



# 2G HTS Wire and High Field Magnet Demonstration

Presented by: Drew W. Hazelton  
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**

- Jason Duval, Venkat Selvamanickam, Yi-Yuan Xie
- ...and the rest of the SuperPower Team
- 2G HTS Wire Development Program funding from Title III and DOE through UT-Battelle
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## **National High Magnetic Field Laboratory / FSU**

- Zhijun Chen, David Larbalestier, Denis Markiewicz, Ed Miller, Patrick Noyes, Ken Pickard, Ulf Trociewitz, and Huub Weijers
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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  $\geq 1000\text{m}$
- Critical Current ( $I_c$ )  $\geq 500\text{A/cm}$  width at 77K, self field
- ( $J_e$ ), without stabilizer  $\geq 15,000\text{ A/cm}^2$  at 65K, 3 Tesla,
- Comparable cost with 1G
- Annual Production Capacity  $\geq 200,000\text{ kA-m}$ , i.e. 1000 km/year of 200 A tape in 4 mm width



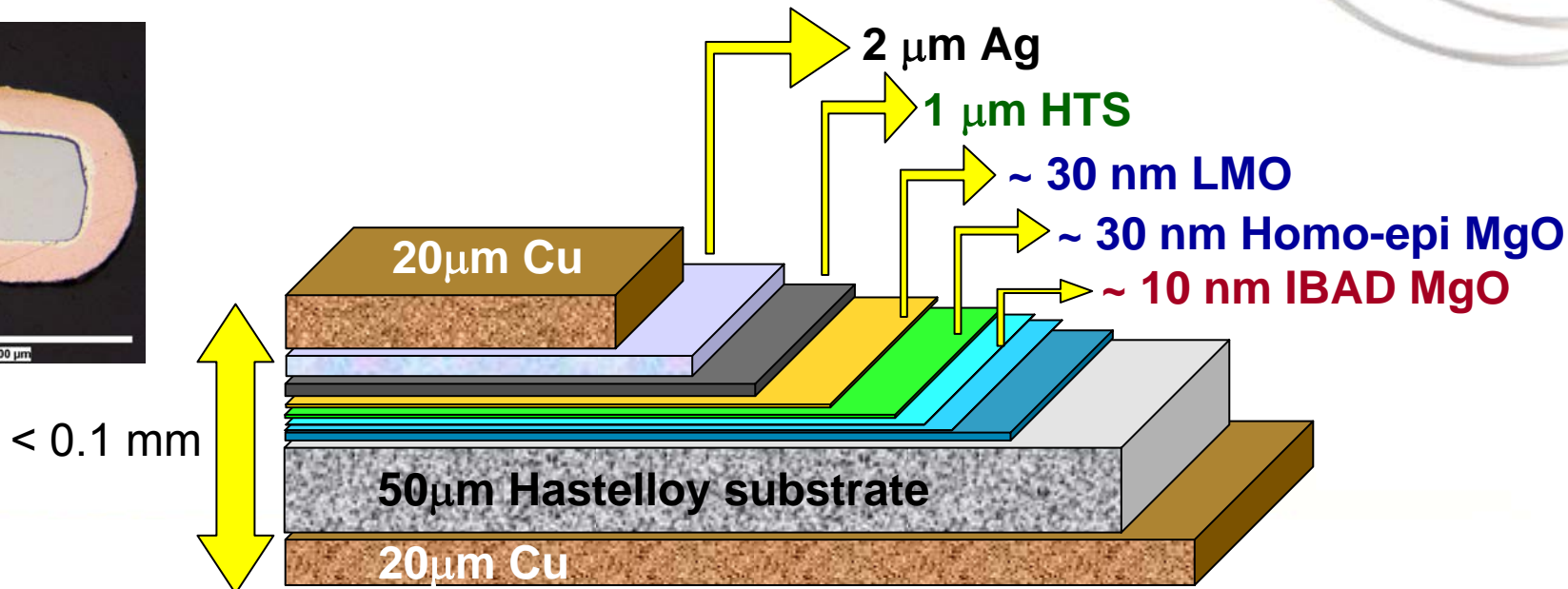
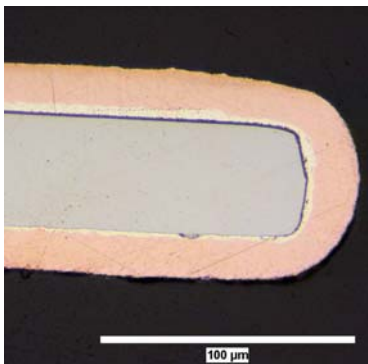
# SuperPower's 2G HTS wire utilizes high strength substrates coupled with high throughput processing

