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High Magnetic Fields Enabled by 2G High Temperature Superconductors

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  - …and the rest of the SuperPower Team
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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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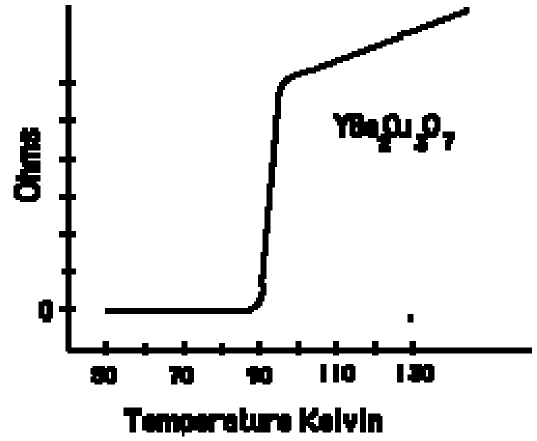
Superconductivity 101

What is a Superconductor?

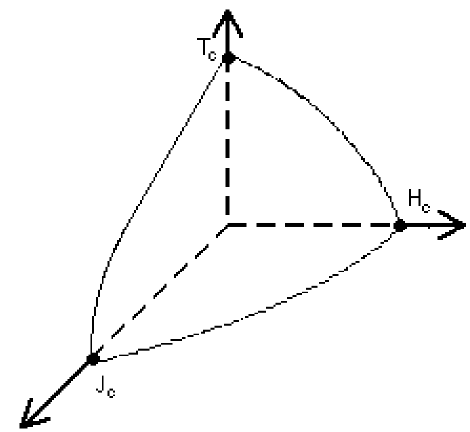
An element, inter-metallic alloy, or compound that will conduct electricity without resistance below a certain temperature. Resistance is undesirable because it produces losses in the energy flowing through the material.



Superconductors exist in a region bounded by:

- **Temperature (Tc)**
- **Magnetic Field (Hc)**
- **Current Density (Jc)**

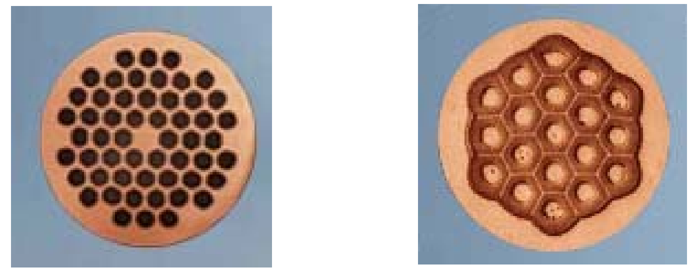
Critical Surface Phase Diagram



Two general classes of superconductors have been commercialized

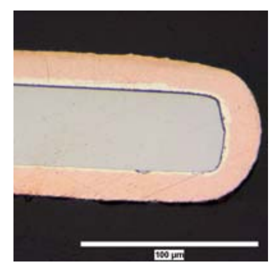
- "Low temperature" superconductors
- Operation limited to low temperatures near 4 K (LHe)
- First commercial superconductors
- NbTi, Nb3Sn

- "High temperature" superconductors
- Operation from 4 K (LHe) to 77 K (LN2)
- 1G – BSCCO based
- 2G – YBCO based
- 2G – thin film vs. wire drawing processing
- Moving from development into commercialization



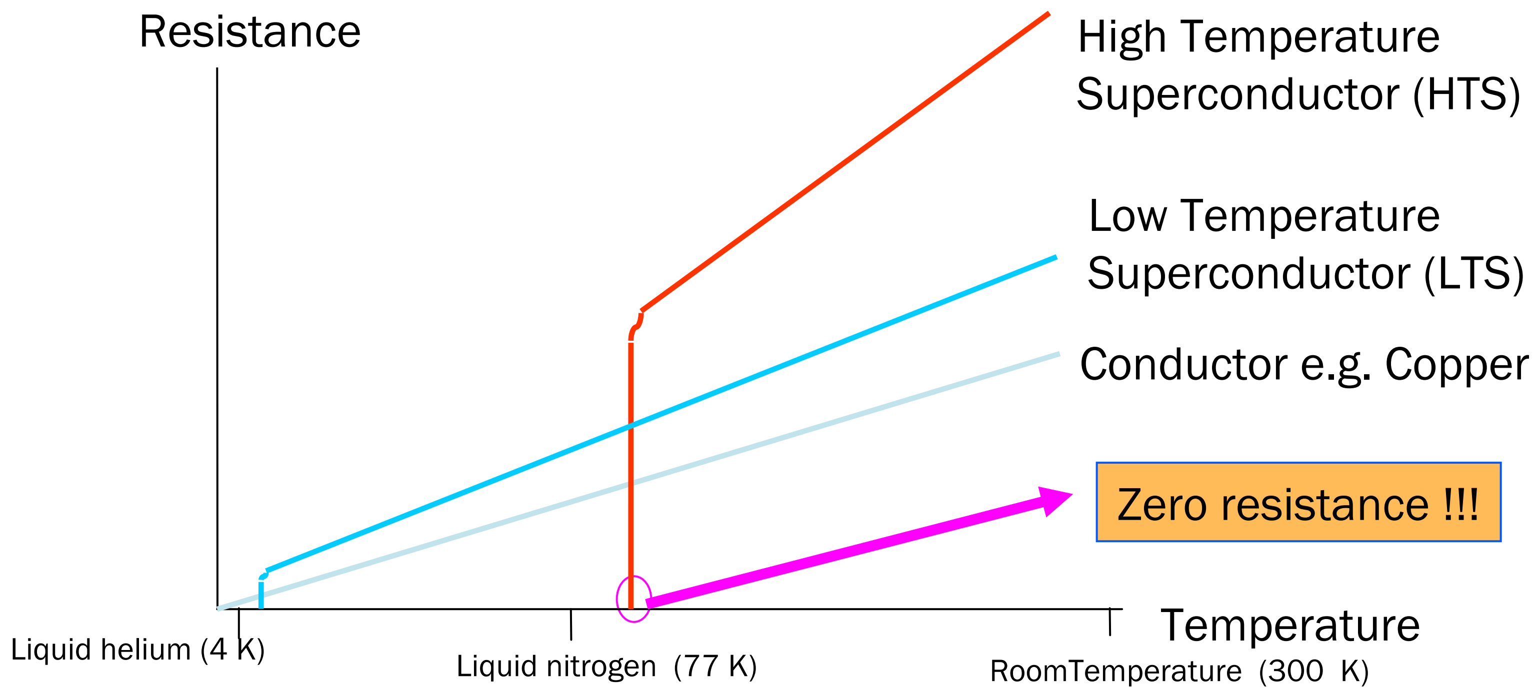
NbTi and Nb3Sn Superconductors (Luvata)

