REBCO Coils R&D for **Muon Cooling**

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MAP HTS Workshop 2012

May 30-31, 2012

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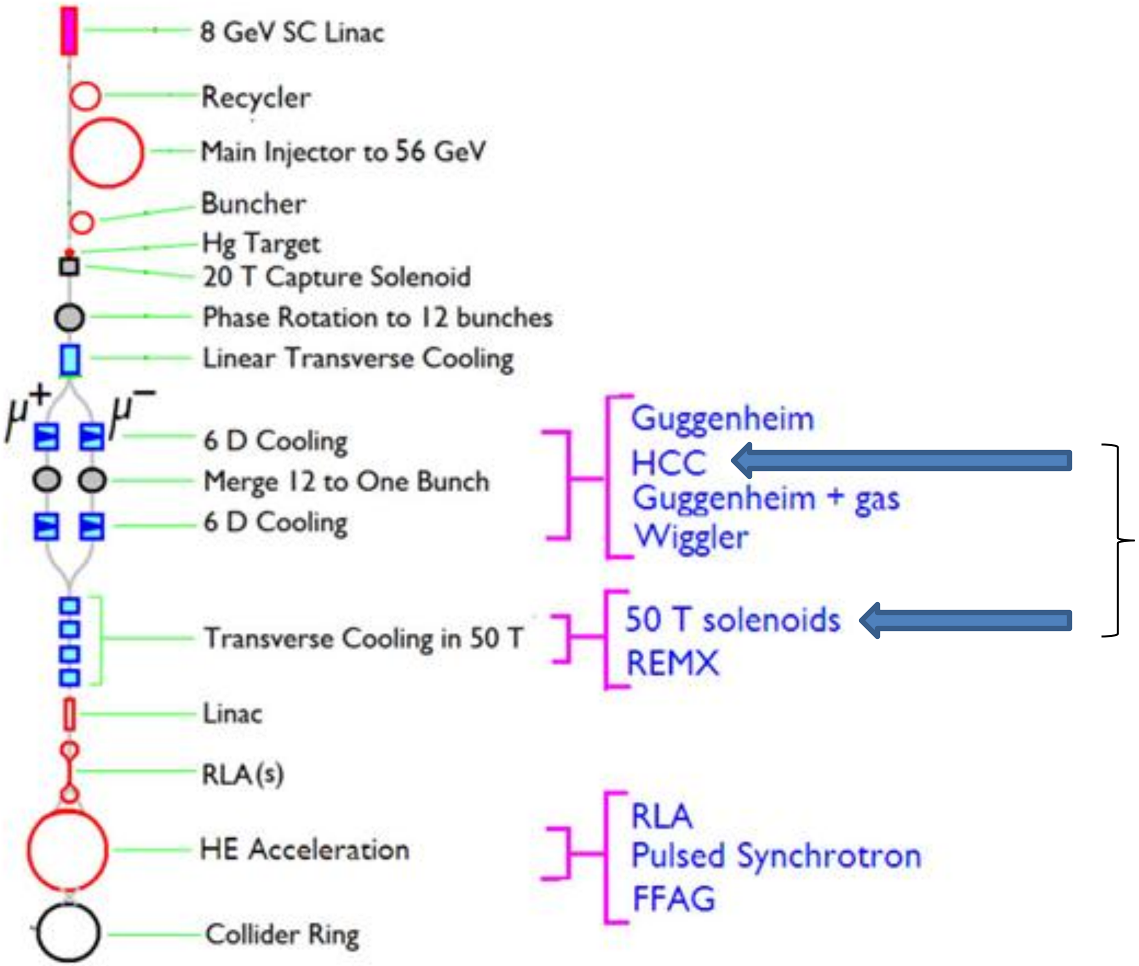
Talk Outline

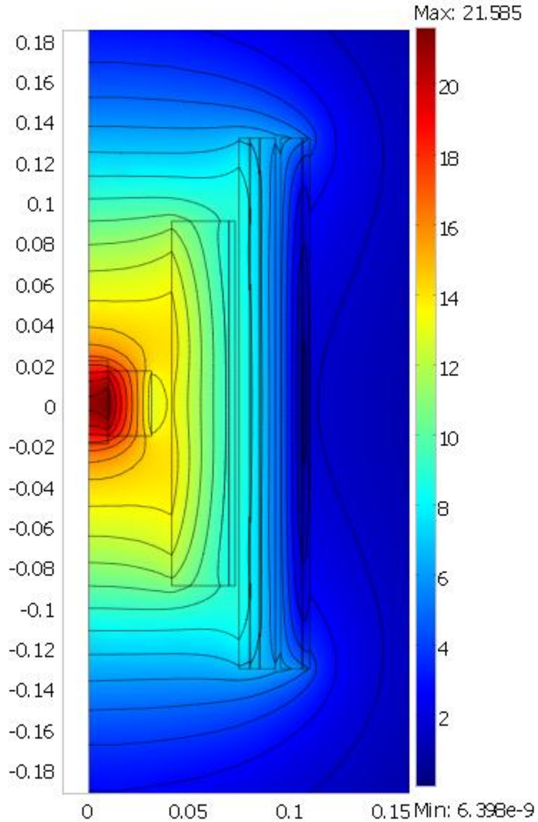
1. REBCO Coils for Muon Cooling - Overview
2. Small REBCO Insert Test Coils
3. REBCO Helical Solenoid Coils
4. Considerations and Conclusions

Muon Collider Facility Outline



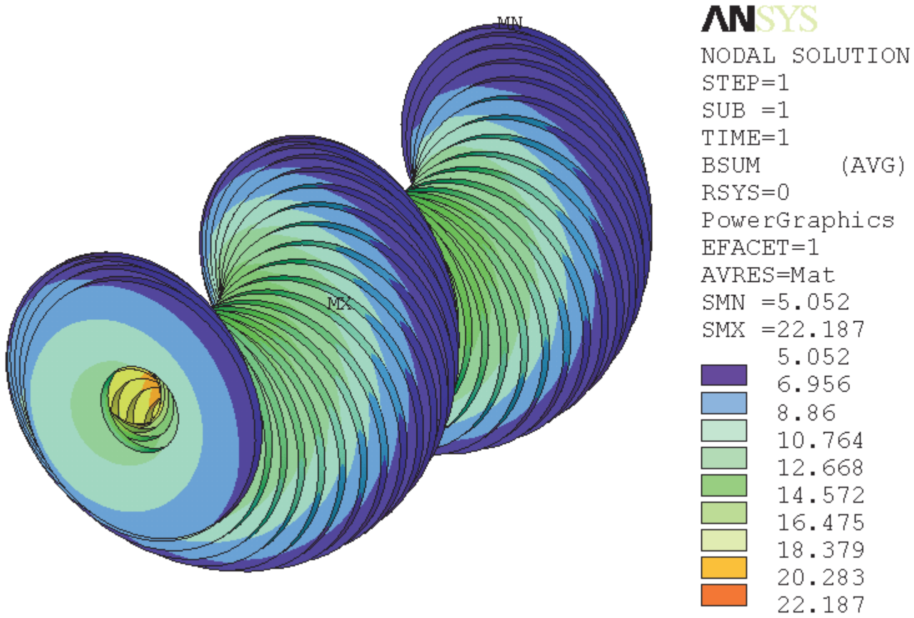
Two REBCO applications of interest for MC community

REBCO Insert Solenoids
for high field magnet applications



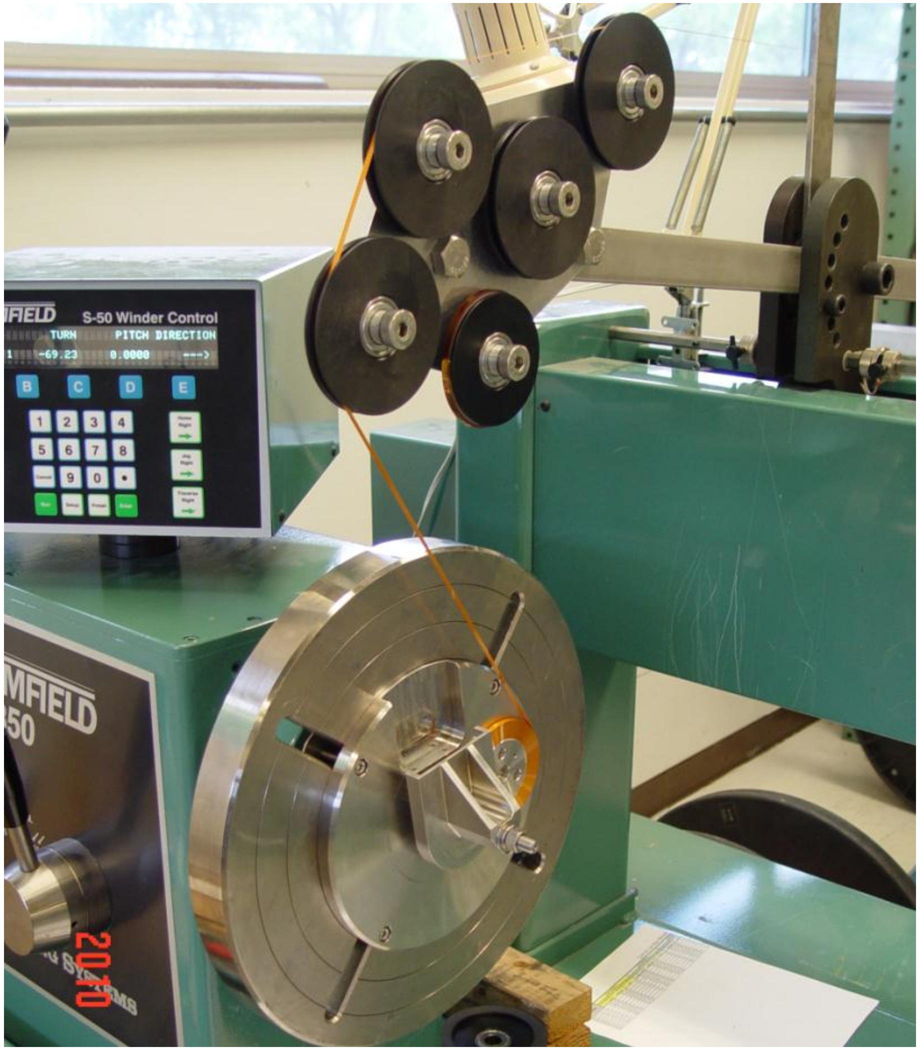
Latest at *"Insert Coil Test for High Field Magnets based on YBCO CC Tapes"*. V. Lombardo, E. Barzi, D. Turrioni, A.V. Zlobin

REBCO Helical Solenoids
for high field section of HCC



Latest at *"Fabrication and test of short helical solenoid model based on YBCO tapes"*, M. Yu et al.

