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)

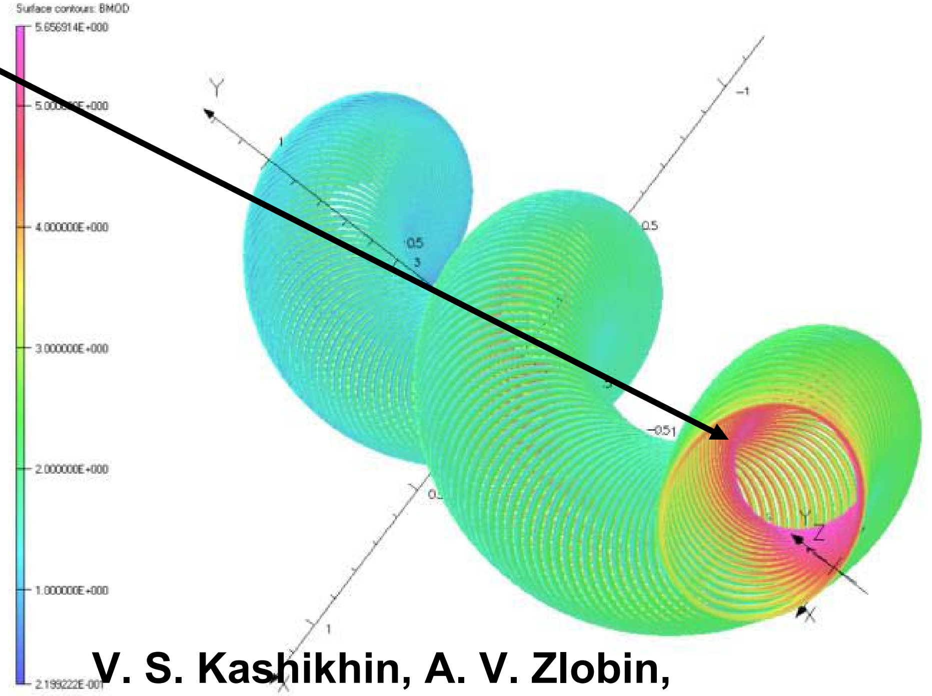
OUTLINE

- 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

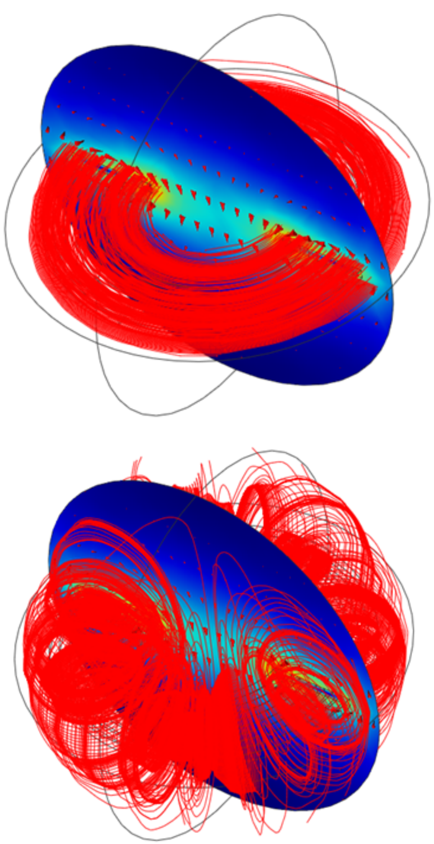
High field solenoids for muon beam cooling include the high field (> 17 T) sections of a 6D Helical Cooling Channel, and high-field solenoids (> 30 T) for the final, low emittance stage of the muon cooling channel.

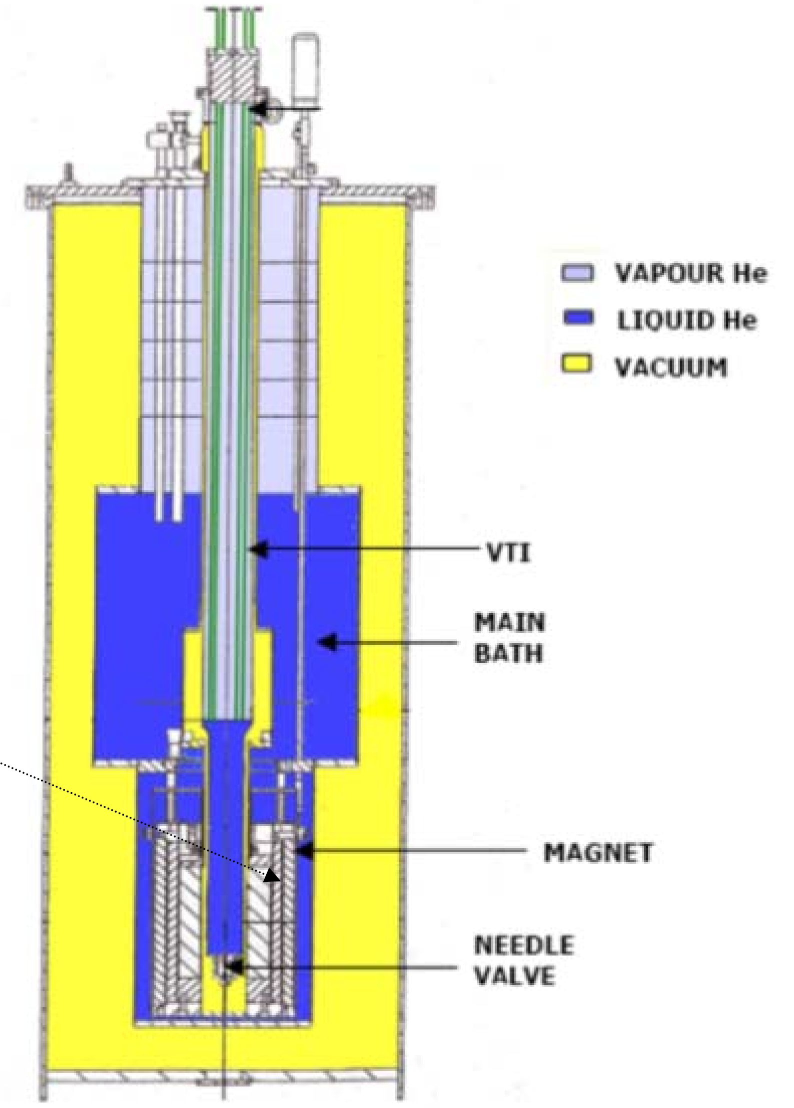
The robust and versatile infrastructure that was developed in Technical Division for advanced superconductor and accelerator magnet R&D, together with the expertise acquired in the Nb_3Sn and Nb_3Al technologies by the scientists and engineers of the Magnet Systems Department, makes TD an ideal setting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

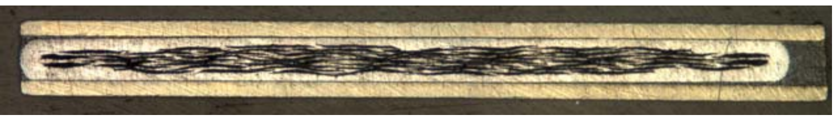
Wire R&D

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:

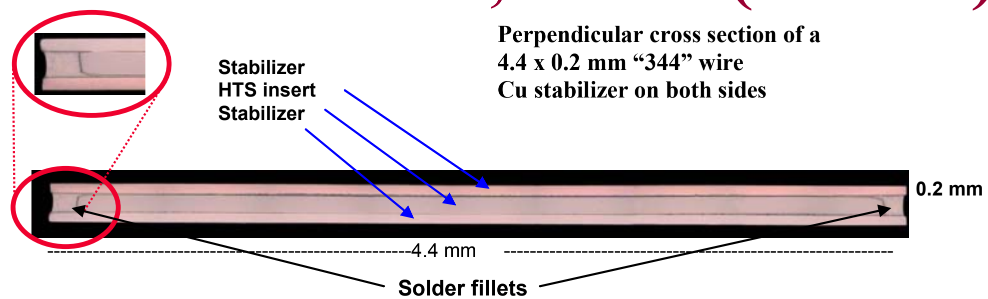
- **magnetic field -> new data up to 28 T within a FNAL-NIMS collaboration;**
- **temperature -> data from superfluid He to nitrogen temperature;**
- **for anisotropic tapes, field orientation -> data are continuously produced on new tapes released by Industry;**
- **bending strain -> new equipment was designed and commissioned, and data were produced for a number of HTS conductors;**
- **longitudinal strain -> new fixture was designed and is under procurement;**
- **transverse pressure -> setup will be used within the HTS National Collaboration**

Available Conductors

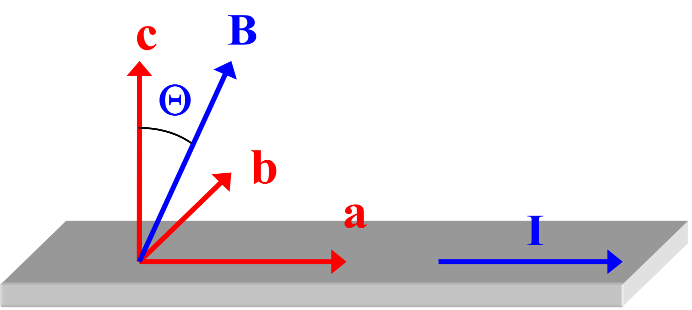
Bi-2223, or 1G (AMSC)



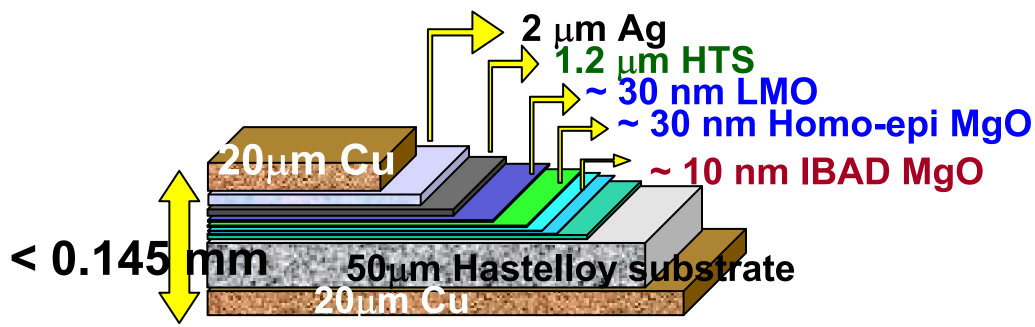
RABiTS™ YBCO, or 2G (AMSC)



