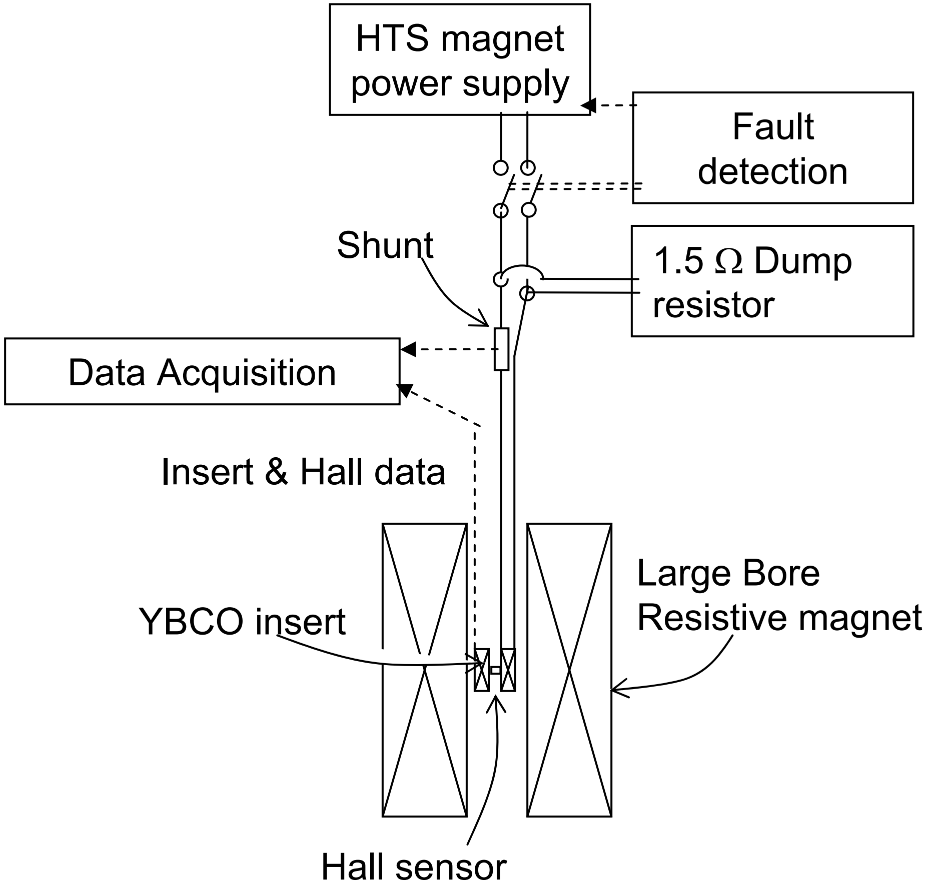
Insert coil tested in NHMFL's unique, 19-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet





2G HF insert coil showing terminals, overbanding and partial support structure. Flange OD is 127 mm.

