Magnet Coil

Design, Construction, Quench Protection and Test Results

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BROOKHAVEN NATIONAL LABORATORY
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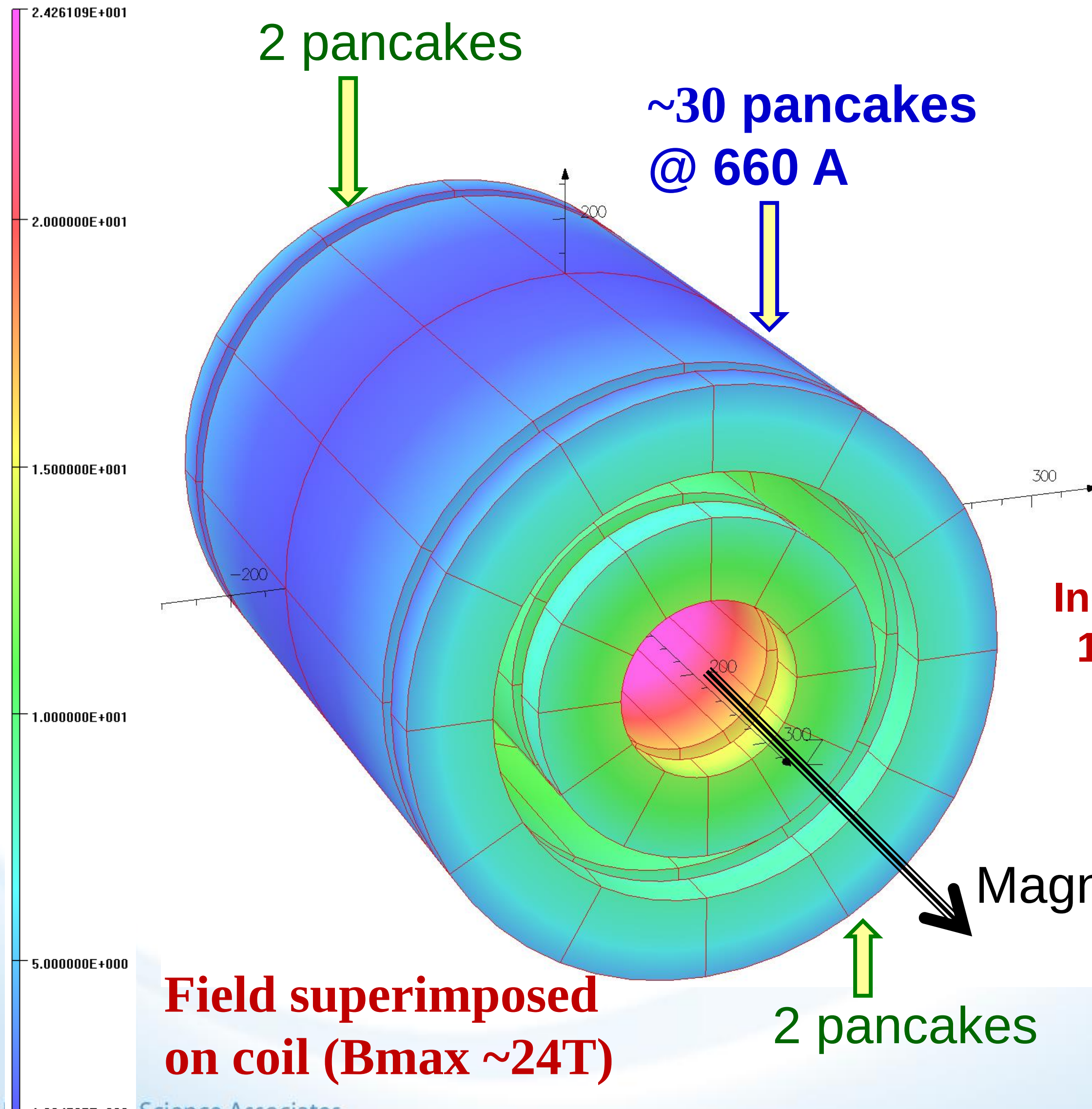
Office of Science
U.S. DEPARTMENT OF ENERGY

Overview

- **Progress in the Design**
- **Construction and Test Results**
  - **Significant part of this presentation**
- **Design Studies and Possible Feedback**
- **Quench Protection**
  - **Including measurements**
- **Status of Milestones & Major Accomplishments**
- **Summary**

Progress in Design

Basic Magnetic Design of 2.5 MJ Demo Coil



2 pancakes

~30 pancakes @ 660 A

2 pancakes

Magnet axis

Field superimposed on coil (Bmax ~24T)