1G BSCCO-2223 Tape (AMSC)



2G YBCO Wire (SuperPower, Inc.)

Superconductivity is an enabling technology to move high energy density power



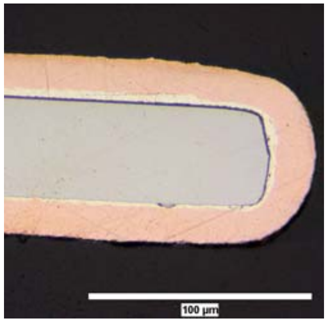
Current carrying capability of copper ~ 200 A/cm^2

Current carrying capability of 2G superconductor film ~ 5,000,000 A/cm^2

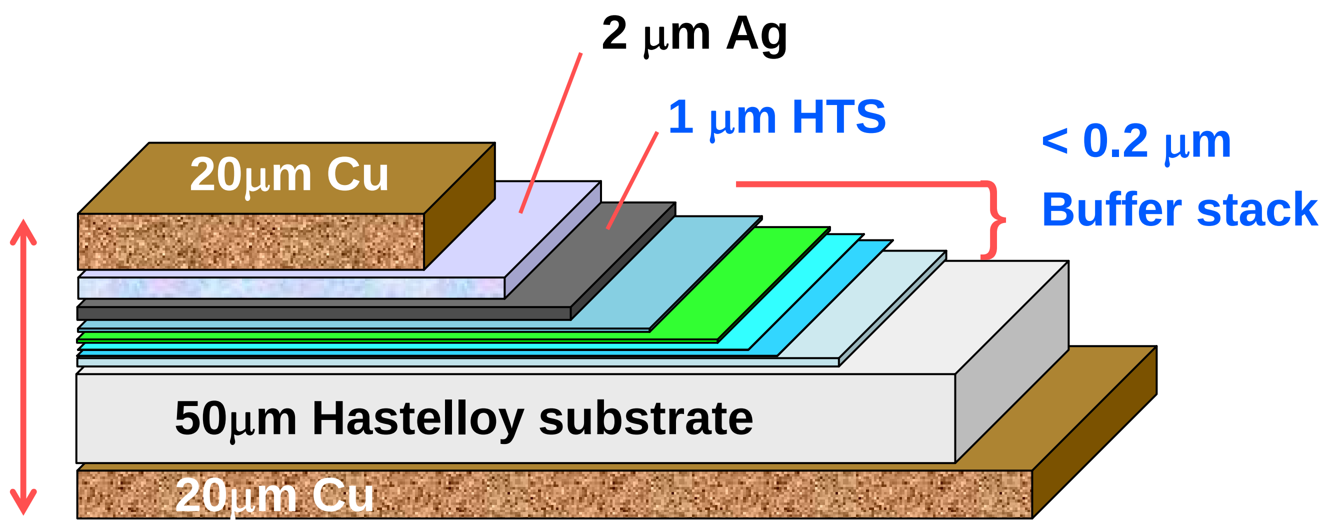
Current carrying capability of 2G superconductor wire ~ 50,000 A/cm^2

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

- SuperPower's 2G HTS wire is based on a high throughput thin film manufacturing approach permitting a wide choice of materials combinations
  - Advantages include 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 to enable early commercial adoption



< 0.1 mm



SuperPower Inc.

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

SuperPower is unique in the world in having established operational 2G Pilot Manufacturing facilities

