$YBa_2Cu_3O_{7-\delta}$ Conductors and Insert Coil Technology for High Field Magnets

E. Barzi, G. Gallo, V. Lombardo, A. Rusy, E. Terzini, D. Turrioni, T. VanRaes

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SC R&D Group

Fermilab

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Overview of the HTS Coil Program by the SC R&D Group
see also **E. Barzi's** presentation **"Towards 50T Solenoids"**
https://indico.fnal.gov/conferenceDisplay.py?confId=3148

1. **HTS Conductor R&D – Ongoing since 2005, E. Barzi, L. Del Frate, V. Lombardo, D. Turrioni**

- Conductor characterization – Studies of J_e as a function of B, T, angle, and bending, longitudinal and transverse strains.
- YBCO Roebel Cables – Nitrogen Test Completed - Present challenges are anisotropy and J_c homogeneity over tape width.

2. **Magnet design studies - Since 2008, E. Barzi, G. Norcia, A. Bartalesi, E. Terzini, G. Gallo, V. Lombardo**

- Analytical Study of Stress State in HTS Solenoids – Stress distribution in a solenoid was studied for various constraint configurations, max. stresses were produced as a function of coil self-field, and results compared with Finite Element Model.
- Co-wound and impregnated YBCO coil represented by meso-mechanic models.
- Magnetic models for insert and background field were developed to account for anisotropic behavior of YBCO tapes into magnet design.

3. **Coil Technology – Since 2008, E. Barzi, G. Norcia, A. Bartalesi, A. Cattabiani, T. VanRaes, V. Lombardo**

- Winding method and tooling.
- Impregnation techniques.
- Splicing procedures.
- R&D on thermally conductive insulation.

4. **Coil Test – Since 2009, D. Turrioni, P. Vicini, A. Rusy, T. Van Raes, V. Lombardo**

- Development of DAQ systems for insert coil tests
- Test pancake assemblies in 14 T/77 mm bore existing magnet and provide feedback to coil technology development.

Talk Outline

1. High Temperature Superconductors:
    1. HTS YBCO CC tapes at a glance

2. Overview of YBCO Insert Coil Technology for High Field Magnets
    1. Notes on Coil Geometry
    2. Development of winding technology
    3. Insert Test Facility - Nb_3Sn/NbTi external magnet details

3. Details of Single coil assembly
    1. Short Sample Limit Estimation
    2. Test Results in Liquid Nitrogen and Helium

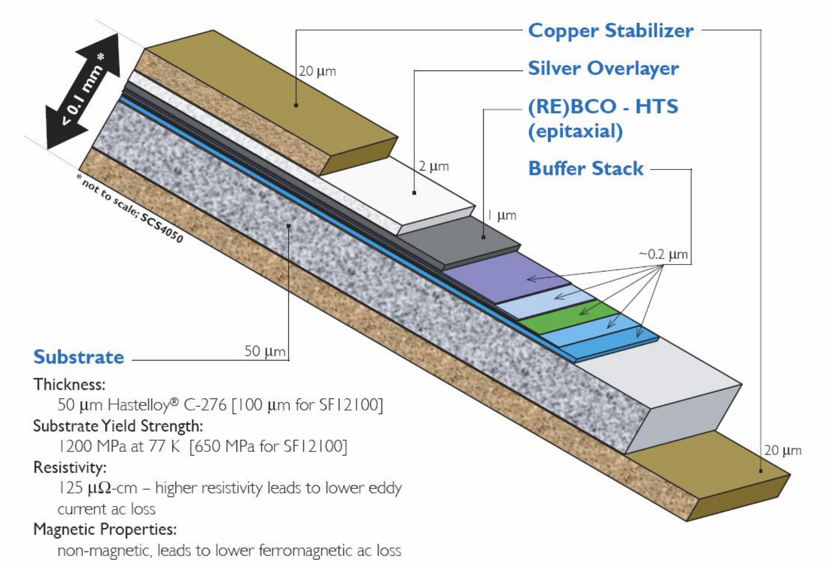
4. Scale-up to multi-pancake coil
    1. Short Sample Limit Estimation
    2. Test Results in Liquid Nitrogen and Helium
    3. More scaling up

5. Conclusions

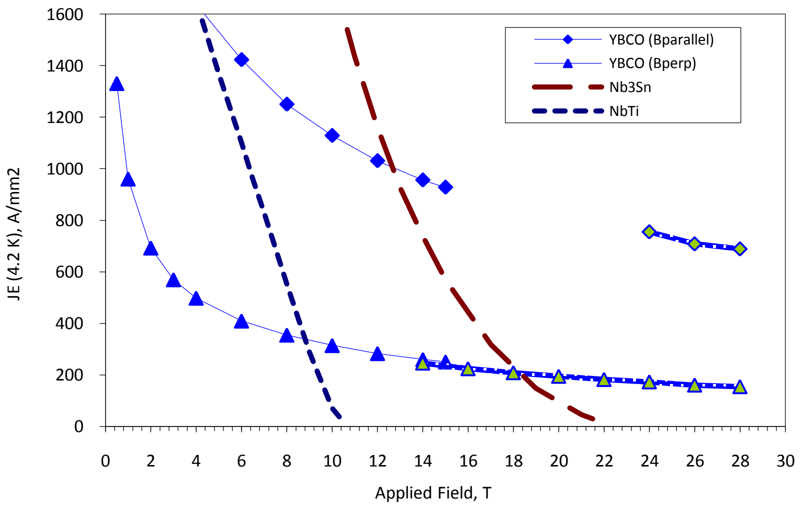
High ~~Temperature~~ Field Superconductors ?

1. YBCO comes as **SC tape** (0.1mm thickness) in **different widths** from 4mm to 12mm.
2. YBCO **does not require reaction**
3. YBCO shows s**trongly anisotropic behavior** with respect to field orientation, which needs to be accounted for during magnet design.
4. YBCO is available in **reasonably** long lengths for a ~~**reasonable**~~ price
5. Tight Ic **uniformity** over long lengths and width (mainly for cabling reasons) needs to be considered.

Cross-section of commercially available YBCO tape from SuperPower



Tape Manufacturer	SuperPower
Ic (A) Average @77K,0T	80-120 A
Nominal Conductor Thickness	0.1 mm
Nominal Conductor Width	4 – 12 mm
Stabilizer	Copper (2 x 20 μm)
Substrate thickness	Hastelloy C270 (50 μm)
YBCO layer thickness	1 μm

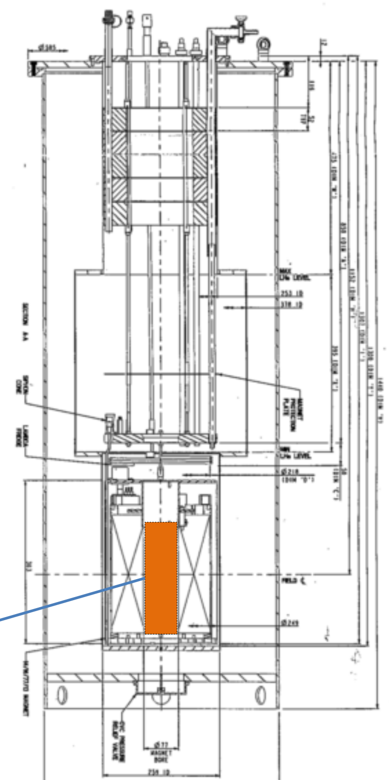


D. Turrioni, E. Barzi, M. J. Lamm, R. Yamada, A. V. Zlobin, A. Kikuchi "Study of HTS Wires at High Magnetic Fields" – IEEE Trans. On Appl. Superconductivity 19, No 3, Part 3, 3057-3060 (2009)

Choosing the test stand

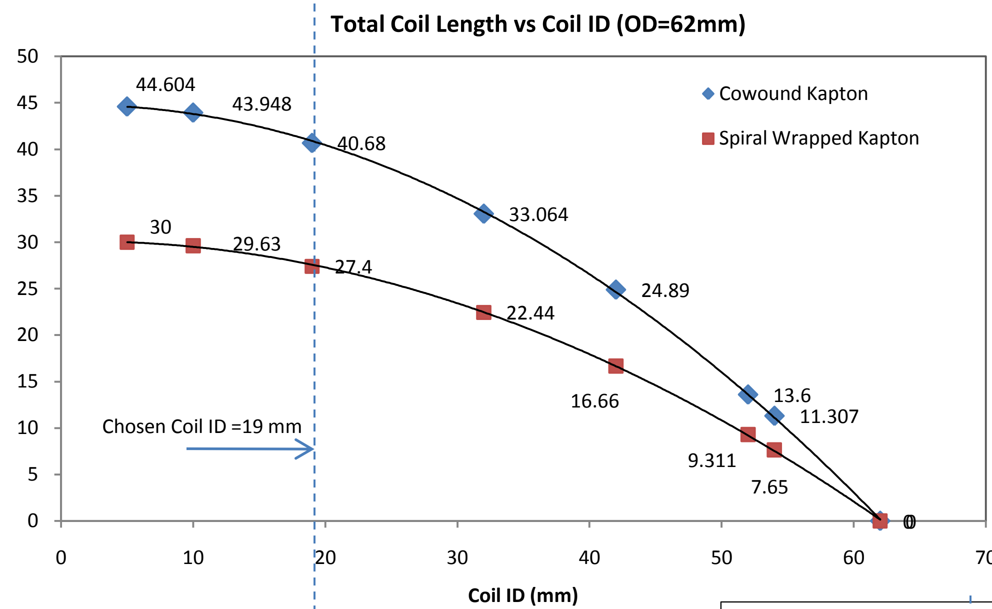
	Teslatron #1	Teslatron #2	Teslatron #3	Teslatron #4
Background Bz_max	15 T (4.2K) 17 T (2.2K)	14 T (4.2K) 16 T (2.2K)	n/a	8.5 T (4.2K) 10 T (2.2K)
External Nb_3Sn/NbTi Magnet Geometry	ID: **68 mm** OD: 192 mm Height: 167 mm	ID: **77 mm** OD: 218 mm Height: 180 mm	Max Magnet OD: **253 mm** (accommodates up to 4 DP helical units) – see next talk	ID: **147 mm** OD: 224 mm Height: 240 mm

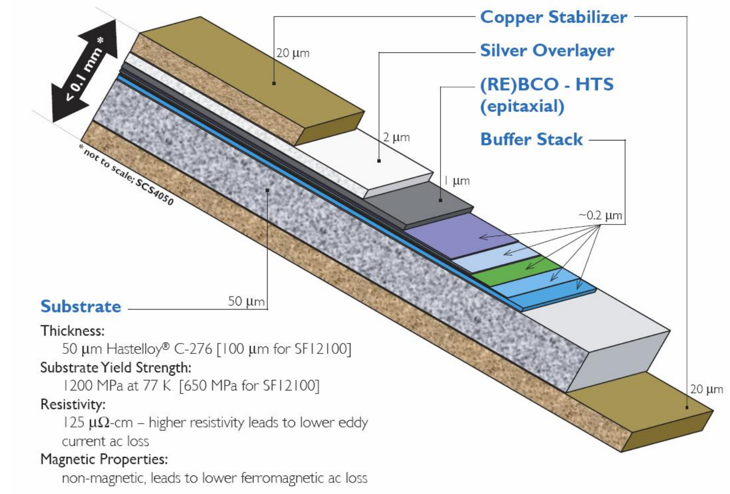
Teslatron 2 offered the largest bore for inserts, while delivering 14T @4.2K as background field. Probe, leads, magnet supports and instrumentations were then designed and procured to fit this setup.



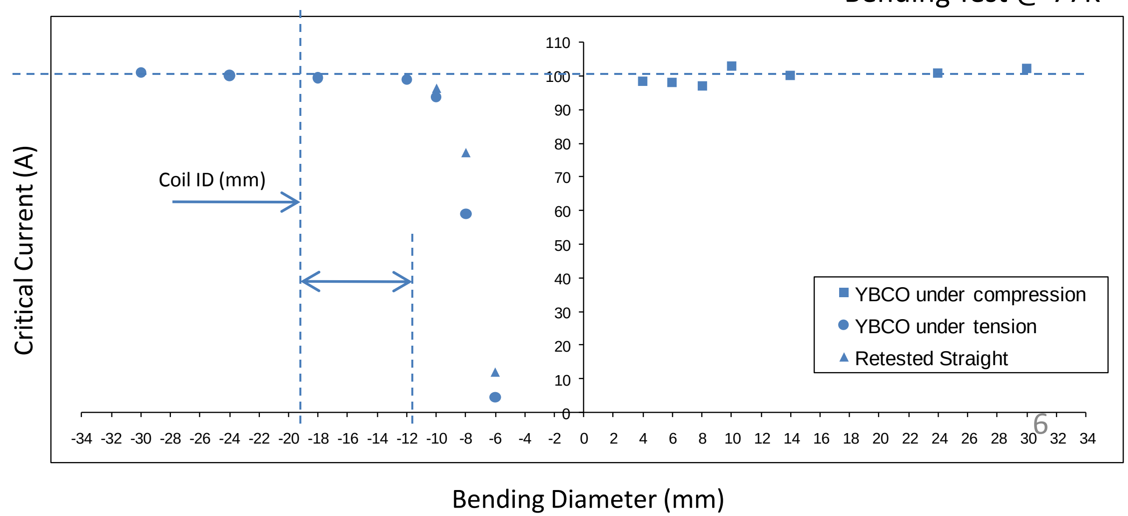
Available volume for inserts.

Finalizing the geometry of YBCO CC Insert Coils

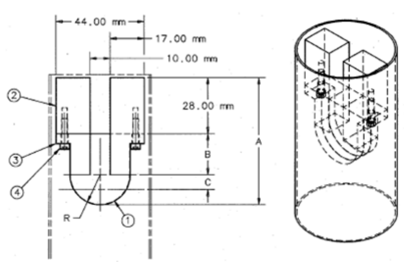




Bending Test @ 77K



Bending tests were run to finalize the coil geometry. The final inner diameter chosen for the inserts was 19mm. Enough to allow for winding supports while leaving enough clear bore for the insertion of a Hall probe



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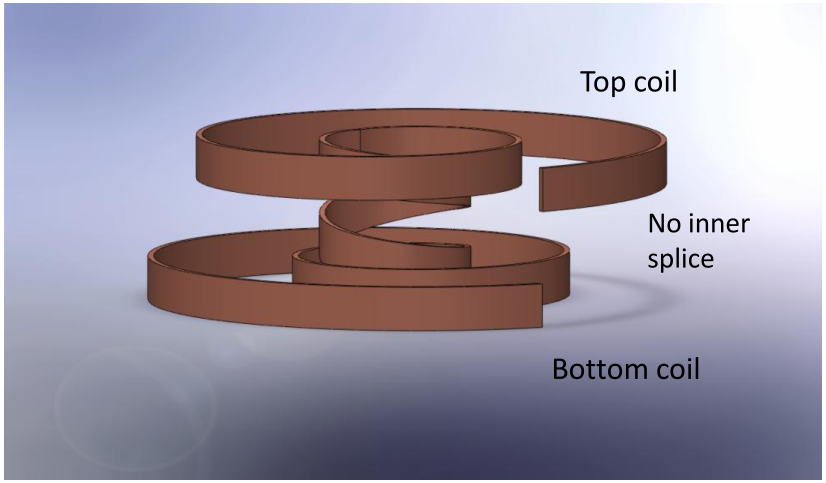
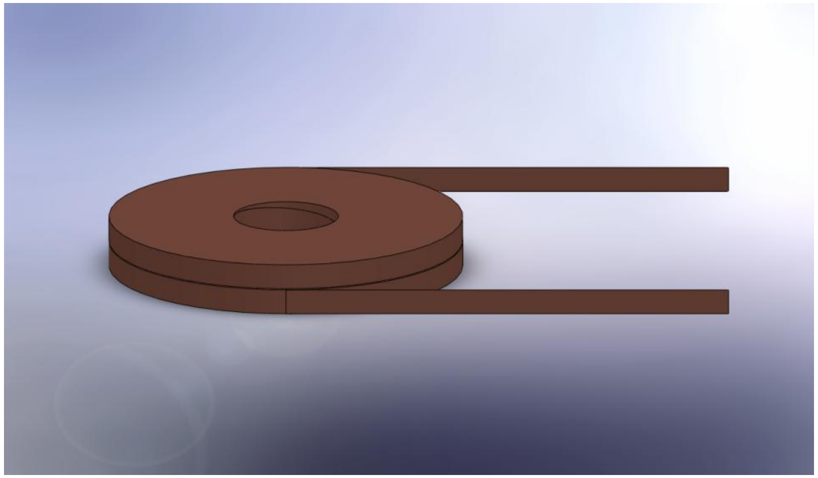
V. Lombardo, E. Barzi, G. Norcia, M. Lamm, D. Turrioni, T. Van Raes and A. V. Zlobin. "*Study of HTS Insert Coils for high field Solenoids*" – Transactions of the Cryogenic Engineering Conference – CEC Vol. 55

Winding YBCO CC Coils

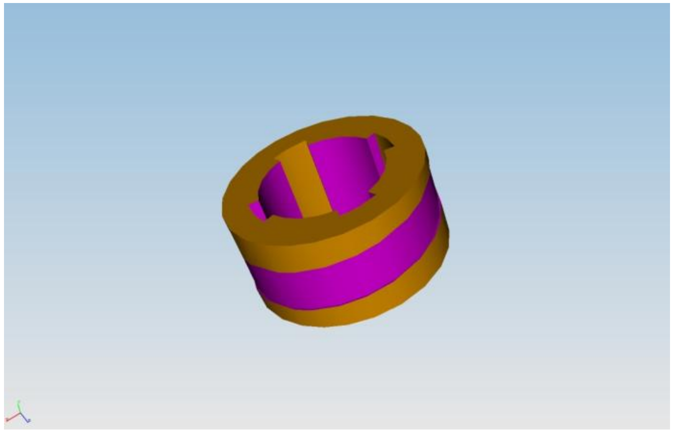
The approach chosen to wind double pancakes coil was to avoid inner splice due to the small coil ID (only 19mm). The process allows to wind the whole coil using the same tape with **no electrical joints**.
A 2-step winding process was chosen and winding fixture was designed and procured to implement this approach.

1. Wind half supply material on a temporary spool
2. Wind first half of the coil out of original supply spool
3. Use temporary spool to feed material and wind the second half of the coil





This approach was needed due to the extremely small ID chosen for the conductor. A winding support was specifically designed and machined with a groove to support the innermost turn during the winding. Whereas this approach slightly complicates the winding process, it avoids the need for an inner splice which could be complicated to perform on a 19mm inner diameter.



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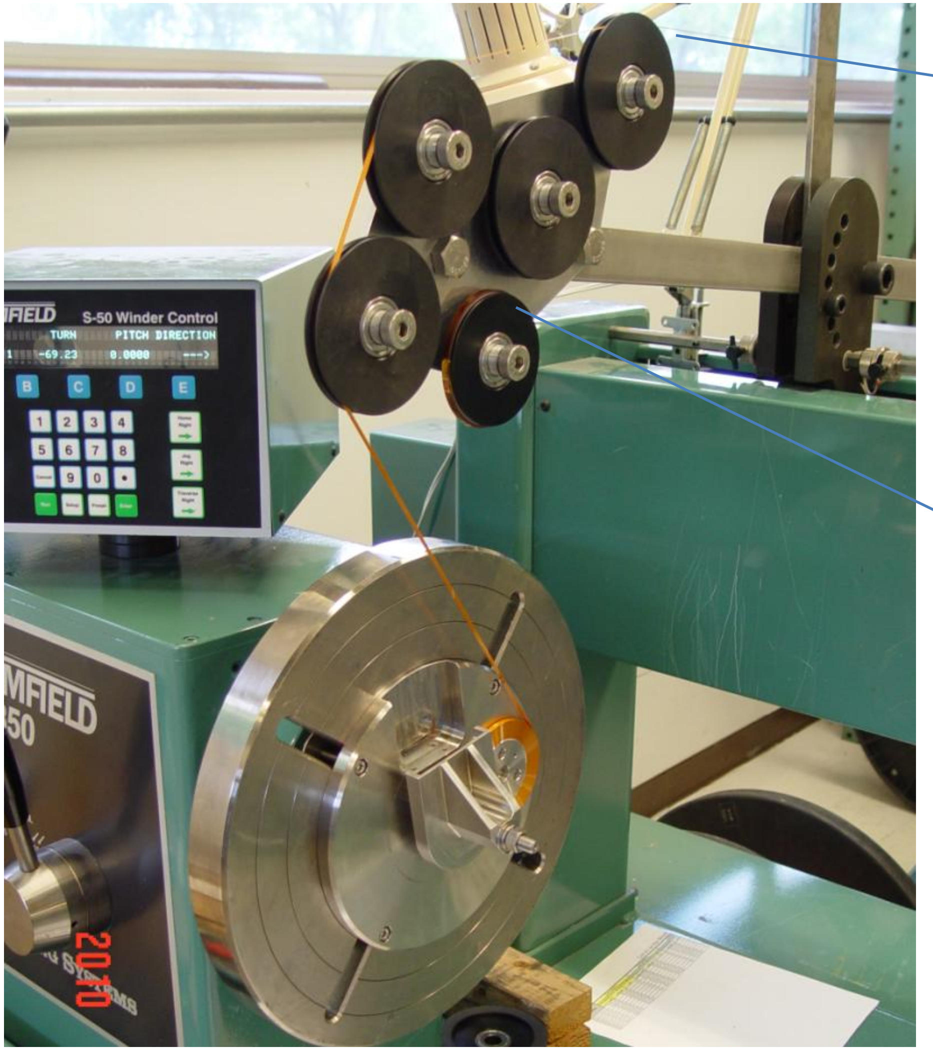
Overview of Winding Setup for YBCO CC Coils