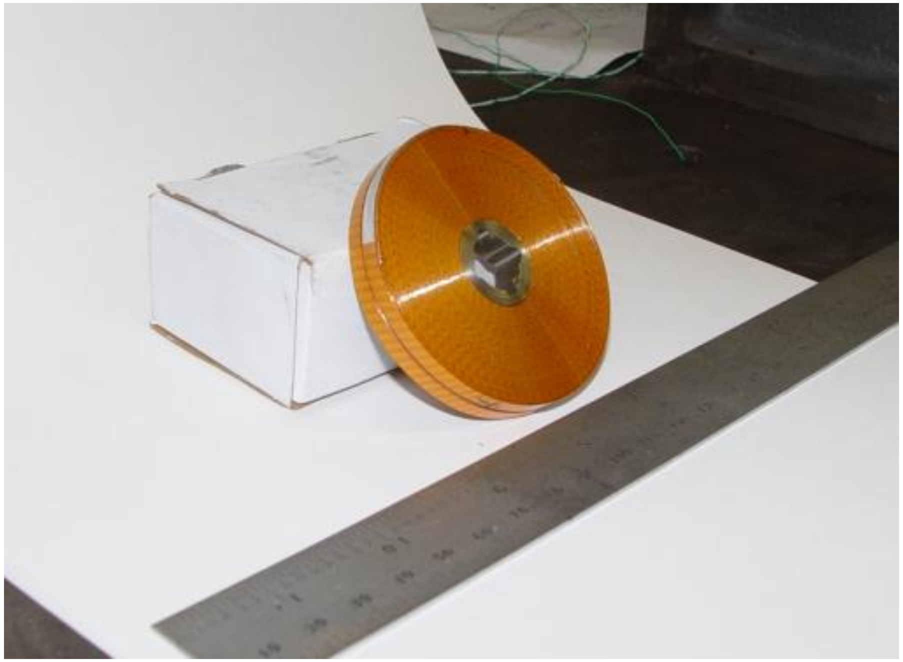
Winding REBCO coils



Small REBCO Insert Coil Overview

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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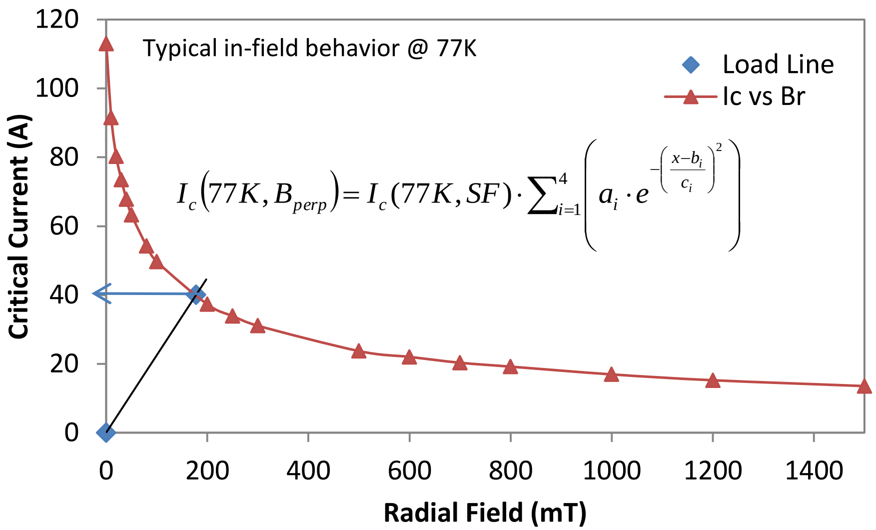
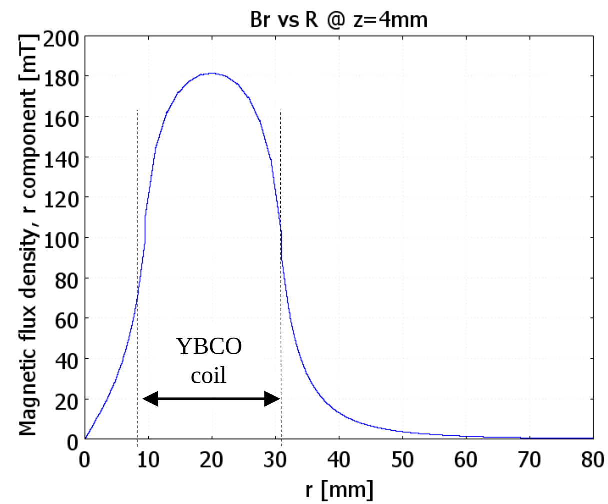
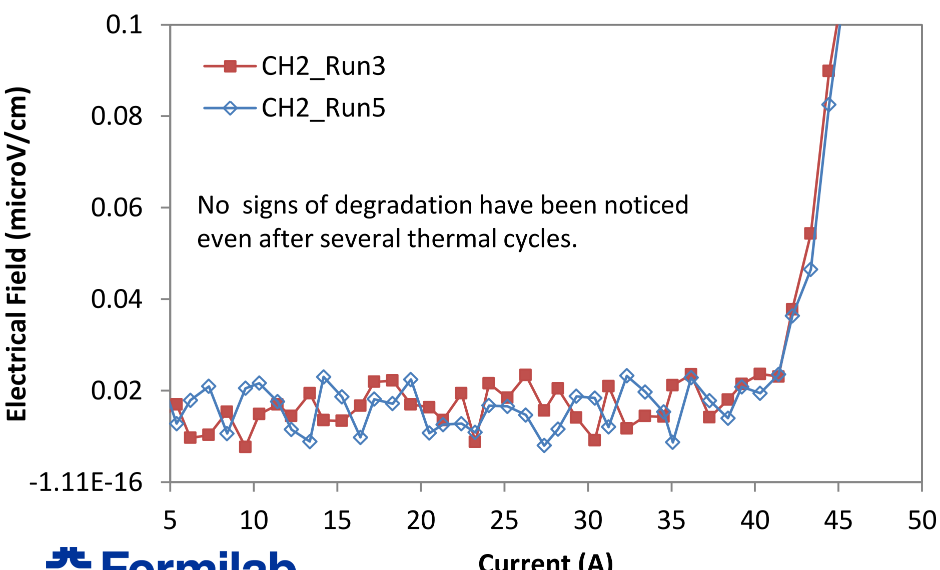
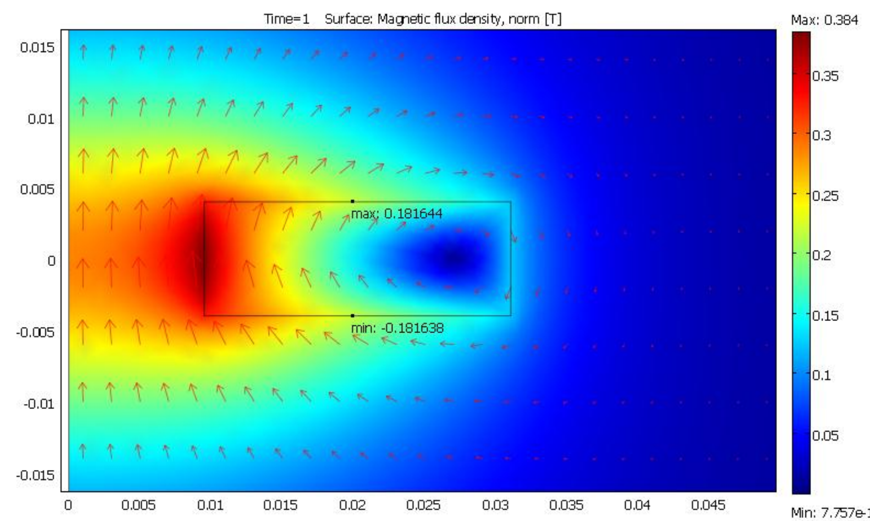
Accounting for anisotropy in Liquid Nitrogen, Self Field Test

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**.