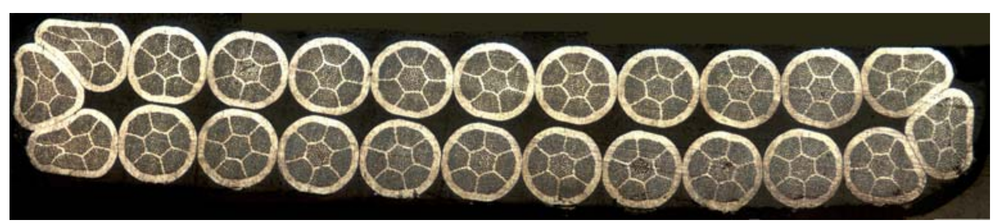
Tape anisotropy



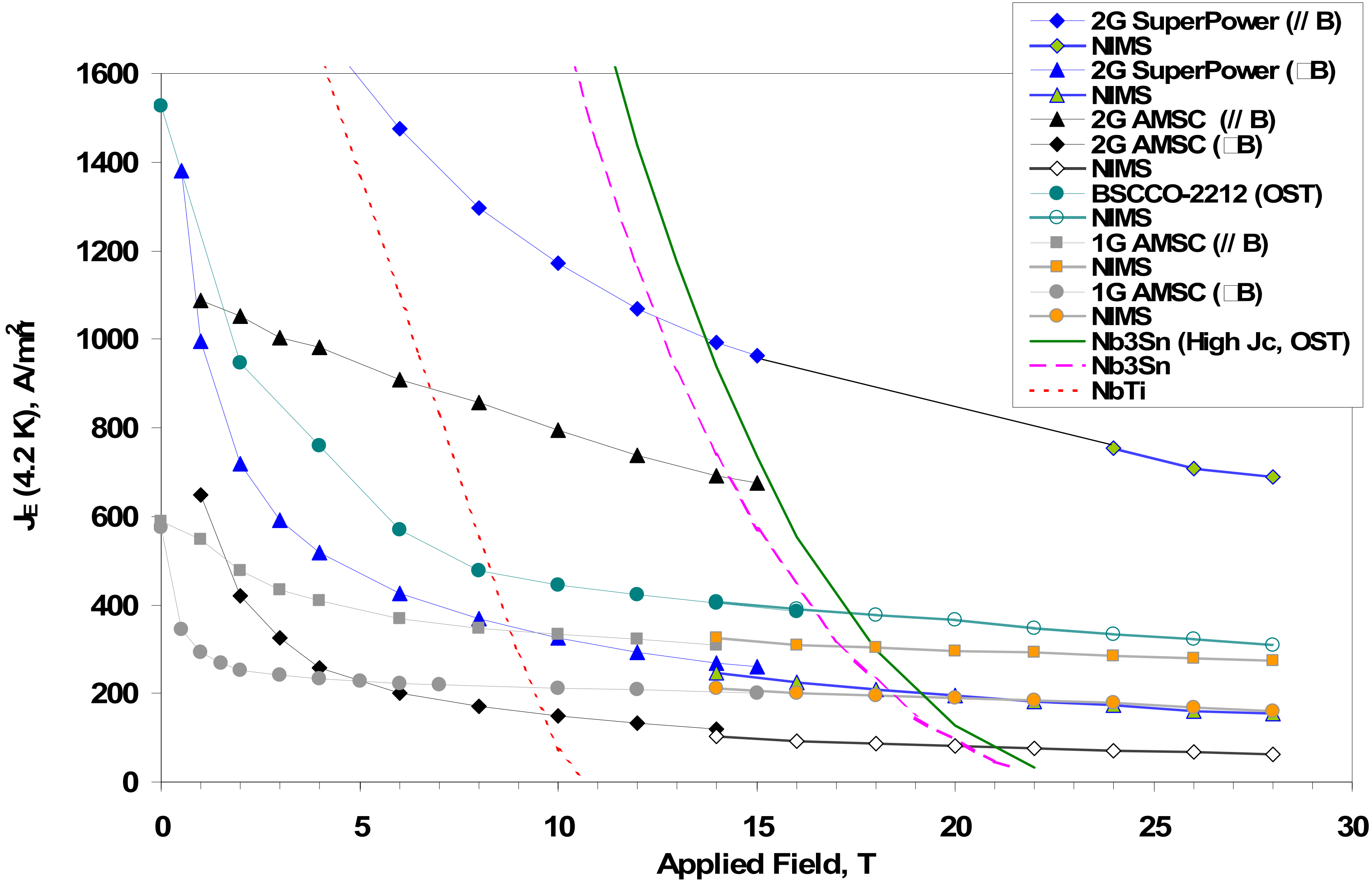
IBAD YBCO, or 2G (SuperPower)



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



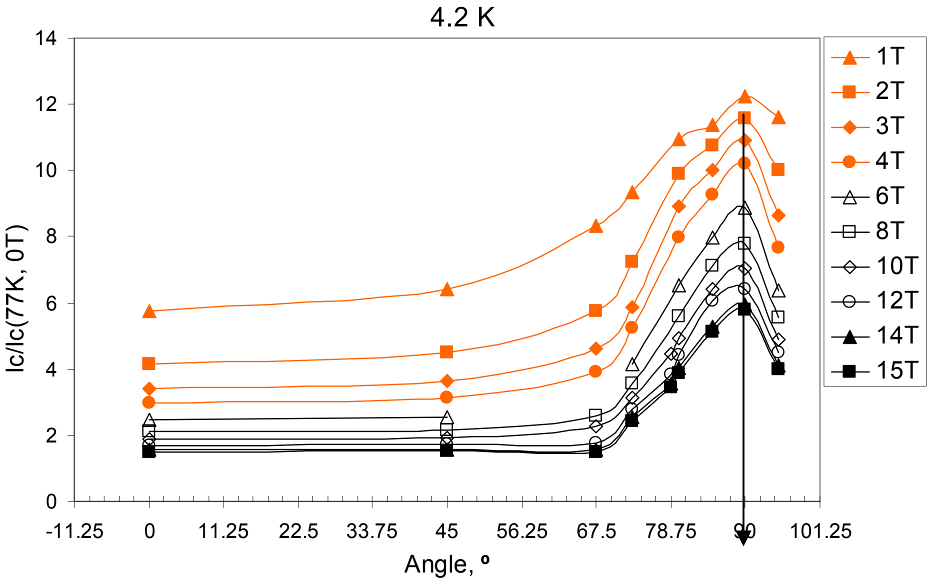
New Data within FNAL-NIMS Coll.

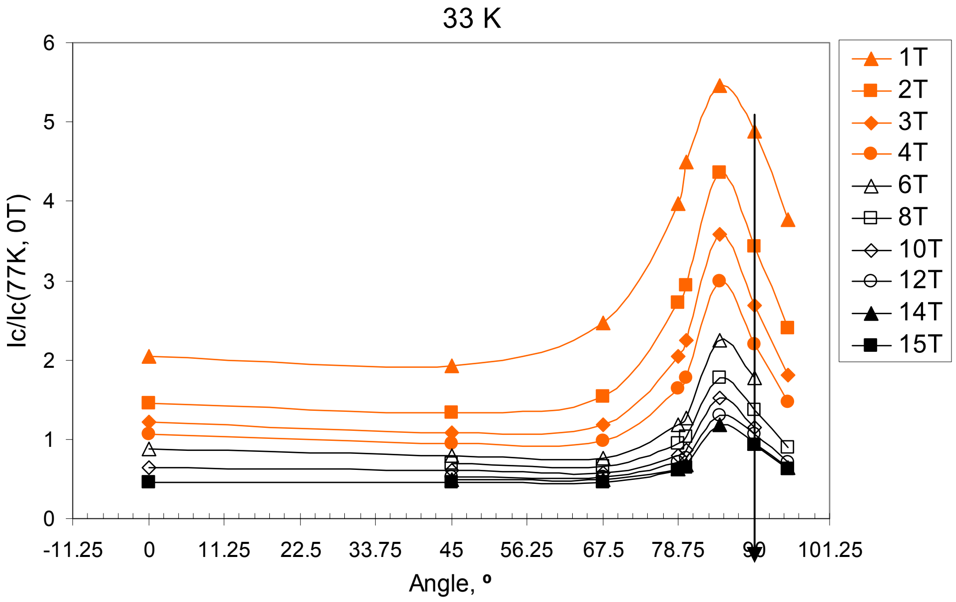


D. Turrioni et al., "Study of HTS Wires at High Magnetic Fields", accepted in IEEE Transactions on Applied Superconductivity

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.





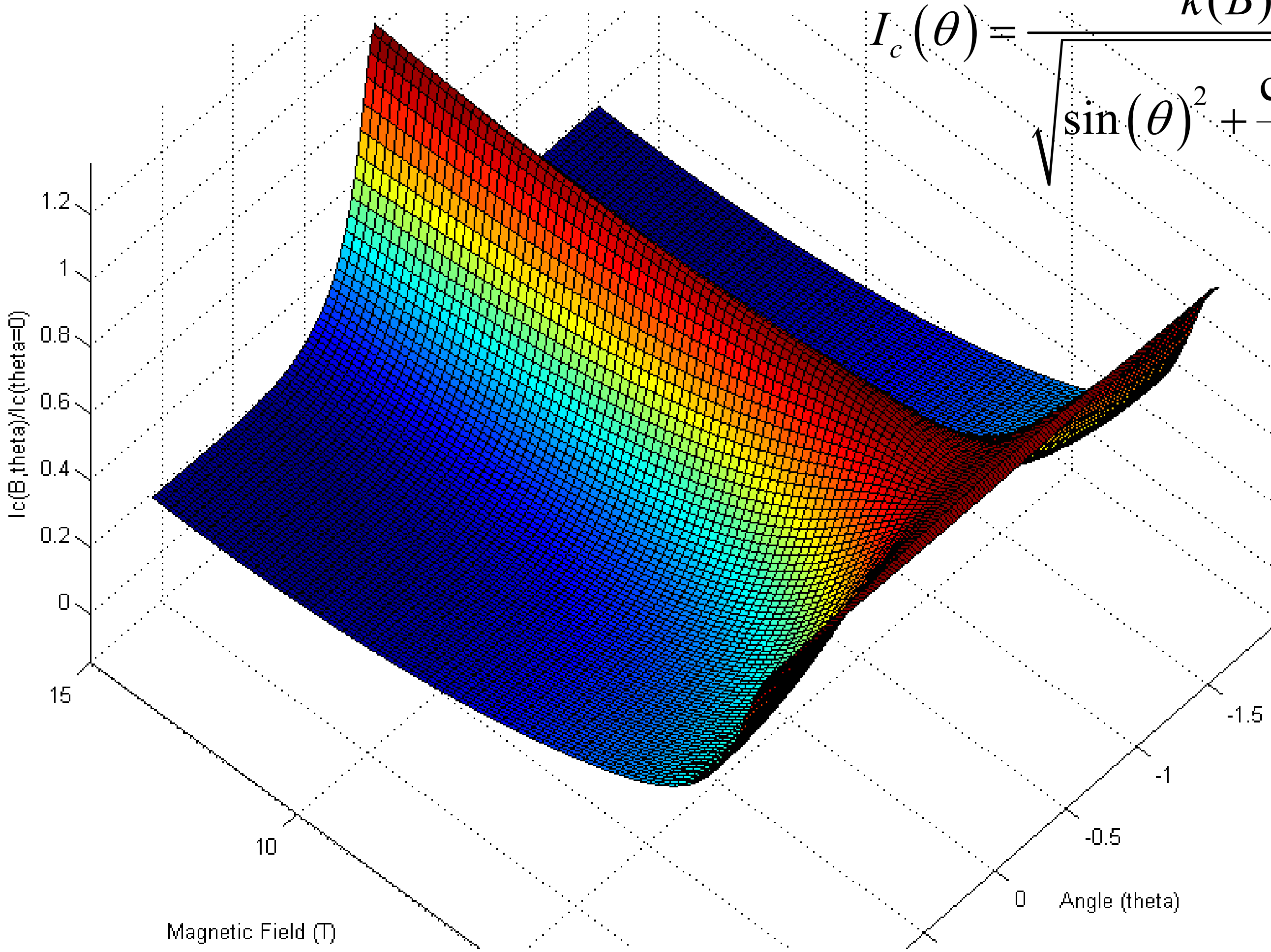
D. Turrioni et al., "Study of HTS Wires at High Magnetic Fields", accepted in IEEE Transactions on Applied Superconductivity