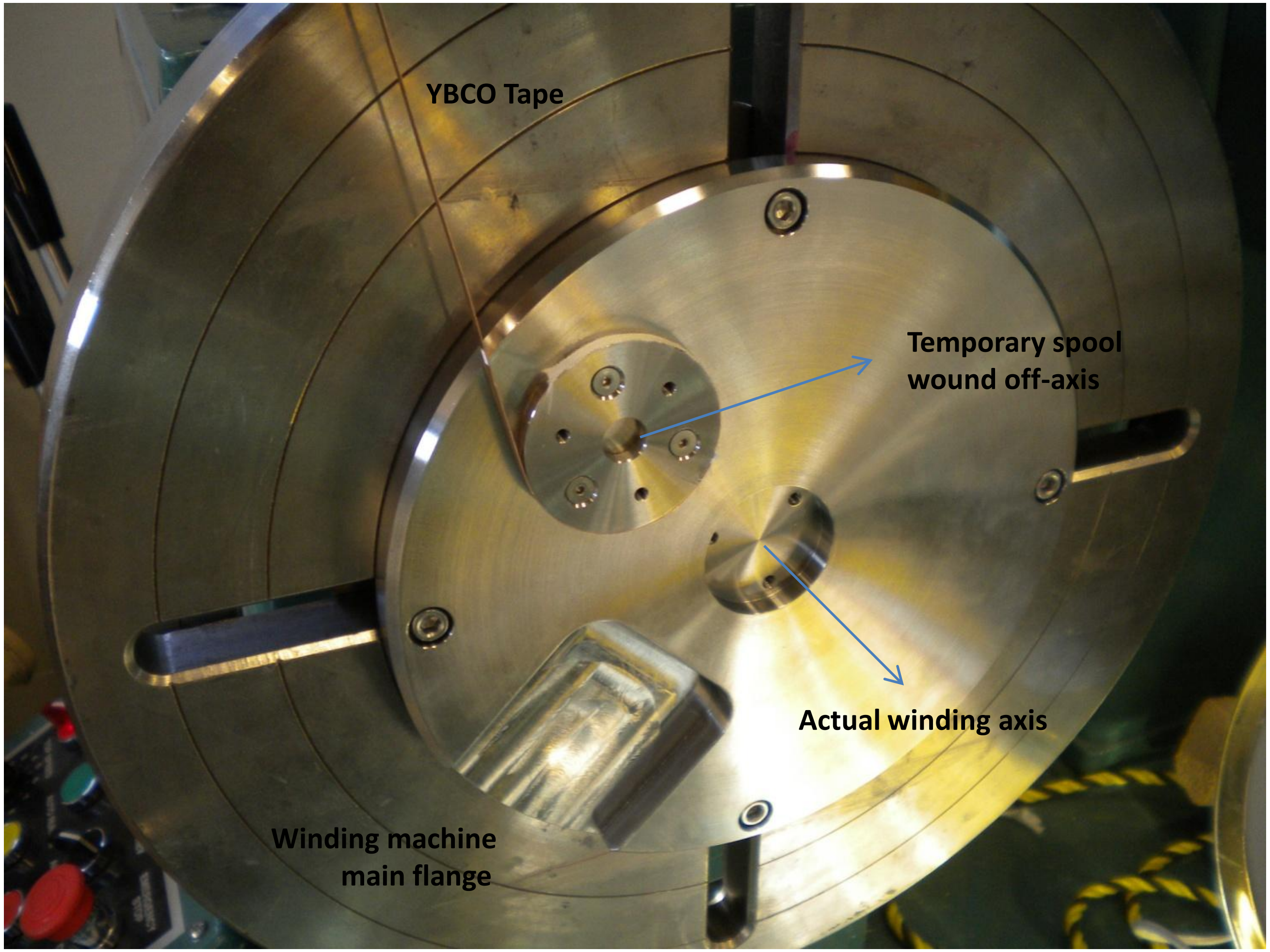


From tensioned YBCO supply spool

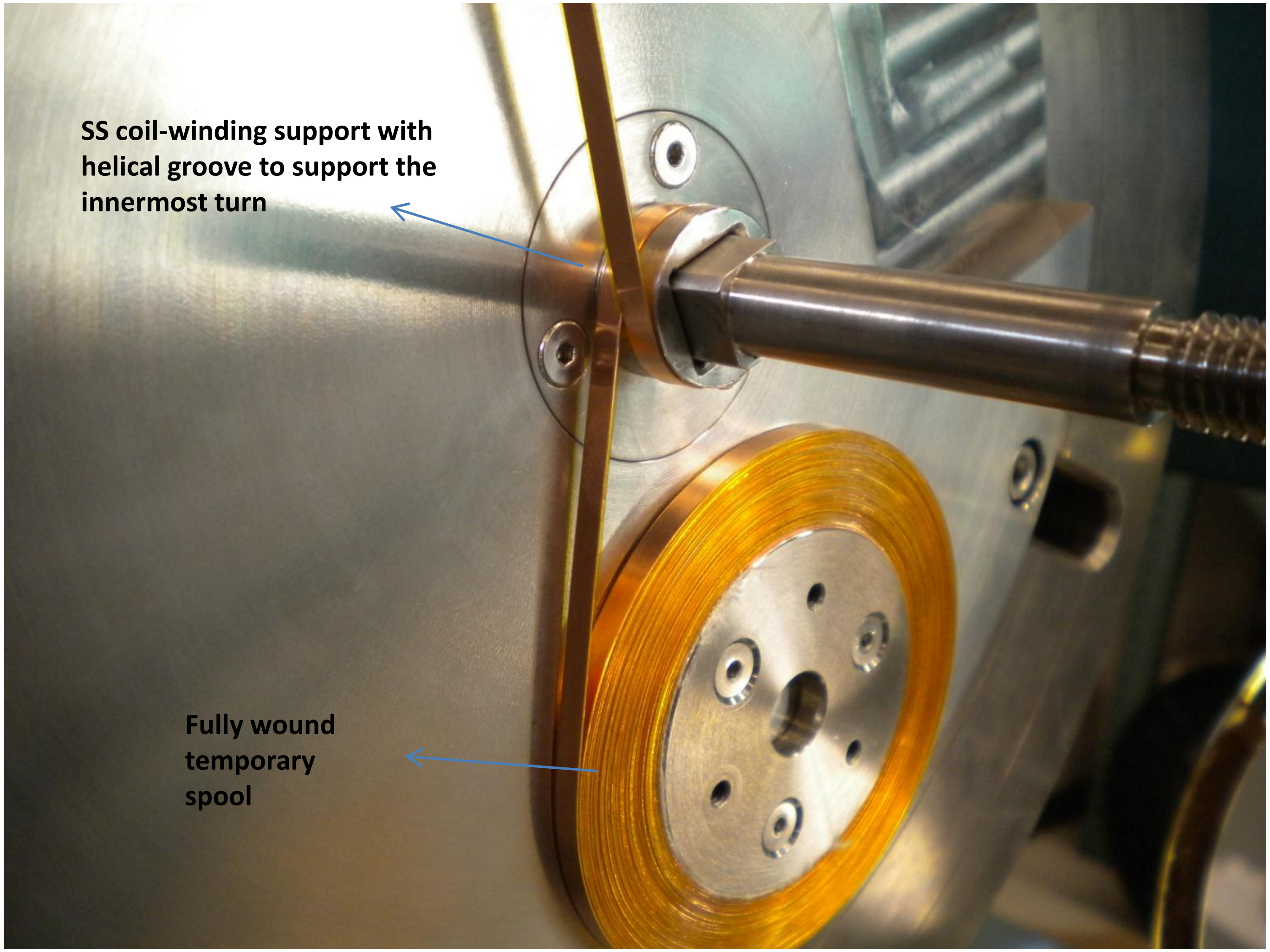
Kapton tape supply spool for turn to turn insulation

A. Bartalesi, V.Lombardo, A. Cattabiani.

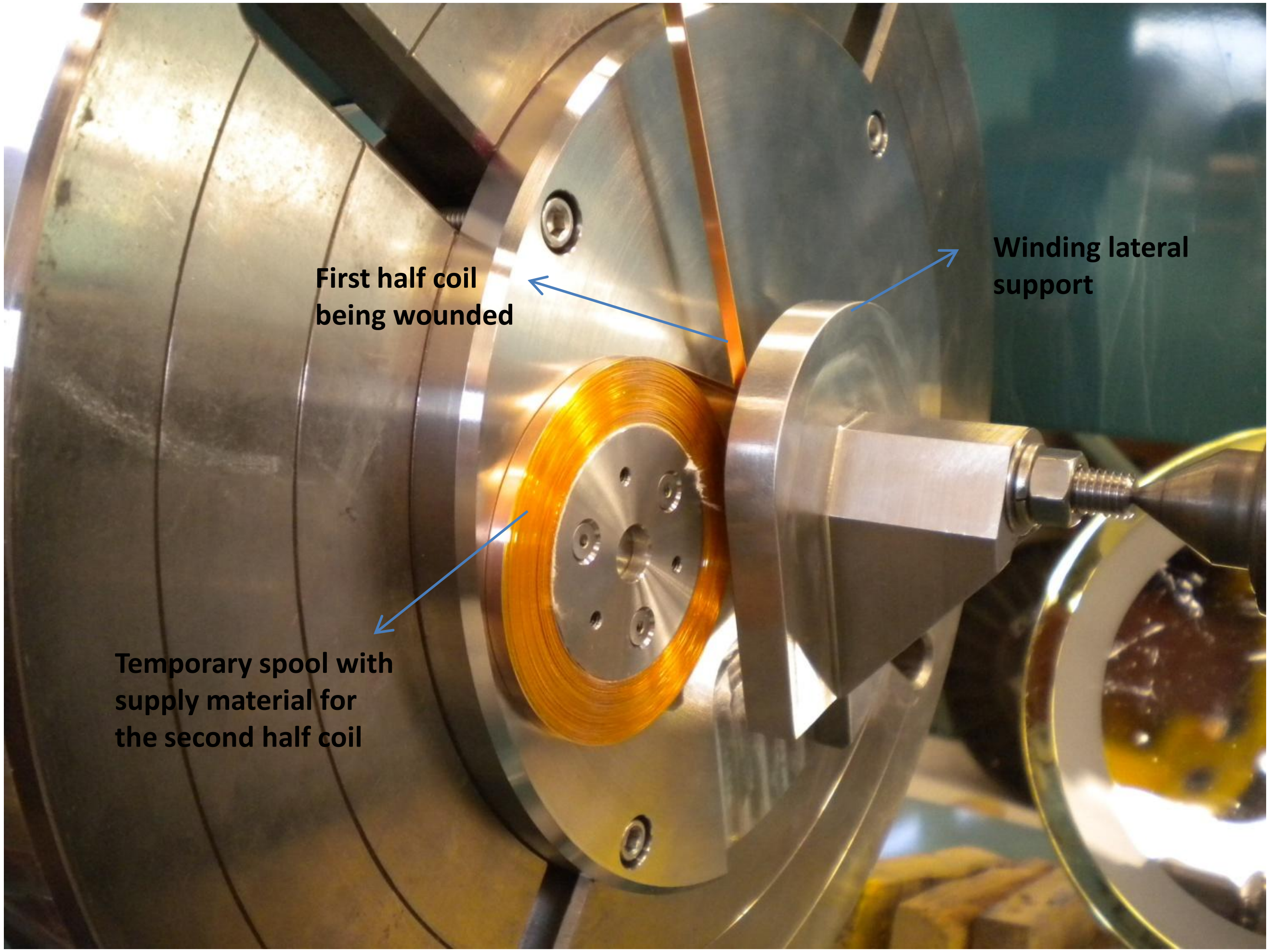
Winding YBCO CC Coils



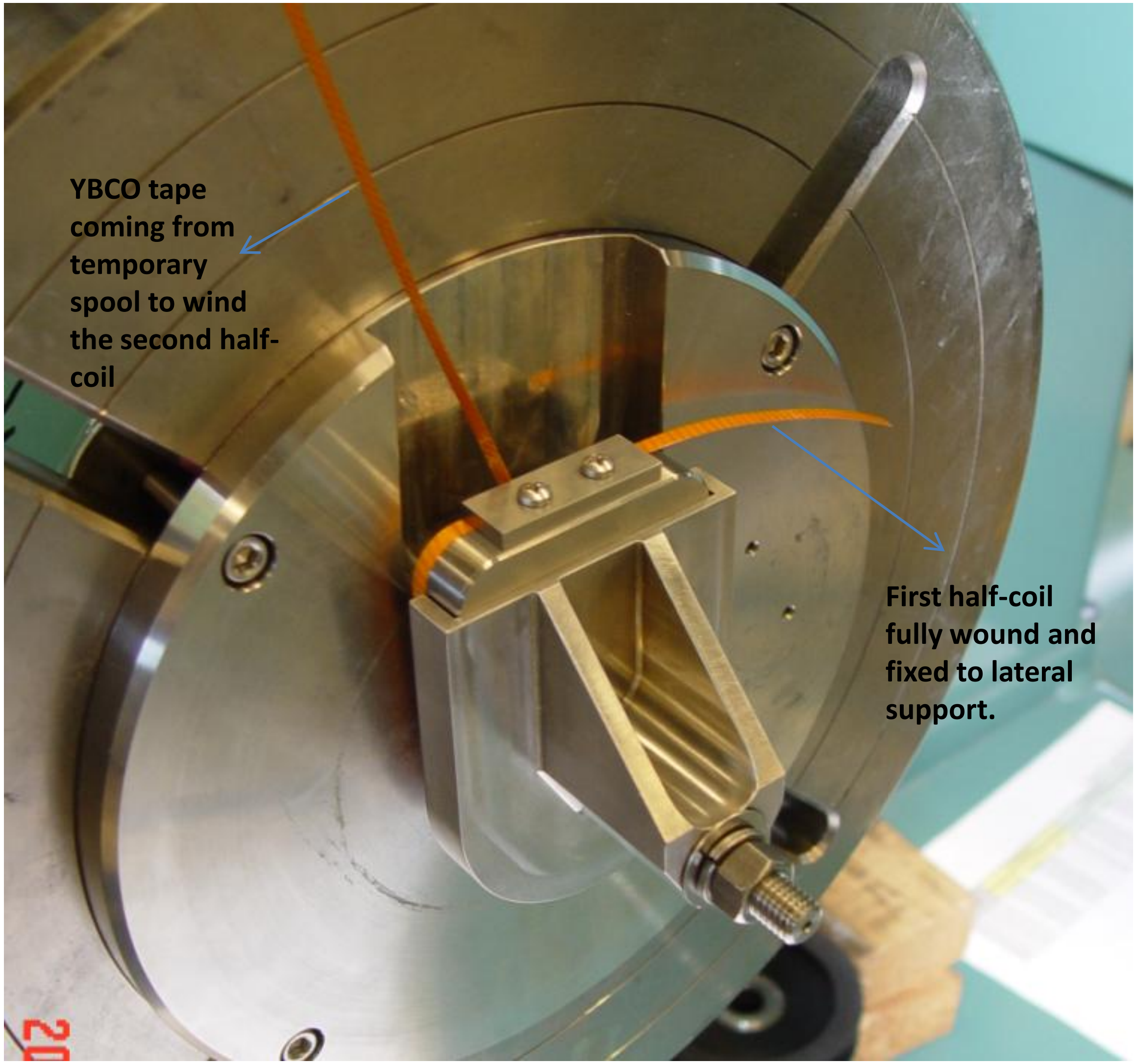
Winding YBCO CC Coils



Winding YBCO CC Coils



Winding YBCO CC Coils



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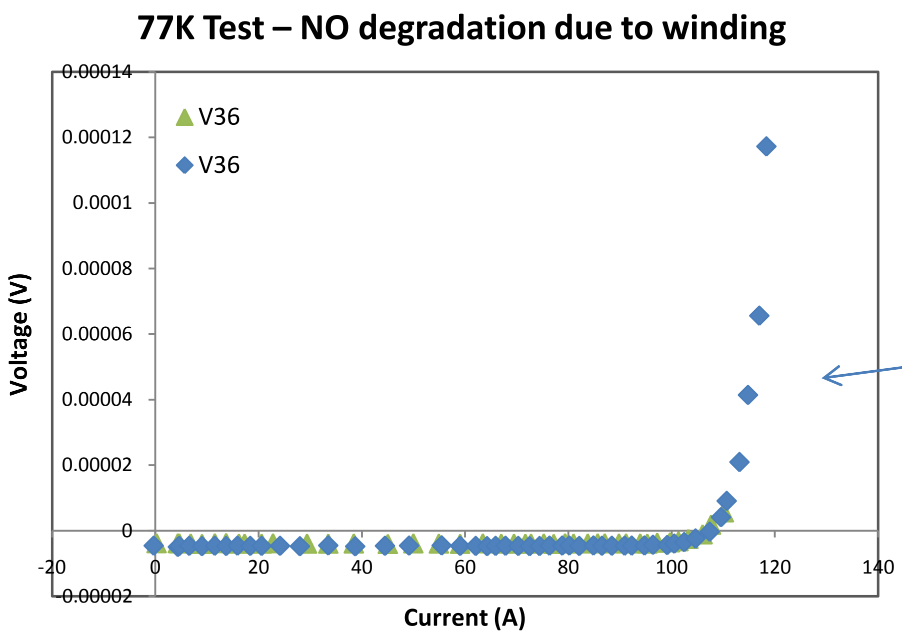
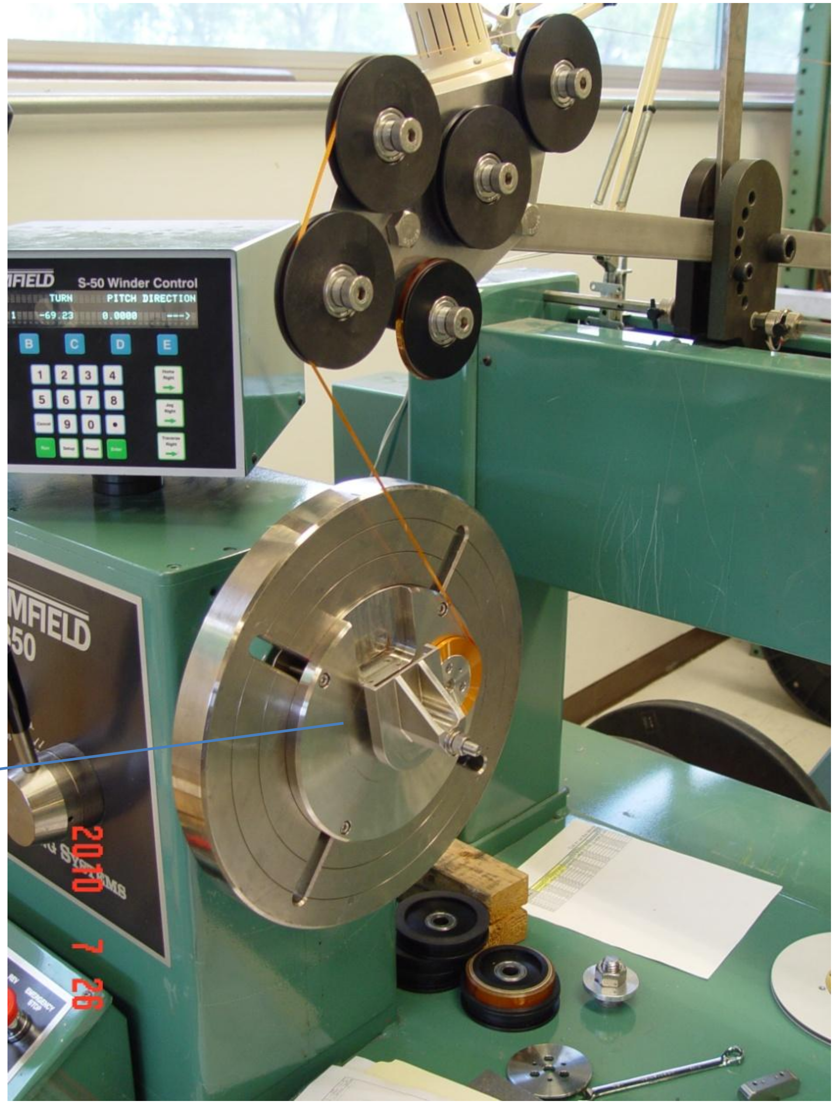
Winding YBCO CC Coils

Fully wound 19mm/62mm double pancake coil with co-wound adhesive Kapton tape for turn to turn insulation

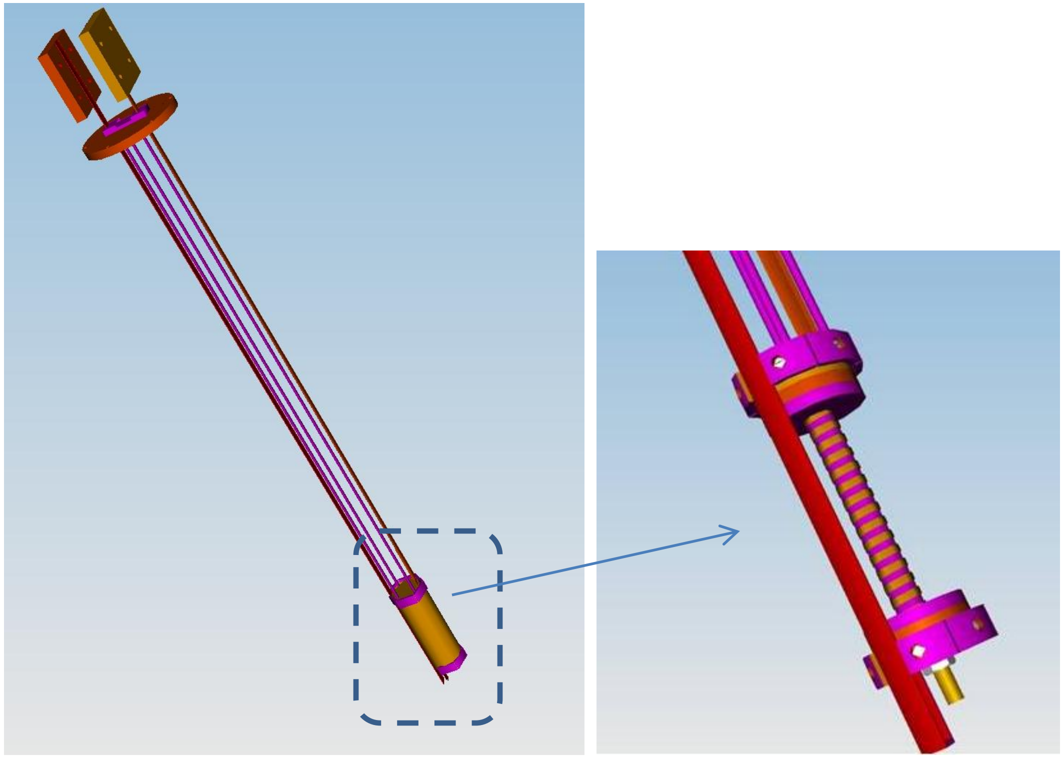
Practice Winding of YBCO CC Coils

Before winding an actual coil, several practice winding runs were performed with copper tape. A few turns were finally wound using YBCO tape (10 pounds were applied during winding) and measured on a G-10 spiral sample holder to check for damages due to winding technology. No degradation was seen on extracted pieces from practice winding.