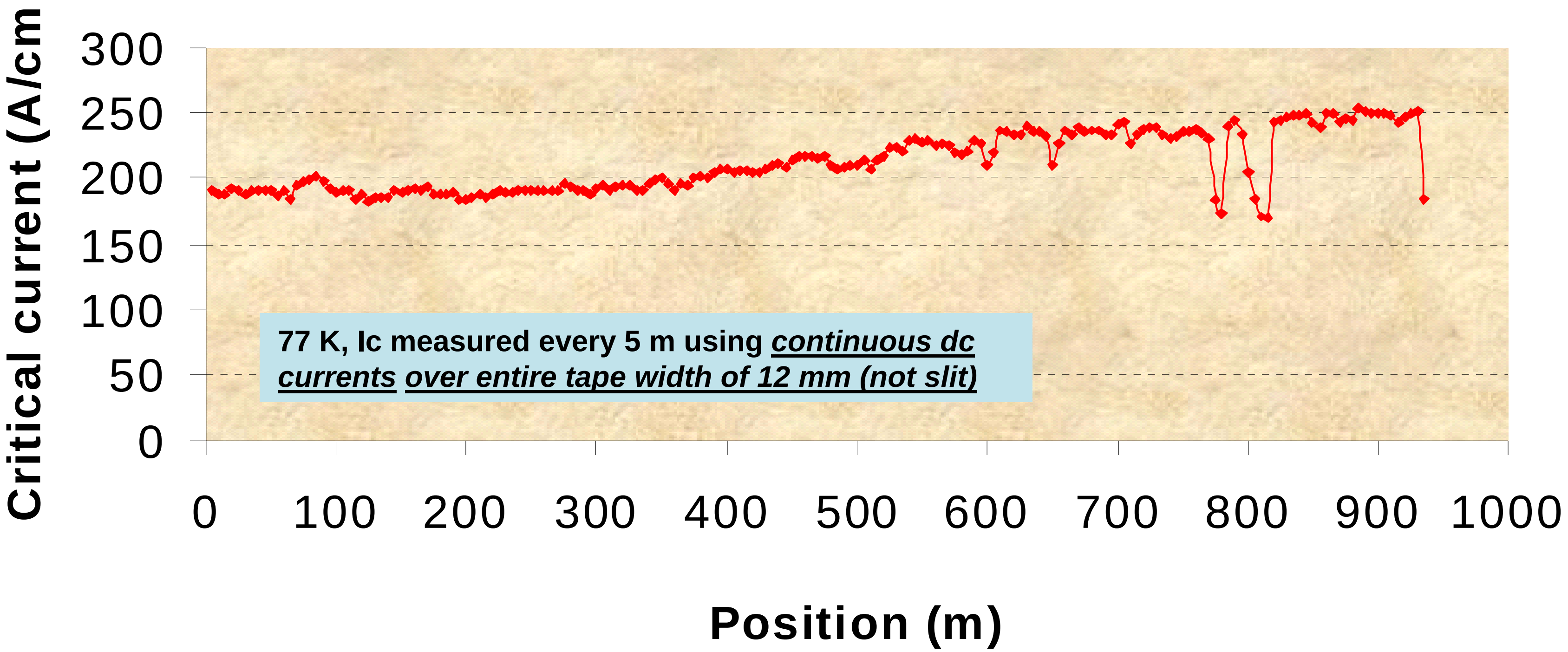
Pilot Substrate Electropolishing

Pilot Buffer

Pilot IBAD

Pilot HTS

Long length processing of 2G HTS wire demonstrated



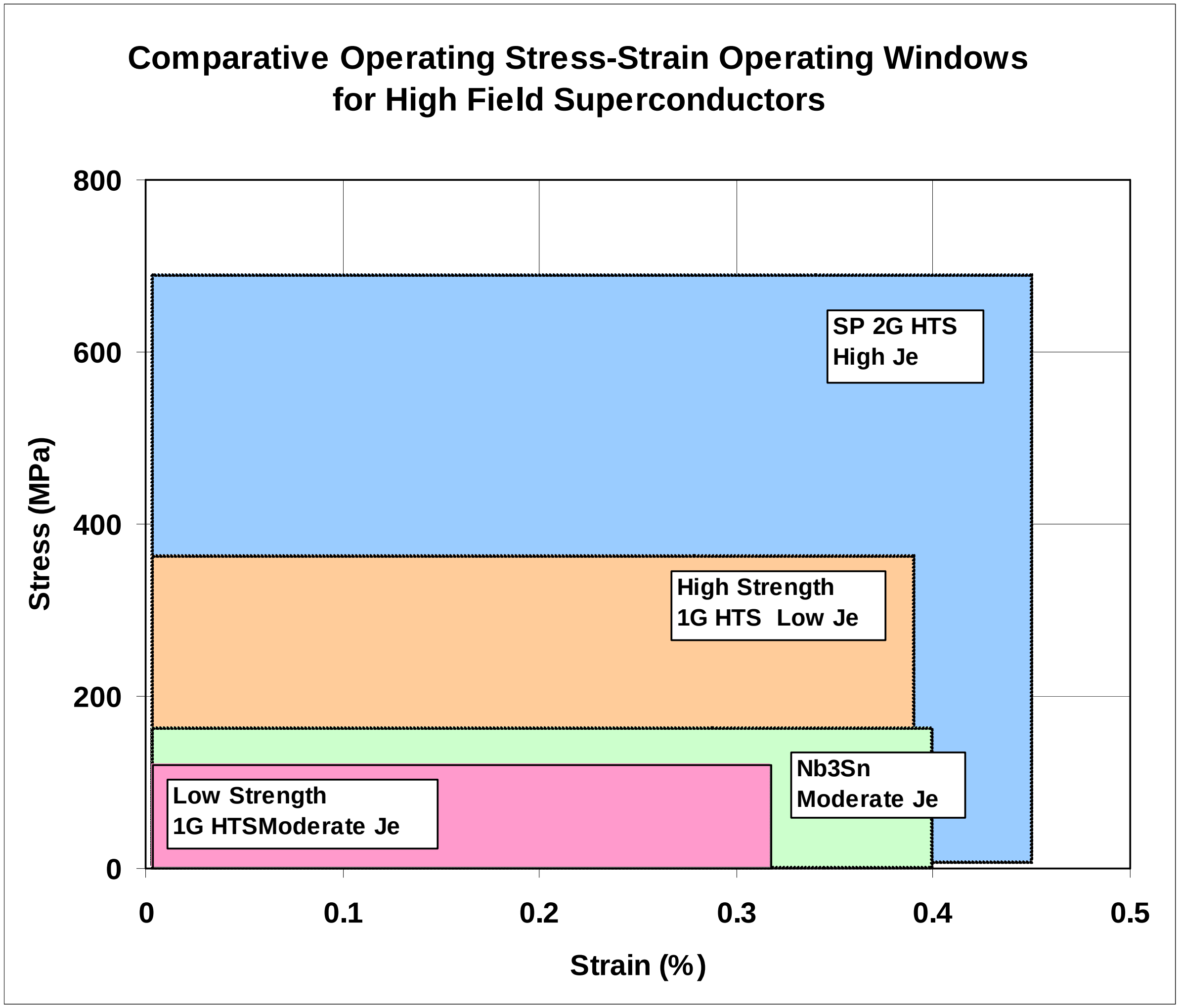
- Minimum Ic = 170 A/cm over 935 m
- Ic ´ Length = 158,950 A-m
- Uniformity over 935 m = 10.6%