HTS Tapes Data Parameterization

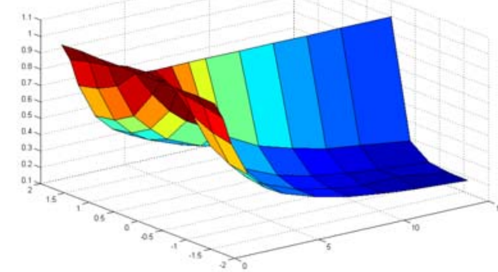
Fit of critical current as a function of **magnetic field** and **field orientation**

$$I_c(\theta) = \frac{k(B)}{\sqrt{\sin(\theta)^2 + \frac{\cos(\theta)^2}{\varepsilon(B)^2}}} + \left(a(B)\sin(\theta)\right)^2$$

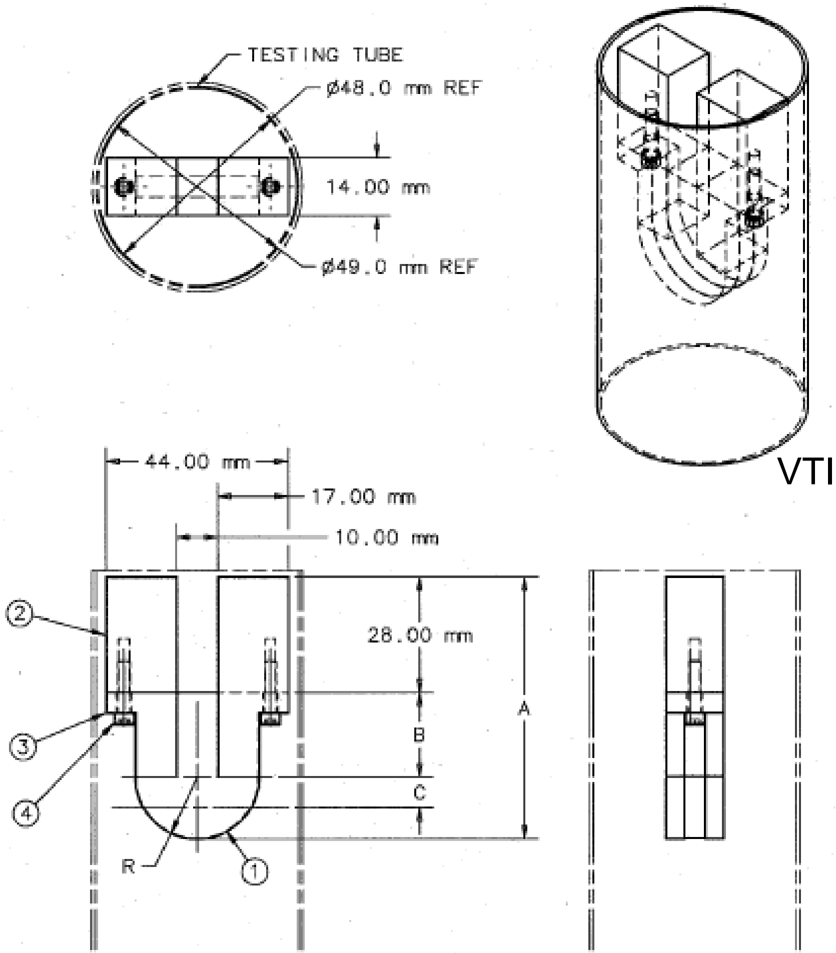
V. Lombardo



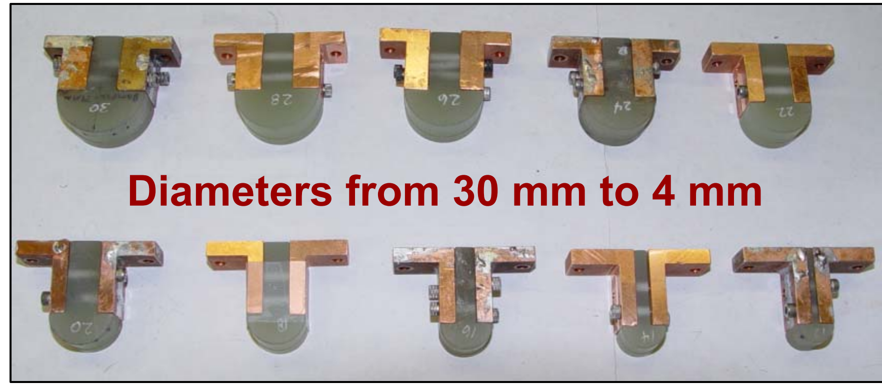
Linear interpolation of experimental data

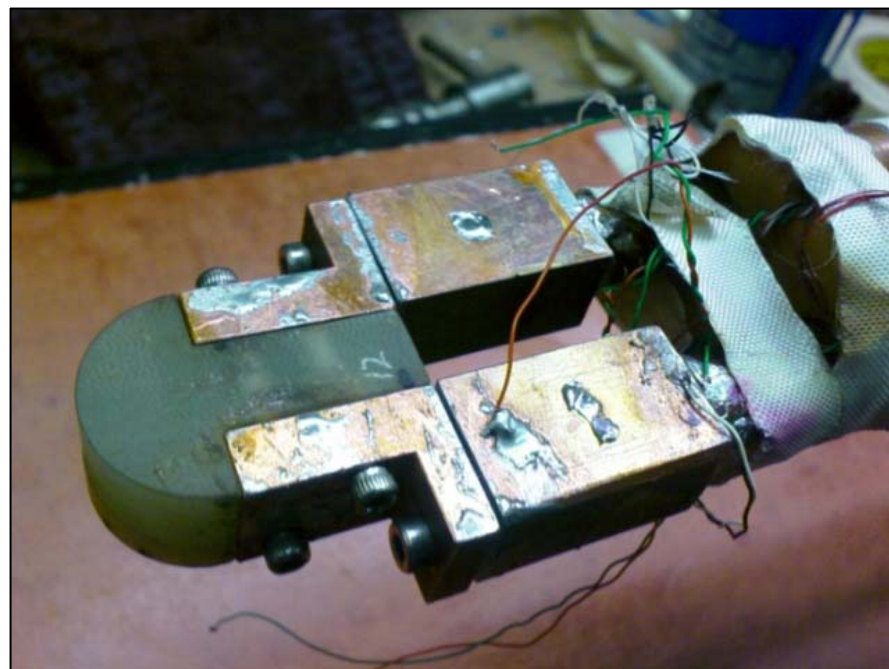


Bending Strain – Sample Holders

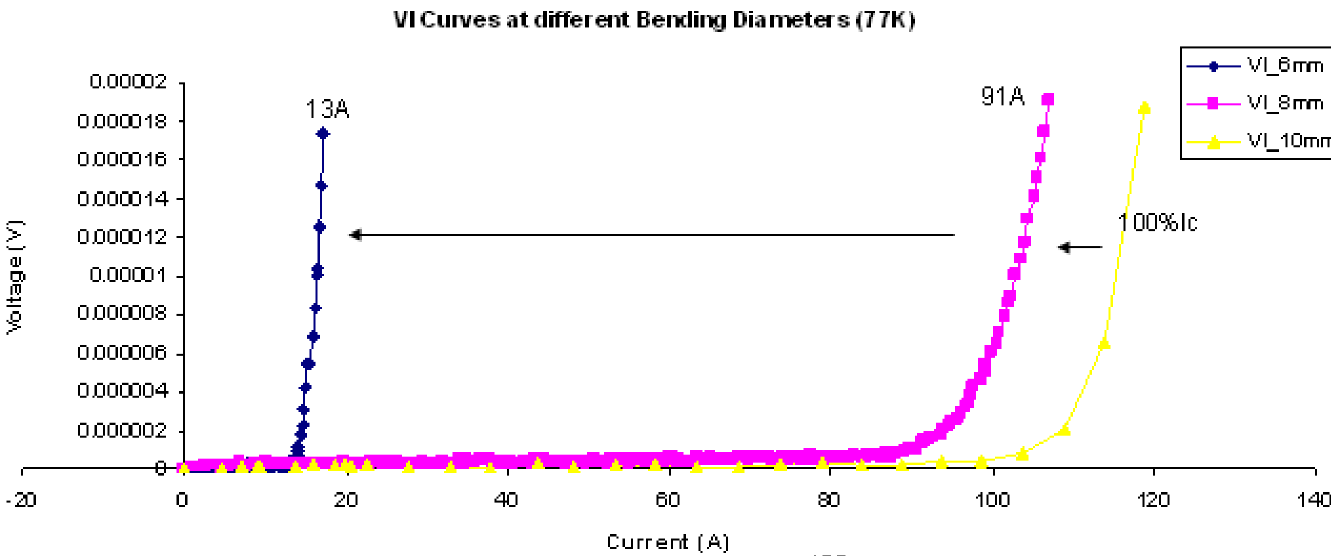


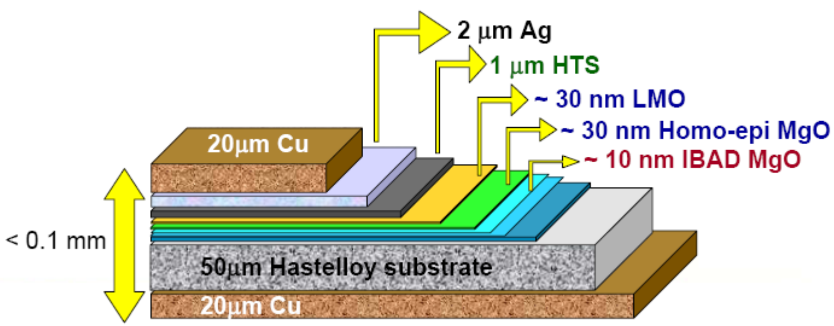
V. Lombardo et al.