Design and procurement of a setup for insert coils



G. Norcia, A. Bartalesi, E. Barzi, V. Lombardo

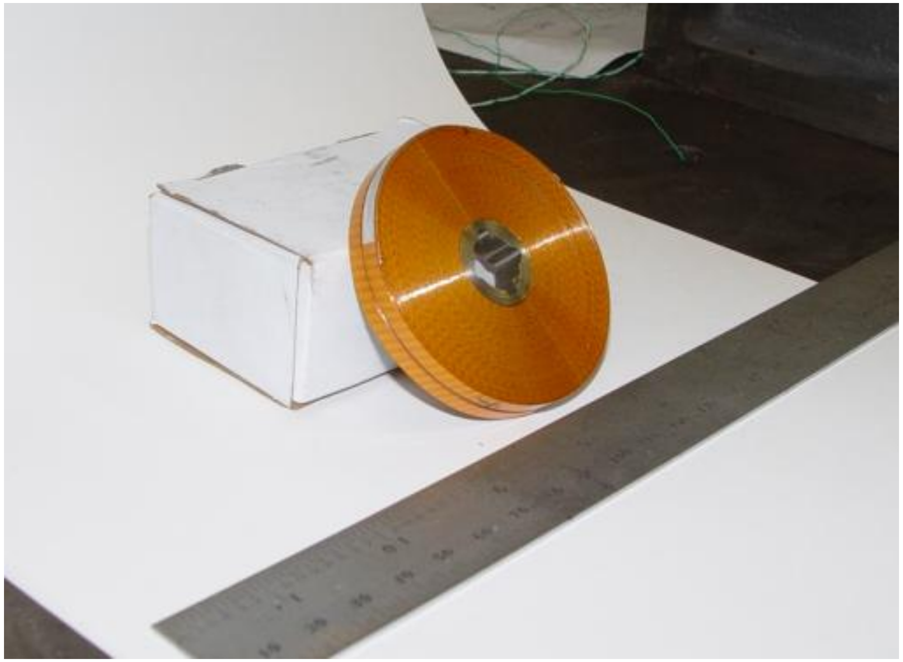
- Modular and Flexible to different coil geometries and number of coils
- Allow the insertion of a Hall probe to measure axial field
- Allow up to 2kA, while minimizing the room allocated to leads for max coil OD

V. Lombardo, A. Bartalesi, E. Barzi, M. Lamm, D. Turrioni and A.V. Zlobin. *"Modular Test Facility for HTS Insert Coils"* – IEEE Trans. Appl. Sup., V. 20, No. 3, p. 587 (2010)

Full-scale $YBa_2Cu_3O_{7-\delta}$ CC Insert Coil

Conductor	SuperPower SCS4050-i
Spool ID	20100306-1e
Ic (A) Average @77K,0T	113A
Ic (A) Minimum @77K,0T	107A
Ic Standard Deviation	2.7%
Turn to Turn Insulation	Spiral Wrapped Kapton
Coil Geometry	Double Pancake – no inner splice
Coil ID	19 mm
Coil OD	62 mm
Conductor Thickness	0.1 mm
Conductor + Insulation Thickness	0.2 mm
Packing Factor	50%
Turns per Single Coil	108
Conductor length per Coil	13.9m
Overall Conductor Length	27.8m
Coil Resistance @ 300K	2.87 Ohm
Coil Inductance @1kHz	1.5 mH

After completion of practice winding runs, a full scale YBCO coil was wound and assembled. Details are on shown on the left.



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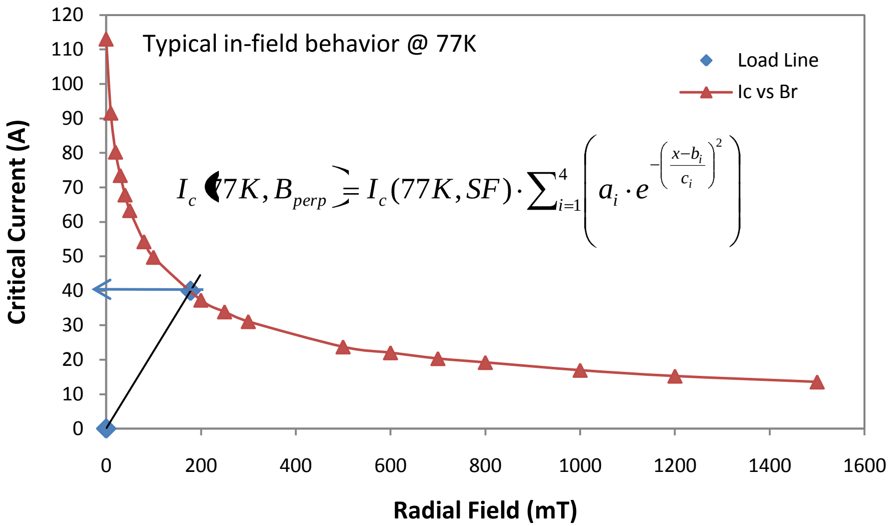
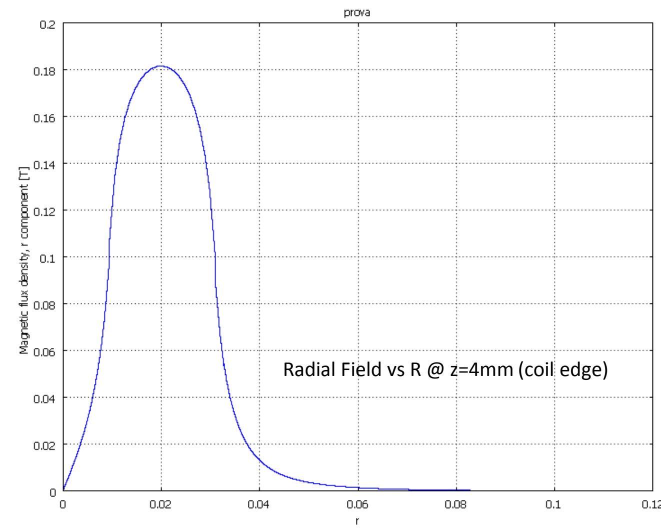
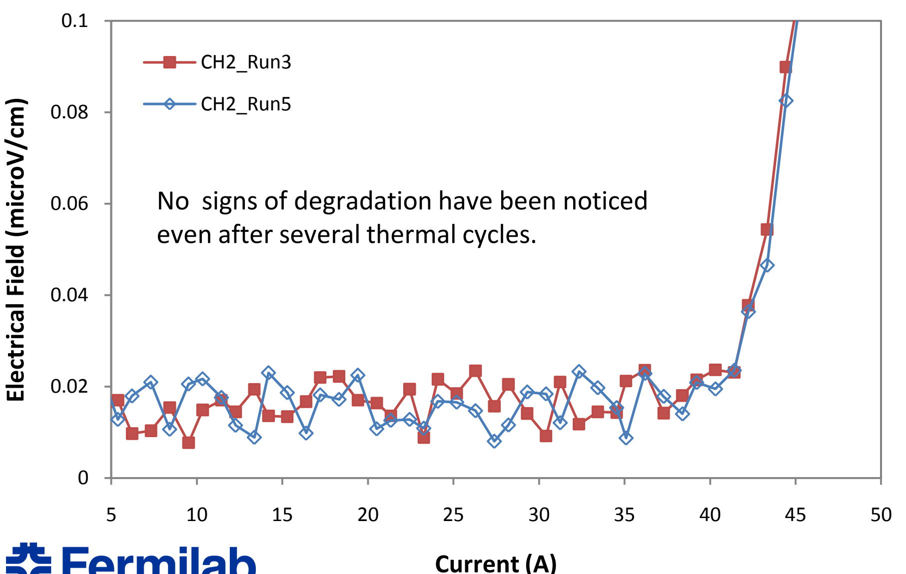
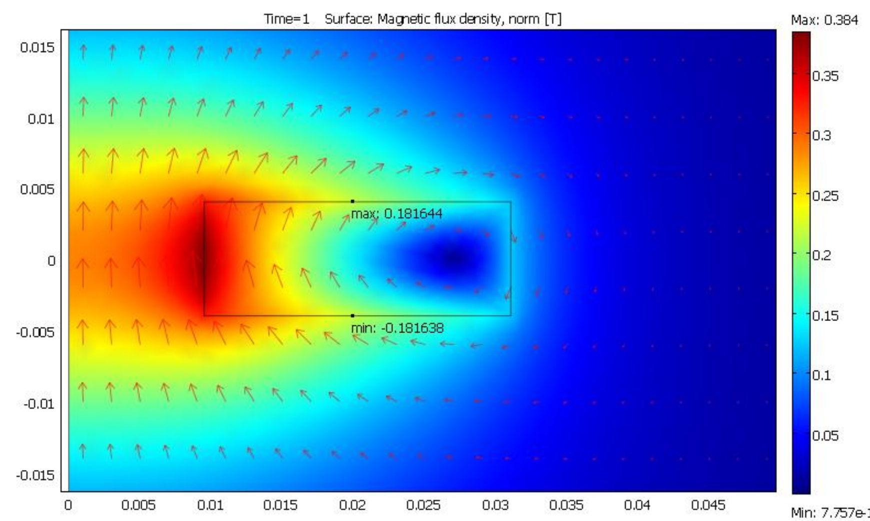
Liquid Nitrogen Test Results



Expected coil current ranges were far below the nominal critical current measured on short samples due to self field impacting **perpendicularly to the ab plane of the tape**.







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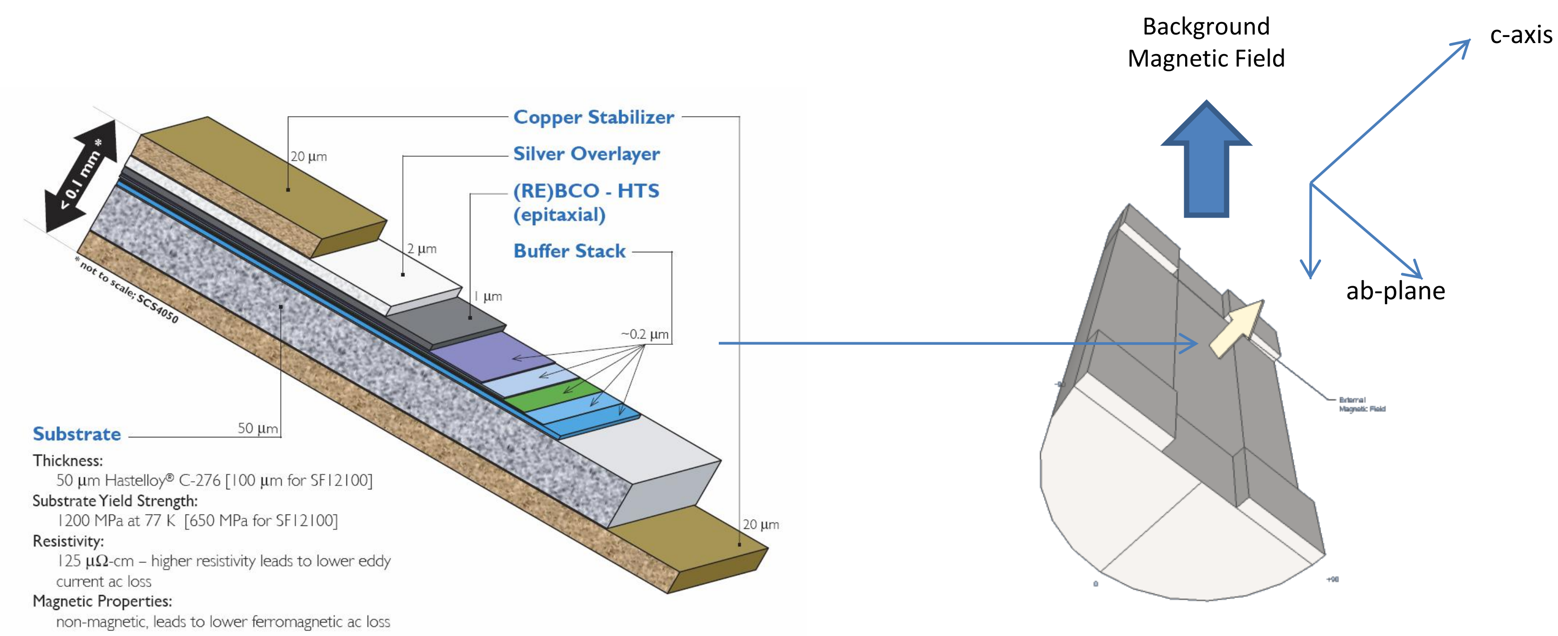
Approach to Coil Performance Estimation at 4.2K

Due to anisotropy of YBCO CC tapes, estimating the short sample limit of insert coils requires additional effort compared to isotropic conductors. Field orientation needs to be accounted for during magnet design, especially when tested within an external field.

Approach to SSL estimation:

In order to evaluate short sample limit of insert coils, two sets of data were needed

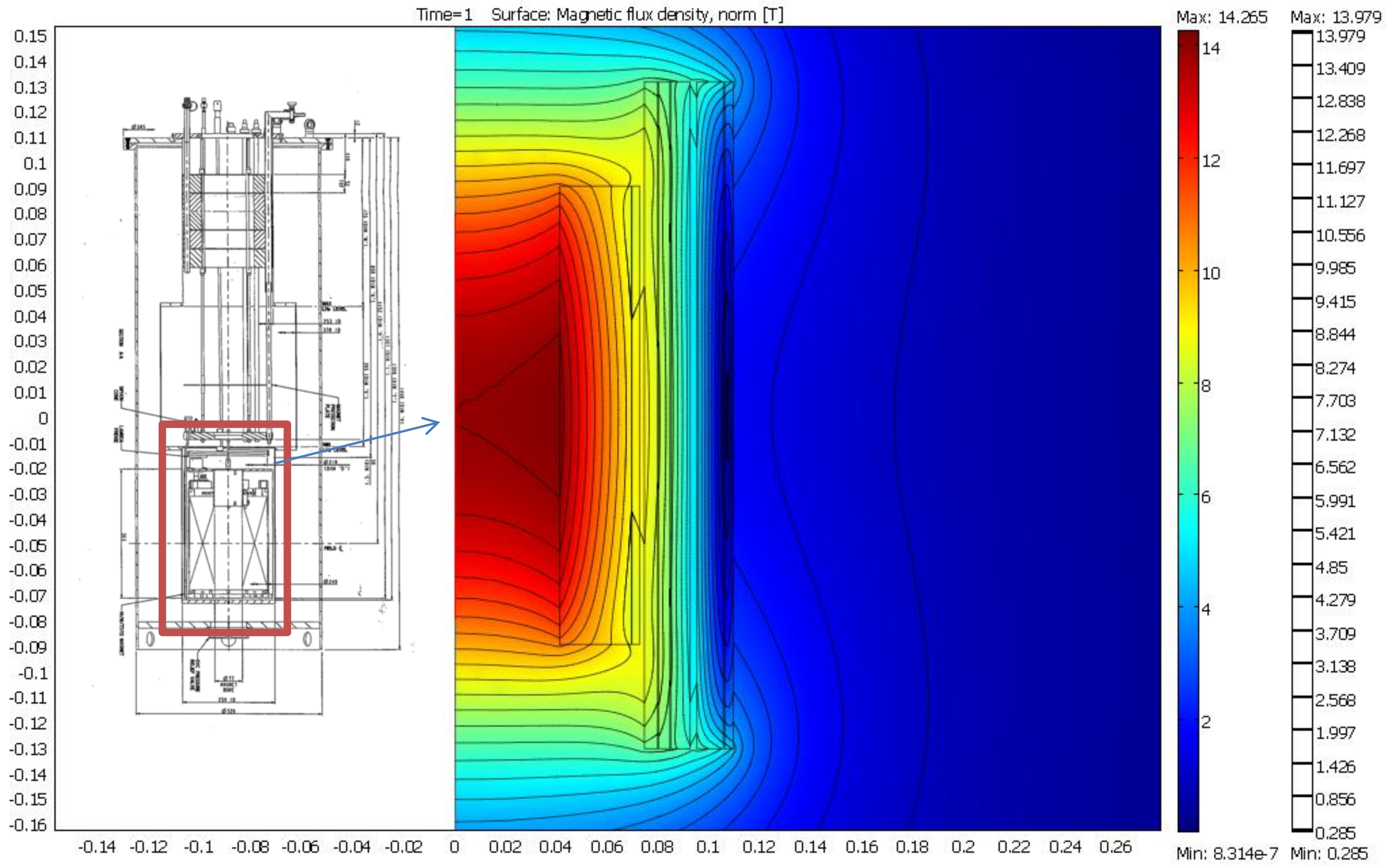
1. Actual magnetic field distribution from external Nb_3Sn/NbTi magnet
2. Short sample Measurement of YBCO CC tape as a function of field and field angle to account for anisotropy effects.



Sample Holder for Angular measurements

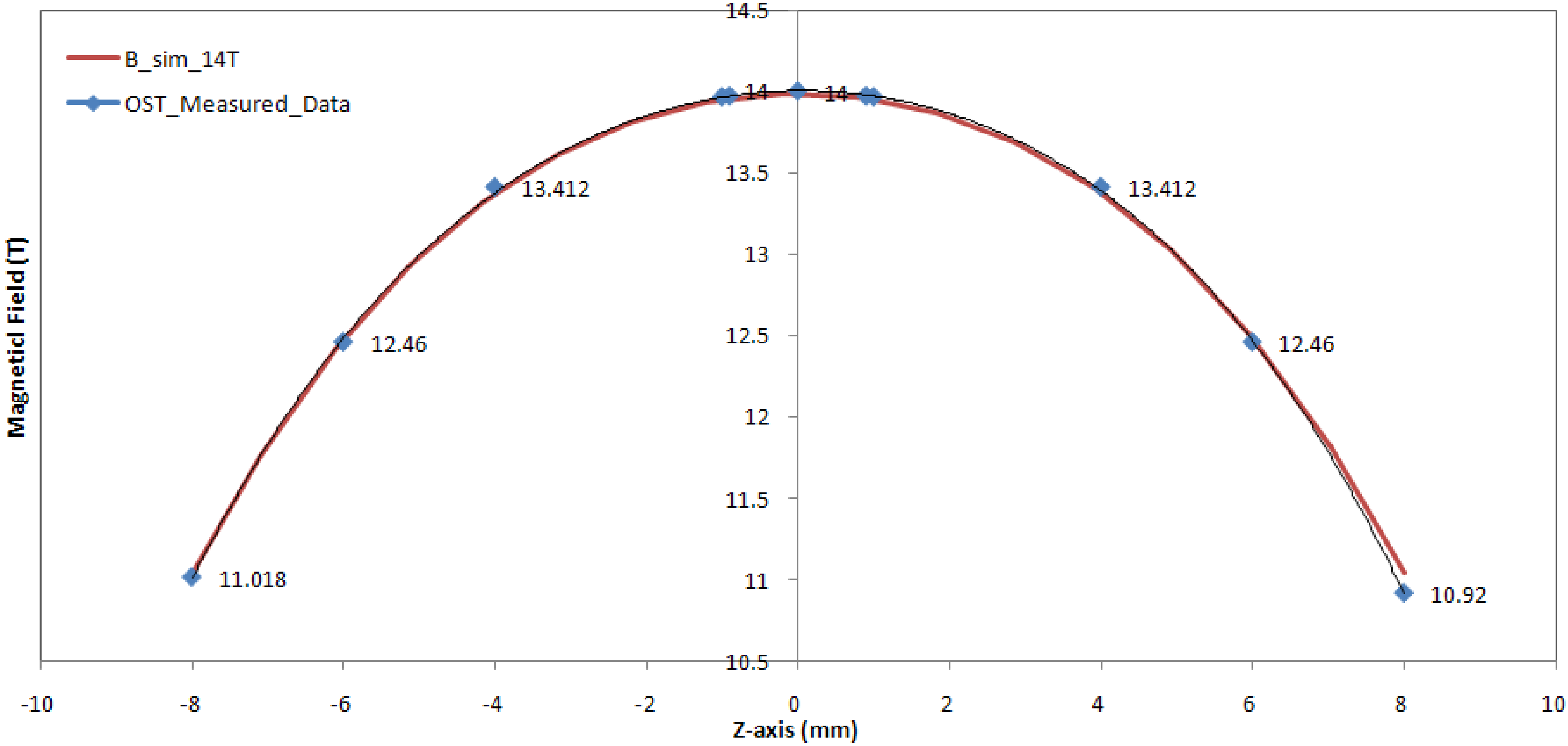
Background Field provided by Nb_3Sn/NbTi external magnet

Magnetic calculations were performed using the 14T background field provided by Nb_3Sn/NbTi fully SC solenoid available @ Fermilab



Background Field provided by Nb_3Sn/NbTi external magnet

Magnetic Field simulations were benchmarked against available magnetic measurements.
Simulations results compare nicely with experimental data.



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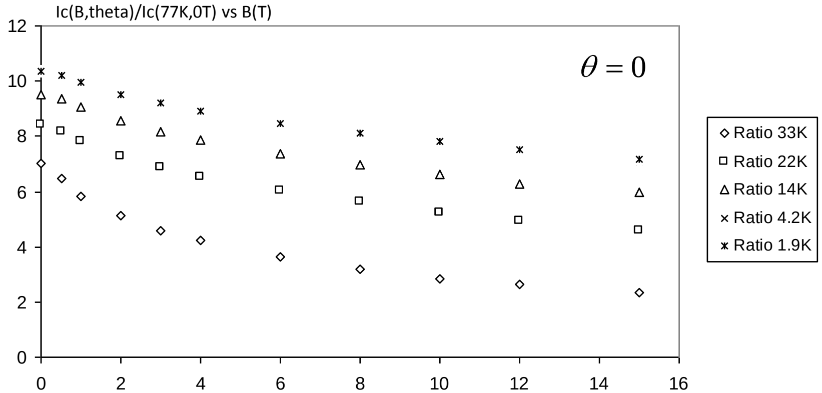
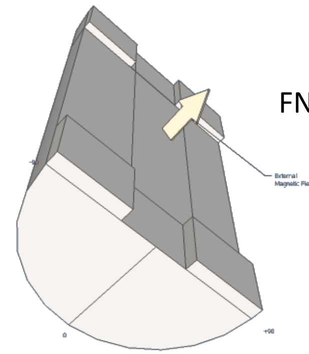
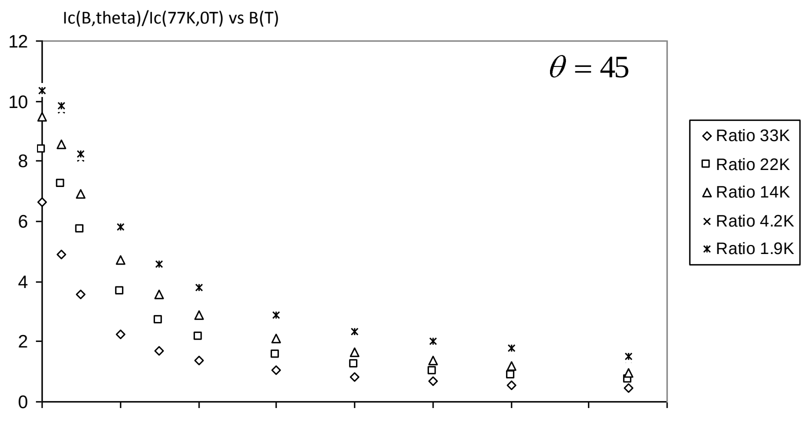
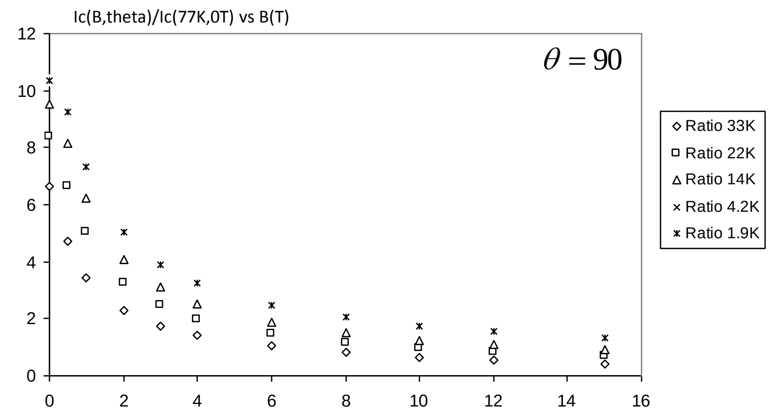
Angular measurements for SP YBCO

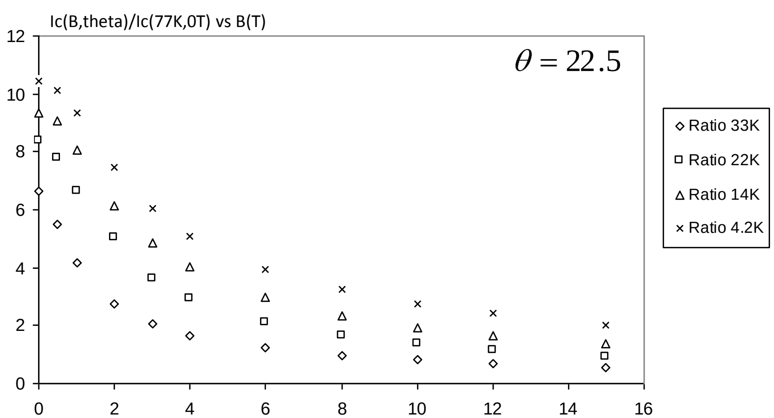
FNAL data are shown for SCS4050 Superpower Tape, for different magnetic field angles of incidence (and temperature).

