$YBa_2Cu_3O_{7-\delta}$ Coil R&D for Muon Cooling

E. Barzi, G. Gallo, V. Lombardo, A. Rusy, E. Terzini, D. Turrioni, T. Van Raes, A. V. Zlobin
M. Yu, M.L Lopez, G. Flanagan, R.P. Johnson
Graduate Students: G. Norcia, A. Bartalesi, A. Cattabiani, P. Vicini

June 29, 2011

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Overview and Main References for HTS work

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, A.V. Zlobin, V.V. Kashikhin**

- E. Barzi - "Towards 50T Solenoids" - https://indico.fnal.gov/conferenceDisplay.py?confId=3148
- "Study of High Field Superconducting Solenoids for Muon Beam Cooling", V. V. Kashikhin et al.. IEEE Trans. Appl. Sup., V. 18, No. 2, p. 928 (2008)
- 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. E Terzini et al., FERMILAB-TM-2448-TD
- Co-wound and impregnated YBCO coil represented by meso-mechanic models. A. Bartalesi, FERMILAB-MASTERS-2009-04
- Magnetic models for insert and background field were developed to account for anisotropic behavior of YBCO tapes into magnet design.

3. **Insert Coil Development – 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. **Insert 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.

5. **High Field Helical Solenoid Coil Technology and Test**

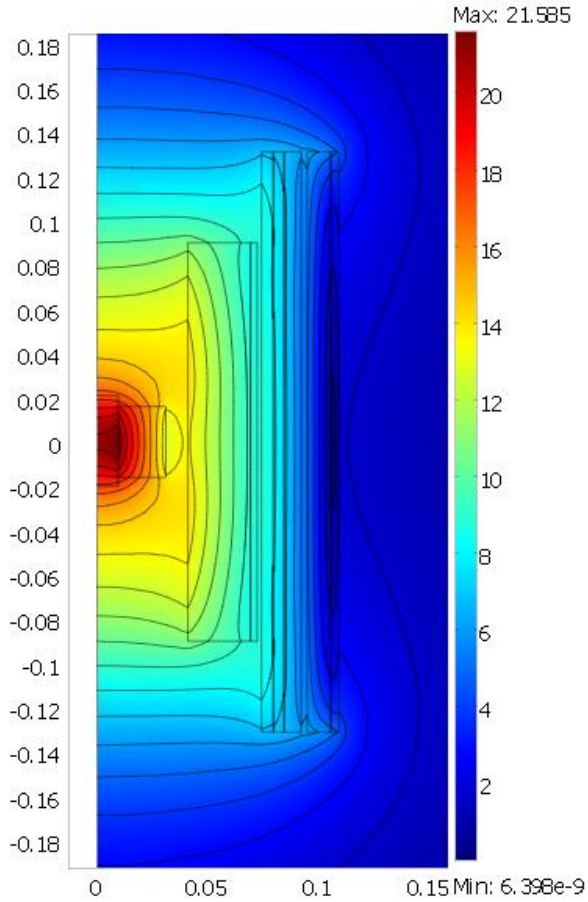
- M. L. Lopes et al. "Studies of the high-field section for a muon helical cooling channel"
- A. V. Zlobin et al. "Modeling the high-field section of a muon helical cooling channel"
- M. Yu et al. "Fabrication and test of shirt helical solenoid model based on ybco tape"

Talk Outline

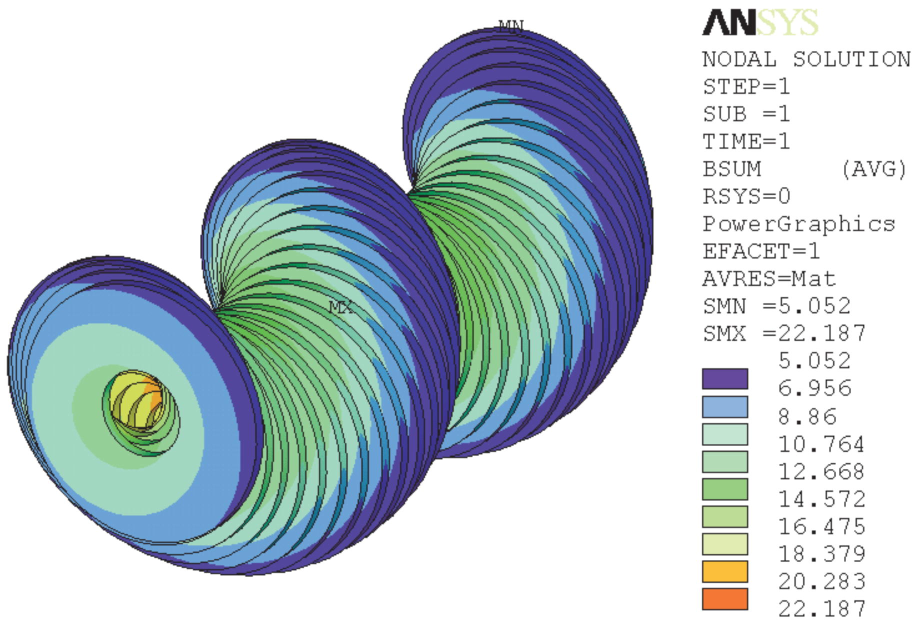
1. YBCO Coated Conductors
2. YBCO Insert Coils for High Field Magnets
    1. Overview of Manufacturing and Testing of YBCO insert coils
    2. How to account for anisotropy in YBCO magnet design both for self field and in-field operation
    3. Overview of Single and multi-pancake coil assembly
    4. Short sample predictions and test results at 77K and 4.2K at field
    5. High Current YBCO Cables?
3. YBCO Helical Solenoid Coils
    1. Overview of technology
    2. Challenges
4. Conclusions

Two YBCO applications of interest for MC community

YBCO Insert Solenoids
for very field magnet applications



YBCO Helical Solenoids
for high field section of HCC

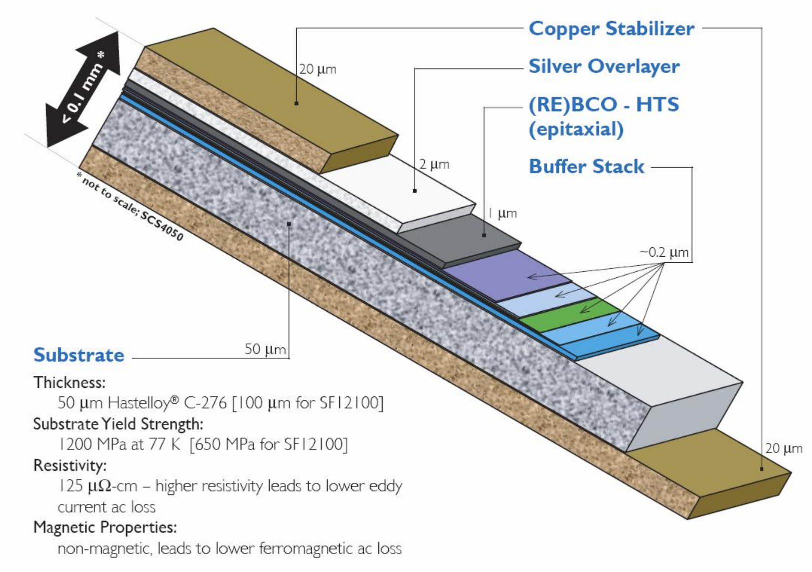


High ~~Temperature~~ Field Superconductors ?

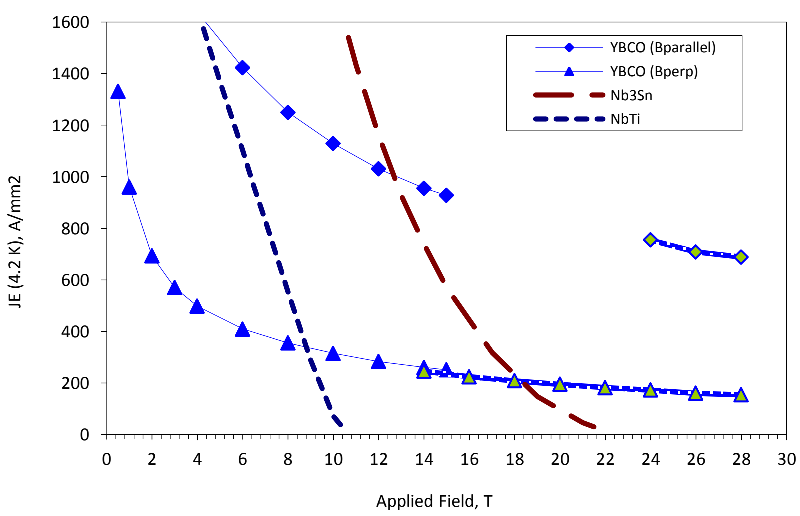
Moving to very high field magnets or magnets operating at 'high temperature' clearly requires moving past 'traditional' Low Temperature SC such as **Nb_3Sn** and **NbTi**

1. YBCO shows interesting Jc values at very high fields, very high Tc and mechanical proprierties.
2. YBCO comes as **SC tape** (0.1mm thickness) in **different widths** from 4mm to 12mm.
3. YBCO **does not require reaction**
4. YBCO shows s**trongly anisotropic behavior** with respect to field orientation, which needs to be accounted for during magnet design.
5. YBCO is available in **reasonably** long lengths for a ~~**reasonable**~~ price
6. Tight Ic **uniformity** over long lengths 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)

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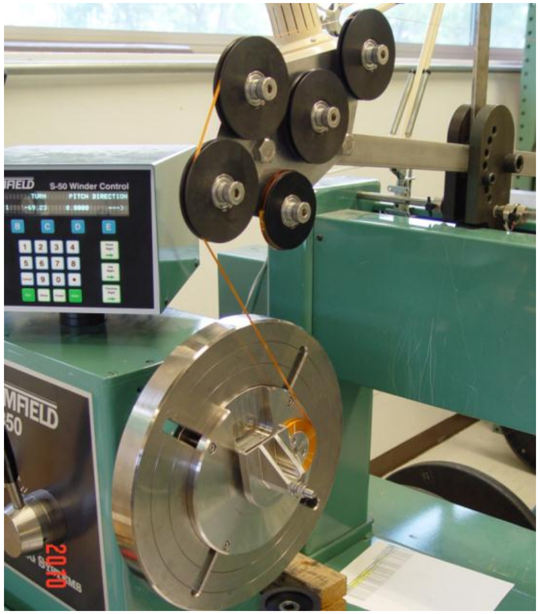
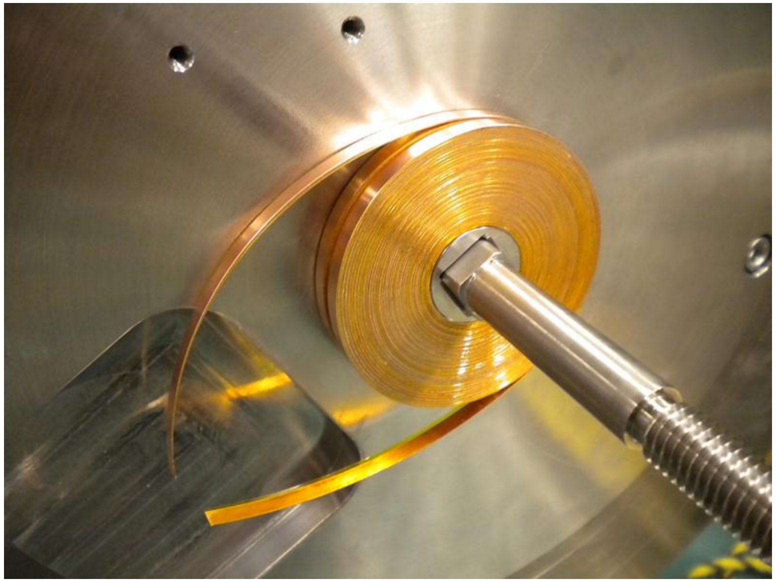
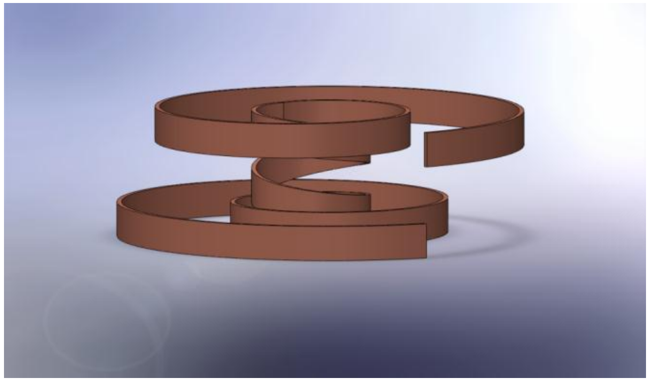
Muon Accelerator Program

Winding YBCO Insert Coils

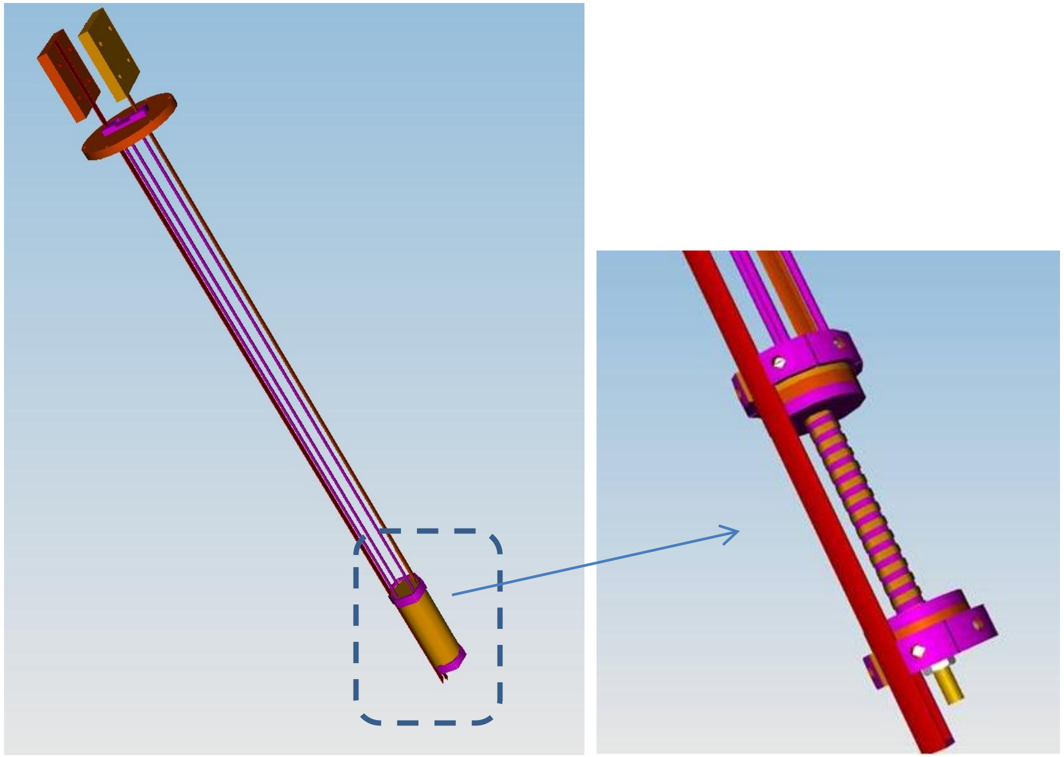






A. Bartalesi, V.Lombardo, A. Cattabiani.

Design and procurement of a setup for YBCO 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

