# HTS Wire, Cable and Coil R&D

*E. Barzi with the Superconductor and High Field Magnet Groups, FNAL*

*in close collaboration with:*

*National Institute of Materials Science (NIMS), Japan*
*American Superconductors (AMSC)*
*SuperPower, Inc.*
*Oxford Superconducting Technology (OST)*
*Muons, Inc.*
*Florida State University (FSU)*

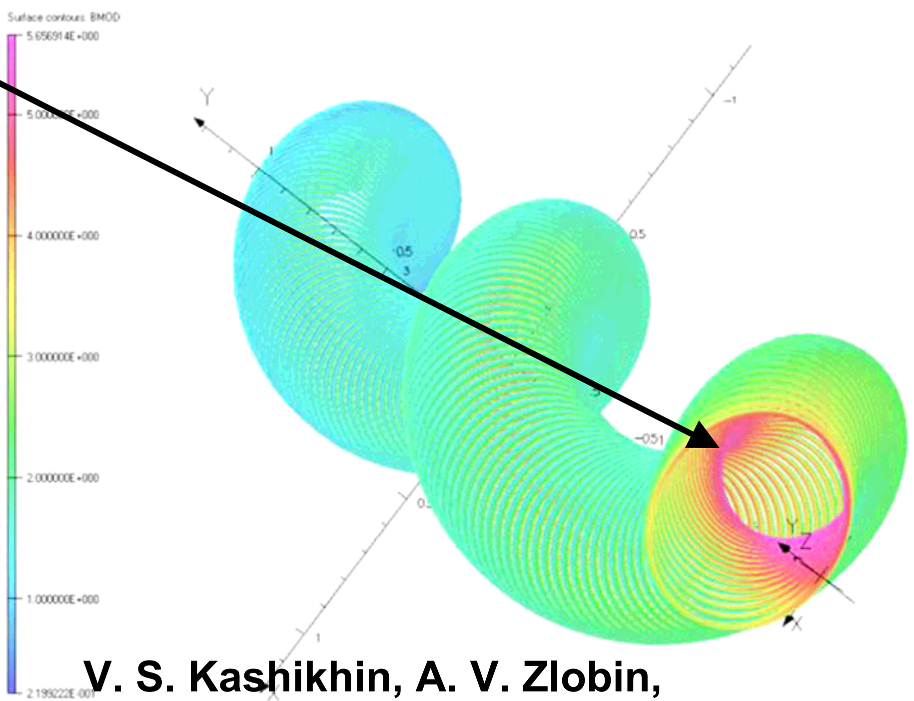
# OUTLINE

- Our ultimate goals within the Muon Collider Task Force
- Wire R&D
- Cable R&D – Previous work
- Cable R&D – Plans within the HTS National Collaboration
- Coil R&D

# Our ultimate Goals

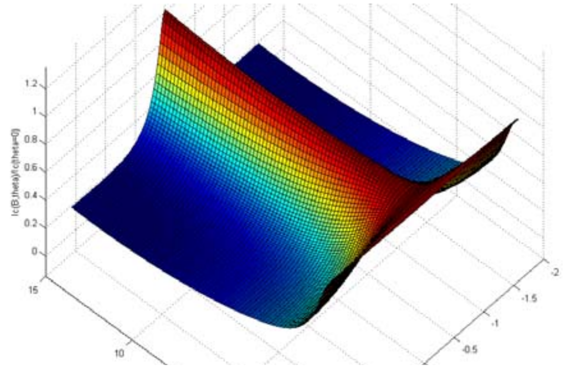
**High field solenoids for muon beam cooling include the high field (> 17 T) sections of a 6D Helical Cooling Channel, and high-field solenoids (> 30 T) for the final, low emittance stage of the muon cooling channel.**

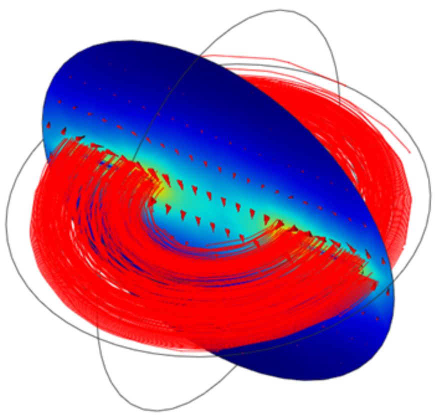
**The robust and versatile infrastructure that was developed in Technical Division for advanced superconductor and accelerator magnet R&D, together with the expertise acquired in the $Nb_3Sn$ and $Nb_3Al$ technologies by the scientists and engineers of the Magnet Systems Department, makes TD an ideal setting for exploring HTS magnets.**

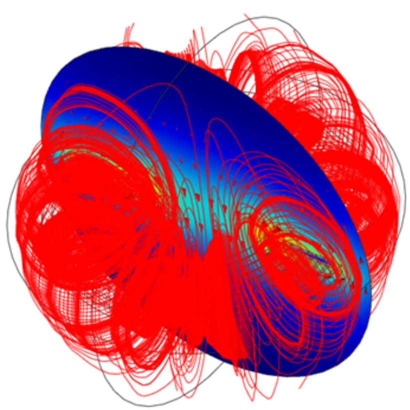


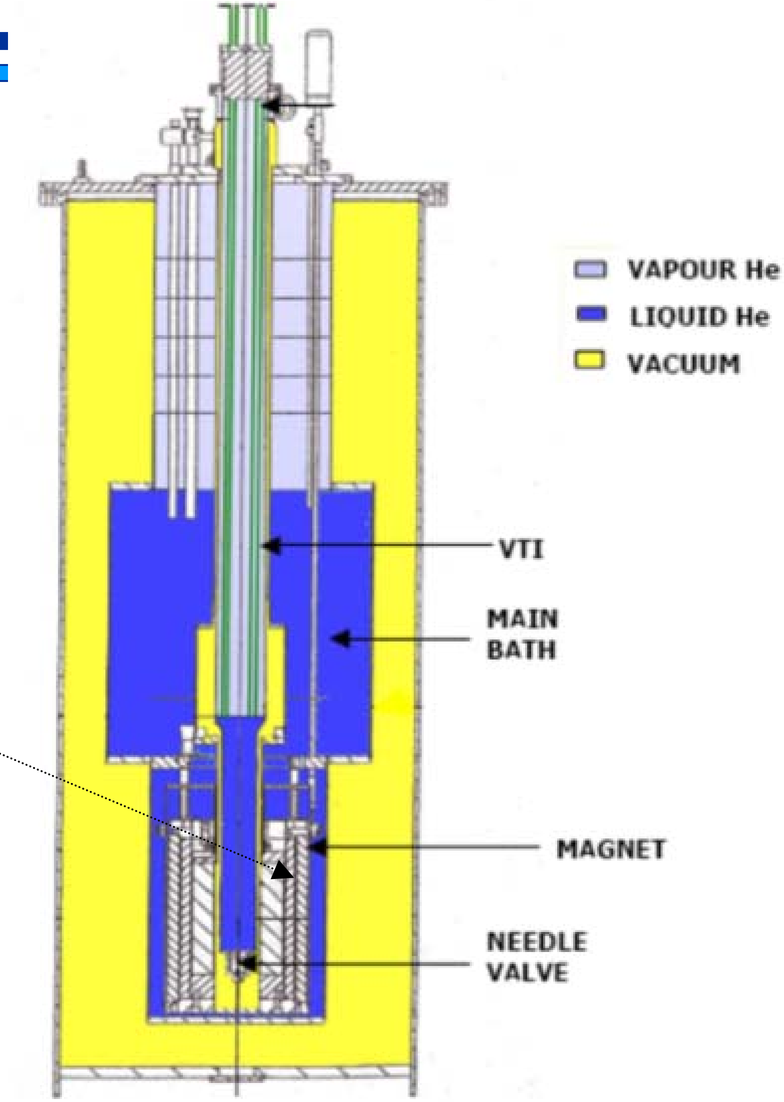

**V. S. Kashikhin, A. V. Zlobin, M. Lopes, M. Yu, M. Lamm et al.**

# 14/16 T Cryogenic Test Facility










**Magnet: 77 mm bore**
**VariableTemp. Insert: 49 mm diameter**

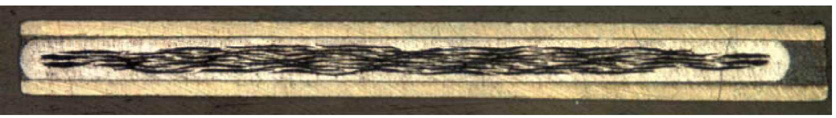
# Wire R&D

**Monitoring industry progress by characterizing state-of-the-art HTS's is essential input to magnet design. This includes knowing the engineering current density ($J_E$) as a function of:**

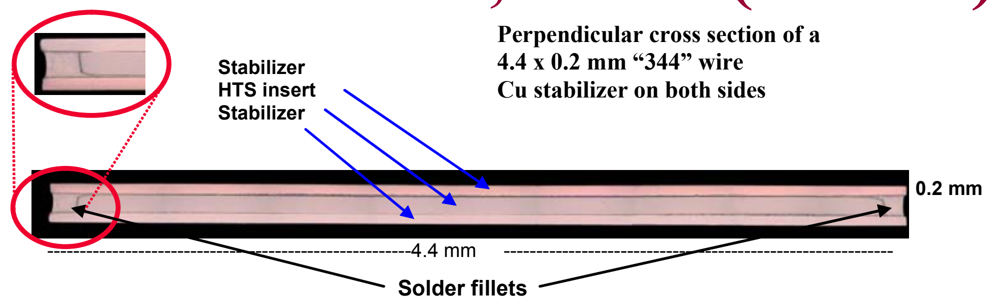
- **magnetic field -> new data up to 28 T within a FNAL-NIMS collaboration;**
- **temperature -> data from superfluid He to nitrogen temperature;**
- **for anisotropic tapes, field orientation -> new data;**
- **bending strain -> new equipment was designed and commissioned;**
- **longitudinal strain -> new fixture was designed and drawings are being released;**
- **transverse pressure -> setup is available.**

# Available Conductors

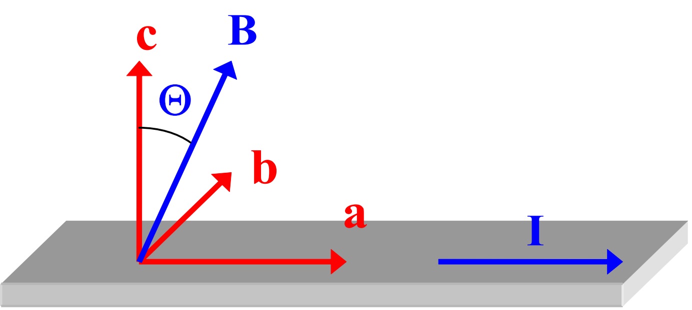
## Bi-2223, or 1G (AMSC)



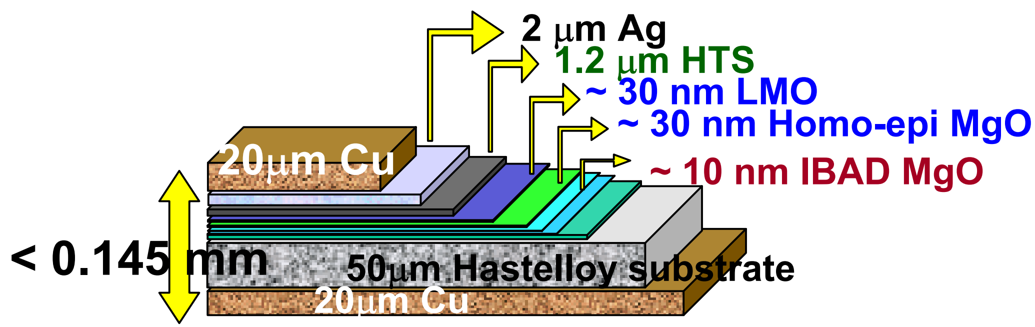
## RABiTS™ YBCO, or 2G (AMSC)