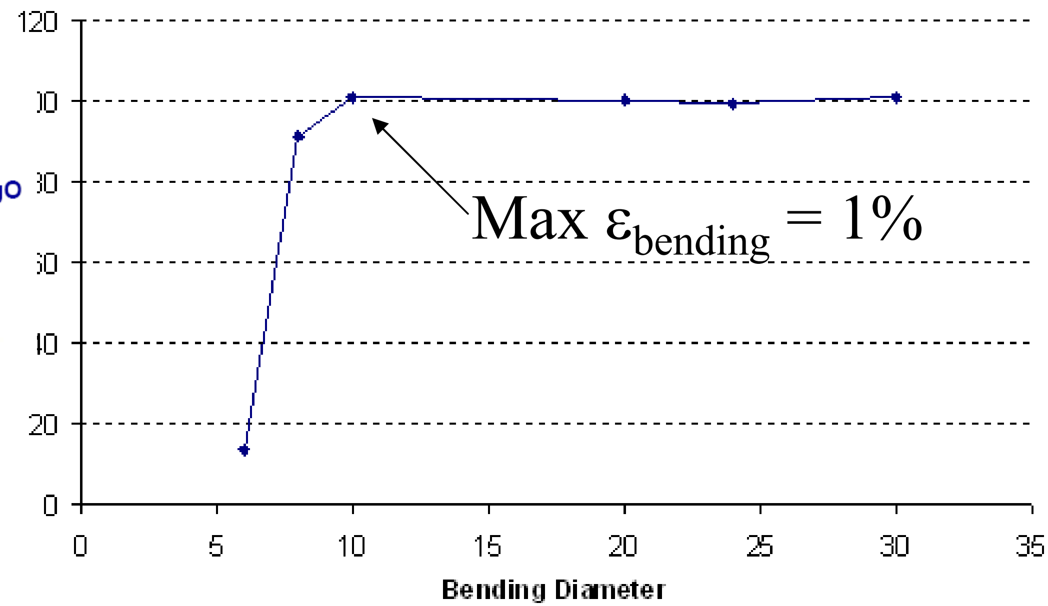




Bending Strain – Test Results for YBCO Tape

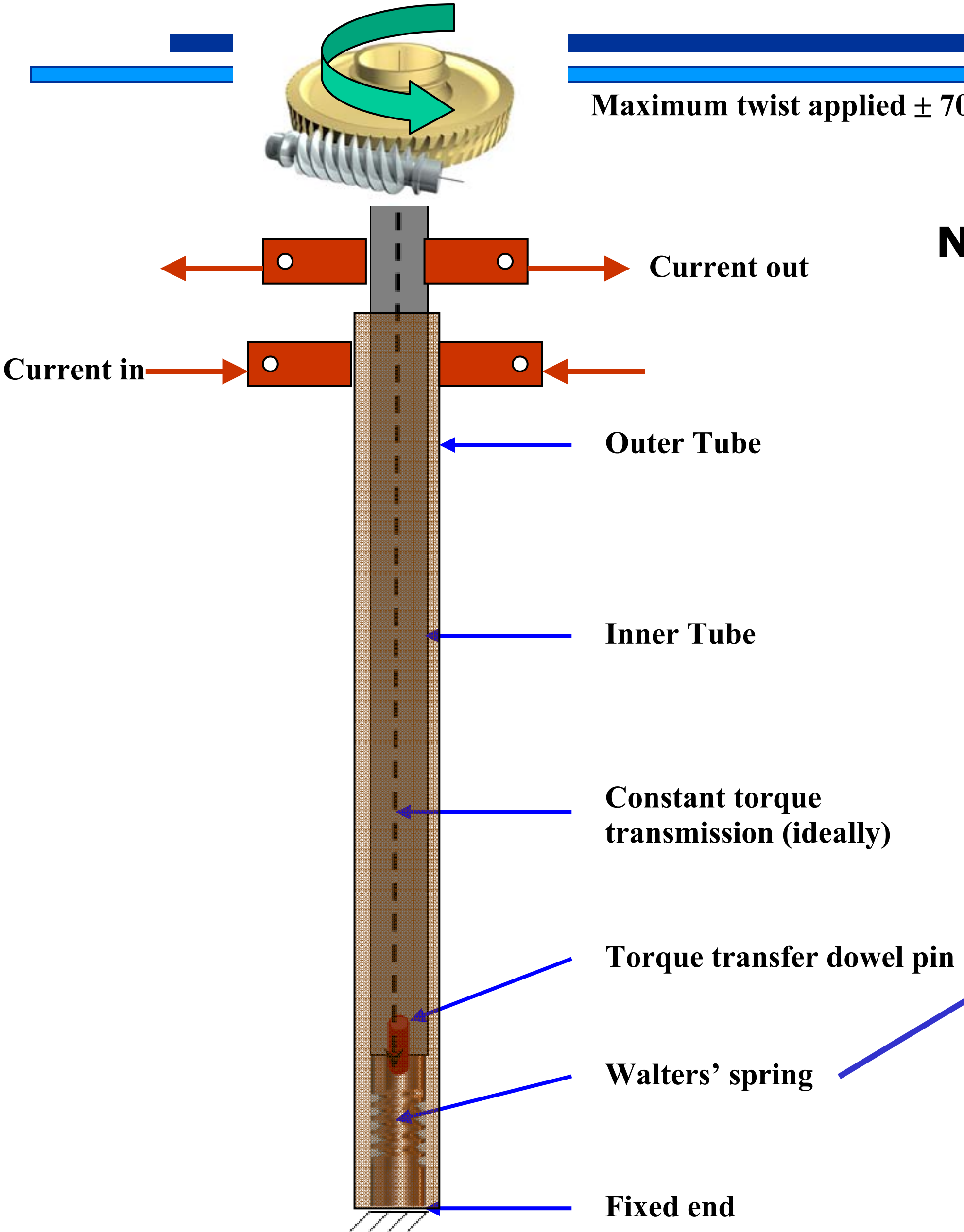




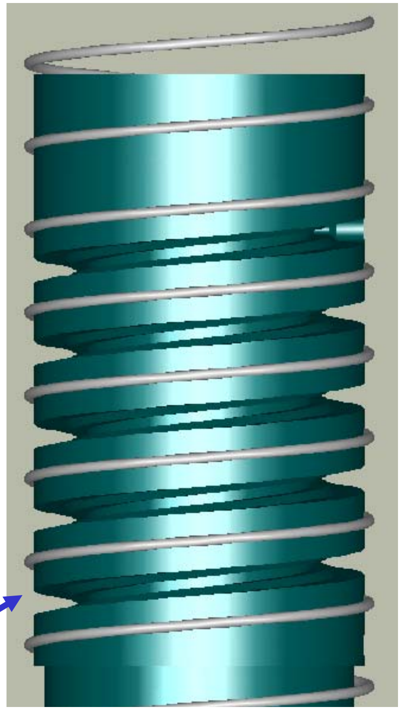


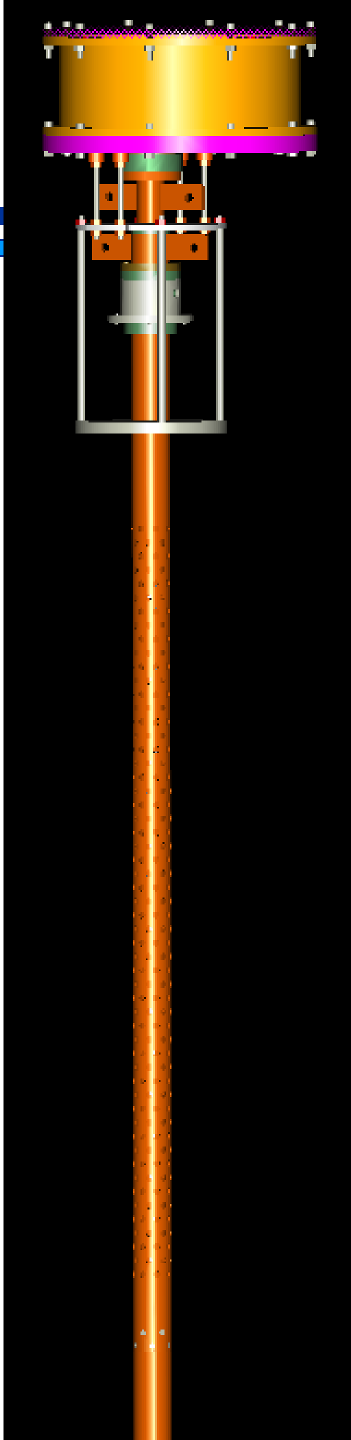
V. Lombardo et al.

Longitudinal Strain Fixture



N. Dhanaraj et al.



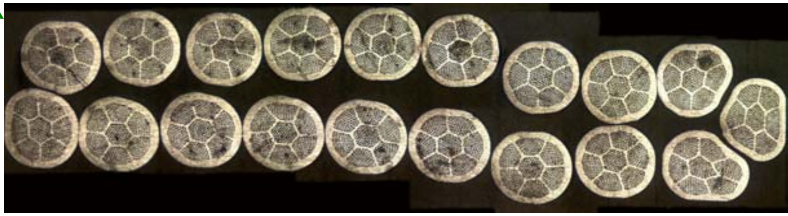


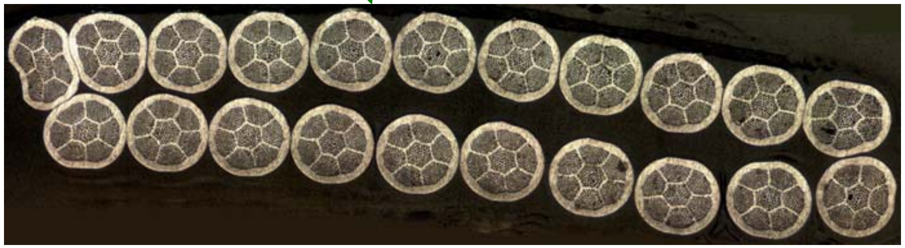
Cable R&D

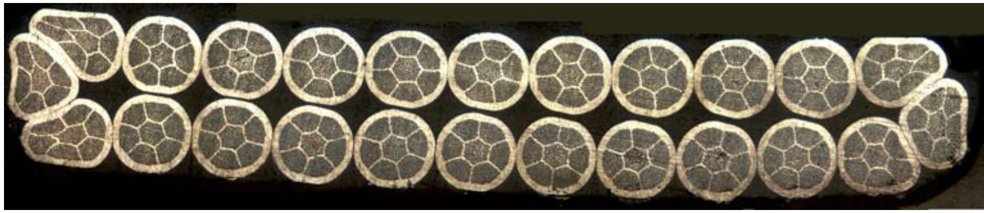
- **Strand number: up to 42**
- **Strand diameter: 0.3-1.5 mm**
- **Cable transposition angle: 8-16 degree**

Cable Samples

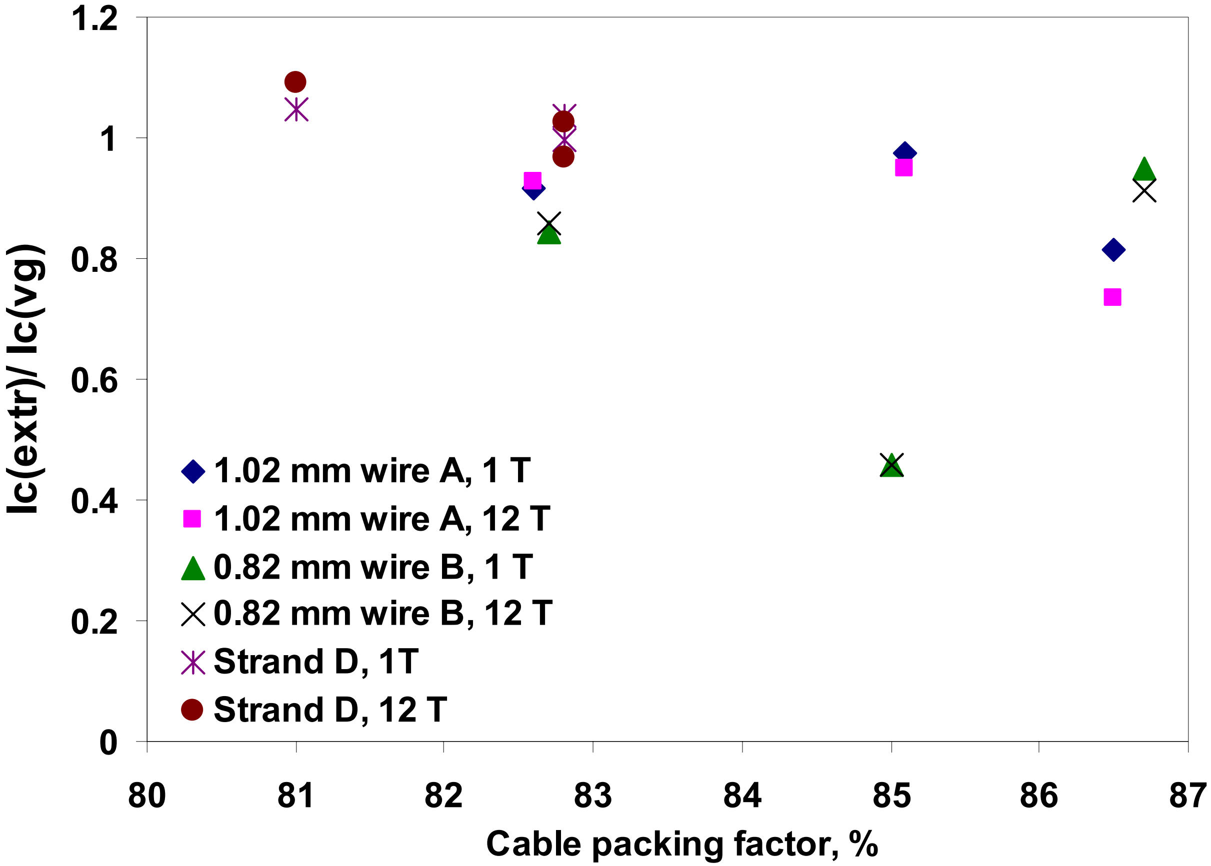
Cable ID	No. strands	Strand size, mm	Strands used	Ave. thickness, mm	Average width, mm	PF, %	Tested
1	19	1.02	A	1.938 ±0.003	9.992 ±0.050	82.6	Y
2	"	"	"	1.883 ±0.007	9.987 ±0.031	85.1	N
3	"	"	"	1.848 ±0.009	10.008 ±0.022	86.5	Y
4	24	0.81	B	1.554 ±0.008	9.921 ±0.072	82.7	Y
5	"	"	"	1.51 ±0.010	9.928 ±0.035	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







