10 T HTS Solenoid

Ramesh Gupta
BNL

Persons Involved at SMD/BNL

- Mike Anerella
- Arup Ghosh
- Ramesh Gupta
- Steve Plate
- Bill Sampson
- Peter Wanderer
- … and valuable designers and technicians

Overview

- Goal of the program
- Proposed Enhancements
- Preliminary solenoid design
- Future plans and initial schedule

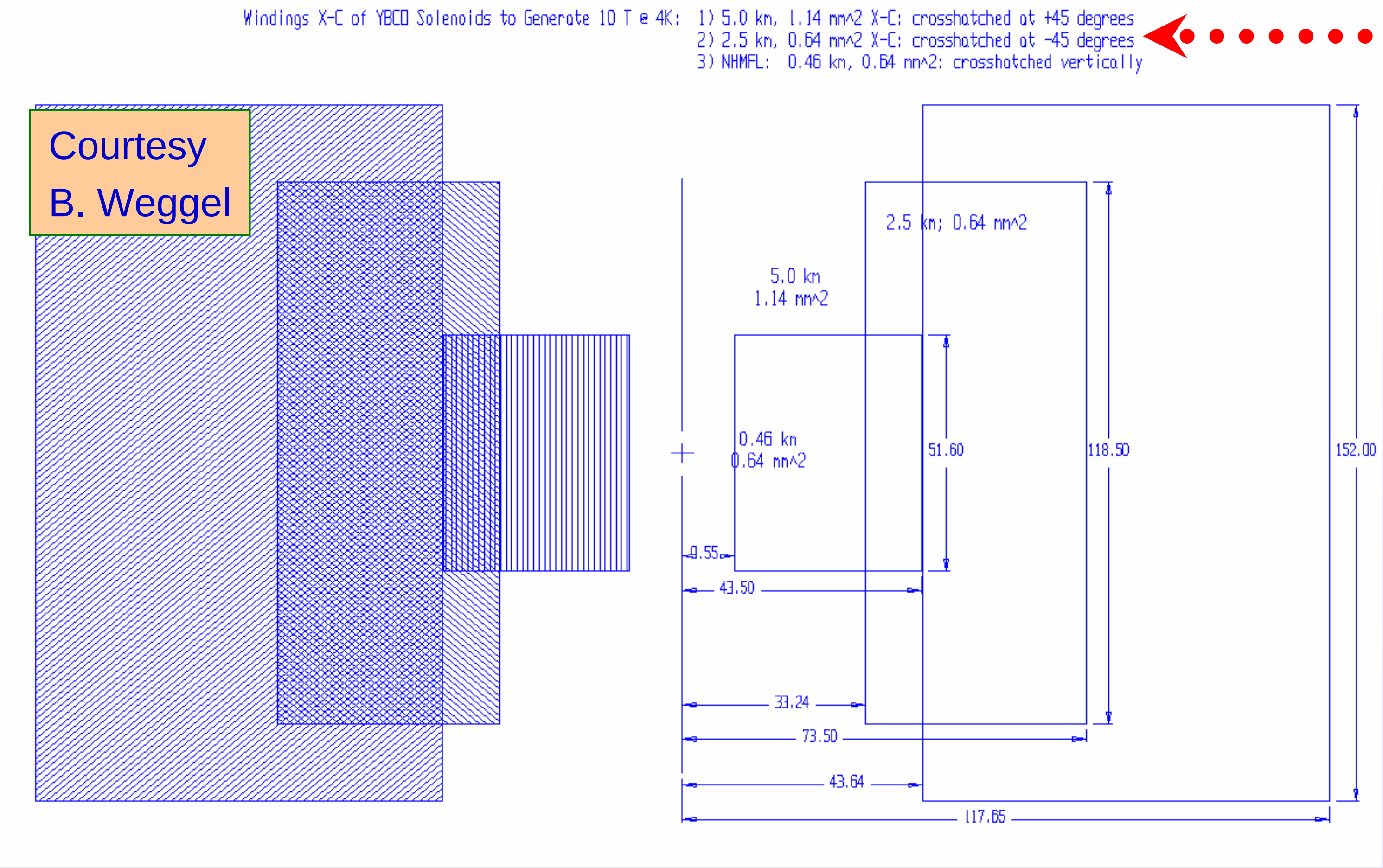
GOALS OF THIS SBIR
(related to the component on HTS solenoid)

- **Ultimate stated goal (target) of the solenoid proposal**
  - 10 T, 10 cm solenoid operating at 30-40 K (if we were not limited by budget)
- **Well defined deliverable (along with other components of SBIR)**
  - 10 T at 4 K (and ~5 T at 33 K) in a solenoid with coil i.d. approaching 10 cm
  - Measure performance (achievable B) as a function of temperature (4 -70 K)
- **Other vaguely defined goals (mentioned at various places)**
  - Develop technology for 10 T, 10 cm solenoid operating at 30-40 K
  - Carry out this R&D as a step towards small bore, high field solenoids at 4 K
  - Develop HTS technology for other muon collider magnets that reside in high radiation environment and/or may benefit from high temperature operation

Benefit from this SBIR to launch more in related fields

Superconducting Magnet Division

10 T HTS Solenoid Designs (as presented in the proposal)

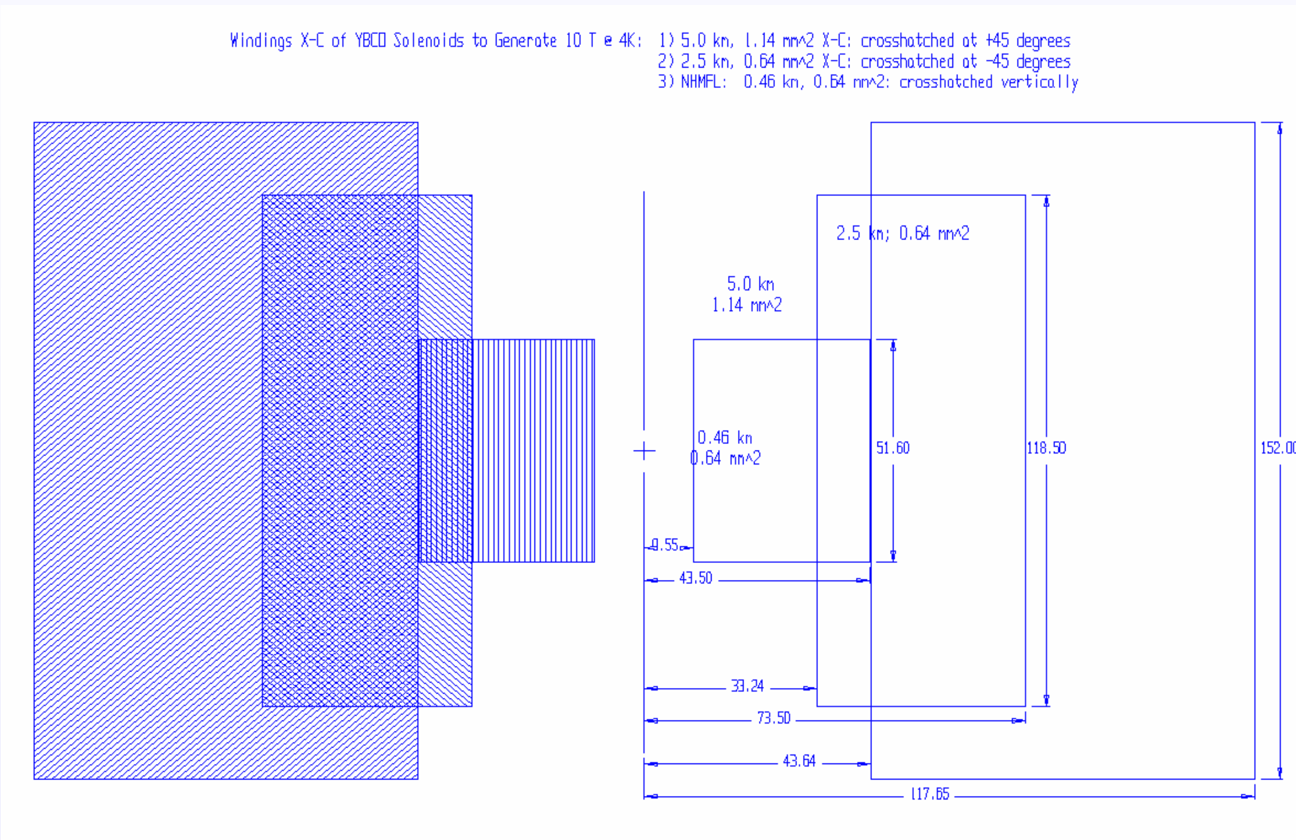


All cases for 10 T at 4.2 K

- In the original SBIR proposal, we promised case (2) - which was for coil i.d. = 66.5 mm
  - o Case (1) was for coil i.d. = 87.2 mm
  - o Case (3) 9.8 T SuperPower/NHFML solenoid was for coil i.d. = 19 mm

HTS Solenoid
Enhancement #1 – Larger Bore

- In the original proposal, we promised 66.5 mm coil i.d.
- Thanks to better Je, we are now aiming for a significantly higher value – 110 mm coil i.d.
    - ➢ this is better than even case (1) of the original proposal, which was for 87.2 mm coil i.d. (more on this later)