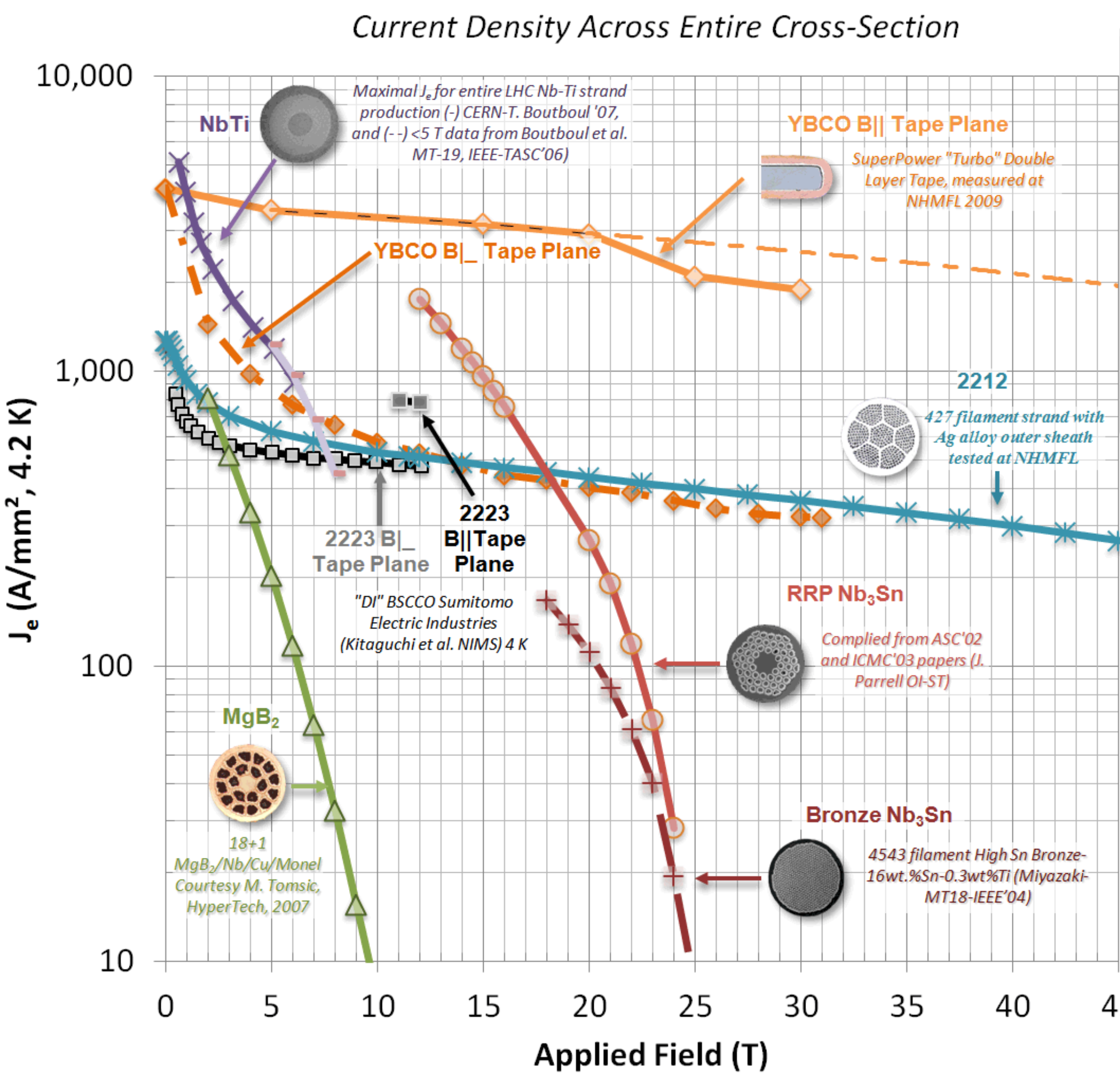
Inductance: 11-12 Henry

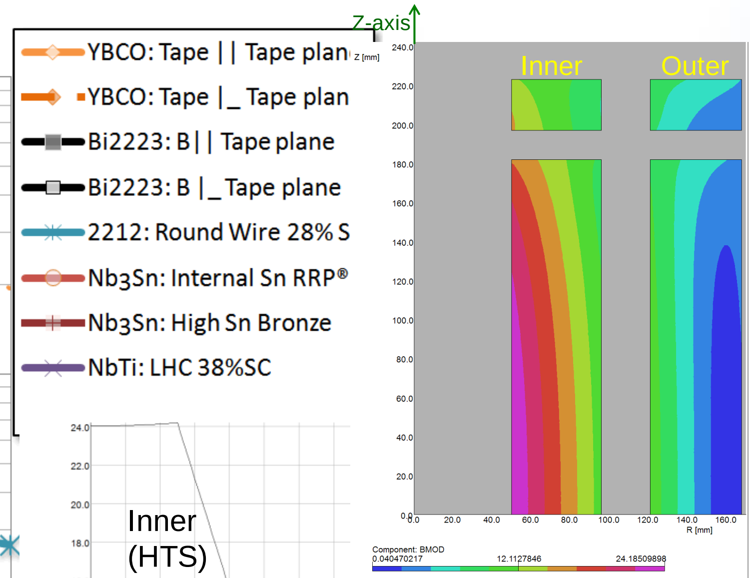
Magnet axis

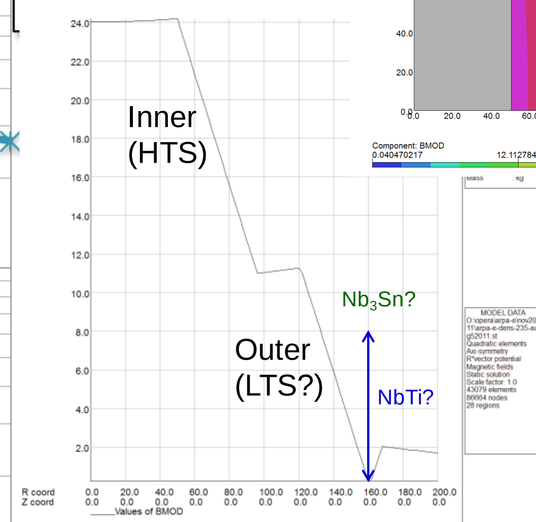
2-d axi-symmetric model

Magnetic Design Optimization

Spacers to reduce perpendicular component and stresses

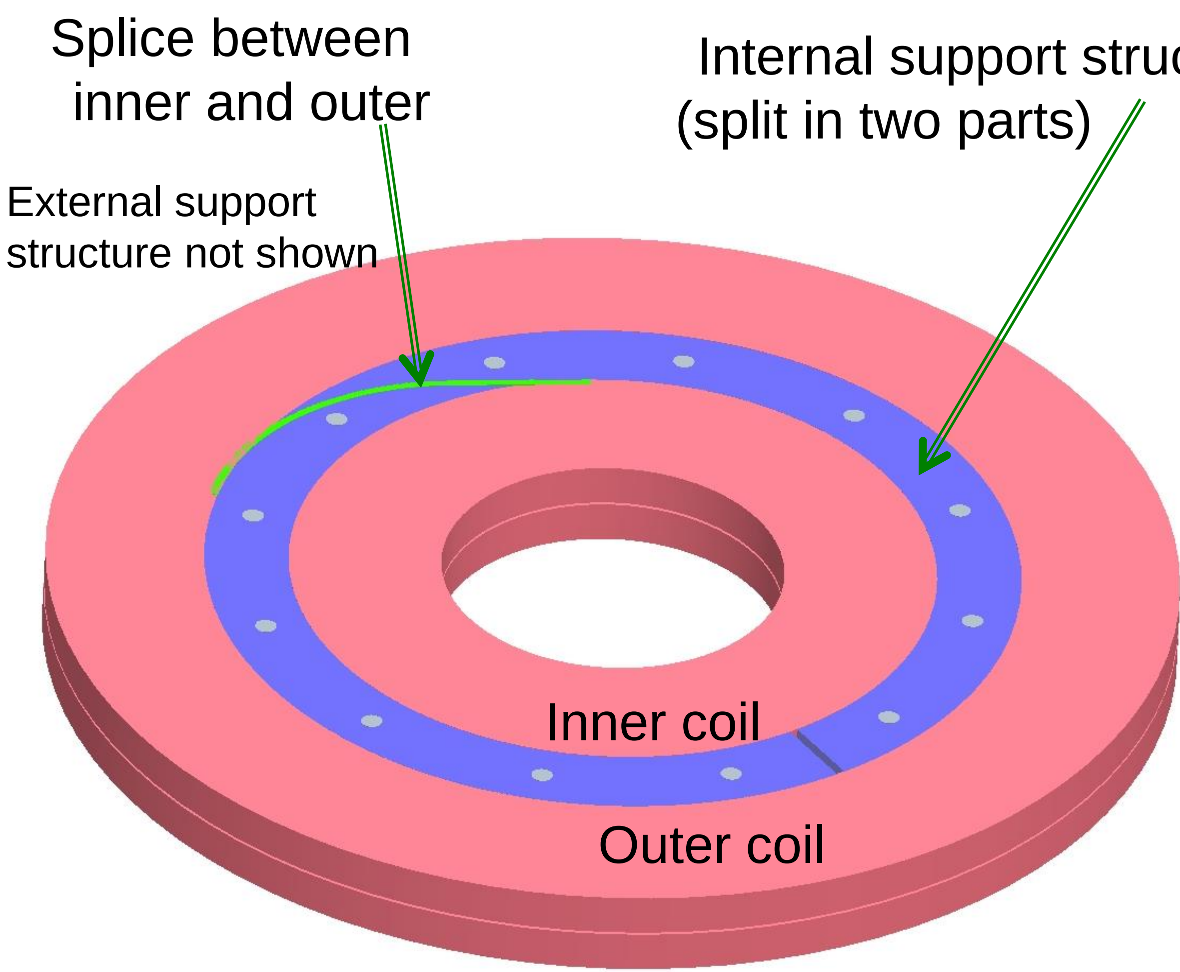


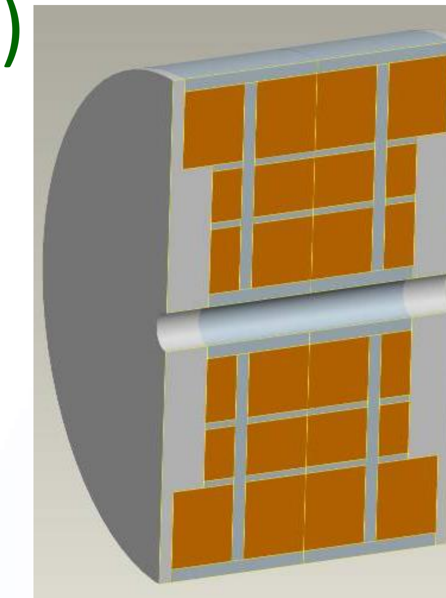




Mechanical Structure Consisting of Double Pancakes

(with internal support structure)





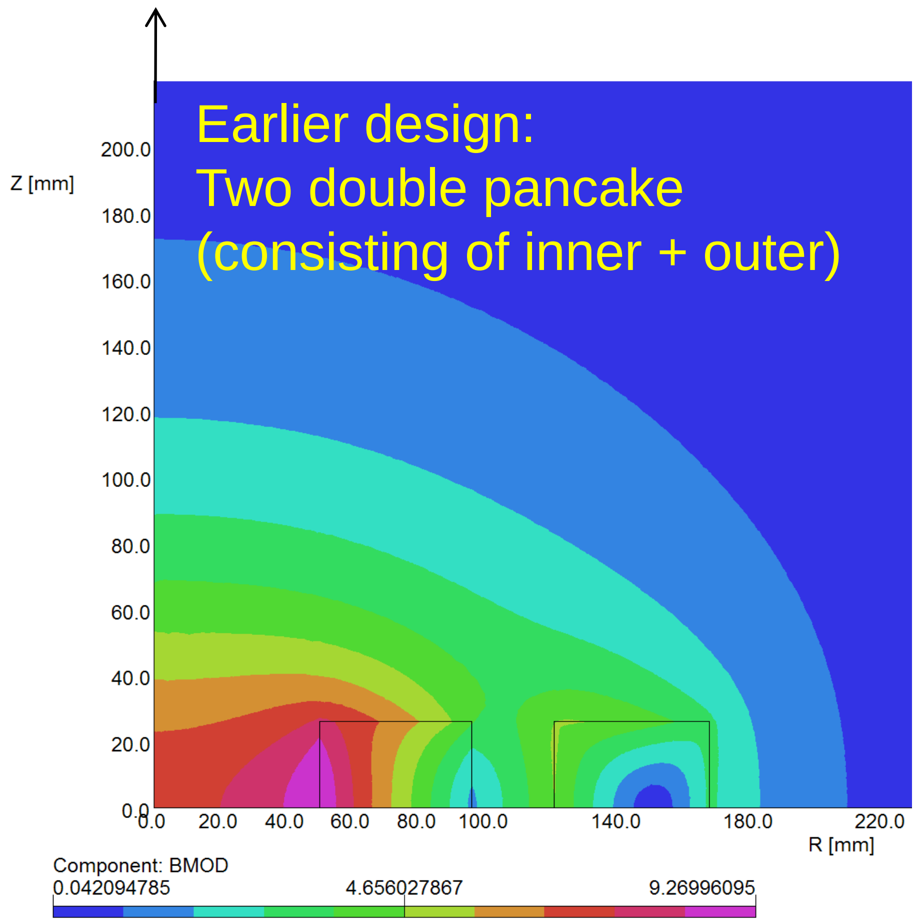
This design requires significant analysis and engineering before we can proceed with construction

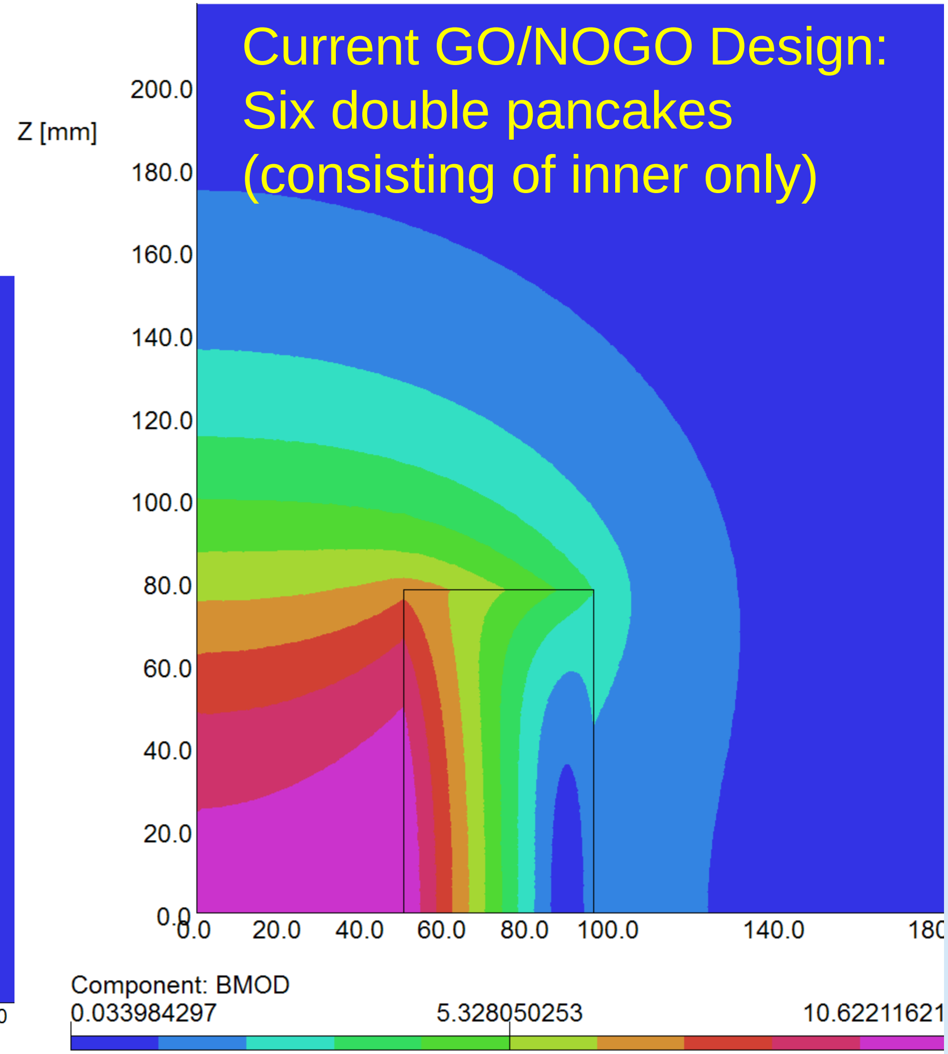
Current (new) design is a two coils (inner and outer) each consisting of a number of pancakes. We can proceed with inner coil construction now.

Design of Q6 GO/NO GO Test

Part of the Q6 outer coil

Magnet axis



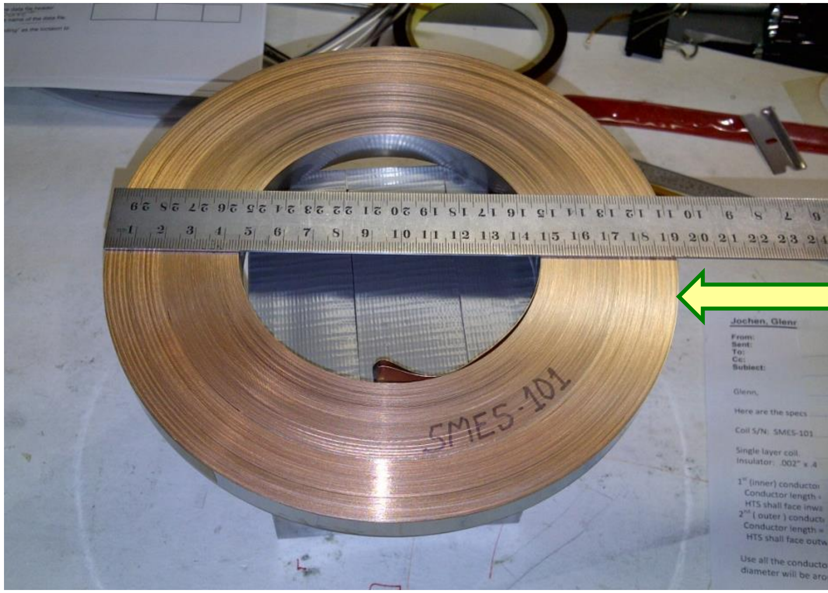


Construction and Test Results

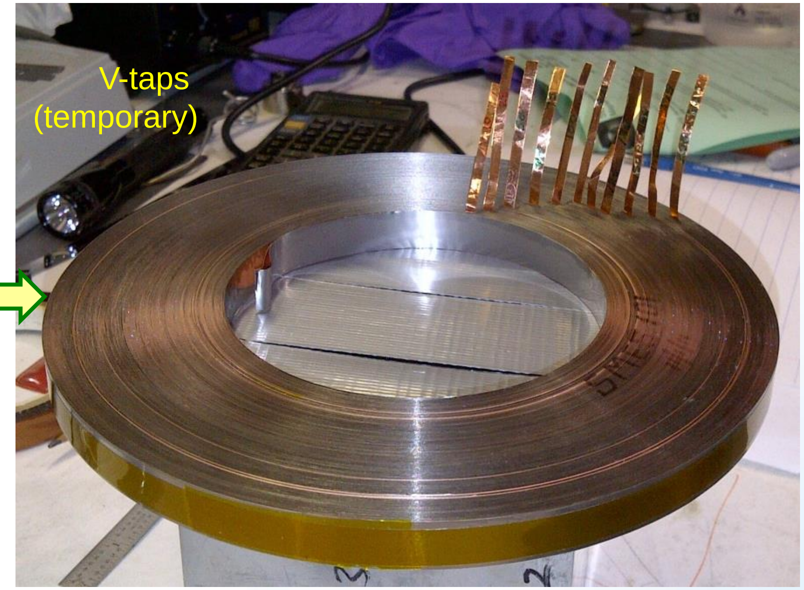
Q4 GO/NOGO Milestone

- We take the motivation behind GO/NOGO milestone (*Successful test of a mini stack of coils at 77 K*) seriously
- "Successful Test" means demonstration (not design) to show that the magnet division has most if not all technologies ready before starting the full construction
- Critical components of mini coil stack technology:
  - Demonstration winding and other tooling with real coils
  - Demonstration of splice joints (within coil and between coils)
  - Demonstration of the capability of test facility
  - Demonstration of the basic quench protection system

New Coils Wound with Improved Winder



HTS Coil



HTS Coil
(Full Size)

SS Coil
(Full Size)

Step 1 for Making Stack of Coils: Joints

➢ Joints are one of the most critical component of the magnet. Magnet performance is often limited because of the joints.