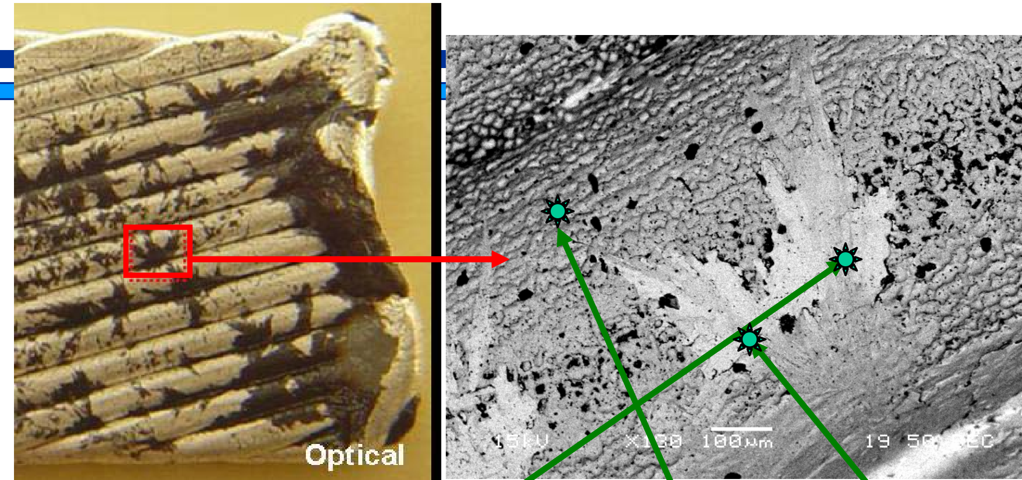
I_c of the Extracted Strand



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? (1) **Bi-2212+MgO?** (3)

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)

Task 3 - Development of 2212 Cable Technology

Emanuela Barzi (FNAL) and Al McInturff (TAMU) co-leaders

GOALS – YEAR 1:

3.1 **Produce Rutherford and round cables, characterize and establish propensity, if any, for cables to leak more than strand, and quantify damage dependence on cable and strand parameters –** *Key personnel: Emanuela Barzi*

3.2 **Study and develop alternate heat treatment and winding (RWS) approaches to mitigate strand damage and powder leakage –** *Key personnel: Emanuela Barzi and Justin Schwartz*

3.3 **Provide cable samples to other Tasks –** *Key personnel: Emanuela Barzi and Dan Dietderich*

Task 3 - Development of 2212 Cable Technology

GOALS – YEAR 2:

3.1 Fabricate and test small Bi-2212 cable inserts, possibly using RWS HT according to Year 1 results

3.2 Based on Year 1 results from a conceptual model, produce at FNAL a thermal model of the coil to verify its heat treatment feasibility according to the reaction cycle specs

3.3 Provide cable samples to other Tasks

Coil R&D

The coil program was started using 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 <u>second phase</u> 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.

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)

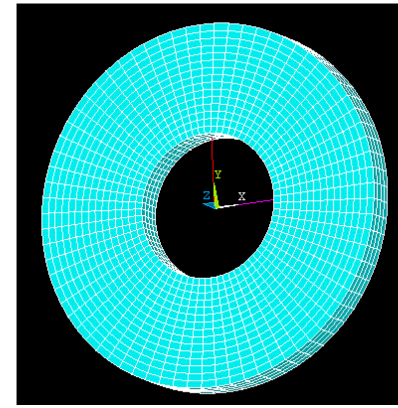
HTS Insert Details

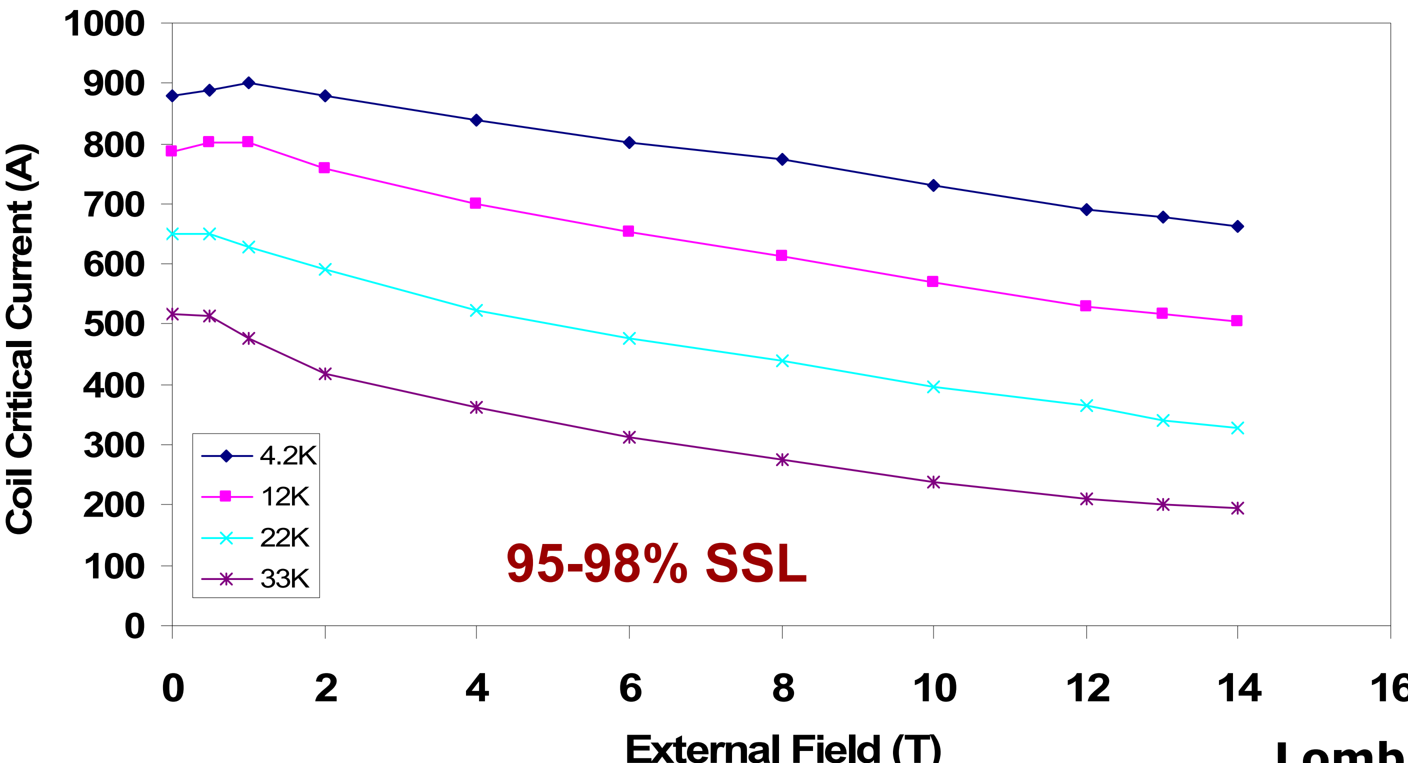
Coil Configuration: Single Pancake

Inner diameter: 38 mm

Outer diameter: 43 mm

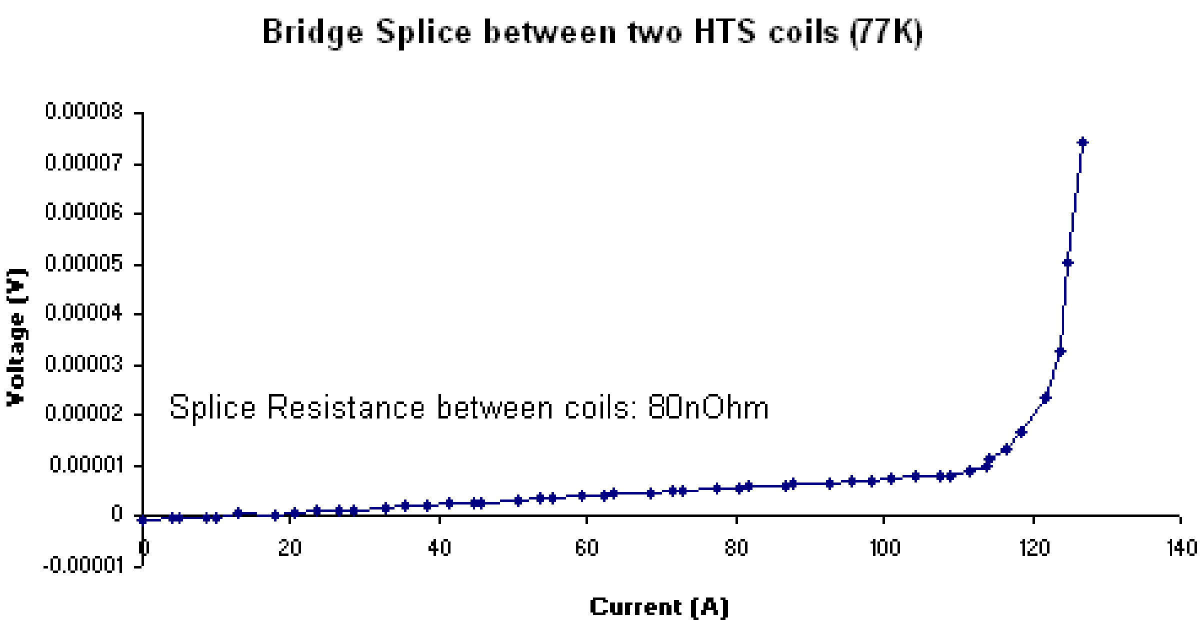
Total conductor length: 1.38 m



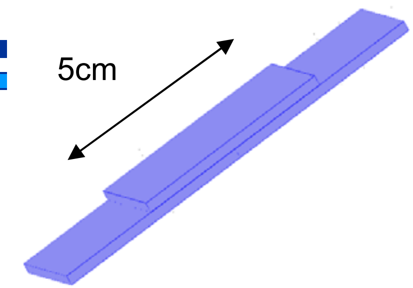


Lombardo, Turrioni et al.