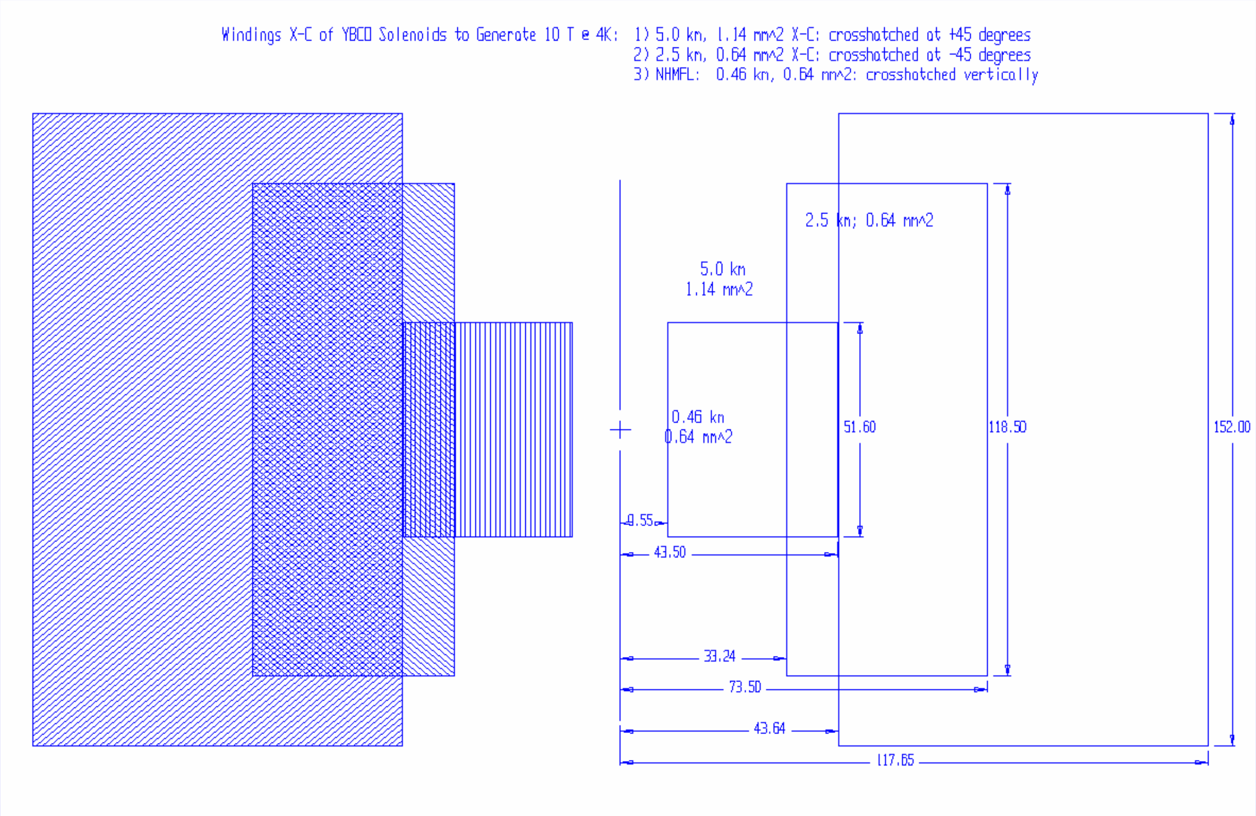
Large coil i.d. is important for some muon collider solenoids

All cases for 10 T at 4.2 K

HTS Solenoid

Enhancement #2- Higher Field or Higher Temperature

- In the original proposal, we promised 10 T in 66.5 mm coil i.d. at 4 K
- Thanks to the collaboration & promised contributions from SuperPower, we are now aiming for 20+ T in ~29 mm coil i.d. (more on this later)
- Alternatively, we can say that we are now aiming a demonstration of ~10 T at higher temperature (30 K) in ~29 mm coil i.d. (more on this later)



High field HTS magnets, particularly high field solenoids, are important for many applications (particularly in muon collider)

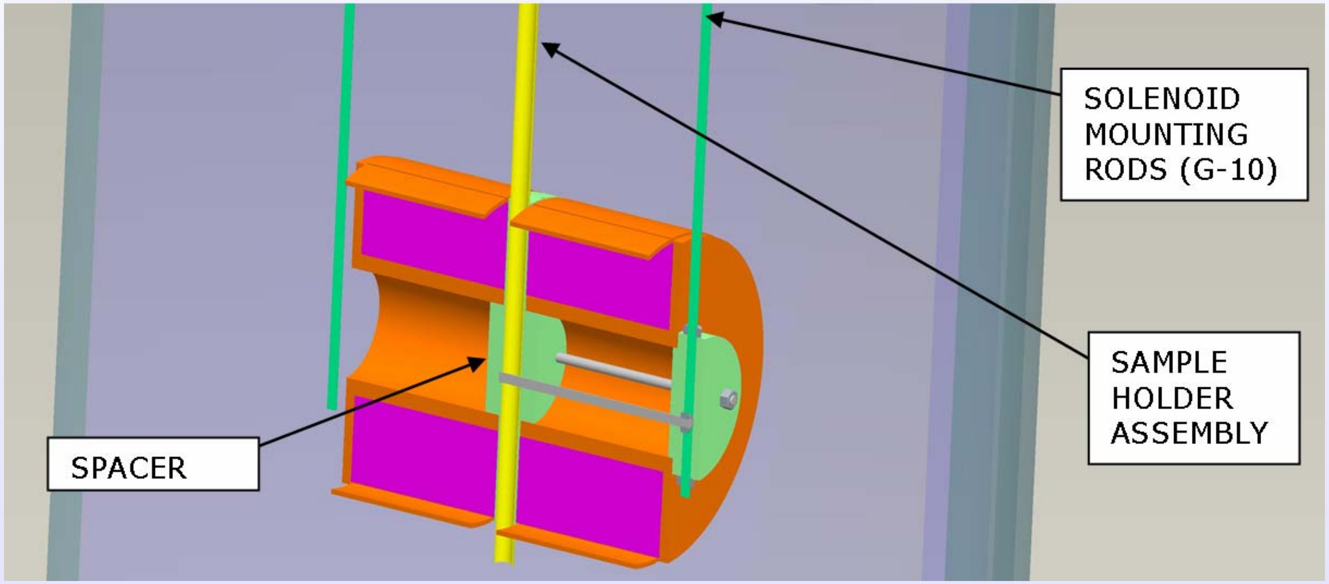
In this SBIR proposal, we had mentioned 10 T at 30-40 K

HTS Solenoid

Enhancement #3 – Making an important test facility

- Current carrying capacity of HTS depends critically on the direction of field, in addition to the magnitude of the field and on the temperature. There is no good facility for such measurements.
- Thanks to the interest of BNL, this solenoid can help create such a facility.

We will make a split-pair 10 T solenoid with sufficient bore (10 cm) and gap in between the two coils to facilitate measurements of HTS as a function of both magnitude and direction of field, at various temperature --- higher than 4K temperature measurements are important for this field.

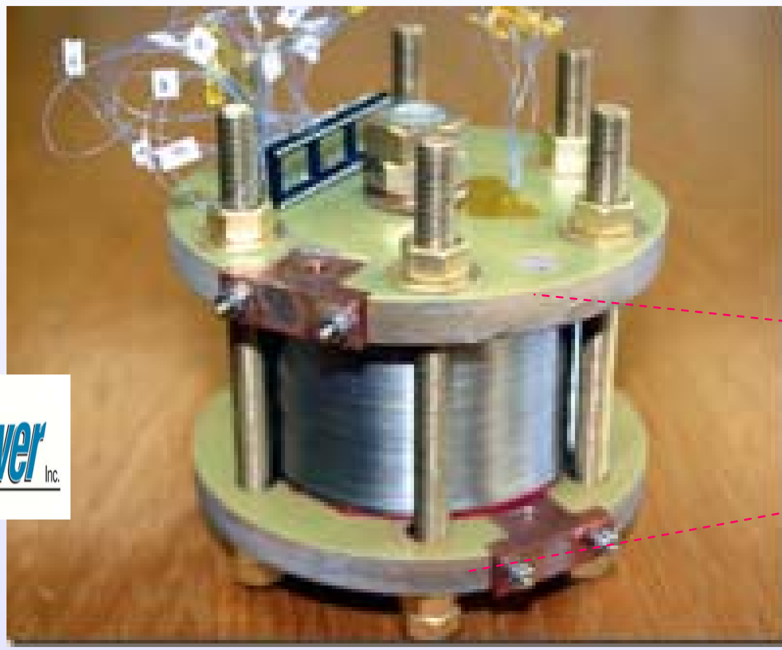


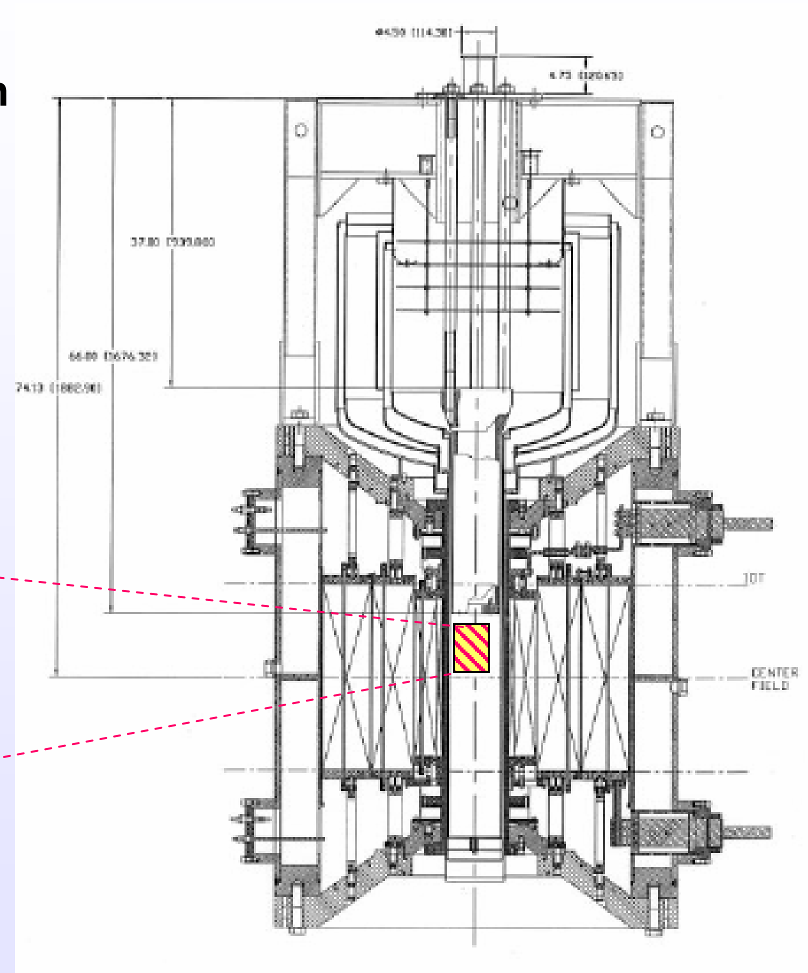
Without gap, the expected field is ~12 T (assuming 30% improvement in conductor). Thus we have 20% margin (more on this later).

Review of the field and update on discussions with our new collaborators

SuperPower HTS Solenoid inside the NHMFL 19 T Solenoid (providing background field)

SuperPower made a ~10 T small aperture HTS solenoid with its own conductor and tested it in NHMFL's unique, 19-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet (solenoid)





SuperPower Inc.