Process (single pass)	Speed of 4 mm tape (m/h)
IBAD MgO	360
Homo-epi MgO	345
LMO	345
MOCVD	135

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

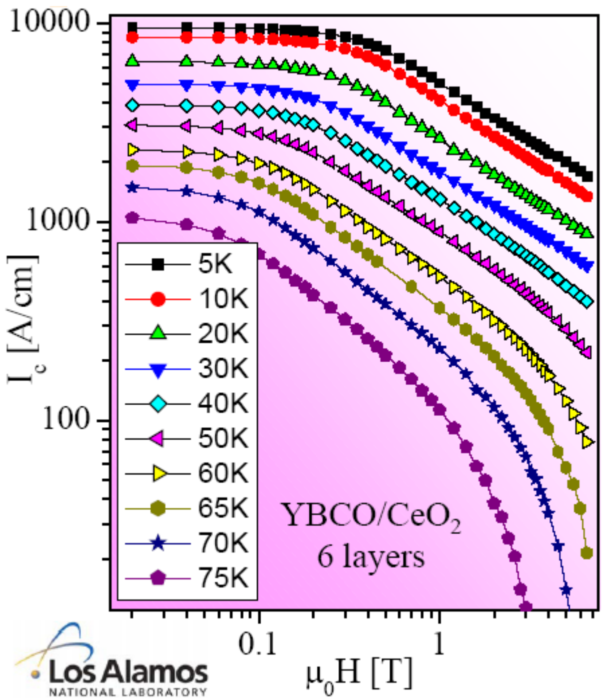
Ic retention vs. strain

Conductor	$Ic / Ic_{\varepsilon=0}$
SP 2G	> 0.95 for $\varepsilon \sim 0.45\%$
1G high strength	> 0.95 for $\varepsilon \sim 0.40\%$
1G low strength	> 0.95 for $\varepsilon \sim 0.35\%$
Nb_3Sn, 4 T	< 0.90 @ 0.4%
Nb_3Sn, 8 T	< 0.82 @ 0.4%
Nb_3Sn, 12 T	< 0.68 @ 0.4%
Nb_3Sn, 16 T	< 0.35 @ 0.4%



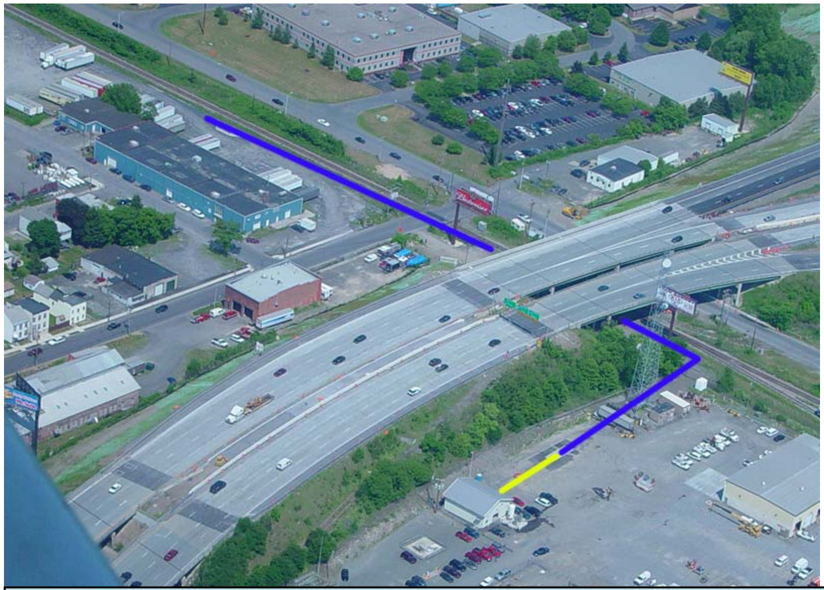
2G HTS wire can be used at higher temperatures than LTS wire

- LTS wire can only effectively operate below 5K (NbTi) and 8K (Nb3Sn)
- 2G HTS can effectively operate as high as 77 K



Plot of Ic vs Field (H//c) for an experimental LANL 6 layer YBCO deposition on CeO2.