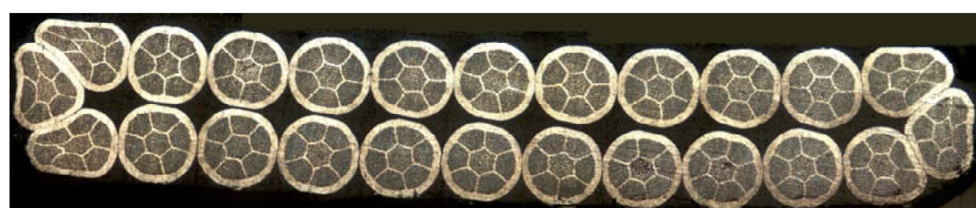

## Tape anisotropy



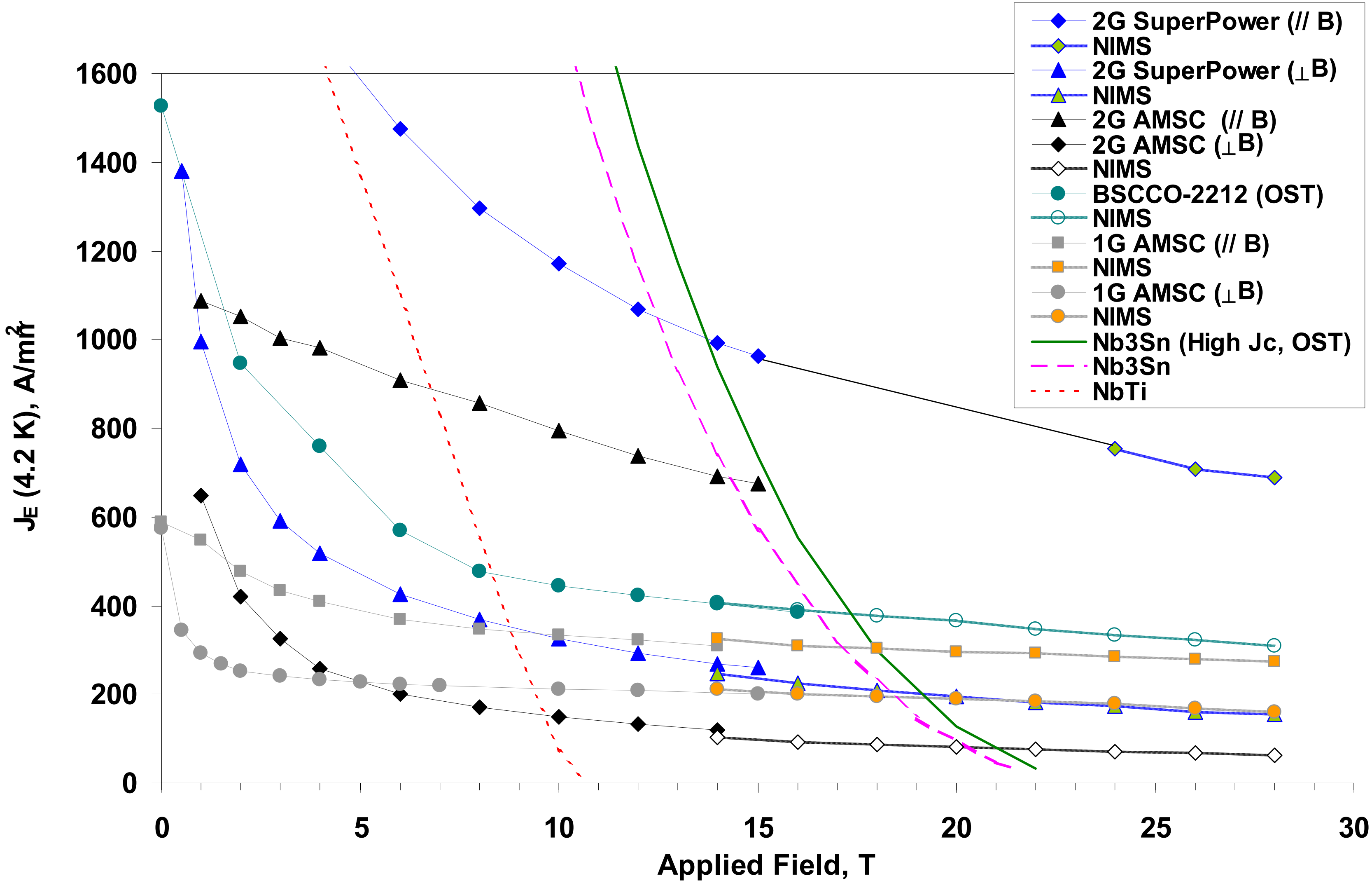

## IBAD YBCO, or 2G (SuperPower)




## Bi-2212 Round wire (OST), made into a cable



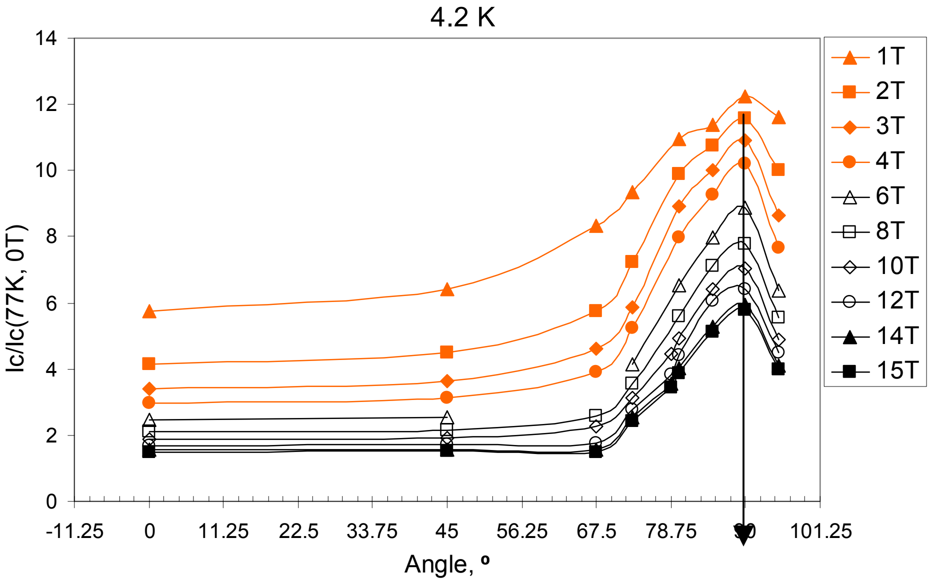
# New Data within FNAL-NIMS Coll.

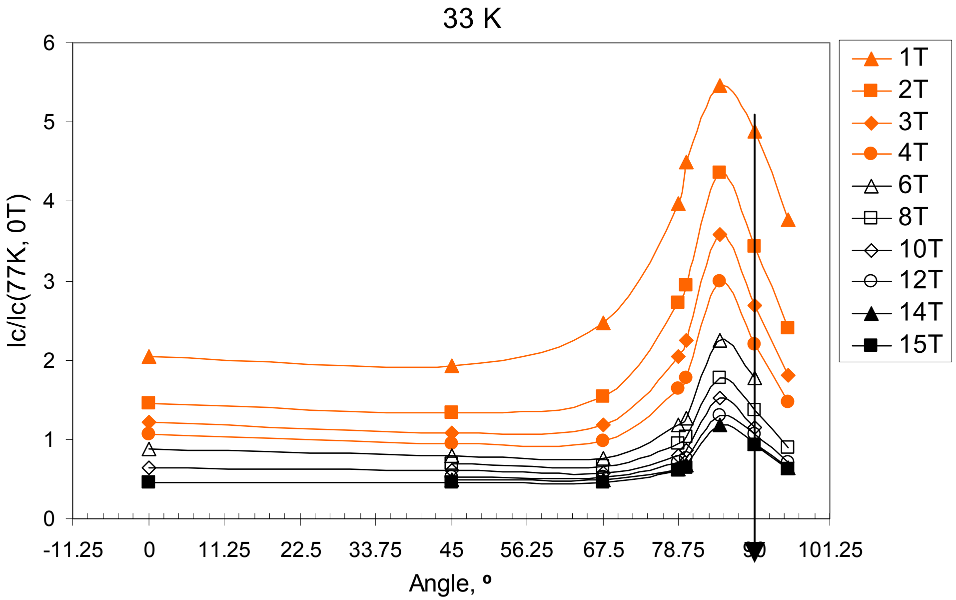



**D. Turrioni et al., "Study of HTS Wires at High Magnetic Fields", accepted in IEEE Transactions on Applied Superconductivity**

# $I_c$ Angular Dependency

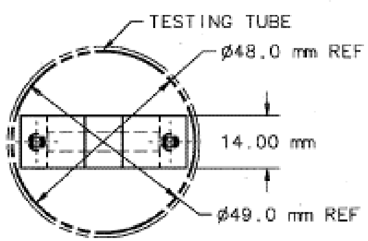
**For the SuperPower standard 2G conductor, improved resolution allowed determining a shift of the peak current to field angles that are not parallel to the tape.**

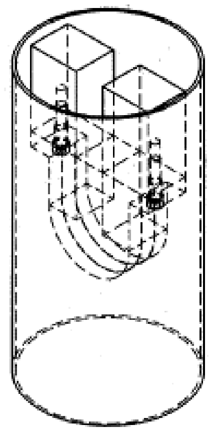


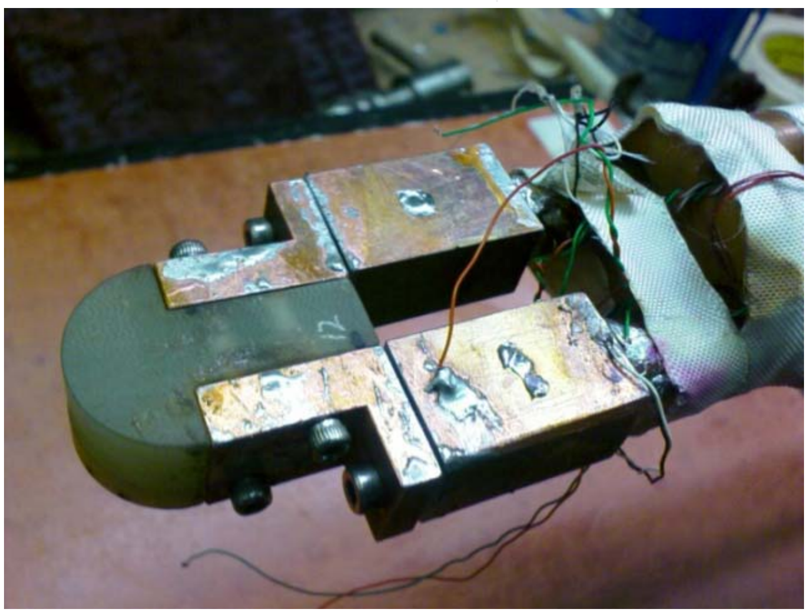

**D. Turrioni et al., "Study of HTS Wires at High Magnetic Fields", accepted in IEEE Transactions on Applied Superconductivity**