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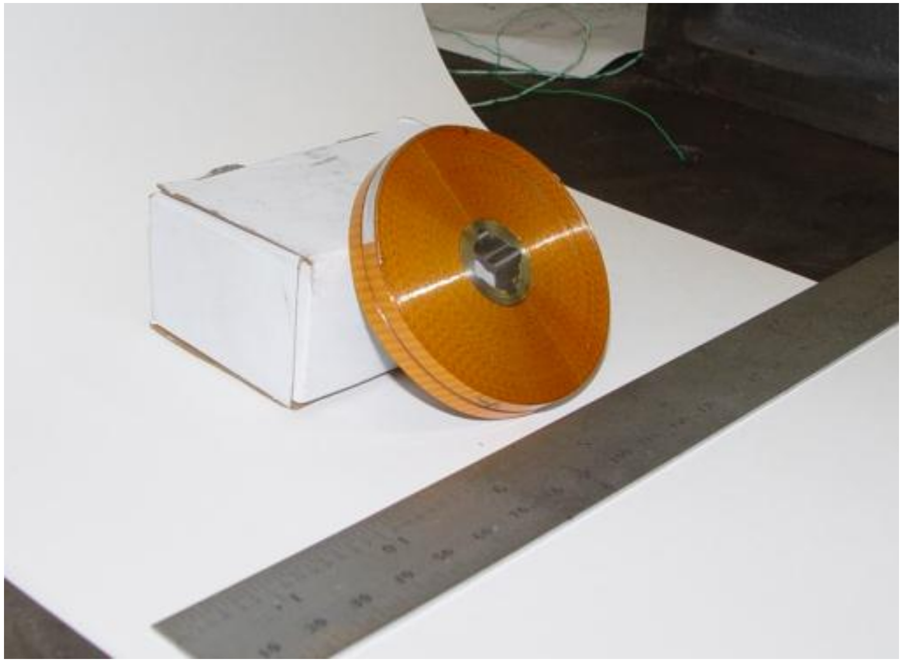
V. Lombardo, A. Bartalesi, E. Barzi, M. Lamm, D. Turrioni and A.V. Zlobin. *"Modular Test Facility for HTS Insert Coils"* – IEEE Trans. Appl. Sup., V. 20, No. 3, p. 587 (2010)

Muon Accelerator Program

Full-scale YBCO 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
Coil ID	19 mm
Coil OD	62 mm
Conductor Thickness	0.1 mm
Conductor + Insulation	0.2 mm
Packing Factor	50%
Turns per Single Coil	108
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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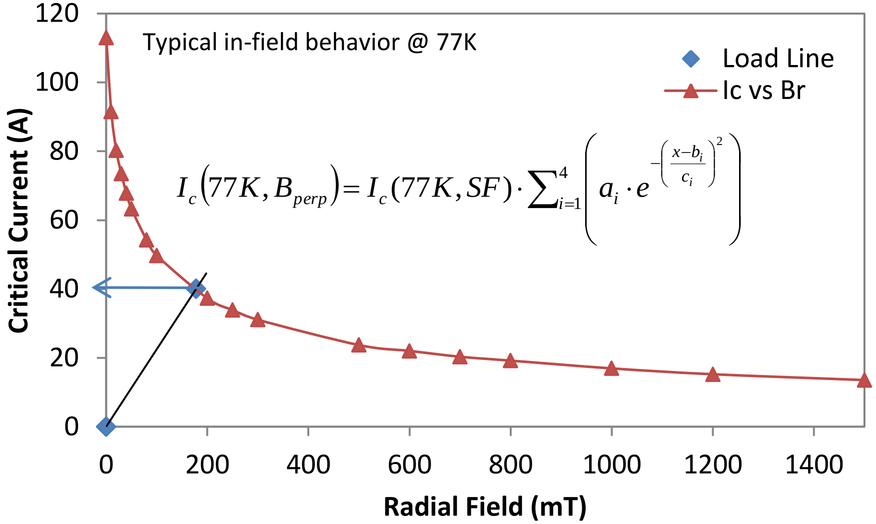
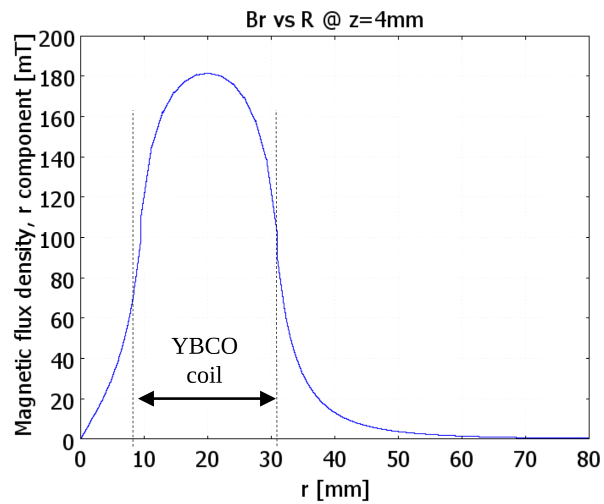
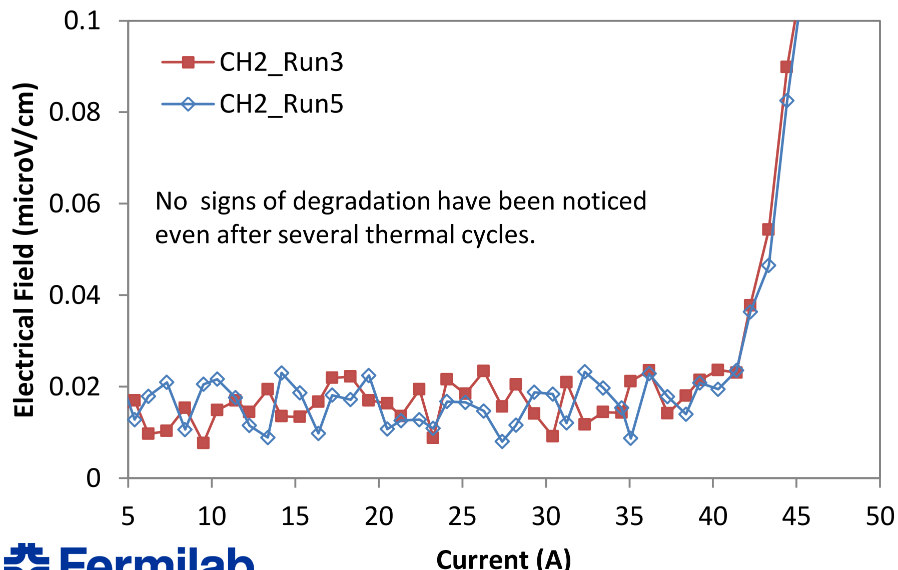
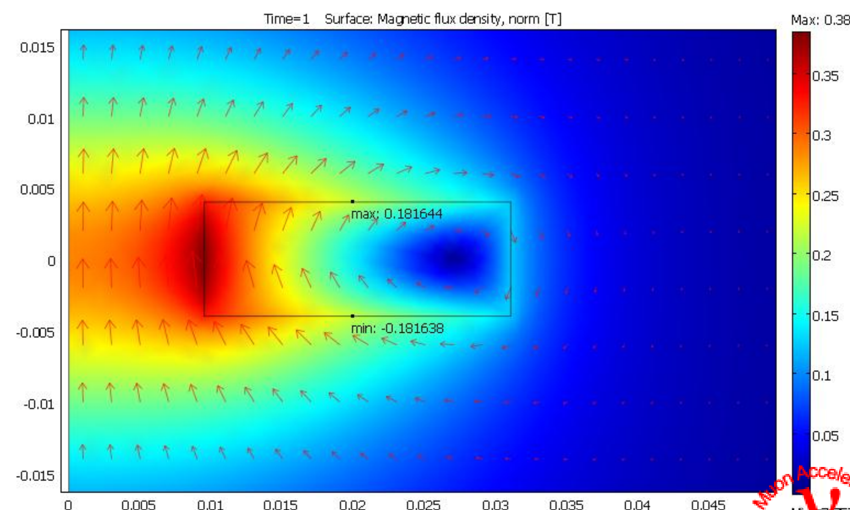
Accounting for anisotropy in Liquid Nitrogen, Self Field Test

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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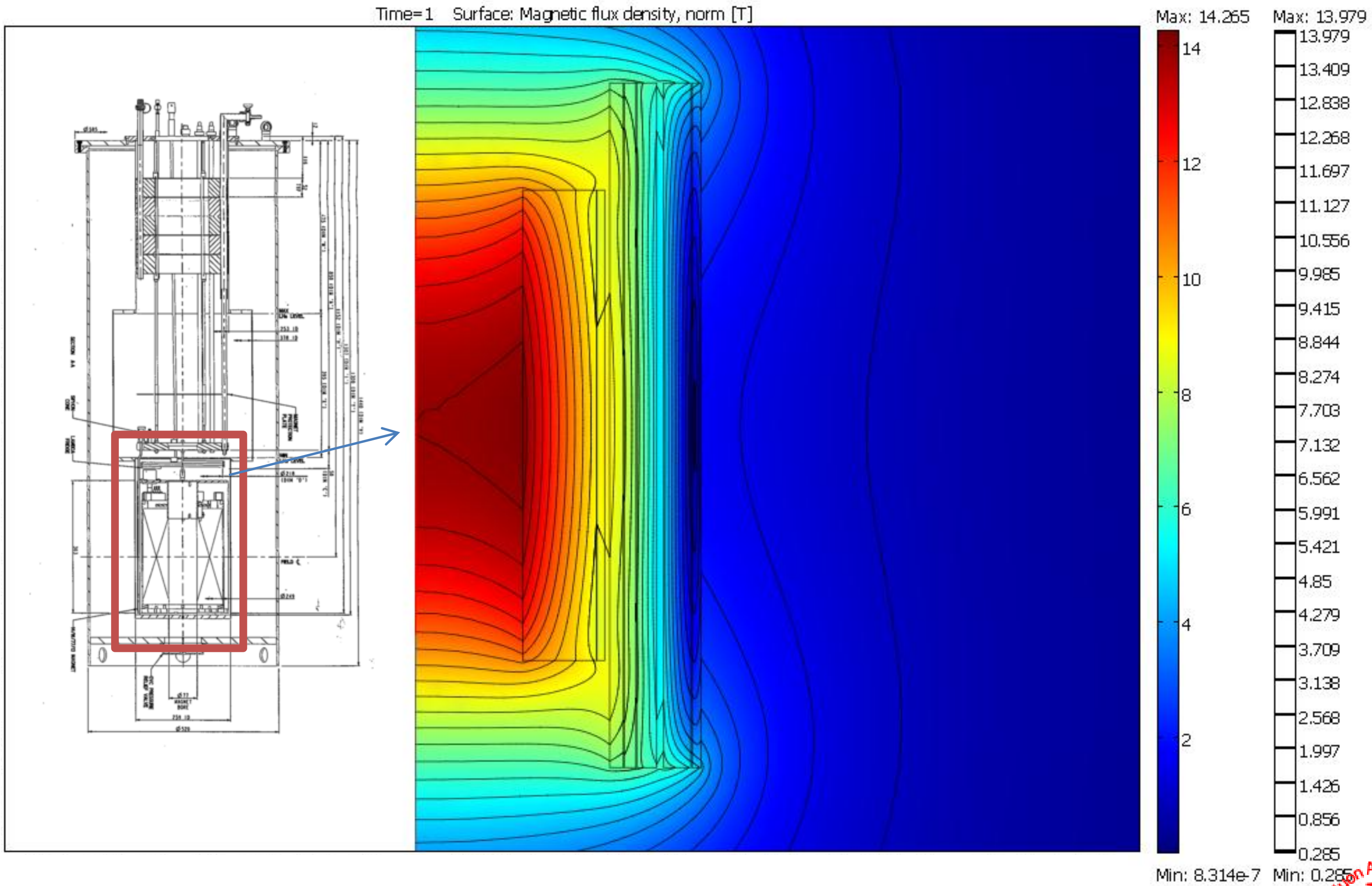
Accounting for anisotropy in Liquid Helium, In-Field Test

Magnetic field maps of outsert magnet are needed to fully understand insert coil performance



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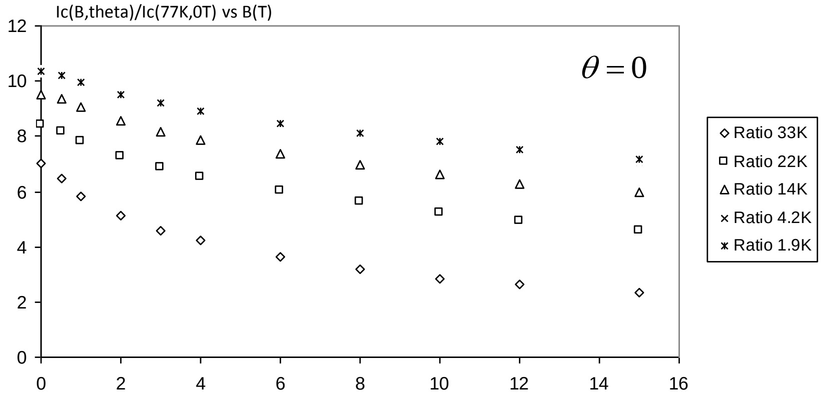
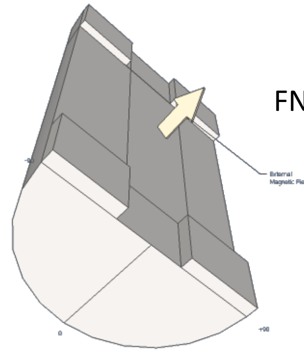
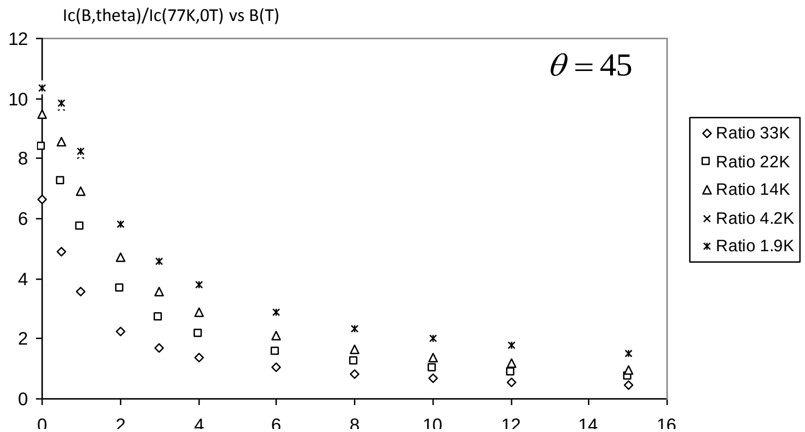
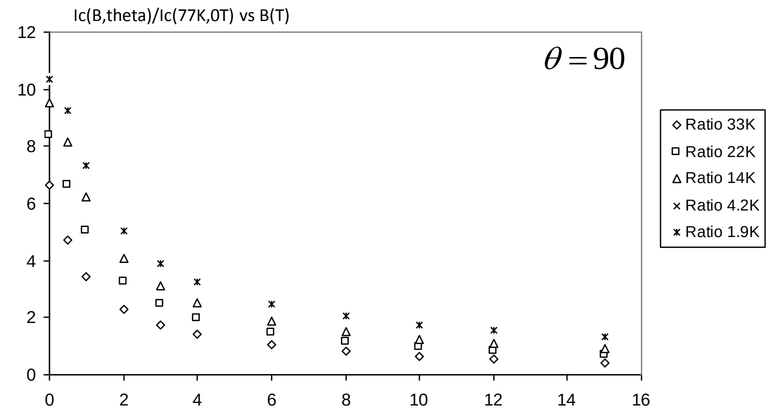