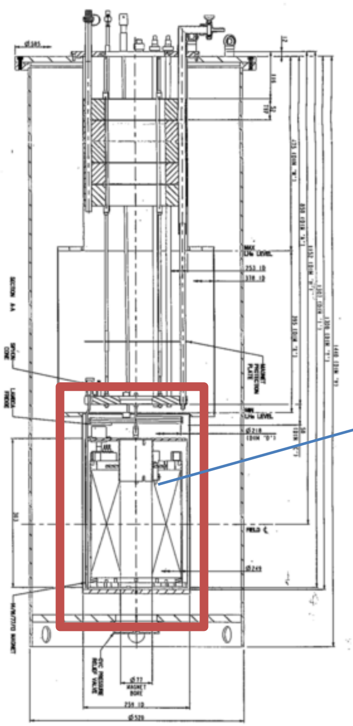


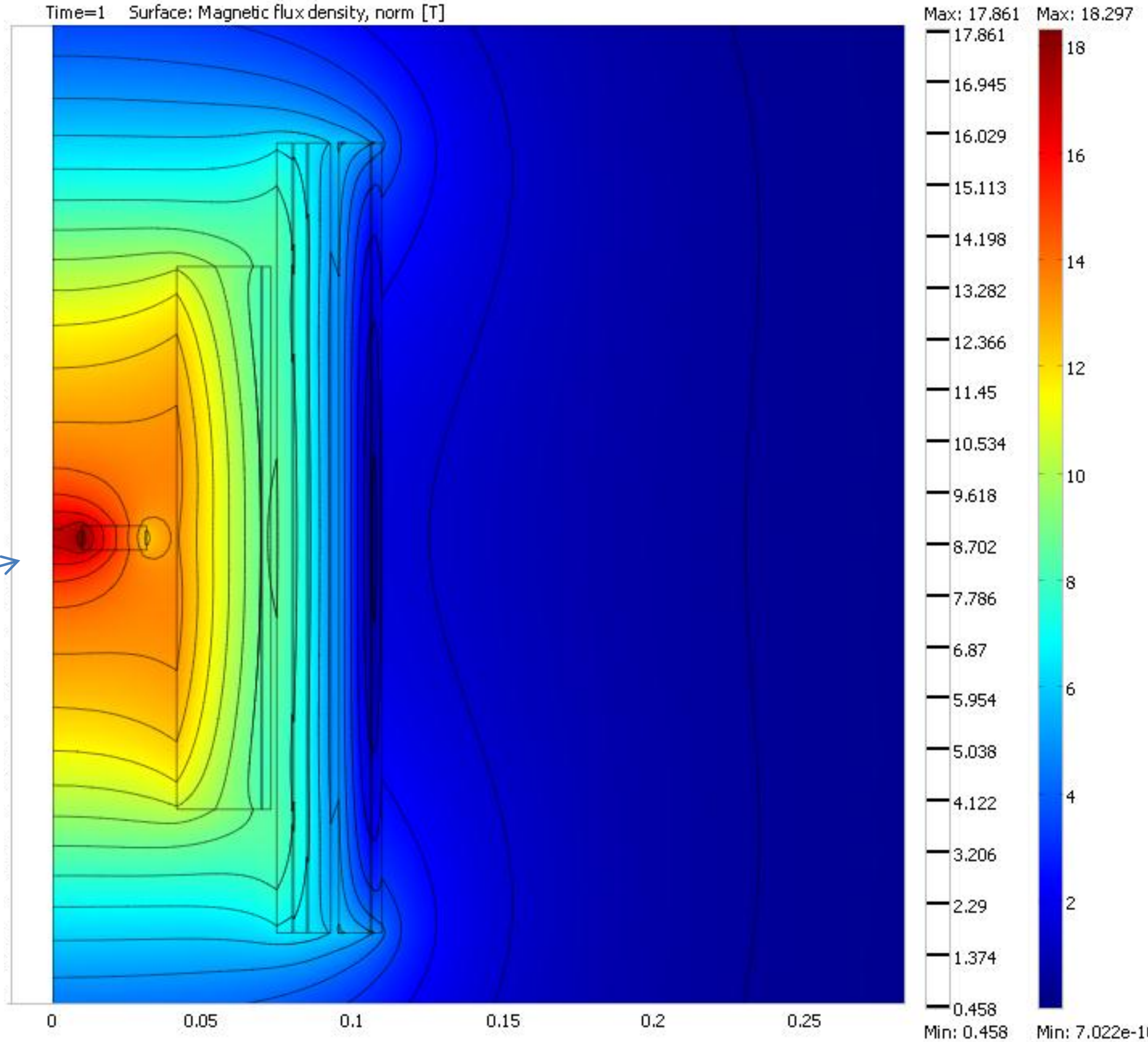






Magnetic Field Distribution with YBCO Insert + bkgr Field





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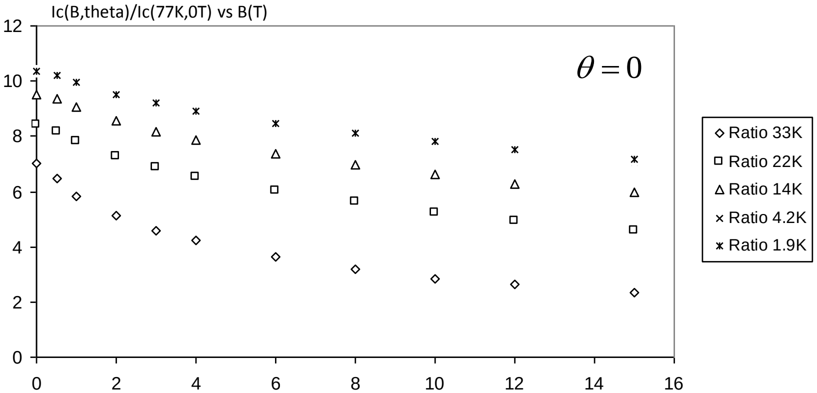
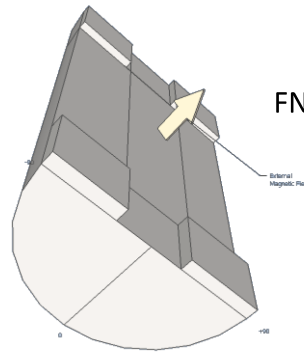
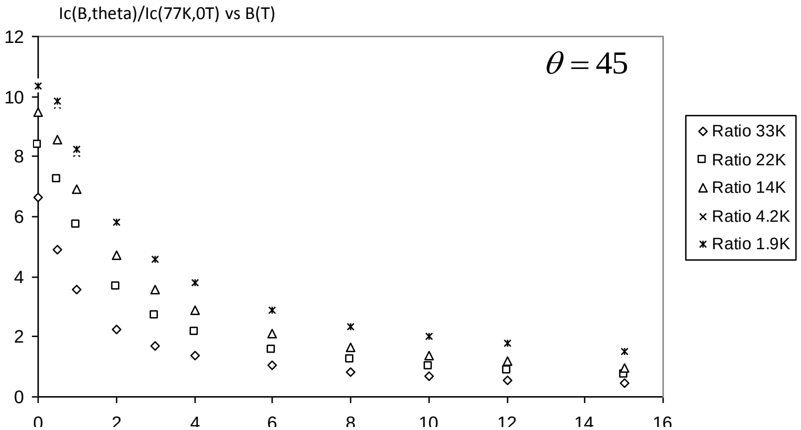
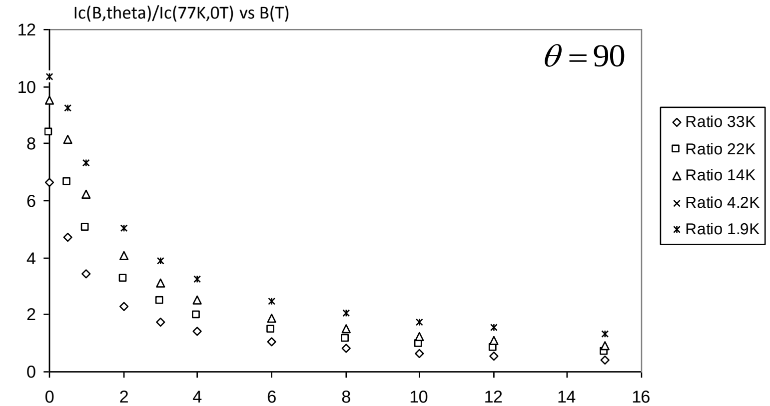
Angular measurements for SP YBCO

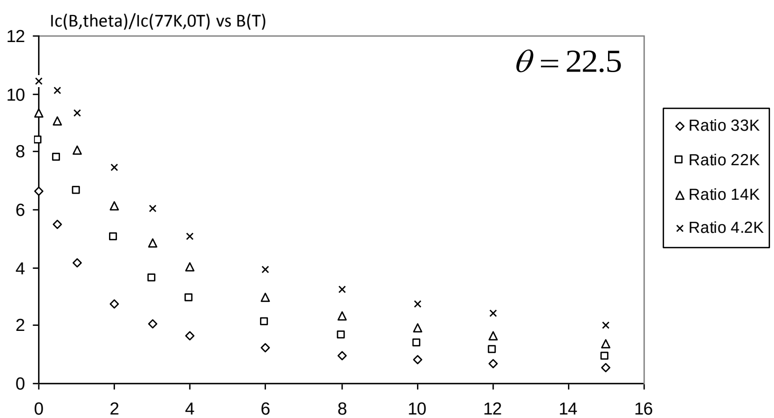
FNAL data are shown for SCS4050 Superpower Tape, for different magnetic field angles of incidence (and temperature).