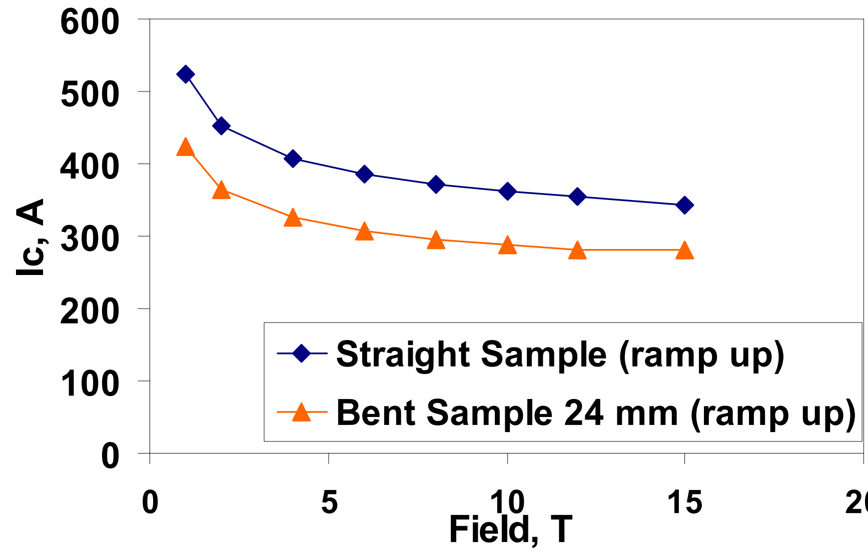
# Bending Strain Tests

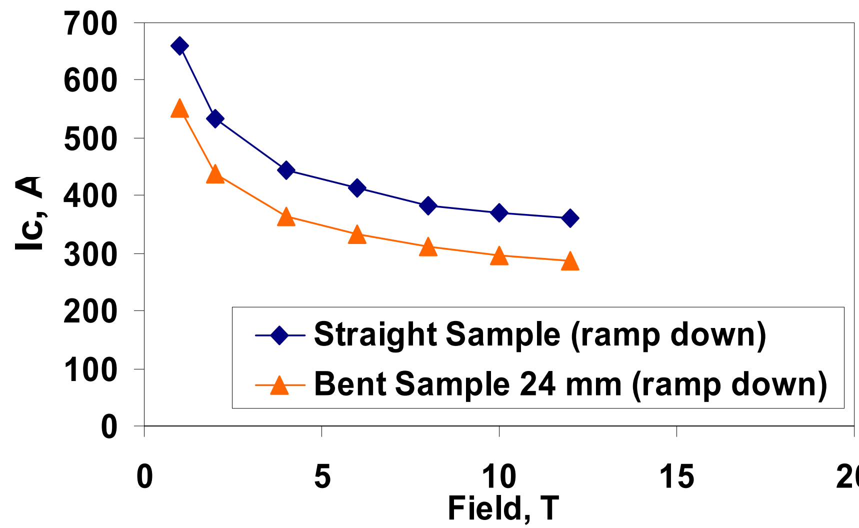


**V. Lombardo et al.**

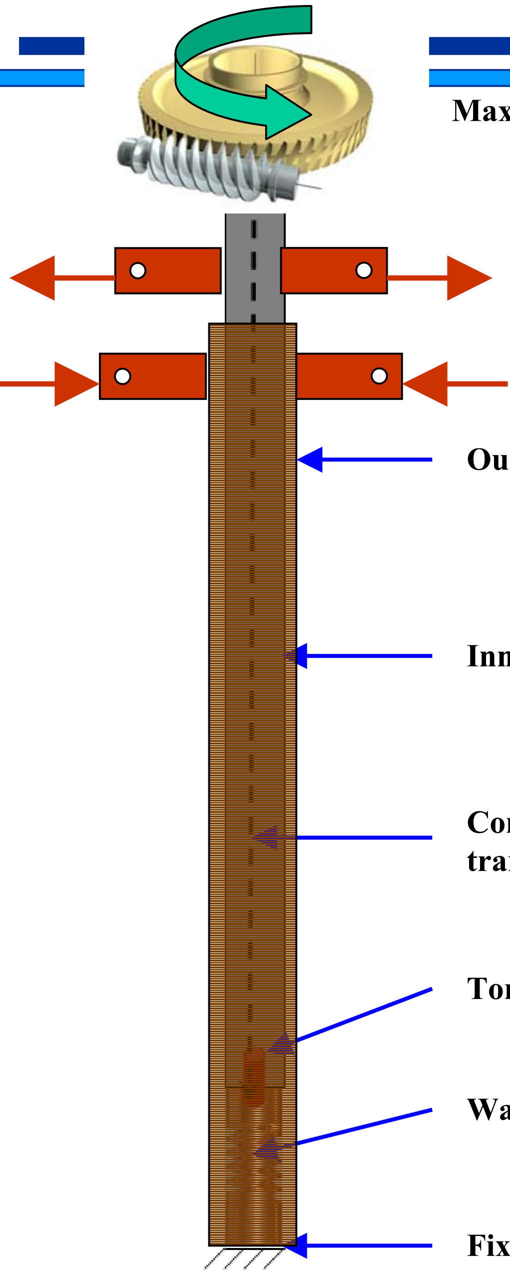




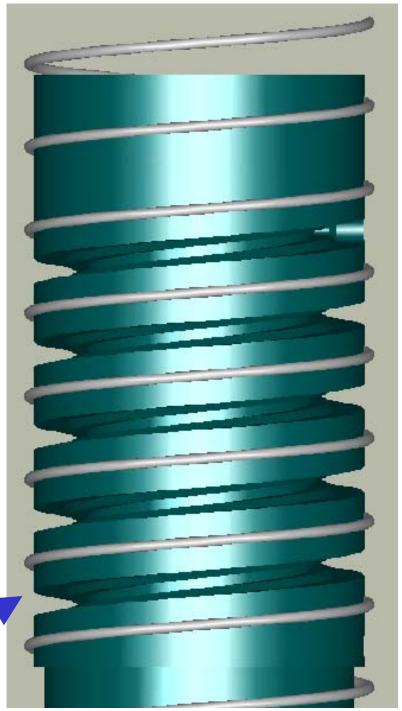



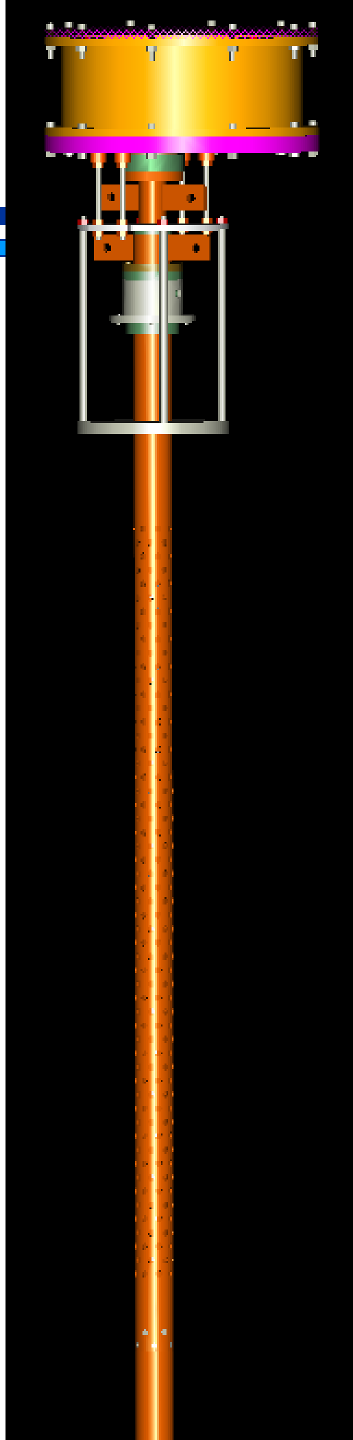
# Longitudinal Strain Fixture

Maximum twist applied ± 70°




N. Dhanaraj et al.



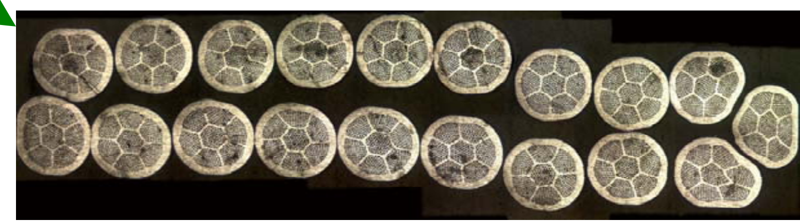


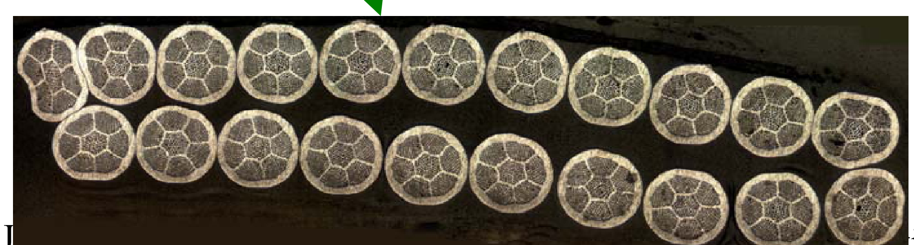
# Cable R&D

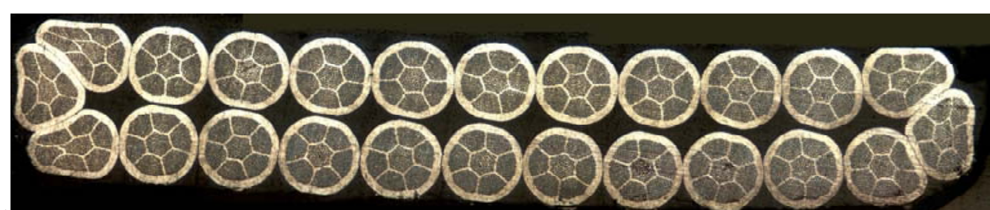
- **Strand number: up to 42**
- **Strand diameter: 0.3-1.5 mm**
- **Cable transposition angle: 8-16 degree**

# Cable Samples

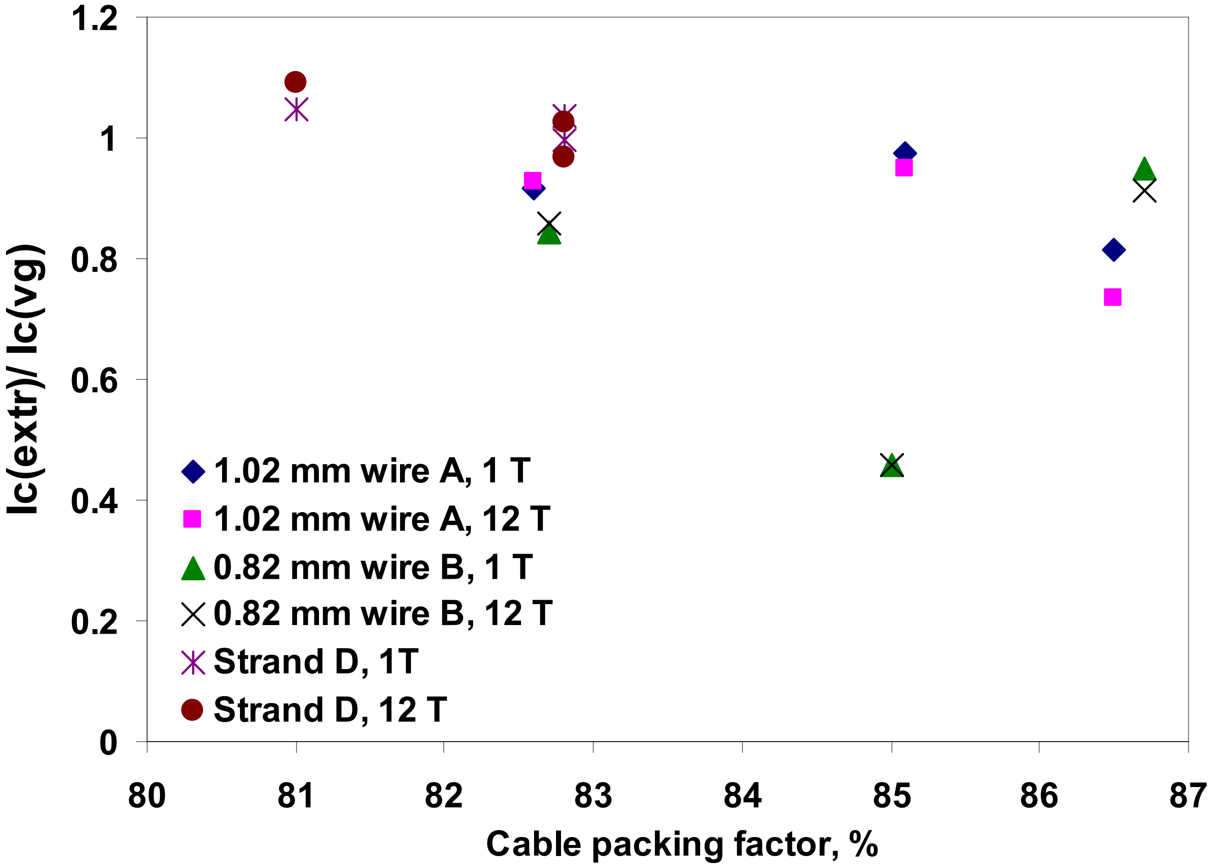
| Cable ID | No. strands | Strand size, mm | Strands used | Ave. thickness, mm | Average width, mm | PF, % | Tested |
|---|---|---|---|---|---|---|---|
| 1 | 19 | 1.02 | A | 1.938 ±0.003 | 9.992 ±0.050 | 82.6 | Y |
| 2 | " | " | " | 1.883 ±0.007 | 9.987 ±0.031 | 85.1 | N |
| 3 | " | " | " | 1.848 ±0.009 | 10.008 ±0.022 | 86.5 | Y |
| 4 | 24 | 0.81 | B | 1.554 ±0.008 | 9.921 ±0.072 | 82.7 | Y |
| 5 | " | " | " | 1.51 ±0.010 | 9.928 ±0.035 | 85.0 | N |
| 6 | " | " | " | 1.485 ±0.014 | 9.896 ±0.051 | 86.7 | Y |
| 7 | 27 | 0.692 | D (24), copper (3) | 1.309 ±0.011 | 9.876 ±0.059 | 81.0 | N |
| 8 | 24 | 0.81 | D (20), B (4) | 1.551 ±0.022 | 9.921 ±0.056 | 82.8 | Y |
| 9 | 21 | 0.911 | D | 1.711 ±0.007 | 9.959 ±0.082 | 82.8 | Y |







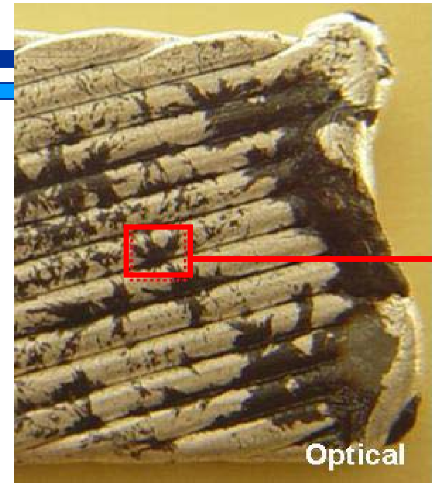
# $I_c$ of the Extracted Strand

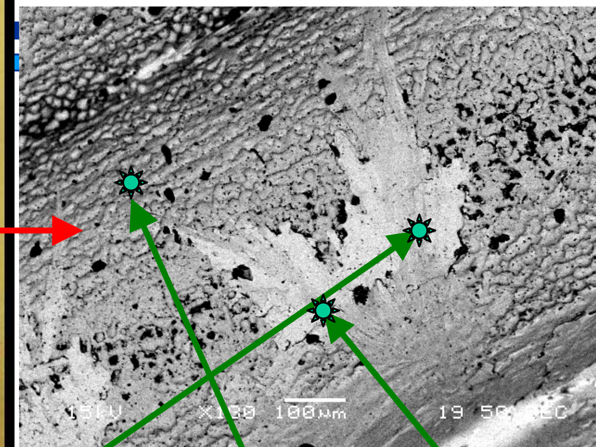



**There is no noticeable dependence on B. Besides for a reproducible single case, <u>the $I_c$ degradation of the extracted strands was less than 20% at least up to 85% of packing factor</u>. Strands of different designs behave differently to cabling, as is the case for other brittle materials like $Nb_3Sn$.**

# SEM/EDS Cable Surface Analysis

The surface of all the cables after reaction showed black spots embedded in the silver coating.



| Spectrum No. | 1 | 2 | 3 |
|---|---|---|---|
| Element | At. % | At. % | At. % |
| Ag (L) | 0 | 100 | 0 |
| Bi (M) | 14.91 | 0 | 3.59 |
| Sr (L) | 9.04 | 0 | 2.21 |
| Ca (K) | 5.53 | 0 | 0.78 |
| Cu (L) | 11.49 | 0 | 5.80 |
| Mg (K) | 0 | 0 | 29.33 |
| O (K) | 59.03 | 0 | 58.28 |
| Totals | 100.00 | 100.00 | 100.00 |

**Bi-2212?** **Bi-2212+MgO?**

**Caused by filament powder leaks**

**For all the cables, tested at self-fields of 0.1 to 0.3 T, an $I_c$ degradation of about 50% was measured.** This was much larger than the reduction found on the extracted strands.

**E. Barzi et al., "BSCCO-2212 Wire and Cable Studies", Advances in Cryogenic Engineering, AIP, V. 54, p. 431 (2008)**

# The HTS National Collaboration

A LABORATORY-UNIVERSITY-INDUSTRY COLLABORATION FOR THE DEVELOPMENT OF MAGNETS WITH FIELDS > 22 TESLA USING HTS CONDUCTOR

A proposal to the Office of High Energy Physics, Department of Energy (Attention Dr B P Strauss)

At a cost of $6 million for 3 years on behalf of the

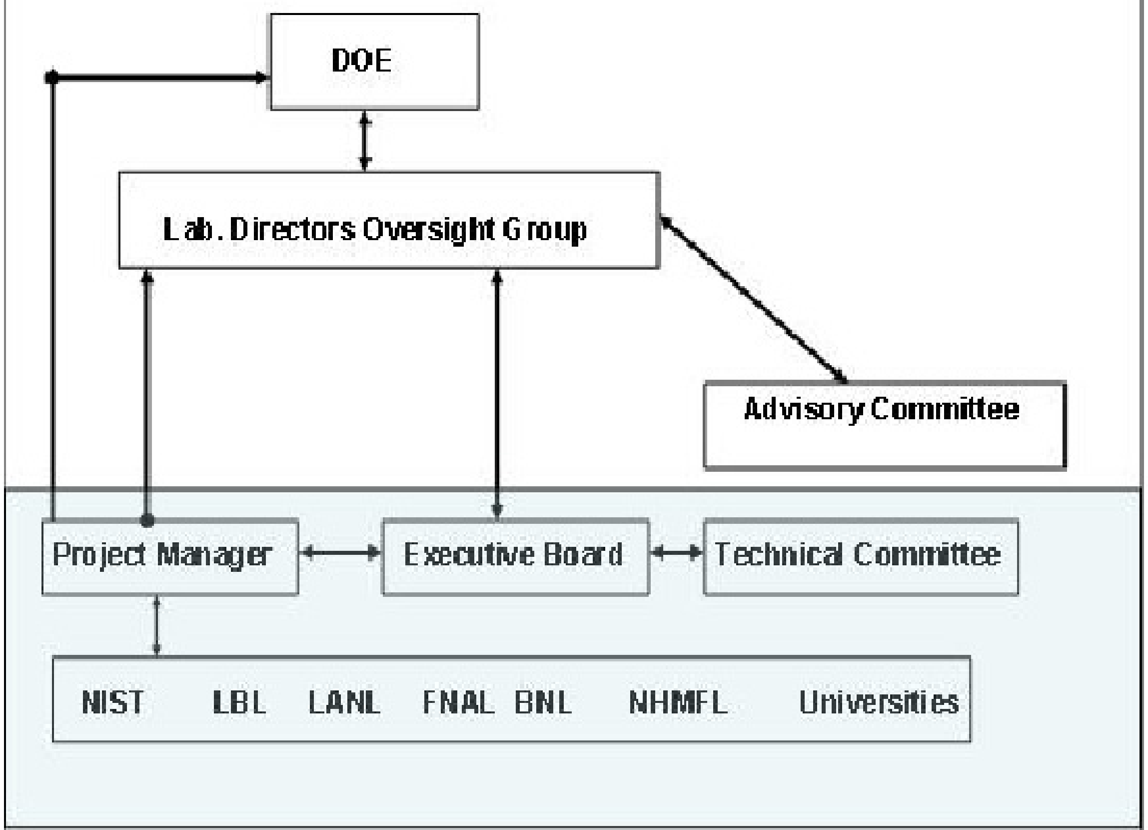
*Very High Field Superconducting Magnet Collaboration (VHFSMC)*