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**

**SuperPower** Inc.

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



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

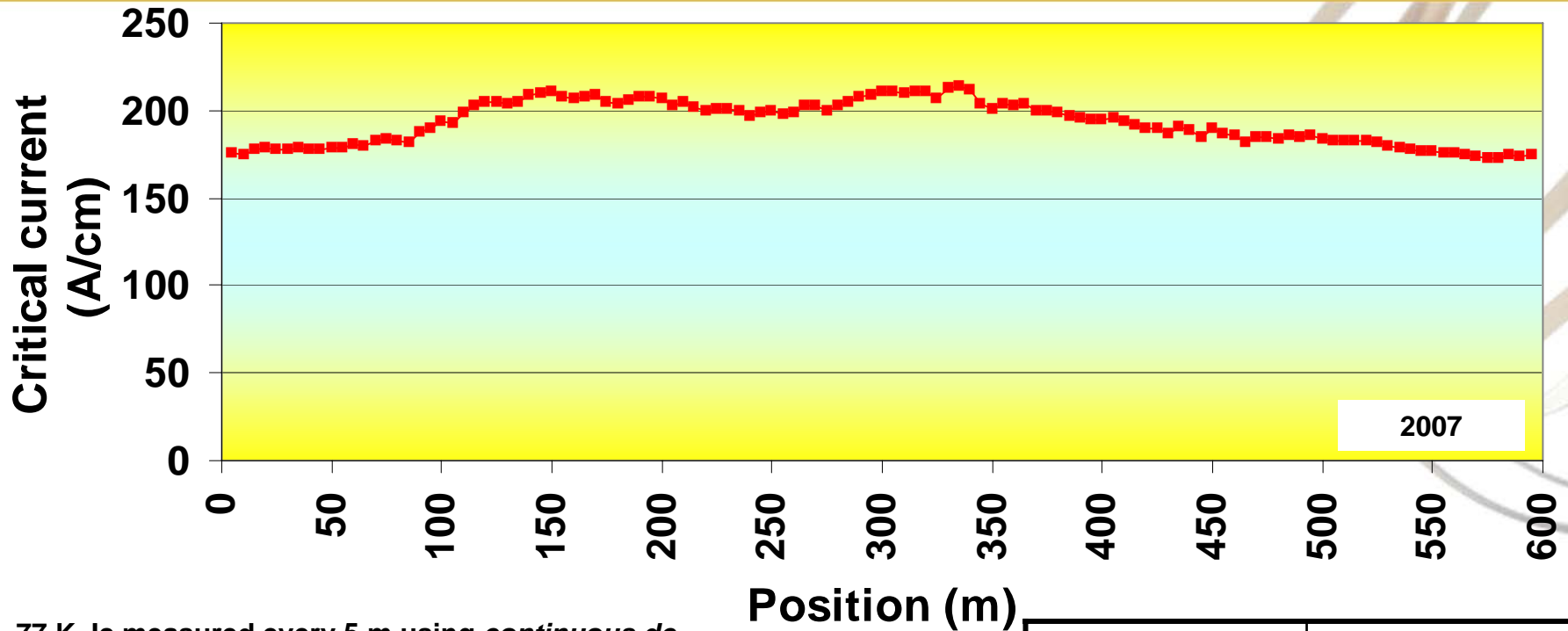
Process	Improvements already Made
IBAD	Throughput increased 100%
Buffer	Throughput increased up to 200%
Intermediate QC	Throughput increased 65%
MOCVD	Throughput increased 100% Precursor cost decreased 33%
Silver	Target cost decreased 70%
Electroplating	Cost reduced 15%; Yield increased 12%
Final QC	~ 4x increase in Transport Ic test speed ~ 3x increase in Non contact Ic speed
Several processes	Increase in yield of later-stage processes have <i>cumulative</i> 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%
<b>Total</b>	<b>44%</b>

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



# Long length processing of 2G wire demonstrated



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

**Minimum  $I_c$  = 173 A/cm over 595 m**

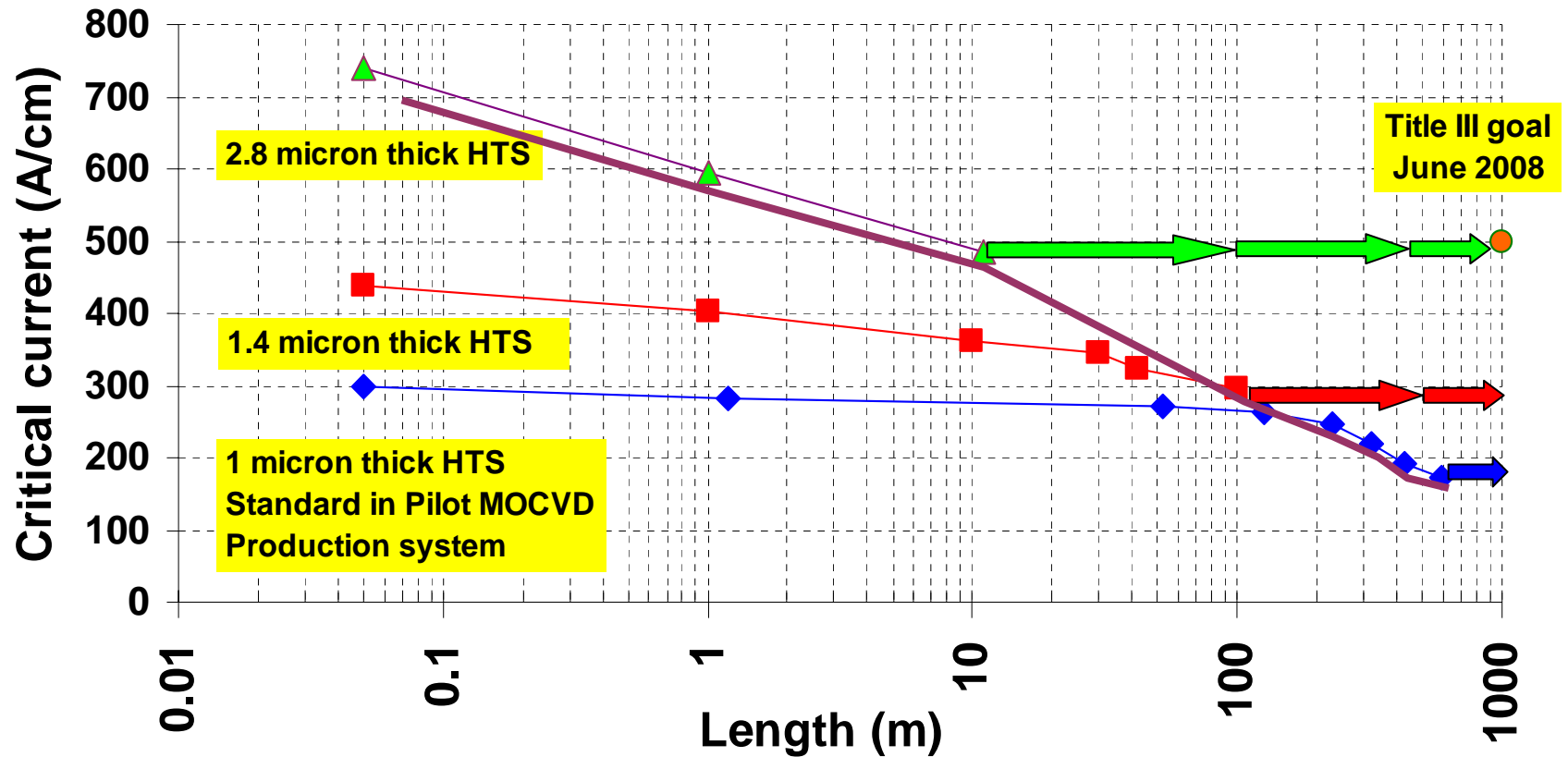
**$I_c \times \text{Length} = 102,935 \text{ A-m}$**