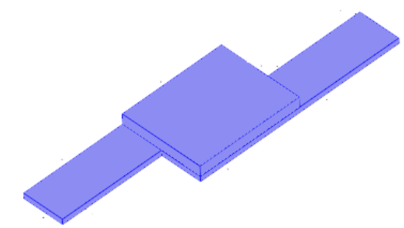
Splicing Techniques



V. Lombardo et al.

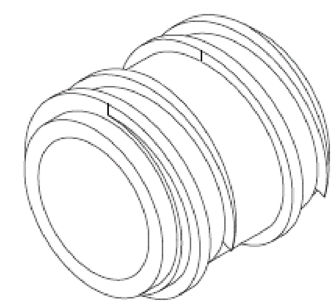


Bridge splice using only 4mm YBCO tapes



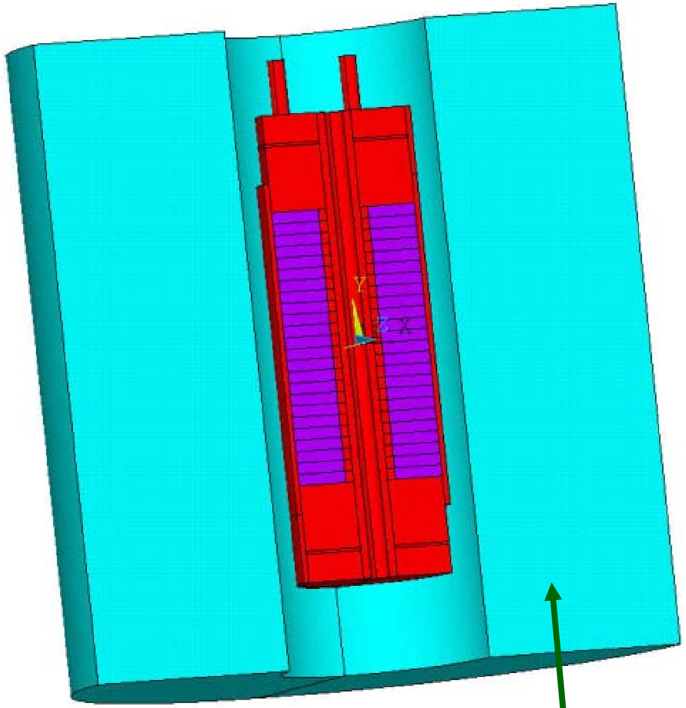
Bridge splice using either 4mm and 8mm YBCO tape (out of 12mm)

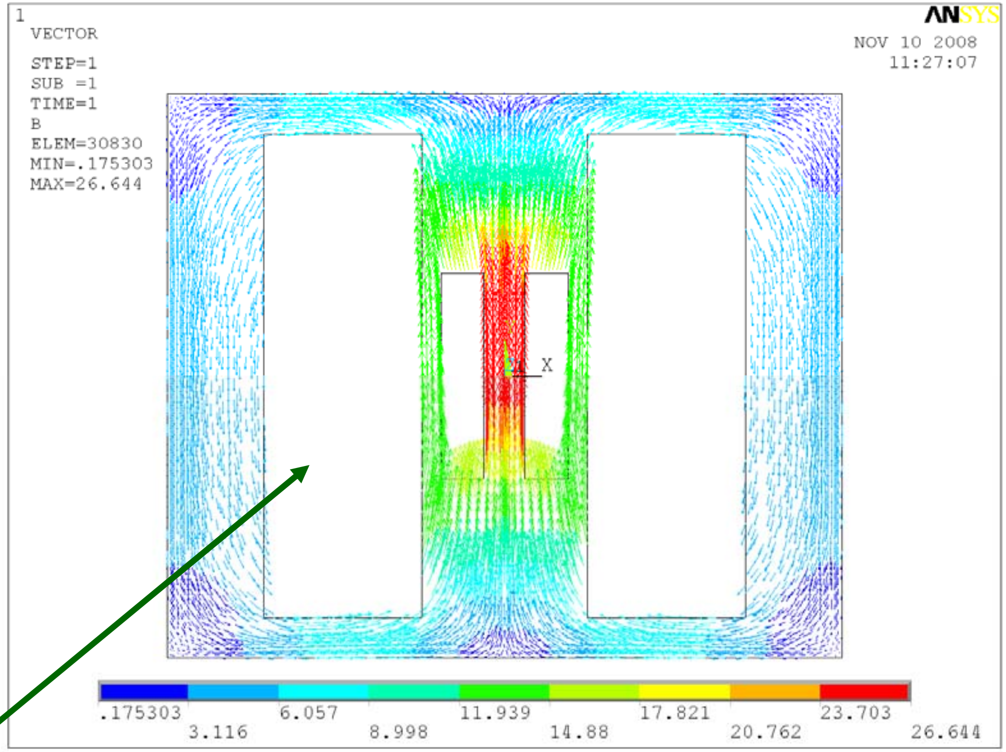
DOUBLE PANCAKE COIL



G10 barrel – 30.7 mm diameter

Modular HTS Insert Test Facility





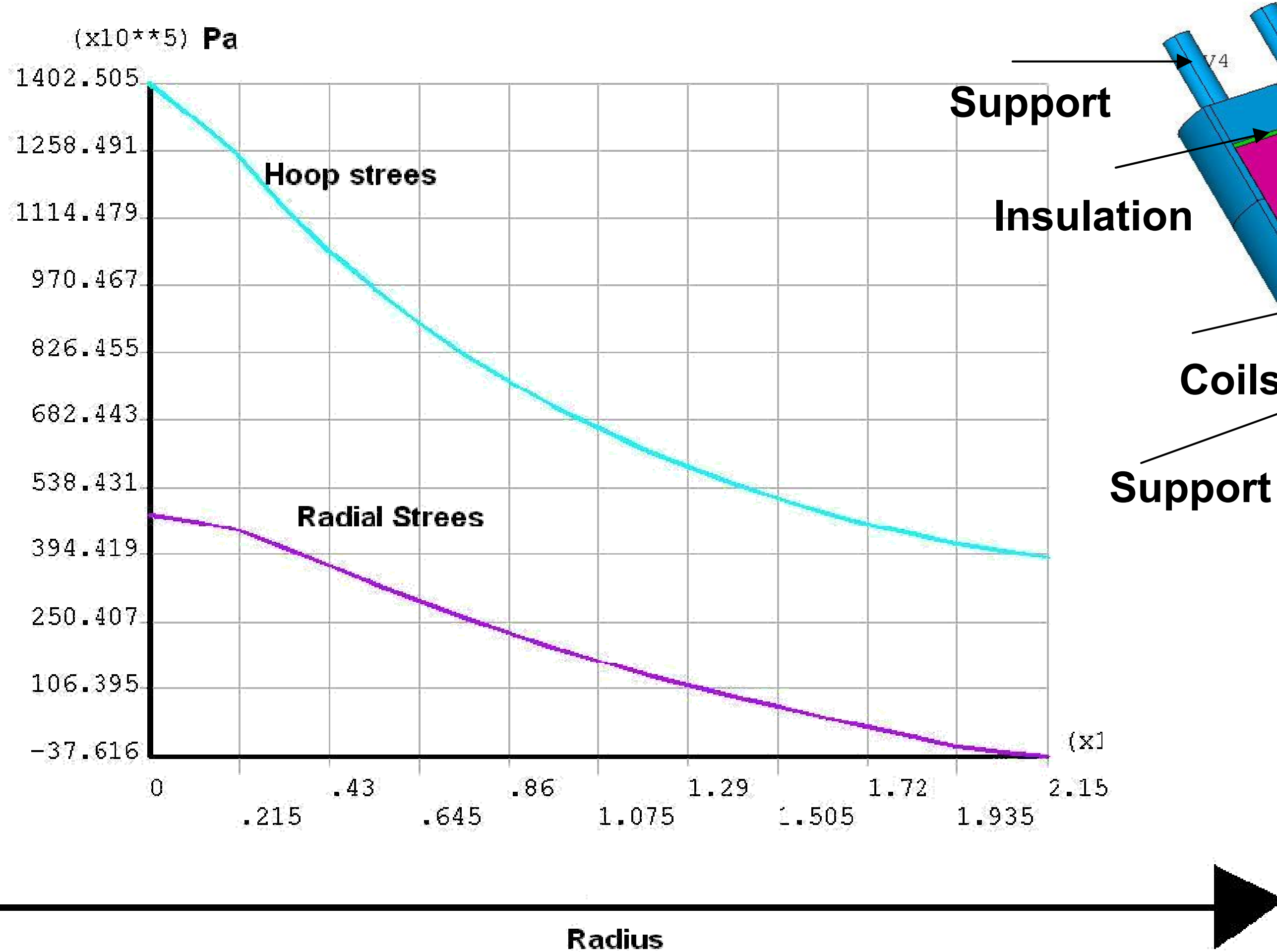
14 T/ 16 T Solenoid

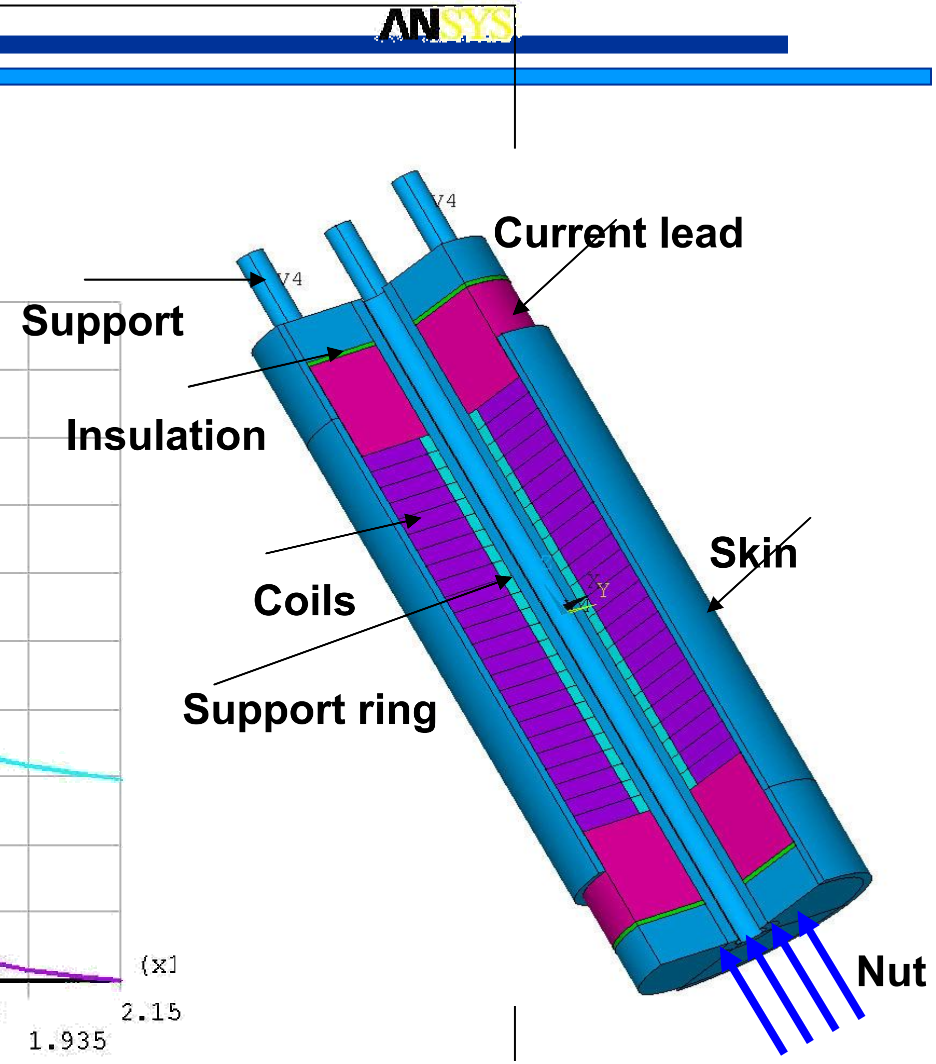
Up to 14 Double Pancakes Units
Modular structure for 19 mm/62 mm units
Wet wound and/or impregnated coils