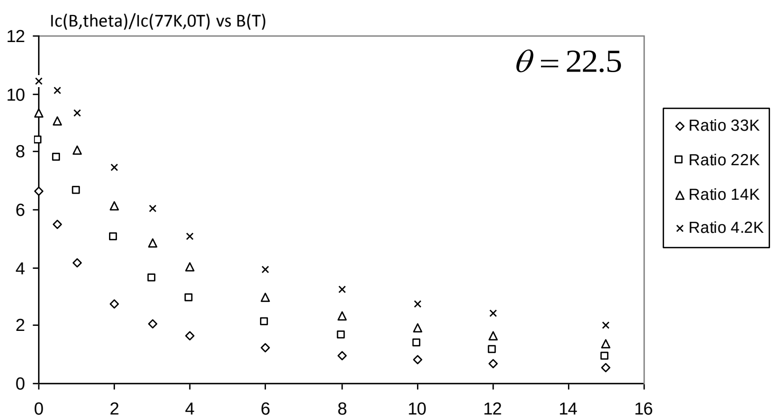


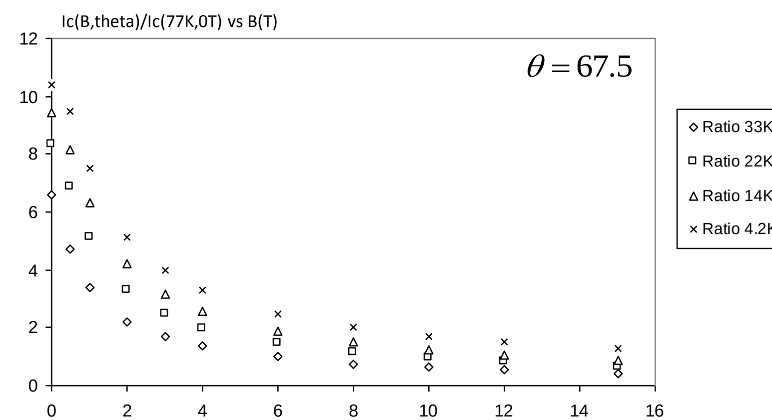
Angular measurements for SP YBCO

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









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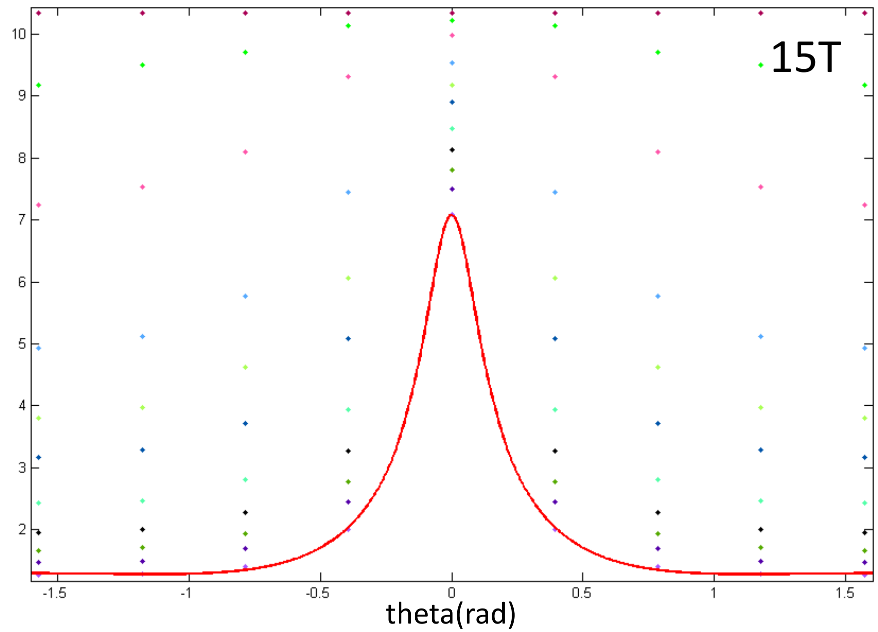
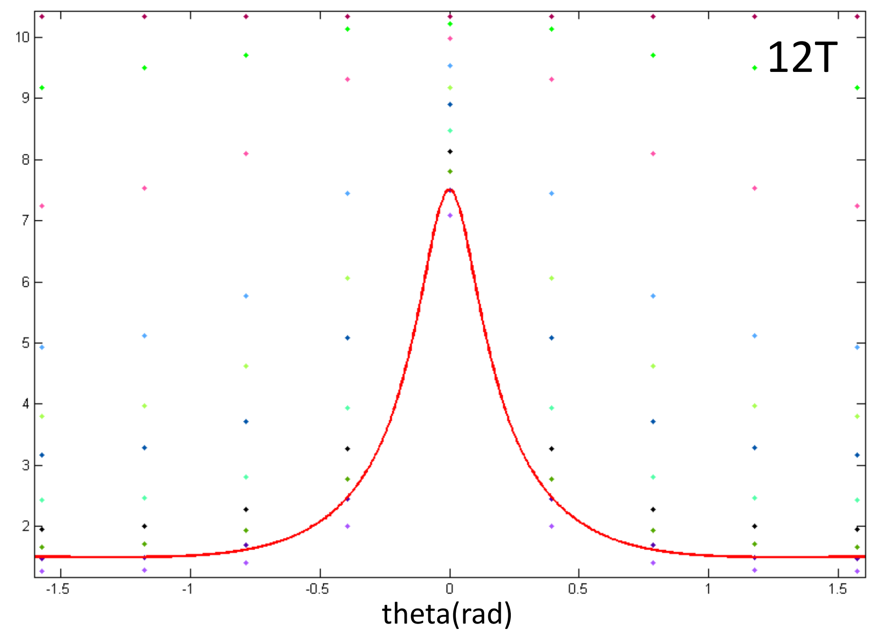
V. Lombardo, A. Bartalesi, E. Barzi, M. Lamm, D. Turrioni and A.V. Zlobin. *"Modular Test Facility for HTS Insert Coils"* - IEEE Trans. Appl. Sup., V. 20, No. 3, p. 587 (2010)

Muon Accelerator Program

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



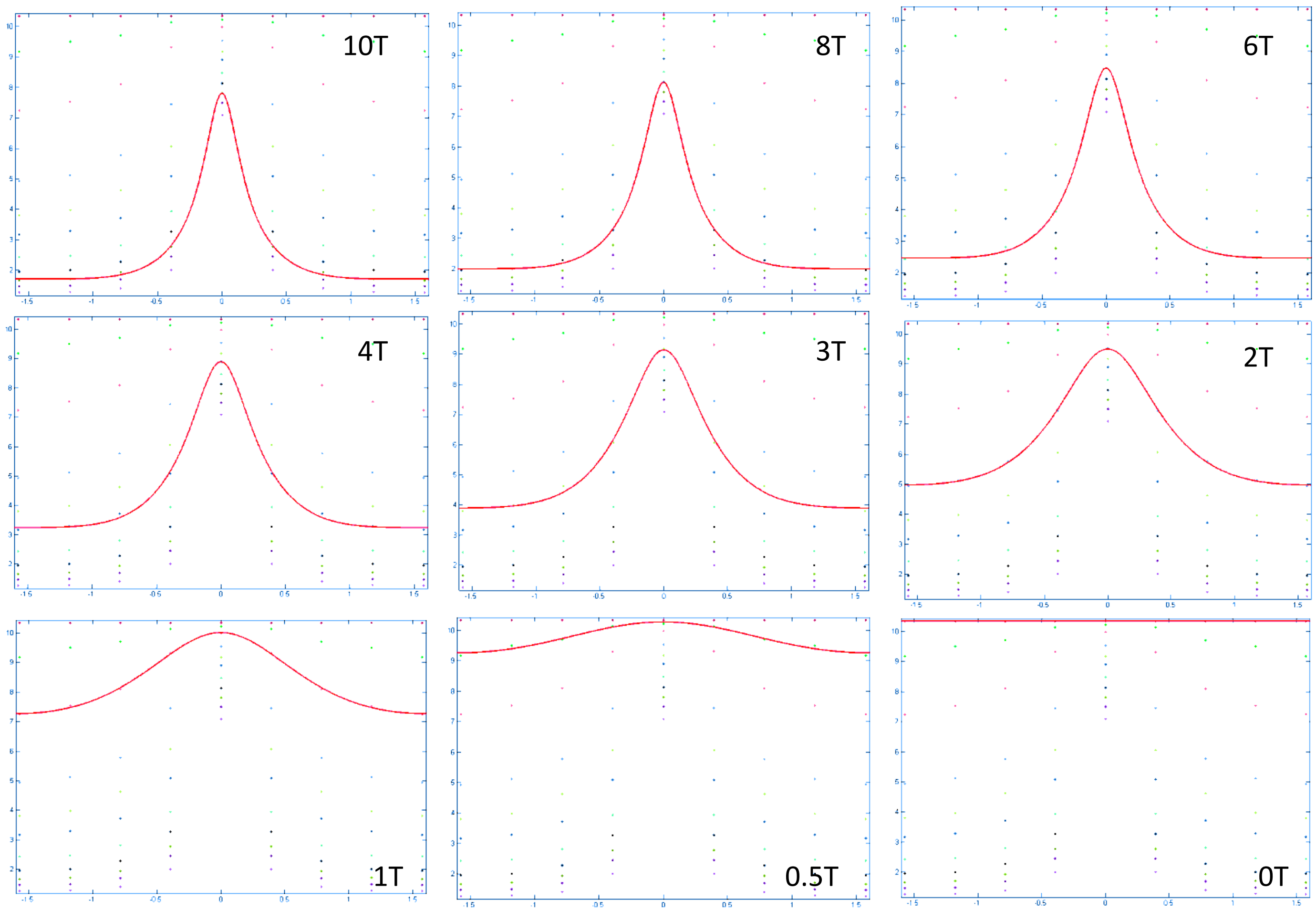


$$I_c(\theta) = \frac{k}{\sqrt{\sin(\theta)^2 + \frac{\cos(\theta)^2}{\varepsilon^2}}} + \left(a\sin(\theta)\right)^2$$

Superpower YBCO critical current fitting

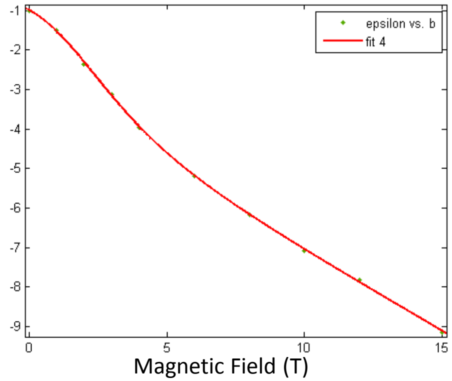
Analytical fitting for angle and field dependency of YBCO critical current can be performed using this expression. In Fig.1 and 2 the expression is plot against FNAL data for Superpower YBCO tape.

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

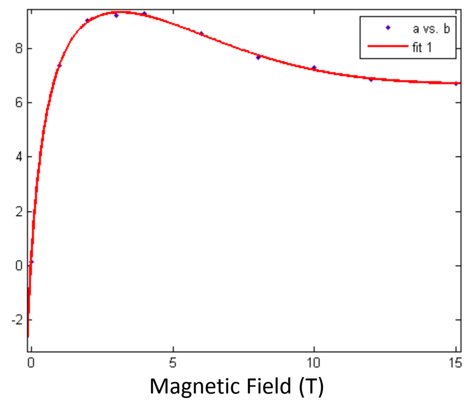


$$I_c(\theta) = \frac{k}{\sqrt{\sin(\theta)^2 + \frac{\cos(\theta)^2}{\varepsilon^2}}} + \left(a\sin(\theta)\right)^2$$

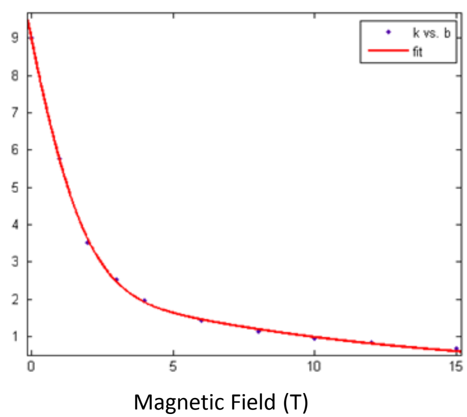
$I_c(B,\Theta)$ parameterization for SSL calculation at 4.2K