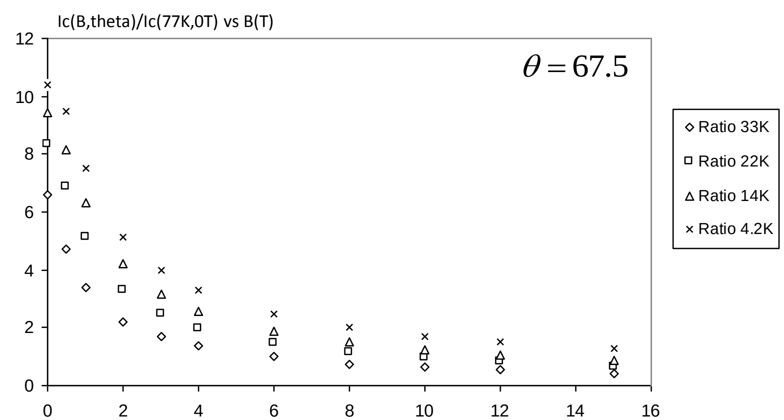






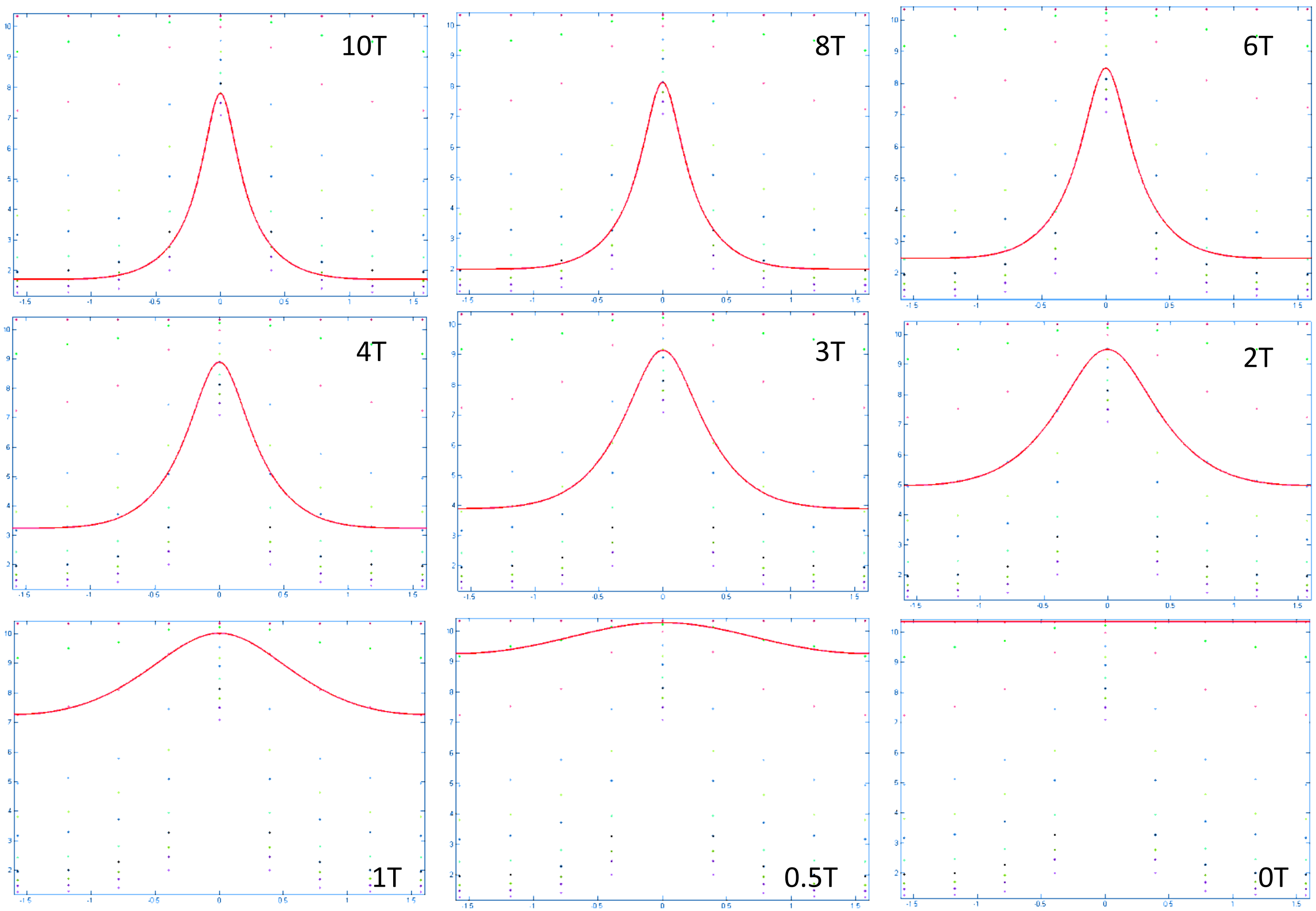






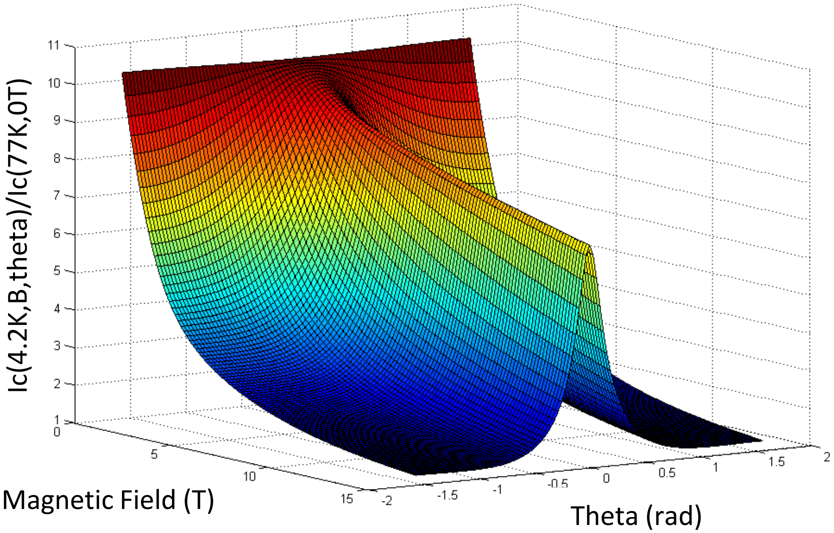
V. Lombardo, A. Bartalesi, E. Barzi, M. Lamm, D. Turrioni and A.V. Zlobin. *"Modular Test Facility for HTS Insert Coils"* - IEEE Trans. Appl. Sup., V. 20, No. 3, p. 587 (2010)

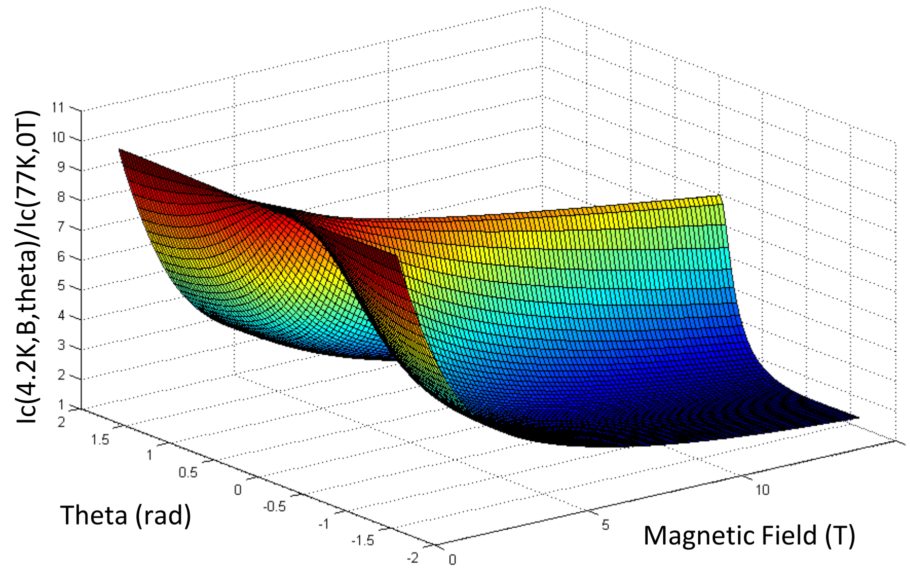
Ic(B,Θ) parameterization for SSL calculation at 4.2K



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

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





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

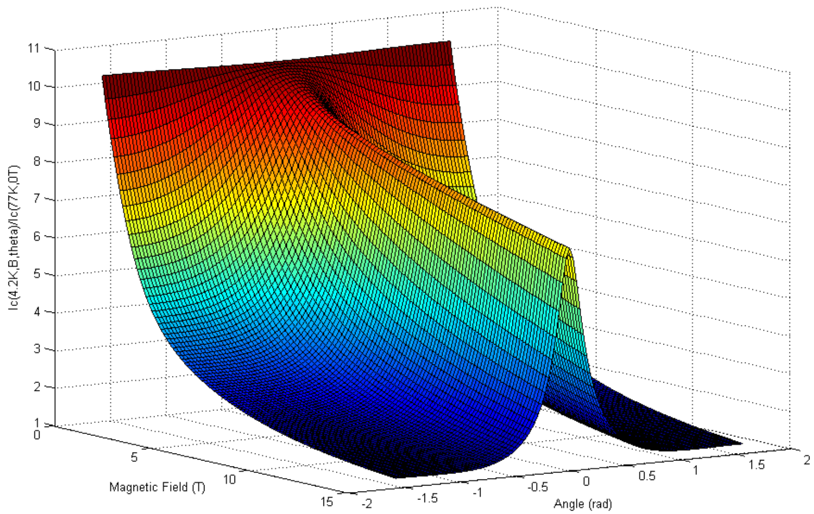
V. Lombardo, E. Barzi, G. Norcia, M. Lamm, D. Turrioni, T. Van Raes and A. V. Zlobin. "*Study of HTS Insert Coils for high field Solenoids*" – Transactions of the Cryogenic Engineering Conference –

V. Lombardo - *"An Ic(B,ϑ) parameterization for $YBa_2Cu_3O_{7-\delta}$ CC Tapes" – FERMILAB-TM-2461-TD*

More HF data available at

D. Turrioni, E. Barzi, M. J. Lamm, R. Yamada, A. V. Zlobin, A. Kikuchi, "Study of HTS Wires at High Magnetic Fields"

Insert Coil performance estimation at 4.2K

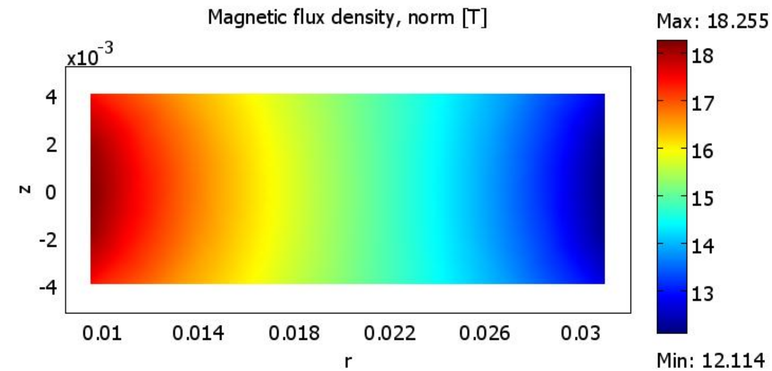


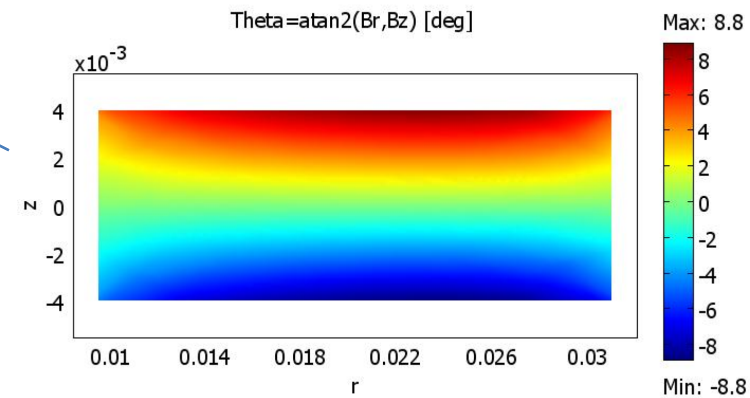
B

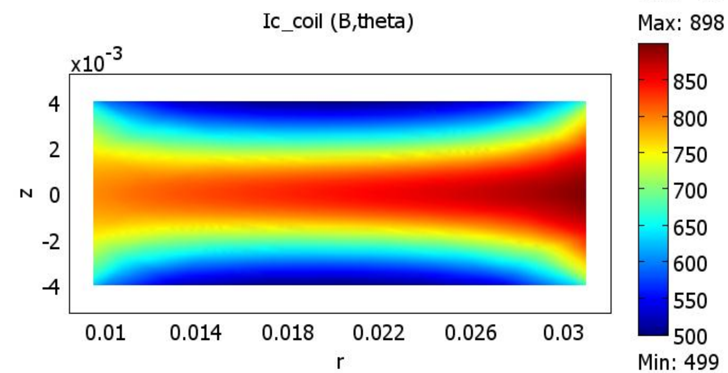
Θ

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

I_c







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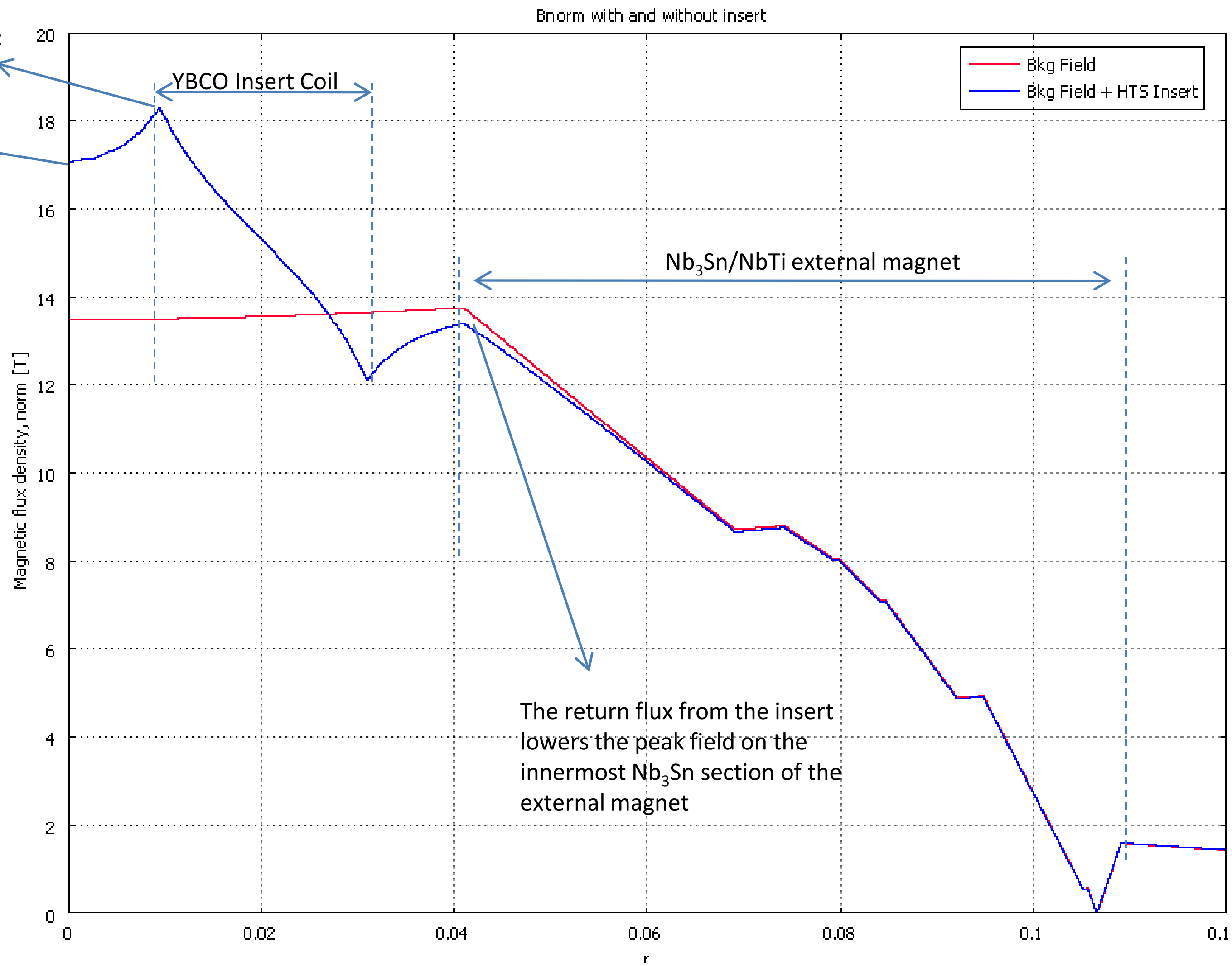
Magnetic Field Distribution with and without Insert