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

G. Norcia et al.

Mechanical Analysis





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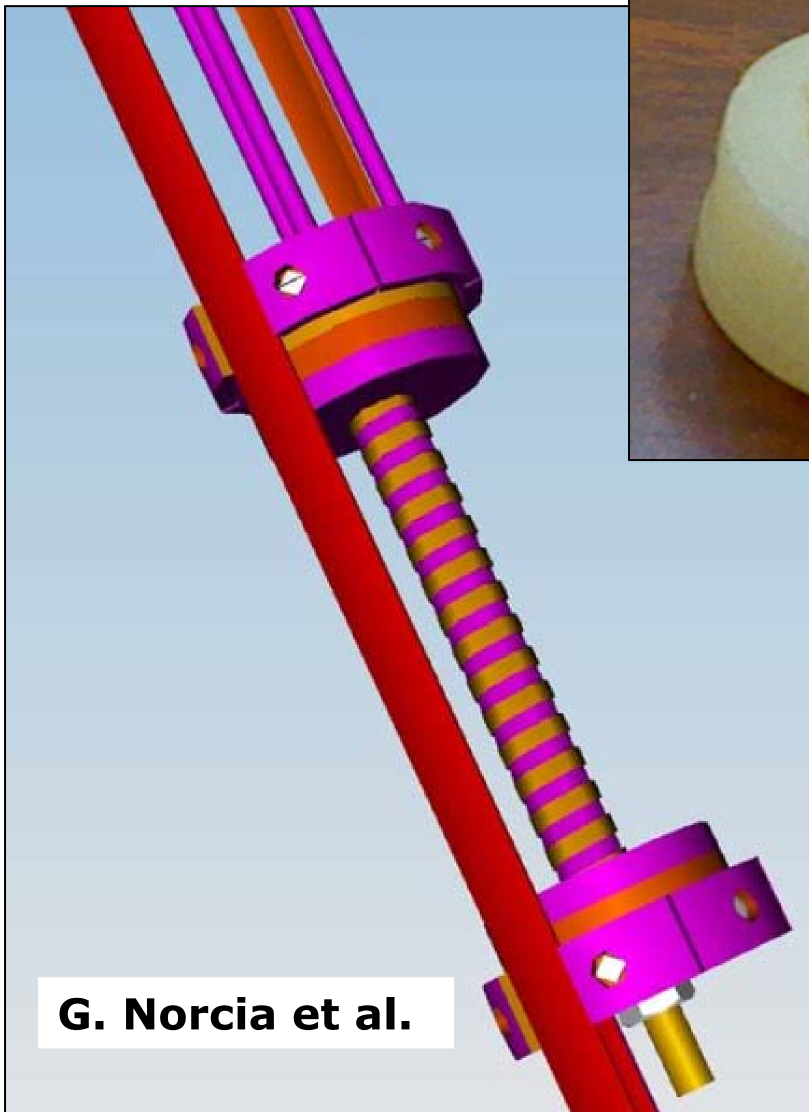
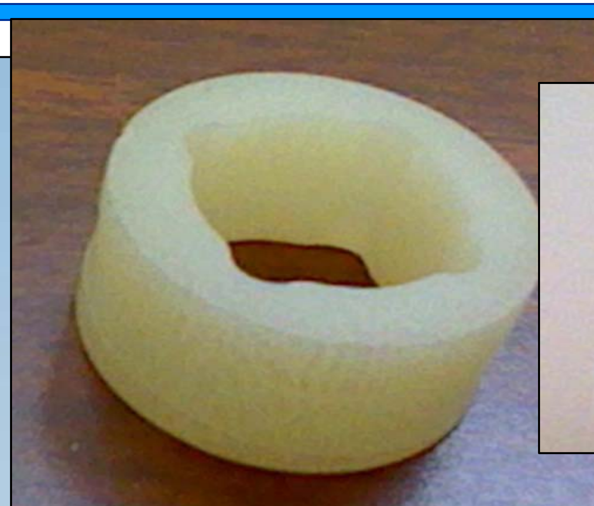
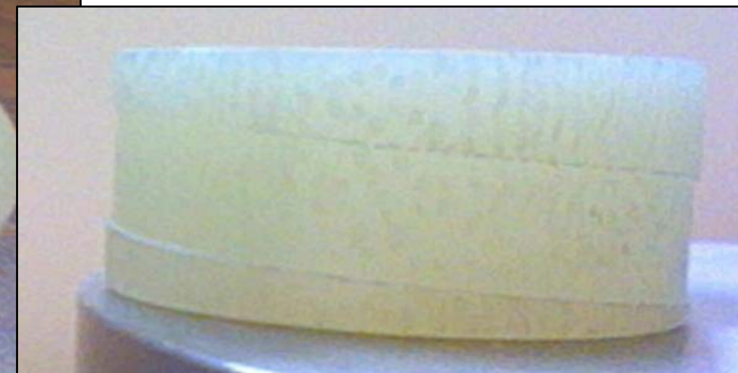
3D Modeling



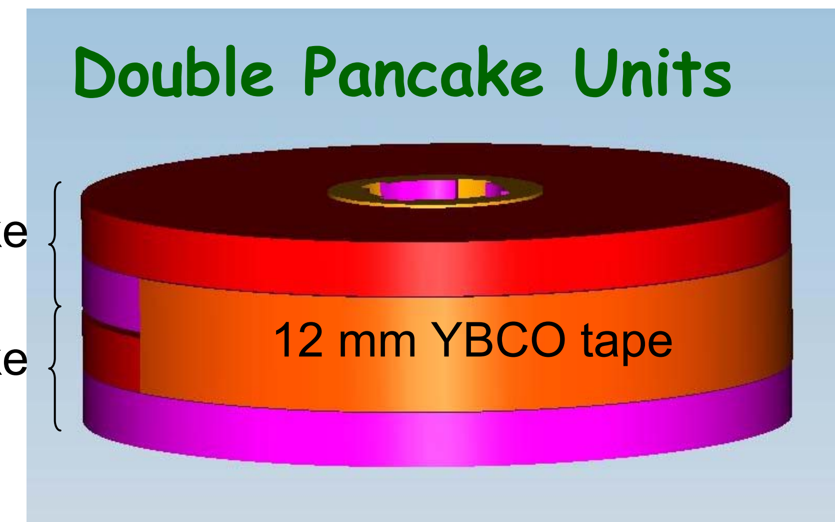




Double pancake unit winding support

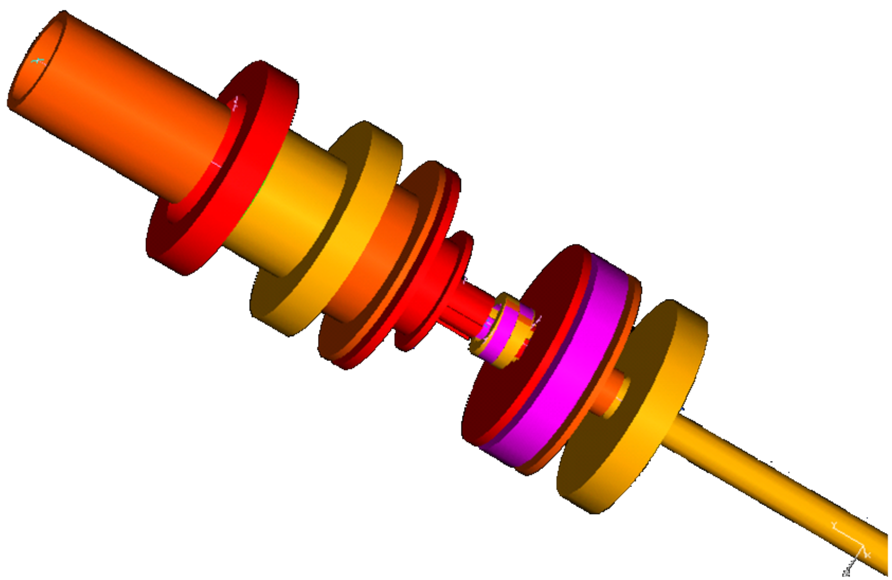
1° Pancake

2° Pancake



Independent Setup to Test Units

The structure will allow for **fast turnaround** in testing units of HTS double pancakes that will be assembled in the final solenoid. Final design will have **12 double pancakes units** (di=19mm, do=62mm). Coil critical current is important to establish the stacking order of the units in the solenoid, as top and bottom coils will need higher critical current at high angles. Top and bottom coils will be possibly assembled using 12mm tape. **Unit-to-unit** and **unit-to-lead** splices are made using 12mm Superpower tape. Turn to turn insulation : 1mil Kapton + adhesive.

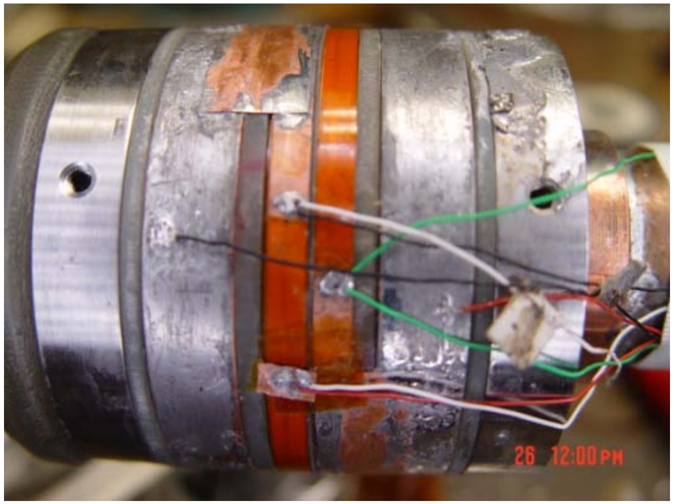


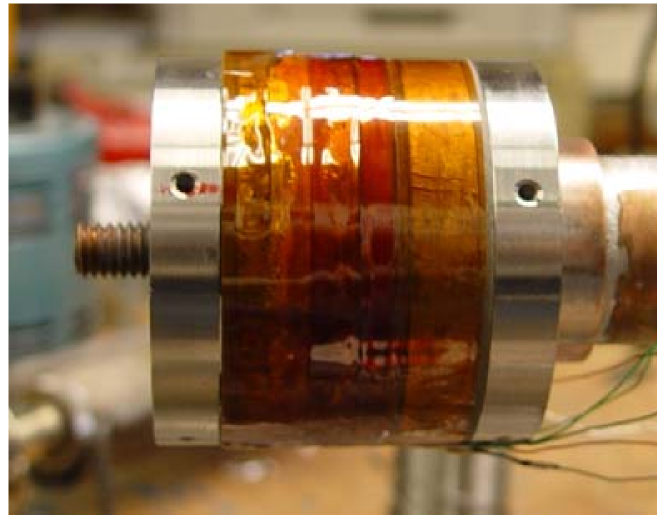
Vacuum impregnation of double pancakes units is being investigated. Bending studies and Ic retention due to epoxy curing cycles are in progress for B2223 and YBCO.