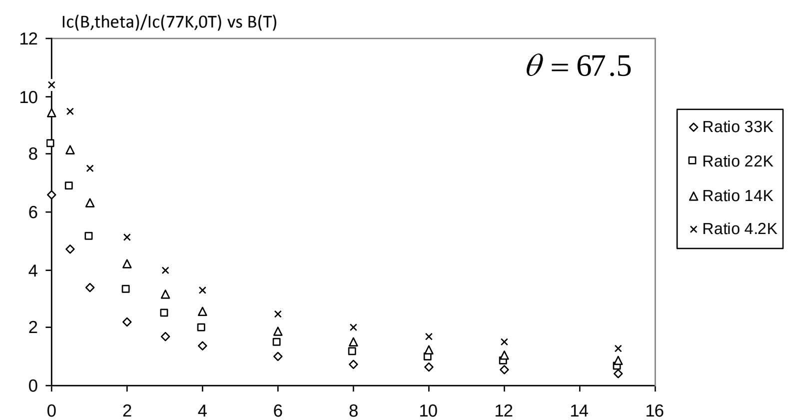








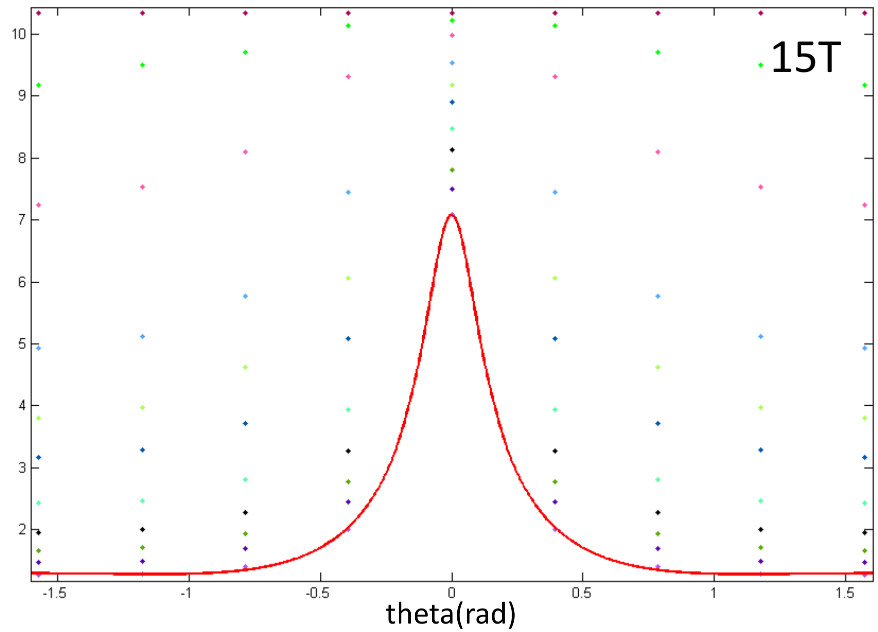




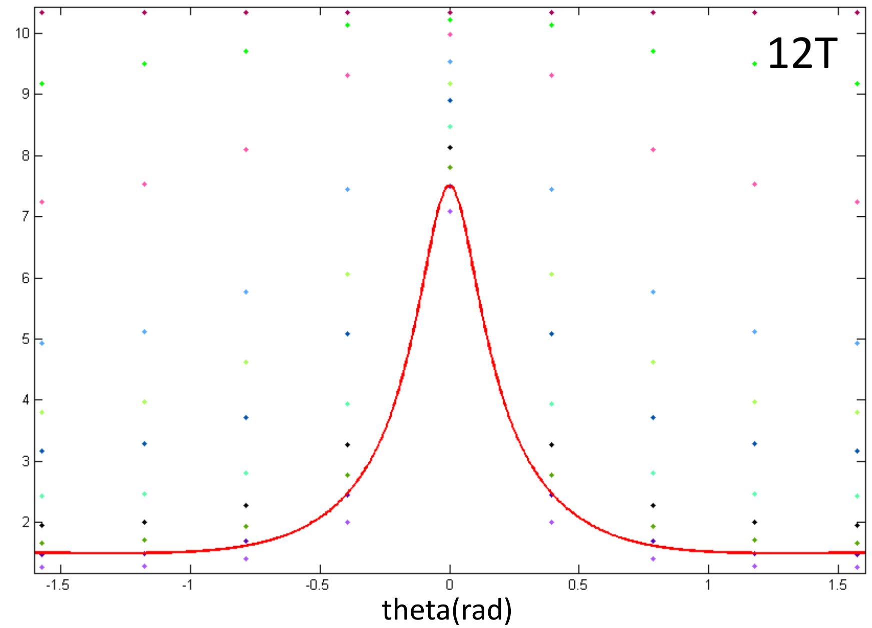
V. Lombardo, A. Bartalesi, E. Barzi, M. Lamm, D. Turrioni and A.V. Zlobin. *"Modular Test Facility for HTS Insert Coils"* – IEEE Trans. Appl. Sup., V. 20, No. 3, p. 587 (2010)

$I_c(B,\Theta)$ parameterization for SSL calculation at 4.2K

Ic(15T,theta)/Ic(77K,0T) vs theta(rad)



Ic(12T,theta)/Ic(77K,0T) vs theta(rad)

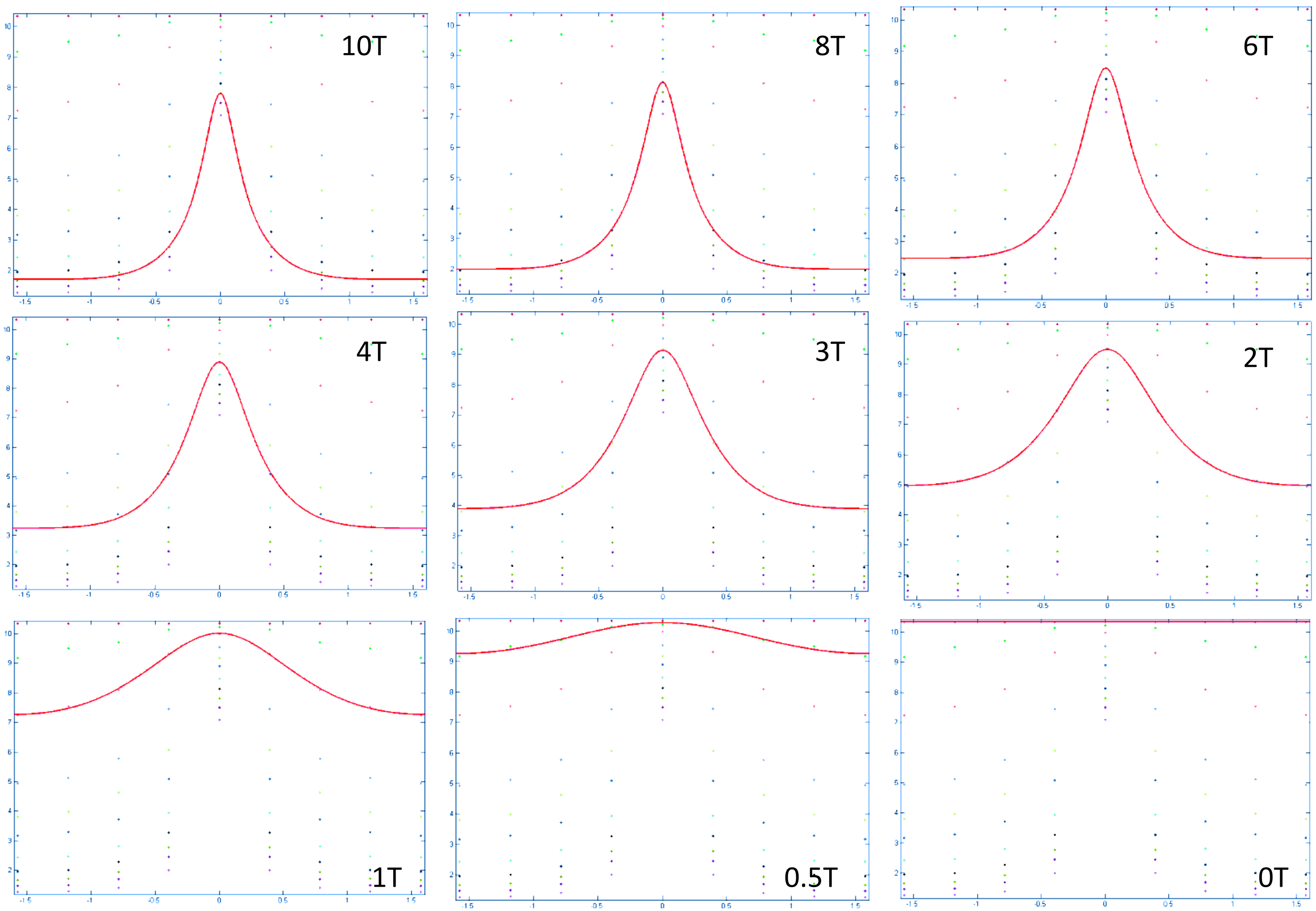


$$I_c(\theta) = \frac{k}{\sqrt{\sin(\theta)^2 + \frac{\cos(\theta)^2}{\varepsilon^2}}} + \left(a\sin(\theta)\right)^2$$

Superpower YBCO critical current fitting

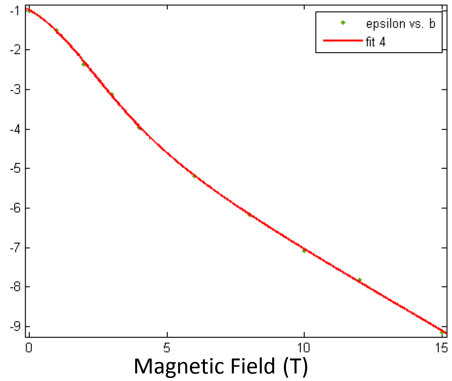
Analytical fitting for angle and field dependency of YBCO critical current can be performed using this expression. In Fig.1 and 2 the expression is plot against FNAL data for Superpower YBCO tape.

Ic(B,Θ) parameterization for SSL calculation at 4.2K



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

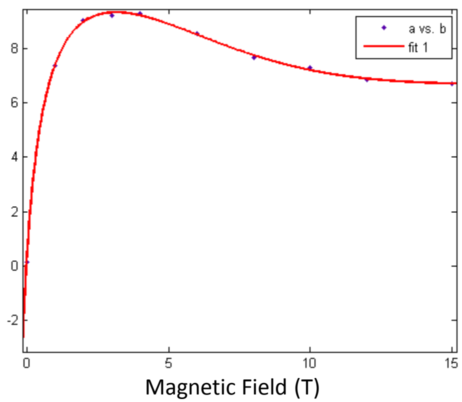
$I_c(B,\Theta)$ parameterization for SSL calculation at 4.2K



$$\varepsilon(B) = \frac{\sum_{i=0}^{3} p_i \cdot B^i}{\sum_{i=0}^{2} q_i \cdot B^i}$$

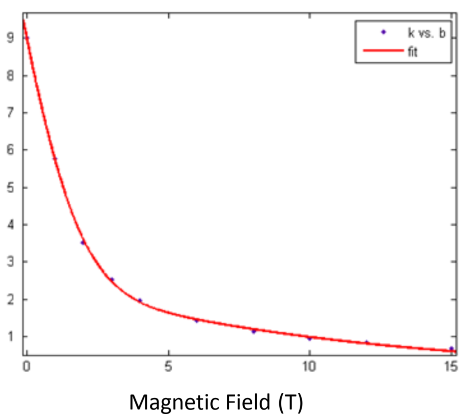
Adding one dimension to the fit

The expression can be extended to include field dependency by fitting the three parameters (k,epsilon,a) as a function of field. This can be done using *rational polynomial* or sums of *exponential expressions*, as shown. Doing this, one can obtain a self contained expression for theta and field dependency. This is useful to calculate SSL of solenoids made of anisotropic materials.



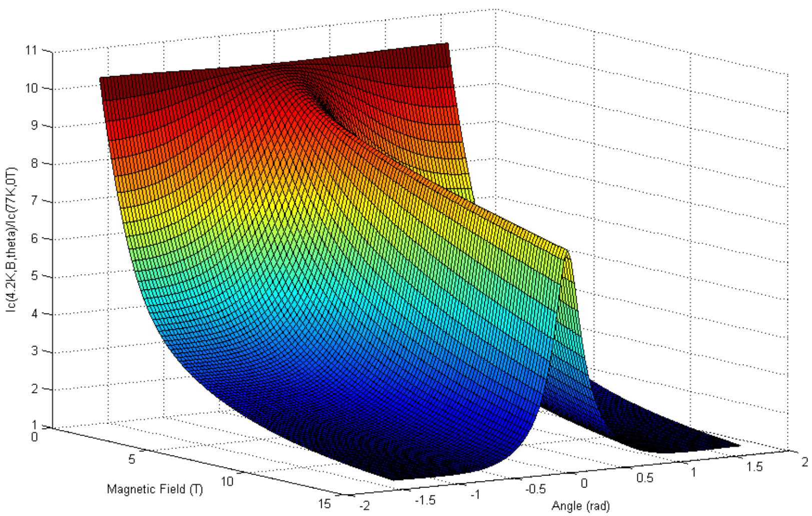
$$a(B) = \frac{\sum_{i=0}^{4} r_i \cdot B^i}{\sum_{i=0}^{3} s_i \cdot B^i}$$

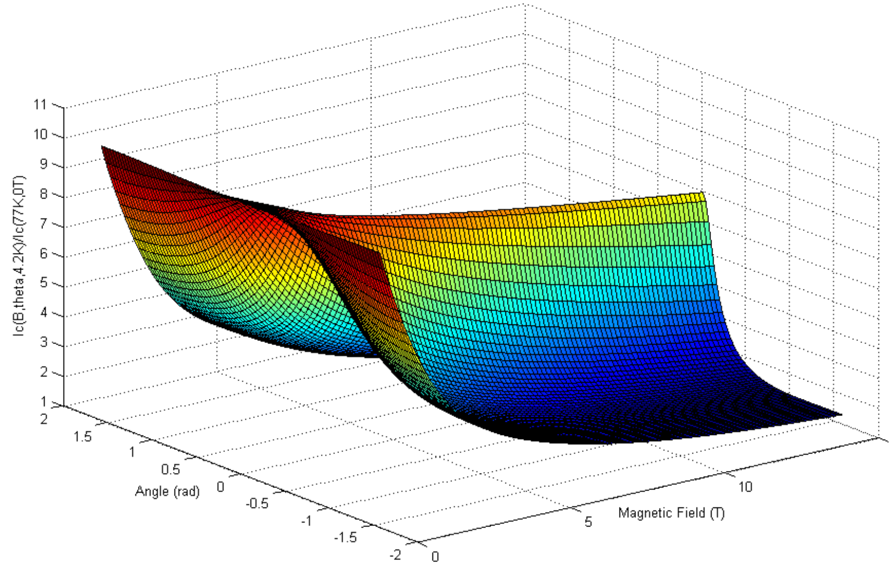
$$I_c(B,\theta) = \frac{k(B)}{\sqrt{\sin(\theta)^2 + \dfrac{\cos(\theta)^2}{\varepsilon(B)^2}}} + \left(a(B)\sin(\theta)\right)^2$$



$$k(B) = a_1 \cdot e^{-\left(\frac{B-b_1}{c_1}\right)^2} + a_2 \cdot e^{-\left(\frac{B-b_2}{c_2}\right)^2} + a_3 \cdot e^{-\left(\frac{B-b3}{c_3}\right)^2} \quad \frac{\sum_{i=0}^{2} q_i \cdot B^i}{\sum_{i=0}^{3} p_i \cdot B^i}$$

$I_c(B,\Theta)$ parameterization for SSL calculation at 4.2K



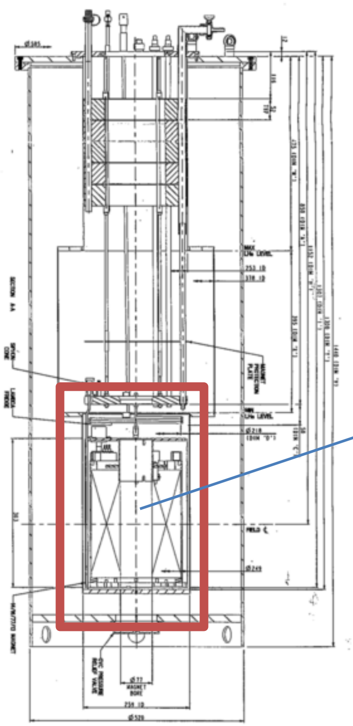


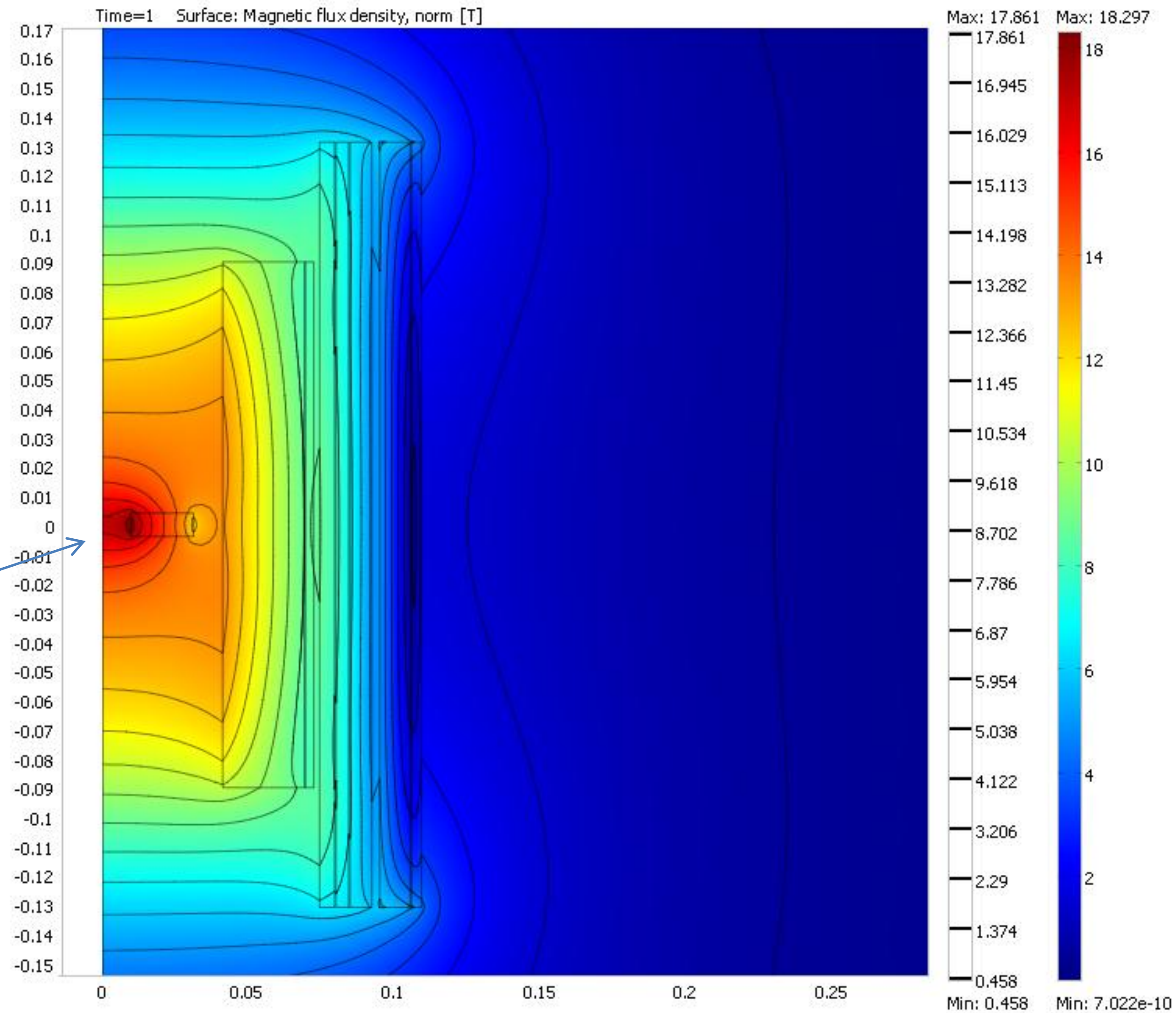
$$I_c(B,\theta) = \frac{\left[a_1 \cdot e^{-\left(\frac{B-b_1}{c_1}\right)^2} + a_2 \cdot e^{-\left(\frac{B-b_2}{c_2}\right)^2} + a_3 \cdot e^{-\left(\frac{B-b_3}{c_3}\right)^2} \right] \cdot \frac{\sum_{i=0}^{3} n_i \cdot B^i}{\sum_{i=0}^{2} m_i \cdot B^i}}{\sqrt{\sin(\theta)^2 + \frac{\cos(\theta)^2}{\left(\frac{\sum_{i=0}^{3} m_i \cdot B^i}{\sum_{i=0}^{2} n_i \cdot B^i}\right)^2}}} + \left(\frac{\sum_{i=0}^{4} p_i \cdot B^i}{\sum_{i=0}^{3} q_i \cdot B^i} \cdot \sin(\theta) \right)^2$$