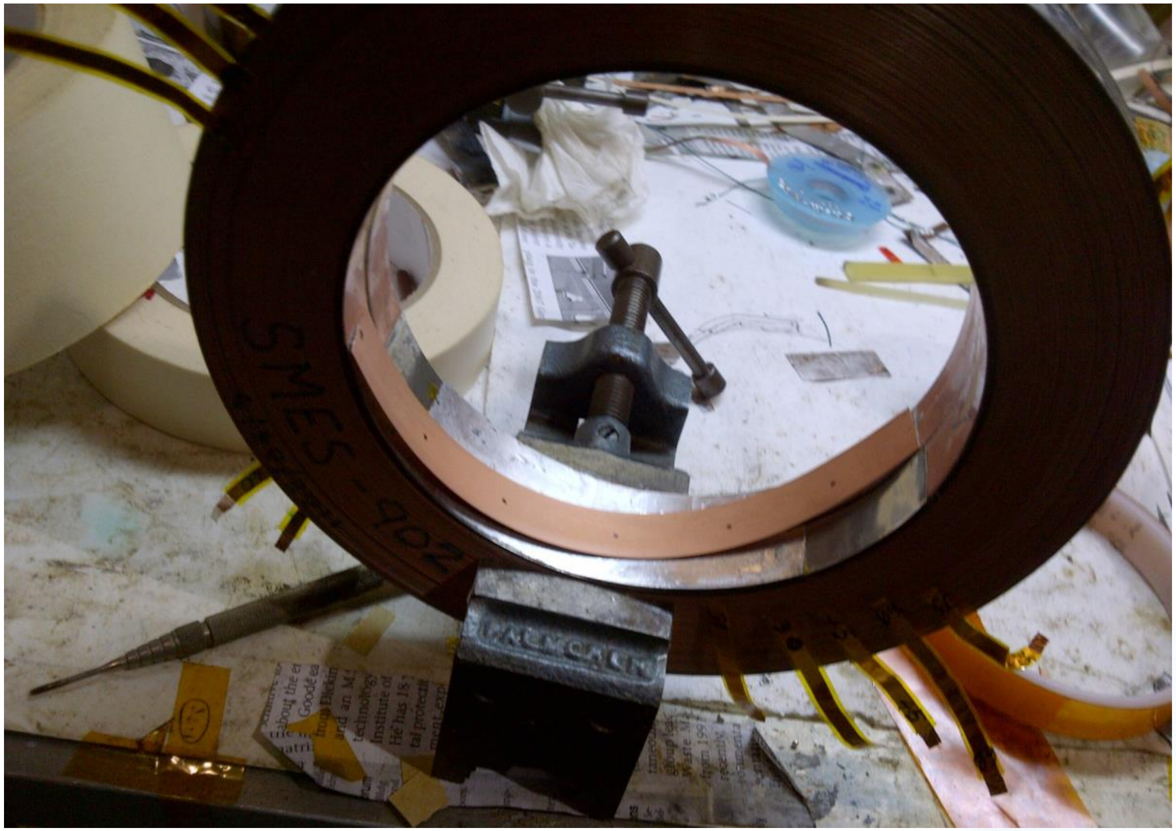
For expediency, we carefully apply the technology in use in SMD.

Necessary steps:

1. Finalize geometry for both joints (in coil and between coils)
2. Either (a) make "in coil" joint straight and bend them in coil or (b) make them bent while winding; (a) preferred if degradation is small
3. Check reproducibility
4. Most joint tests are performed at 77K. Determine 77K to 4K scaling
5. Prove mechanical robustness in a real coil test

Note: Above work is not part of the R&D for joint milestone. That is being carried out by AEM & will be incorporated later in the coil.

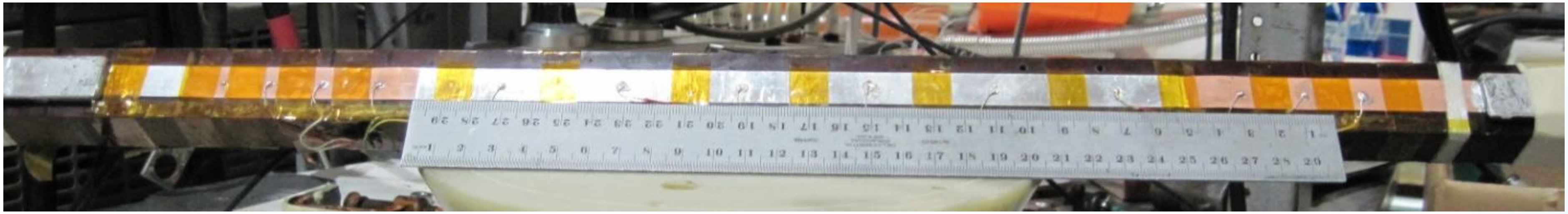
Two Types of Splices

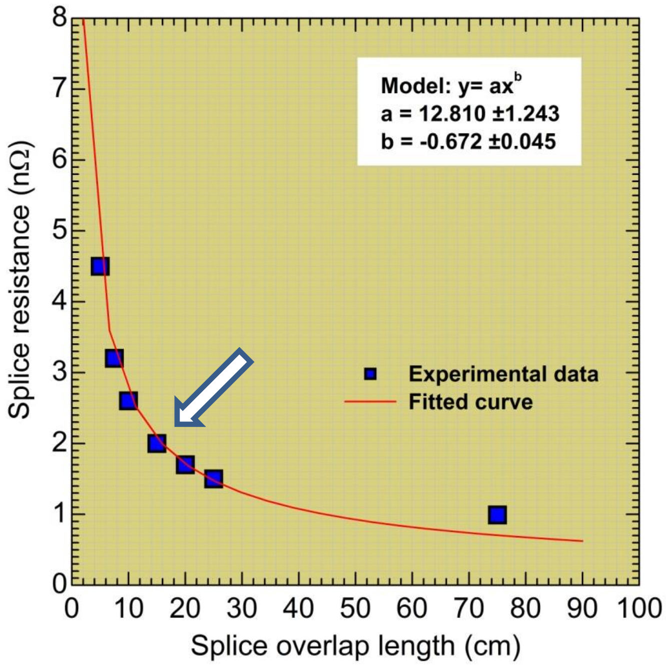


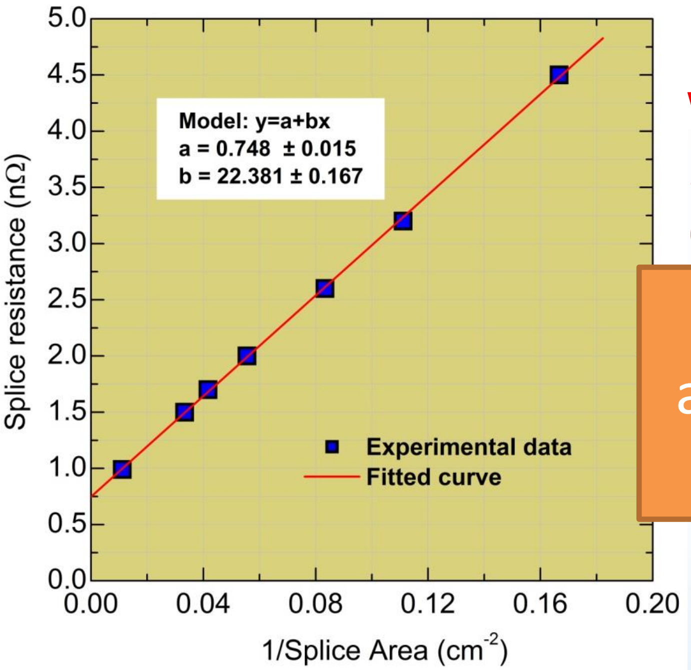
Splice to join two single pancakes to make a double pancake (diagonal splice)

Splice within a single pancake (lap joint)

Determination of the Length of the "In Coil" Joint







Most of this joint work is performed by S. Lakshmi (post-doc)

15 cm (~2 nΩ) appears to be the optimum length

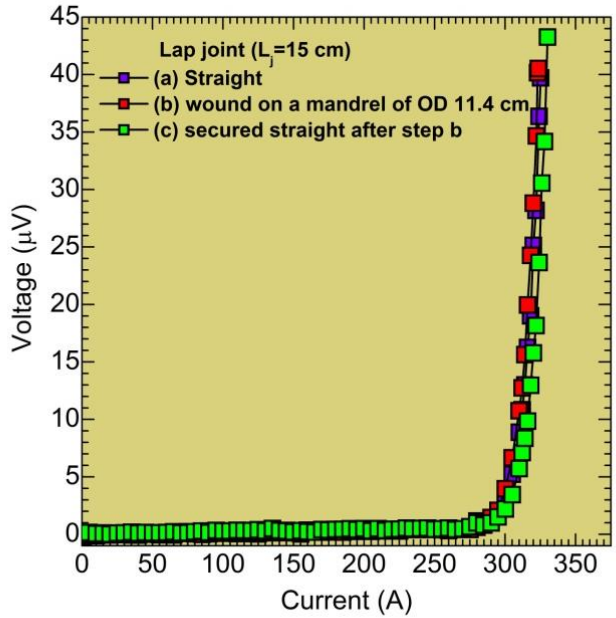
✓**We already have a fixture for this.**

Above puts ~0.75 nΩ (@77 K) joint resistance as the limit of this technology for the material (including 2G tape) used here.

Bending Degradation of the Lap Joint

Question: Is there significant bending degradation of the joint made straight? If not, then it will allow straight splicing fixture to be used which will simplify the coil manufacturing and increase the efficiency.

Examined at R~11 cm – worst case as coil i.d. is 10 cm and joint will appear at higher radius.

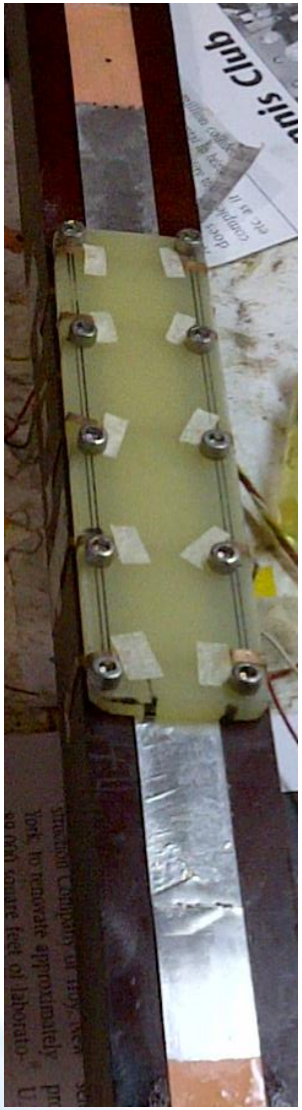


Good News: No degradation in joint performance

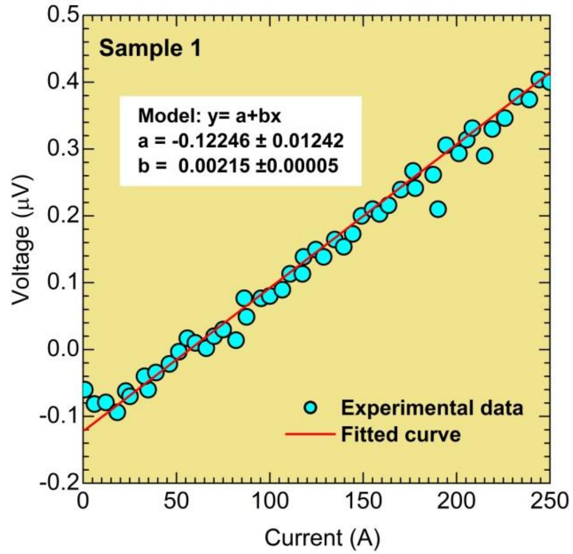
Slightly reduced (?) resistance is perhaps due to increased pressure?