Principal Investigators:

Alvin Tollestrup (Fermilab) and David Larbalestier (National High Magnetic Field Laboratory,Florida State University)

Representing a collaboration of groups at BNL, FNAL, FSU-NHMFL, LANL, LBNL, NIST, and Texas A&M University

# VHFSMC Organization



# VHFSMC Goal

**Answer whether a round wire Bi-2212 magnet technology is feasible**

**Task 1 (k$650).** Obtaining the needed high *Jc* and *Je* in long-length RW2212 by improving the microstructure and optimizing the heat treatment: **FSU, LANL, LBNL, NIST**

**Task 2 (k$250).** Understanding the mechanical response of RW2212 conductors to axial and transverse strains: **NIST, LBNL**

**Task 3 (k$250).** Develop RW2212 cables into the Rutherford cable forms essential for accelerator magnets: **FNAL, TAMU, LBNL, FSU**

**Task 4 ($250).** Study the quench process in RW2212 conductors and test coils: **FSU, LBNL, BNL**

**Task 5 (k$100).** Construct small prototype coils that provide the essential demonstration that RW2212 is ready for real magnet construction: **FSU, LBNL**

**Task 6 (k$500).** Development of an integrated industrial partnership with the large and small businesses: **LANL, LBNL**

# Coil R&D

**The first phase of the coil program is based on HTS tapes, which are high performing and do not require reaction. Focus is on single and multi-layer pancake coils to be tested in a 14T/16T solenoid at FNAL. A series of coils of increasing sizes are being designed and tested to gradually enhance the magnetic field on the conductor.**

**–> Splice techniques were studied.**

**–> Single and double-layer pancake coils made of YBCO and Bi-2223 were built and tested.**

**–> A modular HTS Insert Test Facility was designed and is being procured to assemble and test up to 14 double-layer pancake coils within the 14T/16T solenoid.**

**For the second phase of the coil program, larger multi-section HTS coils will be fabricated and tested to achieve higher magnetic fields and force levels. To reduce the effect of inductance, a special cryostat with several independent power leads will be designed and procured.**

# Single Pancake Instrumentation

**Conductor Details**

**Tape:** AMSC YBCO

**Nominal Thickness:** 0.2 mm

**Nominal Width:** 4.4mm

**Insulation:** 1 mil turn to turn kapton

**Winding:** wet winding (stycast)

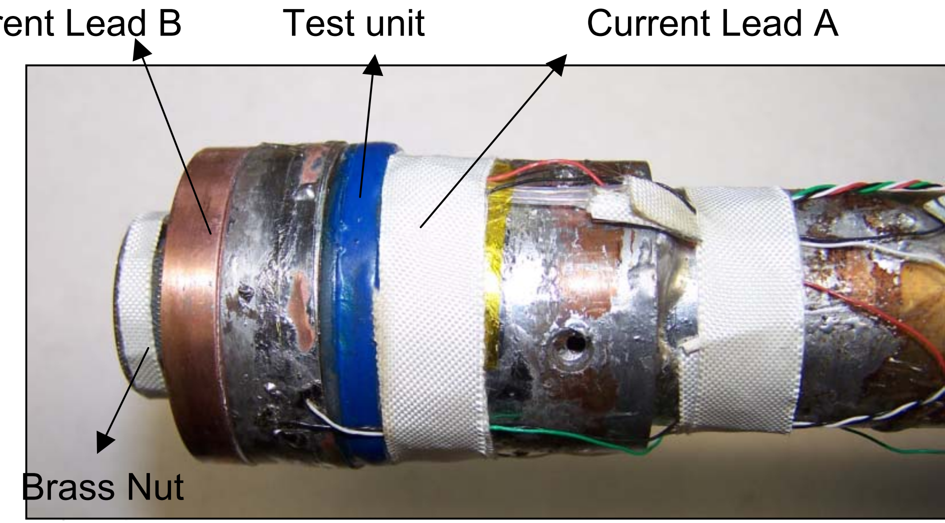
**HTS Insert Details**

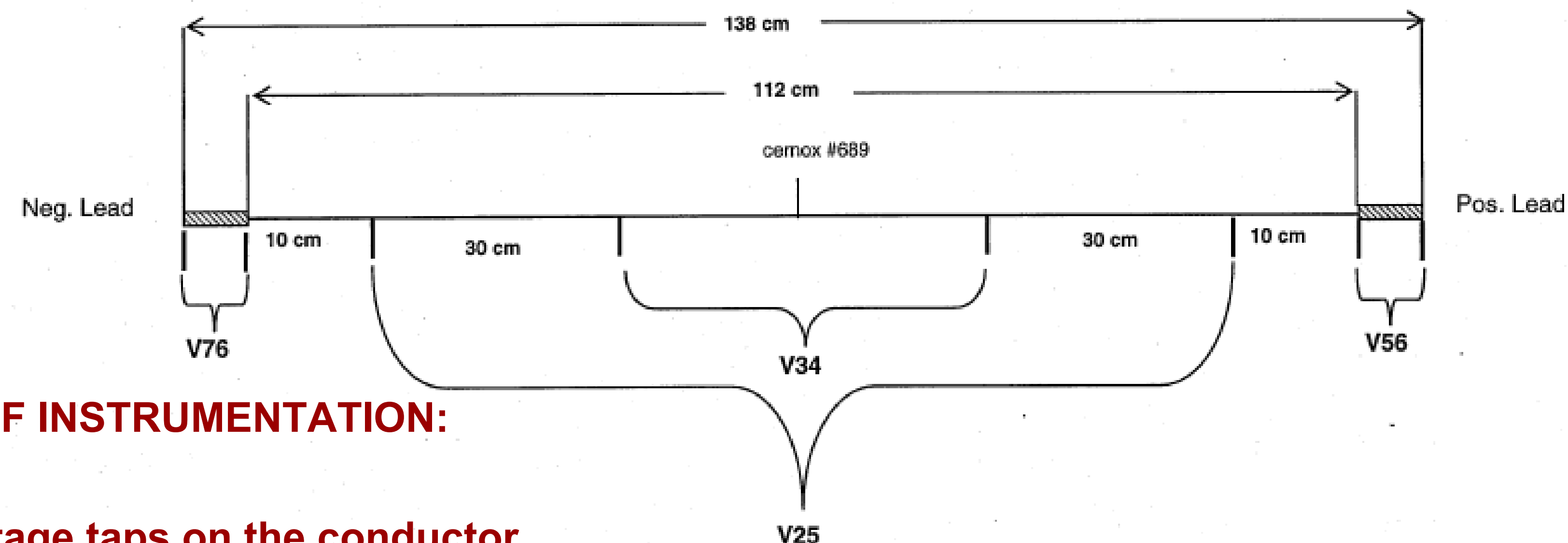
**Coil Configuration:** Single Pancake

**Inner diameter:** 38 mm

**Outer diameter:** 43 mm

**Total conductor length:** 1.38 m




**OVERVIEW OF INSTRUMENTATION:**

**1 Cernox**

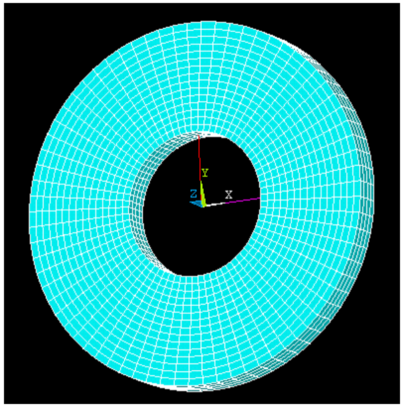
**2 pairs of voltage taps on the conductor**

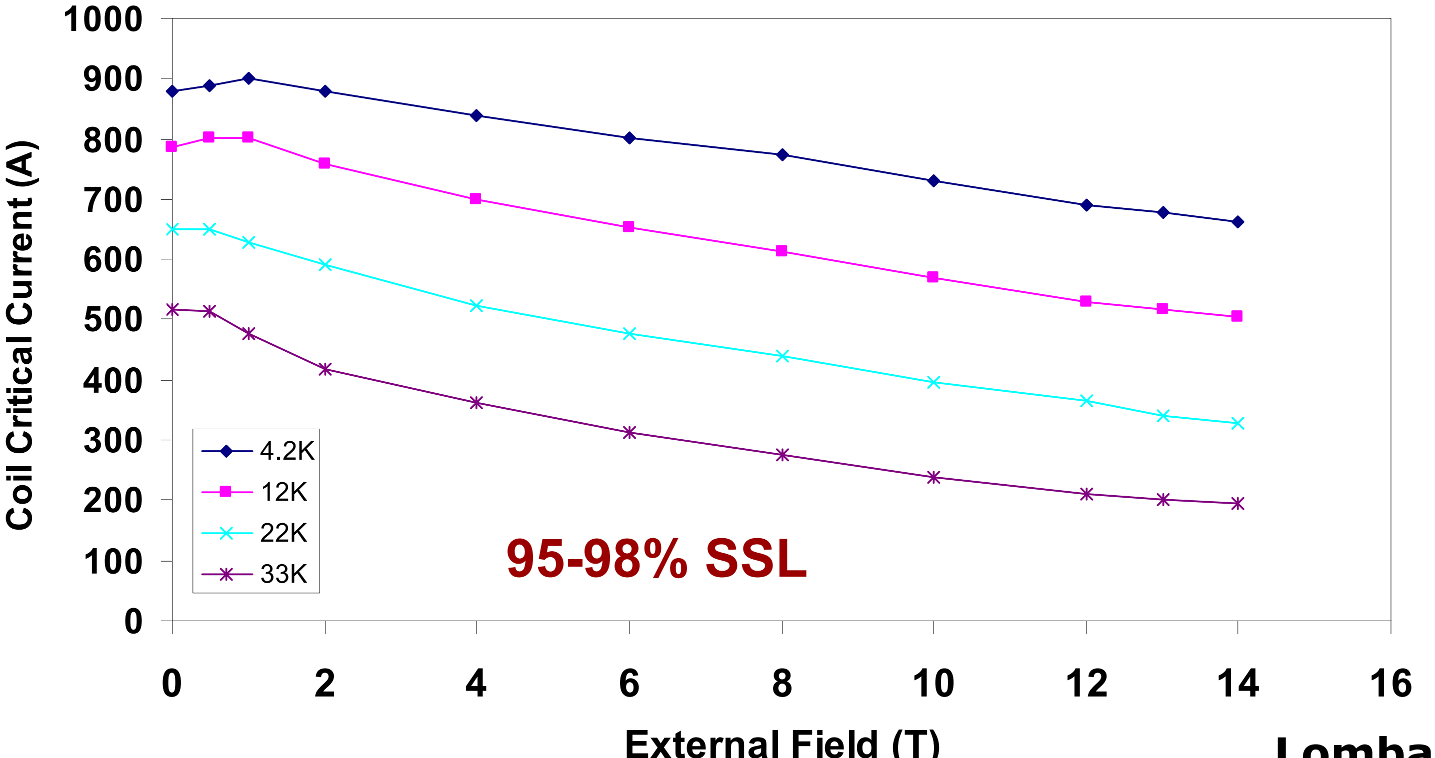
**2 pairs of voltage taps on the leads**

# AMSC 2G Single Pancake Test Results

**Conductor Details**
**Tape:** AMSC YBCO
**Nominal Thickness:** 0.2 mm
**Nominal Width:** 4.4 mm
**Insulation:** 1 mil turn to turn kapton
**Winding:** wet winding (stycast)

**HTS Insert Details**
**Coil Configuration:** Single Pancake
**Inner diameter:** 38 mm
**Outer diameter:** 43 mm
**Total conductor length:** 1.38 m






Lombardo, Turrioni et al.