Peak Field on the conductor:
18.3 T @ 498A

Peak Central Field
Bz(0): **17 T** @ 498A



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

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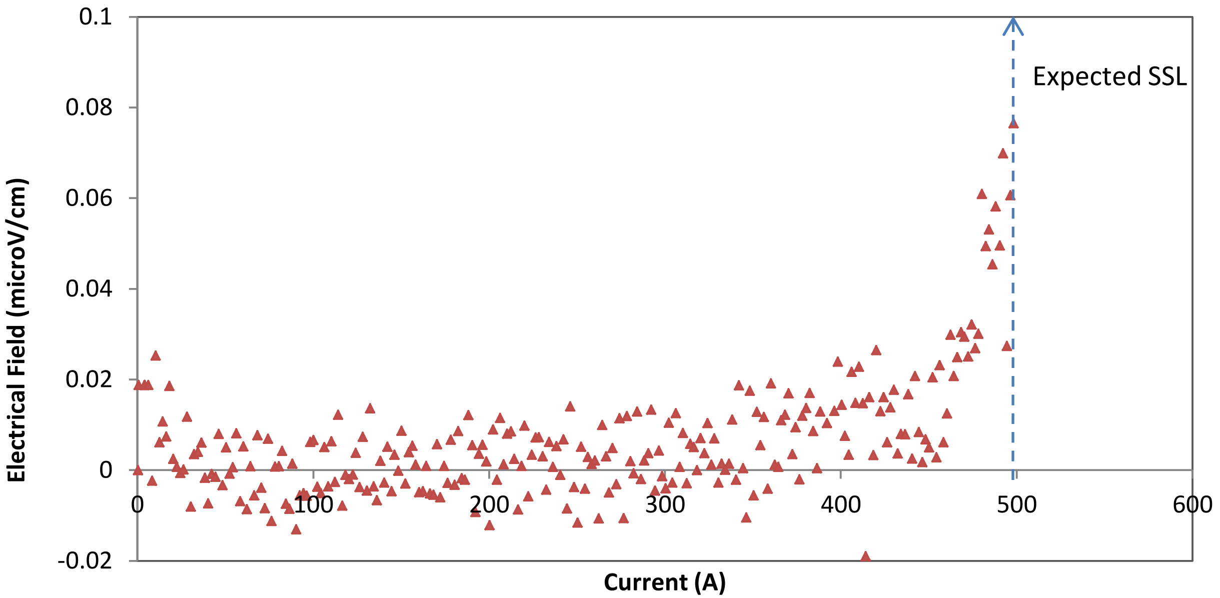
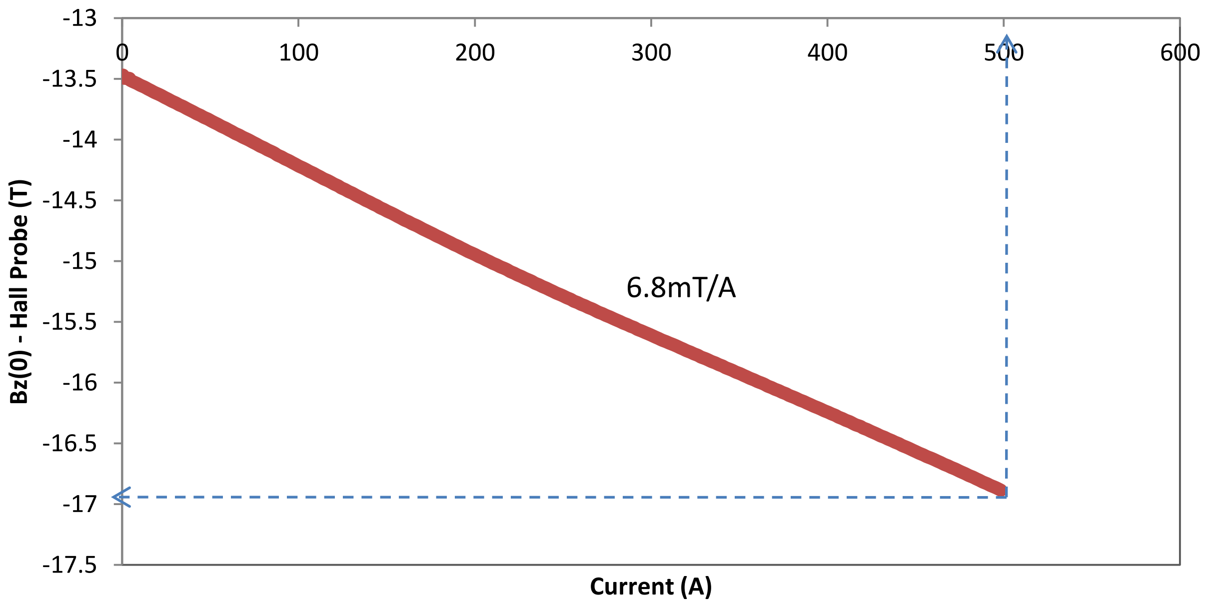
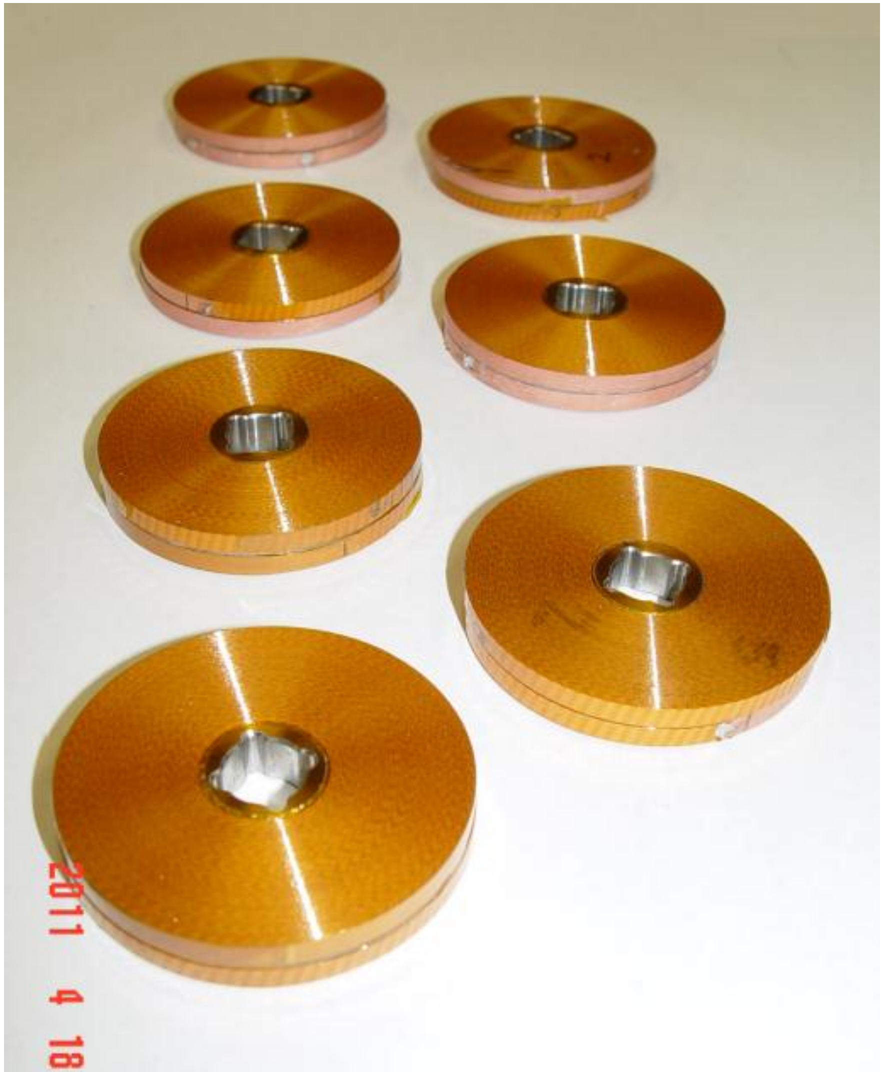
Test results at 4.2K in 13.5T background field