V. Lombardo, E. Barzi, G. Norcia, M. Lamm, D. Turrioni, T. Van Raes and A. V. Zlobin. "*Study of HTS Insert Coils for high field Solenoids*" – Transactions of the Cryogenic Engineering Conference – CEC Vol. 55

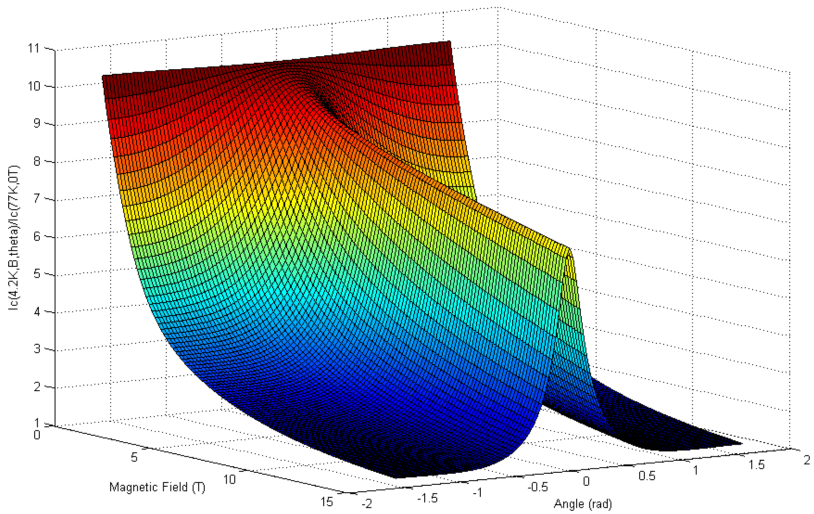
V. Lombardo - *"An Ic(B,ϑ) parameterization for YBa2Cu3O7−δ CC Tapes" – FERMILAB-TM-2461-TD – Technical Division Note*

Magnetic Field Distribution with YBCO Insert + bkgr Field

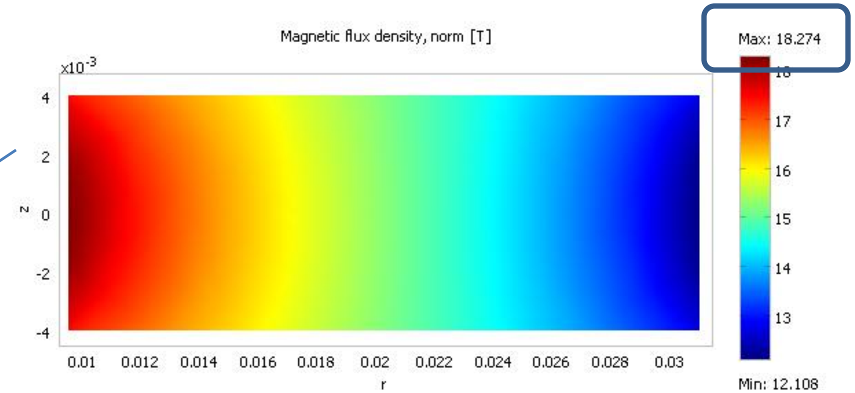




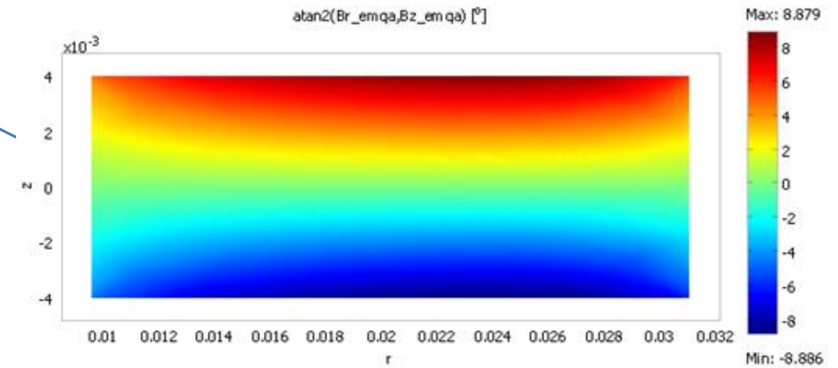
Insert Coil performance estimation at 4.2K



B

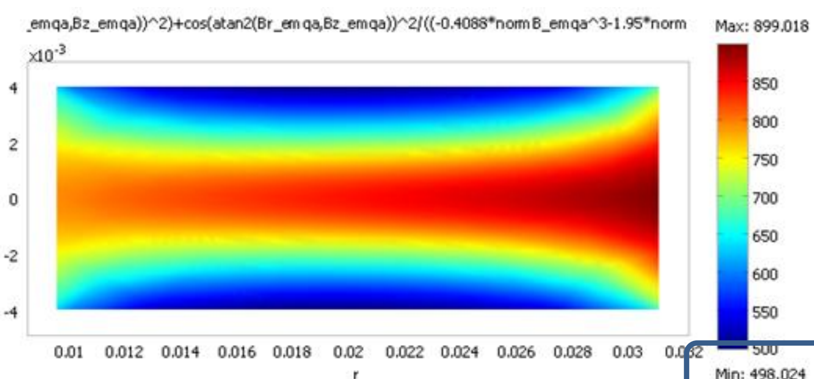


Θ

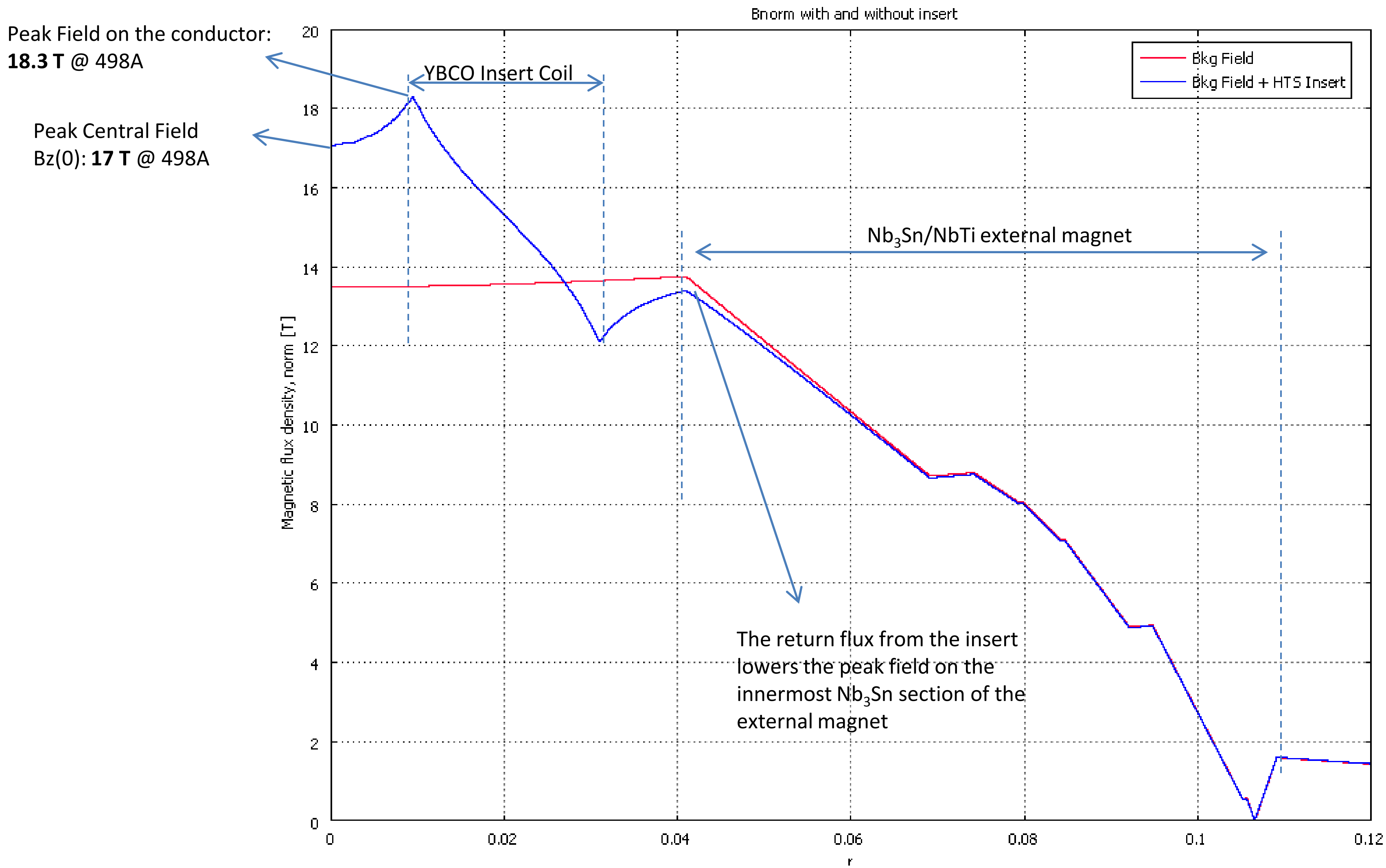


$$I_c(B,\theta)=\frac{\left[a_1\cdot e^{-\left(\frac{B-b_1}{c_1}\right)^2}+a_2\cdot e^{-\left(\frac{B-b_2}{c_2}\right)^2}+a_3\cdot e^{-\left(\frac{B-b_3}{c_3}\right)^2}\right]\cdot\frac{\sum_{i=0}^{3} n_i\cdot B^i}{\sum_{i=0}^{2} m_i\cdot B^i}}{\sqrt{\sin(\theta)^2+\frac{\cos(\theta)^2}{\left(\frac{\sum_{i=0}^{3} m_i\cdot B^i}{\sum_{i=0}^{2} n_i\cdot B^i}\right)^2}}}+\left(\frac{\sum_{i=0}^{4} p_i\cdot B^i}{\sum_{i=0}^{3} q_i\cdot B^i}\cdot\sin(\theta)\right)^2$$

I_c

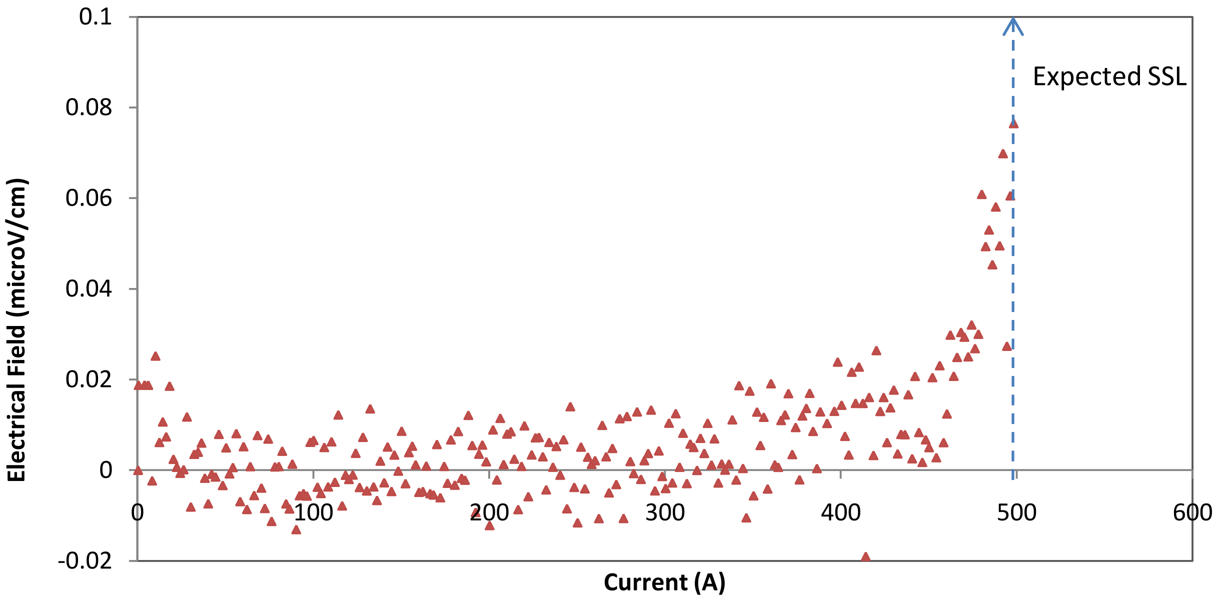


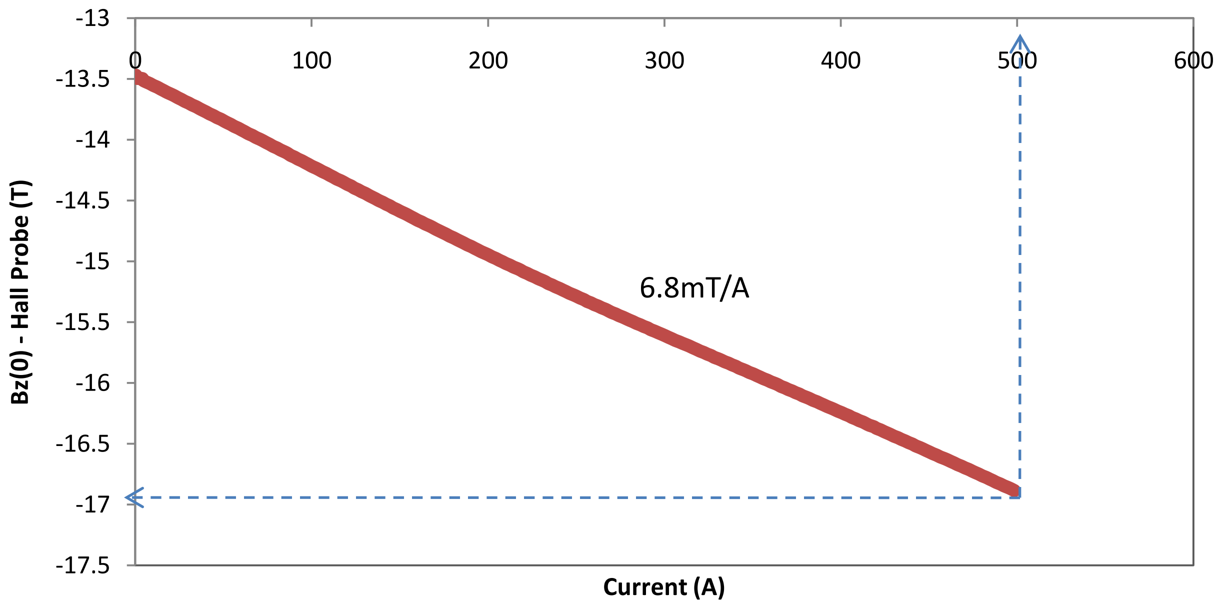
Magnetic Field Distribution with and without Insert



E. Barzi et al. *"Latest on YBCO Small Coil Technology" – LTHFSW 2011*

Test results at 4.2K in 13.5T background field





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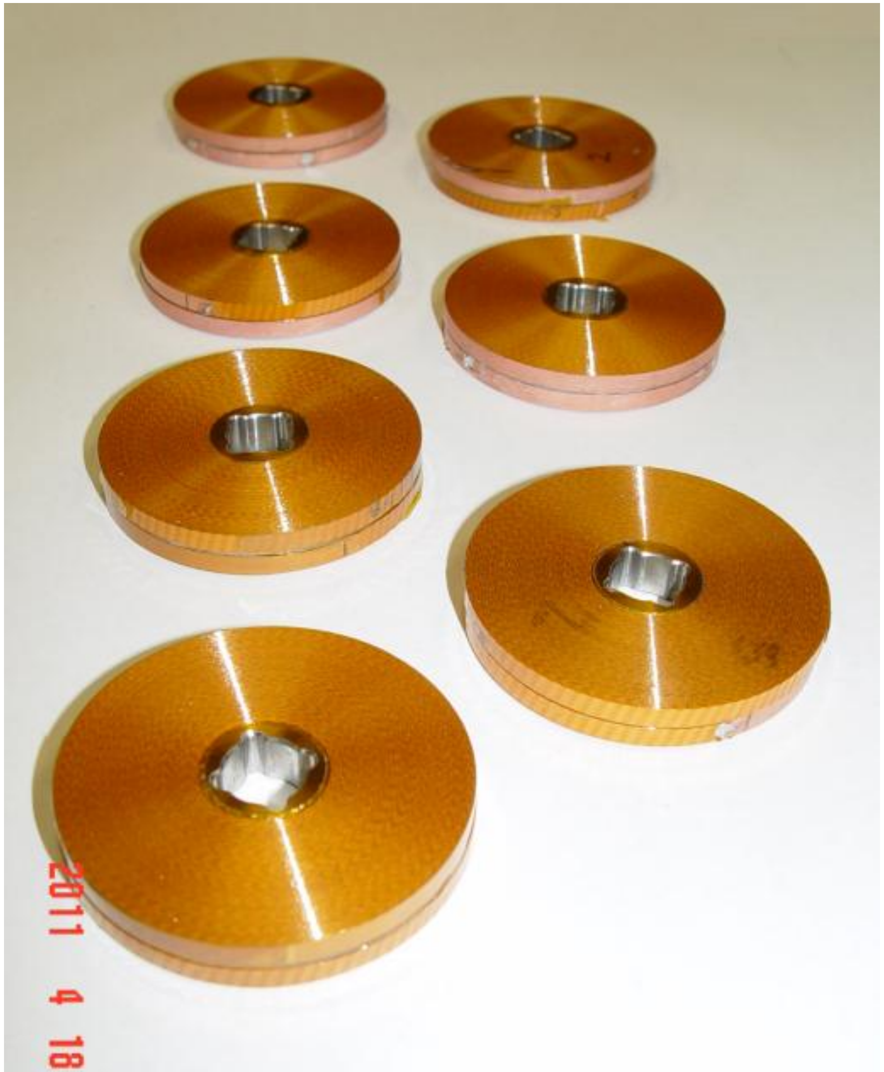
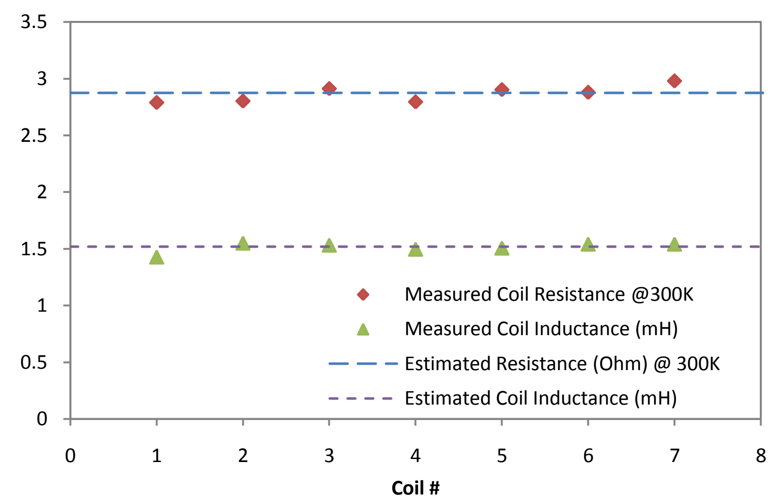
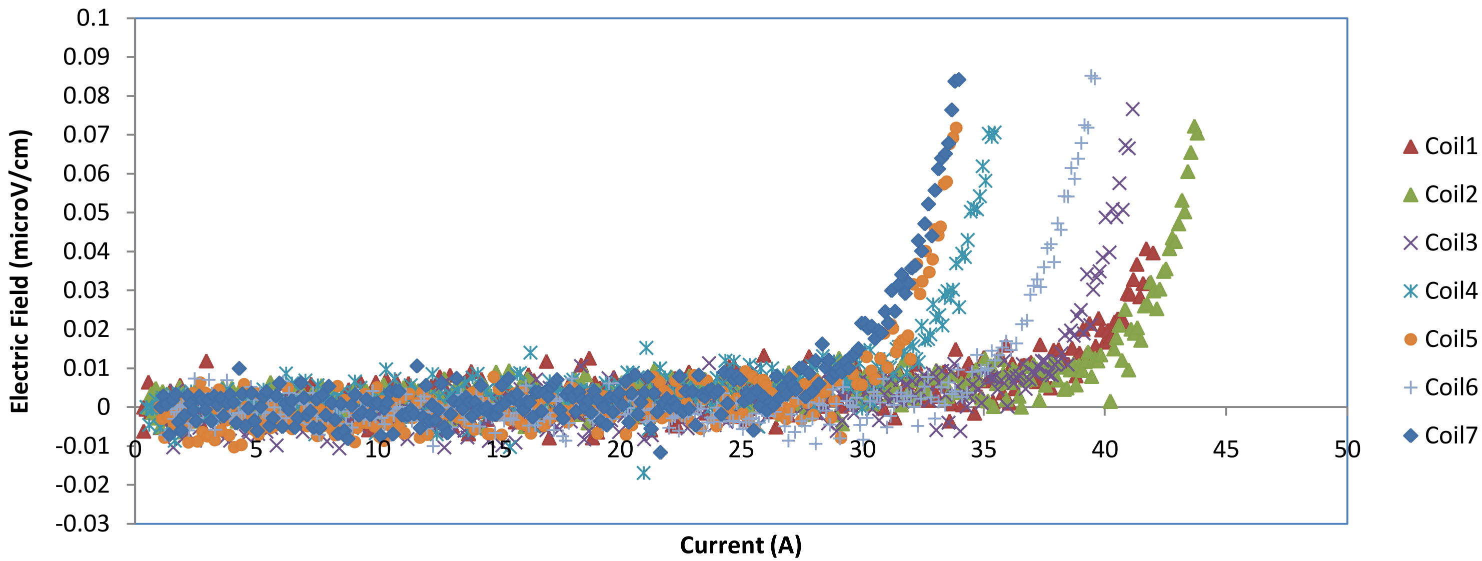
Scale-up work