2G HF insert coil showing terminals, overbanding and partial support structure. Flange OD is 127 mm.

MAGNET LAB
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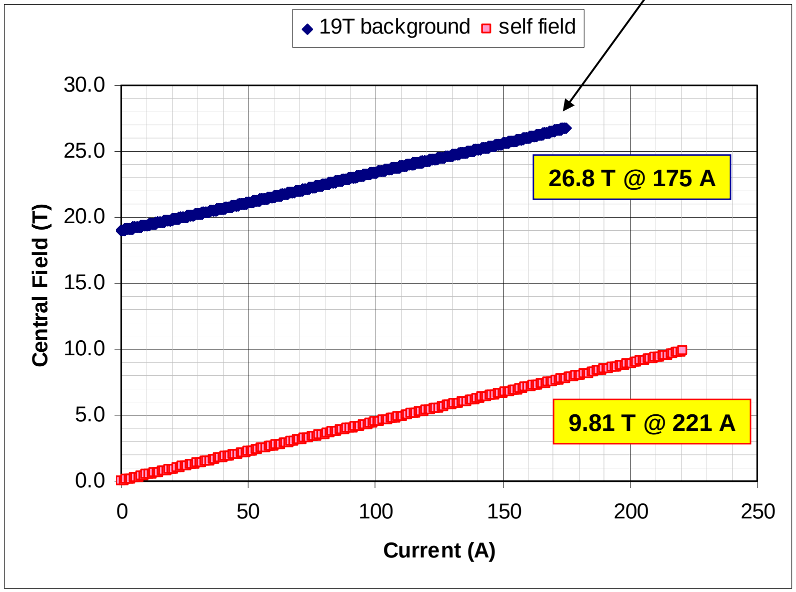
SuperPower/NHFML YBCO Solenoid

High field insert coil achieves world records for highest HTS field, highest magnetic field by a SC magnet

Peak hoop stress ~ 215 MPa, well below tape limit



Ic of Wires in Coil	72 A – 82 A (77K, sf)
4.2 K Coil Ic - self field	221 A
4.2 K Amp Turns @ Ic-self field	612,612
4.2 K Je @ Ic, self field	346.7 A/mm^2
4.2K Peak Radial Field @ Ic, self field	3.2 T
4.2 K Central field – self field	**9.81 T**
4.2 K Coil Ic – 19 T background (axial)	175 A
4.2 K Amp Turns @ Ic – 19 T background (axial)	485,100
4.2 K Je @ Ic, 19 T background (axial)	274.6 A/mm^2
4.2 K Peak Radial Field @ Ic, 19 T bkgd (axial)	2.7 T
4.2K Central Field – 19 T background (axial)	**26.8 T**

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SuperPower Inc.

Low Temperature Superconductivity Workshop, 10/29/07 – 19 –

BNL/PBL/SuperPower Collaboration (1)

➢ **A very productive visit to SuperPower on 9/9/2008**

Superconducting
Magnet Division

http://www.bnl.gov/magnets/staff/gupta

2G HTS Magnet R&D

Ramesh Gupta

A discussion on the potential of 2G conductors in more HTS magnet applications in accelerators and medical sciences

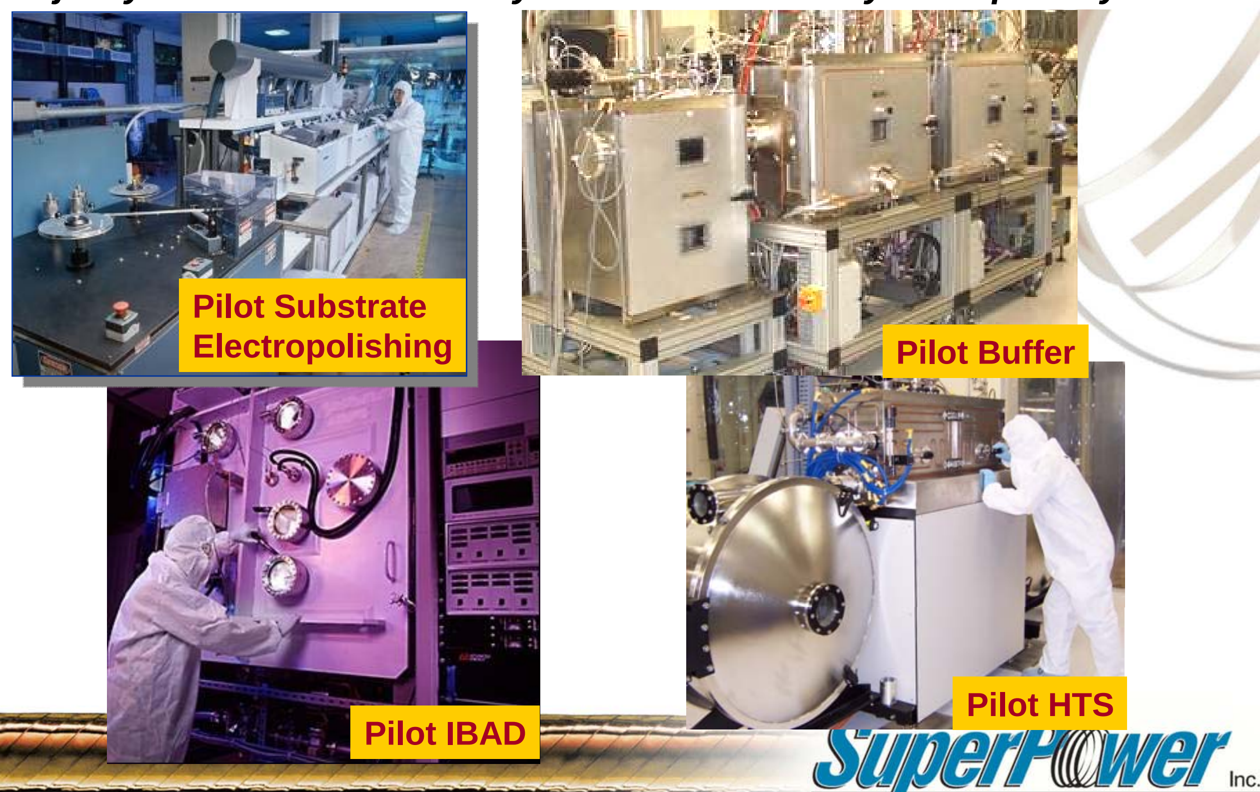
Ramesh Gupta, BNL | *2G HTS Magnet R&D* | SuperPower, September 9, 2008

BNL/PBL/SuperPower Collaboration (2)

➢SuperPower Site in Schenectady, NY

SuperPower's 2G pilot manufacturing facilities have been *operational* since 2006

Majority of investment already made for 1000 km/year capability



Low Temperature Superconductivity Workshop, 10/29/07 – 4 –

BNL/PBL/SuperPower Collaboration (3)

➢ And a return visit of SuperPower to BNL on 9/23/2008

- First meeting at ASC2008 where we discussed the possibility for SuperPower providing insert coil for high field solenoid.
- The collaboration was finalized during a visit to SuperPower.
- Now SuperPower has promised two coils. We are working together so that the length of our coils in split-pair solenoid matches with the length of their coils.

INFORMAL SEMINAR

SuperPower Second Generation (2G) HTS Wire for Magnet Applications

BY

Drew Hazelton
Trudy Lehner

Tuesday, September 23, 2008

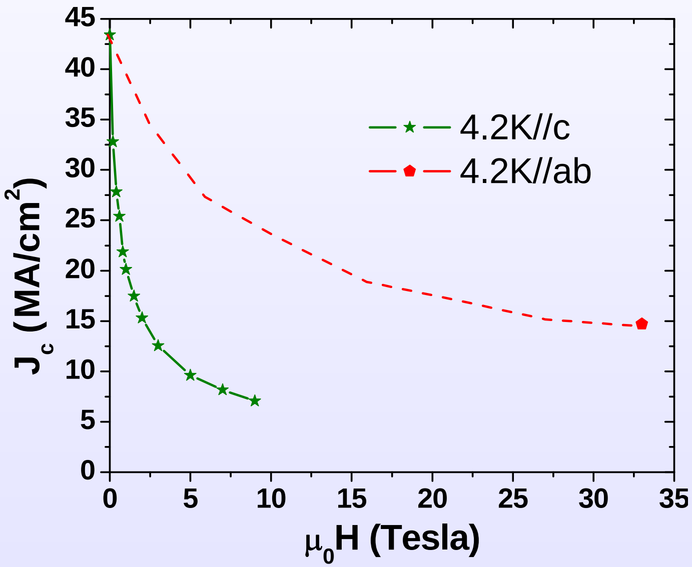
2:30 p.m.

902A Conference Room 63

Angular Dependence of I_c in HTS

Unlike in LTS, Ic generally has a strong angular dependence in presence of field

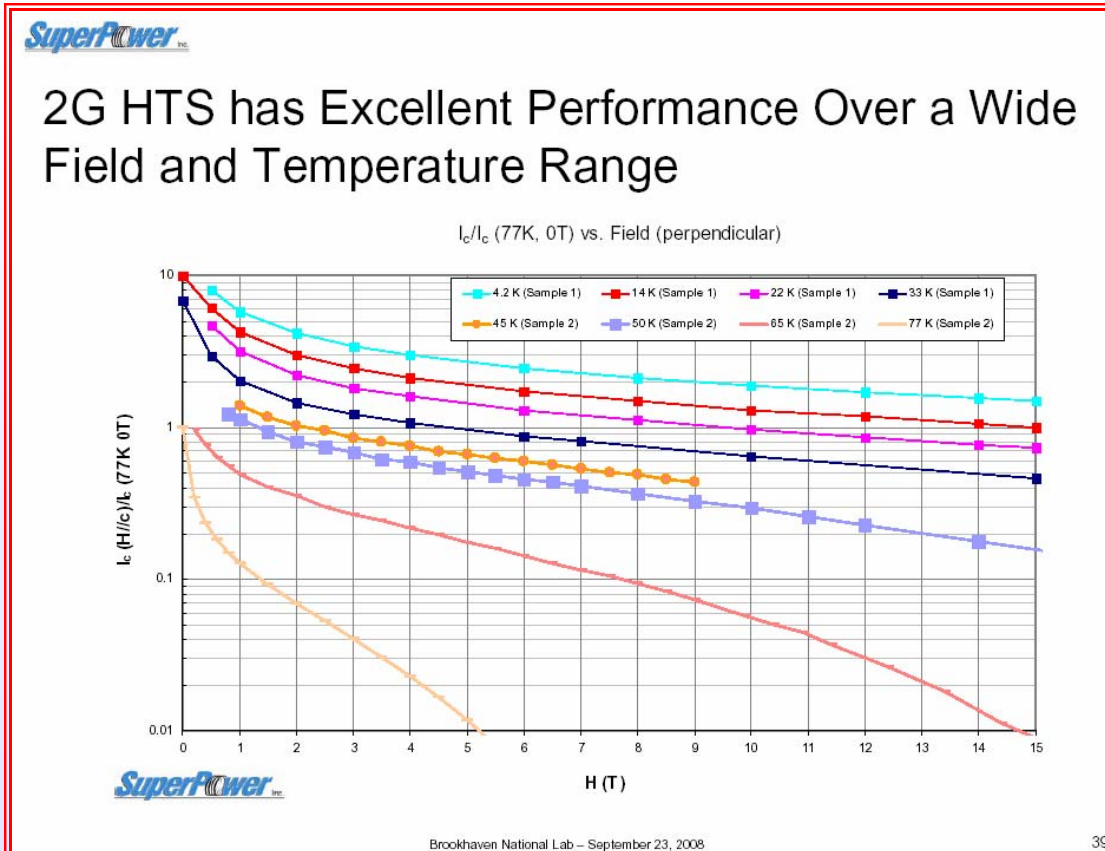
SuperPower (earlier sample)



Data (solid figures) taken on bridge sample.
Dashed red line is hypothetical curve.