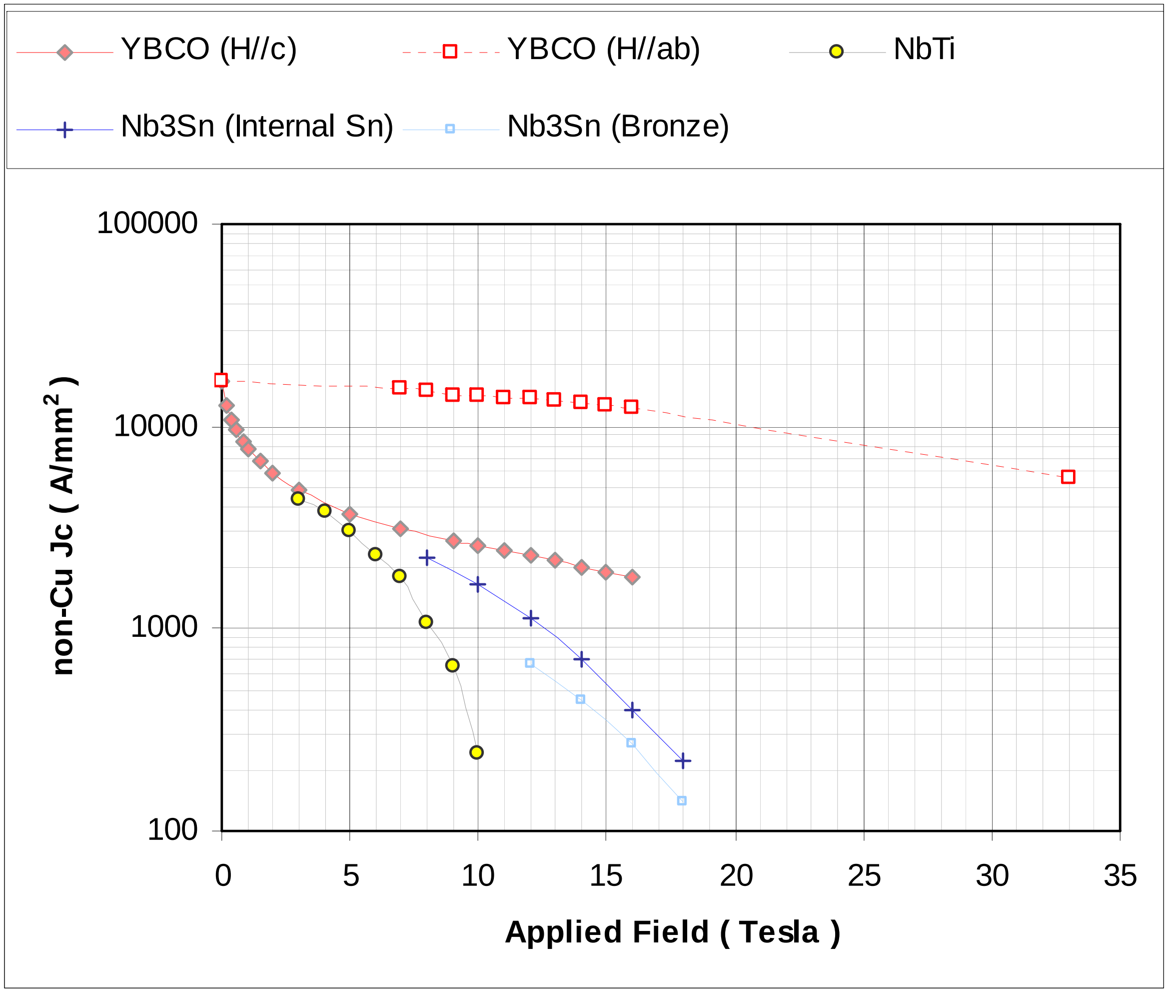
Sumitomo Electric 3-in-1 2G HTS Cable Configuration Using SuperPower 2G HTS



Site of the Albany Cable Project on the National Grid electrical network in Albany, NY (Blue = 320 m 1G HTS Cable, Yellow = 30 m SuperPower 2G HTS Cable using ~10 km of SP 2G wire)

World's first 2G device energized on a live power grid

2G YBCO HTS offers distinct advantages in high magnetic field current density over "traditional" LTS wire



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

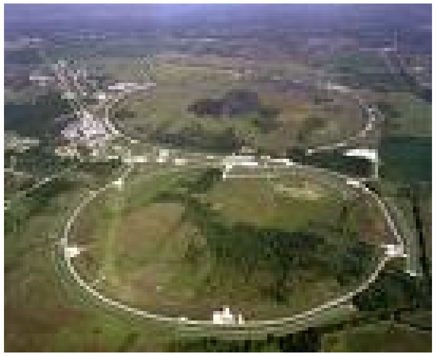
High field applications can be further realized with 2G HTS

- High Field NMR Spectroscopy
- High Energy Physics
- High Field Research Magnets

Compact Muon Collider Solenoid

Varian 21T NMR Spectrometer at Birmingham, UK research facility

Fermilab Tevatron Accelerator Ring With View Inside Tunnel



2G High field insert coil demonstration

Conductor:

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

Tape Ic 72 – 82 A, 77 K, sf

Coil Winding

Double Pancake Construction

Dry Wound (no epoxy)

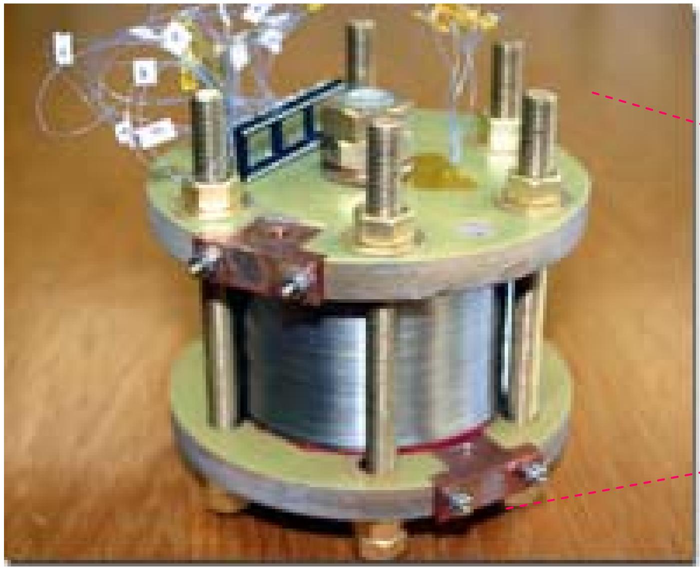
Kapton polyimide insulation (co-wound)