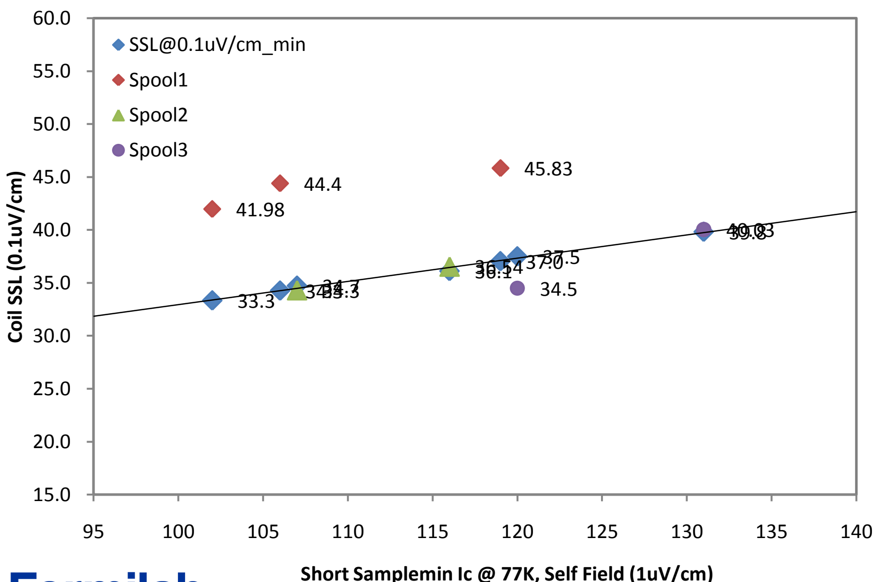


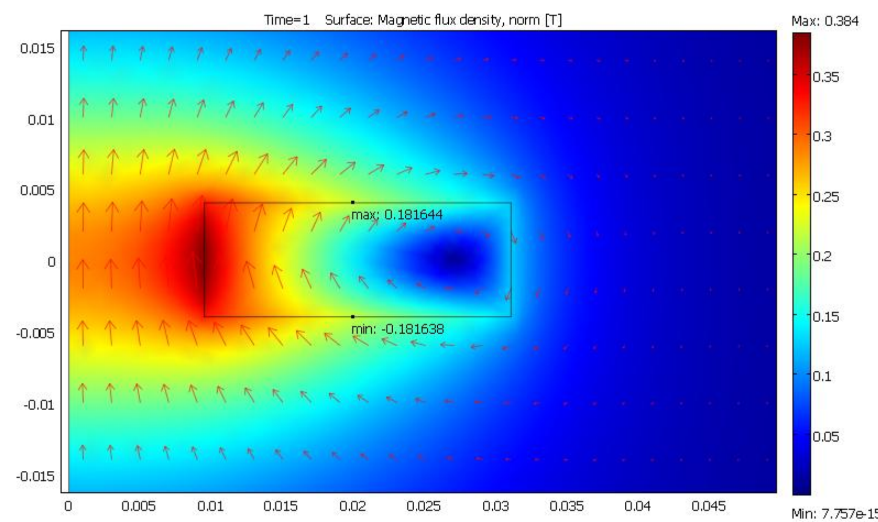
Conductor	SuperPower SCS4050-i
Turn to Turn Insulation	Spiral Wrapped Kapton
Coil Geometry	Double Pancake – no inner splice
Coil ID	19 mm
Coil OD	62 mm
Conductor Thickness	0.1 mm
Conductor + Insulation Thickness	0.2 mm
Packing Factor	50%
Turns per Single Coil	108



Test of full batch of 7 coils in Liquid Nitrogen



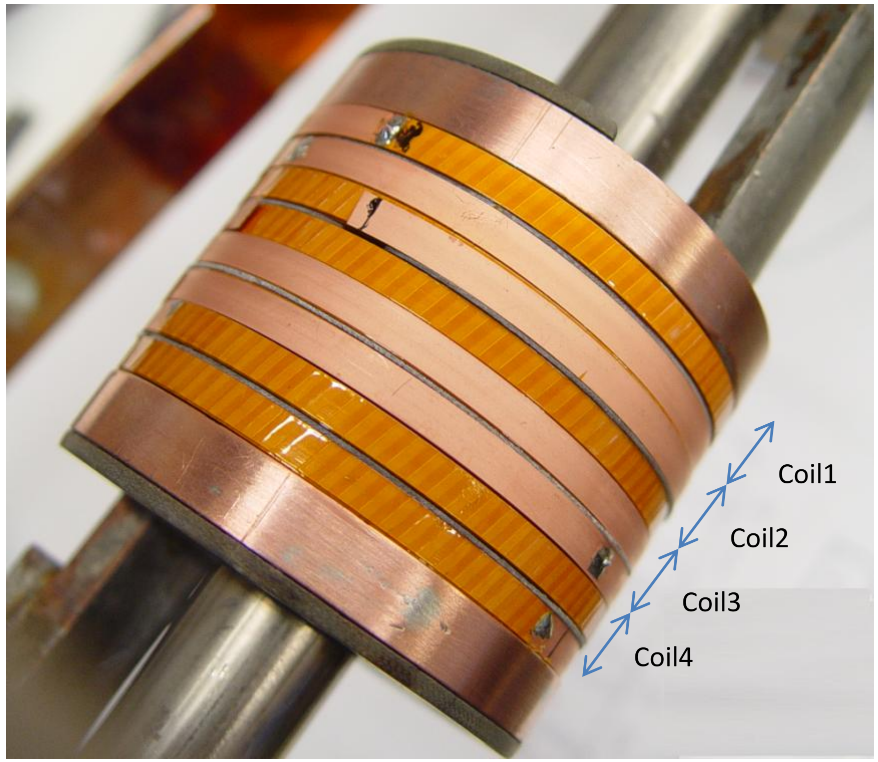


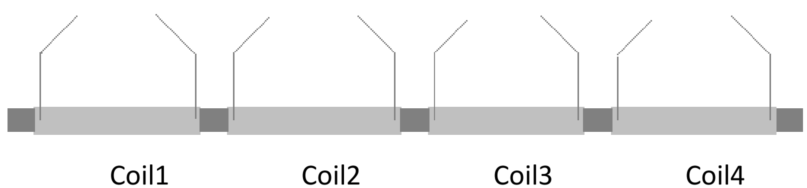


Fermilab

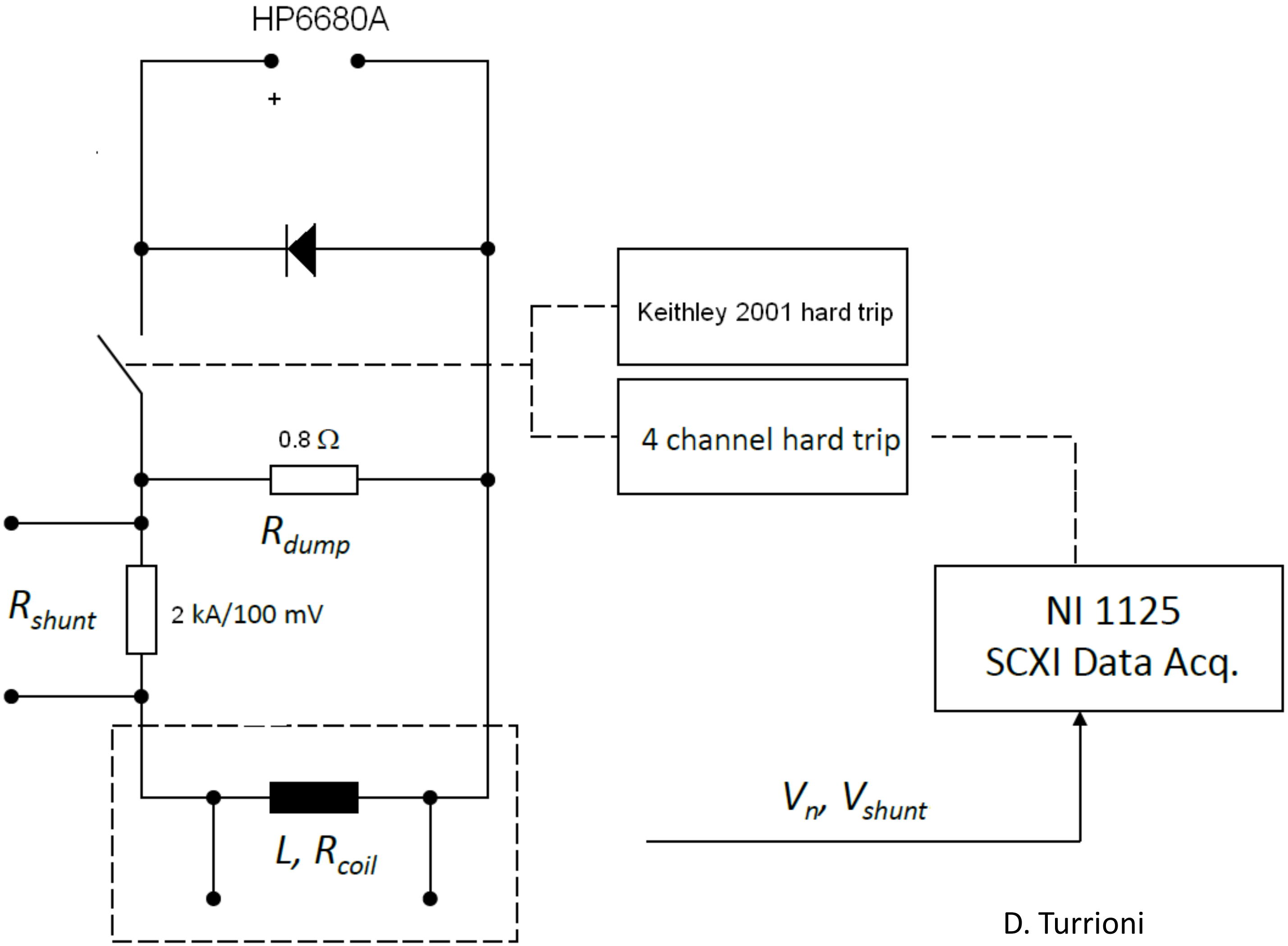
Final Assembly of 4 Double Pancake Coils

The final assembly before instrumentation and final SS wrap



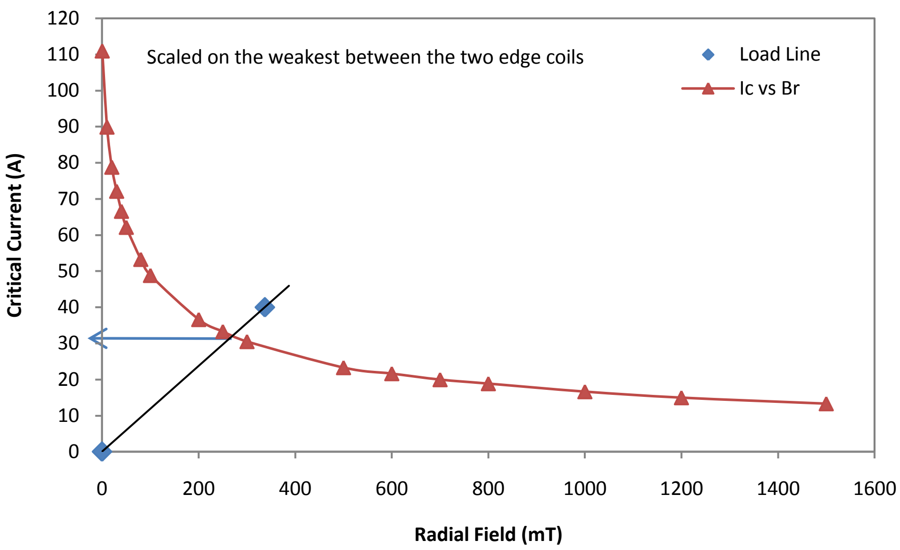


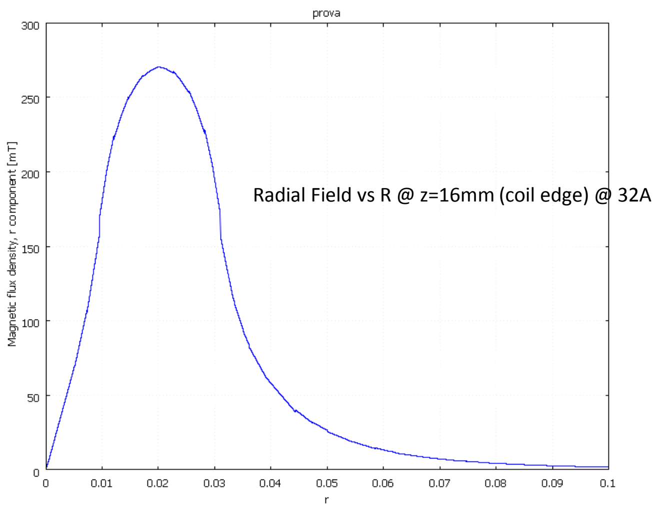
Quench protection

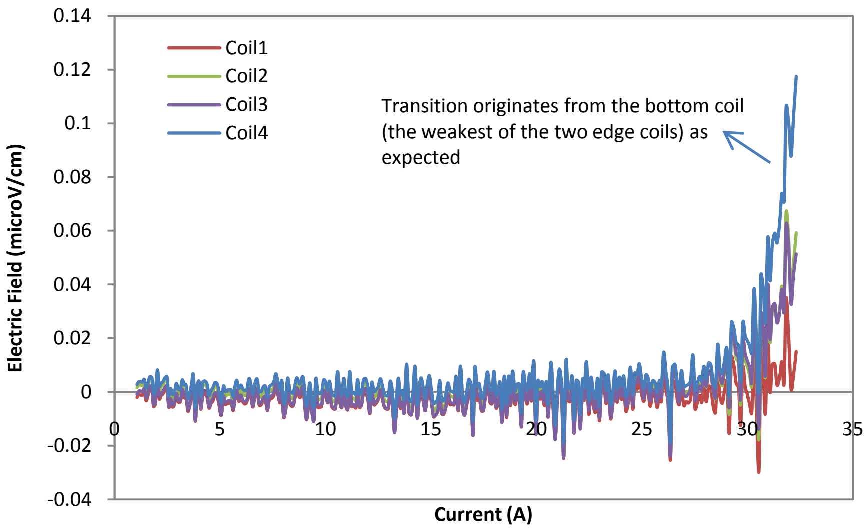


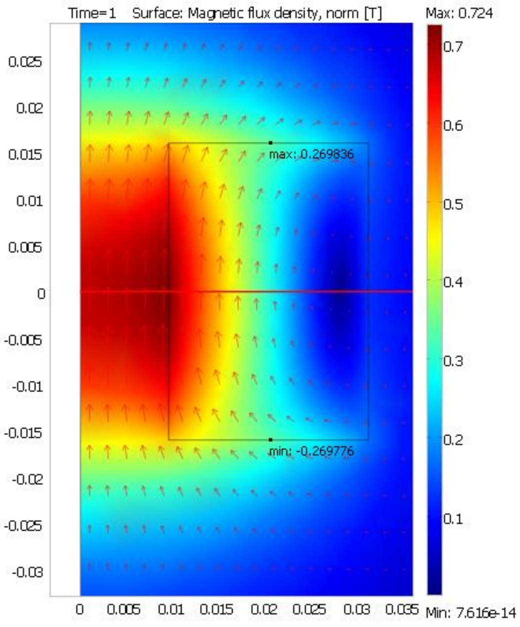
D. Turrioni

4coils Liquid Nitrogen test

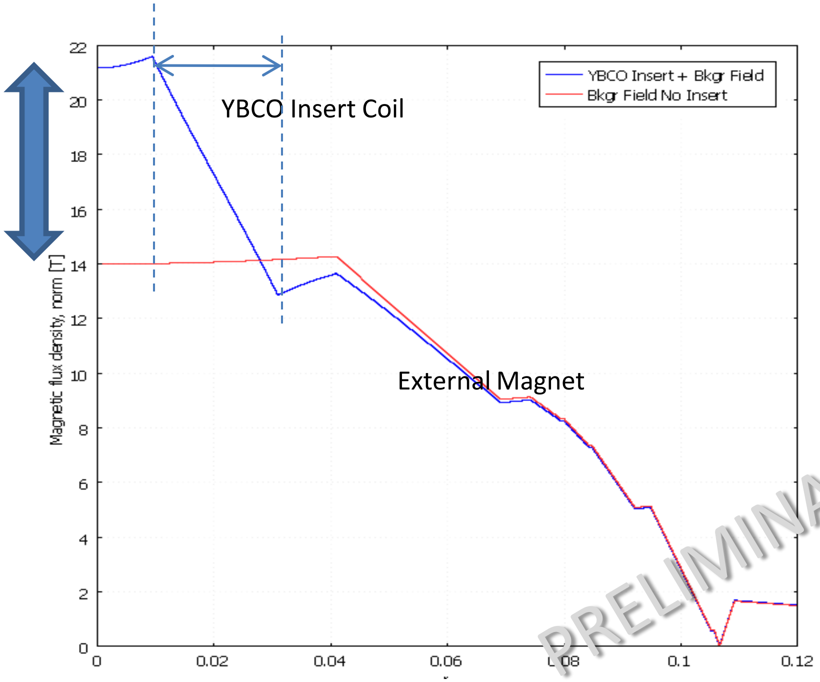


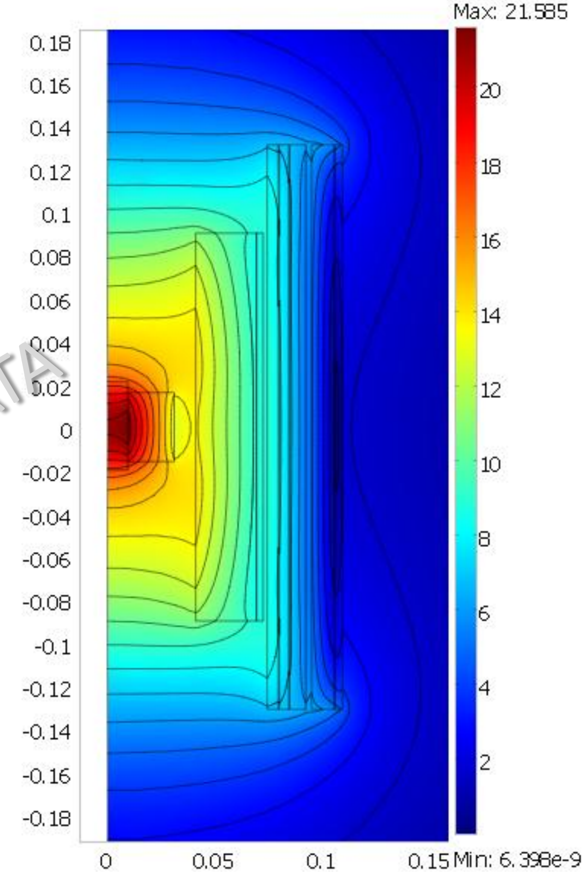


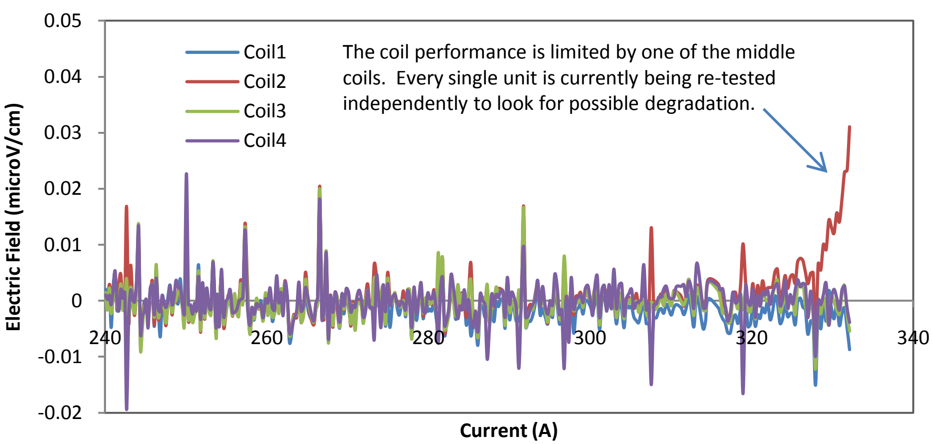




4coils Liquid Helium Test --- 21.2T in 14T bkgr field







Max Current Reached	335A
SSL	92%
Peak Field on Conductor	21.5T
Peak Axial Field	21.2T

Improvements and Questions

Needed Improvements

1. Splicing over small diameters is extremely delicate. Splicing and unsplicing YBCO without damaging the conductor is even harder. More effort will be needed in making reproducible curved splices between coils.
2. Quench development studies at field adding heaters to induce quench and monitor voltage/temp could help at this stage of development. Given the small NZPV in CC (few cm/s) if the area responsible for voltage integration is localized (a few mm) due to manufacturing defects (i.e. poor copper stabilization or locally low Ic), stress concentration or bad splice, temp can rise locally before any voltage is detected.

Some questions (among the others)

1. How good is Ic(B ,Theta) reproducibility between different production runs ?
2. And within the same run ? Almost impossible to assess at 4.2K, no easy way to setup an online rig for measurements.
3. How does Ic vs B,theta @ 4.2K correlates to Ic(77K,SF) ? Is linear scaling good enough ? Uniformity of Ic(B,theta) could be measurable online, but might not directly correlate to 4.2K

[…]

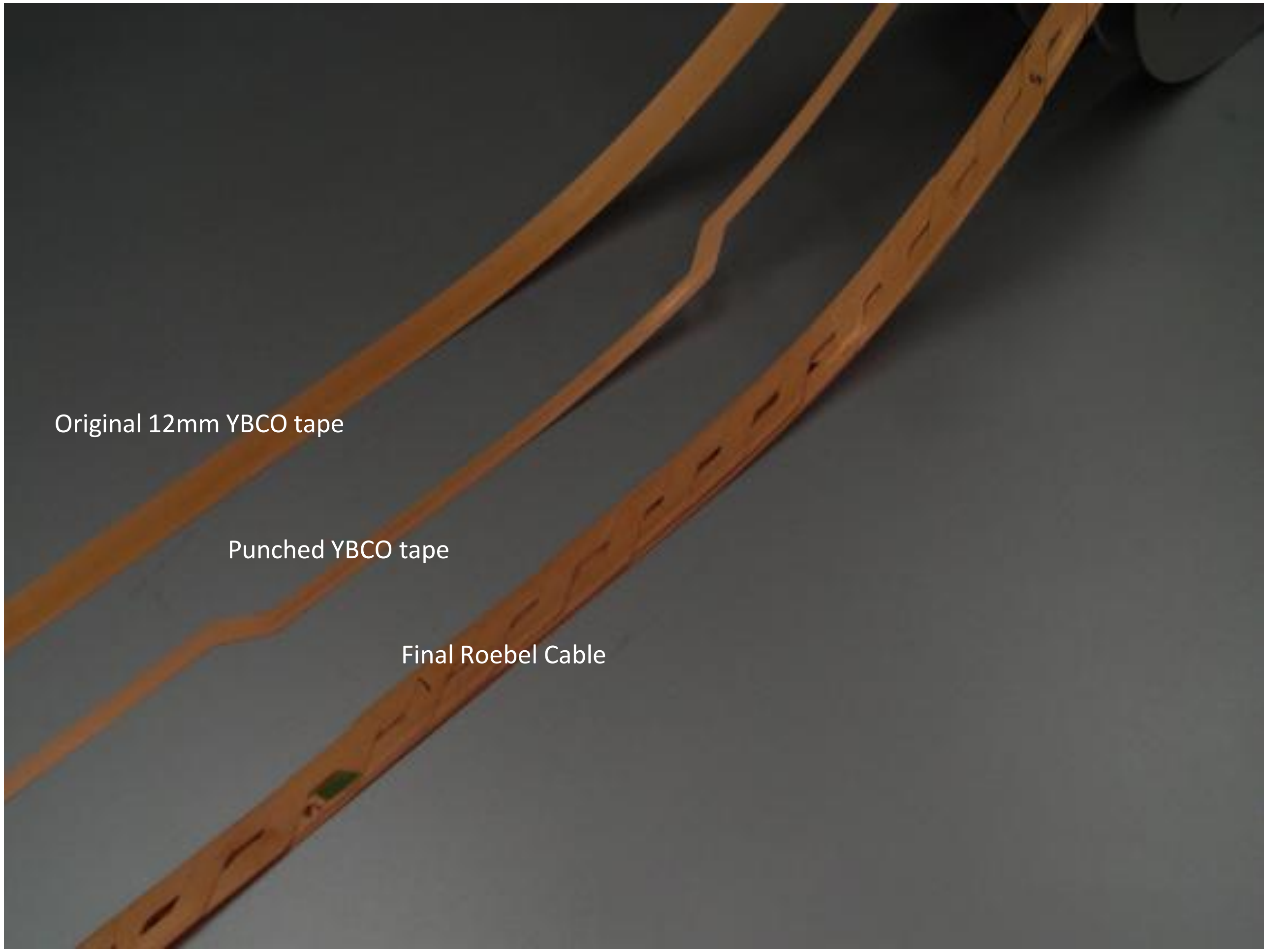
And finally

Can we push accelerator quality dipole and quadrupole magnets beyond Nb_3Sn using YBCO ?