# AMSC 1G Single Pancake Test Results

**Conductor Details**

**Tape:** AMSC BSCCO-2223

**Nominal Thickness:** 0.295 mm

**Nominal Width:** 4.76 mm

**Insulation:** 1 mil turn to turn kapton

**Winding:** wet winding (stycast)

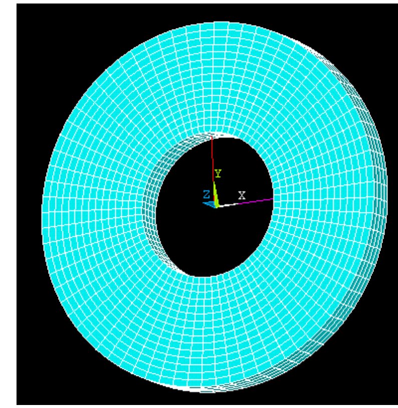
**HTS Insert Details**

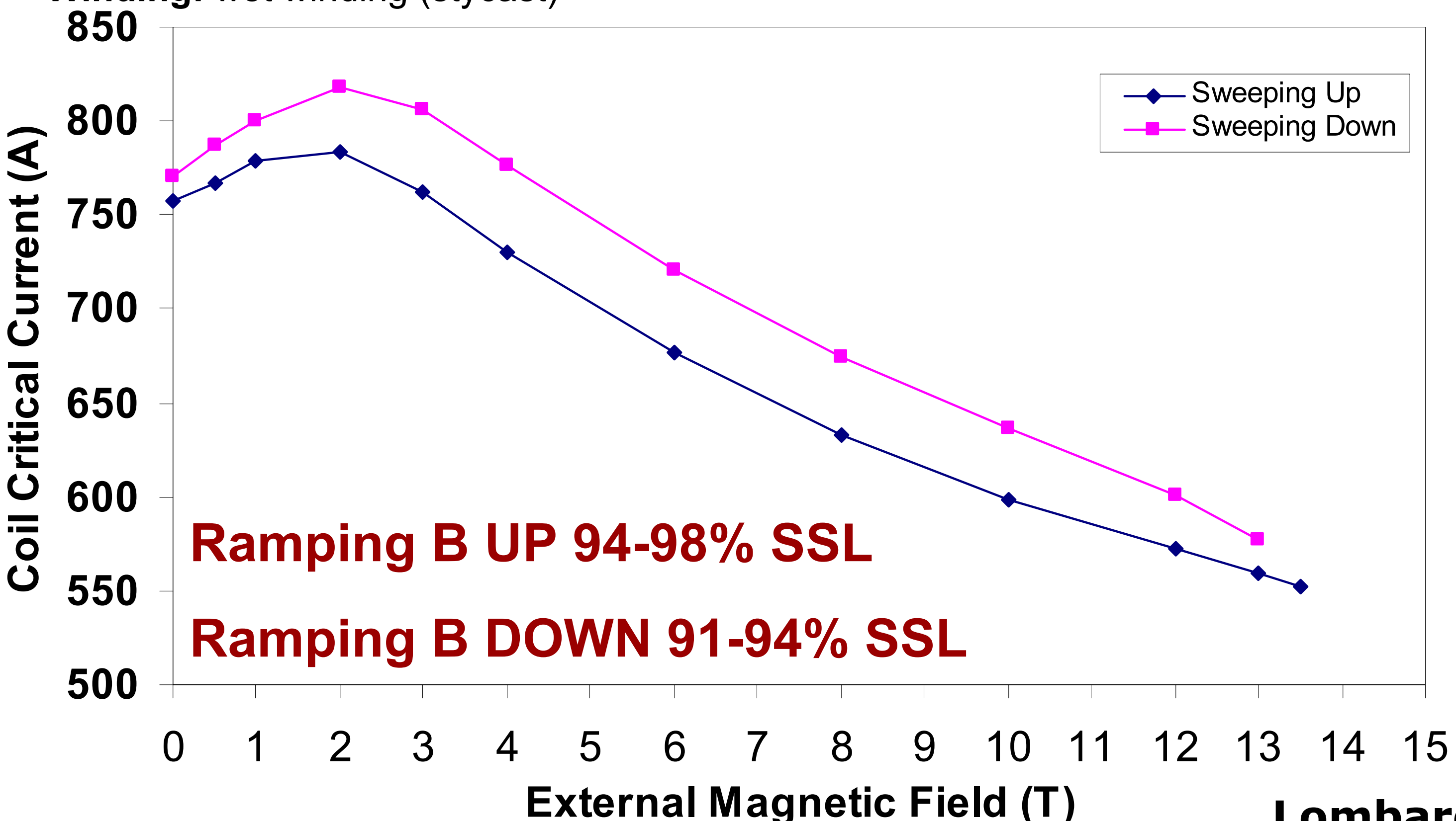
**Coil Configuration:** Single Pancake

**Inner diameter:** 38 mm

**Outer diameter:** 43 mm

**Total conductor length:** 1.04 m

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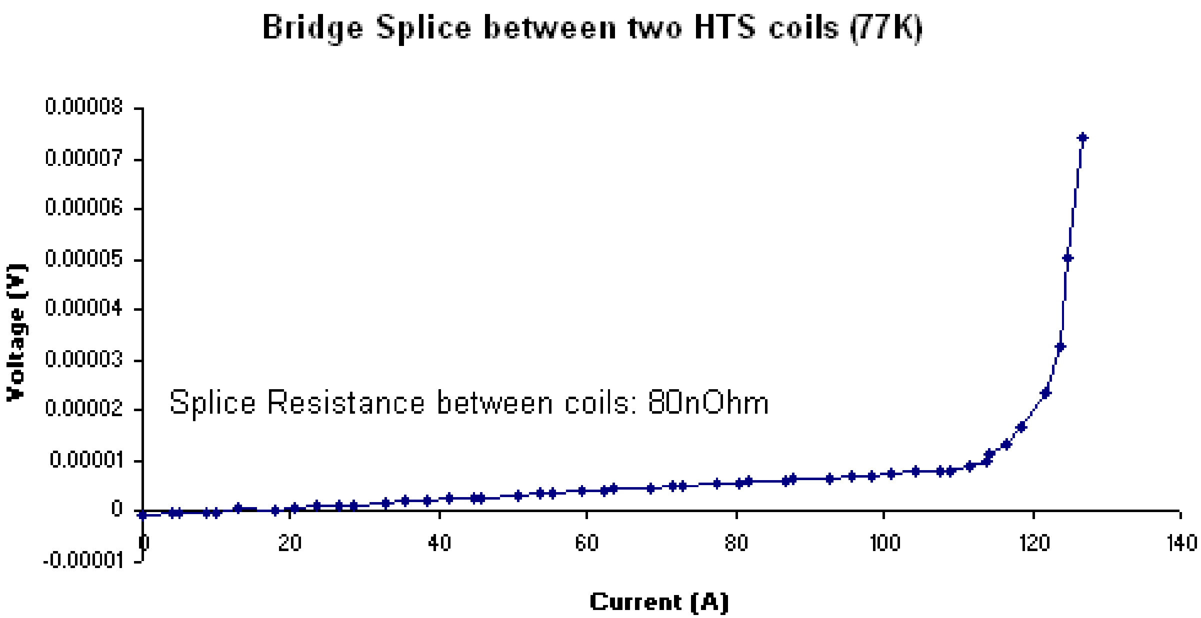
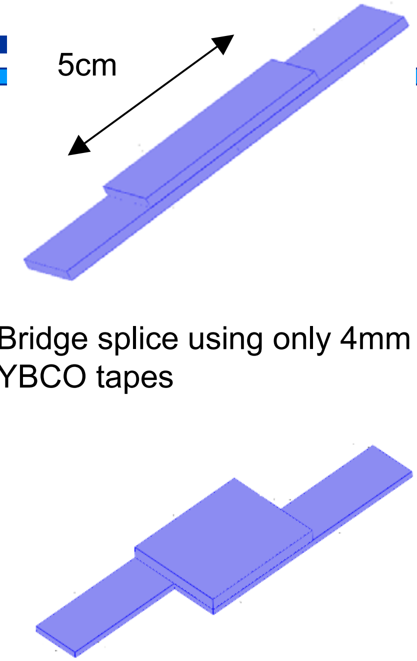
# Splicing Techniques




Bridge splice using only 4mm YBCO tapes

Bridge splice using either 4mm and 8mm YBCO tape (out of 12mm)

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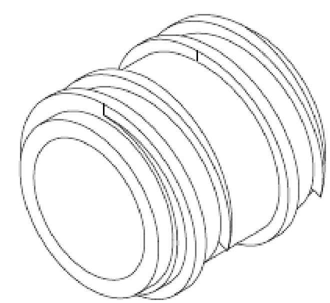
***DOUBLE PANCAKE COIL***



G10 barrel – 30.7 mm diameter

# SuperPower 2G Single and Double Pancake Test Results

**Conductor Details**

**Tape:** SP YBCO tape

**Nominal Thickness:** 0.1 mm

**Nominal Width:** 4 mm

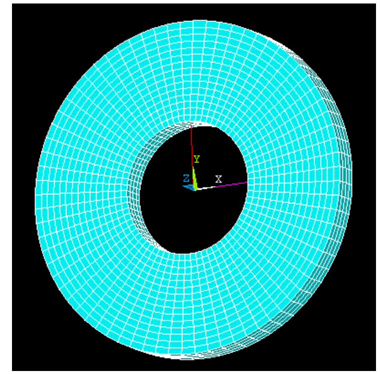
**Insulation:** 1 mil turn to turn kapton

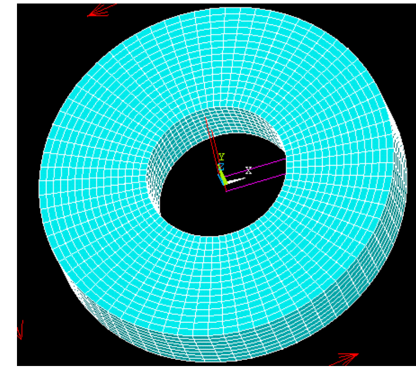
**Winding:** wet winding (stycast)

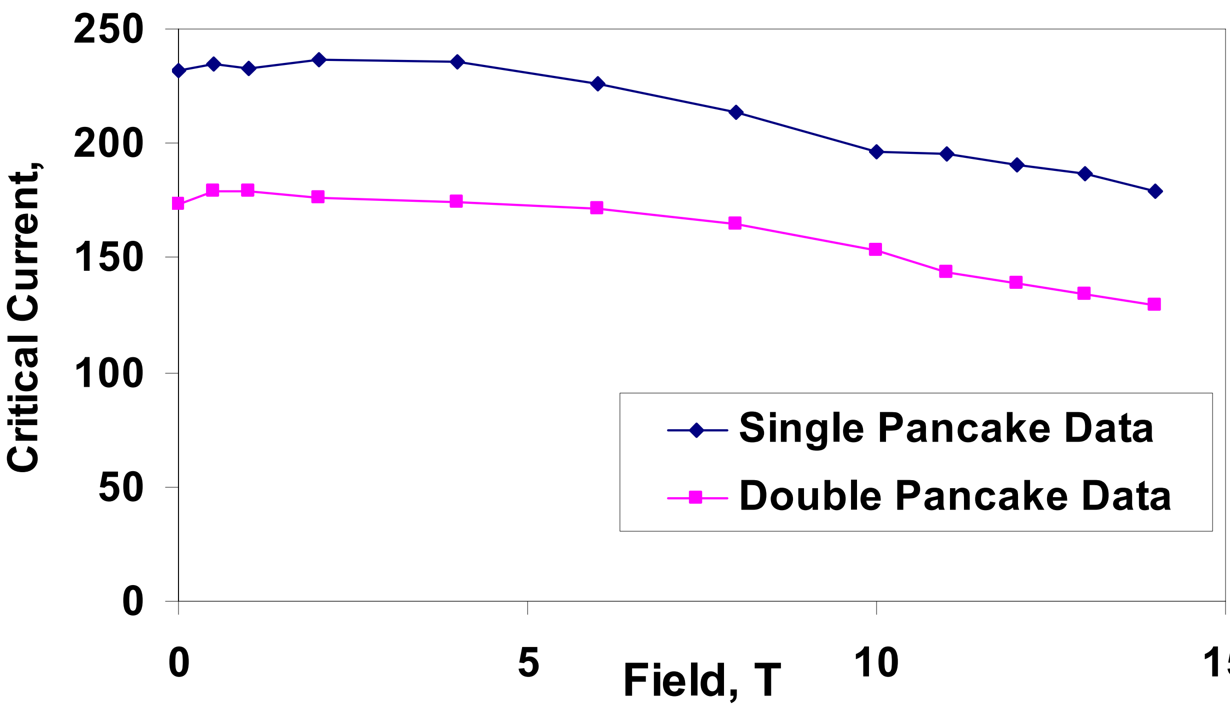
**HTS Insert Details**

**Coil Configuration:** Single Pancake (diam: 38/43 mm)

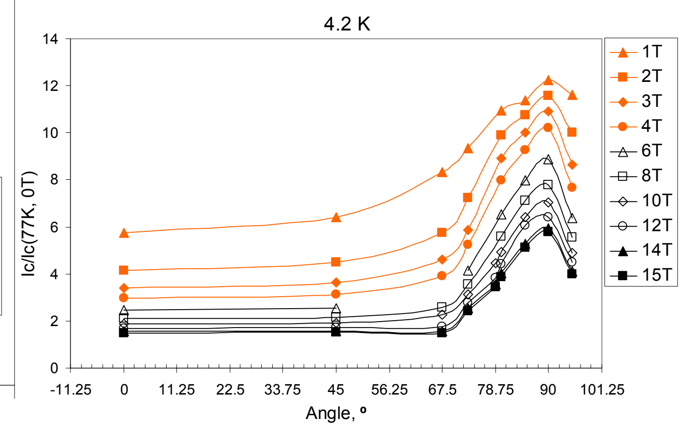
**Coil Configuration:** Double Pancake (diam: 31/43 mm)