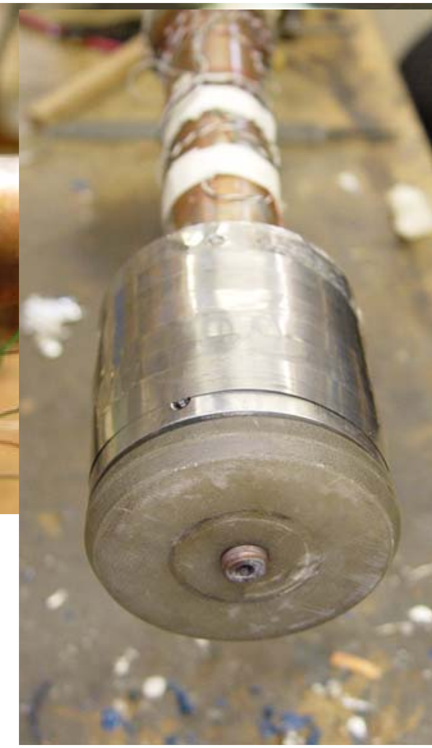
Superpower Double Pancake Unit

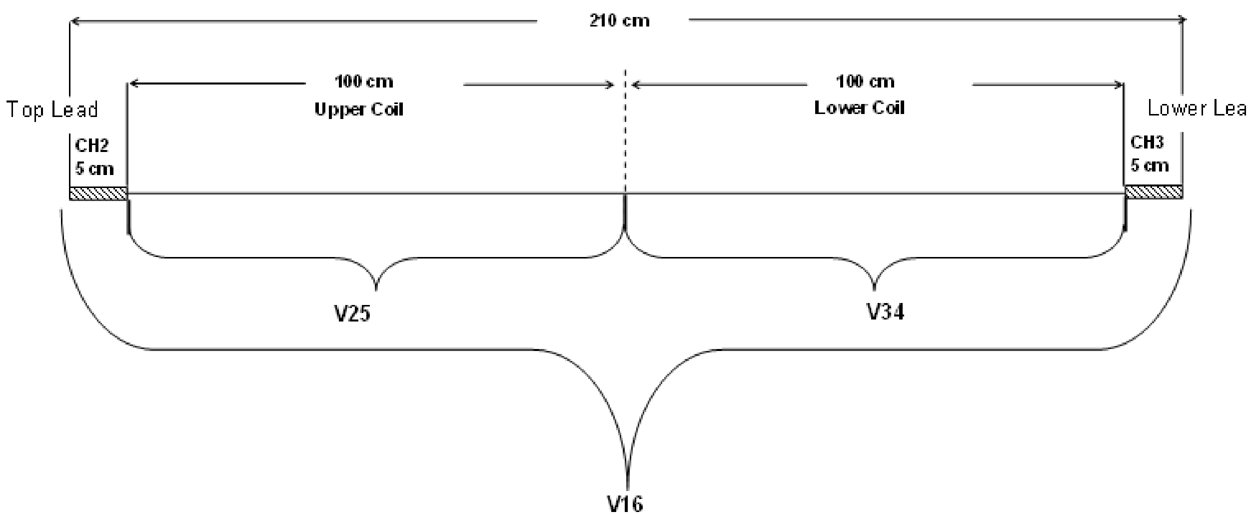
Instrumentation

Final Assembly

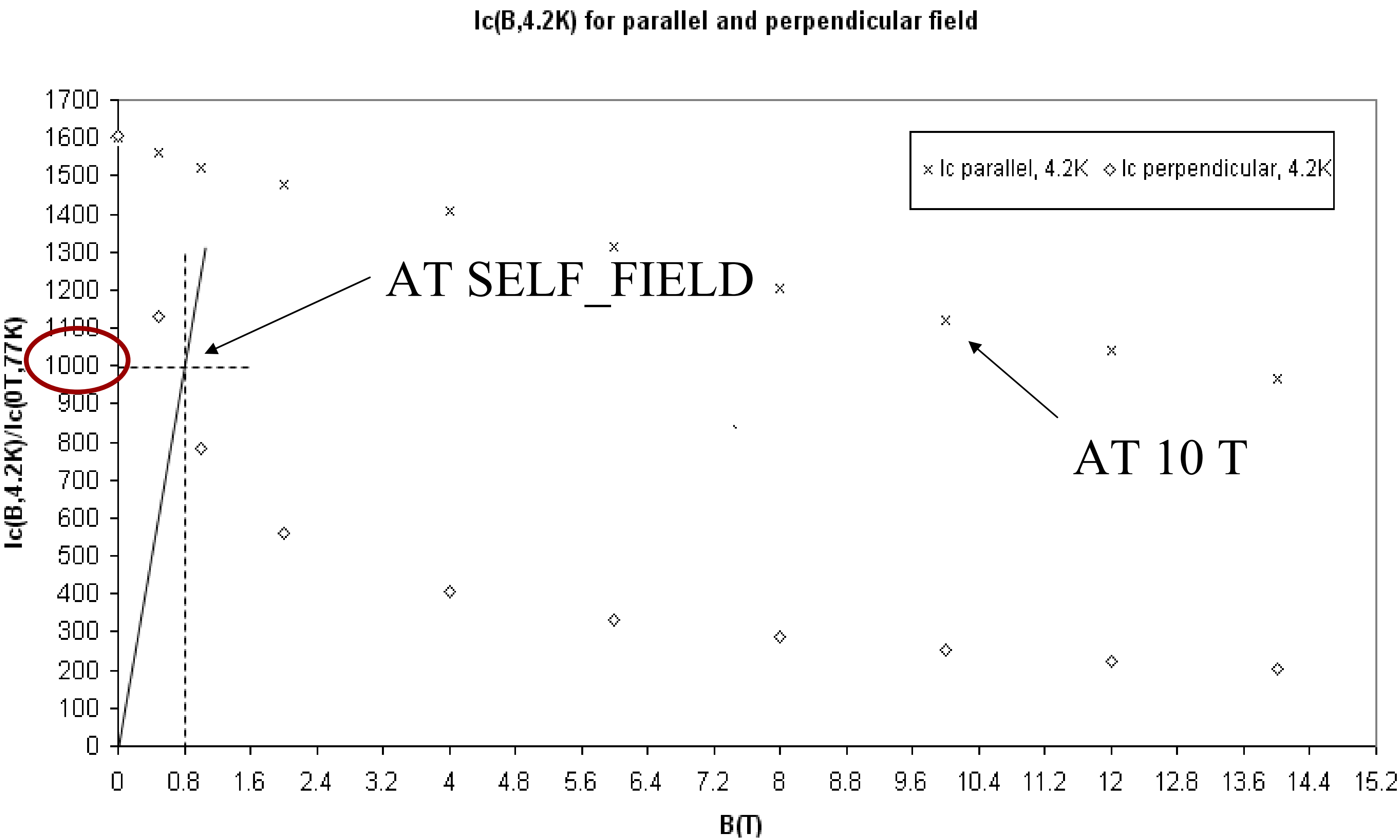




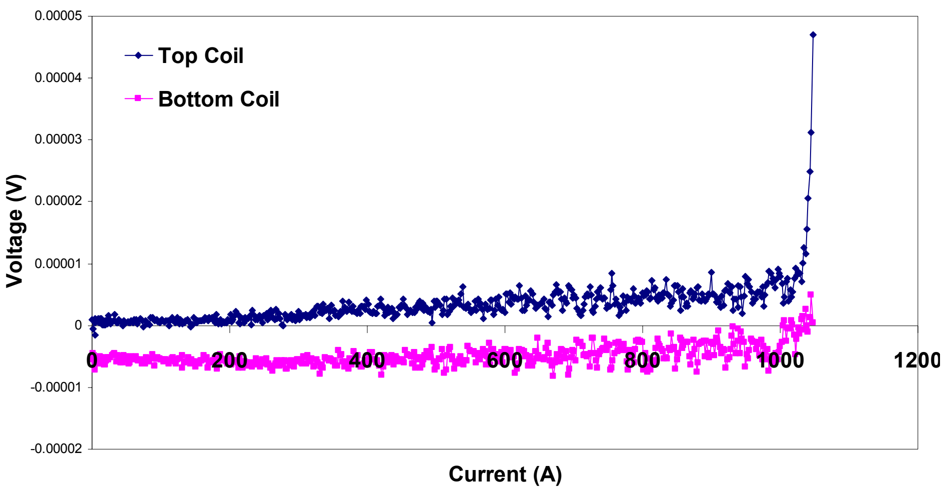


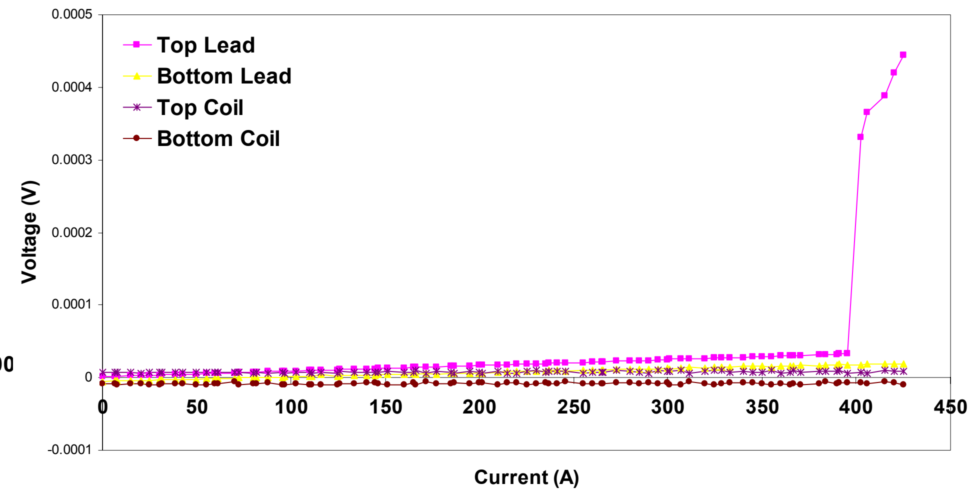


Predicted Performance



Test Results





100% AT SELF_FIELD

50% AT 10 T

HTS Coils Summary

Company	Conductor Type	Coil Geometry	Impregnation	Details of Test	SSL(14T)	Notes
American Superconductor	348 YBCO	Single Pancake	Stycast 2850FT	77K, 4.2K 0T-14T	98%	[Di:38mm-Do:43mm]
American Superconductor	Hermetic BSCCO2223	Single Pancake	Stycast 2850FT	77K, 4.2K 0T-14T	98%	[Di:38mm-Do:43mm]
American Superconductor	Hermetic BSCCO2223	Double Pancake	Stycast 2850FT	77K, 0T	67%	[Di:32mm-Do:43mm] *Bad Splice due to small outer radius and stiffness of tape*
SuperPower	YBCO M3-609 *(R&D conductor)*	Single Pancake	Stycast 2850FT	77K, 4.2K 0T-14T	0%	[Di:38mm-Do:43mm] *Resistive Coil*
SuperPower	YBCO M3-569	Single Pancake	Stycast 2850FT	77K, 4.2K 0T-14T	29%	[Di:38mm-Do:43mm] *Low Ic, Low n values*
SuperPower	YBCO M3-569	Double Pancake	Stycast 2850FT	77K, 4.2K 0T-14T	22%	[Di:32mm-Do:43mm] *Low Ic, Low n values*
SuperPower	YBCO M3-569	Single Pancake	Dry	77K, 4.2K	76%	[Di:38mm-Do:43mm] *Tested in compression*
SuperPower	YBCO M3-	Double Pancake	Dry	77K, 4.2K	Self Field Test 100%	[Di:60mm-Do:62mm]
SuperPower	YBCO M3-	Double Pancake	Dry	77K, 4.2K	In Field 50%	[Di:60mm-Do:62mm] *Bad Splice to Copper*