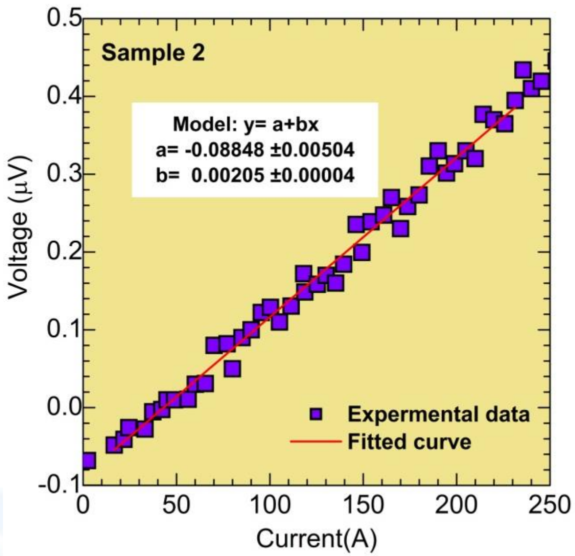
Experimental condition	I_c (A)	N	Rj (nΩ)
Straight sample	325.8	26.8	2.05 ± 0.04
Wound on a mandrel with OD of 11.4 cm	324.7	26.6	1.79 ± 0.04
Unwound and secured on a straight sample	324.5	26.3	1.82 ± 0.03

Reproducibility of Joints



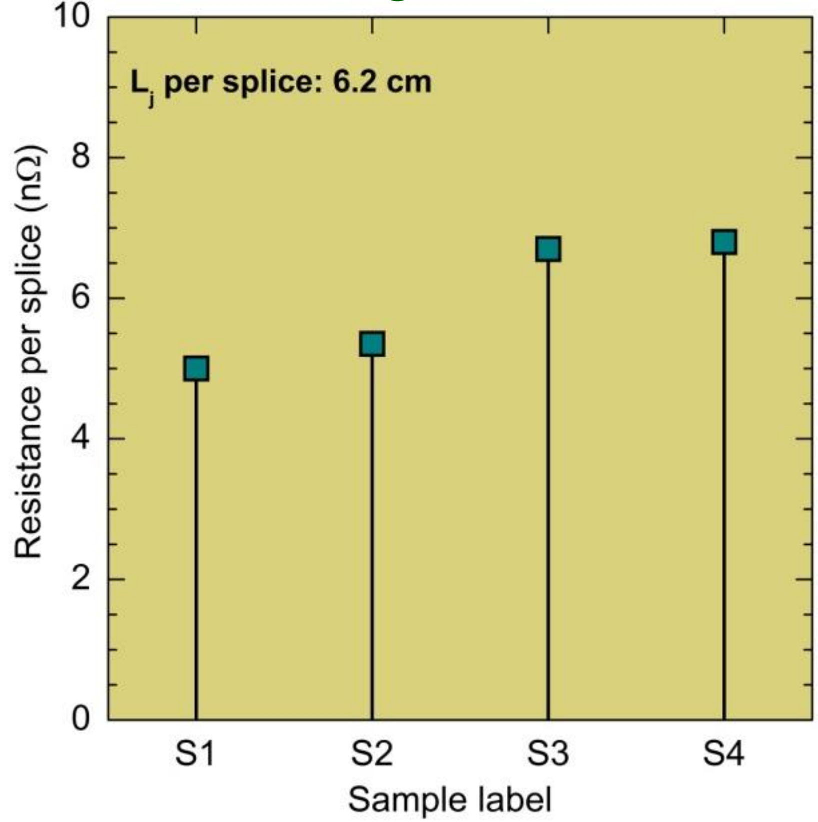
Two 15 cm Lap Joints

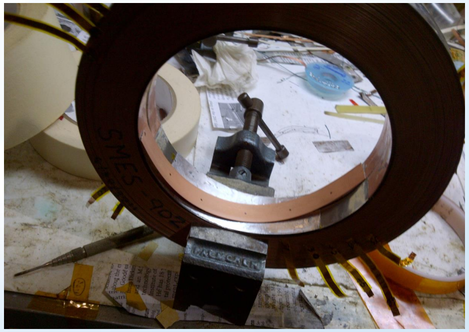




2.05 nΩ and 2.15 nΩ @77 K.

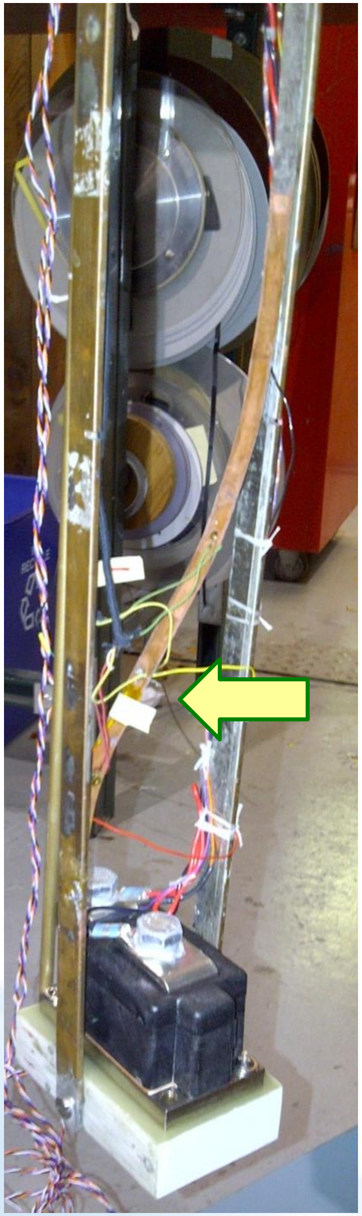
Diagonal Joint



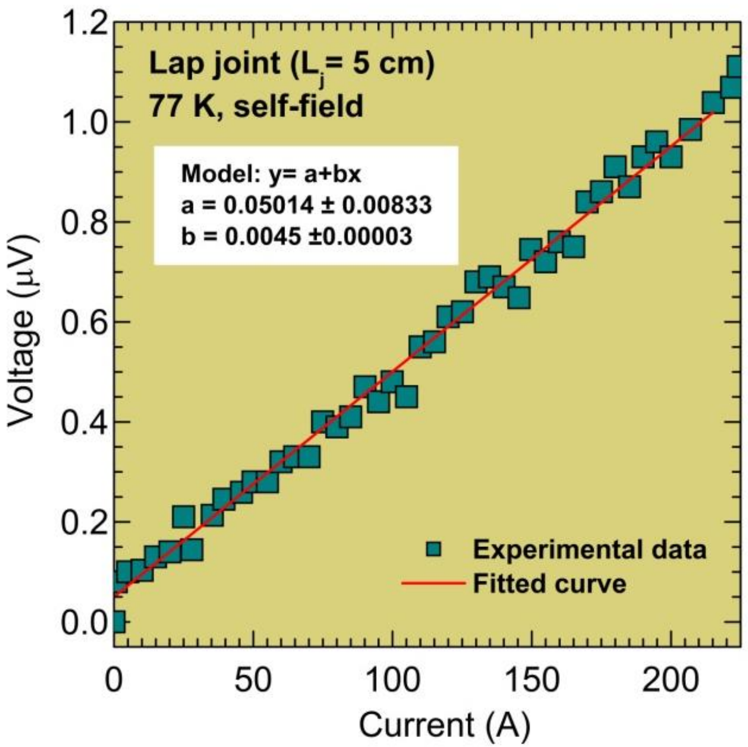


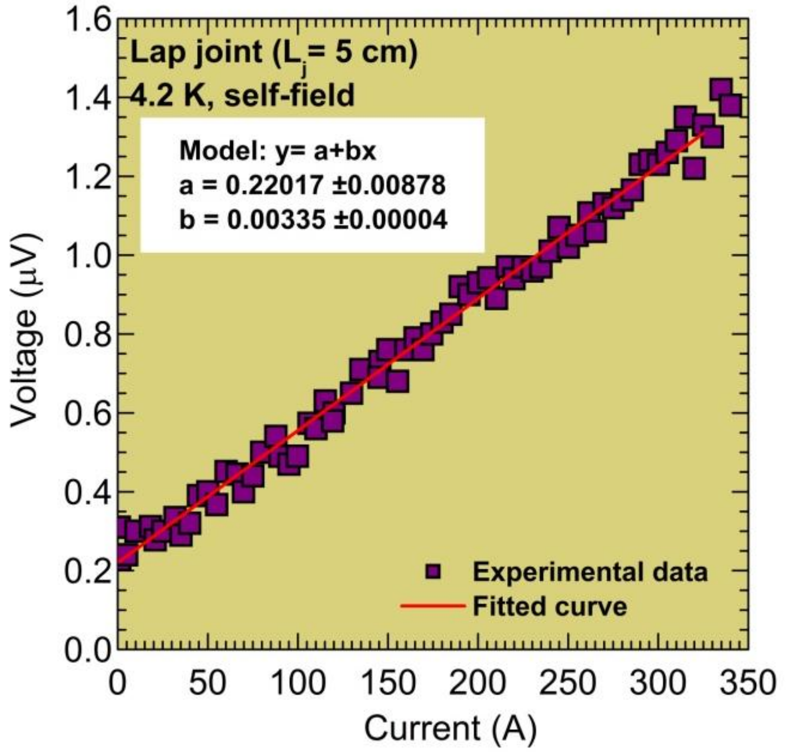
Splice resistance @77 K varied between 5 nΩ and 6.35 nΩ.

Relationship of Joint Resistance between 77 K and 4 K



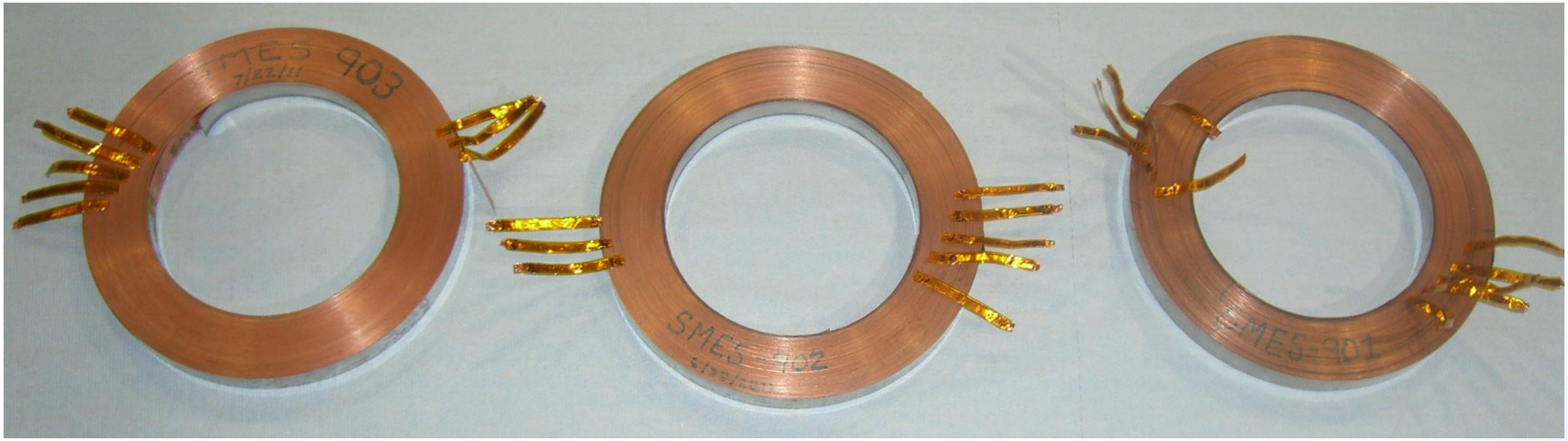
Most measurements during this study were made at 77 K. However, one test was also made at 4 K (in addition to 77 K). This gives an approximate relationship between 77 K and 4 K.



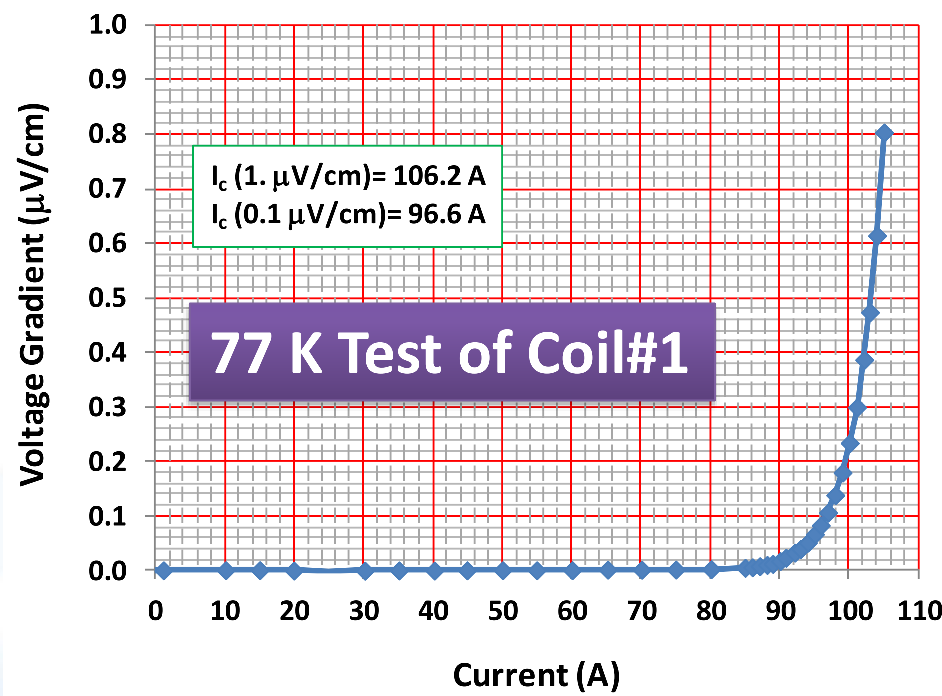


Joint resistance goes down from ~4.5 nΩ at 77 K to ~3.35 nΩ at 4 K (a ~26% reduction).