**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



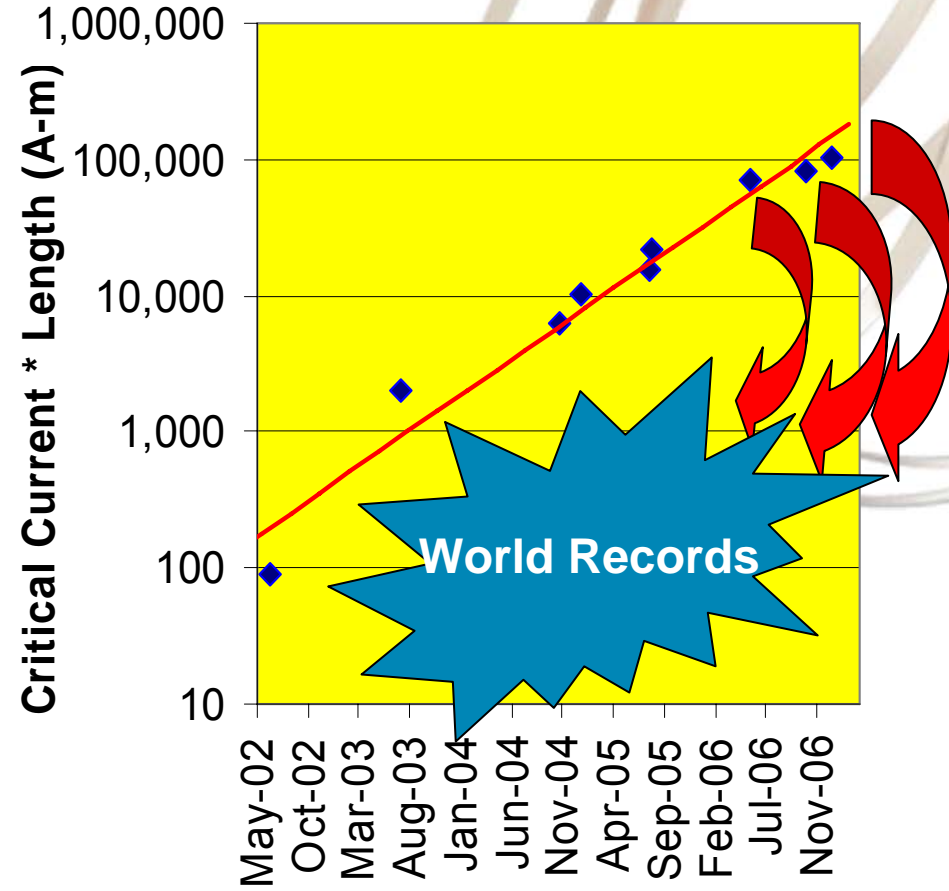
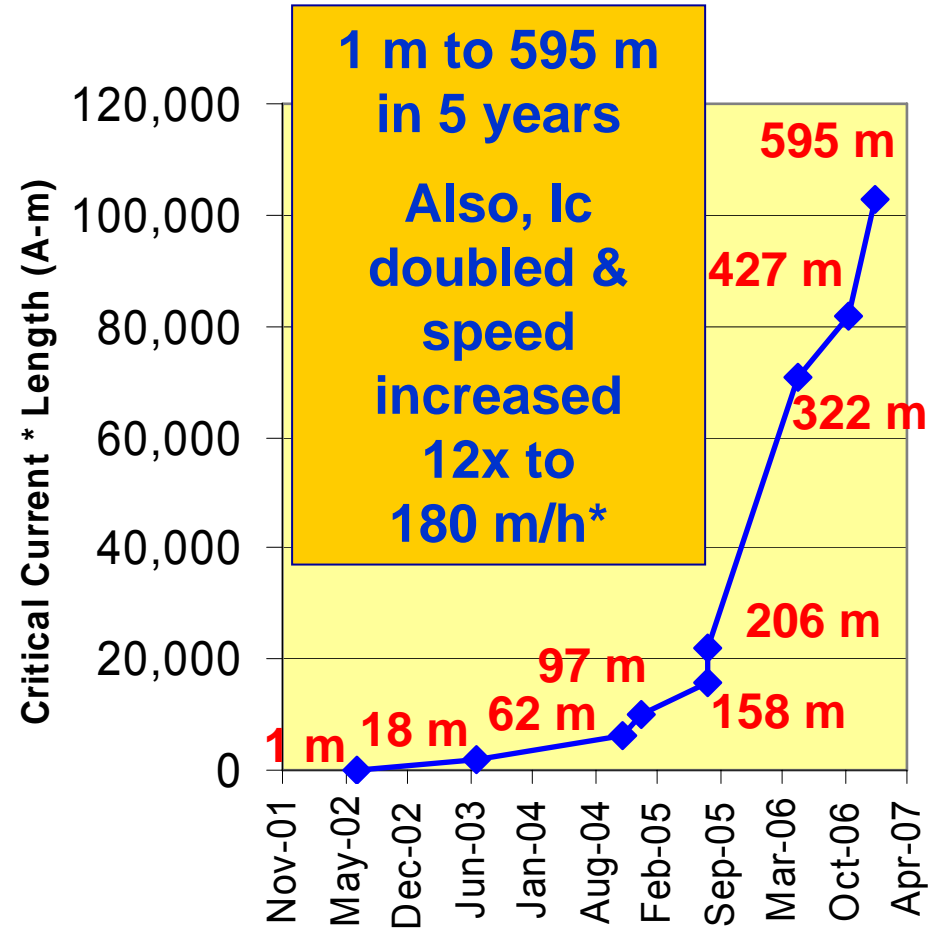
## Next Steps:

**Manufacturing scale-up to reach 1000 m with  $I_c > 200$  A/cm**

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

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

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



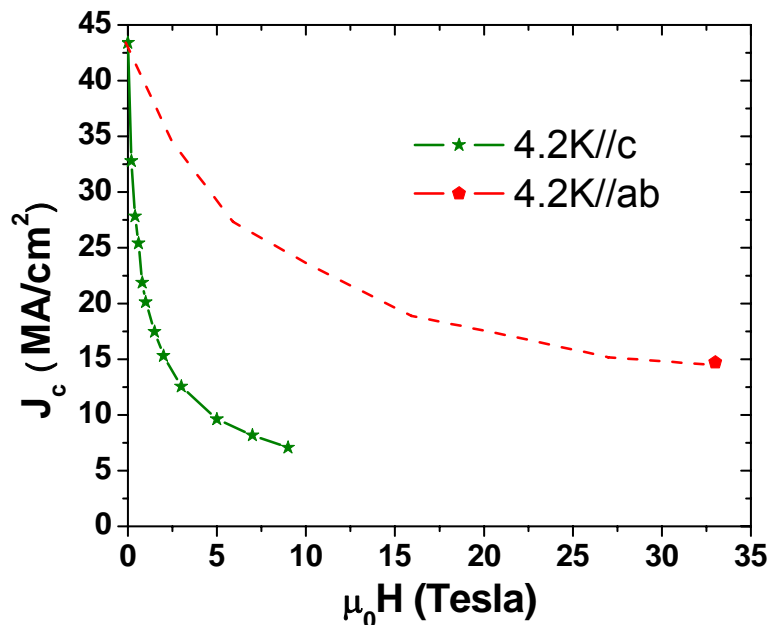
\*4 mm speed equivalent



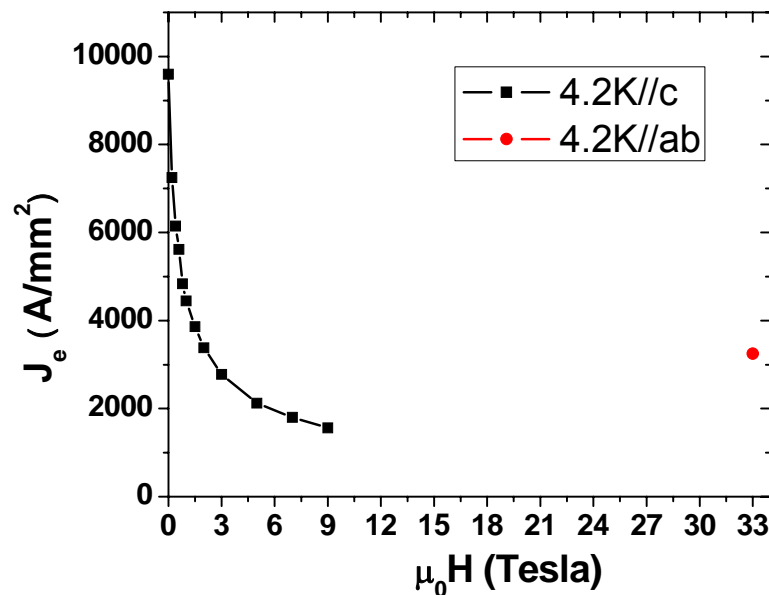
# Critical current properties of the 2G wire make it ideal for lower temperature, high field applications

Data (solid figures) taken on bridge sample.

Dashed red line is hypothetical curve.