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



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



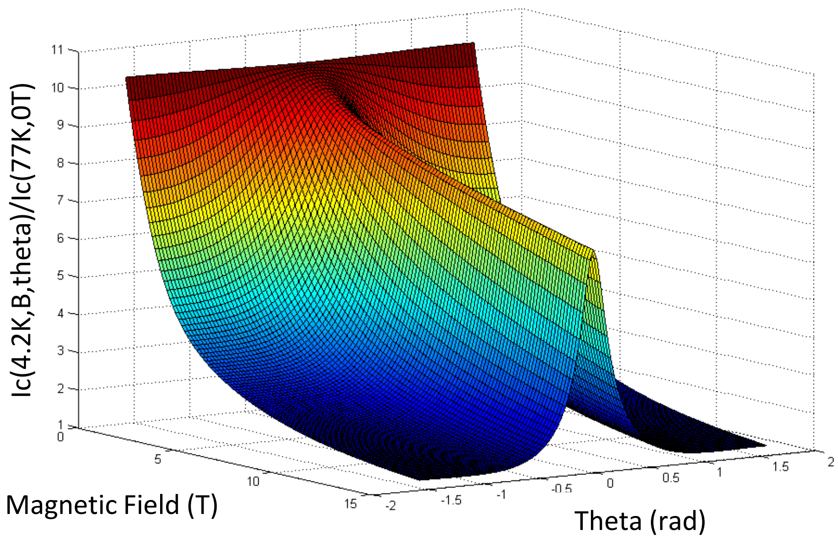
Adding one dimension to the fit

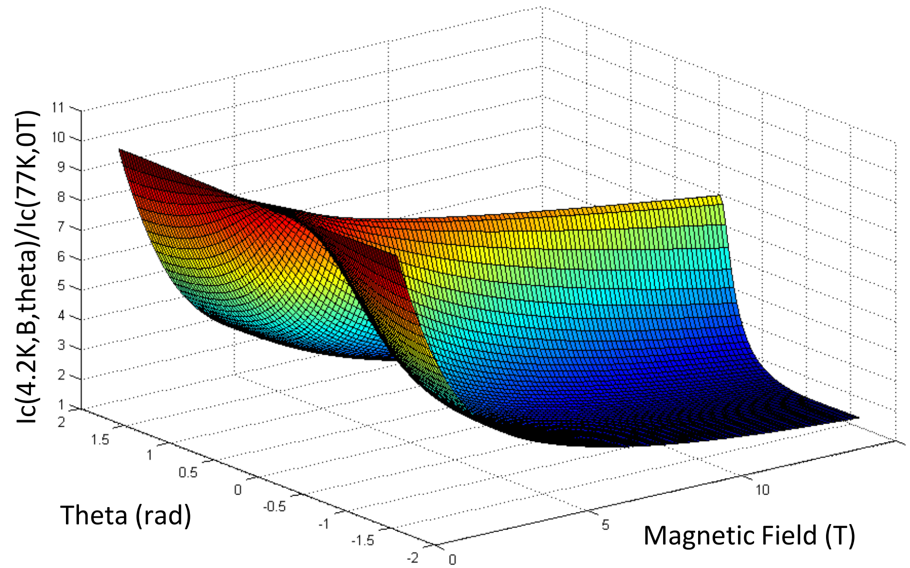
The expression can be extended to include field dependency by fitting the three parameters (k,epsilon,a) as a function of field. This can be done using *rational polynomial* or sums of *exponential expressions*, as shown. Doing this, one can obtain a self contained expression for theta and field dependency.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

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

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

$I_c(B,\Theta)$ 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 –
V. Lombardo - *“An Ic(B,ϑ) parameterization for YBa2Cu3O7−δ CC Tapes” – FERMILAB-TM-2461-TD*

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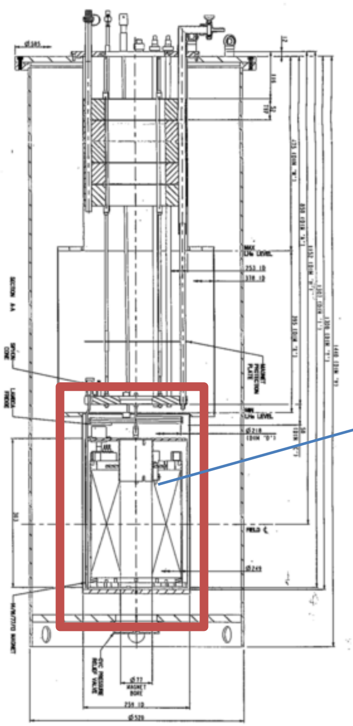
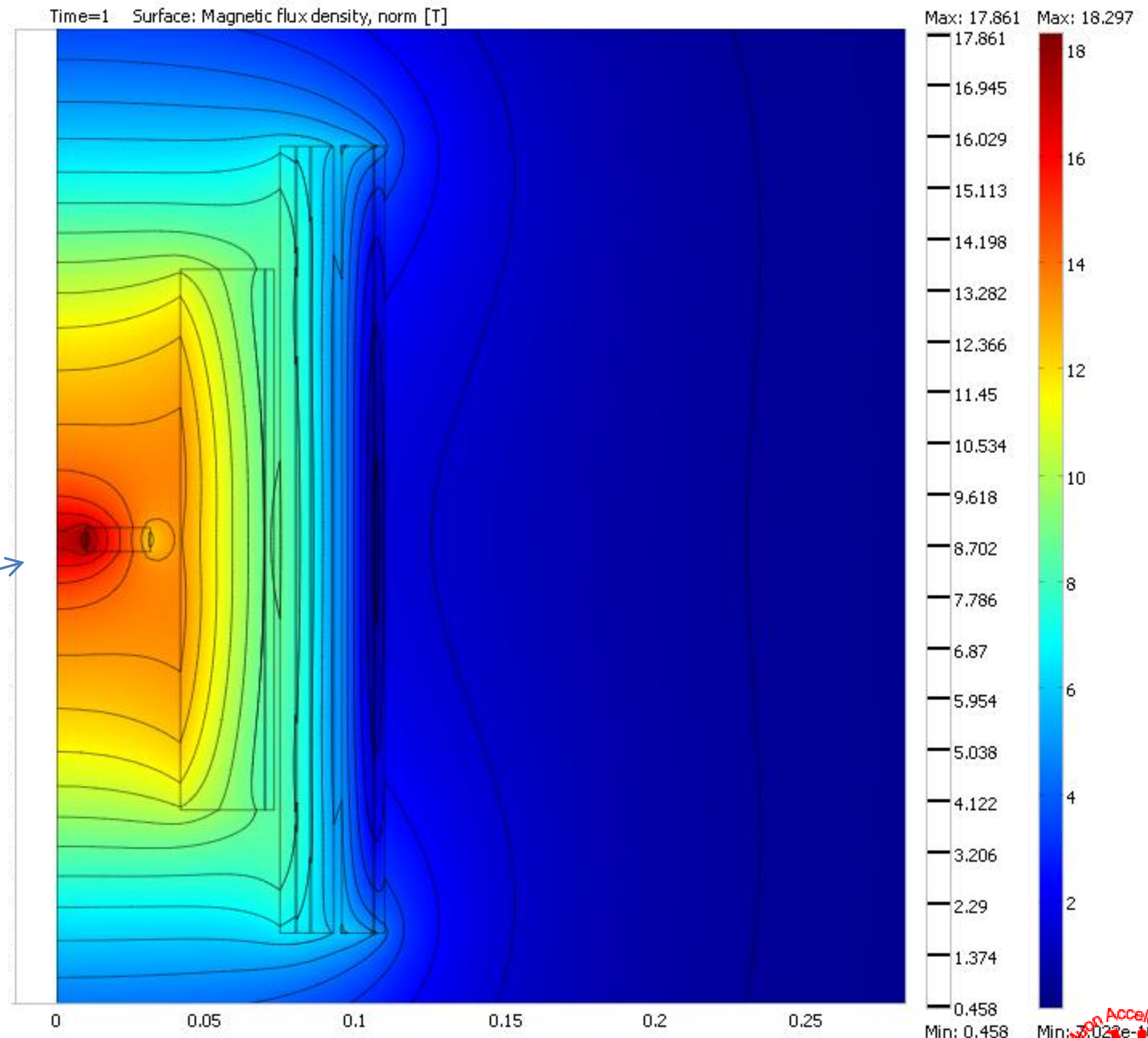
Magnetic Field Distribution with YBCO Insert + bkgr Field





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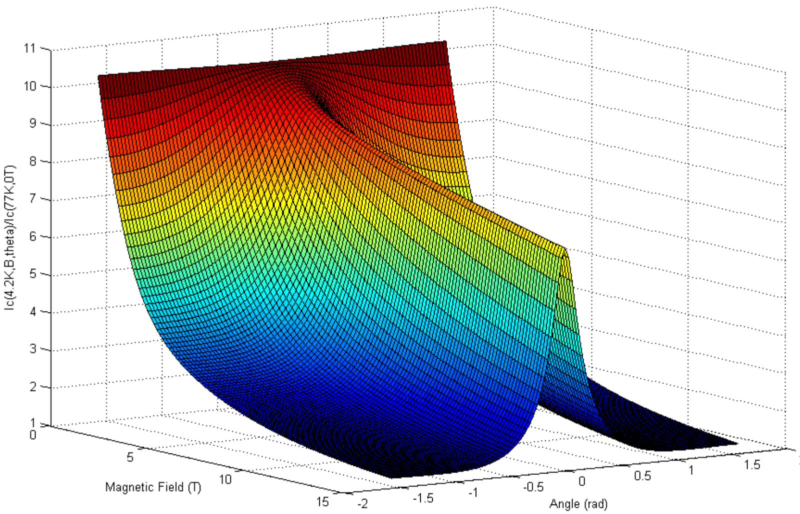
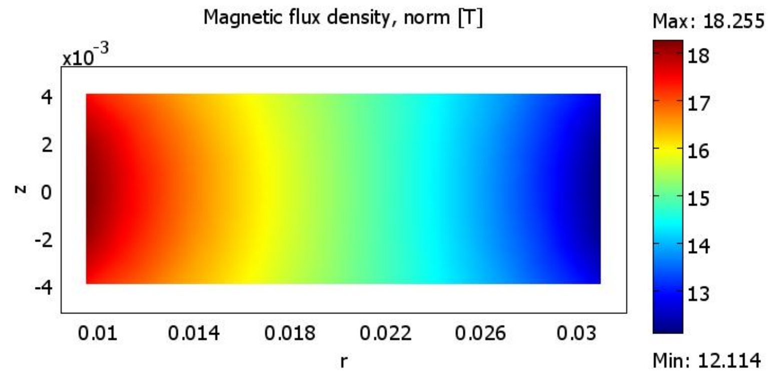
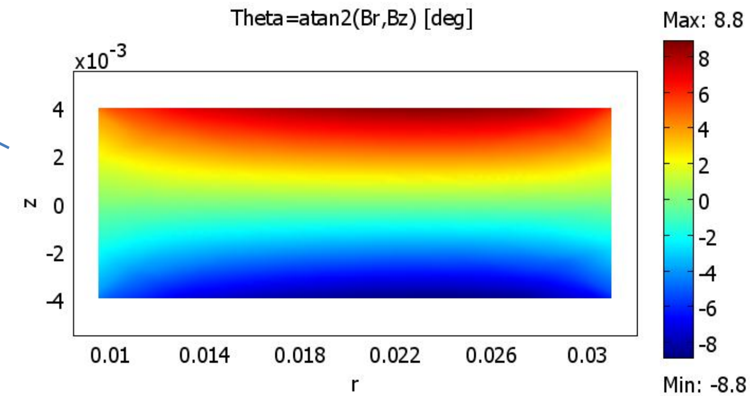
Insert Coil performance estimation at 4.2K



B

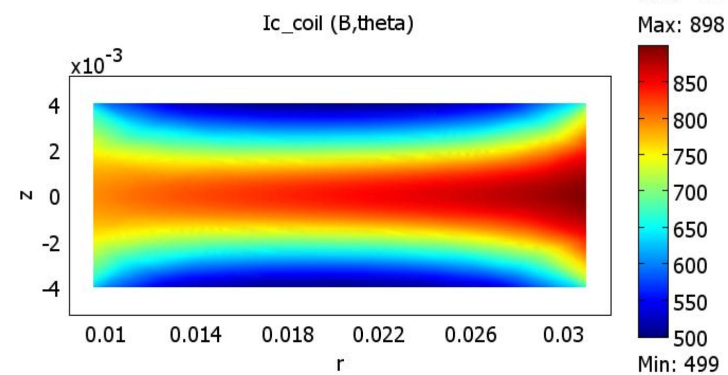
Θ





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

I_c



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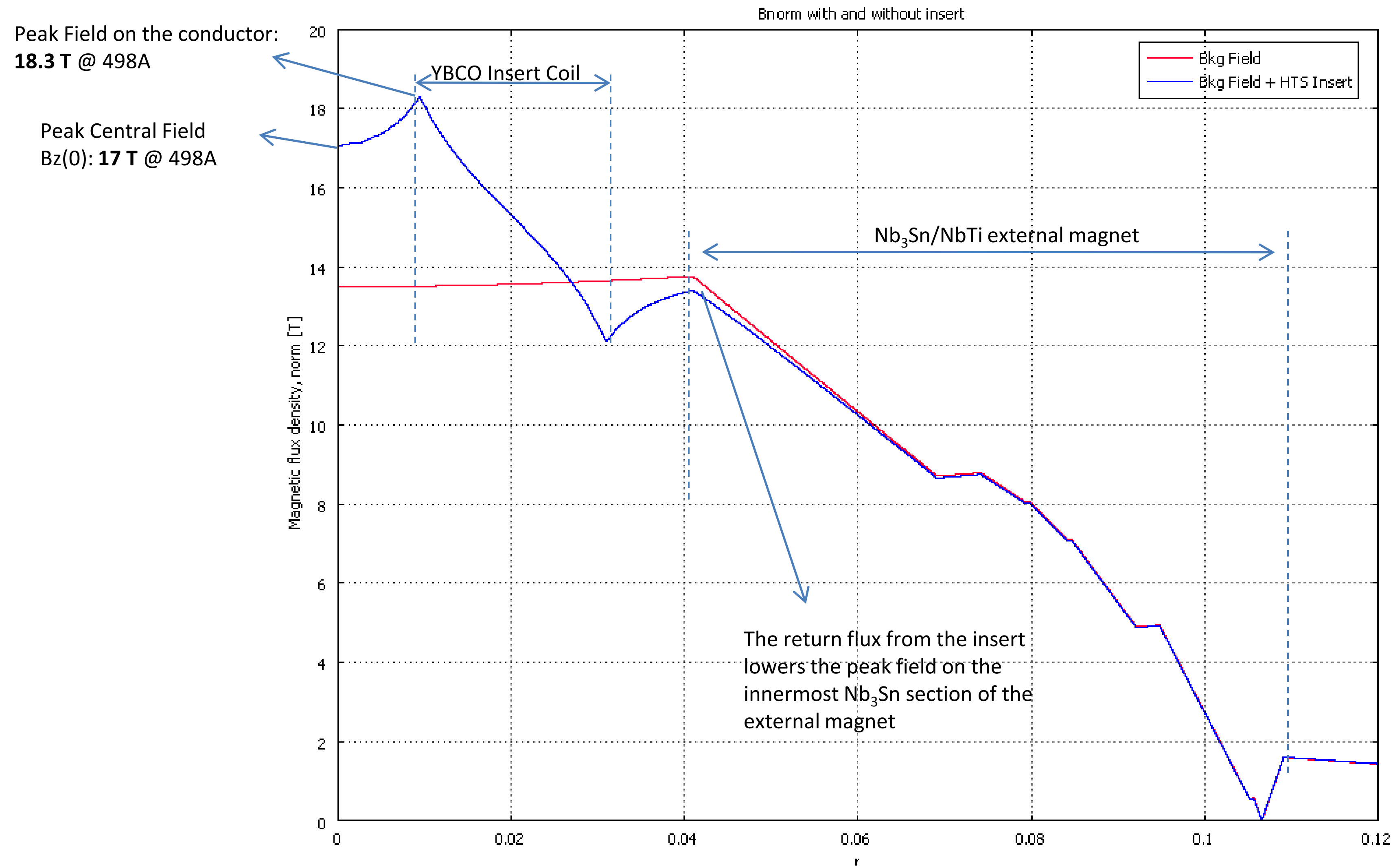
Magnetic Field Distribution with and without Insert