Construction and Test of 1st Series of Pancake Coils

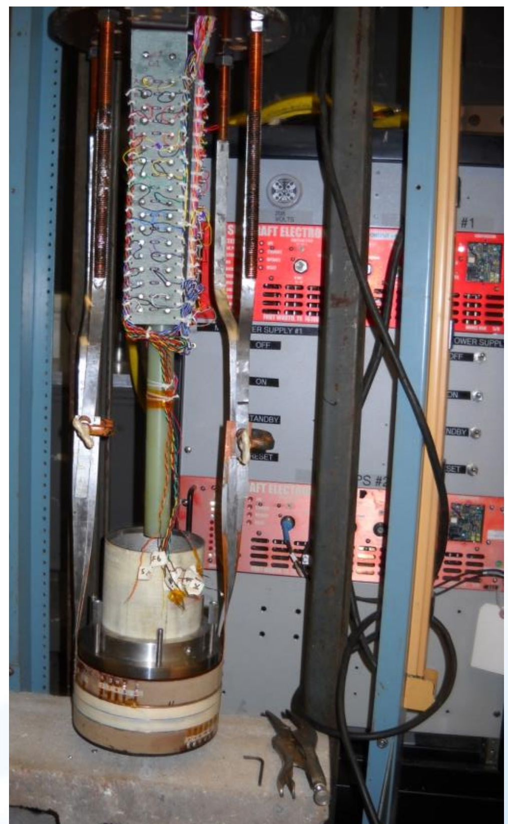


- **Measured 77K I_c of three coils: 97 A, 106 A & 111 A (0.1 μV/cm definition).**
- **After 77 K test, coil #1 is given to AEM for relaxation measurements.**
- **Coil #2 and #3 are used for making the double pancake coil stack for the Q4 GO/NOGO test.**



Construction and Test of Double Pancake Coils

- **Two pancake coils are spliced joint with diagonal joint**
- **Copper sheets are placed on either side of double pancake coil**
- **Coil stack is placed in test fixture, with in-house HTS current leads**
- **Test coils have several voltage taps at this stage for detailed analysis**
- **A series of voltage taps are connected to study quench protection**

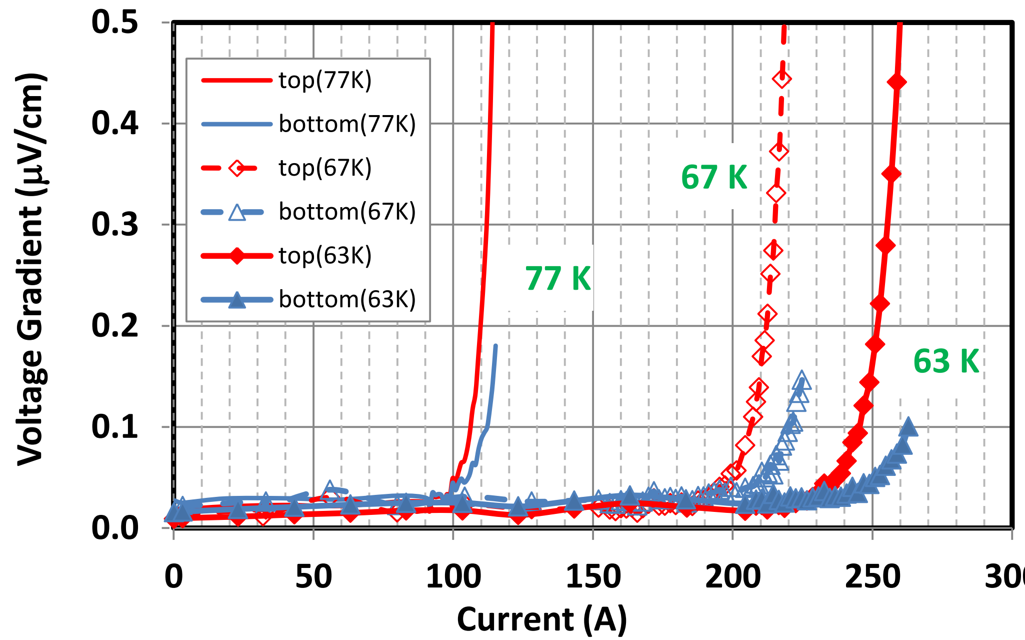


Double pancake coils in test fixture

Critical Milestone Test Result

Q4 GO/NOGO Milestone:

- Successful test at 77 K of a mini stack of coils
  - ➢ Achieved (see on right)
- Also tested at higher current, obtained by reducing temperature by pumping on N_2.

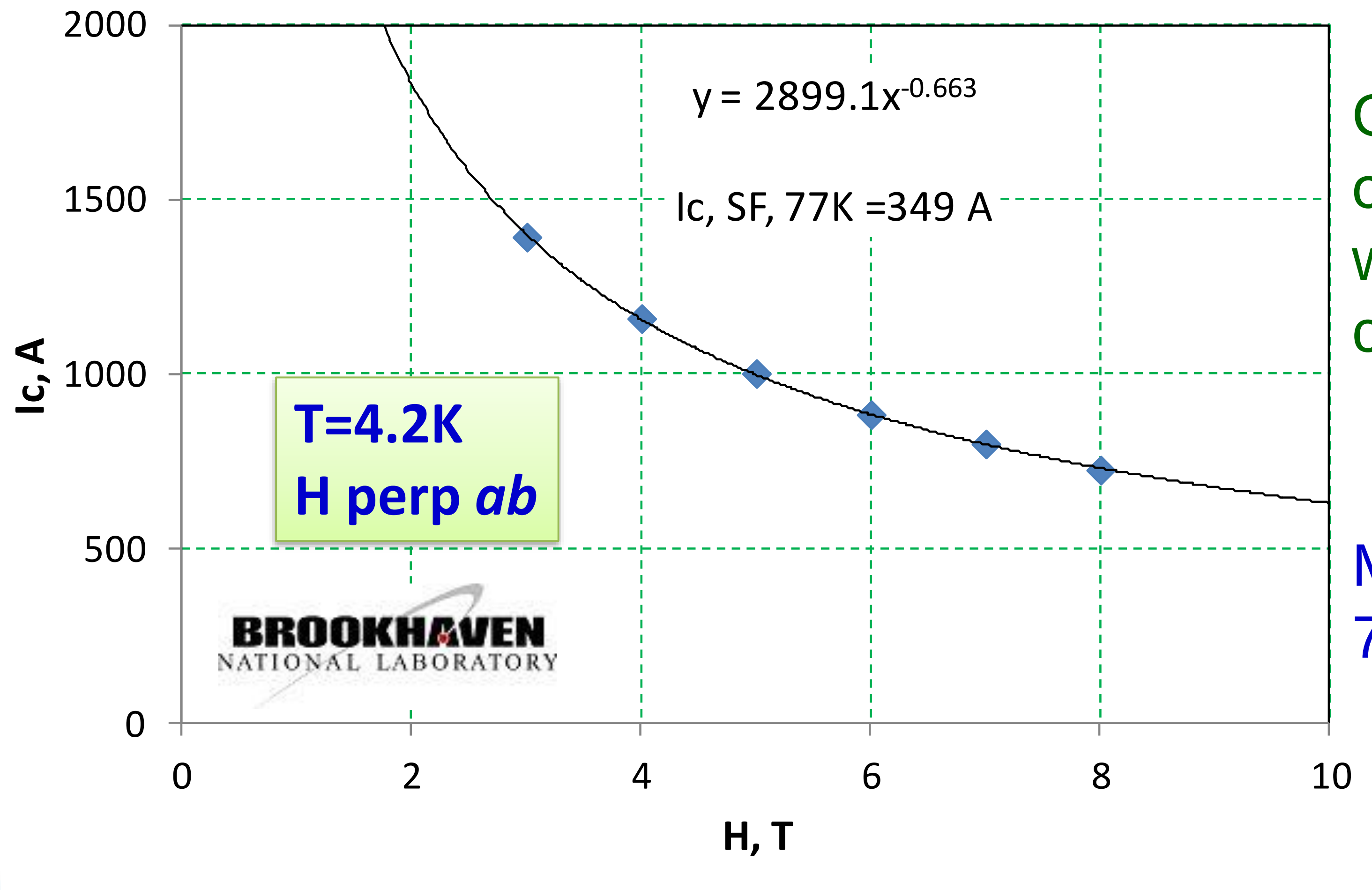


- Note: Definition for critical current in HTS wire industry is 1 μV/cm.
- For ~10 km (10^6 cm), this would allow 1V. This means~650 W dissipation for ~650 A.
- We use a more stringent 0.1 μV/cm definition.
- 0.1 μV/cm permits ~65 W maximum.
- This reduces to a maximum load of ~2 W for a 32 channel quench protection system.

4 K Helium Tests of SMES Double Pancake Coils

- **Important numbers: (a) ~100 A@77K (NO/NOGO milestone - achieved), (b) 250+@63K (useful bonus demonstration), (c) ~650 A@4 K (project goal – still far from there).**
- **Important questions: (a) Will quench protection system be able to protect the coils at ~650 A?, (b) Will coils be able to survive quench at ~650 A?, (c), Are splice joints and other construction techniques OK for ~650 A?, etc., etc., etc…**
- **To answer these questions before committing to a full scale construction, we need a high current test - only possible with Helium - not a part of the Q4 GO/NOGO milestone.**
- **Such a test increases the risk of a possible setback early on but useful feedback reduces the risk to the project later on.**
- **We made a logical decision based on the technical merit and decided to carry out this test.**

Conductor Test at 4 K

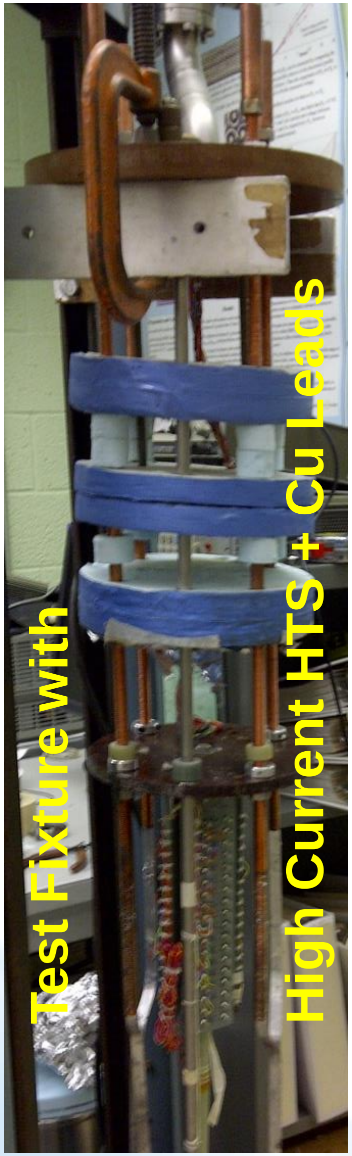


Good magnets can't be made without good conductor.