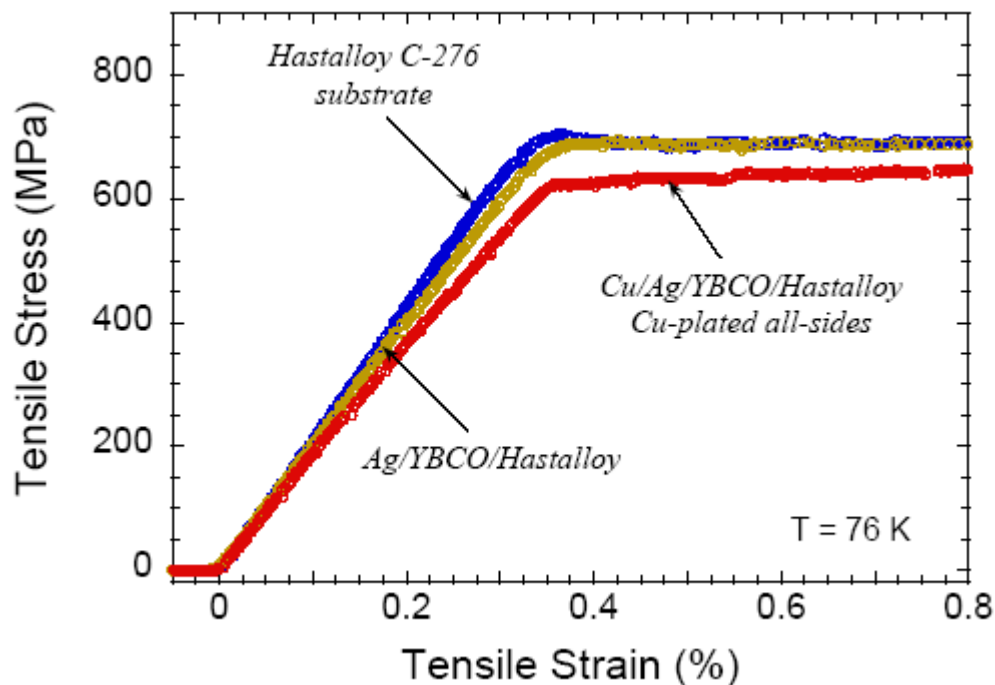
Superconductor critical current density



Conductor critical current density  
thickness ~ 95  $\mu\text{m}$

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

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



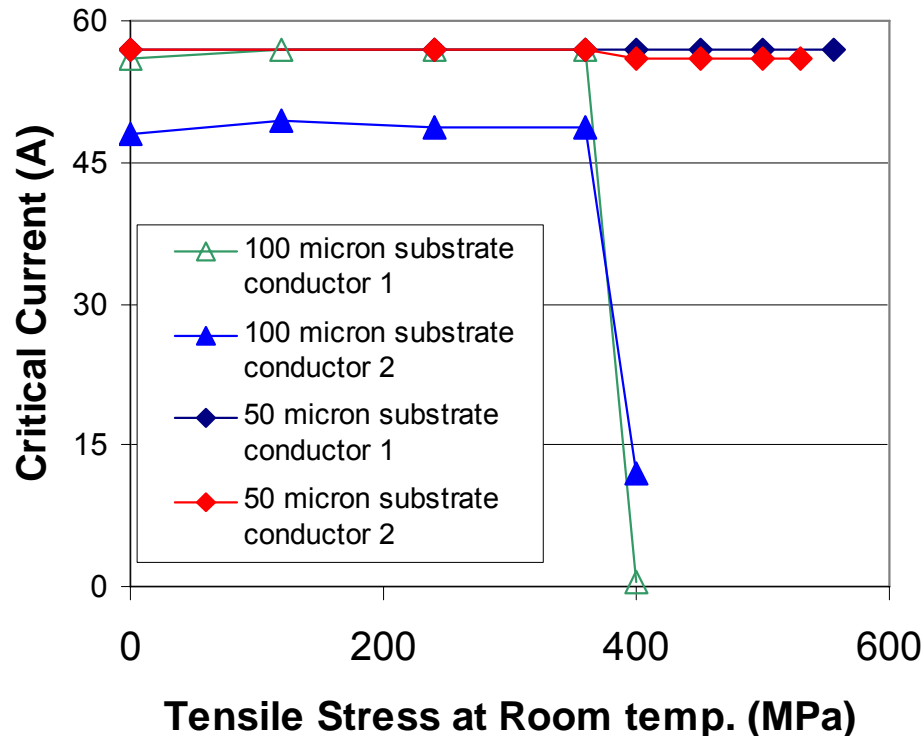
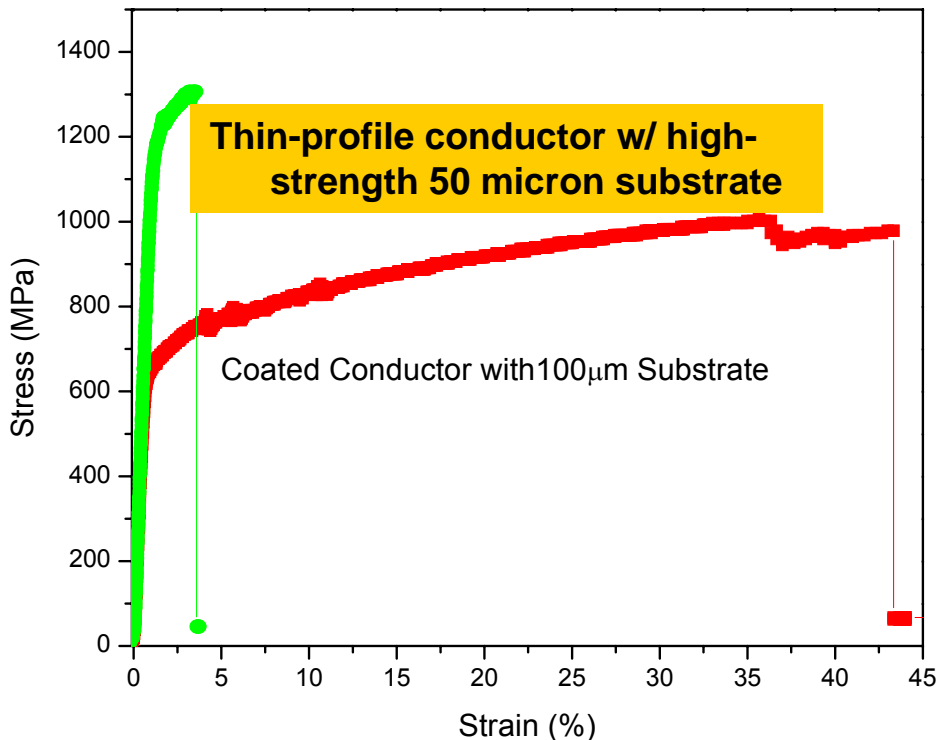
**Stress-strain traces for SuperPower 2G YBCO at 76K. Included are a trace of the base substrate material, Hastelloy C276 which dominates the conductor mechanical properties. Note the impact of copper stabilizer which slightly lowers the overall composite strength.**

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:

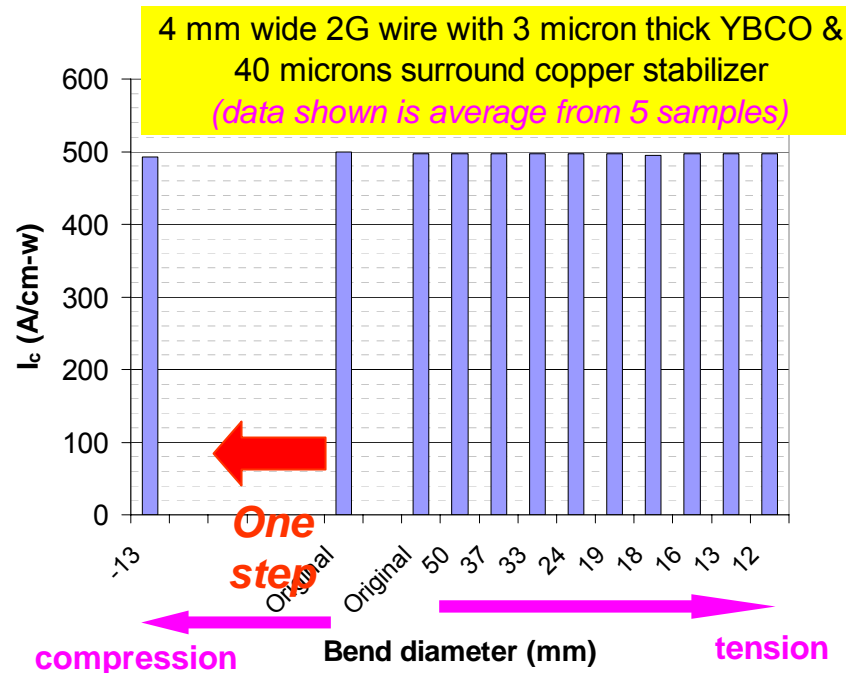
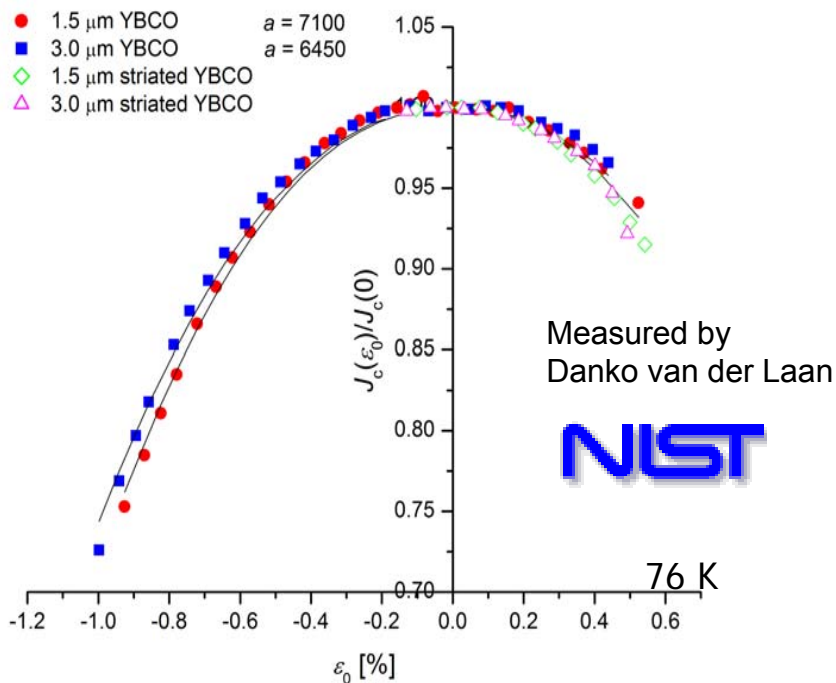
with 100 micron substrate = 350 MPa