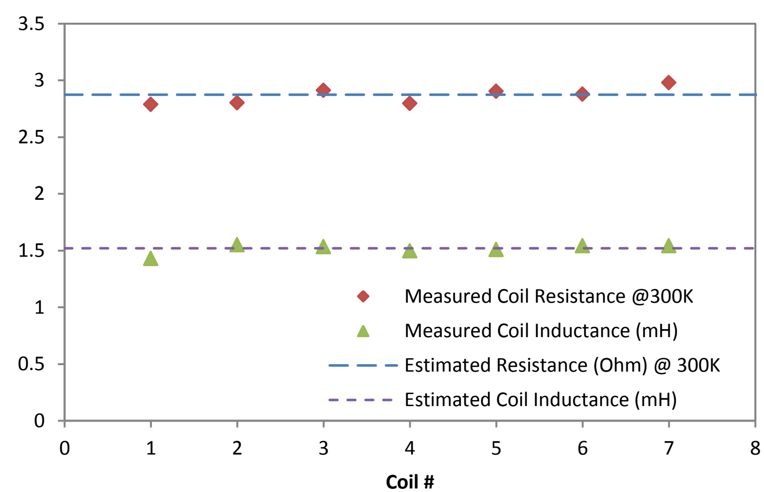




Scale-up work



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



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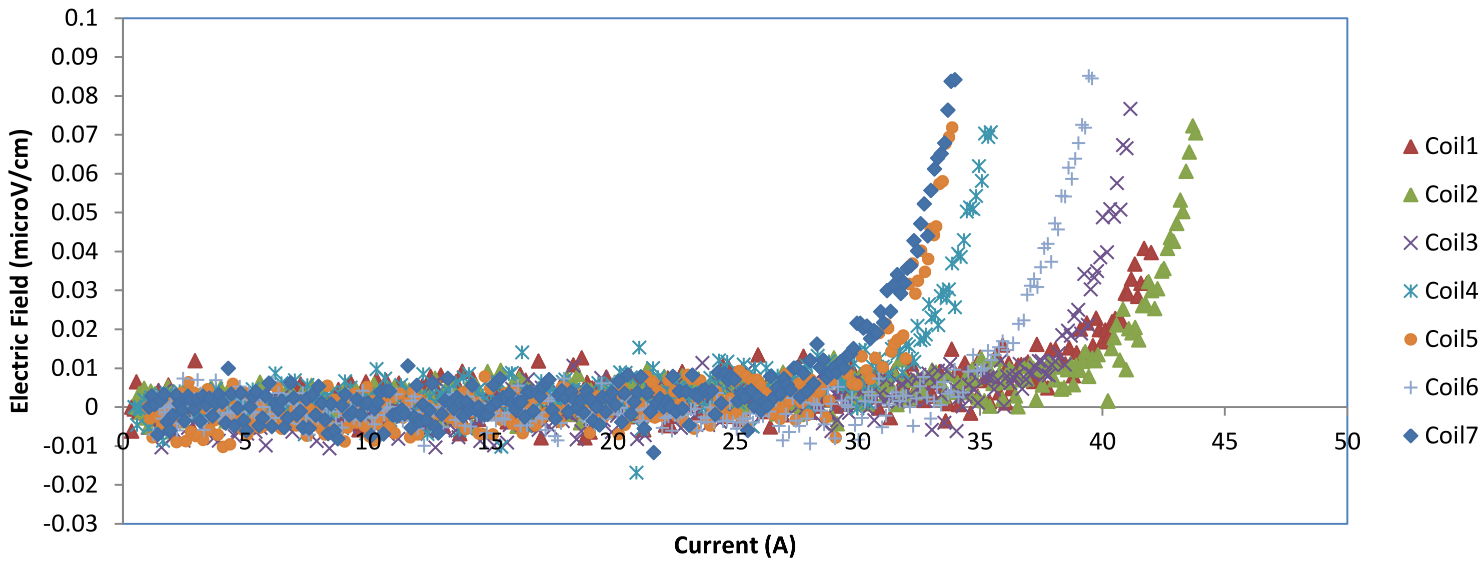
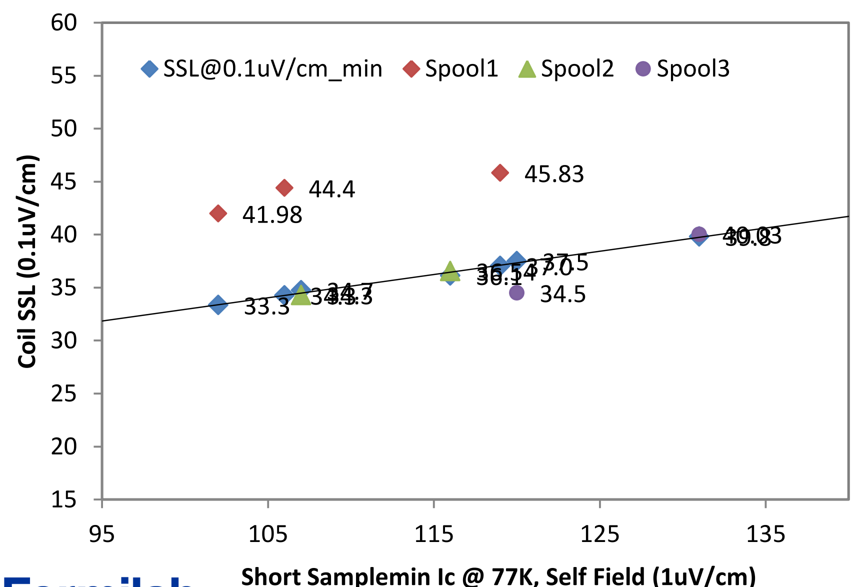
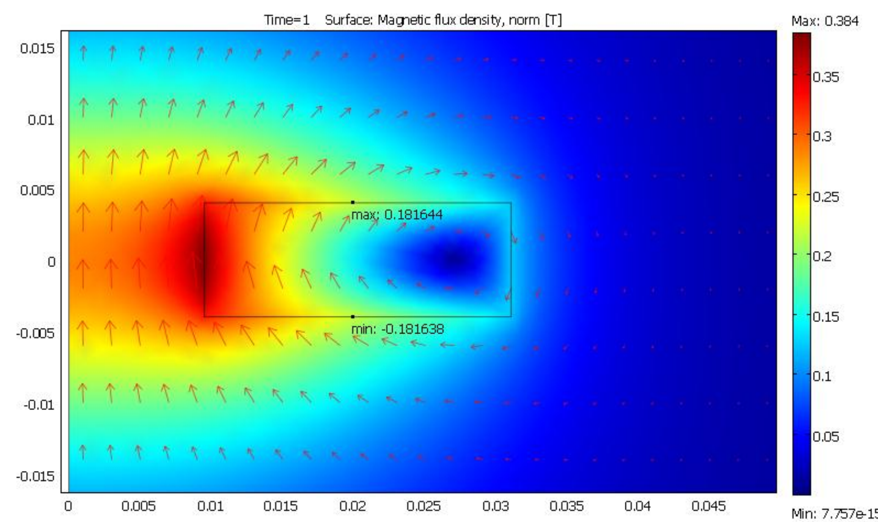
Test of full batch of 7 coils in Liquid Nitrogen







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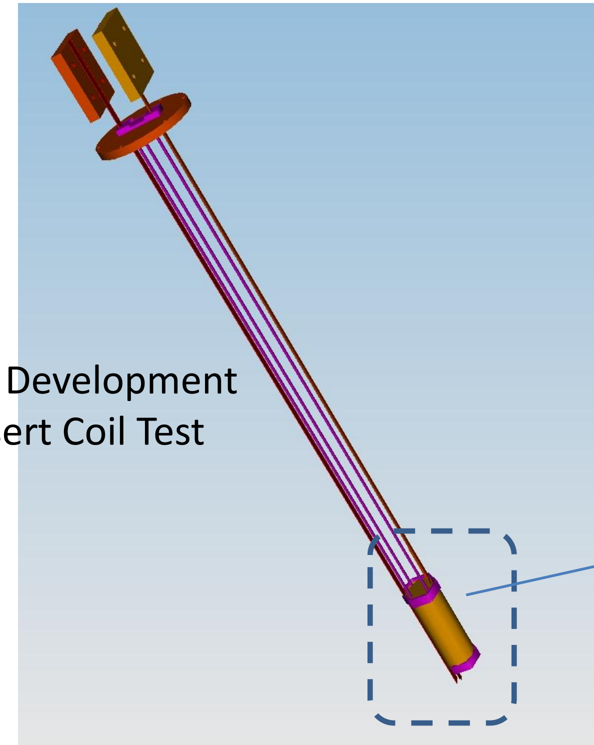
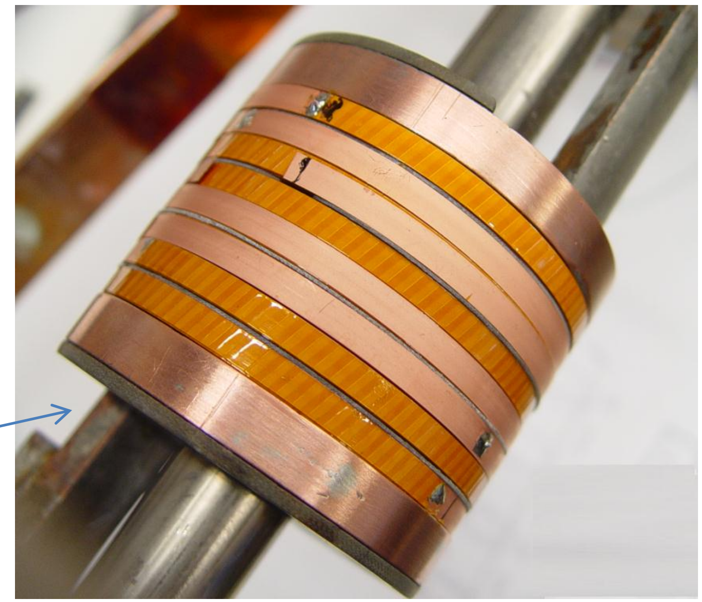
Final Assembly of 4 Double Pancake Coils on the Test Probe