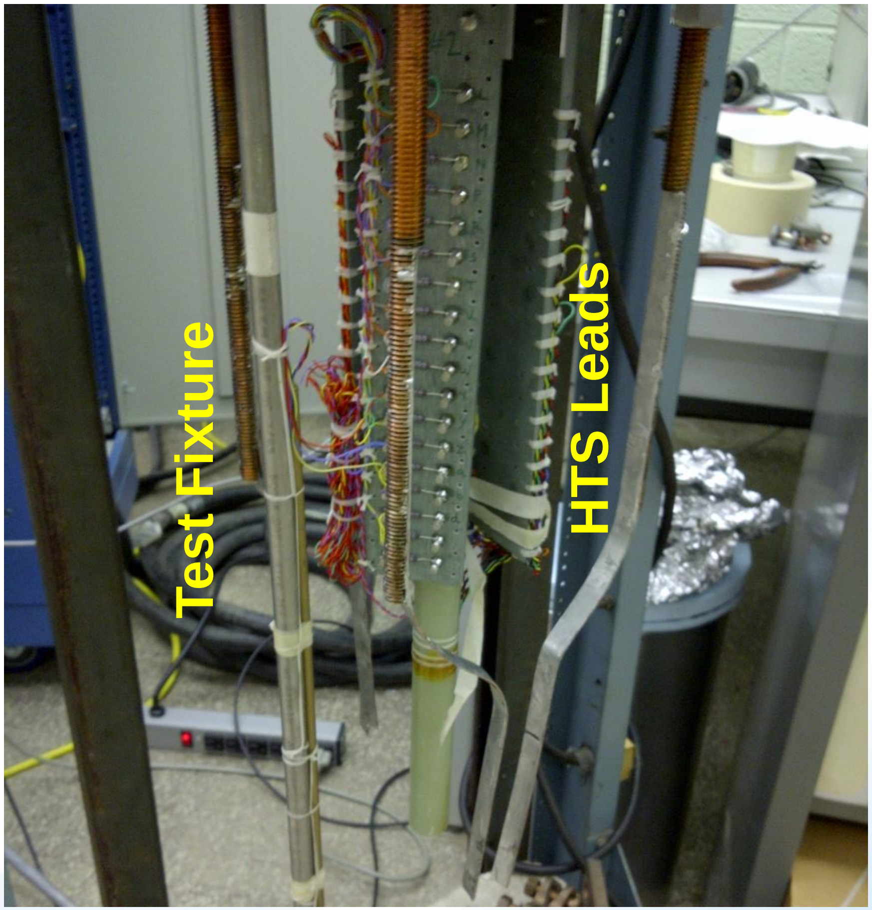
Meets spec of 700 A at 8 T

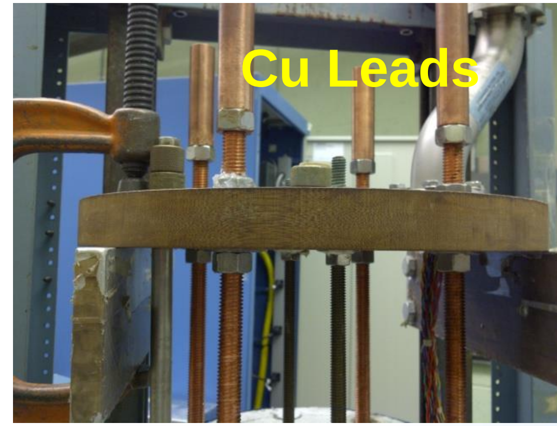
With new high current leads, BNL can measure I_c of full width (12 mm) conductor. We do not perform I_c measurements as a function of angle.

Upgrade of High Current Fixture for 4 K Test

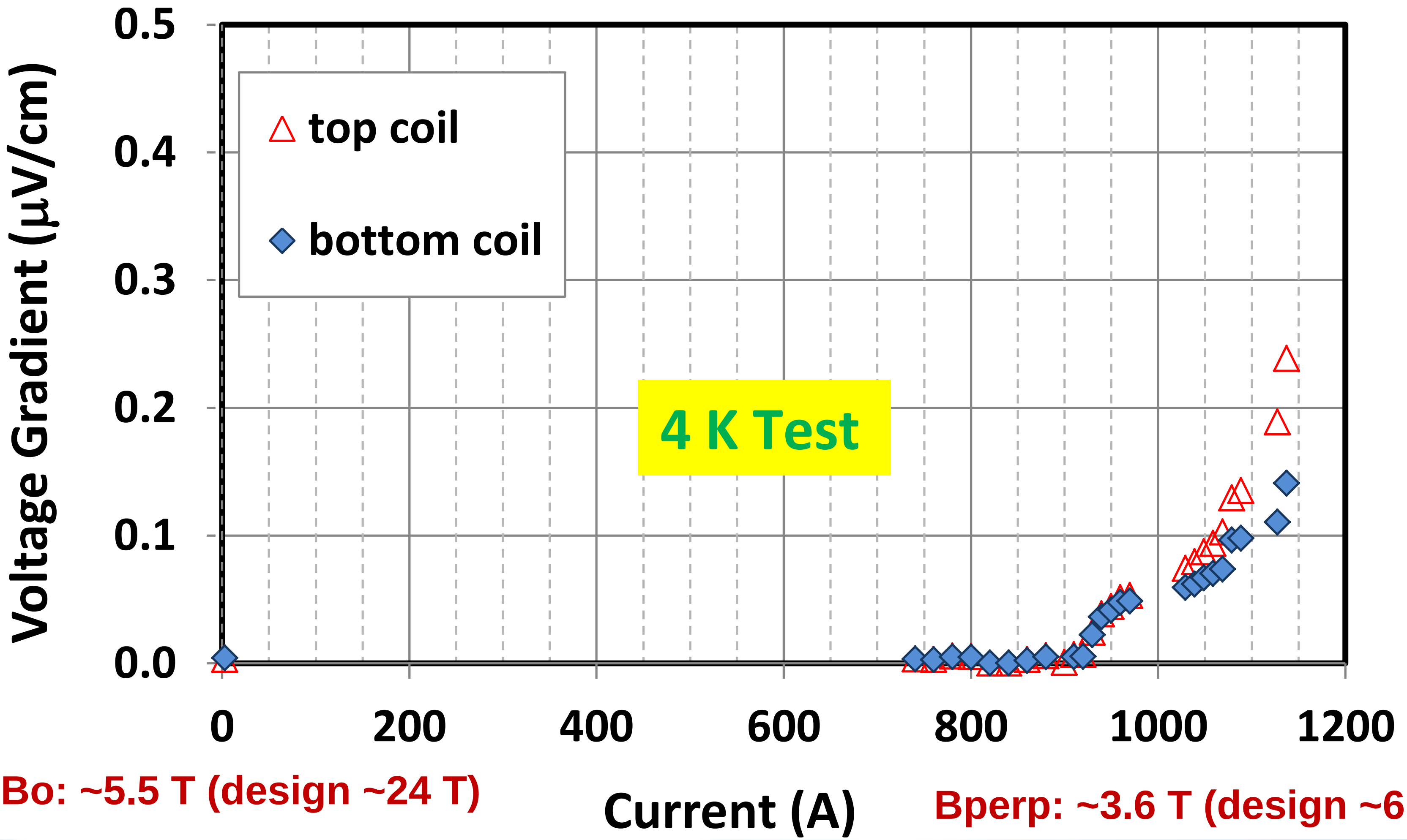


High current test required upgrade of leads (>700 A), fixture, quench protection set-up, etc. early on





First 4 K Test Results of SMES Coils



Bo: ~5.5 T (design ~24 T)

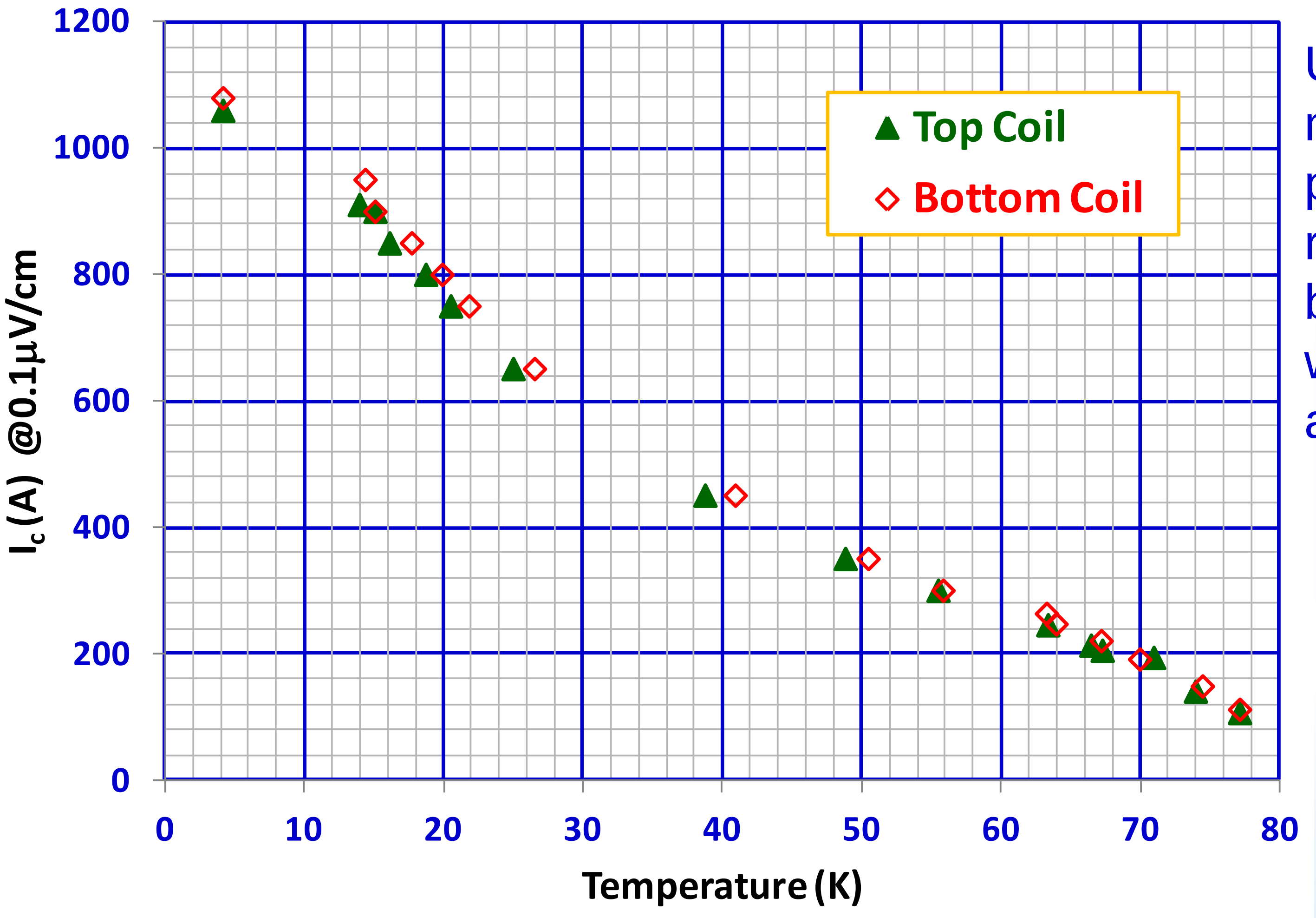
Bperp: ~3.6 T (design ~6 T)

All systems (including quench protection and splice joint) worked well till 1130⁺ A (design current ~650 A)

Observations about Conductor from the 4 K Test Results

- Amount of copper stabilizer (~100 mm) seems to be OK.
- Test coils had many voltage taps for detailed diagnostics. The entire wire (~55 meter in each coil) was good.
- The coil remained protected after repeated shut-off and also up to 10 A/s ramp rate (design 1 A/s). No degradation in wire performance observed.
- This was perhaps the highest current reached in a coil made with SuperPower Wire.
- Good wire makes good coil. Thank you SuperPower.

Critical Current as a Function of Temperature



Useful Ic Vs T measurements, performed routinely at BNL because of the way coil assembly and test setup is.

Important quench protection tests at ~700 A while the conductor is near critical surface (either increase field or reduce temperature)

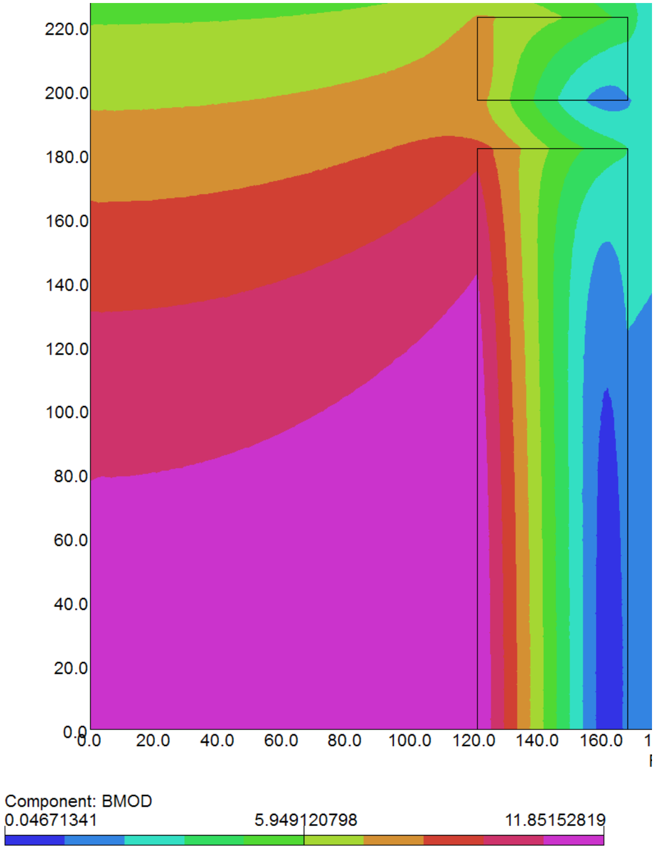
(Operating current in demo device is ~650 A)