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

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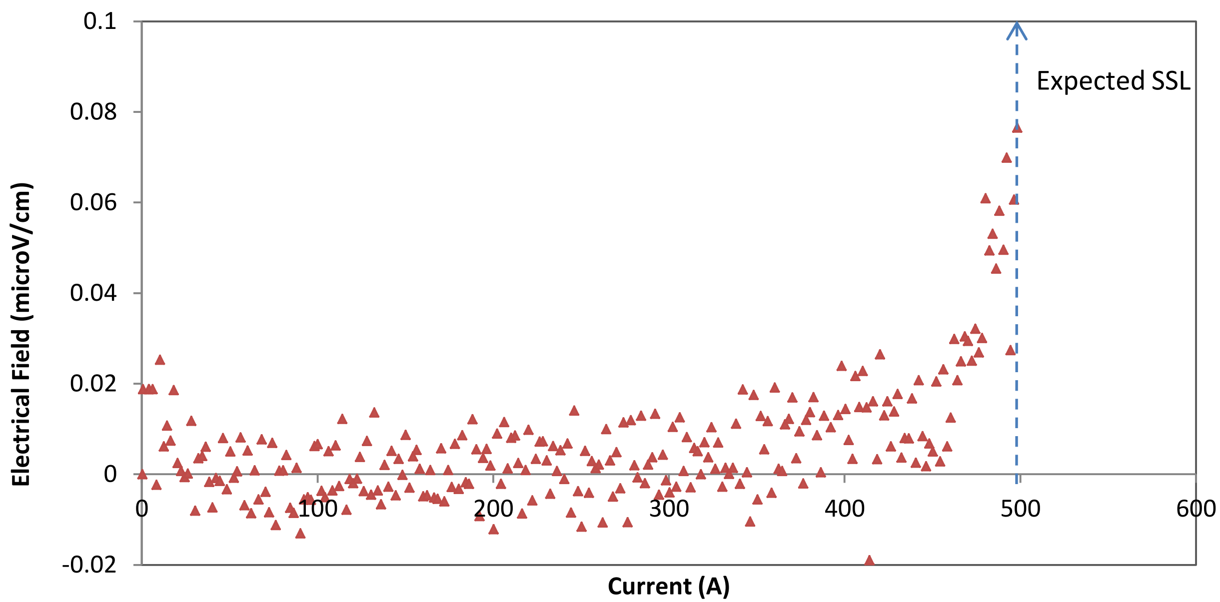
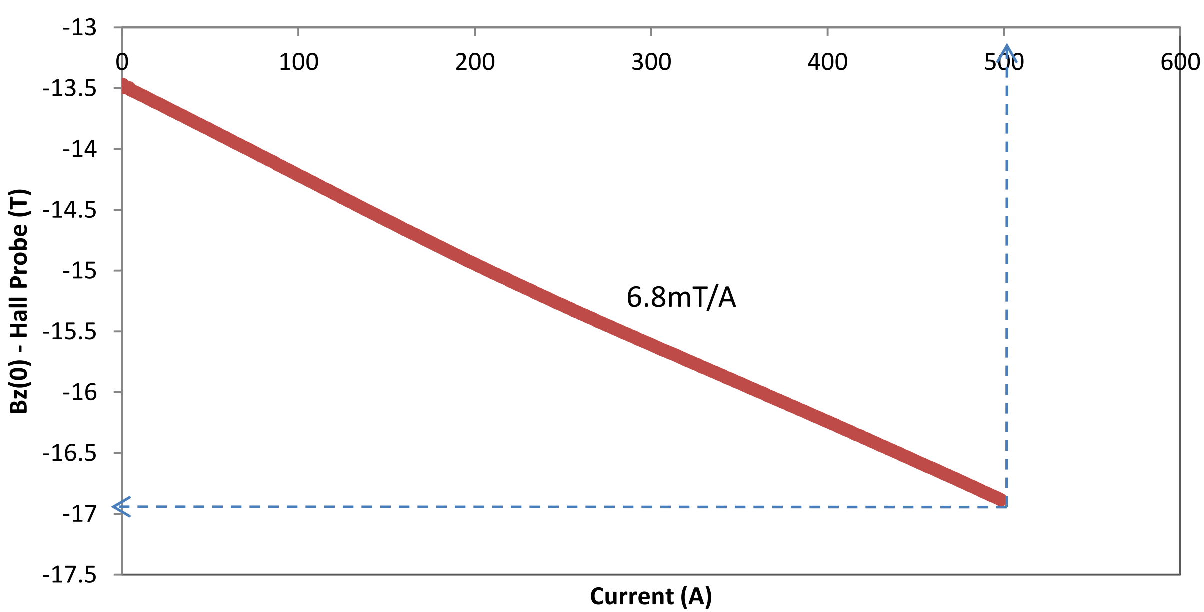
Test results at 4.2K in 13.5T background field





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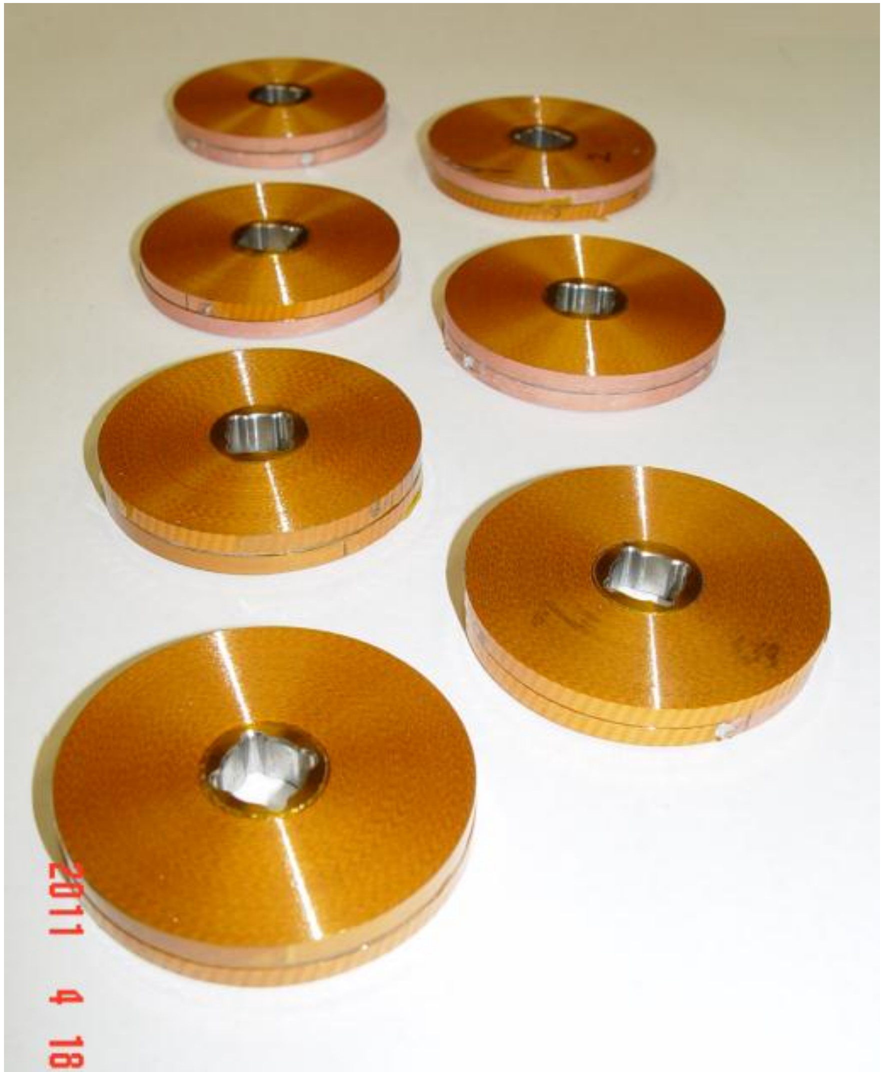
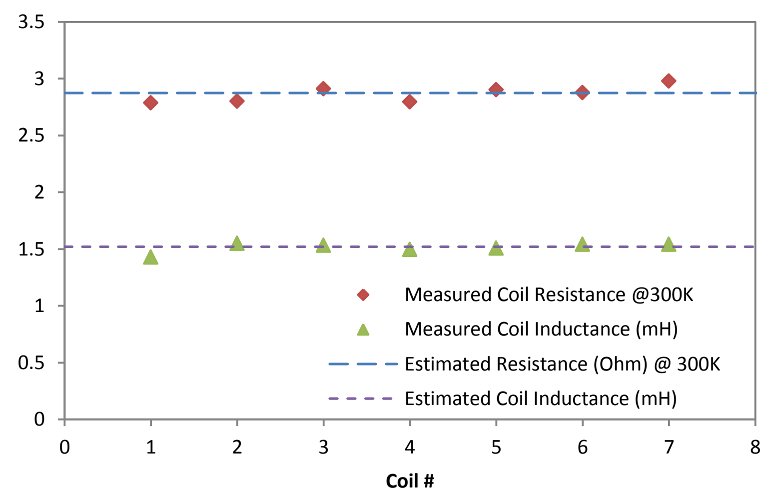
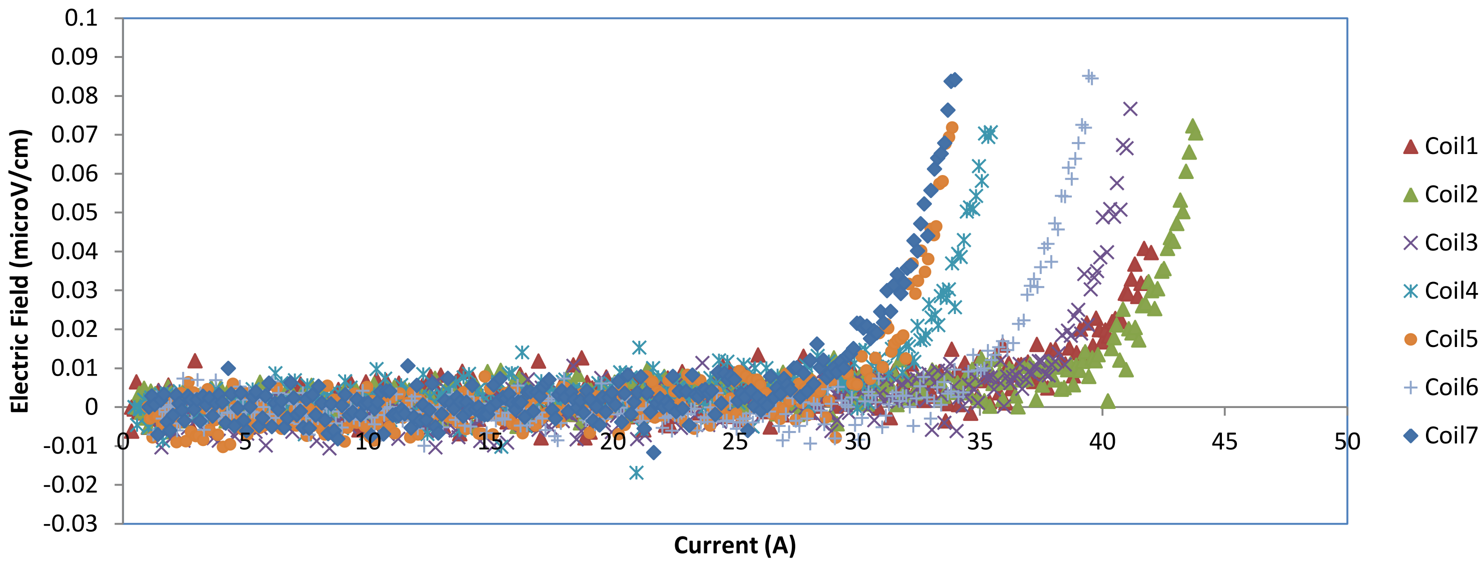
Scale-up work

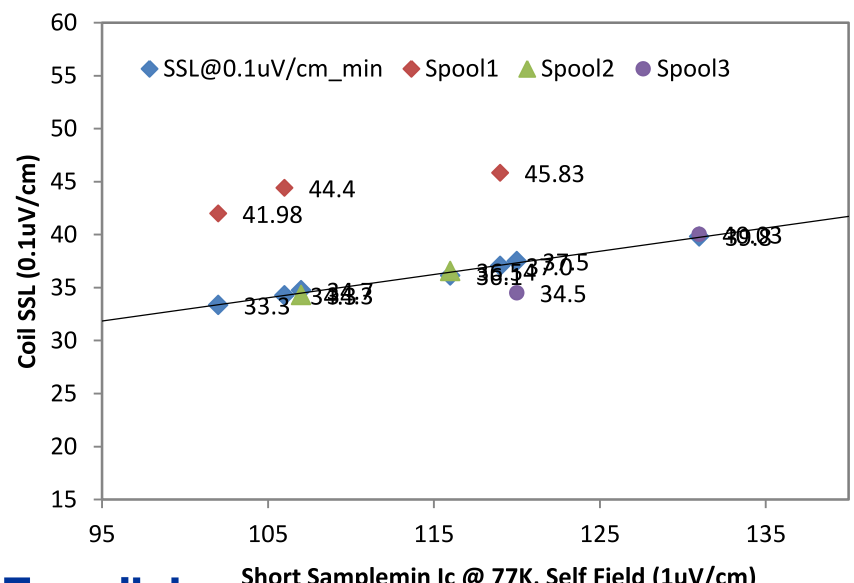


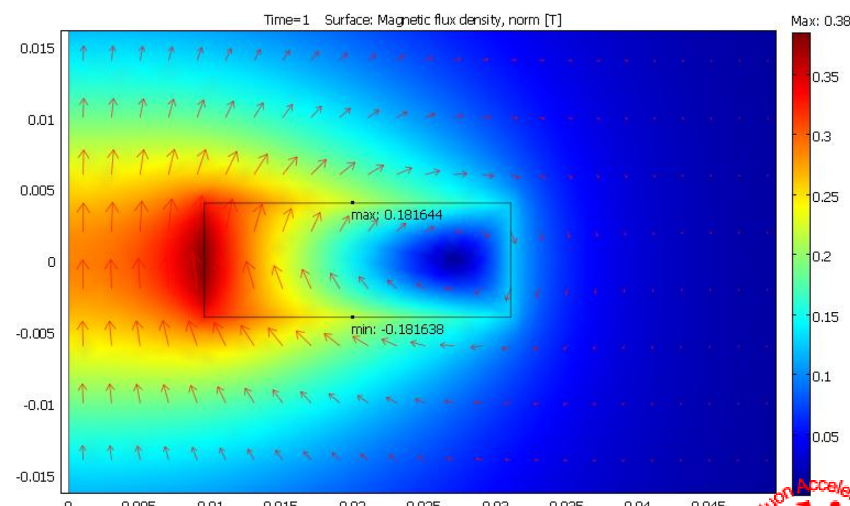
Conductor	SuperPower SCS4050-i
Turn to Turn Insulation	Spiral Wrapped Kapton
Coil Geometry	Double Pancake – no inner splice
Coil ID	19 mm
Coil OD	62 mm
Conductor Thickness	0.1 mm
Conductor + Insulation Thickness	0.2 mm
Packing Factor	50%
Turns per Single Coil	108