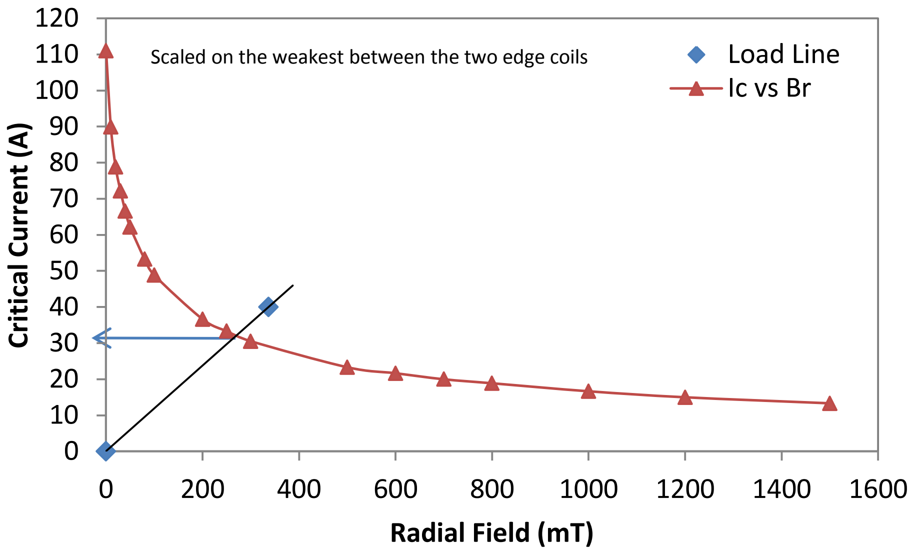
Probe Development
for Insert Coil Test

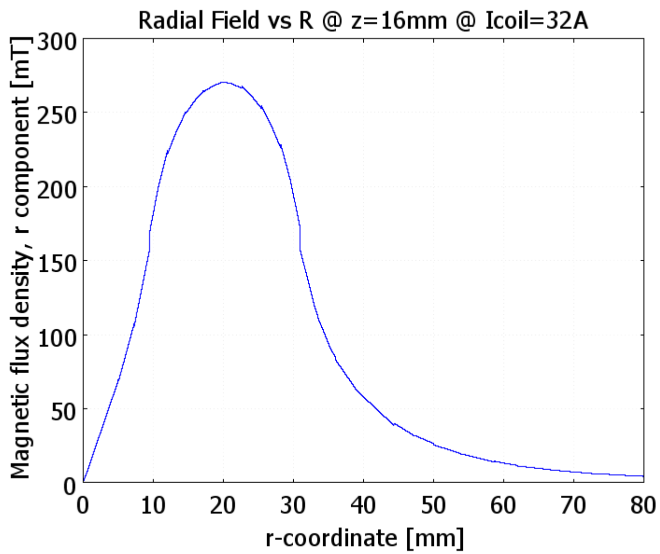


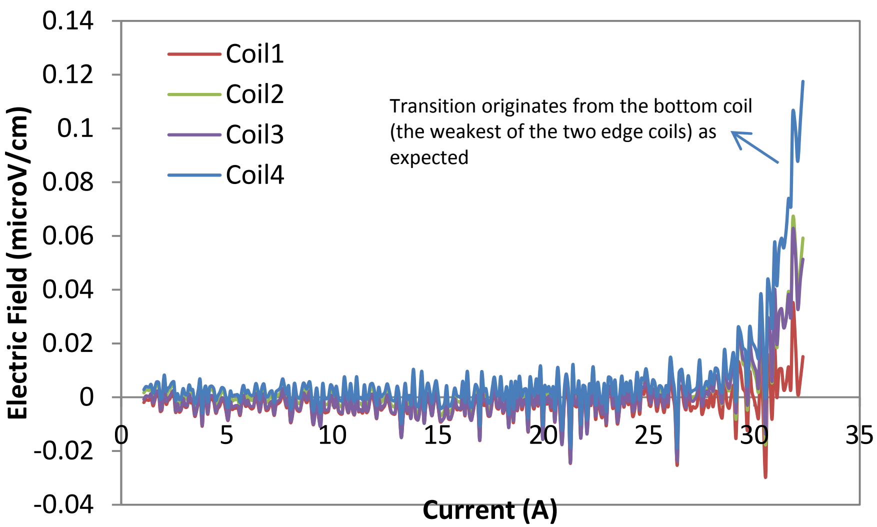
- Modular and Flexible to different coil geometries and number of coils
- Allow the insertion of a Hall probe to measure axial field
- Allow up to 2kA, while minimizing the room allocated to leads for max coil OD

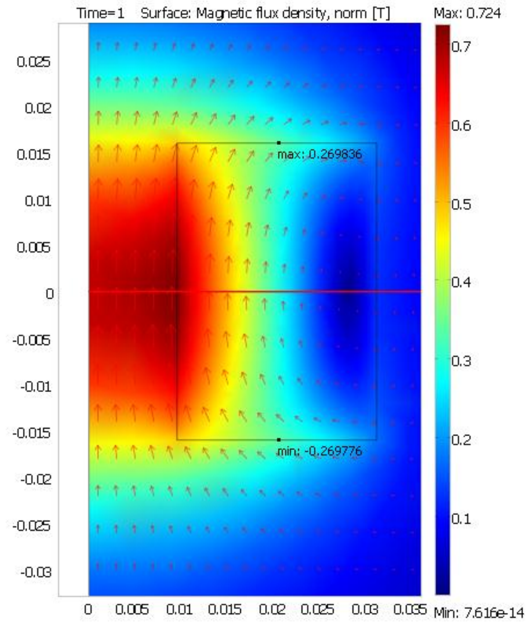
V. Lombardo, A. Bartalesi, E. Barzi, M. Lamm, D. Turrioni and A.V. Zlobin. *"Modular Test Facility for HTS Insert Coils"* – IEEE Trans. Appl. Sup., V. 20, No. 3, p. 587 (2010)

4 coils Liquid Nitrogen test – full coil Ic









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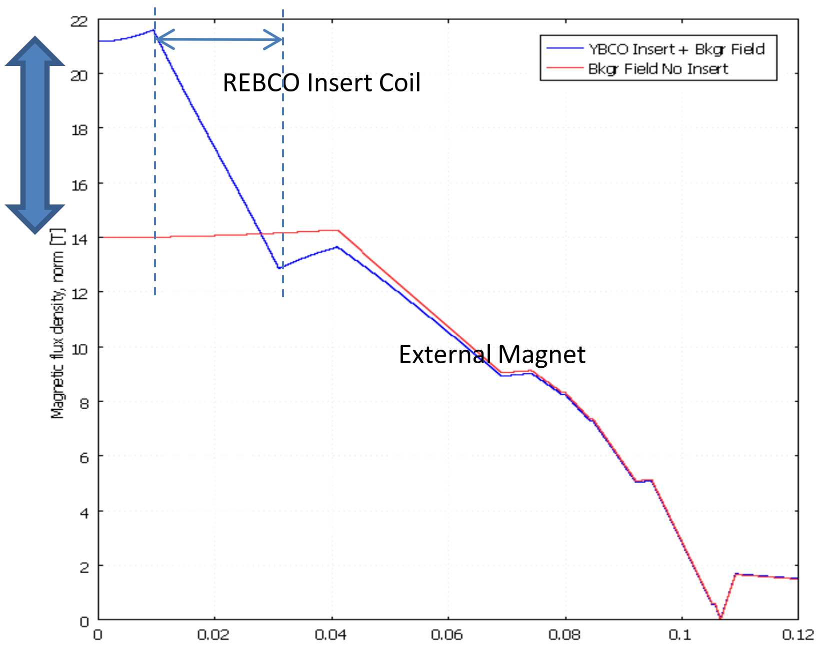
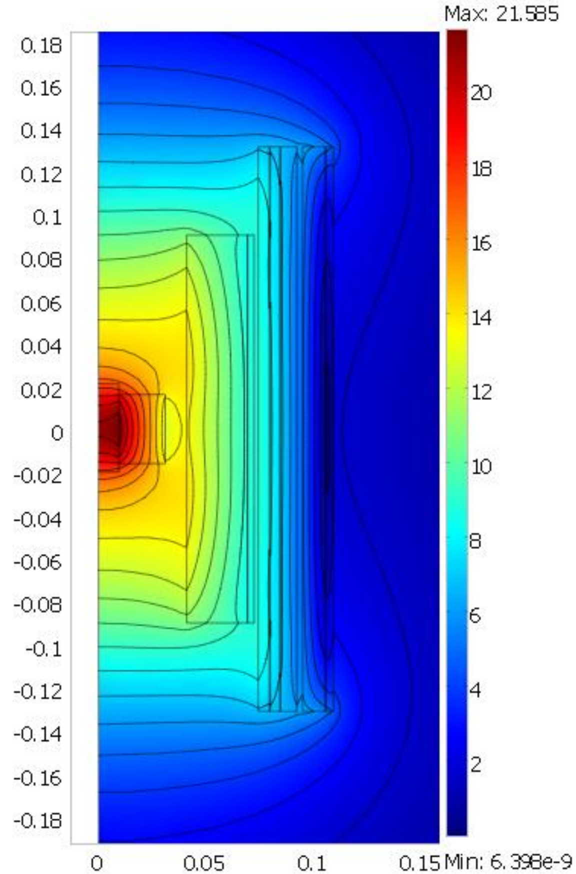
4coils Liquid Helium Test



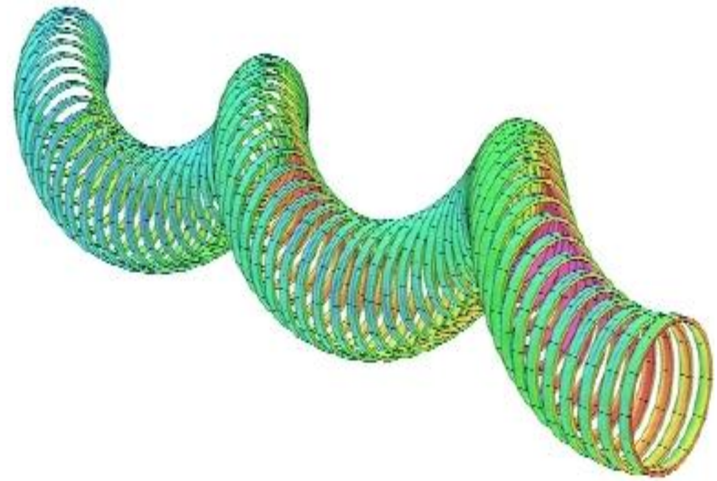


Max Current Reached	335A
SSL	92%
Peak Field on Conductor	21.5T
Peak Axial Field	21.2T

MC Helical Cooling Channel (HCC) Concept

- It includes an helical magnet system combined with RF cavities to recover the beam energy loss in an absorber.
- The coils would follow the helical beam orbit generating solenoidal, helical dipole and helical quadrupole fields
- Studied to be multi-sectional.
- Wide range of fields, helical periods and apertures

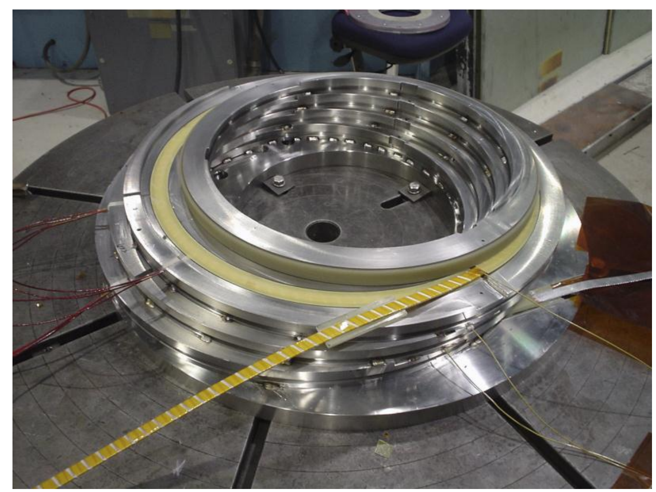
- NbTi, Nb_3Sn and HTS in final stage
- Incorporating RF is a challenge.