Data by Z. Chen at NHMFL / FSU (2007)

Field perpendicular - direction of lower I_c
(no doping)



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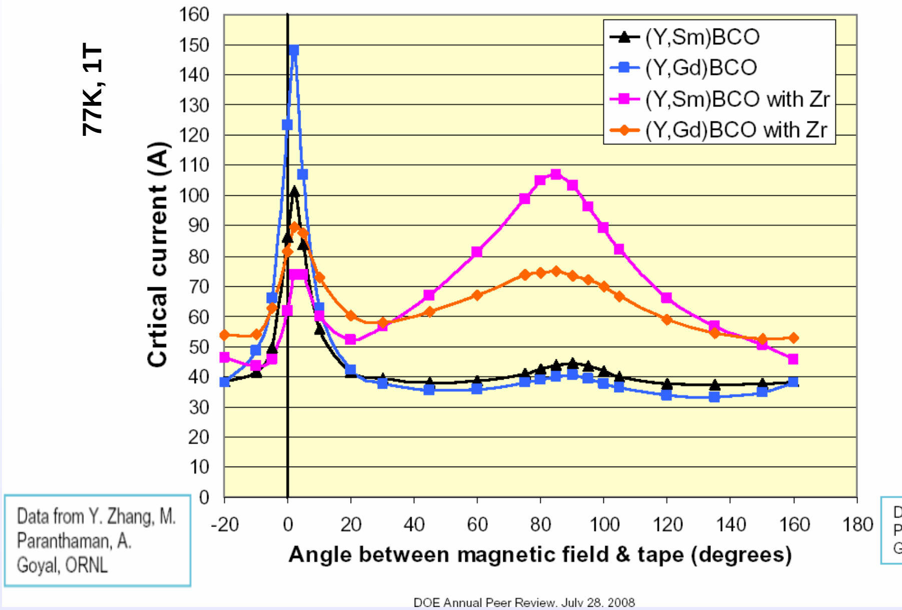
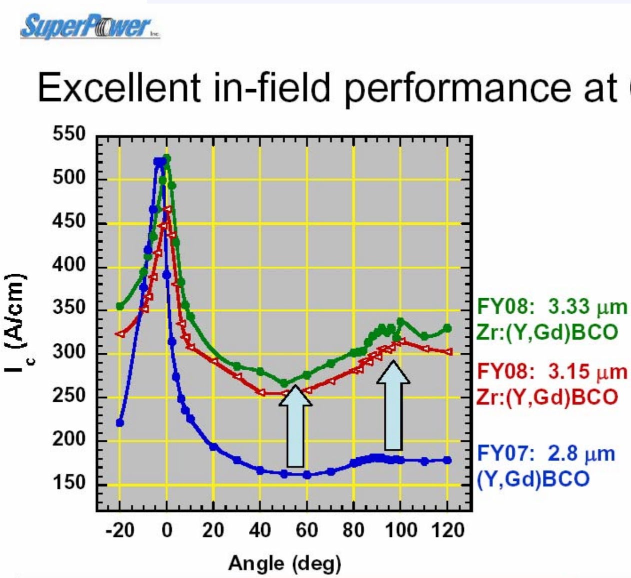
Large Improvements in I_c by Doping

Zr-doped chemistry has been successfully transferred from Research system to Pilot MOCVD



- **Doping has brought major improvements in in-field I_c and has a major influence on the angular dependence of I_c**
  - **It is very important that we examine in-field I_c as a function of field at various temperatures**



- Title III Phase 3 program goal is Je without stabilizer of 15,000 A/cm² at 65 K, 3 T
- Minimum Ic = 267 A/cm corresponds to Je of 41,000 A/cm² at 65 K, 3 T
- Ic perpendicular to tape = 340 A/cm corresponds to Je of 52,300 A/cm²

Ic (77 K, 1 T)	FY08 Zr-doped (Gd,Y)BCO	FY07 (Gd,Y)BCO	Improvement
B // c	340 A/cm	181 A/cm	88%
Minimum Ic	267 A/cm	160 A/cm	67%

Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL

- As a part of FRIB R&D we are purchasing three 100 meter pieces of 2G conductors with three different dopings from SuperPower. This is in addition to two 100 meter pieces of 2G conductor with nano-dots from ASC.
- We will examine performance of coils made with these conductors at lower temperatures.
- This should help HTS solenoid in 2nd year.

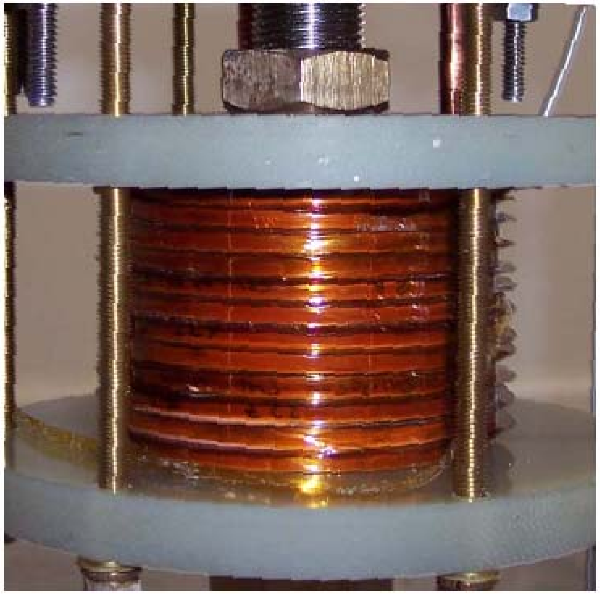
New Coils at SuperPower

SuperPower Inc.

2008 - New Coil with Zr-doped (Gd,Y)BCO 2G With Improved In-field Performance in LN2

	2007 coil	2008 coil
Coil ID (mm) clear	9.5	21
Winding ID (mm)	19.1	28.6
Winding OD (mm)	~ 87	~ 87
Coil Height (mm)	~ 51.6	~ 56.7
# of double pancakes	6	6
2G wire used (m)	~ 462	~ 480
# of turns	~ 2772	~ 2664
Coil Je (A/mm^2) per amp of operating current	~1.569	~1.635
Coil constant (mT/A)	~ 44.4	~ 41.9

	2007 coil	2008 coil
Wire Ic (A) 4 mm	72 – 82	72 to 97



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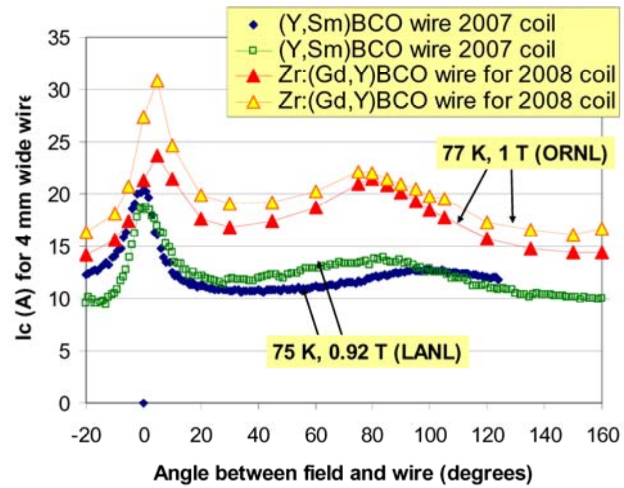
51

Solenoid with Improved Conductor

SuperPower inc.

30% Higher Field Achieved Using 2G with Improved In-field Performance



Temperature (K)	Coil current (A)	Max Central Field (T)
77.4	22.7	**0.95**
70.25	44	1.84
65.8	54	2.26
64.5	57	**2.39**
63.8	58	2.43

Temperature	2008 coil with Zr-doped (Gd,Y)BCO	2007 coil with (Y,Sm)BCO	Improvement
77 K	0.95 T	0.73 T	30%
65 K	2.39 T		

We are taking credit of this 30% improvement in our design work.

Will this improvement be retained at lower temperature ???