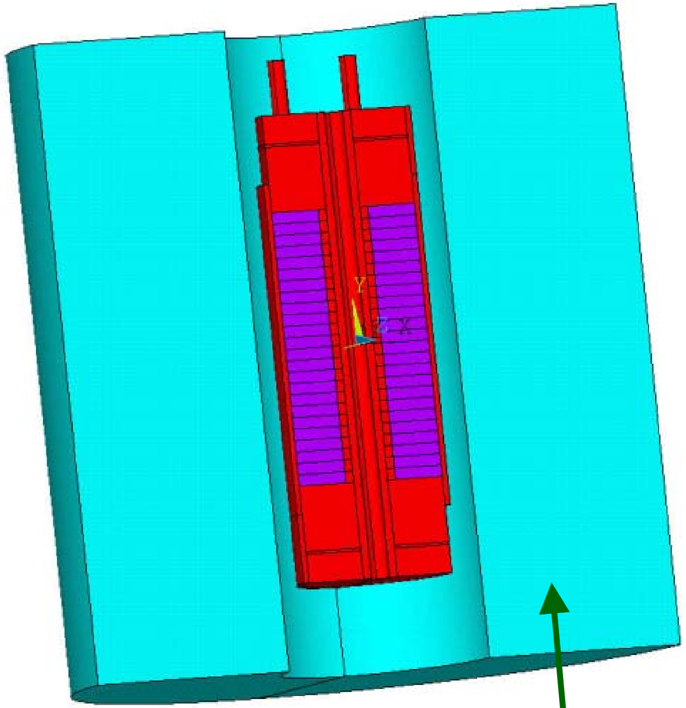


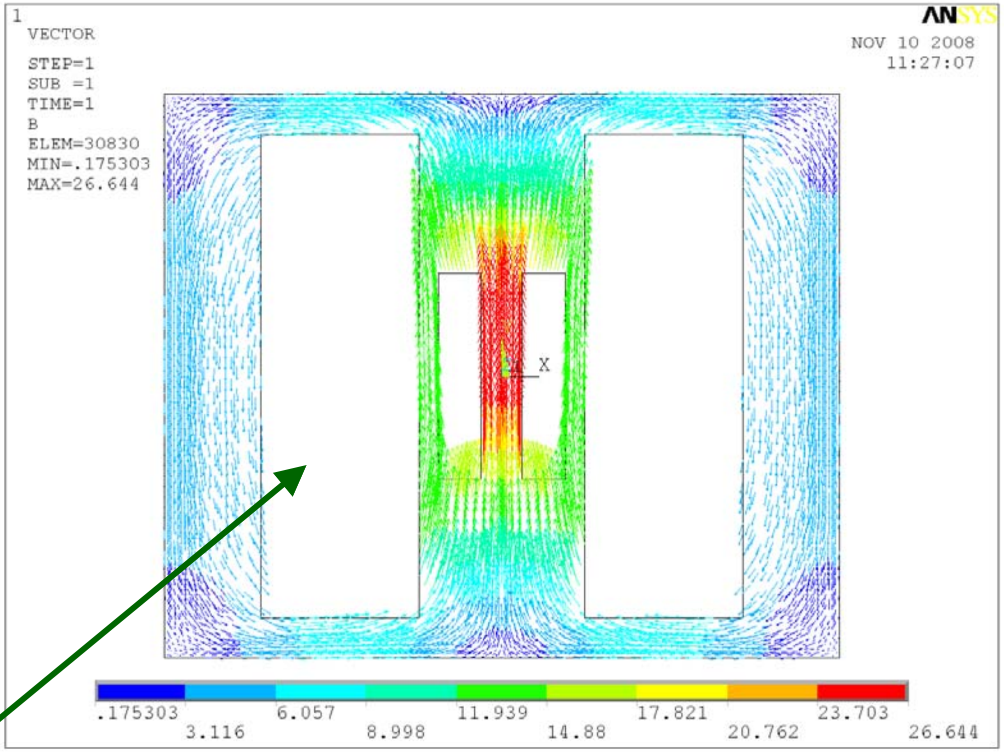



**Turrioni, Lombardo et al.**



# Modular HTS Insert Test Facility





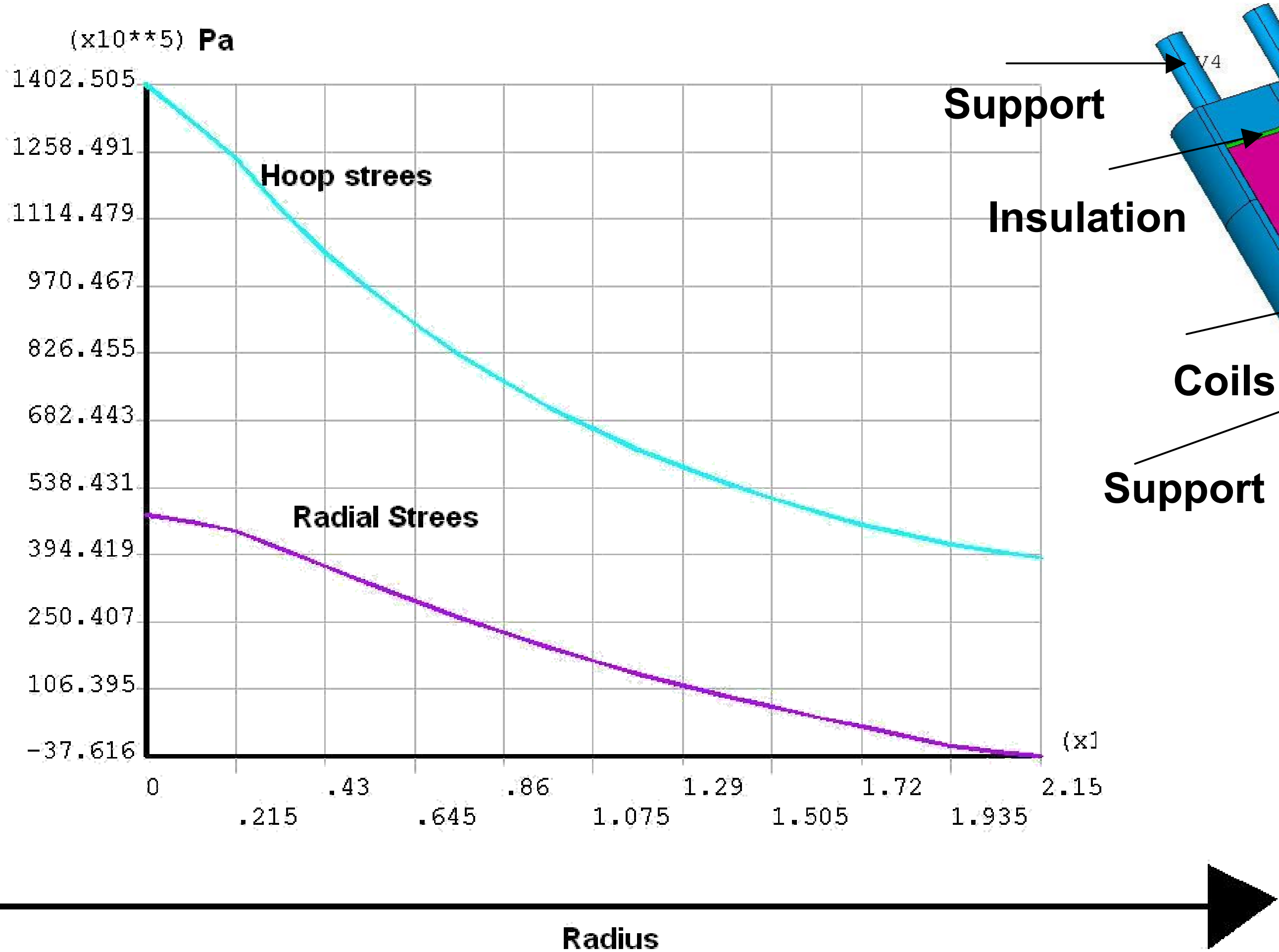

**14 T/ 16 T Solenoid**

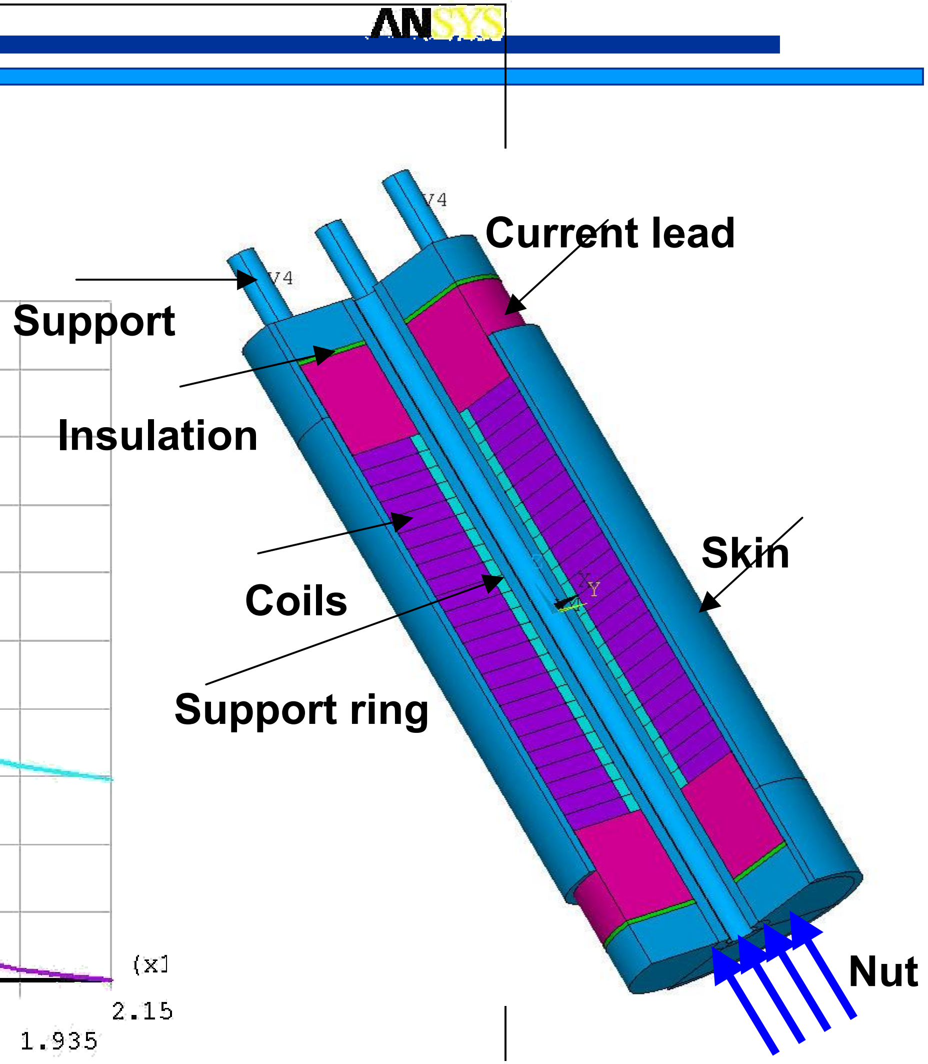
Up to 14 Double Pancakes Units
Modular structure for 19 mm/62 mm units
Wet wound and/or impregnated coils