Overbanding: 316 Stainless Steel

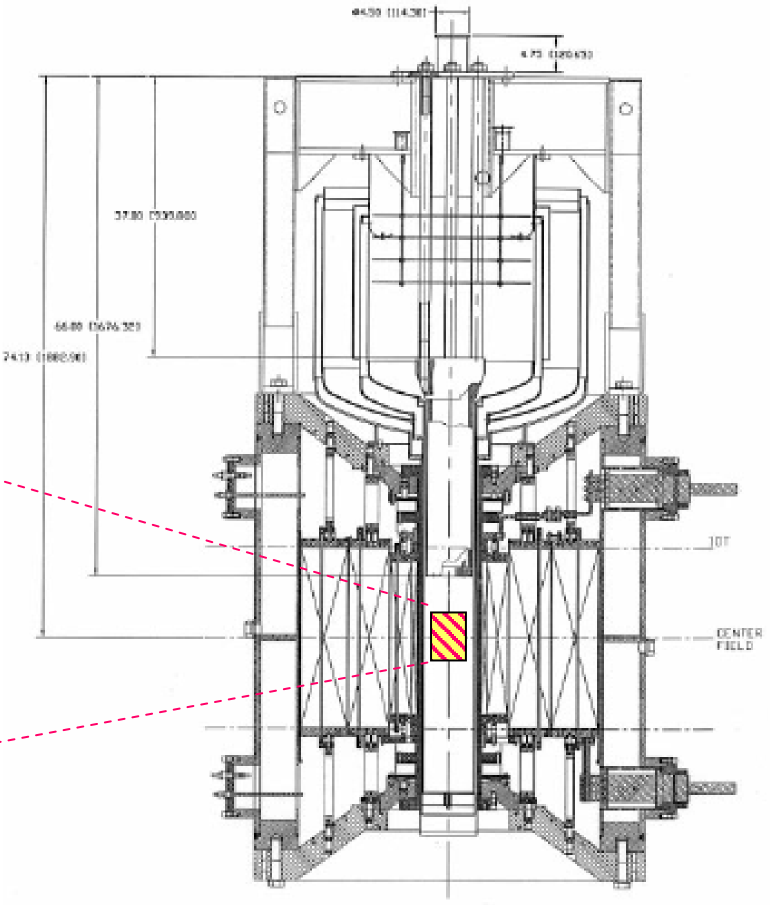
Coil ID	9.5 mm (clear)
Winding ID	19.1 mm
Winding OD	~ 87 mm
Coil Height	~ 51.6 mm
# of Pancakes	12 (6 x double)
2G tape used	~ 462 m
# of turns	~ 2772
Coil Je	~1.569 A/mm^2 per A
Coil constant	~ 44.4 mT/A

NHMFL facilities provide 19T axial background field

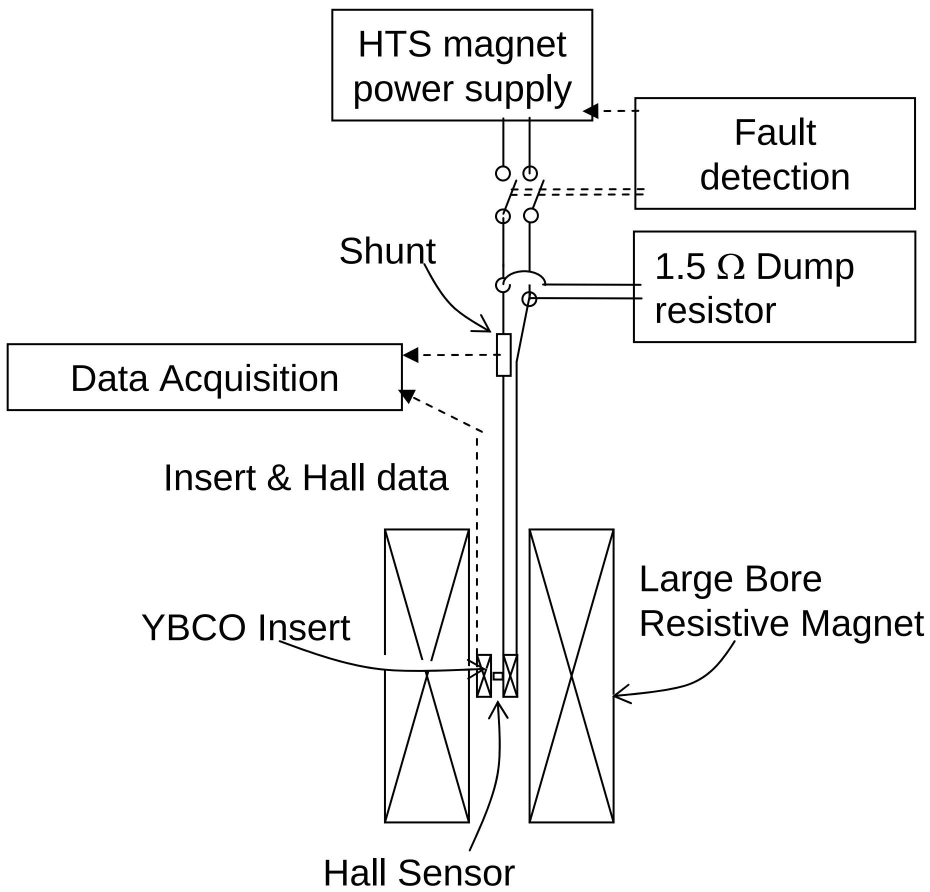
Insert coil tested in NHMFL's unique, 19-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet



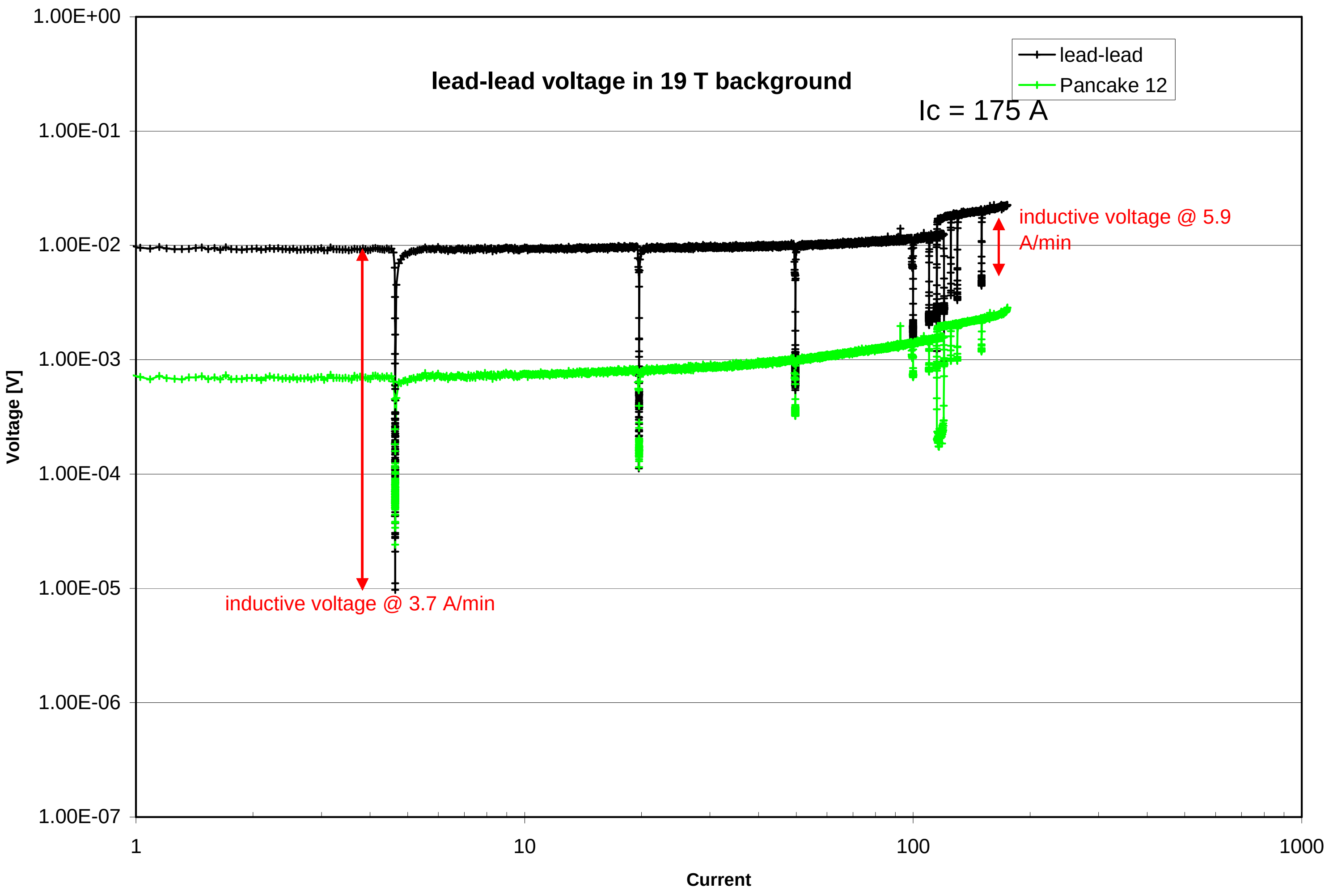
2G HF Insert Coil Showing Terminals, Overbanding and Partial Support Structure. Flange OD is 127 mm.