HTS Solenoid Design

HTS Solenoid (preliminary parameters)

- Coil i.d. : 110 mm
- Coil o.d. : 180 mm (175 mm or more)
- Clear bore : 100 mm
- Coil length (2 coils) : 55 mm
- Gap between two coils : 18 mm (15 mm or more)
- Total length of split pair solenoid : 128 mm (2*55 + 18)
- Je (@10 T, 4K) : 450 A/mm^2 (30% over 2007 SuperPower solenoid)
- Design current (@10 T, 4K) : 287 A (30% over 2007 SuperPower solenoid)
- No. of coils : 24 (12 double pan cake made with ~4.1 mm wide tape)
- Field at the center : 10.7 T (12 T without gap - margin over no-gap baseline)

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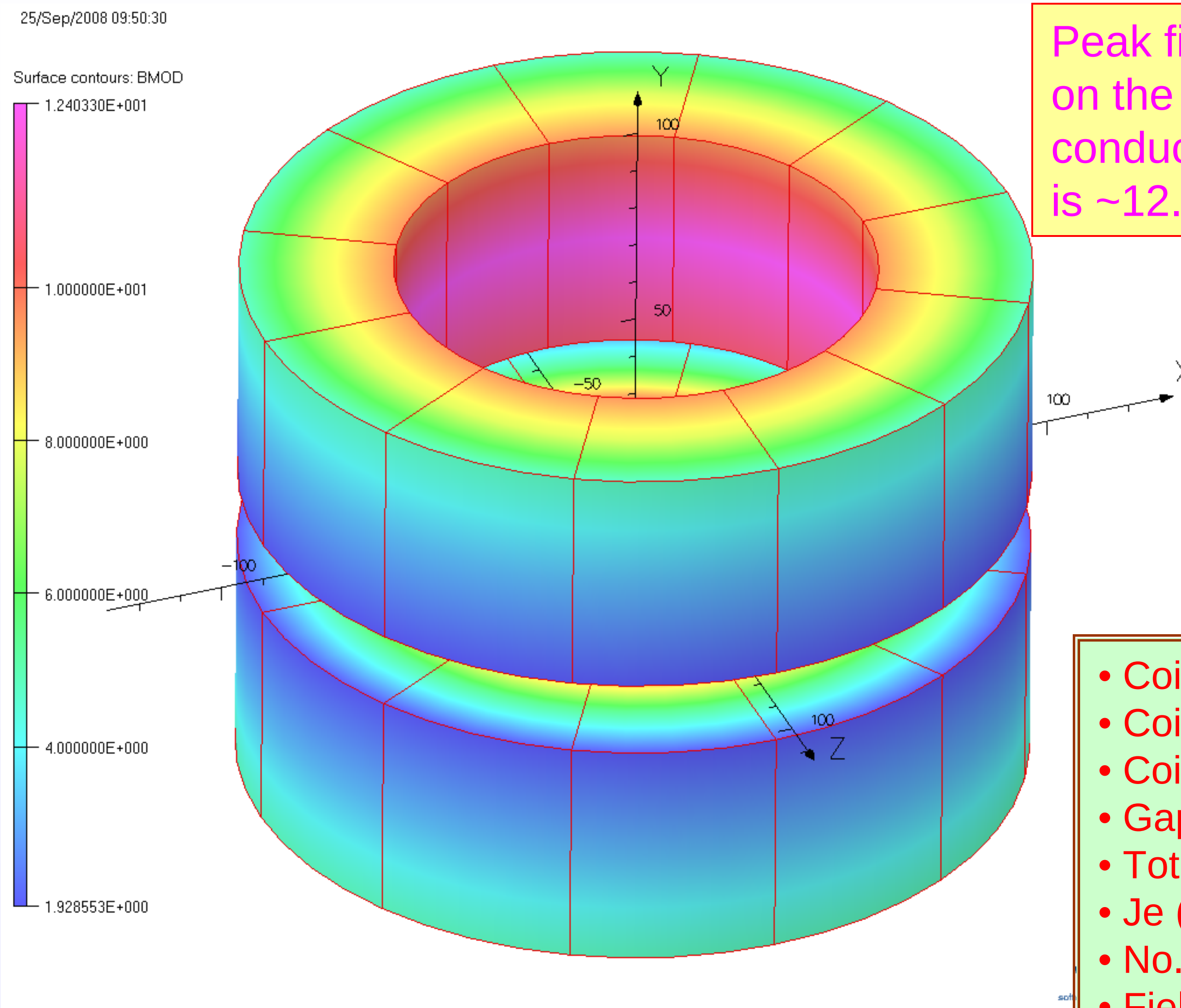
Field on the Conductor of the Solenoid



Peak field on the conductor is ~12.4 T

- **Direction of the field is important.**
- **In fact we are limited by the field perpendicular value and not the field maximum value.**
- **Optimization of this is a part of the detailed design- yet to be carried out.**

- Coil i.d. : 110 mm
- Coil o.d. : 180 mm
- Coil length (each) : 55 mm
- Gap between two coils : 18 mm
- Total length : 128 mm
- Je (@10 T, 4K) : 450 A/mm^2
- No. of coils : 24
- Field at the center : 10.7 T

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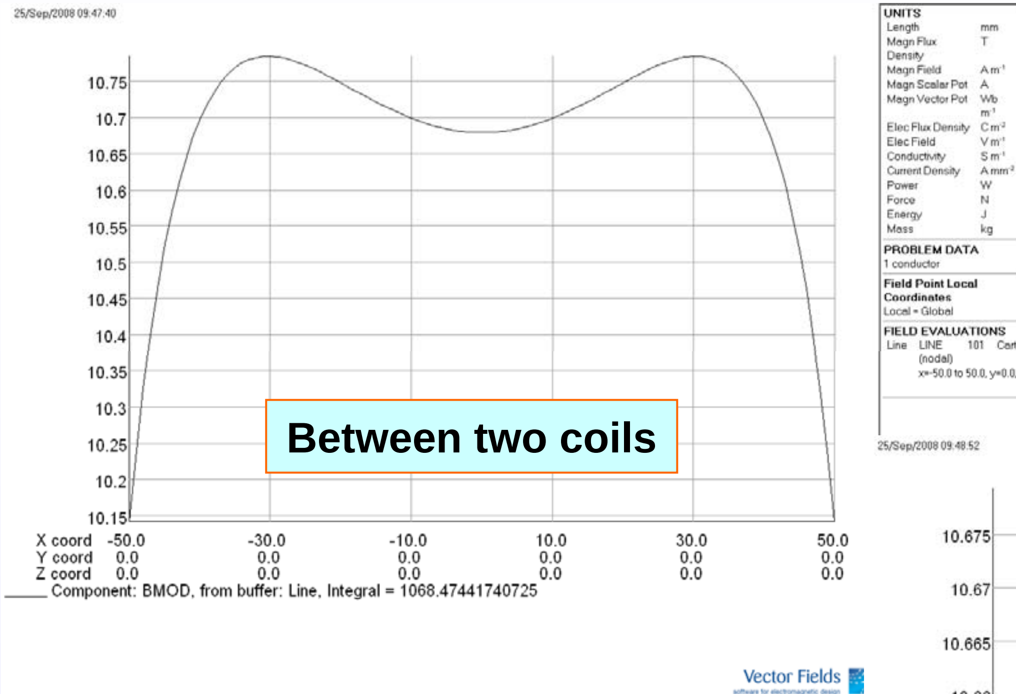
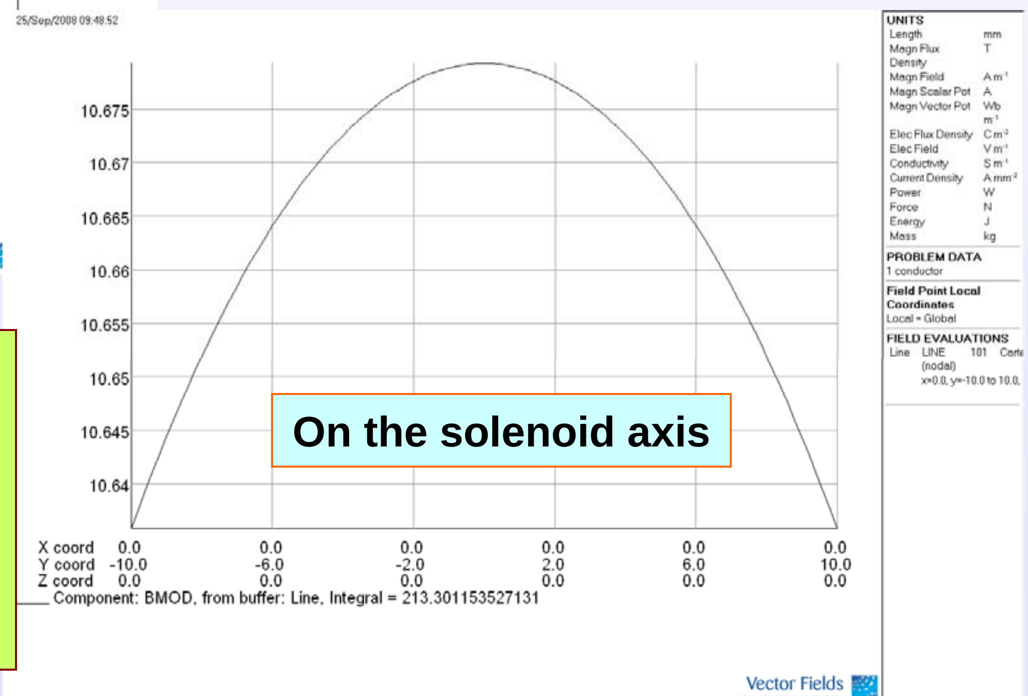
Field inside the solenoid (near the middle)



- Coil i.d. : 110 mm
- Coil o.d. : 180 mm
- Coil length (each) : 55 mm
- Gap between two coils : 18 mm
- Total length : 128 mm
- Je (@10 T, 4K) : 450 A/mm^2
- No. of coils : 24
- Field at the center : 10.7 T



We have some margin:

~10.7 T with gap, rather than ~12 T without gap (and 13.2 T, if conductor price to drop and we were able to put 4 extra coils in that gap - 24+4 = 28 coils, ~ 3 km total length of conductor)

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Baseline Design of the Solenoid (no gap between the coils)

✓ **Baseline design should have a reasonable margin to assure success (10 T @ 4K)**