Expected hoop stress < 200 MPa
Calculated Central Peak Field > 25 T

**G. Norcia et al.**

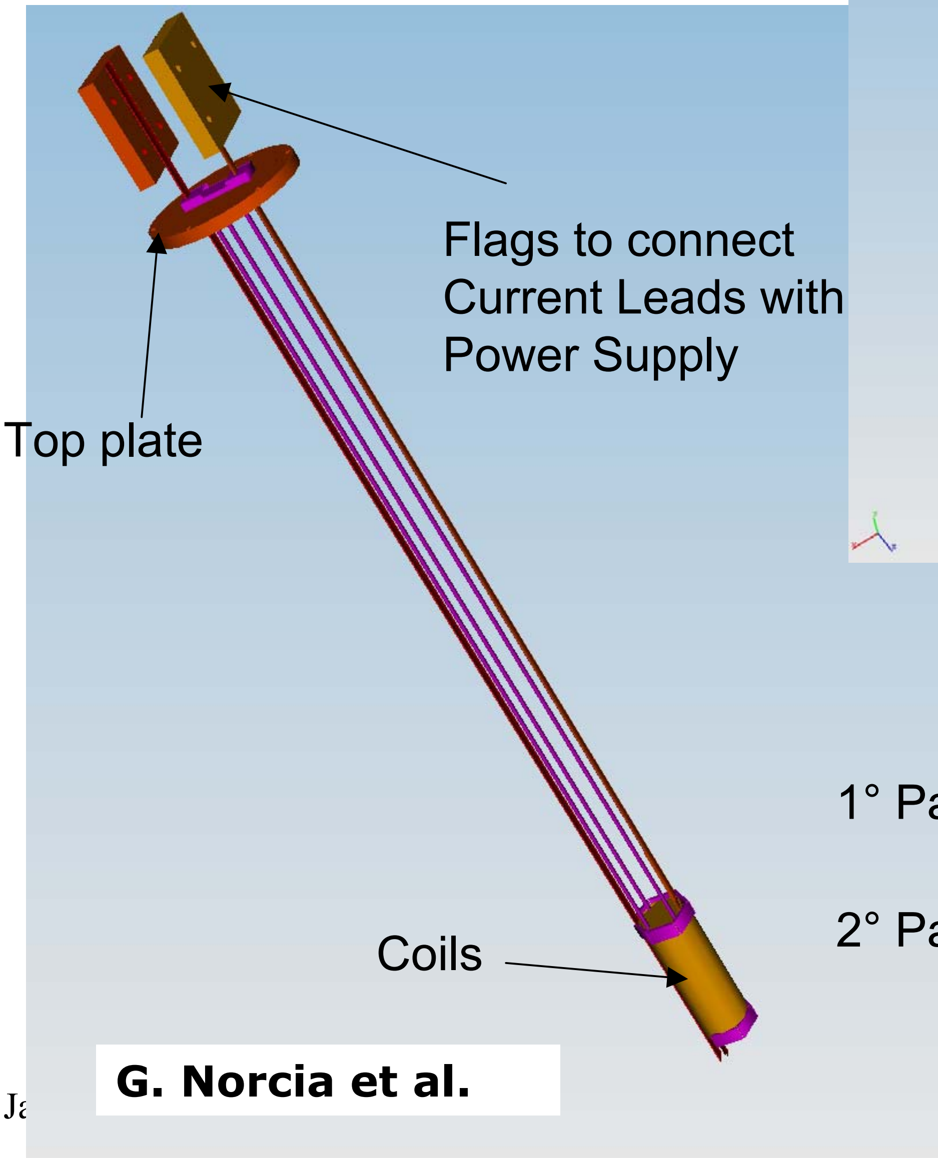
# Mechanical Analysis

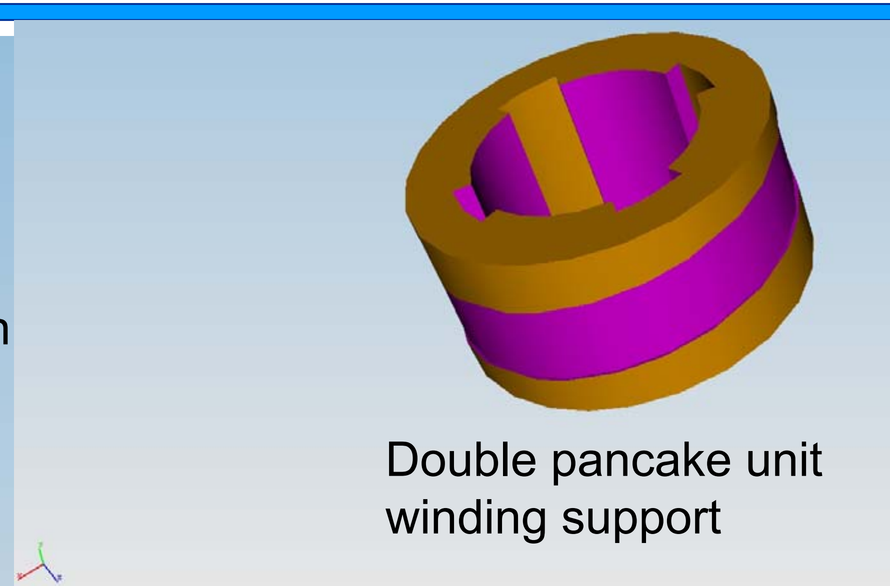


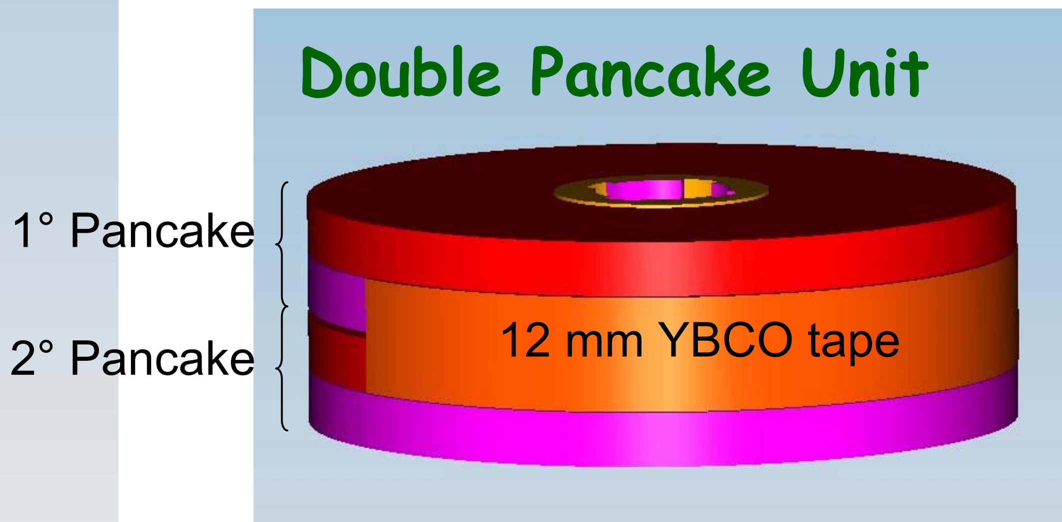




G. Norcia et al.

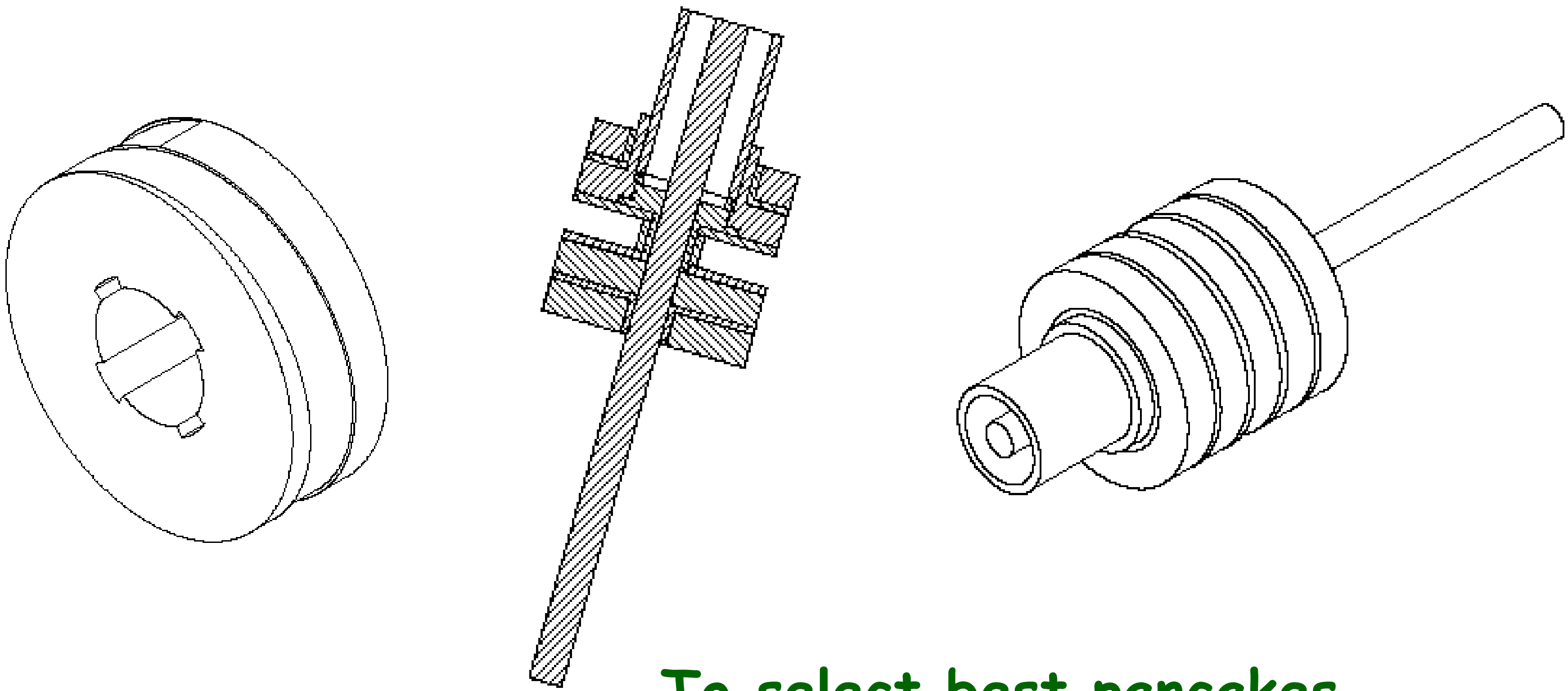
# 3D Modeling


Flags to connect
Current Leads with
Power Supply
Top plate
Coils
G. Norcia et al.


Double pancake unit
winding support


Double Pancake Unit
1° Pancake
2° Pancake
12 mm YBCO tape

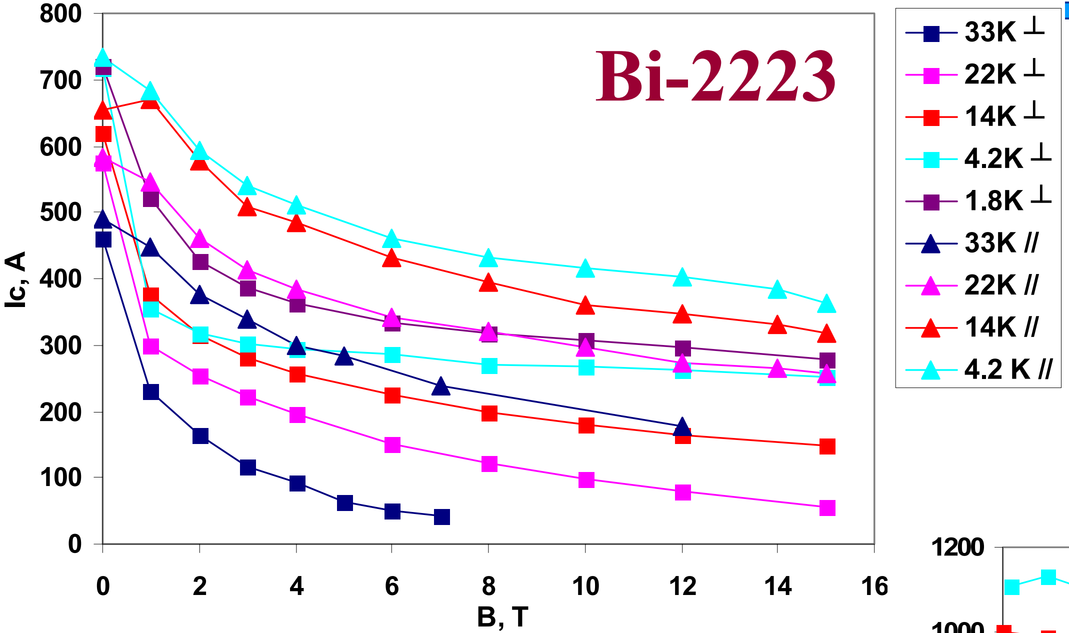
# Independent Setup to Test Units



To select best pancakes.
Will be commissioned next week.

**G. Norcia, V. Lombardo et al.**

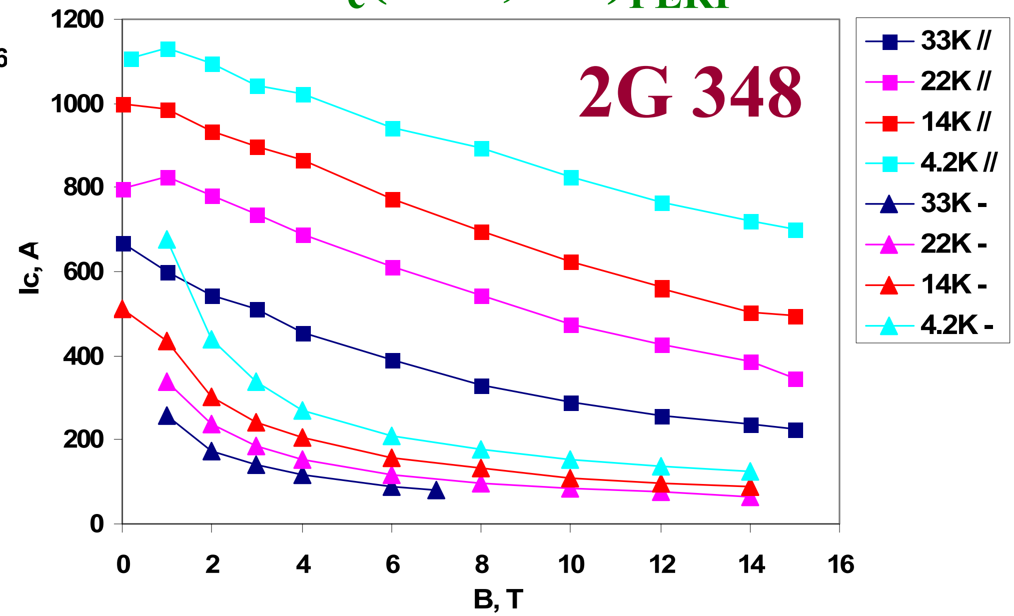
# Critical Currents




$I_c$(77K, 0T)=121±1 A

$I_c$(77K, 0T)$_{PAR}$=127±1 A

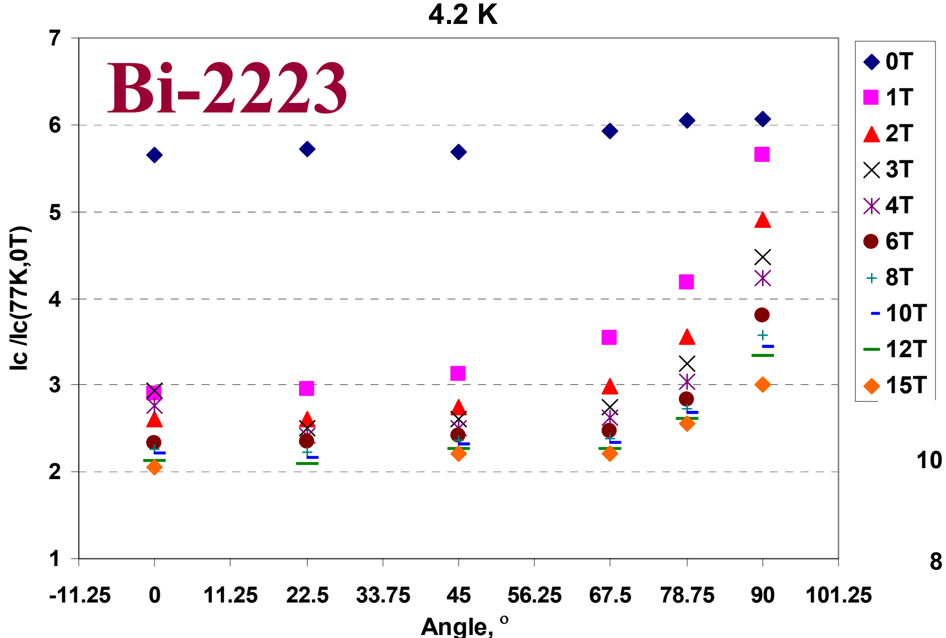
$I_c$(77K, 0T)$_{PERP}$=153±1 A



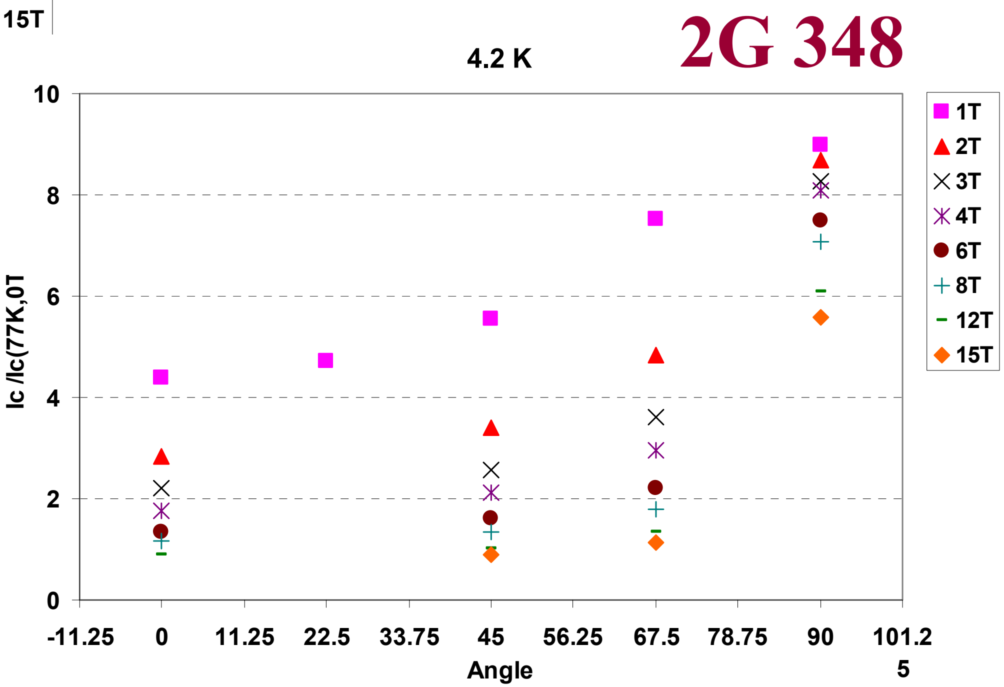

**Effective pinning is maintained for the parallel direction over the entire field range** →

**D. Turrioni et al., "Angular Measurements of HTS Critical Current for High Field Solenoids", Advances in Cryogenic Engineering, AIP, V. 54, p. 451 (2008)**