Test setup at NHMFL



HTS magnet power supply

Fault detection

Shunt

1.5 Ω Dump resistor

Data Acquisition

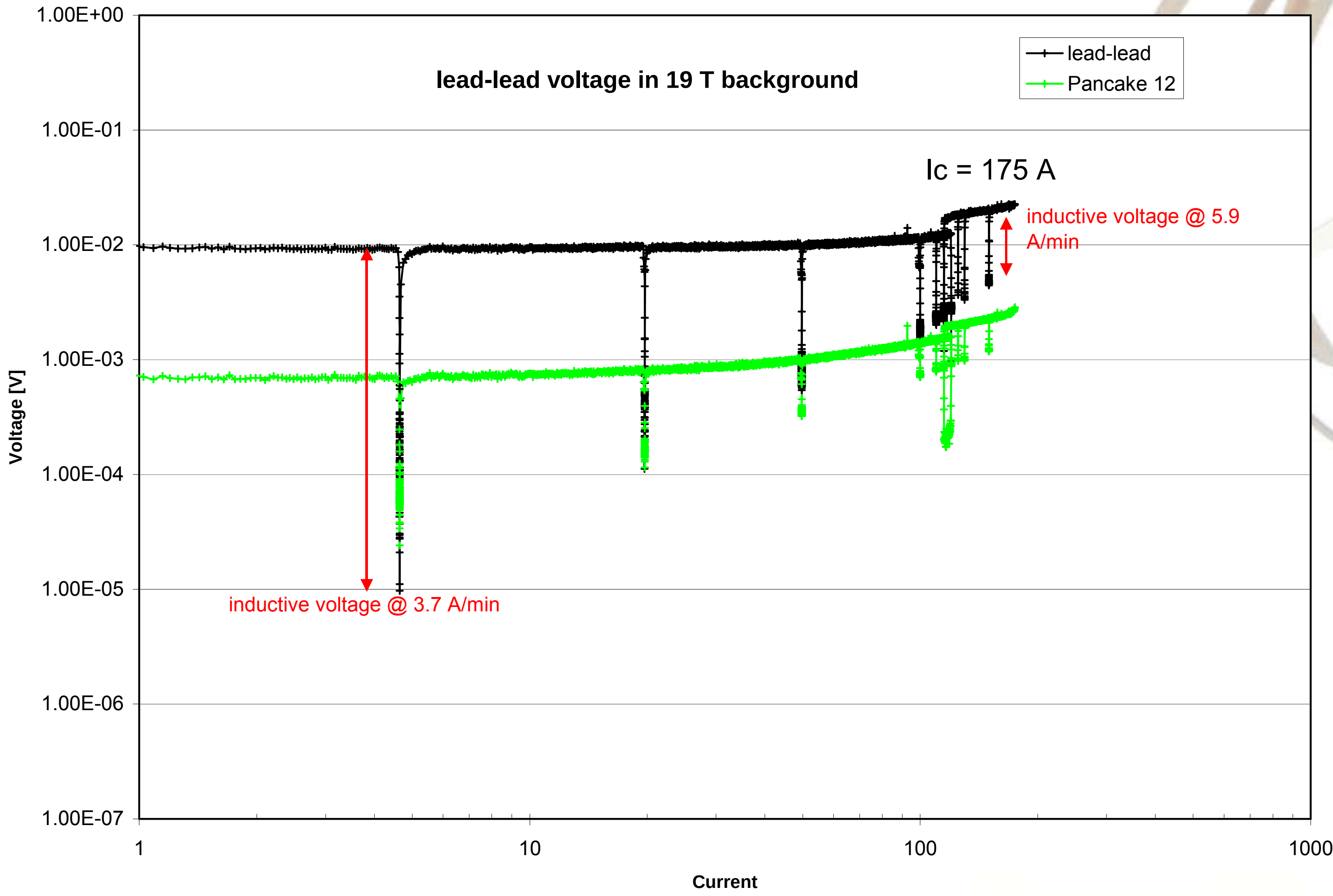