- Je in coil : ~450 A/mm^2

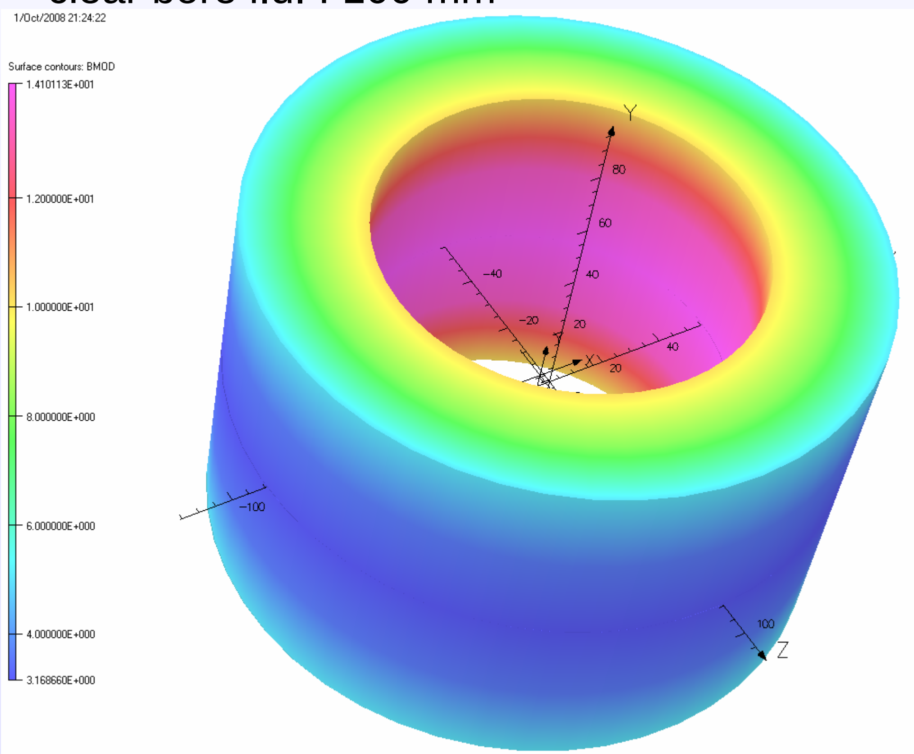
  (30% improvement assumed)

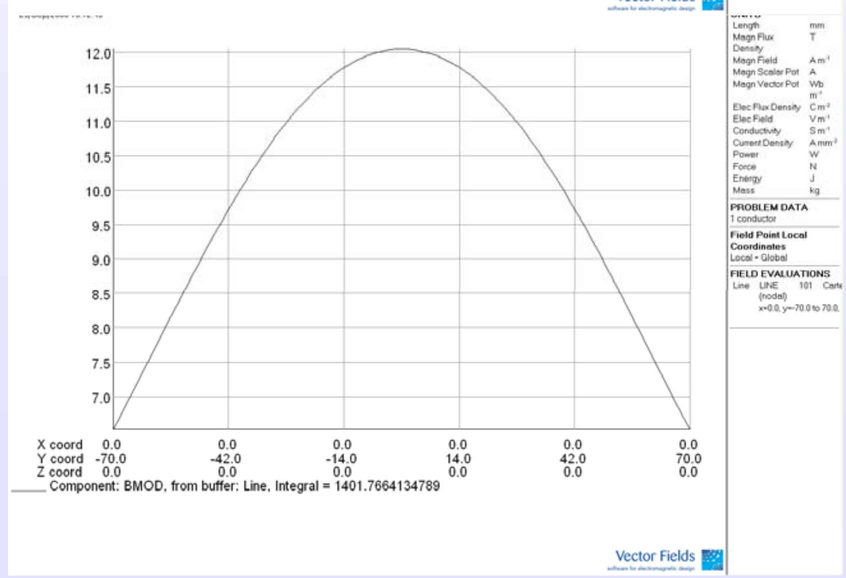
➢ **NO Gap between coils**

- solenoid coil i.d. : 110 mm
- clear bore i.d. : 100 mm

Bo ~ 12 T

B_{pk} ~ 14 T

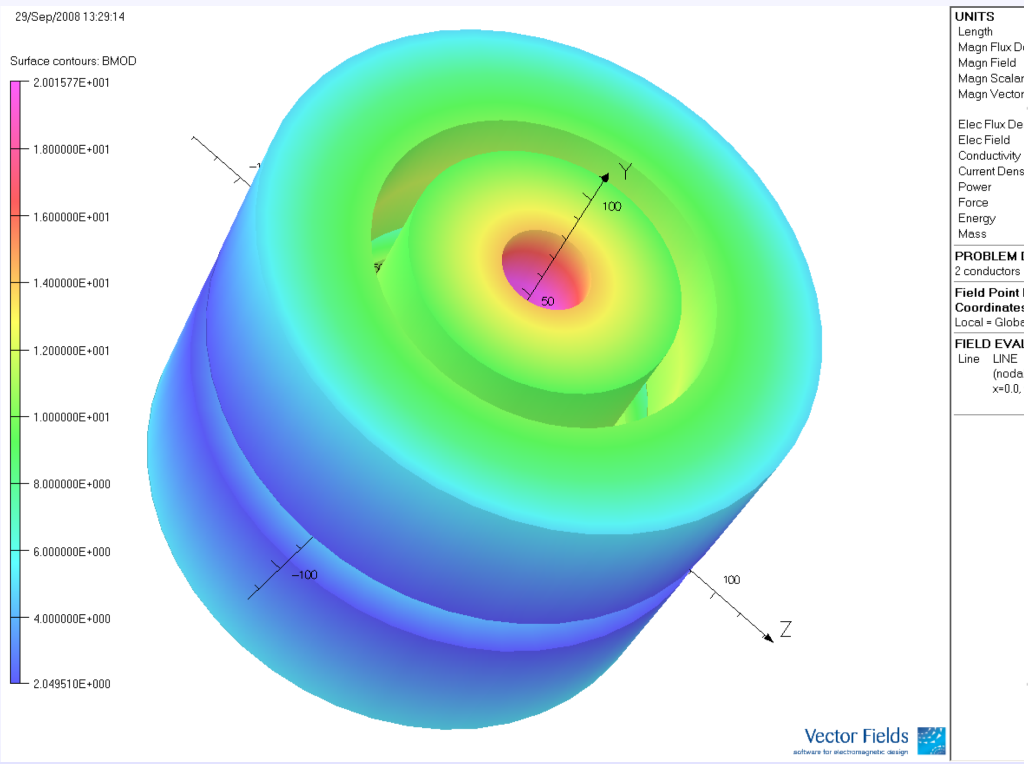


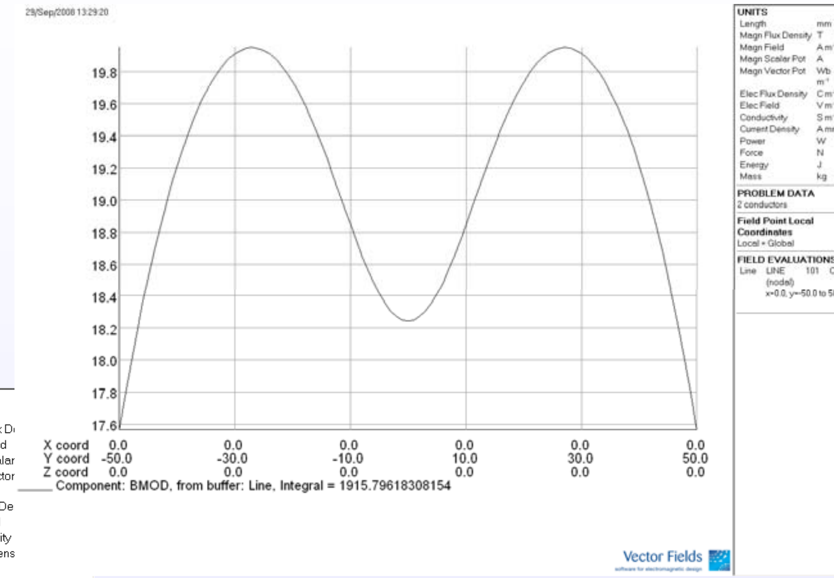


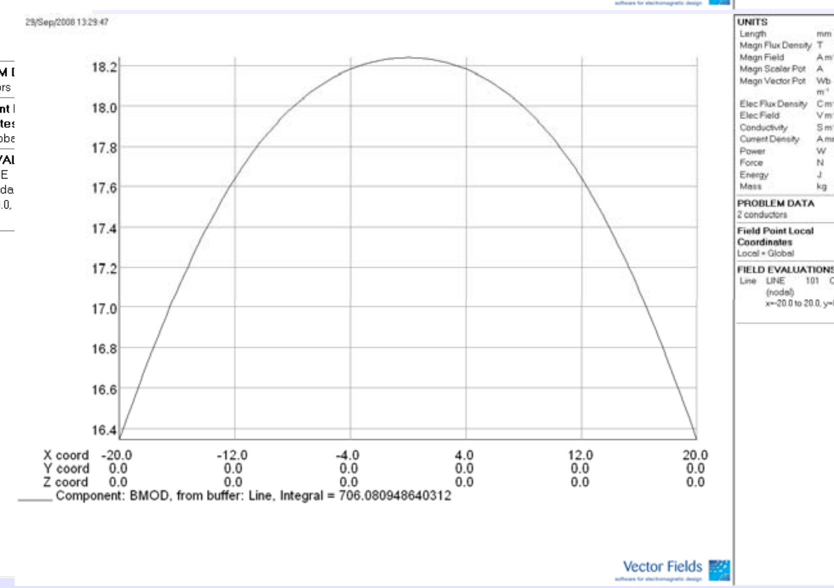
HTS Solenoid with SupePower Insert

Bo ~18 T

- Je in our solenoid : ~450 A/mm^2
  - Je in SuperPower solenoid: ~350 A/mm^2
- ➢ **Gap between the two coils : <u>18 mm</u>**
- i.d. of our solenoid : 110 mm
  - i.d. of SuperPower Solenoid : 28.6 mm