# Angular Dependence at 4.2 K

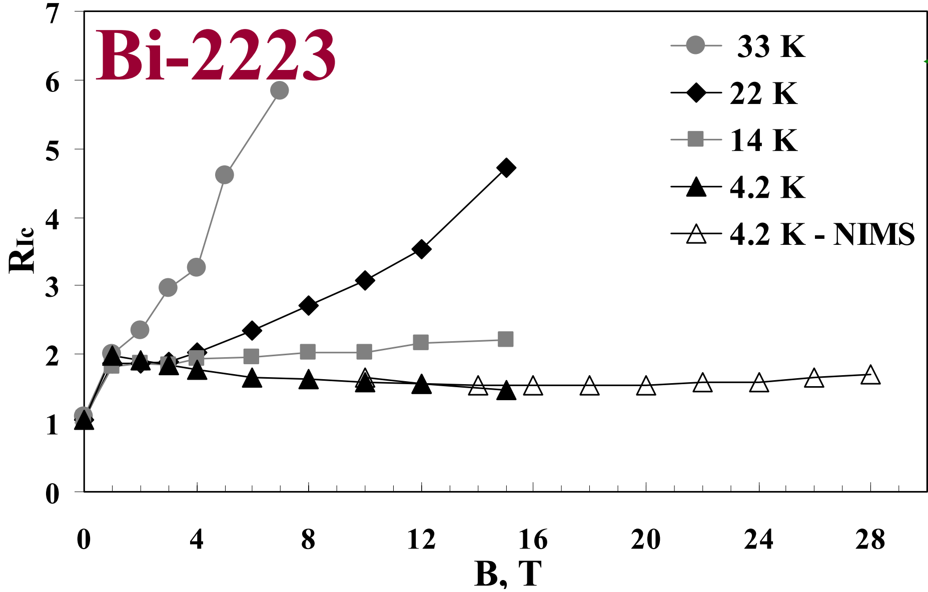



**Most of the $I_c$ reduction occurs between 90 and 45 degree.**



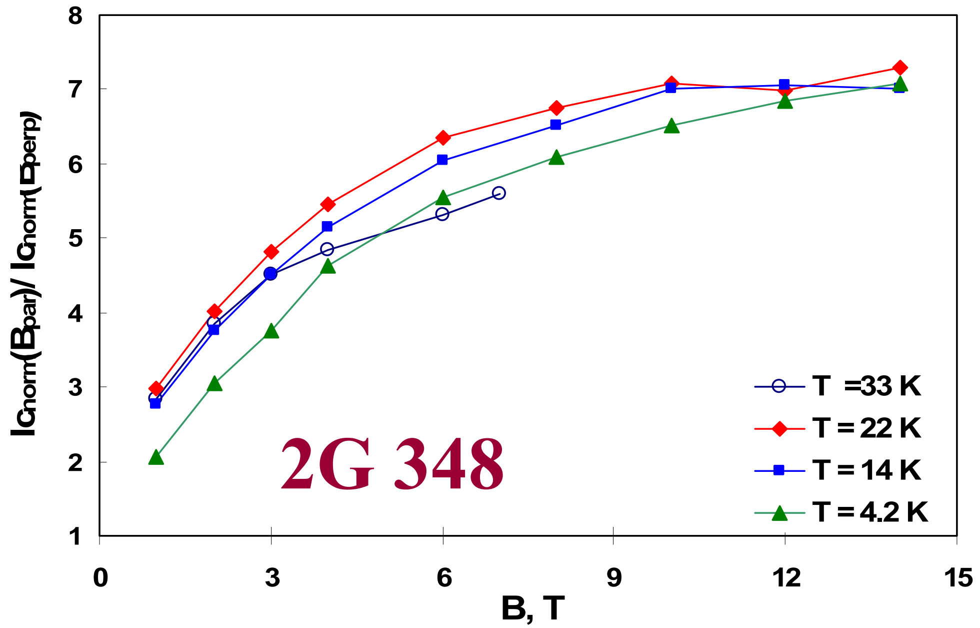

**D. Turrioni et al., "Angular Measurements of HTS Critical Current for High Field Solenoids", Advances in Cryogenic Engineering, AIP, V. 54, p. 451 (2008)**

# B and T Dependence of Anisotropy




The B dependence has a linear trend, where the slope value increases with T.

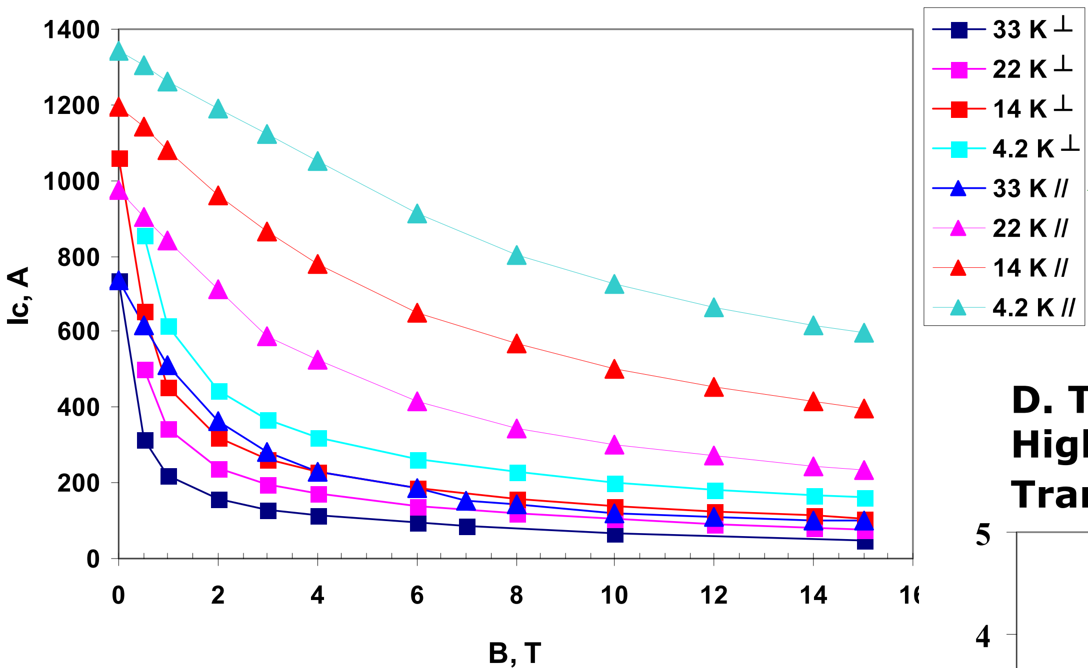
No observable T dependence. The ratio saturates at ~7.




**D. Turrioni et al., "Study of HTS Wires at High Magnetic Fields", accepted in IEEE Transactions on Applied Sup.**

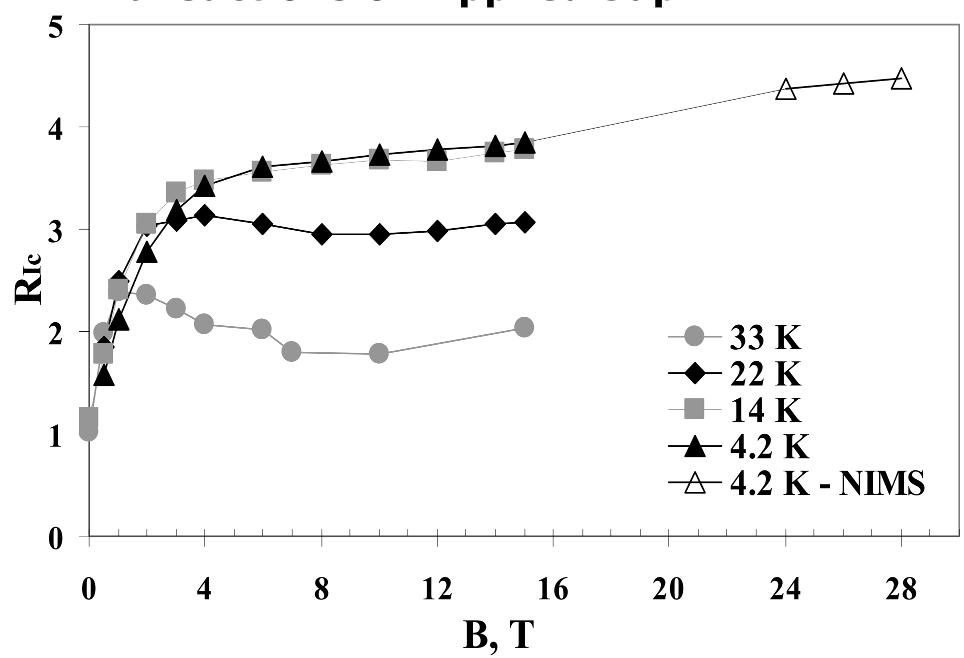
$$\frac{I_c(B_{PAR})/I_c(77K,0\,T)_{PAR}}{I_c(B_{PERP})/I_c(77K,0\,T)_{PERP}}$$

# Comparison with Super Power 2G




$I_c$(77K, 0T)=106±1 A

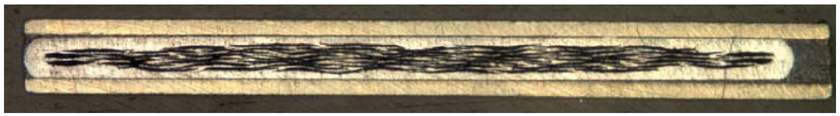
D. Turrioni et al., "Study of HTS Wires at High Magnetic Fields", accepted in IEEE Transactions on Applied Sup.



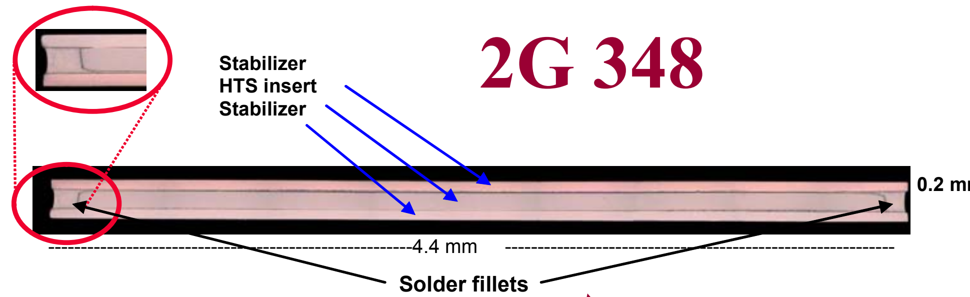

Ratio saturates, but decreases with temperature

# Samples Specs

## Bi-2223



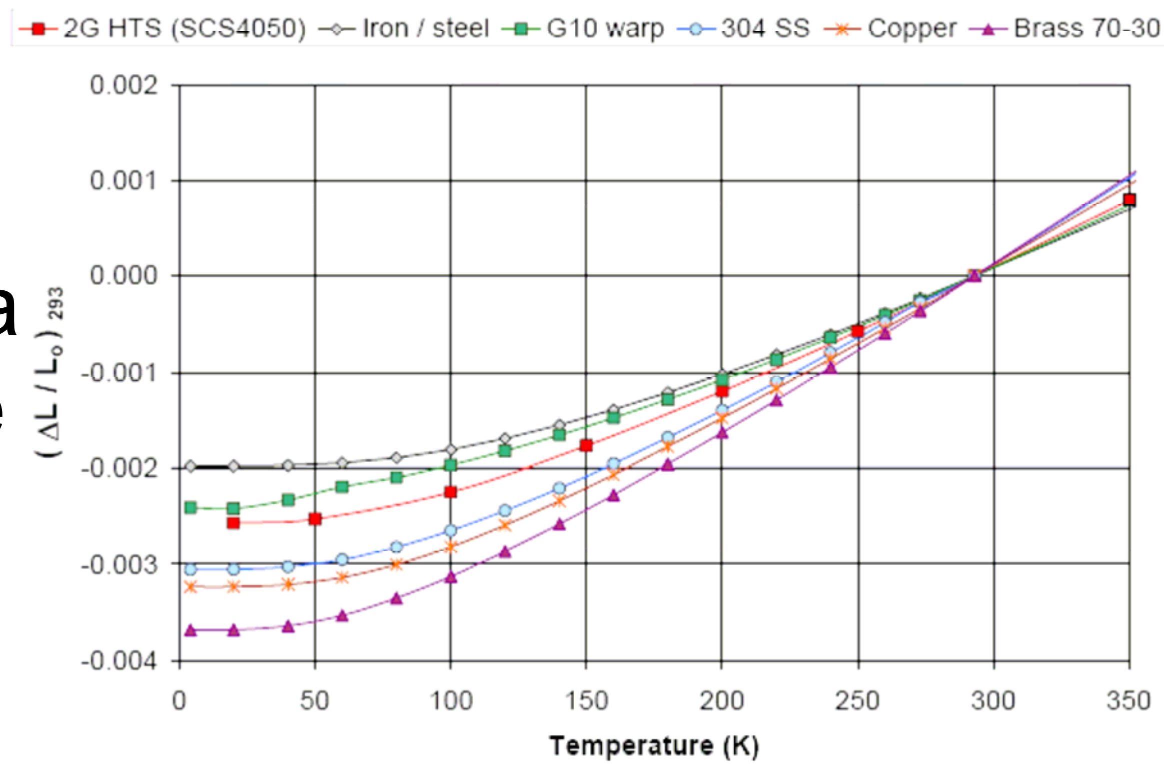
## 2G 348




| | Hermetic BSCCO-2223 tape | 348 Superconductor |
|---|---|---|
| Min $I_c$ (77 K, self-field, 1 μV/cm) | 115 A | 110 A |
| Average thickness $t_T$ | 0.31 mm | 0.2 mm |
| Average width $w_T$ | 4.8 mm | 4.8 mm |
| Laminate | stainless | copper |
| Laminate thickness | 2 x 0.037 mm | 2 x 0.050 mm |
| YBCO layer thickness | | 1.4 μm |
| Min. critical bend diameter | 50 mm | 50 mm |
| Max. rated tensile strain (95% $I_c$ retention ) | 0.3 % | 0.3 % |

# Thermal Stress I

Objective of the Skin is to create a preload to reduce the hoop and the radial stresses




Data from Super Power