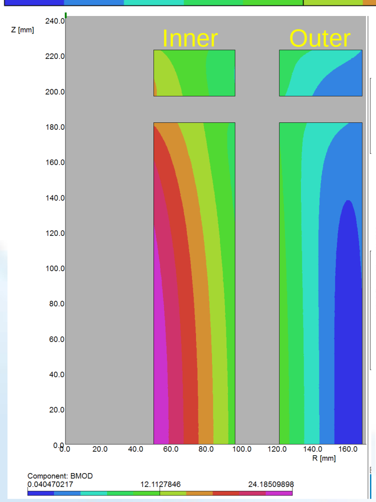
Critical Design Studies

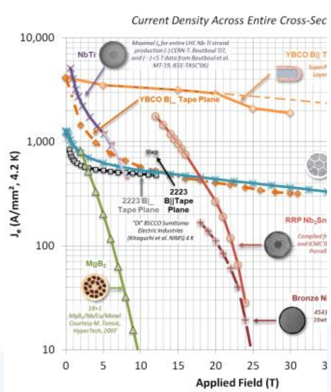
and

Possible Feedback to Current Program

Outer Coil Design



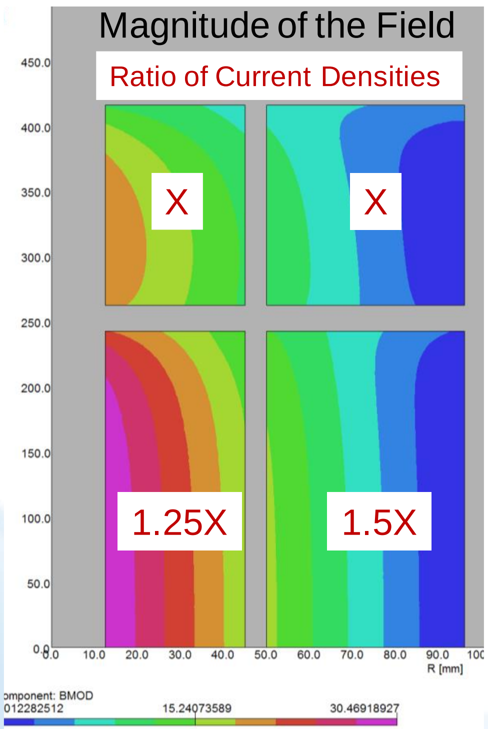




- Design field of outer coil is ~12 T. Such coil can be made with convention LTS technology. In fact one can order this now from a number of commercial vendors.
- Making it with HTS will be much more expensive.
- In an actual SMES device, the outer coil, therefore, is likely to be made with convention LTS. This is similar to what we are doing in other high field magnets also.
- Moreover, making outer coil with HTS will require us to address technical issues associated with large hoop stresses in HTS coils due to larger coil radius.
- **Question:** Is it wise to spend significant resources in solving a major technical issue in a demo device which will not be present in the actual system?
- We definitely have to address the issues associated with “high field HTS coils” but not necessarily those with “high radius HTS coils” – not for SMES program.

Possible Alternate/Future Plan

After building present coil, make second coil going inside rather than outside and generate 24-30 T



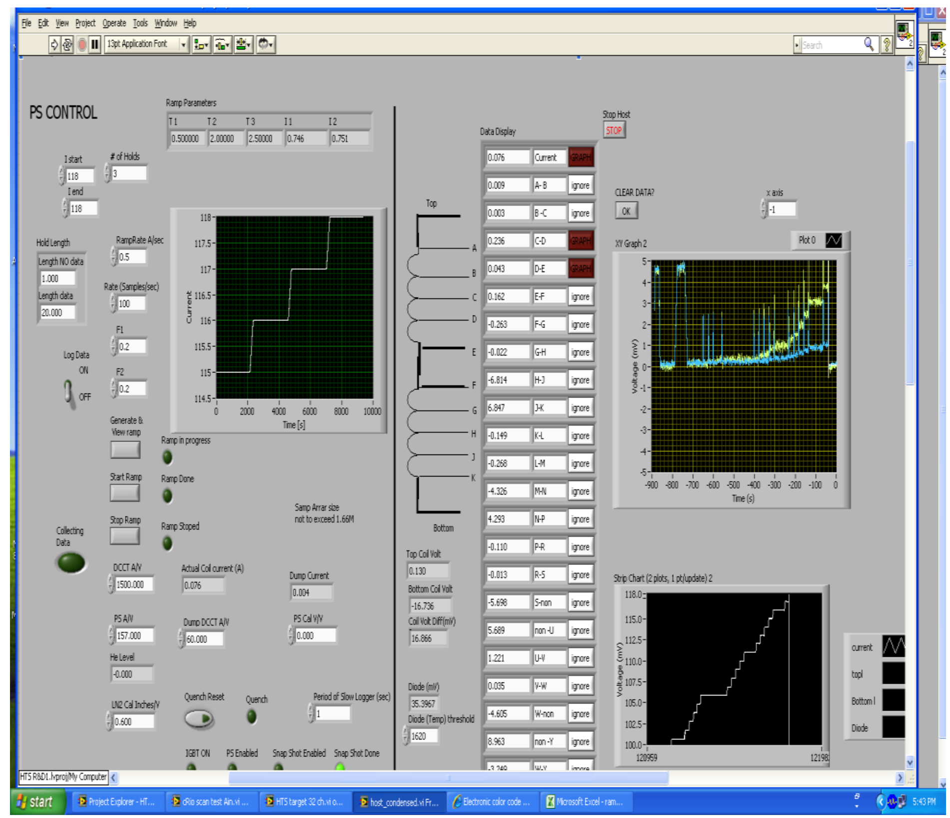
- 24-30 T HTS SEMS coil scenario can be integrated in the present R&D plan seamlessly thanks to an independent earlier design change which decoupled inner and outer coils.
- One can test a set of 100 mm aperture coils to ~30 T field in the background field of 20 T magnet at Florida (as suggested by Drew Hazelton of SuperPower). Technically it doesn't matter where the background field comes from – other SMES coil or somewhere else.
- Proposed design is also likely to bring a major saving in SMES device by reducing conductor cost up to ~60%. This is significant as the conductor represent the majority of the cost in the present design of high energy density SMES System.
- Above proposal addresses all technical issues related to a high field HTS SMES coil (stress, strain, quench protection, etc.) while minimizing spending limited resources in solving technical issues which may never be faced in a real device.

Quench Protection

Quench detection and protection is a major issue in HTS magnets

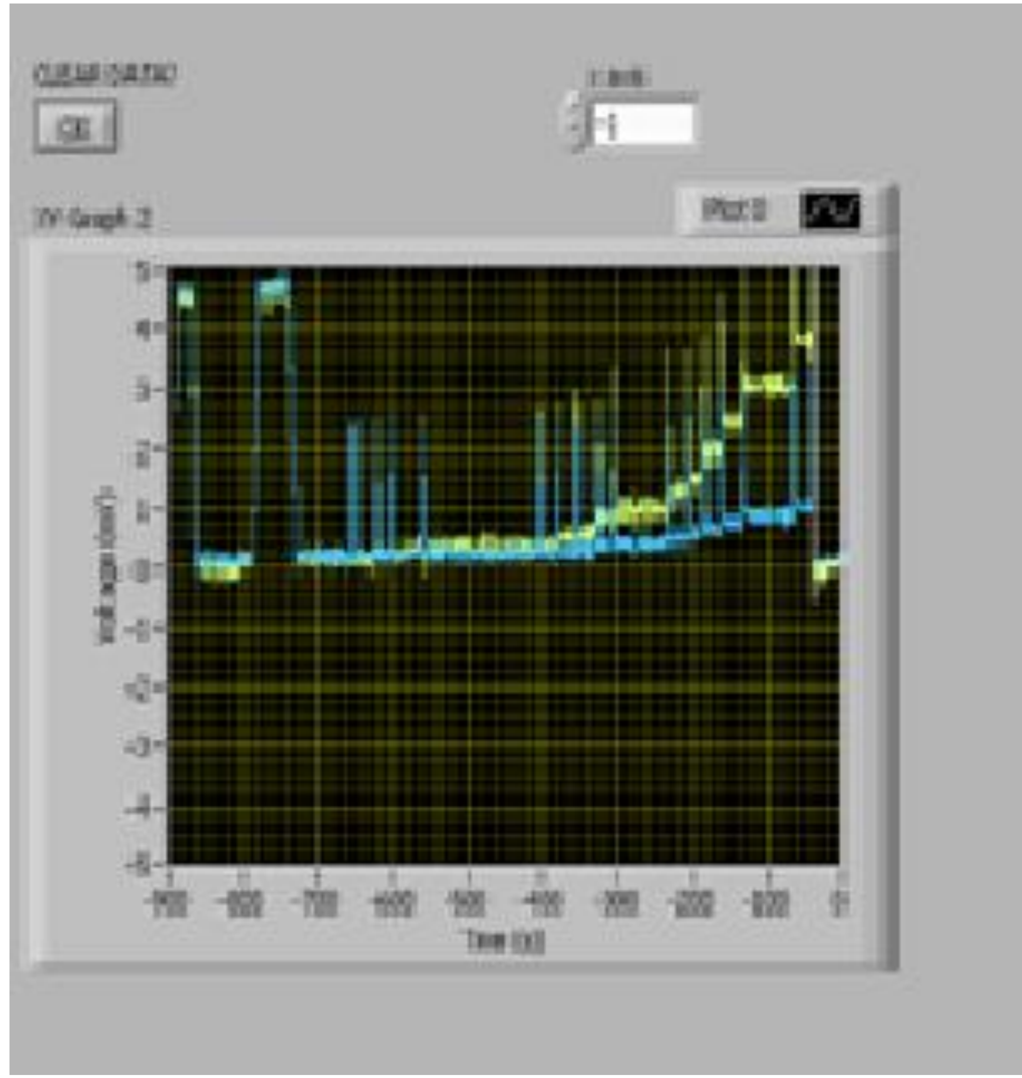
Quench and data Logging system

- Verify the reliability of quench detection system
- Verify the operation of Energy extraction system
- Expand quench and data logging system to 32 channels.

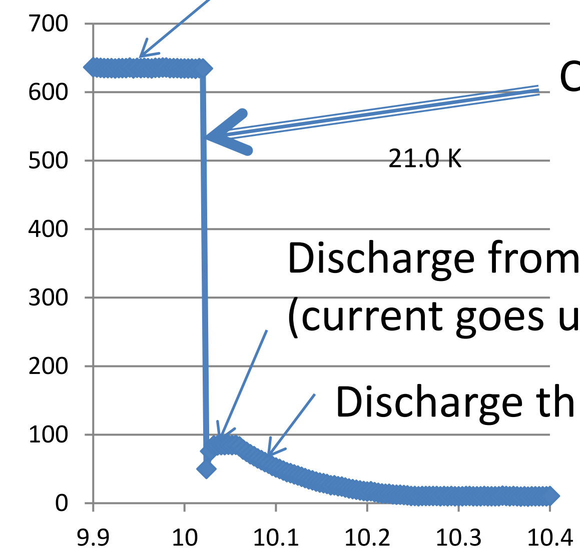


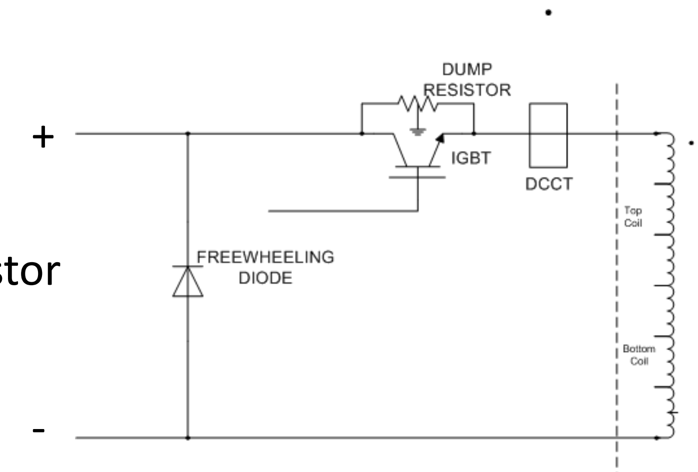
Quench Detection

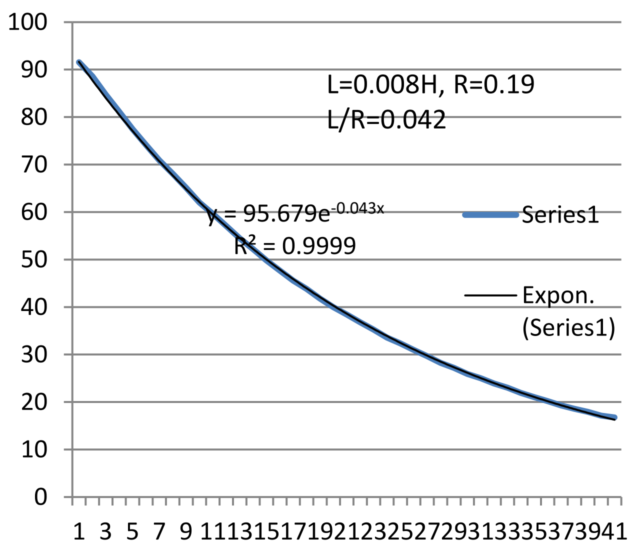
- Threshold of 2mV during ramp for ramp rate up to 10 A/s
- Threshold of 1mV (Q4 milestone) was demonstrated during ramp for ramp rate up to 1 A/s (current design)
- Threshold of 0.7mV at constant current (storage) demonstrated