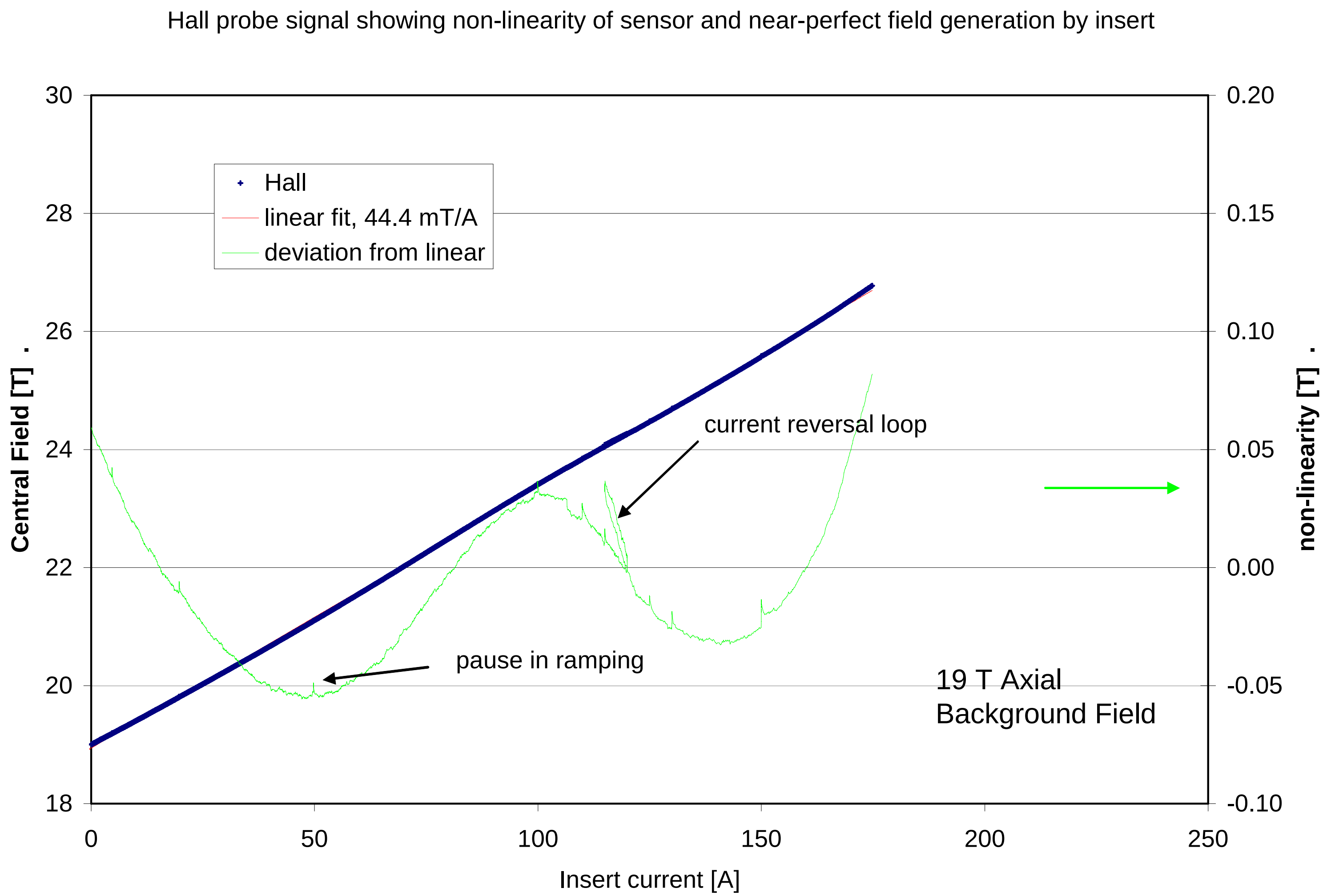
Test setup at NHMFL



Typical V-I trace (19T background field)

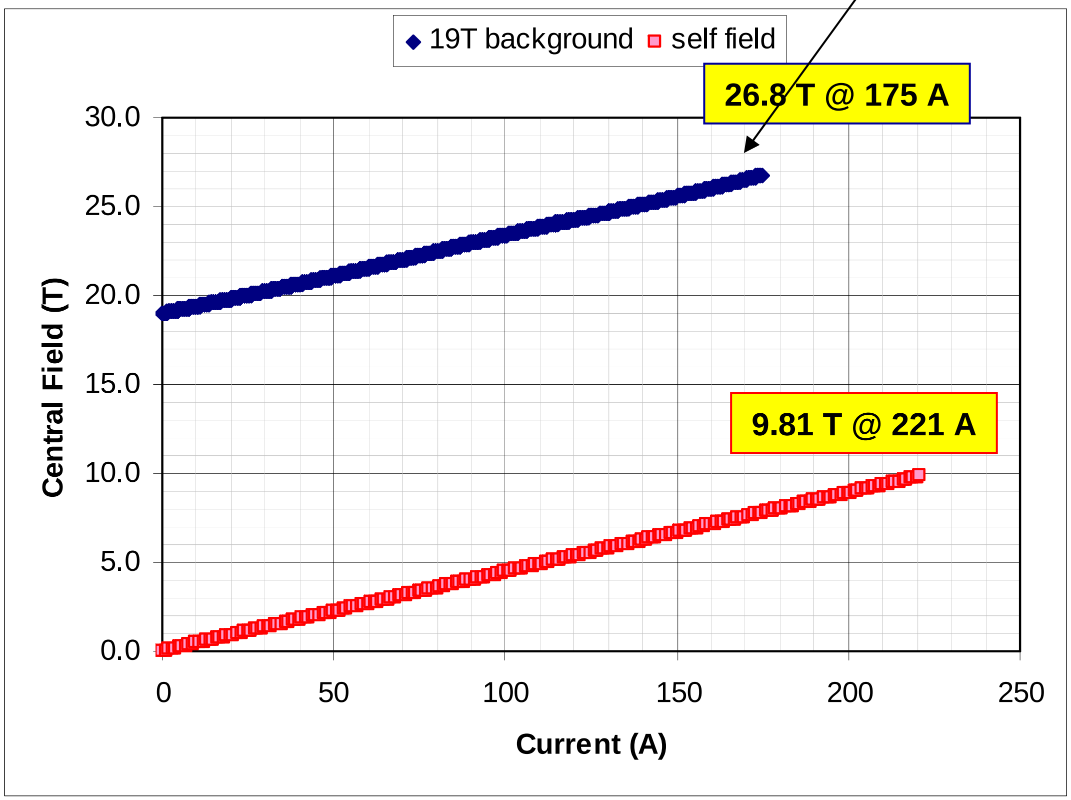


Hall probe data shows linear field generation



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 Tapes 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
  - Continued improvements in Jc, particularly in field
  - Improved conductor properties
    - Low ac losses
    - Improved insulation systems
    - Higher strength
- 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 quantities 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

or e-mail: info@superpower-inc.com