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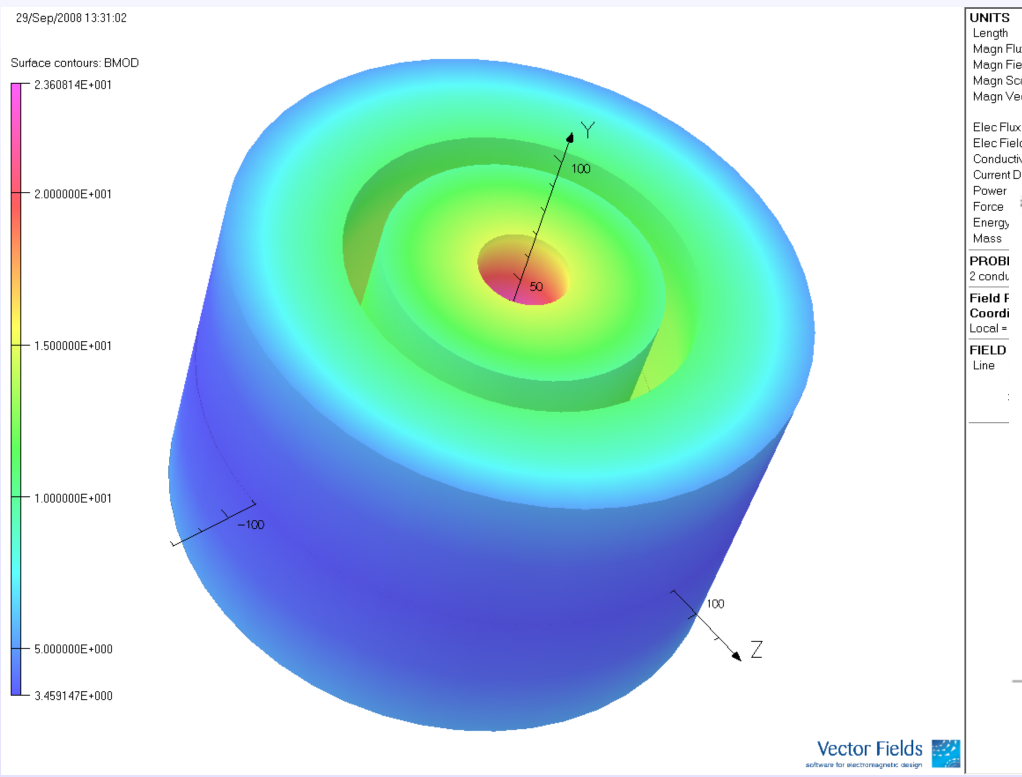
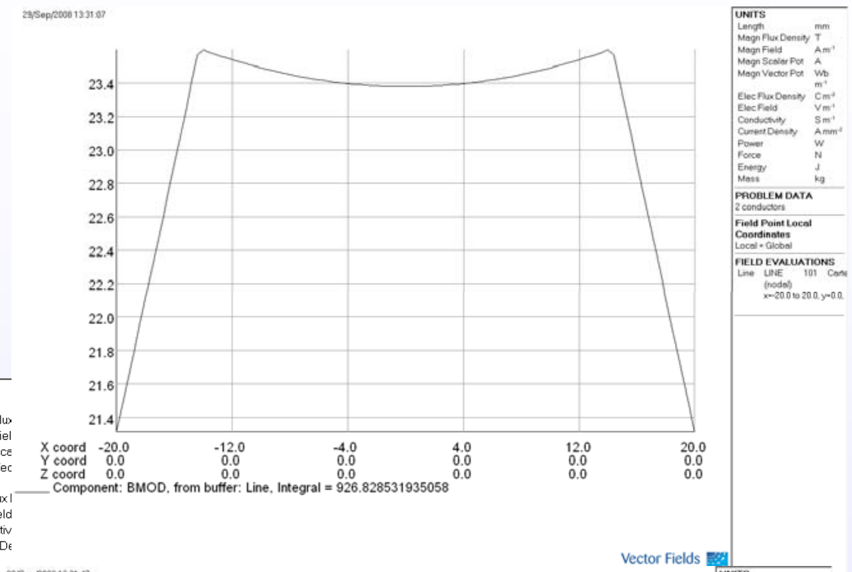
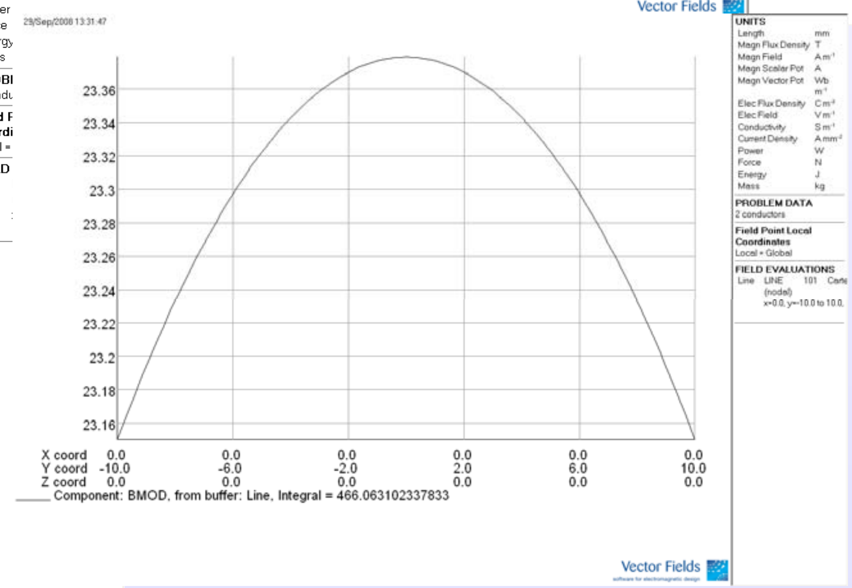
HTS Solenoid with SupePower Insert (no gap between coils)

Bo ~ 23 T

- Je in our solenoid : ~450 A/mm^2
    - Je in SuperPower solenoid: ~350 A/mm^2
- ➢ **Gap between the two coils : 0 mm**
- i.d. of our solenoid : 110 mm
    - i.d. of SuperPower Solenoid : 28.6 mm



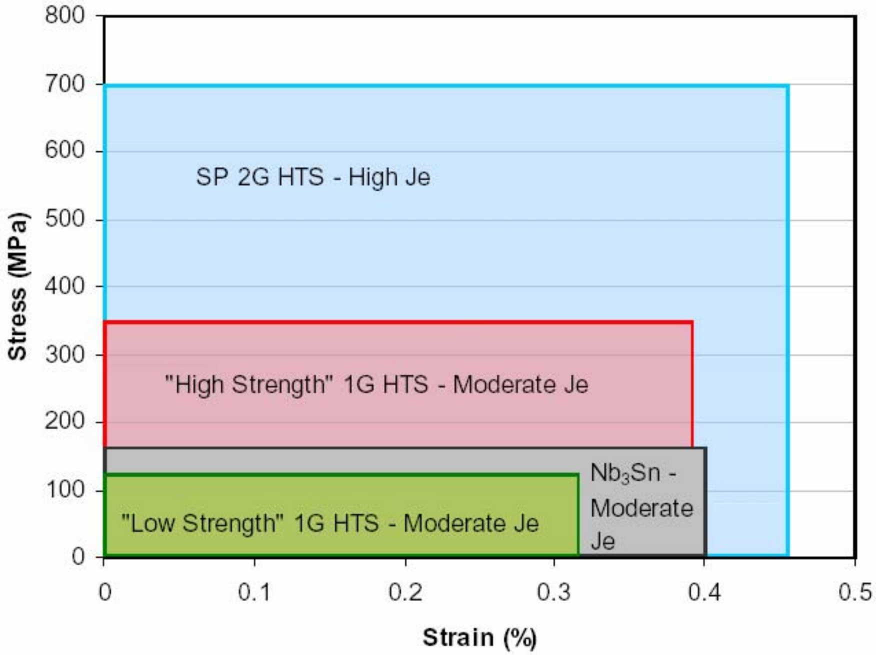




Strength of YBCO

- Question: can YBCO take these large stress associated with high fields ?
- Yes it can! But we will have stainless steel wrap also !!!

"React/Wind" 2G HTS Wire from SuperPower has Larger Operating Stress-Strain Window vs. Others



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Fabrication and Schedule

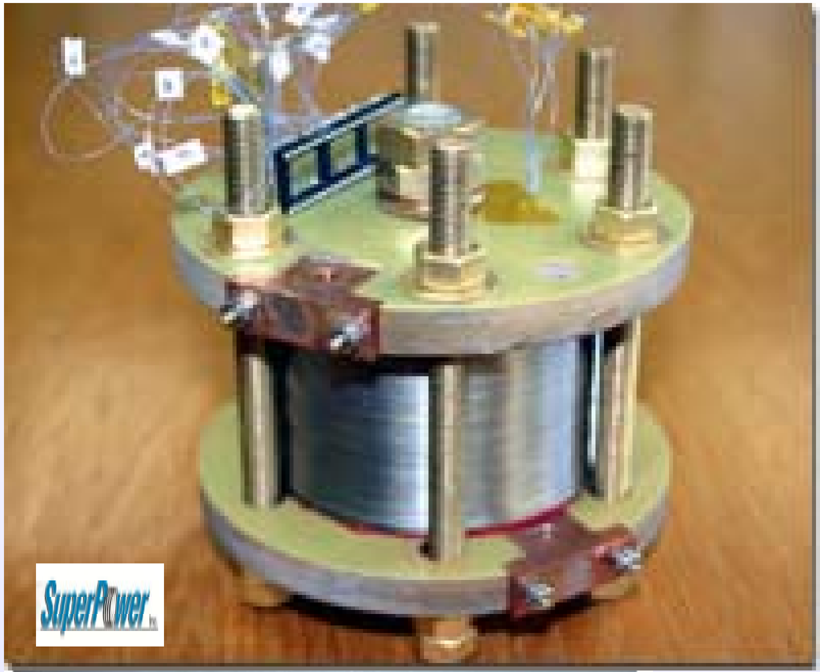
Winding of Coils

FRIB/RIA Coils being wound with S.S. tape over HTS

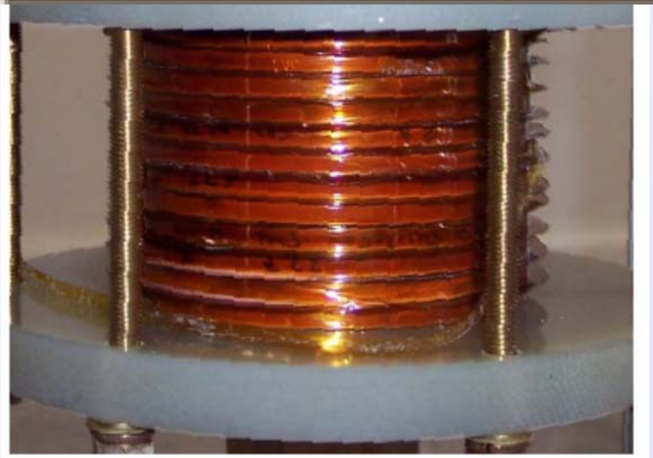
- We will continue to wind coils with stainless steel tape.
- Stainless steel tape gives extra strength. As such it is not needed in this solenoid. But we will continue to use it, in support of future high field solenoid work.