Insert & Hall data

YBCO insert

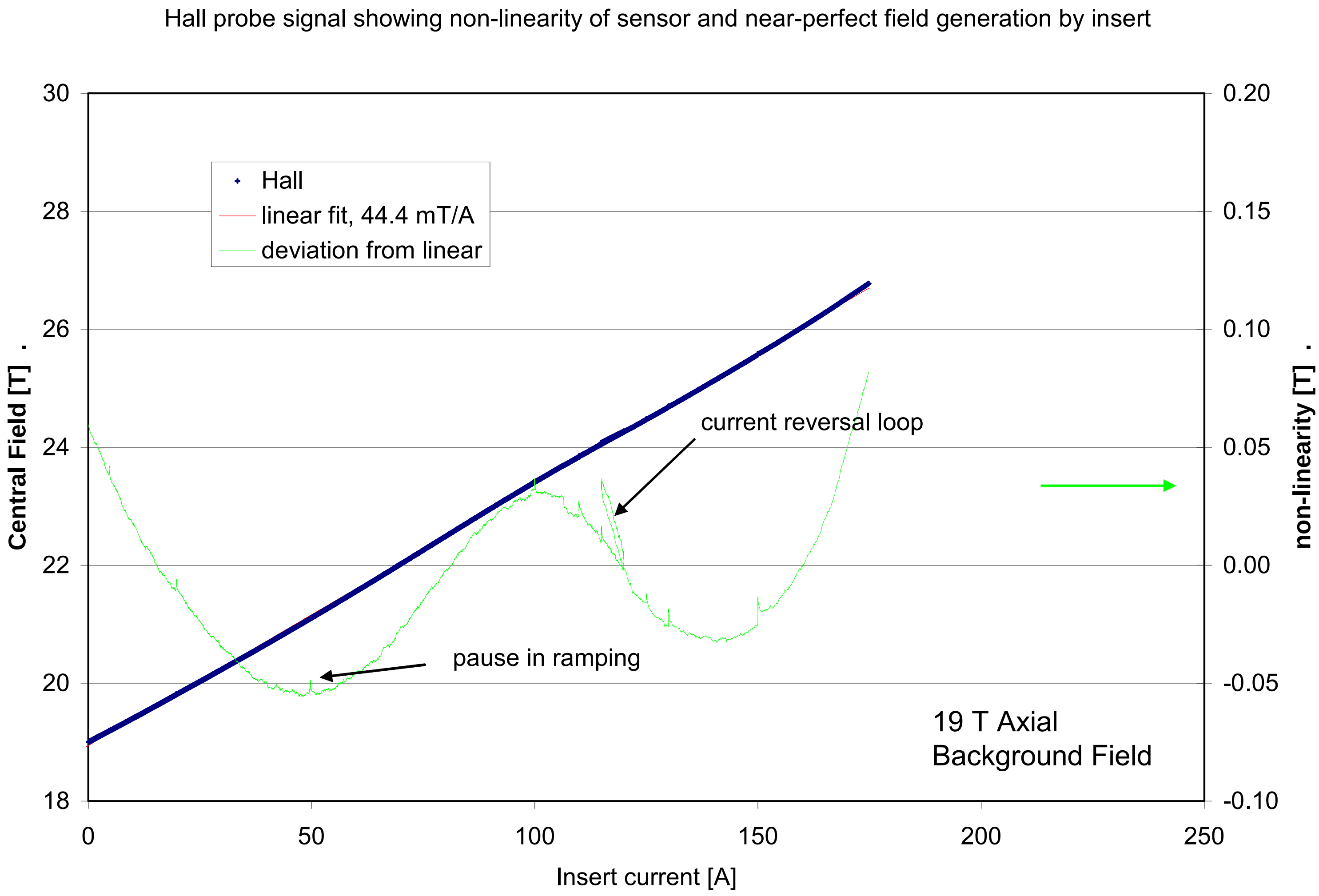
Large Bore Resistive magnet

Hall sensor

Typical V-I trace (19T background field)