Test of full batch of 7 coils in Liquid Nitrogen







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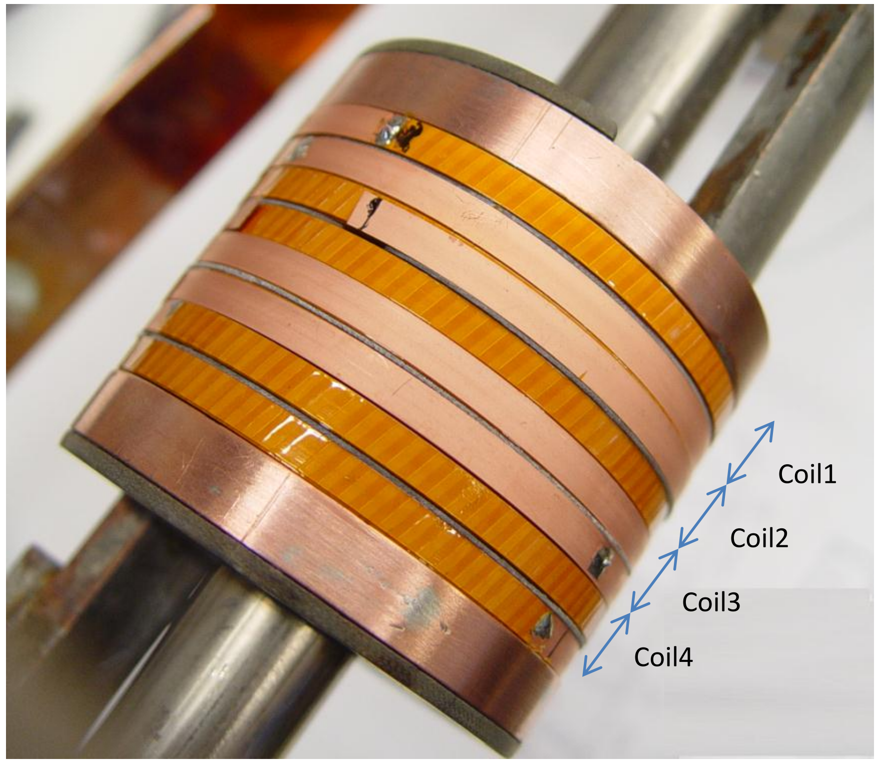
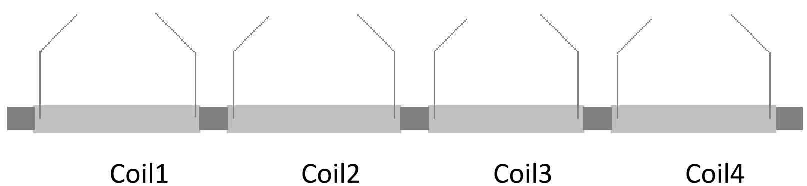
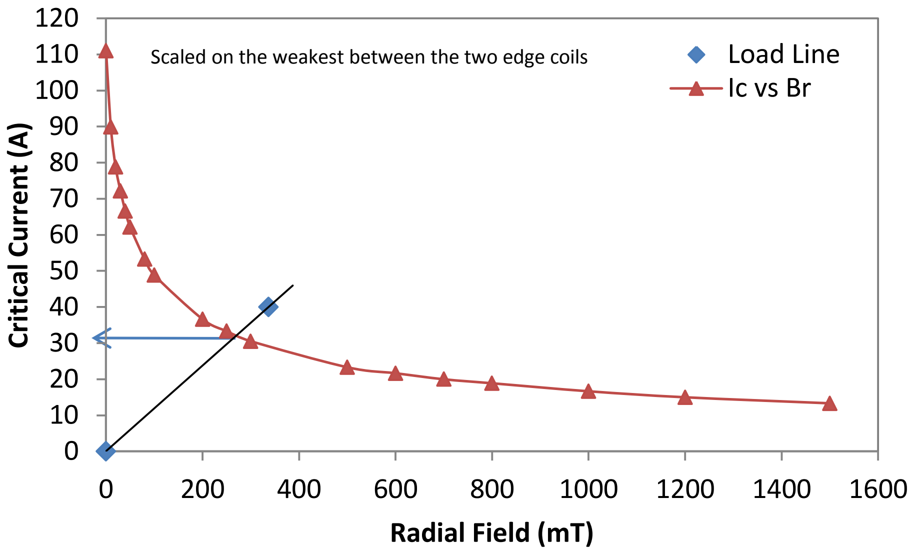
Final Assembly of 4 Double Pancake Coils

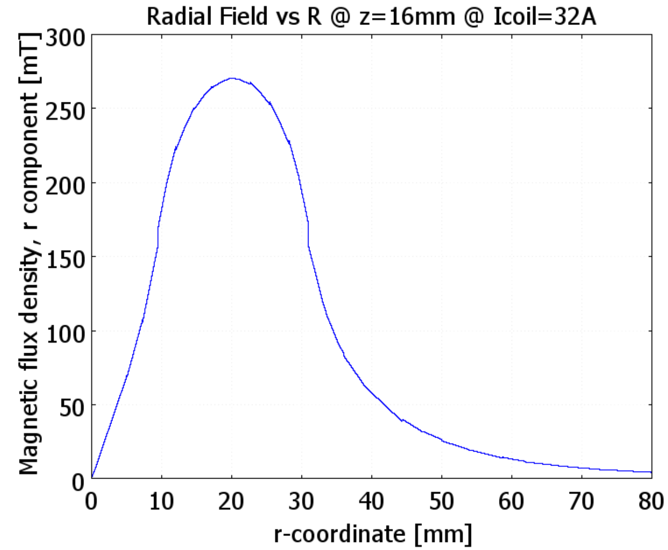
The final assembly before instrumentation and final SS wrap

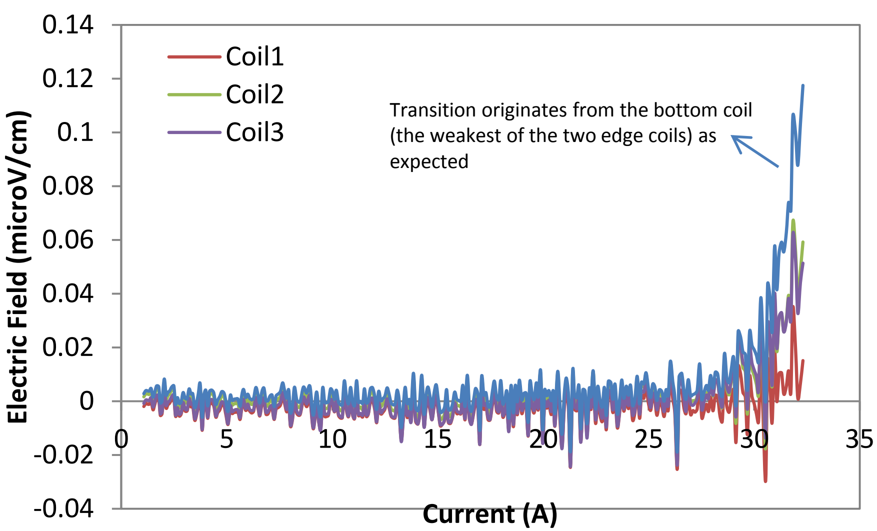


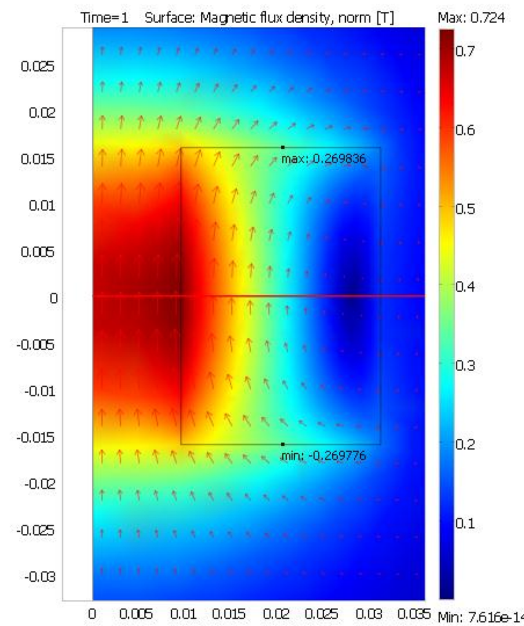


4 coils Liquid Nitrogen test – full Ic









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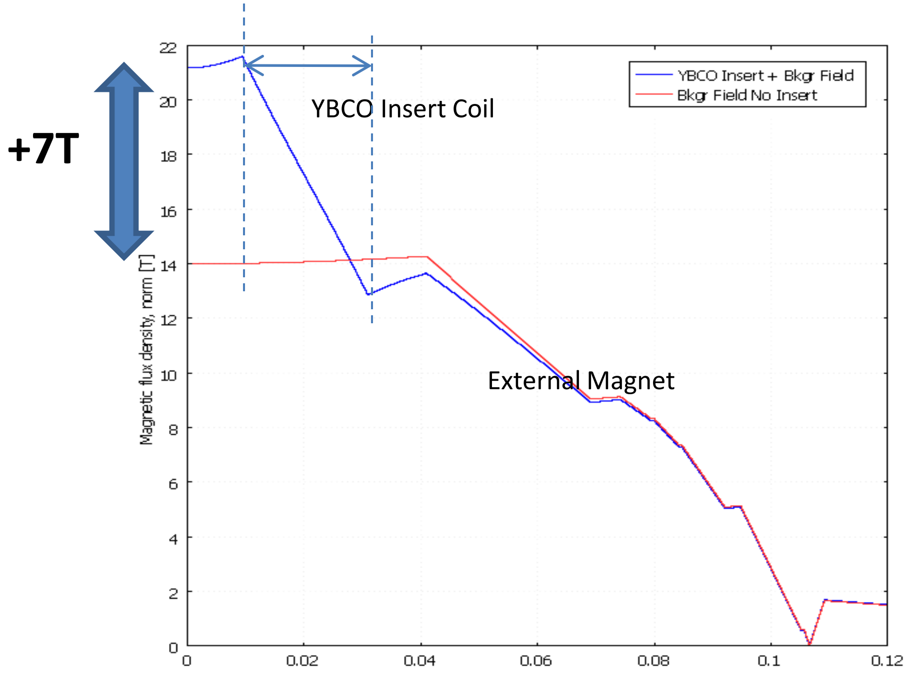
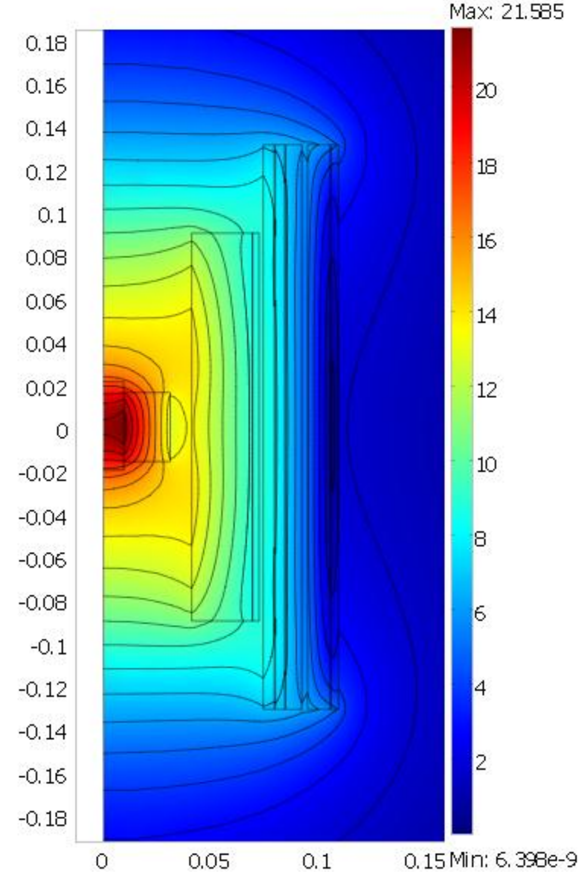
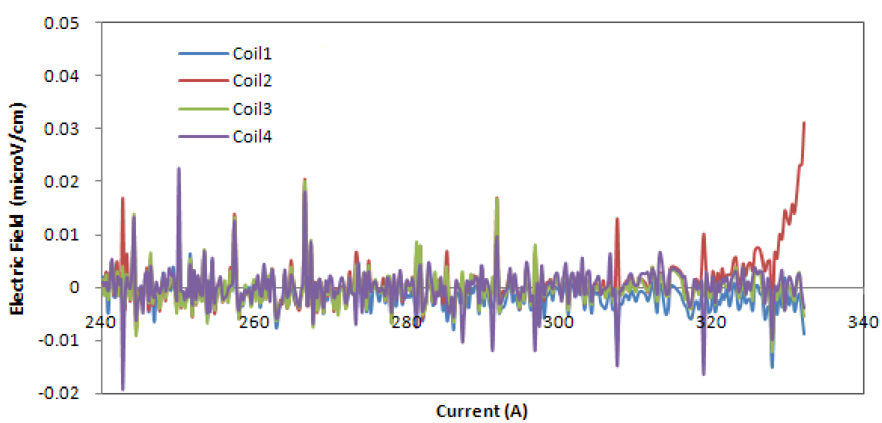
4coils Liquid Helium Test --- 21.2T in 14T bkgr field