with high-strength 50 micron substrate  
> 550 MPa



# 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.



**95%  $I_c$  retention measured in axial tension & compression up to 0.5% even in wire with 3 micron thick HTS layer**

**95%  $I_c$  retention measured in bending with YBCO in tension & compression down to a bend diameter of 13 mm even in wire with 3 micron 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)**

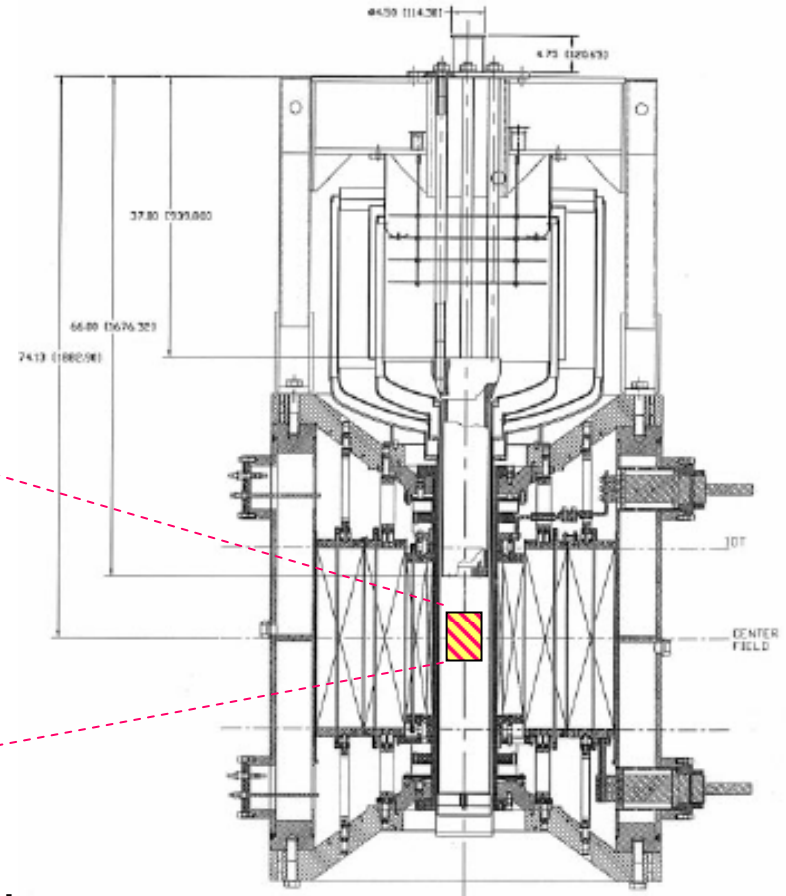
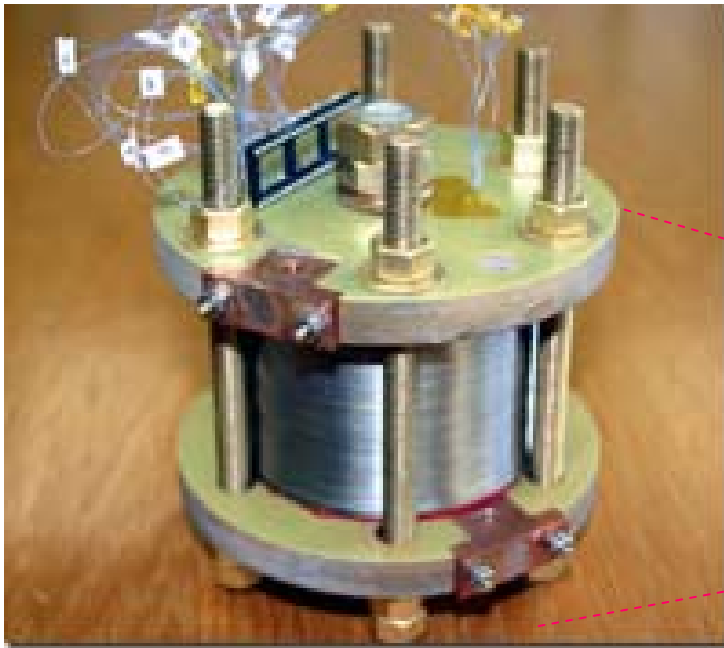
**Overbanding: 316 Stainless Steel**

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



# NHMFL facilities provide 19T axial background field

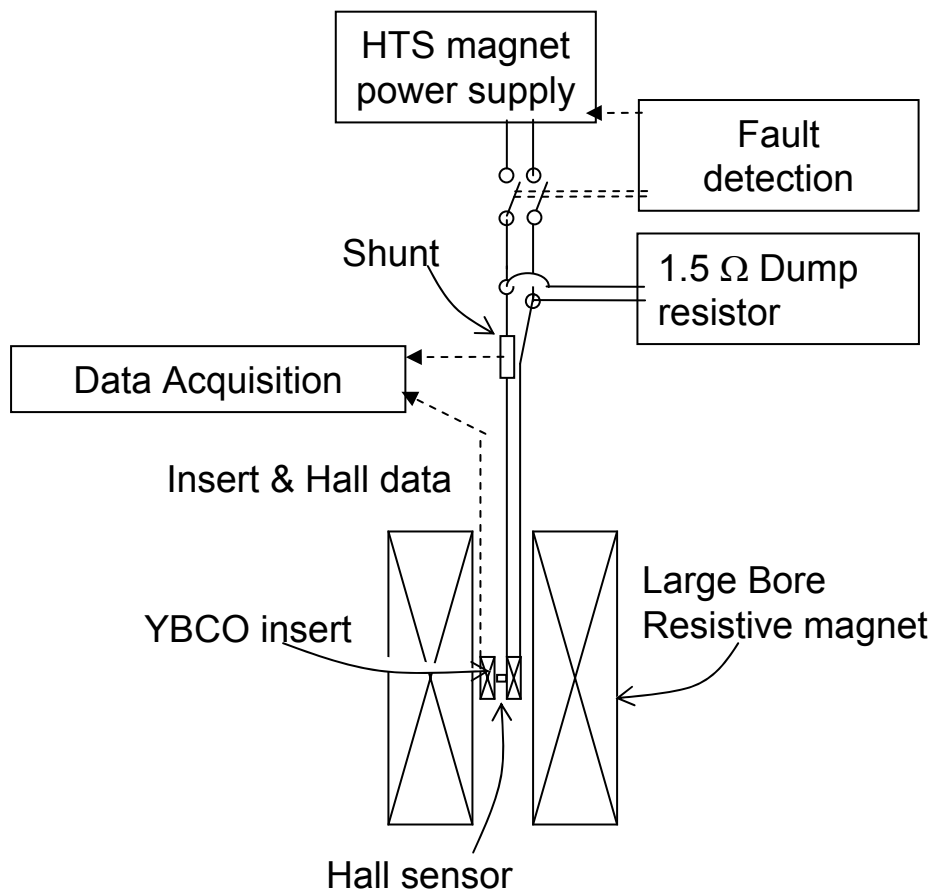
Insert coil tested in NHMFL's unique, 19-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet



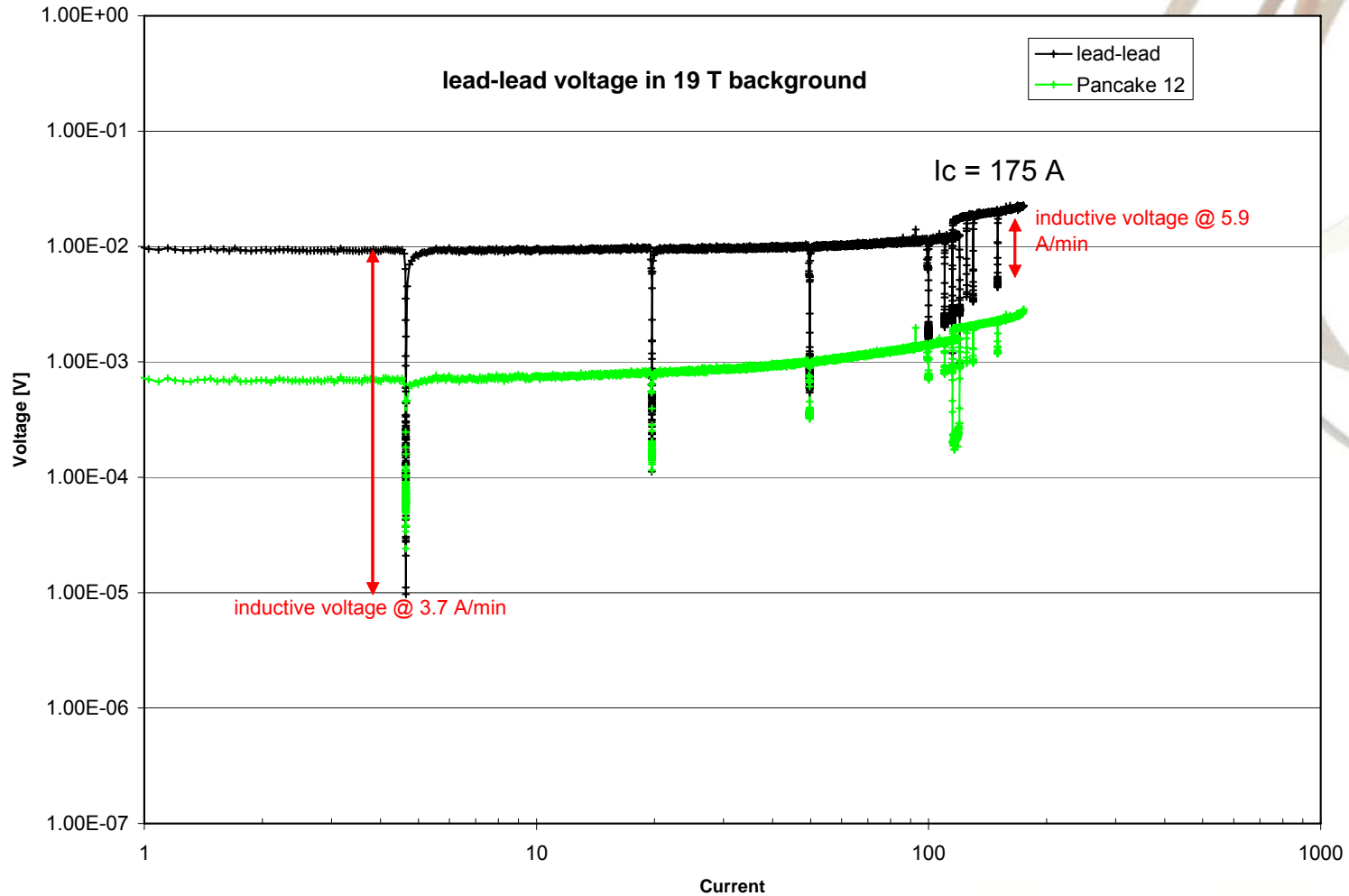
2G HF insert coil showing terminals, overbanding and partial support structure. Flange OD is 127 mm.