Courtesy/Contributions: Dilgen, Ince

Preliminary Support

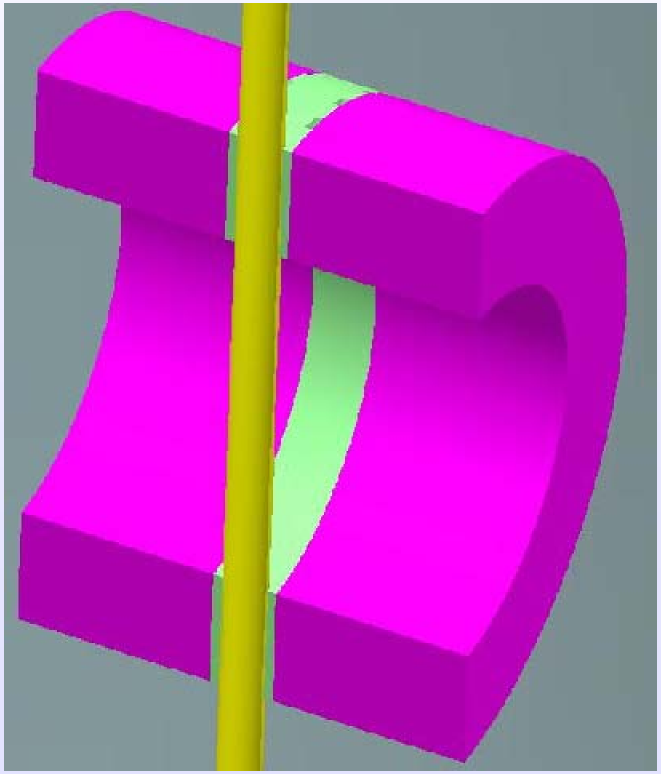


- We will use stainless steel overbend (wrap), flanges in the ends and a disc with a hole for sample holder.
- Bob Weggle is doing stress calculations.
- Detailed engineering design will be carried out in next few months.



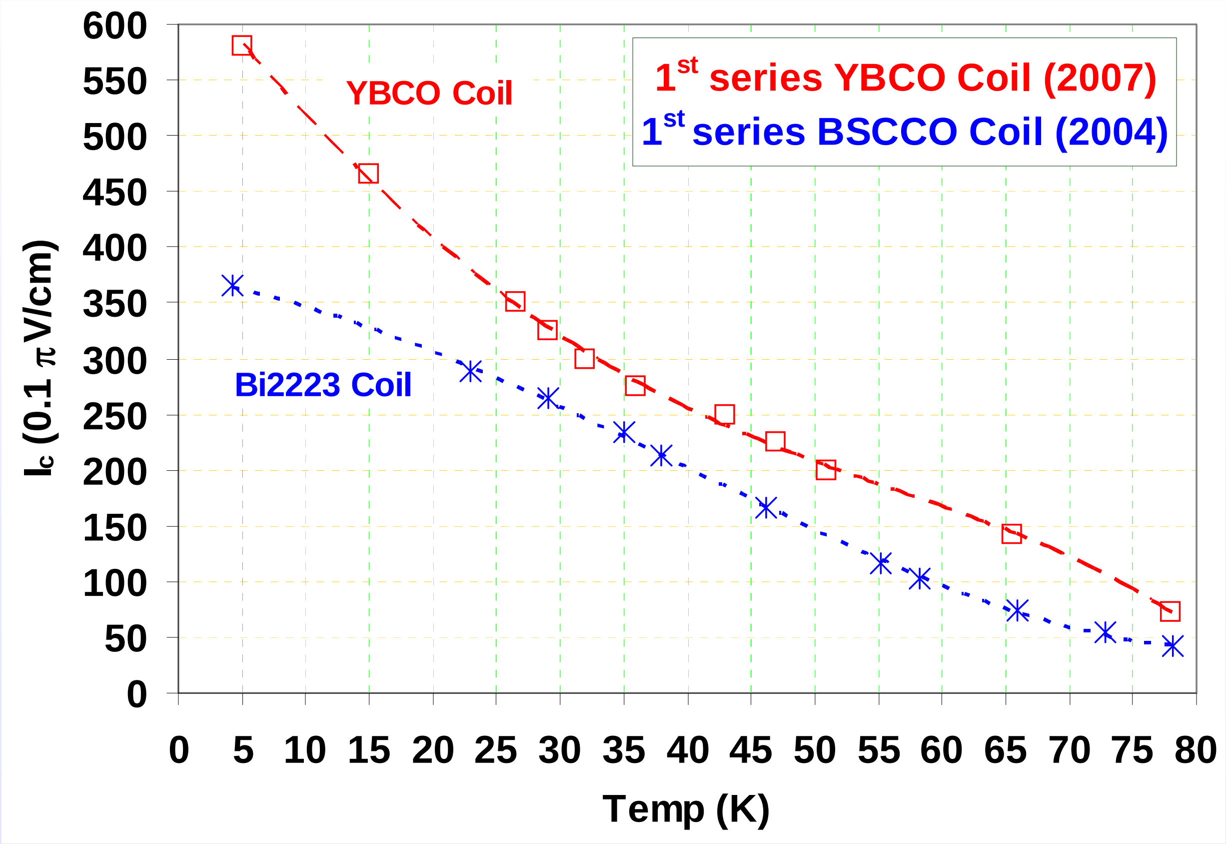
Sample will have its own on-board heaters to vary temperature.

Temperature of the solenoid may rise a bit (OK for HTS)



Performance as a Function of Temperature

FRIB/RIA Coil



- We will measure performance of the solenoids at 4 K, 77 K and <u>in temperatures in between</u>
- The actual curve may depend on the nano-dots or doping ???

Revised Preliminary Schedule

Year #1

0 – 2 months	Conceptual design studies
0– 12 months	Conductor testing (R&D samples and actual conductor)
1 – 6 months	Engineering design
3 – 6 months	Coil tooling design and construction
4 – 6 months	First batch of conductor received
7– 8 months	Coil winding and individual LN2 coil tests (first set)
9 – 10 months	Support structure fabrication and first assembly of solenoid (12 coils)
11 – 12 months	First half of HTS solenoid tested in a temperature range of 4K-77K

Year #2

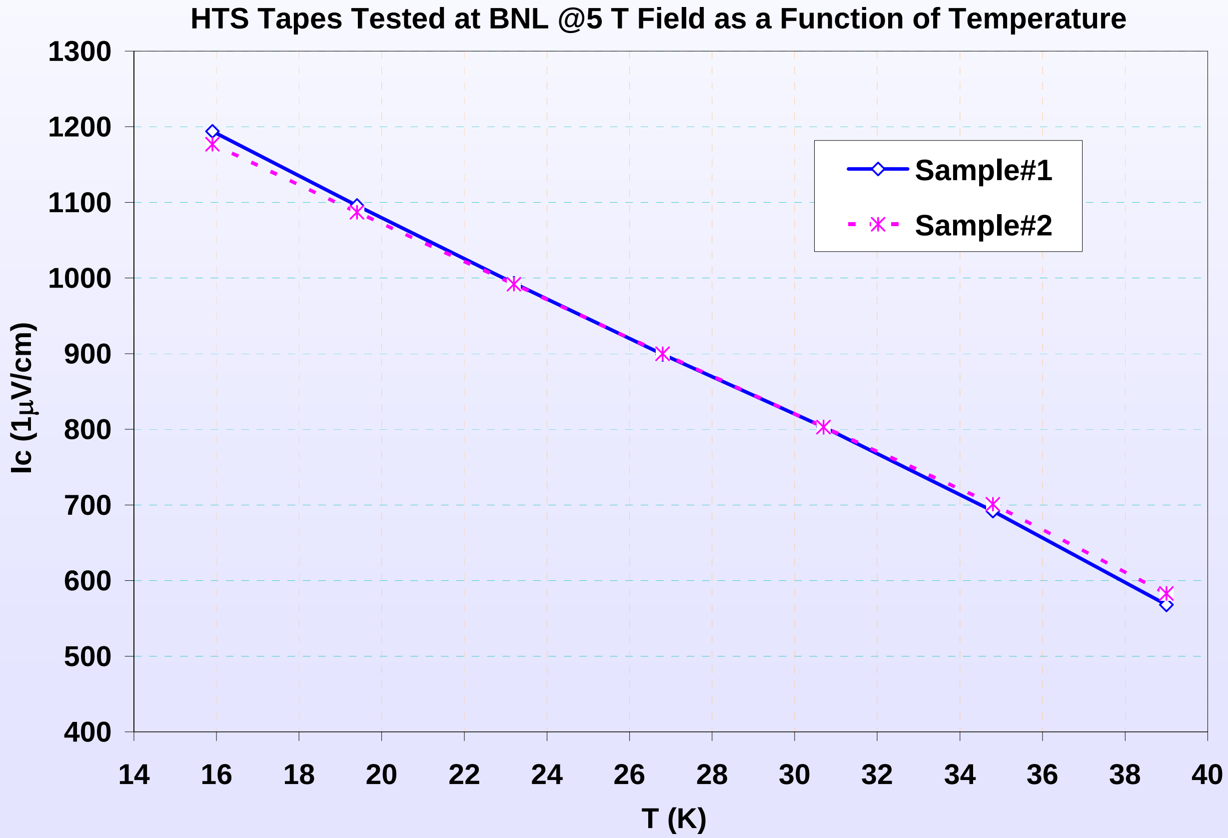
12– 18 months	Conductor testing continues
14– 16 months	Second batch of conductor received
15 – 17 months	Coil winding and individual LN2 coil tests (second set)
18 – 19 months	Re-assembly of solenoid with all 24 coils
20 – 21 months	HTS solenoid testing in a range of temperature (4K-77K)
22 – 23 months	Report preparation

Enhancements - insert coils from Superpower and split-pair assembly - are outside the original scope of the SBIR and are not mentioned explicitly in the schedule.

Induction of HTS Solenoid at BNL Conductor Testing Facility

This magnet would produce a unique research facility for testing the performance of HTS as a function of magnitude of the field, direction of field and as a function of temperature.

These are critical measurements for HTS R&D. And right now there is no convenient facility.



- An earlier test as a function of temperature, where the temperature was changed with the help of heaters.
- At that time we could not change the direction of field, and hence could not measure the angular dependence.
- Also that magnet could not go to very high field either.

SUMMARY

- Thanks to the improvements in second generation HTS (YBCO), we are off to a very good start.

- We have significantly increased the coil i.d. over the proposal submitted – 66.5 mm to 110 mm (100 mm clear bore).

- Thanks to the expected collaborations with SuperPower, we should be able to obtain ~20 T at 4 K or 10 T at ~33 K, however, in a smaller bore.

- At the end of the project, we hope to turn this solenoid in to a useful conductor test facility to measure I_c both as a function of magnitude of the field and direction of the field, which is crucial for such R&D.

    - Perhaps very few SBIR can boast such enhancements.

- A successful outcome of this should help create more such proposals.