- High Ic uniformity over long lengths
- Lower cost (?)
- A reliable way of cabling coated conductors is badly needed (see next slide)

Fermilab

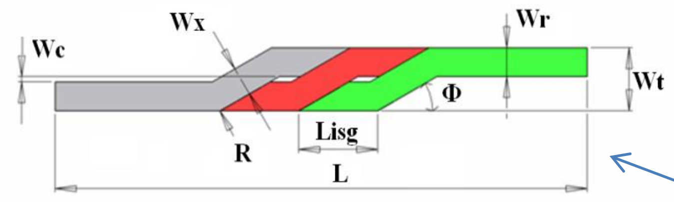
Cabling YBCO tapes ? The ROEBEL approach



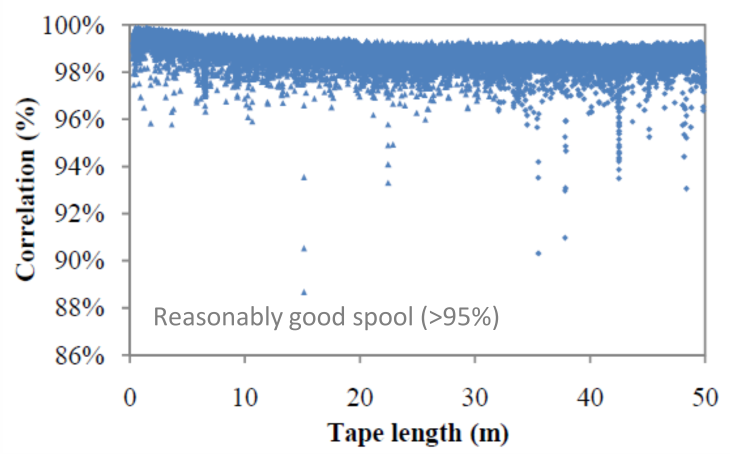
V. Lombardo, E. Barzi, D. Turrioni, A.V. Zlobin, N.J. Long and R.A. Badcock, *"Fabrication, Qualification and Test of High Jc ROEBEL YBCO Coated Conductor Cable for HEP magnets"* - Presented at Applied Superconductivity Conference (ASC 2010)

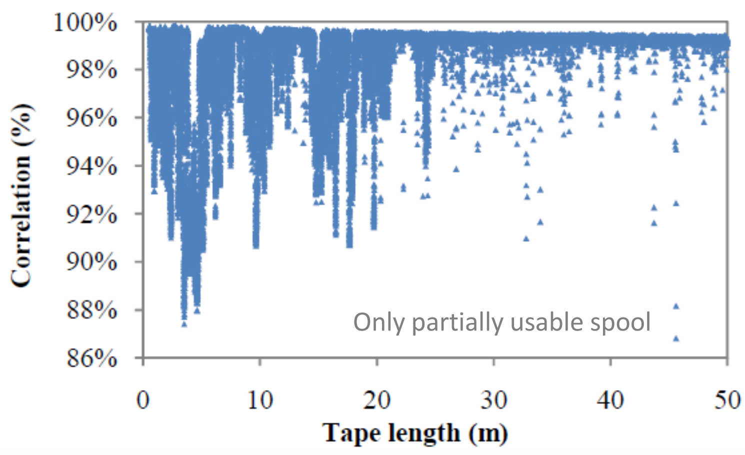
Cabling YBCO tapes ? The ROEBEL approach

- Choose the number of strand per cable and the strand geometry (15/5)



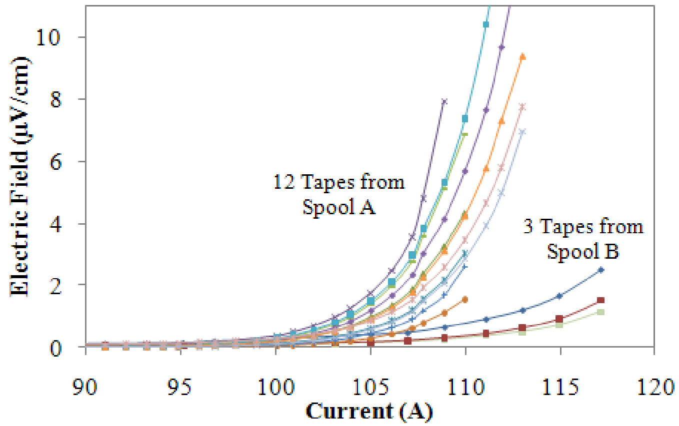
- Select the right 12mm wide YBCO conductor based on Ic uniformity over tape width. An online approach based on Hall sensors is used to measure field penetration along the width of the conductor. (commercial products are available for this)



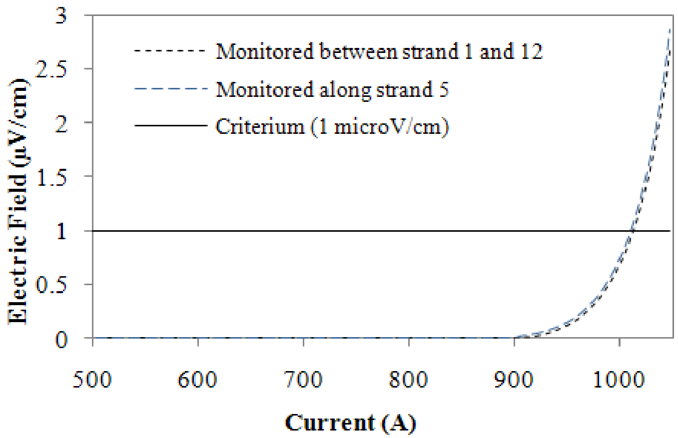


Cabling YBCO tapes ? The ROEBEL approach

- Test of Single Punched Tapes



- Test of Full Scale Cable in Nitrogen, Self Field



Next: What about 4.2K at field ?

Conclusions

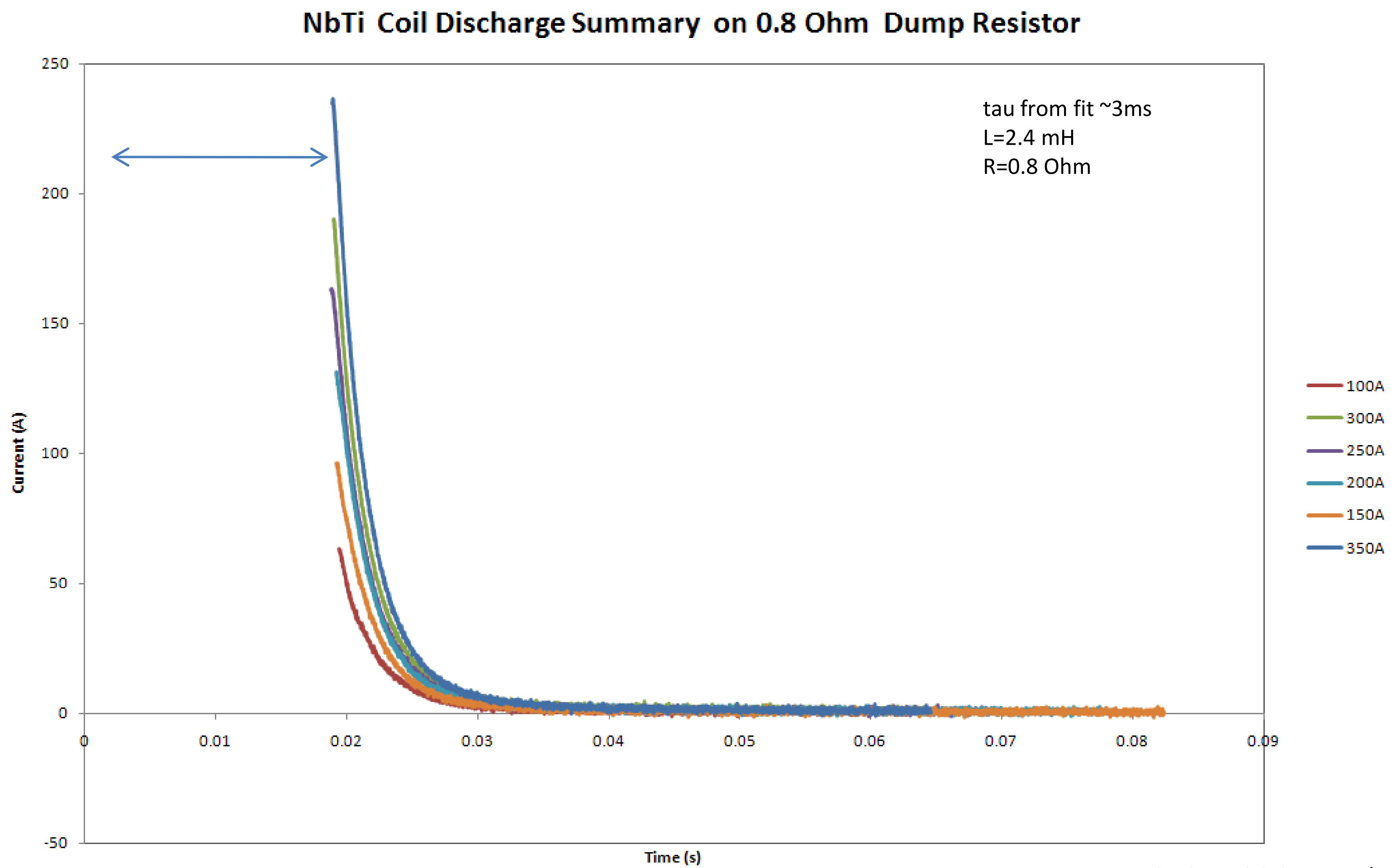
Massive amount of work to be done on many different aspects, given time and resources.

Among other aspects

- Improving conductor characterization at low temperature to better evaluate uniformity in terms of anisotropy at 4.2K.
- Tweaking some aspects of coil manufacturing.
- Study quench development in coils in liquid helium at field.
- Pushing cabling technology for accelerator quality dipole and quadrupole magnets.

Backup Slides

NbTi coil discharge



D. Turrioni, P. Vicini, V. Lombardo

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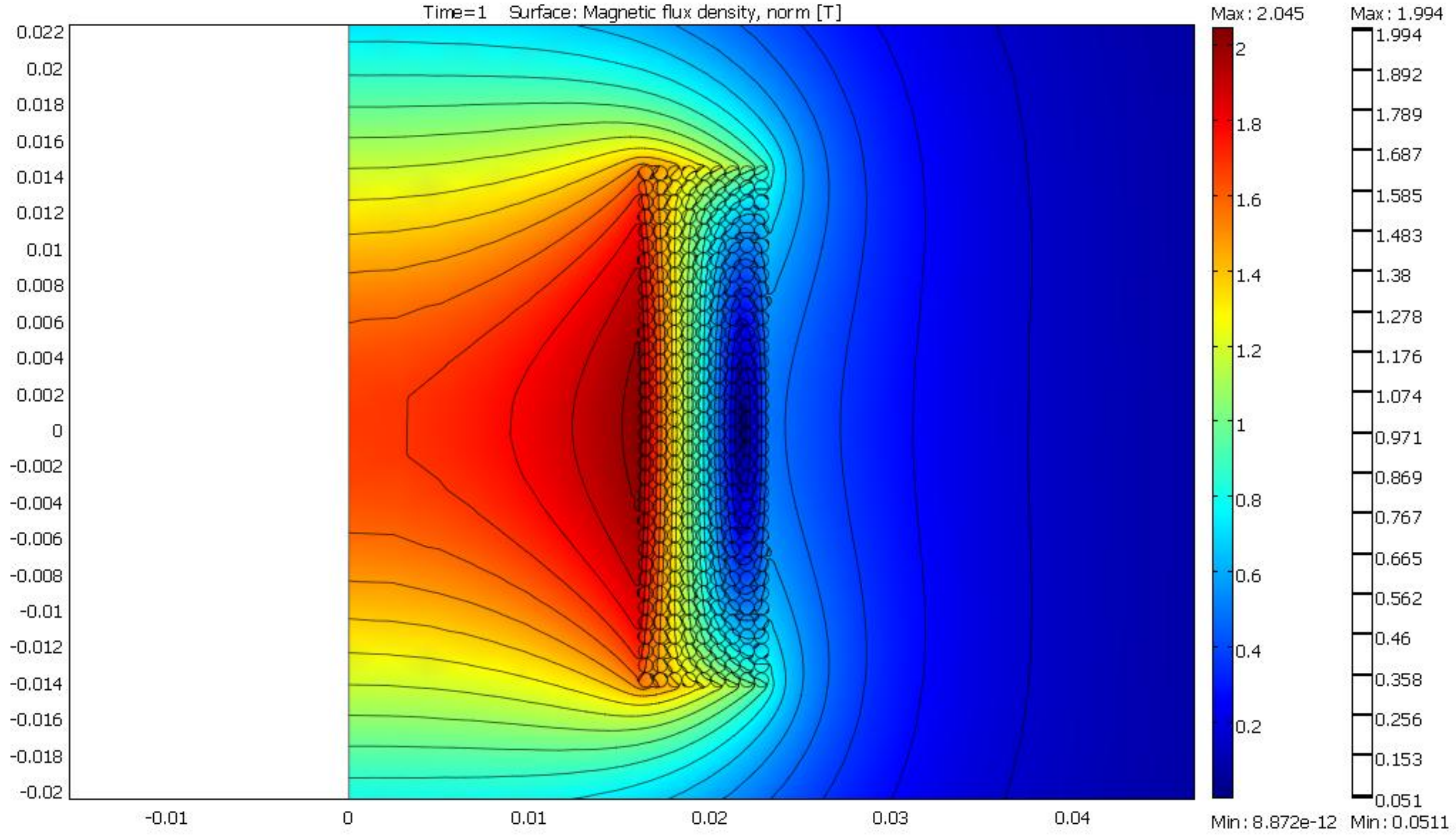
Magnetic Field Distribution in NbTi Coil @ I=200A



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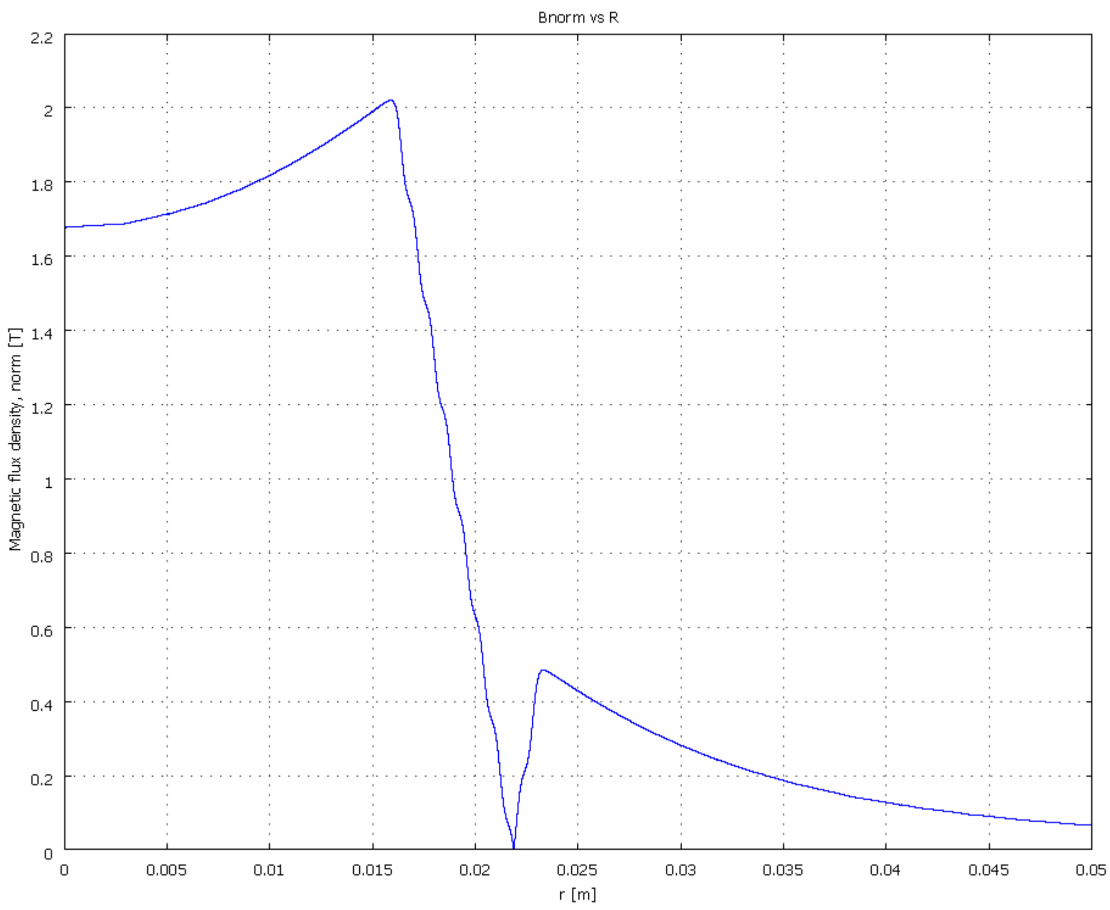
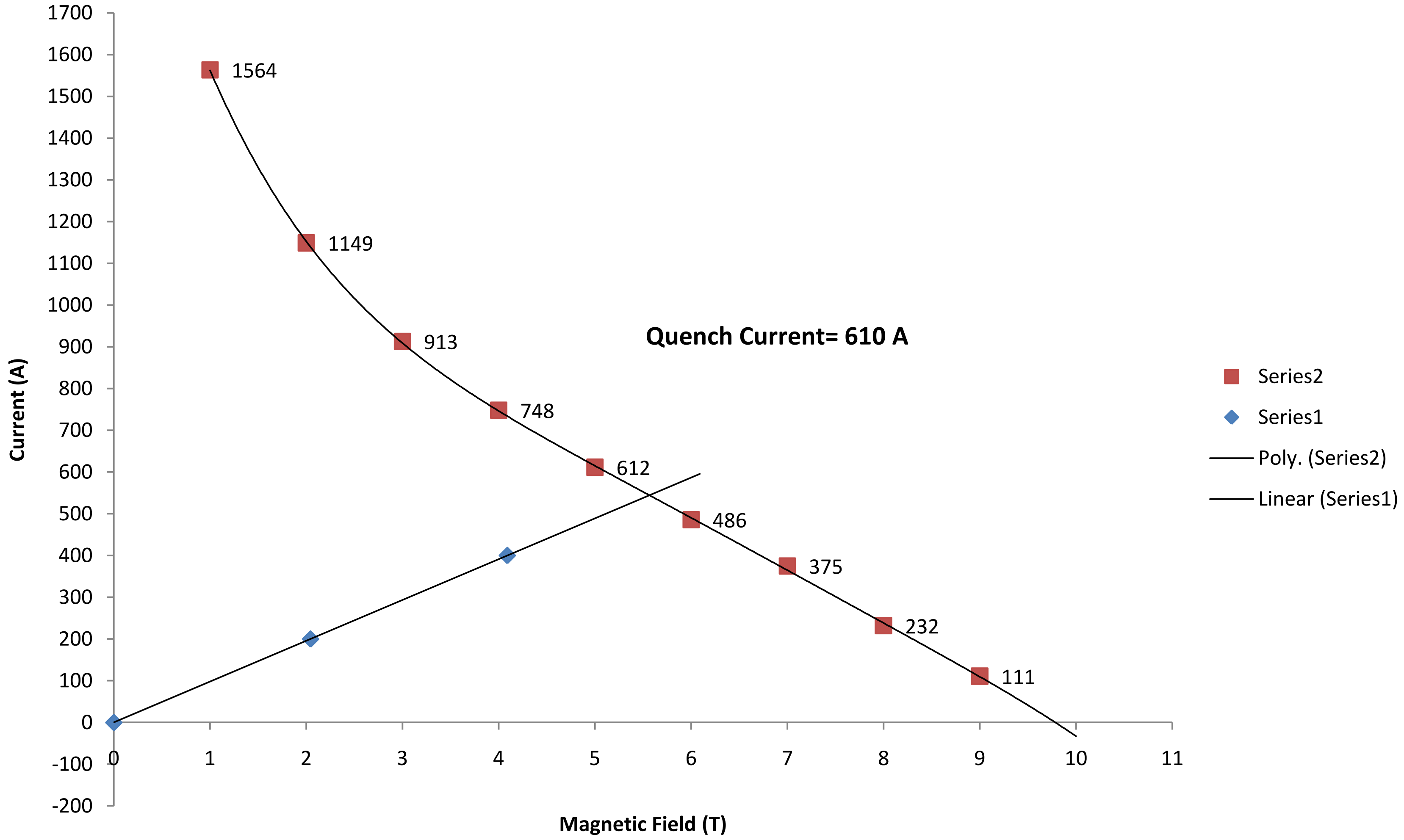
Magnetic Field Distribution in NbTi Coil @ I=200A