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

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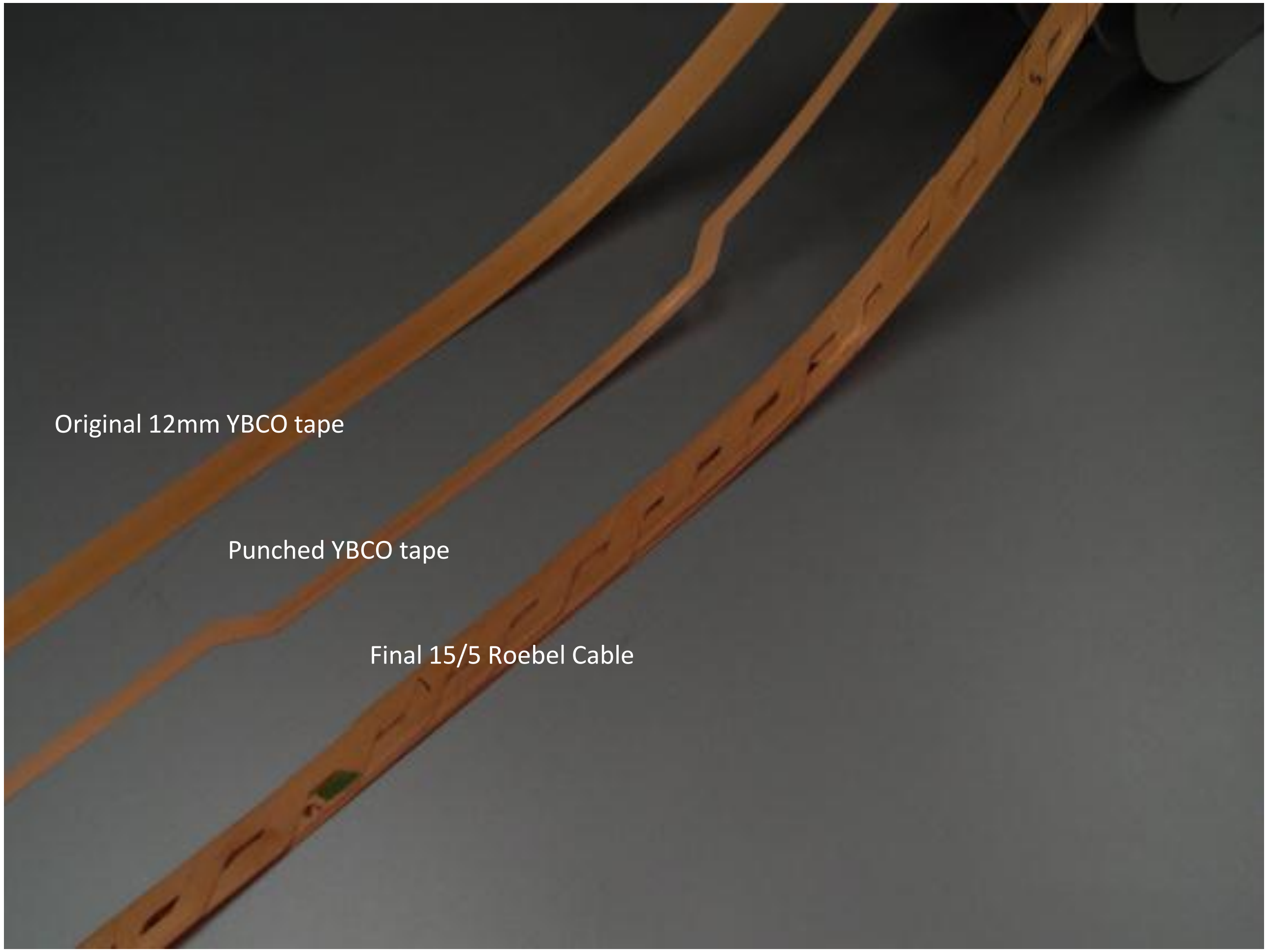
Muon Accelerator Program

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)

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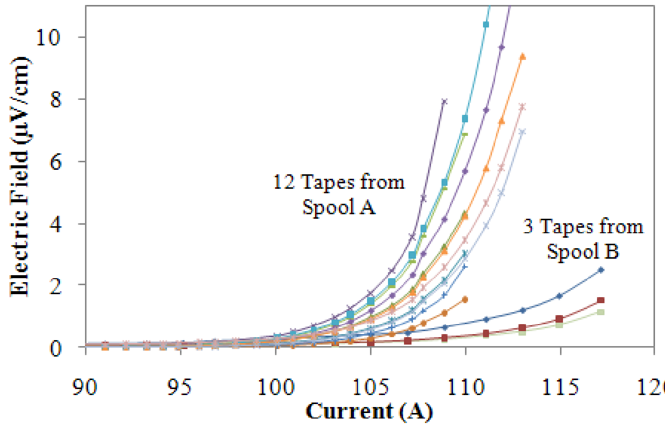
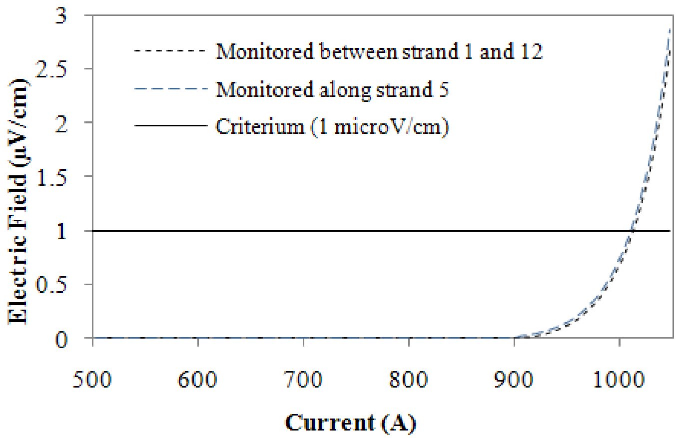
Muon Accelerator Program

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 ?

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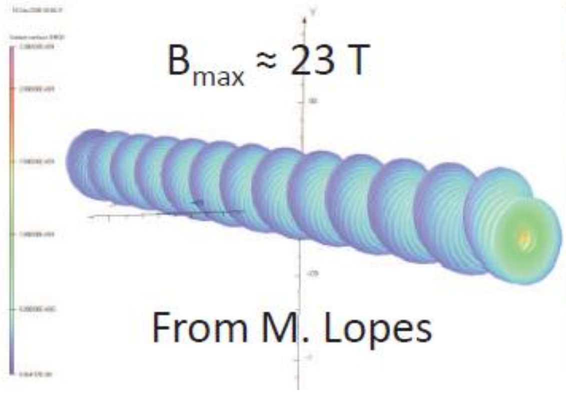
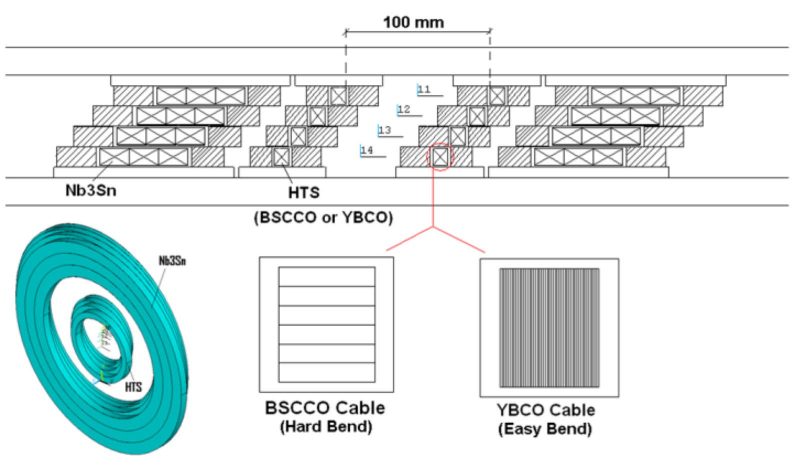
High Field Section of Helical Cooling Channel

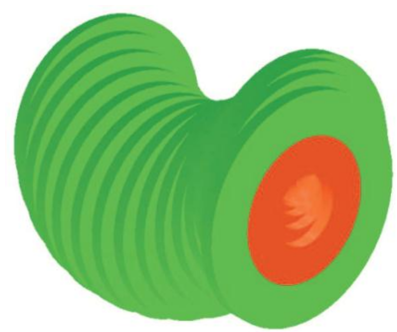
The proposed HCC is divided into several sections, each one with progressively stronger fields, smaller aperture and shorter helix to achieve the optimal muon cooling rate. Conceptual design is still ongoing and parameters are not final, but the final high field section may require high temperature superconductors. The magnet systems superimposes solenoid, helical dipole and gradient fields.



	4th
Total length	50
Period	0.400
Orbit radius	0.060
Solenoidal field	-17.30
Helical dipole field	4.06
Helical field gradient	-4.50

Hybrid models may be considered to achieve required field levels





YBCO Helical Solenoid Short Model

In order to develop technology, 3 YBCO double pancakes units with dummy cavity insertions were designed and assembled.

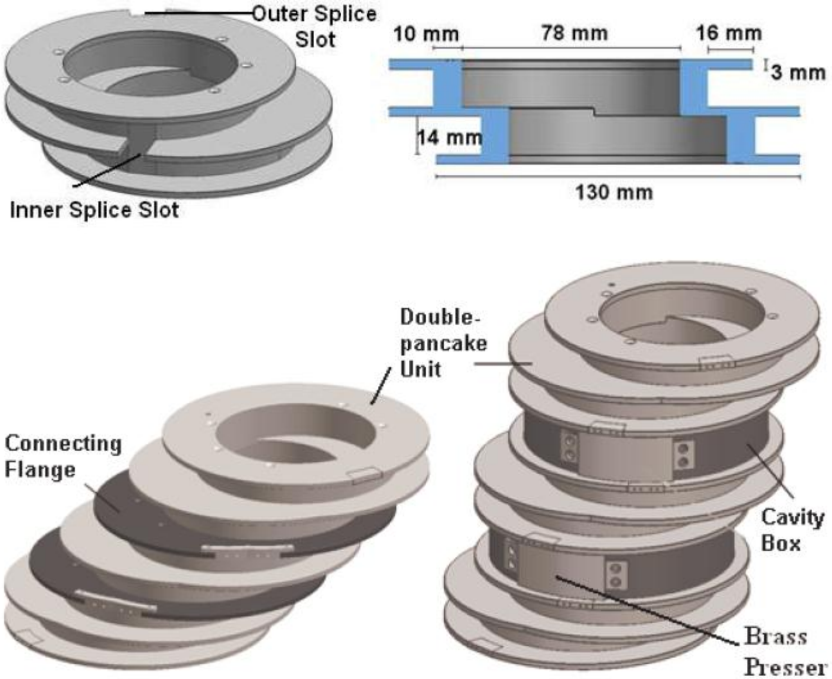


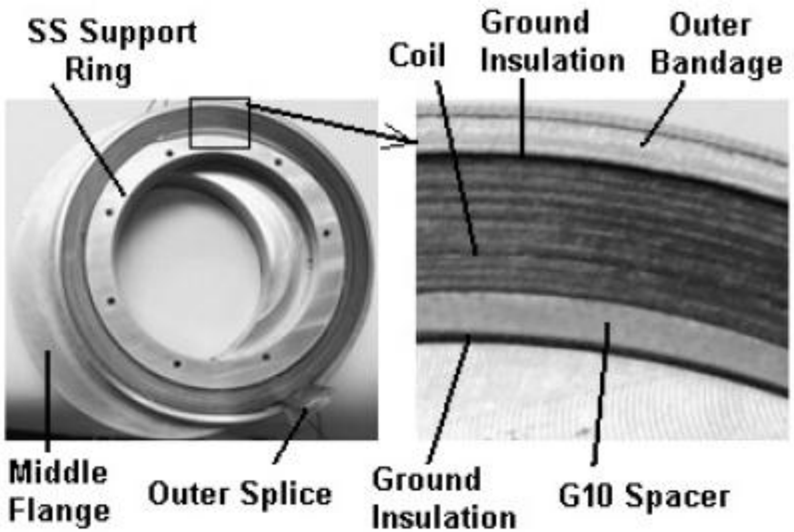
Table 1: HS Short Models Parameters

Parameter	Unit	Number of Double-pancake Units (Number of Cavity Insertion)		
		1 (0)	3 (0)	3 (2)
Coil ID	m	0.10	0.10	0.10
Coil OD	m	0.116	0.116	0.116
Number of turns/coil		58	58	58
Predicted I_{quench}	kA	1.424	1.348	1.375
Maximum Coil B ⊥ Field	T	3.4	3.7	3.6
Inductance	mH	1.6	7.4	9.1
Stored energy	kJ	1.6	6.7	8.6

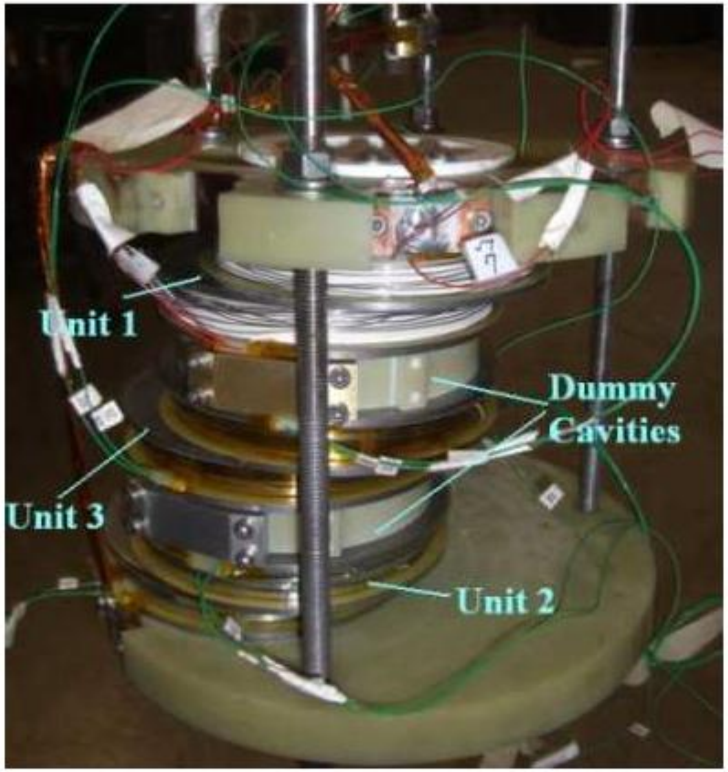
A. V. Zlobin et al. “Modeling the high-field section of a muon helical cooling channel”

The RF cavities inside the coil are required to operate at above 30 K (assuming gaseous H2 is used as the absorber), and there will be very little space to fit the thermal insulation and support structure in between the RF system and the magnets.