First Step: 4 Coil **NbTi** Demonstration Models have been built and tested

Parameter			Section			
			1st	2nd	3rd	4th
Total length		m	50	40	30	40
Period		mm	1000	800	600	400
Orbit radius		mm	159	127	95	64
Solenoidal field	B_z	T	-6.95	-8.69	-11.6	-17.3
Helical dipole	B_t	T	1.62	2.03	2.71	4.06
Helical gradient	G	T/m	-0.7	-1.1	-2	-4.5

K. Yonehara, S. Kahn, R. Johnson et al.



N. Andreev et al, *"Model NbTi Helical Solenoid Fabrication and Test Results"*

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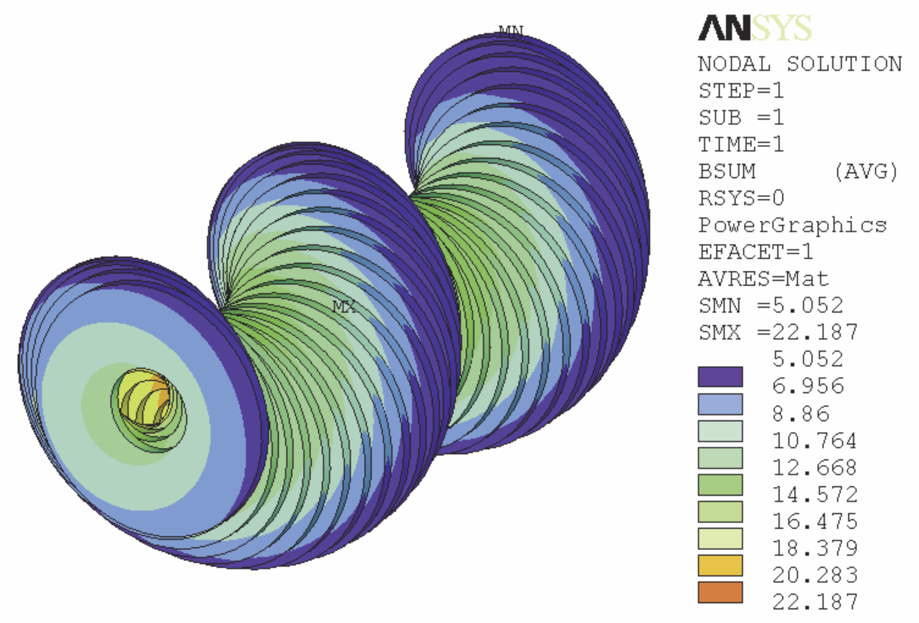
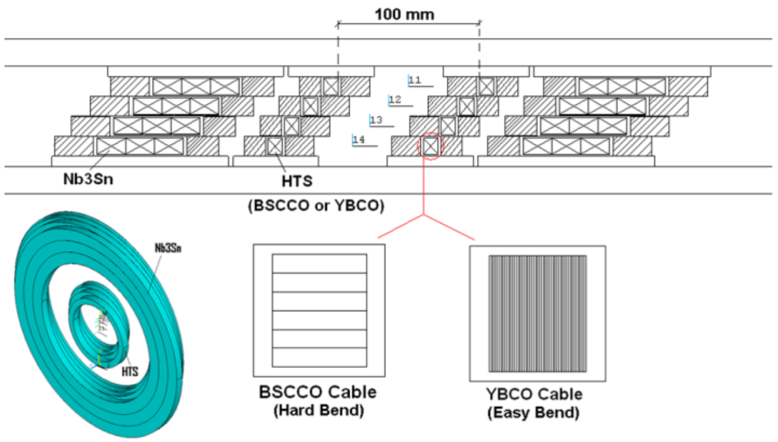
Muons, Inc. Innovation in Research

High Field Section of Helical Cooling Channel

Hybrid models **(Nb_3Sn+HTS)** needs to be investigated to achieve the required field levels for the **last HCC section**.





M. Lopes et al, *"Studies of the High-Field Section for a Muon Helical Cooling Channel"* and *"Studies of the High-Field Sections for a Muon Helical Cooling Channel with coil Separation"*

REBCO Helical Solenoid **Short Model**

In order to start developing the coil technology, 3 REBCO double pancakes units with dummy cavity insertions were designed, assembled and tested according to the following parameters.

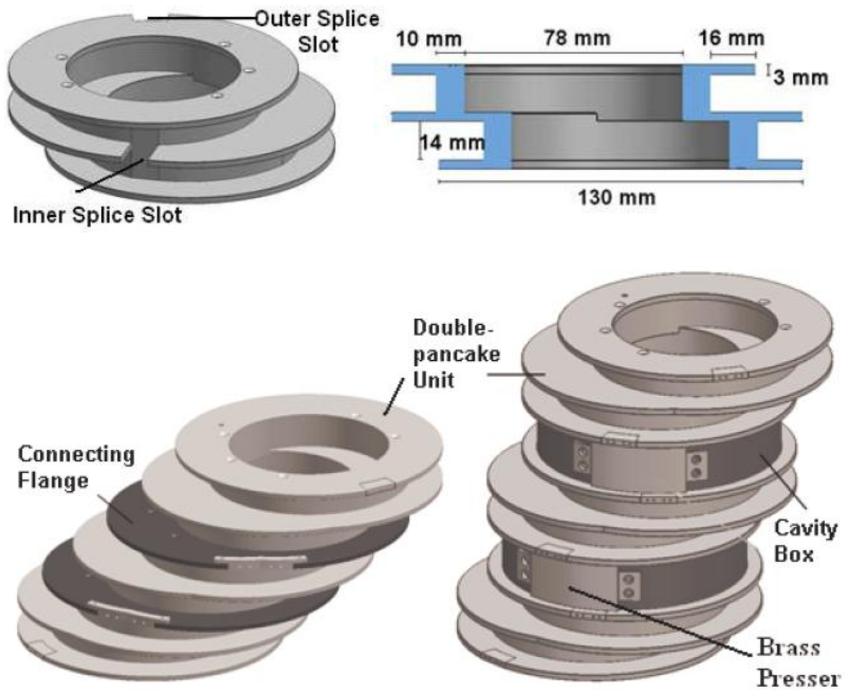
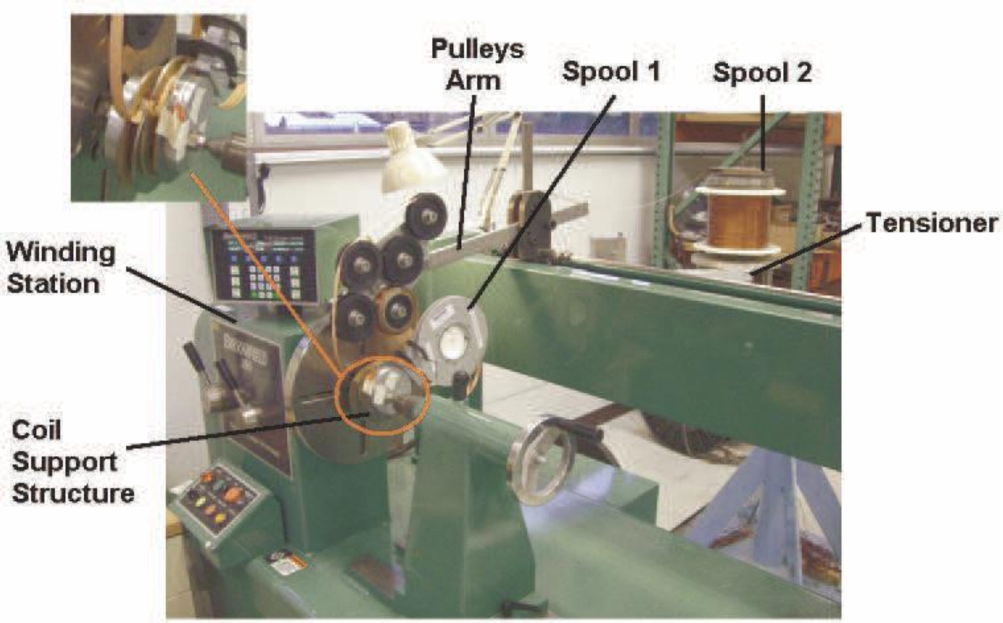


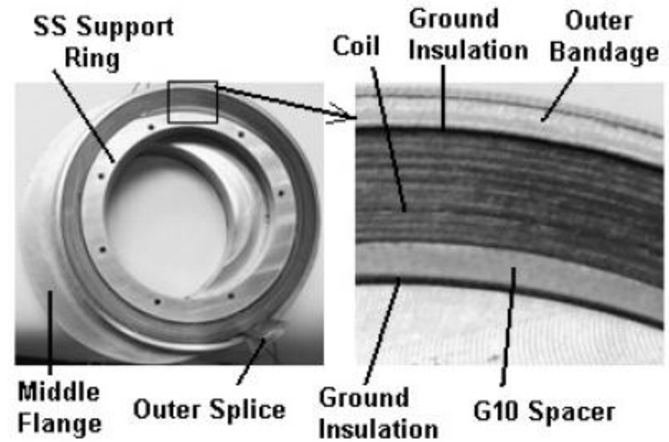
Table 1: HS Short Models Parameters

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

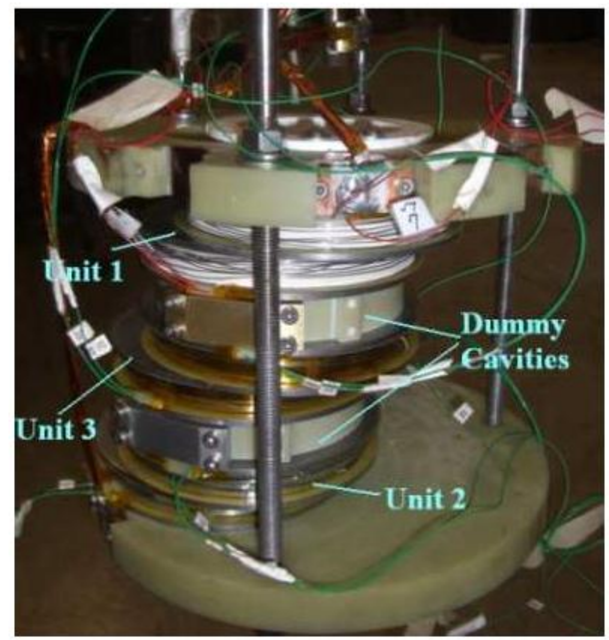
A. V. Zlobin et al. *"Modeling the high-field section of a Muon Helical Cooling Channel"*

REBCO Helical Solenoid **Short Model**





1. Coils assembled using commercially available 12mm wide SuperPower ybco tape. Dry Wound. Kapton insulation.
2. Coils were wound and unwound several times and thermal cycled with no degradation.
3. Non-negligible degradation at inner and outer joints was seen during coil excitation.



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

Some Considerations on **REBCO**

REBCO offers interesting opportunities for 20T-50T magnet development.

- Suitable for **high field-high stress applications** in traditional and more exotic coil geometries.
- It allows magnet operation at temperatures substantially higher than 4.2K -- if needed by the application (HF HCC + cavities operated at 30K+)
- Can be wound as is - **no reaction needed**.

Some topics of interest :

1. **Conductor anisotropy** needs to be carefully accounted for in magnet design. A framework for doing that has been presented.

2. **Conductor uniformity** in terms of $J_c(B,\Theta)$ at 4.2K is critical. Clear need to upgrade from a 77K to some sort of **4.2K QC**. How do we define a '*defect free*' conductor for low temperature, high field applications ?

3. **Splice resistance** is - in most cases - achieved down to the 50 $n\Omega cm^2$ level, nevertheless some degree of degradation in joints has been seen during magnet operation.

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Some Considerations on **REBCO**

4. **Quench protection** remains substantially more challenging than LTS magnets. Up to 100 μm of Cu can be added by manufacturers to commercially available wires. This helps increasing the stability of the conductor and loosening the requirements on the **quench protection**. What is really needed for large scale systems ?

5. All coils wound today rely on **single REBCO tapes**. Far from ideal solution, but only one currently available. Mechanically stable high J_e **cables** are needed to operate this conductor in large high-field high-inductance accelerator-quality magnets. (Roebel, CORC --- more on this tomorrow morning)

6. Last, but not least, **conductor affordability**.