# Test setup at NHMFL

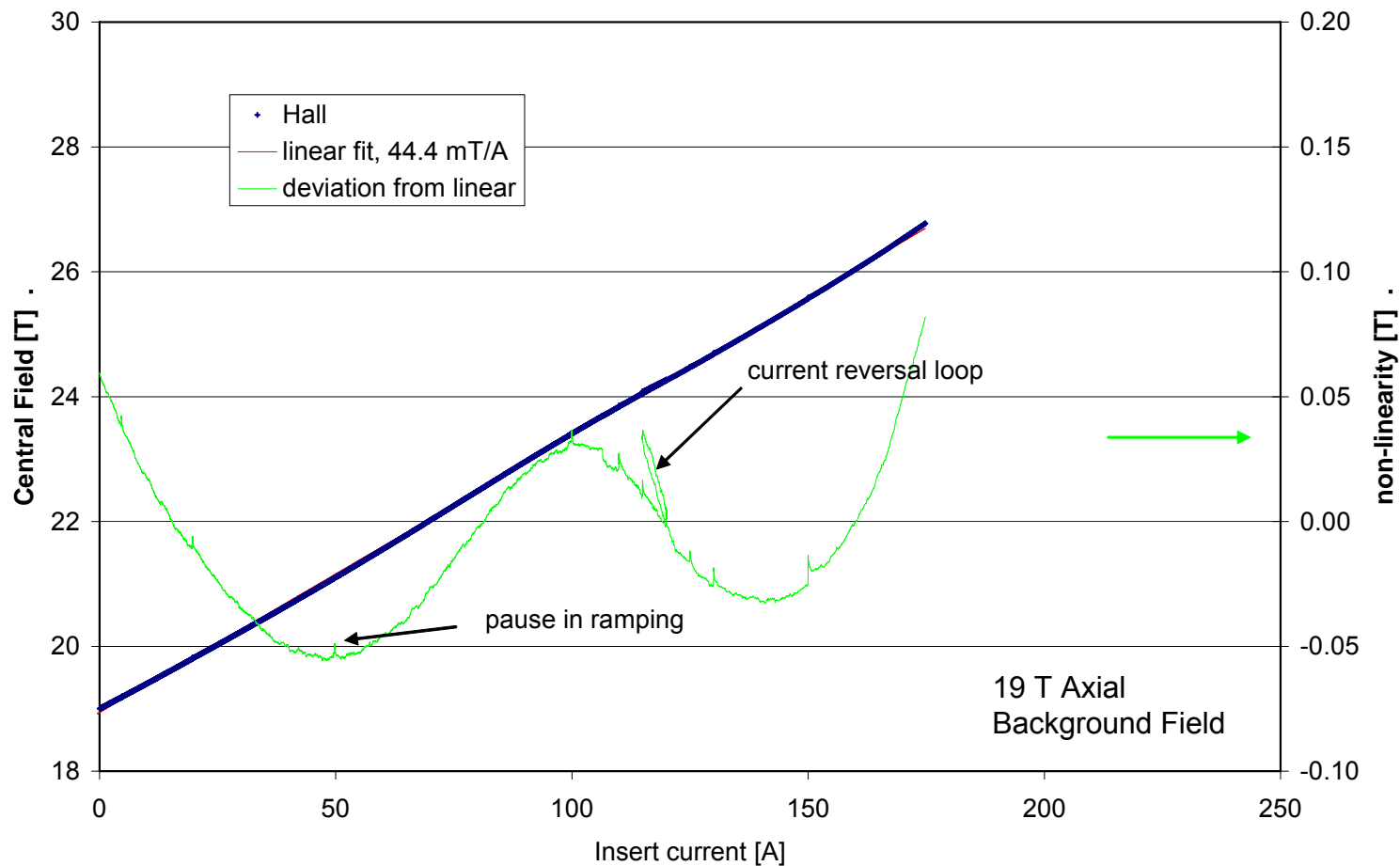


# Typical V-I trace (19T background field)



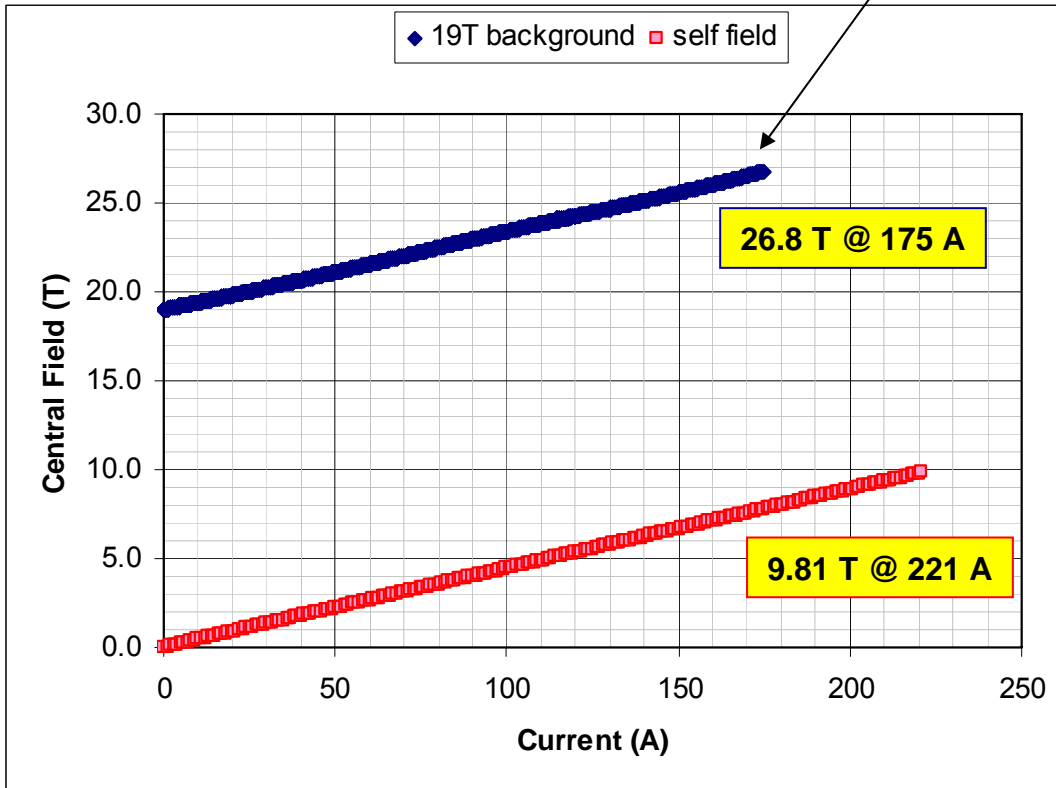
# Hall probe data shows linear field generation

Hall probe signal showing non-linearity of sensor and near-perfect field generation by insert



# 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 <sup>2</sup>
4.2K Peak Radial Field @ Ic, self field	3.2 T
4.2 K Central field – self field	<b>9.81 T</b>
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 <sup>2</sup>
4.2 K Peak Radial Field @ Ic, 19 T bkgd (axial)	2.7 T
4.2K Central Field – 19 T background (axial)	<b>26.8 T</b>



# 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  $J_e$**
- **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!**

**For further information about SuperPower please visit us at**

**[www.superpower-inc.com](http://www.superpower-inc.com)**

**or e-mail: [info@superpower-inc.com](mailto:info@superpower-inc.com)**