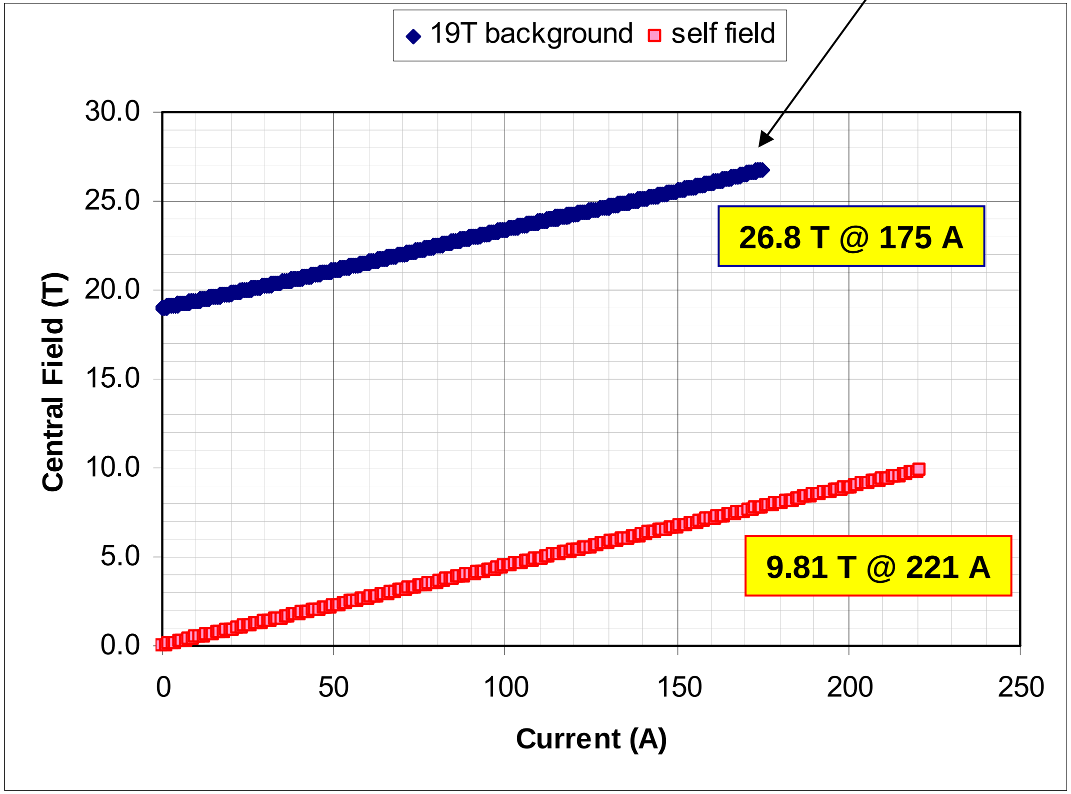


Hall probe data shows linear field generation



High field insert coil achieves world records for highest HTS field, highest magnetic field by a SC magnet

Peak hoop stress ~ 215 MPa, well below tape limit



Ic of Wires in Coil	72 A – 82 A (77K, sf)
4.2 K Coil Ic - self field	221 A
4.2 K Amp Turns @ Ic- self field	612,612
4.2 K Je @ Ic, self field	346.7 A/mm^2
4.2K Peak Radial Field @ Ic, self field	3.2 T
4.2 K Central field – self field	9.81 T
4.2 K Coil Ic – 19 T background (axial)	175 A
4.2 K Amp Turns @ Ic – 19 T background (axial)	485,100
4.2 K Je @ Ic, 19 T background (axial)	274.6 A/mm^2
4.2 K Peak Radial Field @ Ic, 19 T bkgd (axial)	2.7 T
4.2K Central Field – 19 T background (axial)	26.8 T

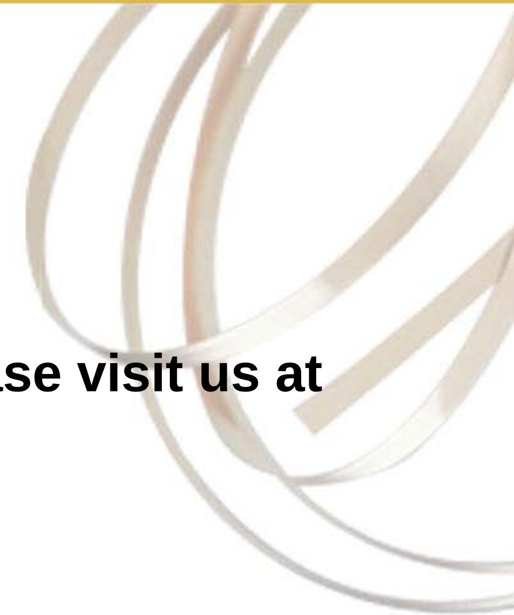
Summary

- We have not reached the limit of 2G HTS wire capability
- Coil performance limited by operation of Pancake 12 (currently being replaced)
- Stress limit on the wire still has significant margin:

  Hoop stress ~ 215 MPa vs. ~ 600 MPa limit

- 2G HTS wire with 50 micron Hastelloy substrate enables high winding pack Je
- 2G HTS wire is available in lengths and quantity to enable development in high field magnet design and construction
- 30 T (and beyond?) is within our grasp……

Questions?



Thank you for your interest!

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