NbTi Coil Short Sample Limit Evaluation



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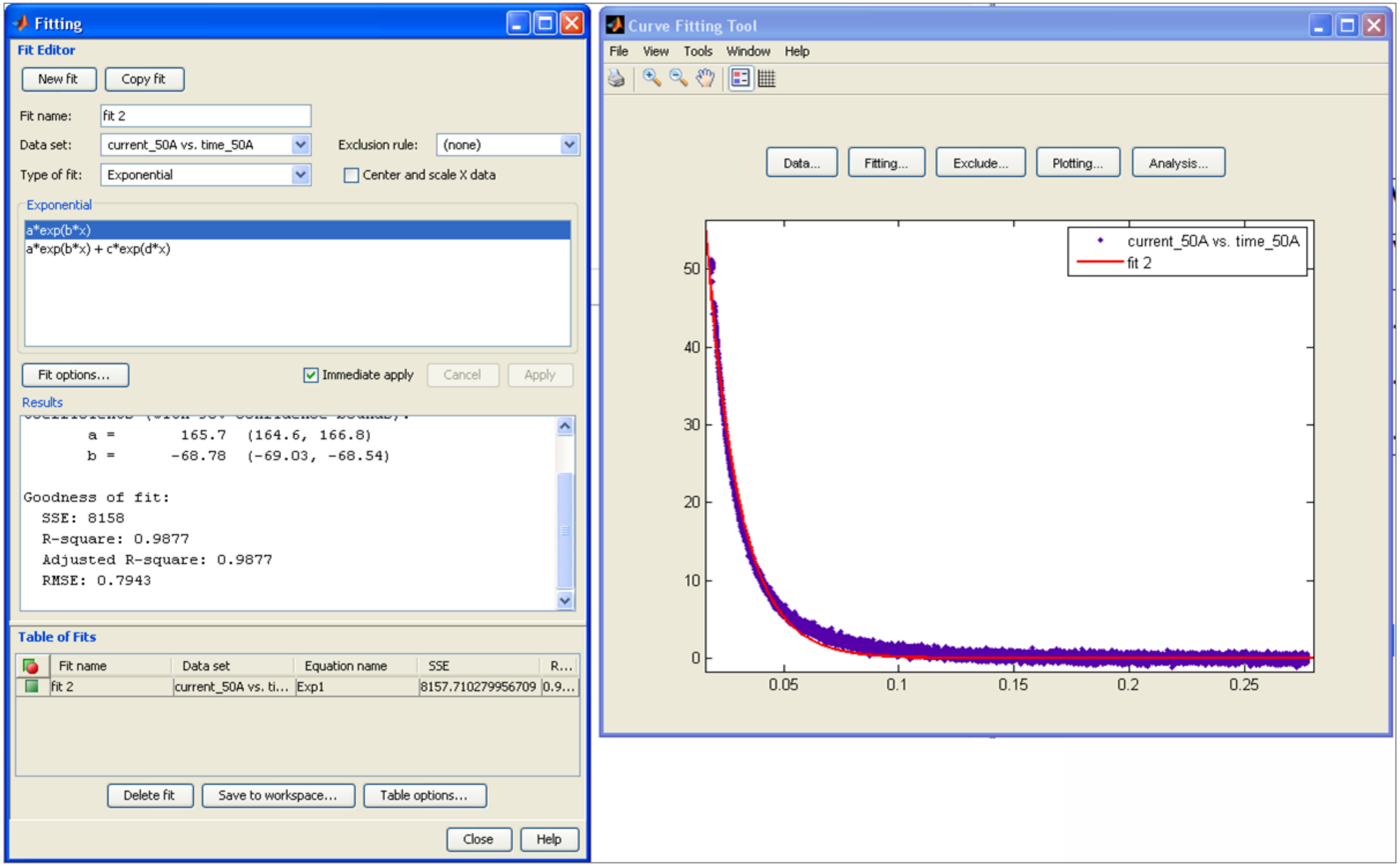
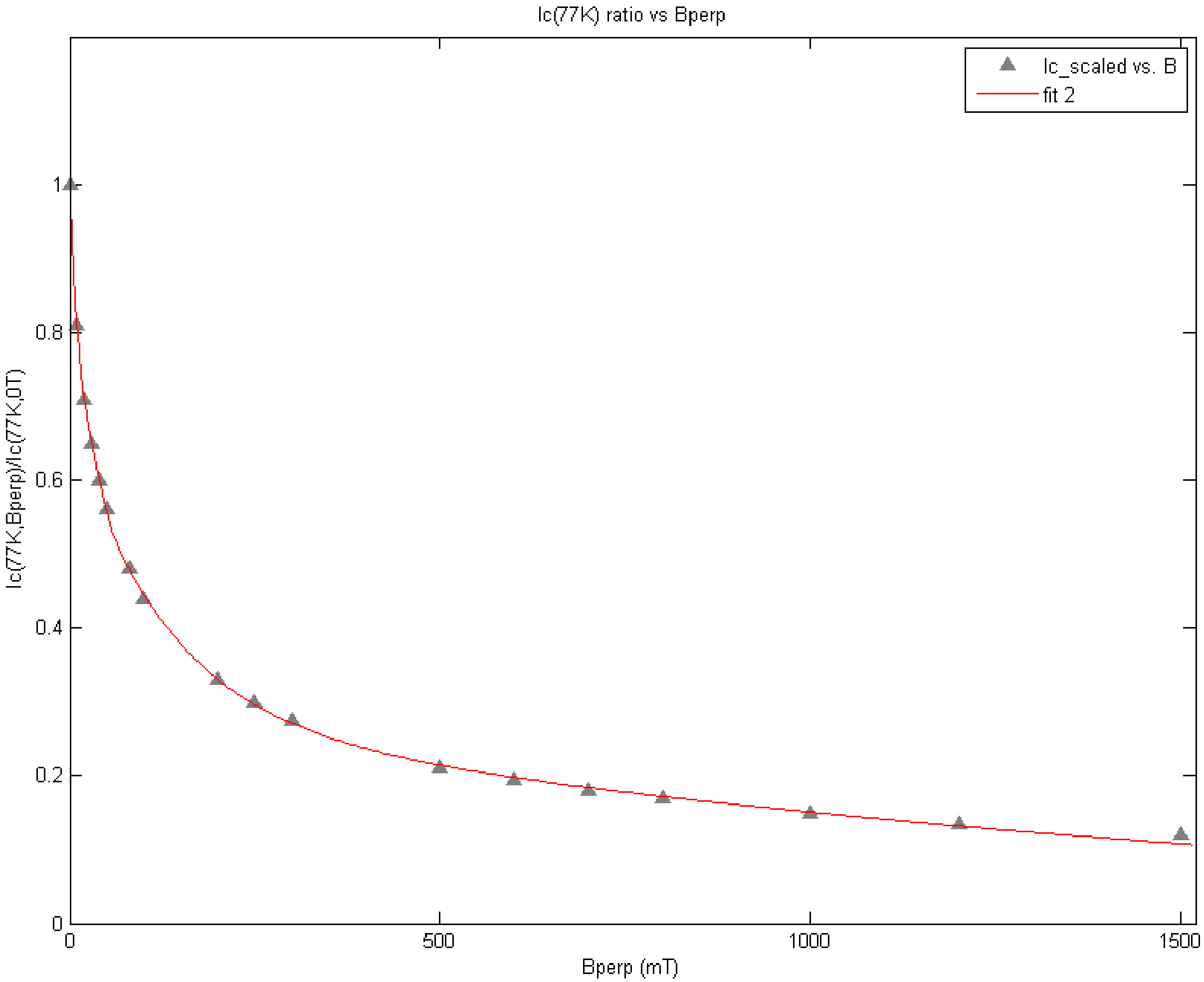
YBCO coil discharge



Ic(77K,Bperp) fit

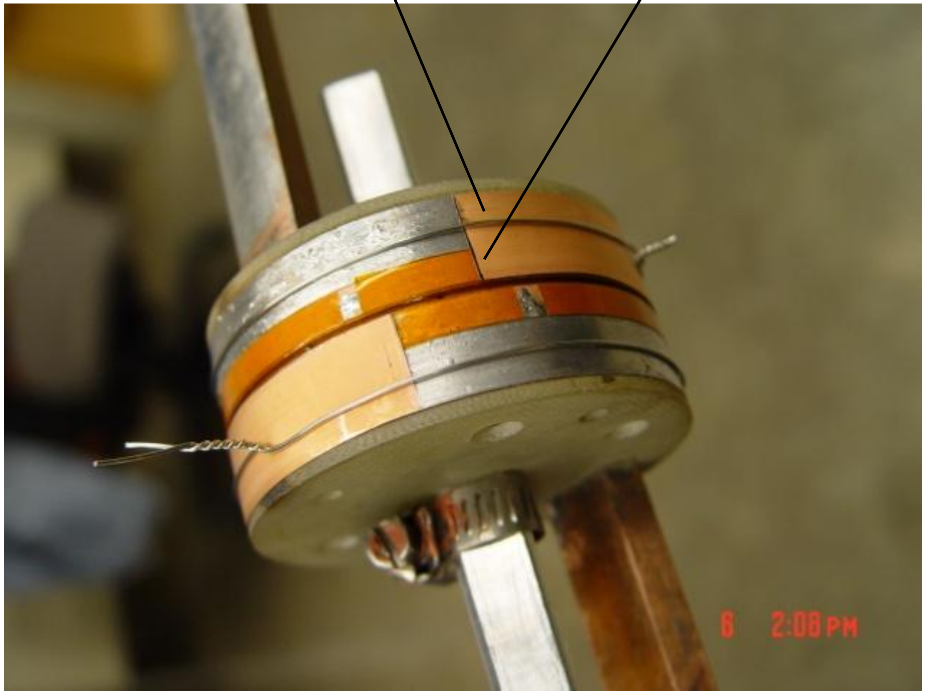


$$I_c(77K, B_{perp}) = I_c(77K, SF) \cdot \sum_{i=1}^{4} \left(a_i \cdot e^{-\left(\frac{x-b_i}{c_i}\right)^2} \right)$$

Joints

1) YBCO to Copper

2) YBCO to YBCO

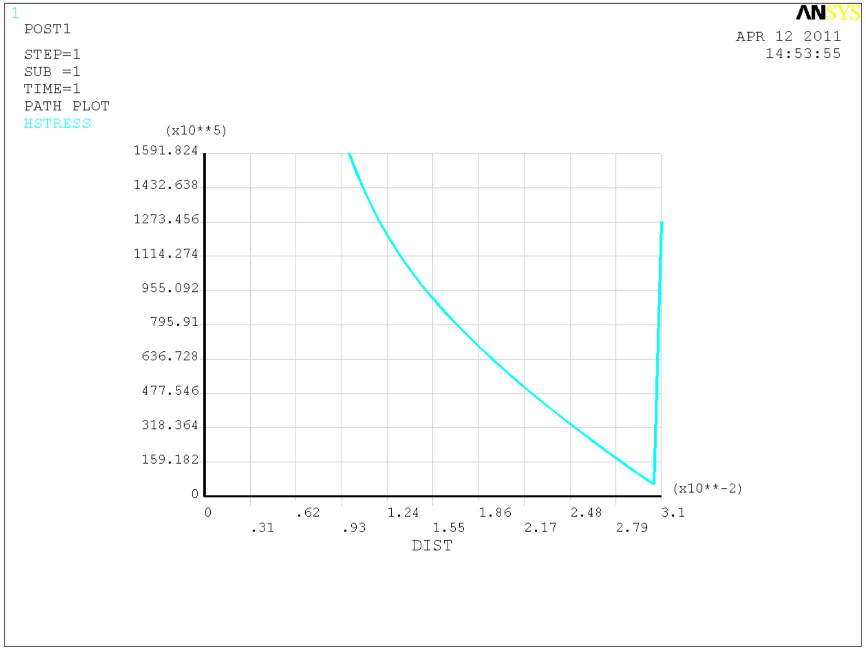


Stress evaluation

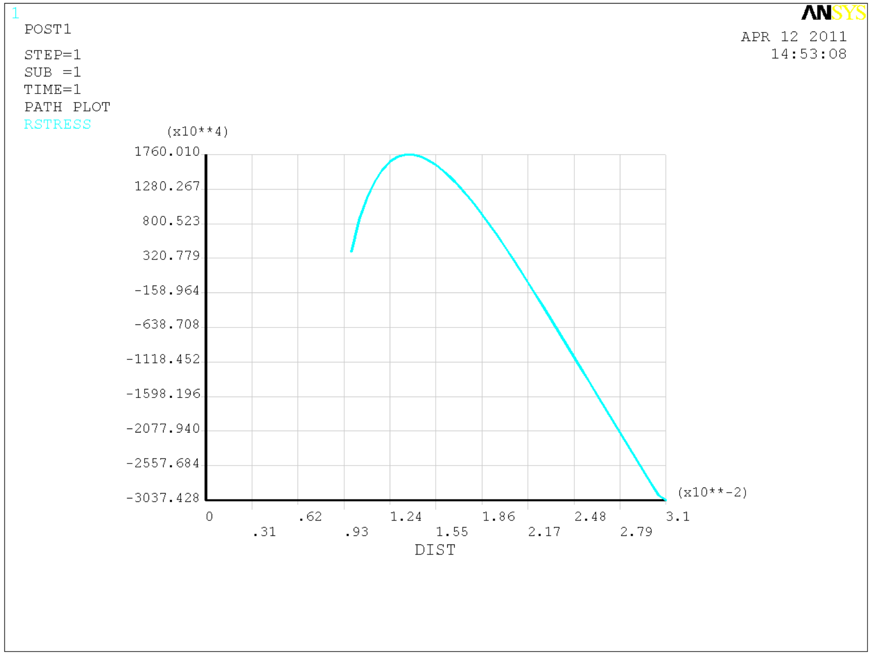
ID=19mm OD=62mm I=335A

Ansys Results

Hoop Stress*



Radial Stress*

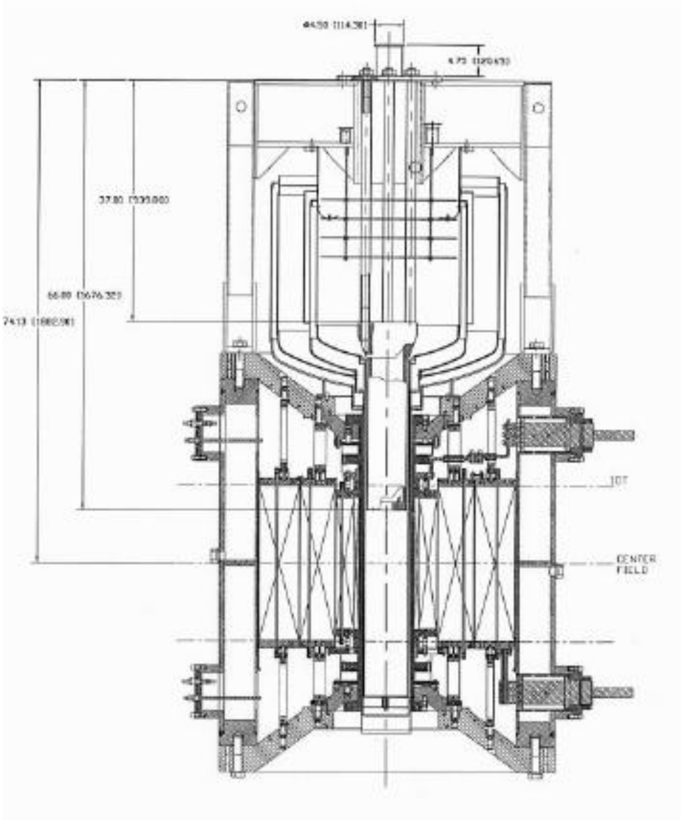


E. Barzi, A. Bartalesi, G. Gallo

*x [m], y[Pa]

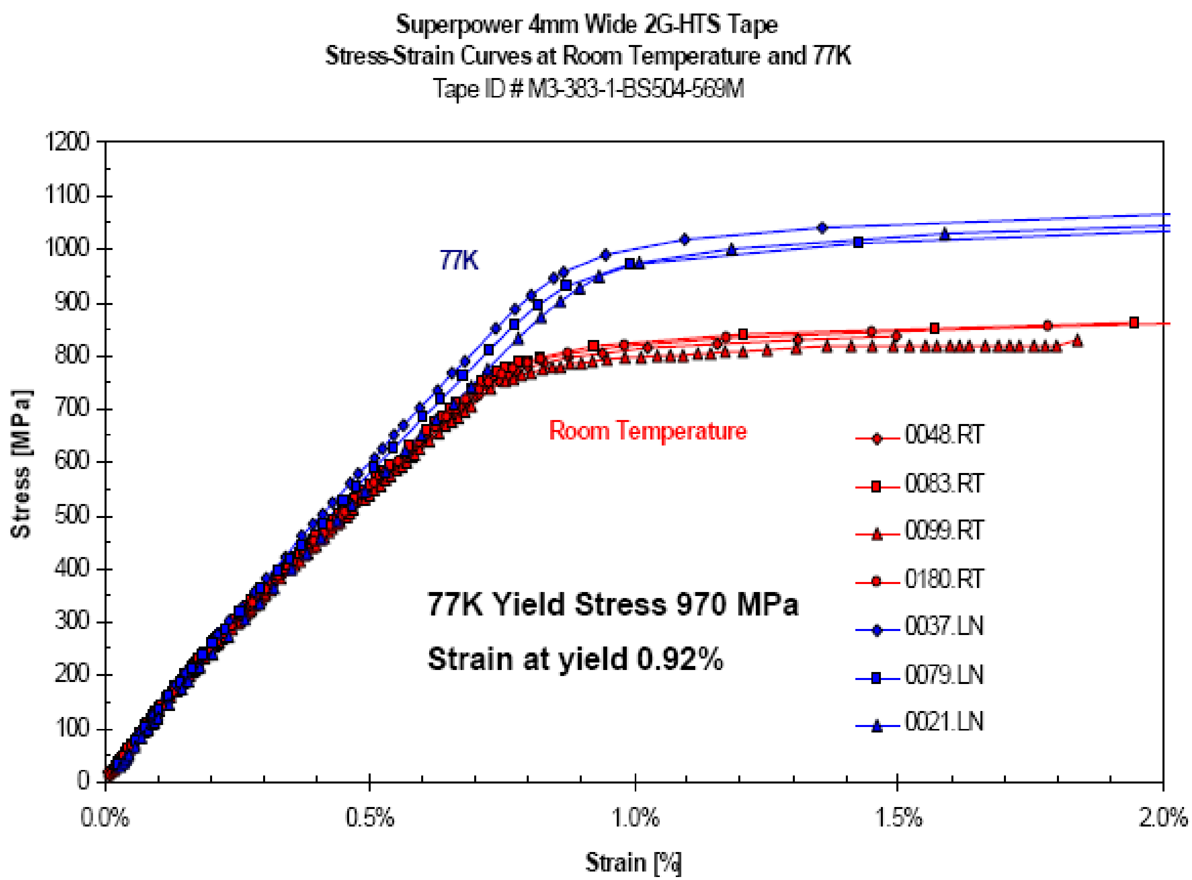
Coil ID	**9.5 mm (clear)**
Winding ID	**19.1 mm**
Winding OD	**~ 87 mm**
Coil Height	**~ 51.6 mm**
# of Pancakes	**12 (6 x double)**
2G tape used	**~ 462 m**
# of turns	**~ 2772**
Coil Je	**~1.569 A/mm^2 per A**
Coil constant	**~ 44.4 mT/A**

26.8 T @ 175 A in 19T bkgr
~ 44.5 mT/A



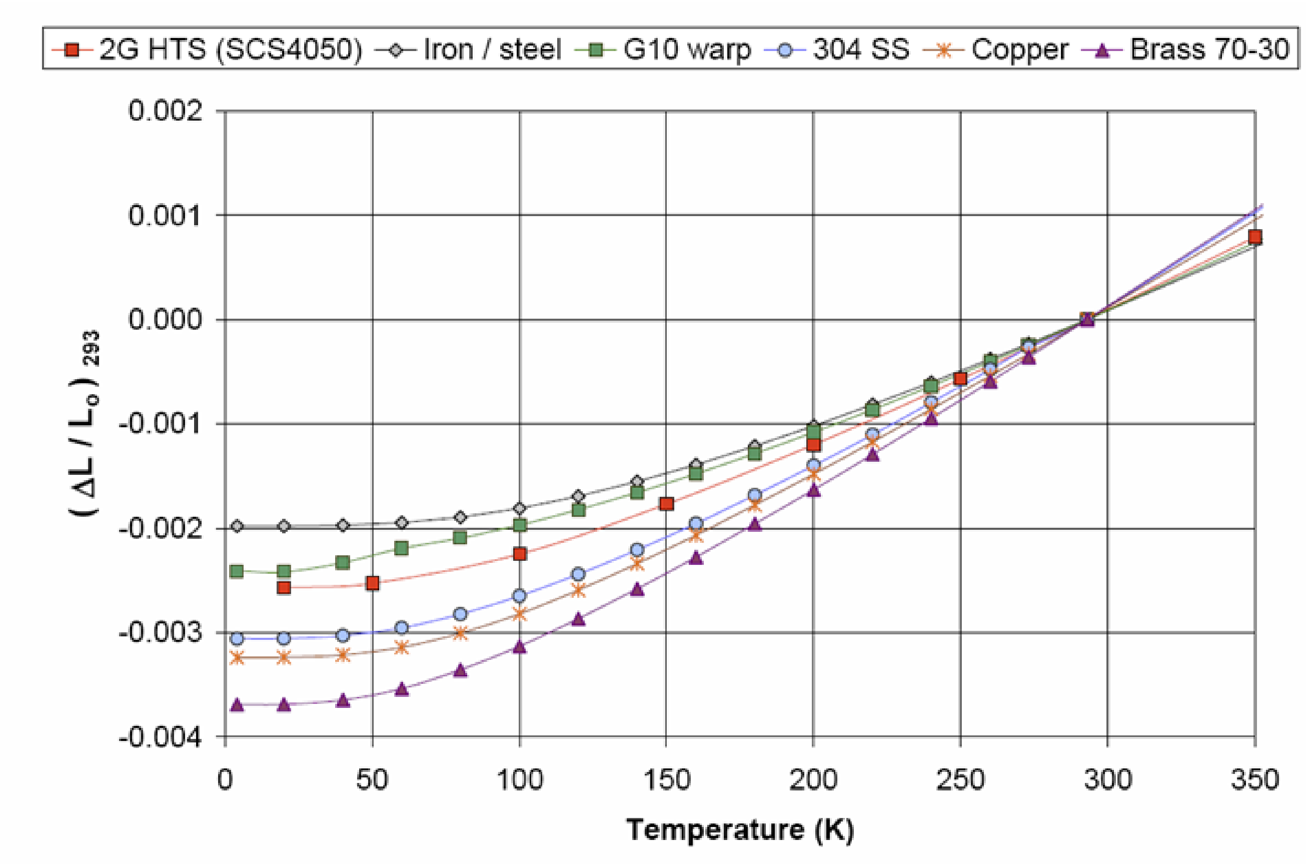
"2G HTS High Field Magnet Demonstration" – SuperPower and NHFML

Stress-Strain Curve for YBCO tapes



Data courtesy of SuperPower

Thermal coefficients



Data courtesy of SuperPower