YBCO Helical Solenoid Short Model



77K and 4.2K Ic test of the final assembled short model are currently being performed



M. Yu et al. "Fabrication and test of short helical solenoid model based on ybco tape"

1. Coils assembled using commercially available 12mm wide SuperPower ybco tape.
2. Each double pancake unit separately tested for I_c at 77K and 4.2K.
3. Coils were wound and taken apart several times and thermal cycled both in helium and nitrogen with no degradation.
4. Inner and outer splices are bridge joints that required optimization (M. Yu et al. "Experimental studies of a helical solenoid using ybco tape with bridge joints")

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Conclusions

YBCO offers interesting opportunities for magnet development and unique features beyond 'low temperature' superconductors

- Suitable for **high field-high stress** applications.
- Allows magnet operation at temperatures **above 4.2K --** if needed.
- Allows **R&W** technology instead of W&R

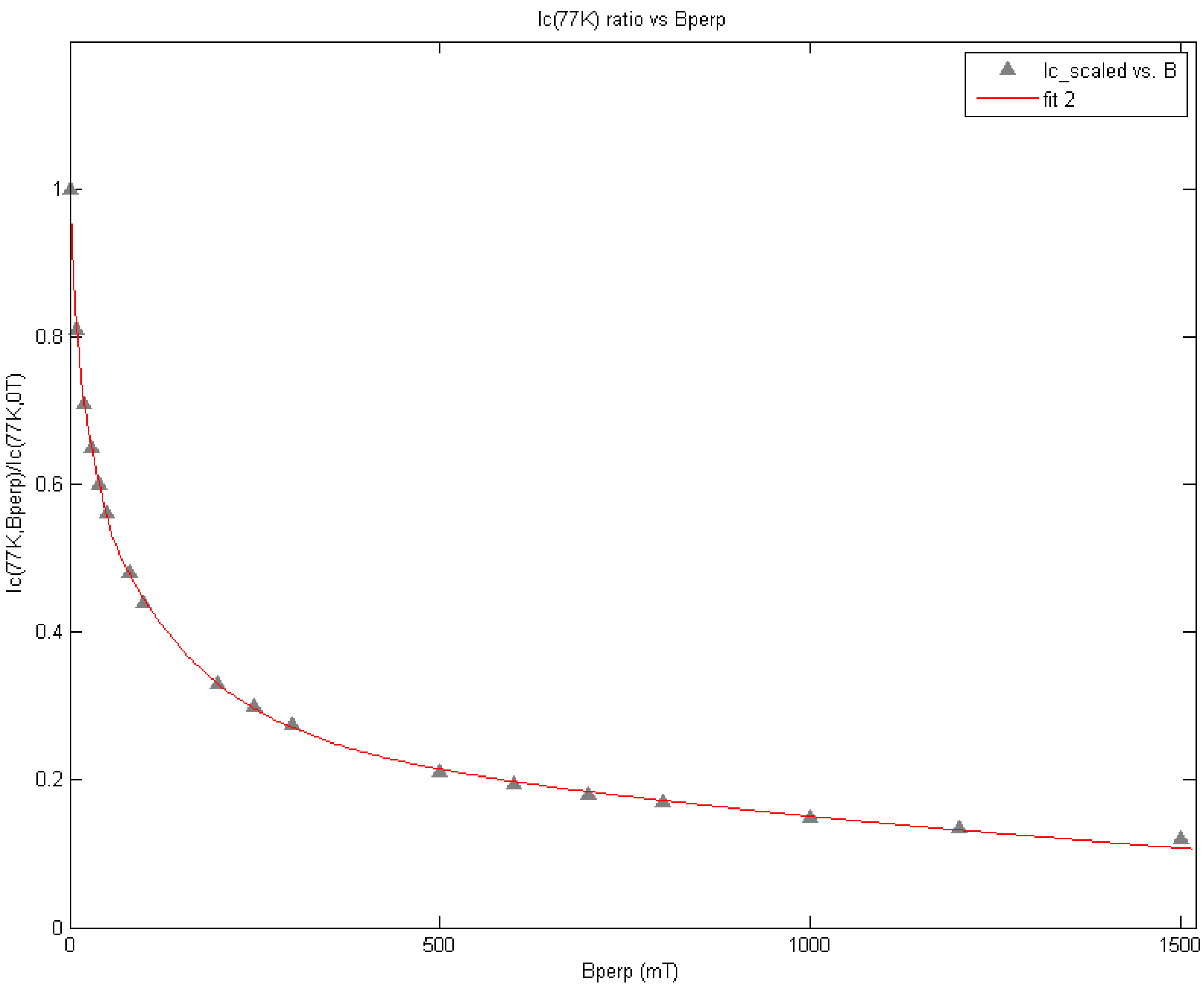
30-40T fully superconducting magnets are achievable
with technology available today.

Some of the challenges:

- Anisotropy needs to be carefully accounted for in magnet design. A framework for doing that has been presented. Improvements at the conductor level could help.
- Low normal zone propagation velocity in YBCO conductors poses technological challenges for quench protection.
- […]
- **COST**.

Backup Slides

Ic(77K,Bperp) fit



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

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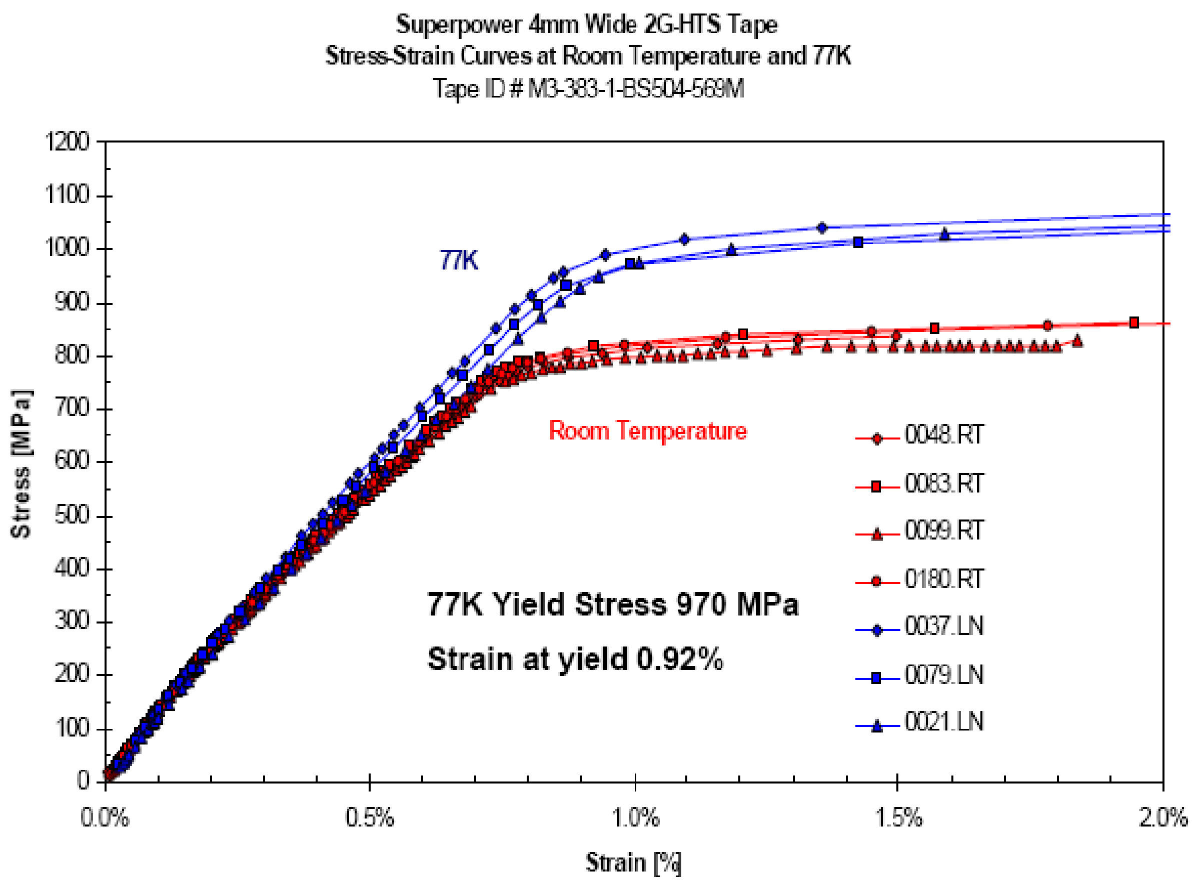
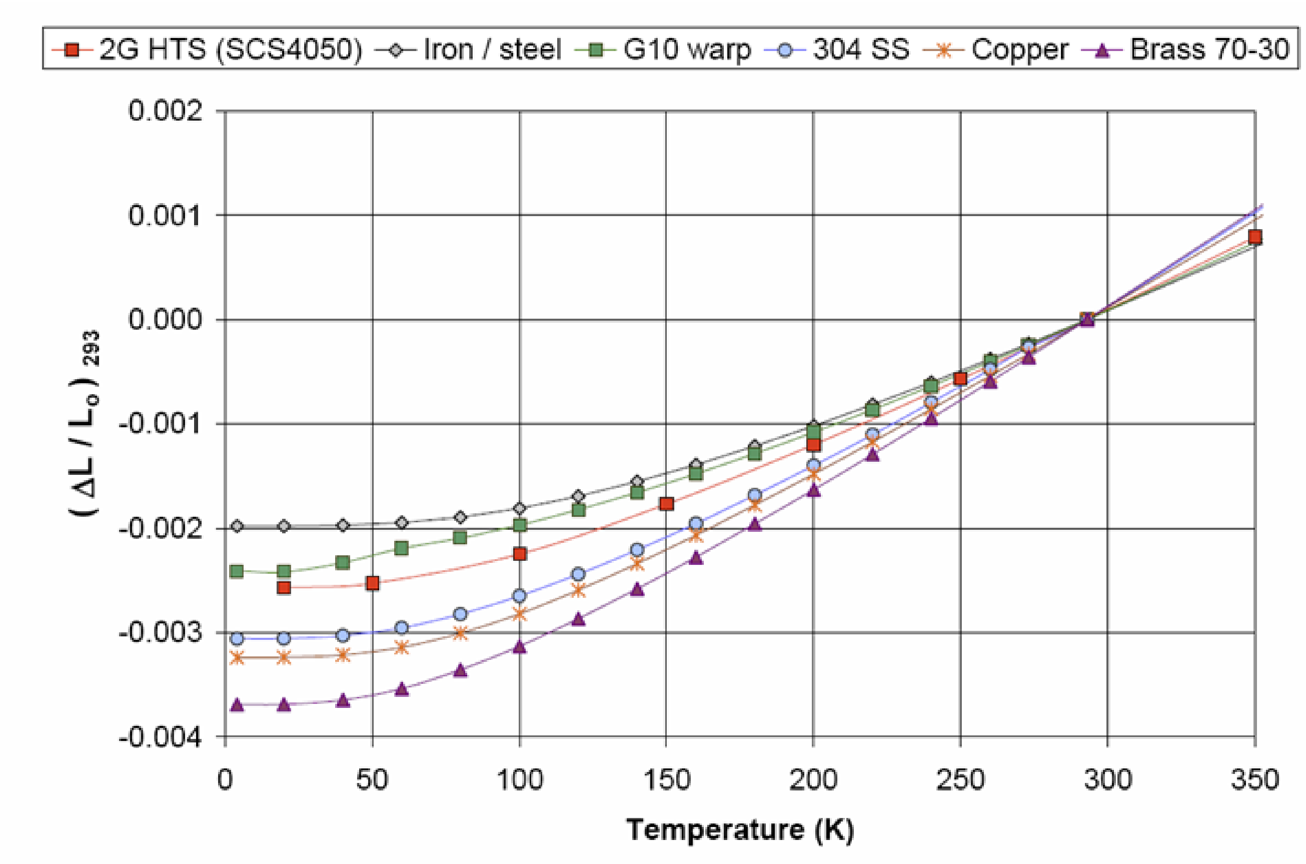
Stress-Strain Curve for YBCO tapes



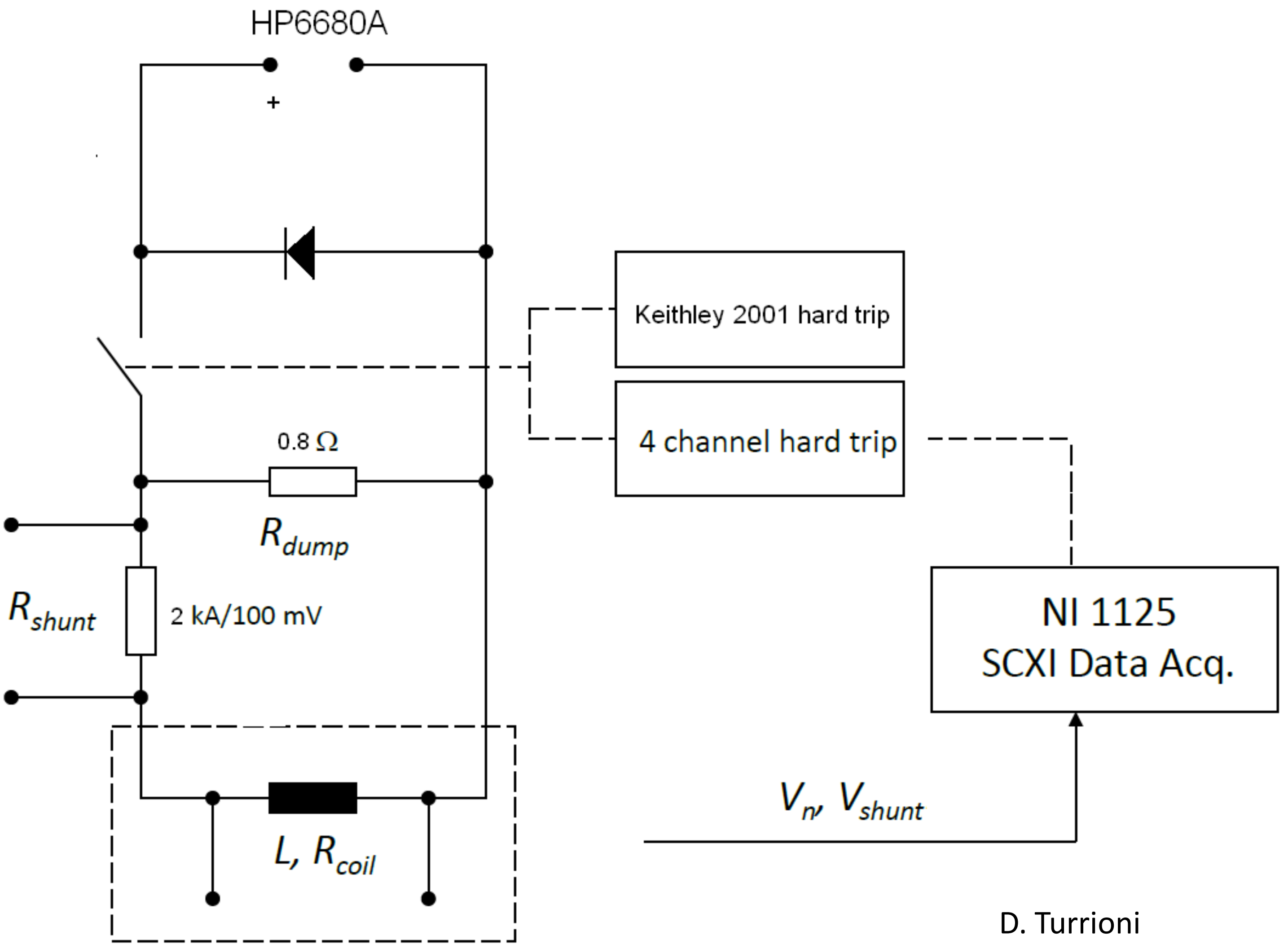
Data courtesy of SuperPower

Thermal coefficients



Data courtesy of SuperPower

Quench protection



D. Turrioni