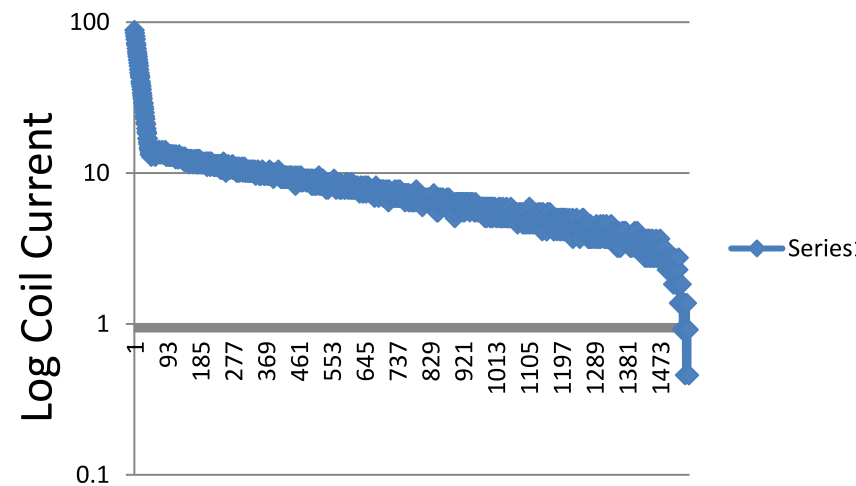


Typical Behavior at Quench (614A at 21K)

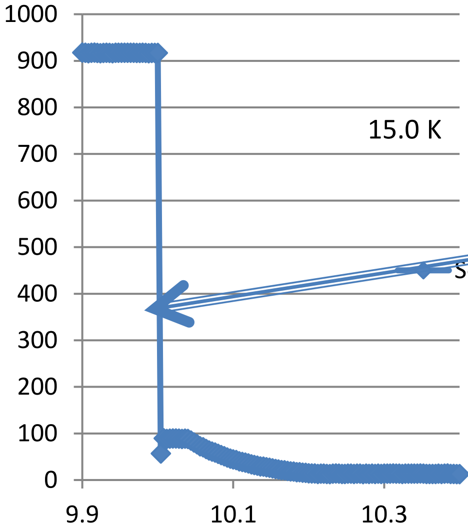




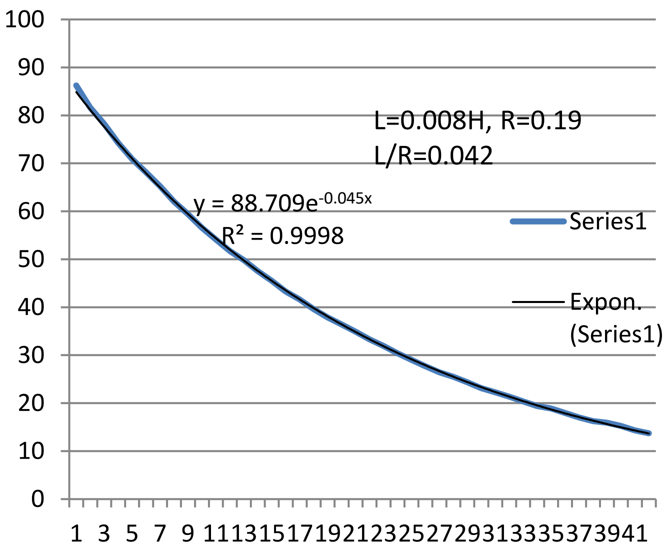


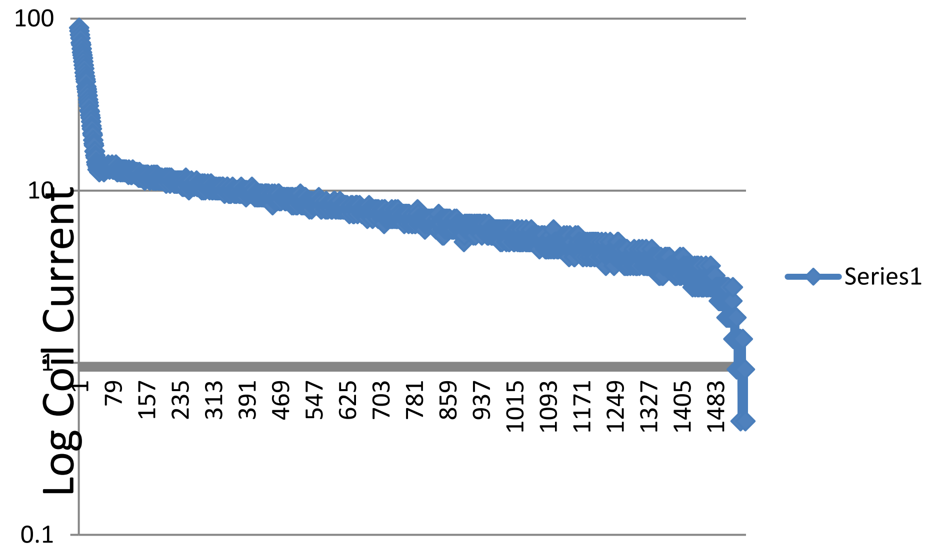


926A at 15K

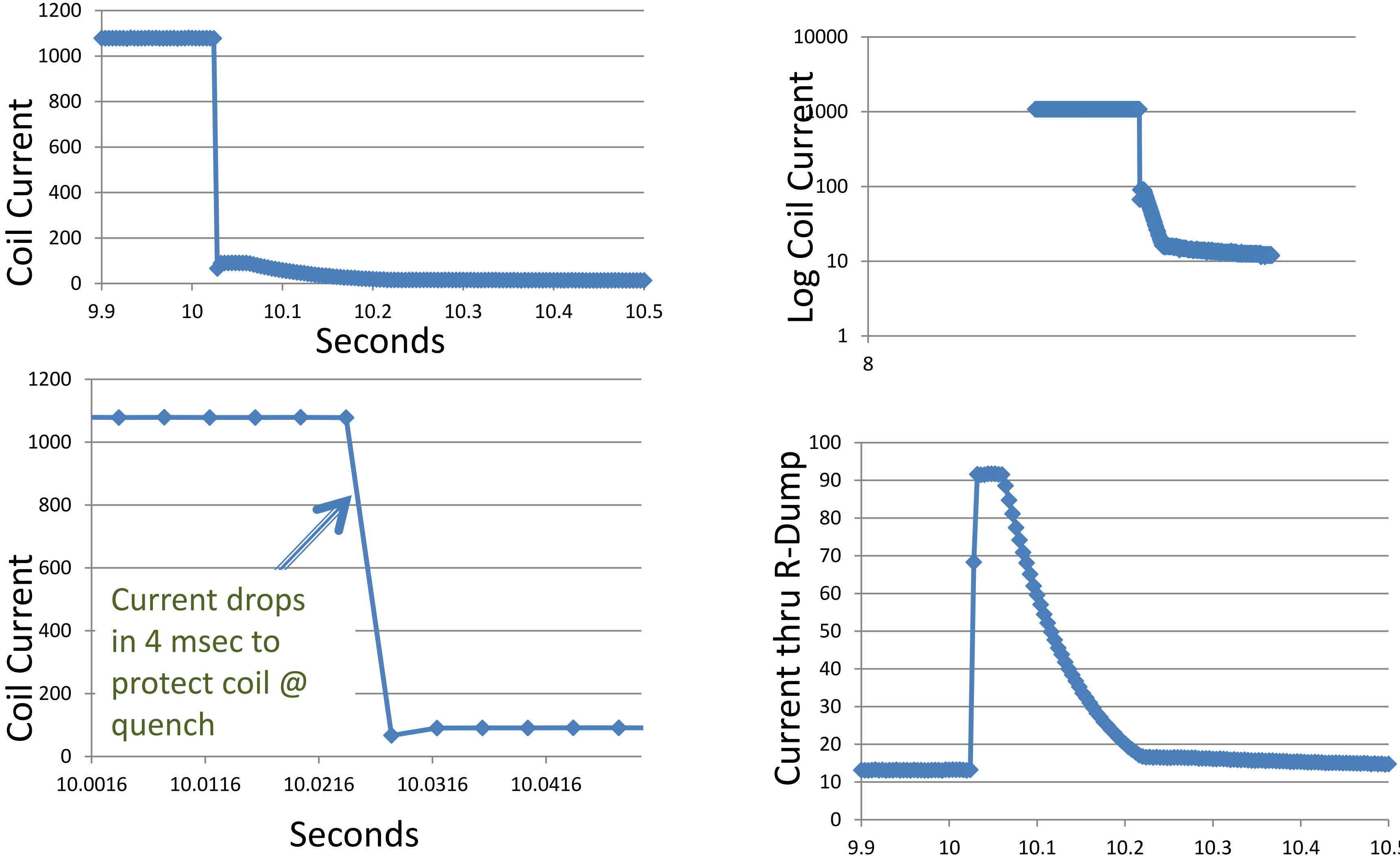


Current thru coil drops quickly as IGBT opens and is diverted to Dump resistor



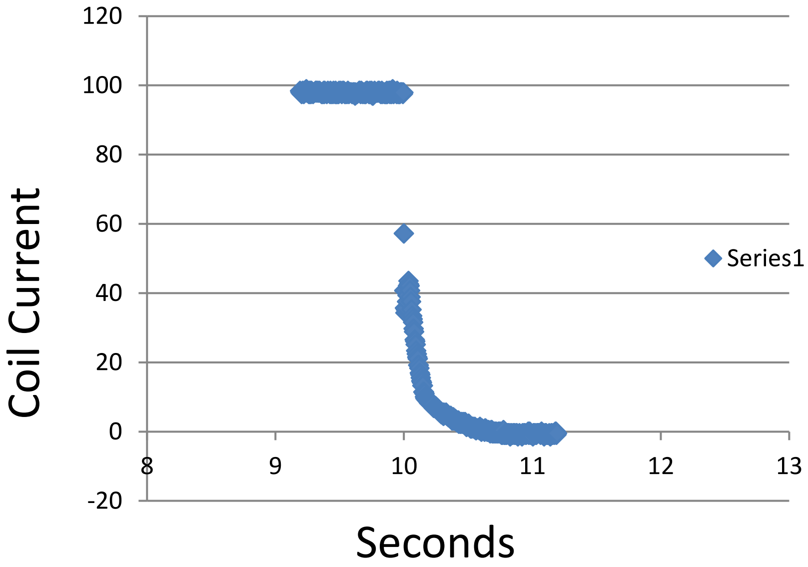


1100A @ 4.2K

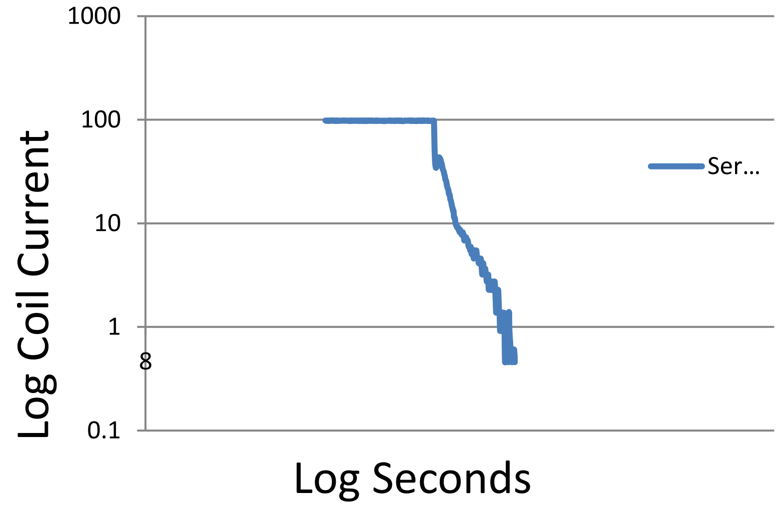


1200
1000
800
600
400
200
0
Coil Current
9.9
10
10.1
10.2
10.3
10.4
10.5
Seconds
10000
1000
100
10
1
8
Log Coil Current
1200
1000
800
600
400
200
0
Coil Current
Current drops in 4 msec to protect coil @ quench
10.0016
10.0116
10.0216
10.0316
10.0416
Seconds
100
90
80
70
60
50
40
30
20
10
0
Current thru R-Dump
9.9
10
10.1
10.2
10.3
10.4
10.5

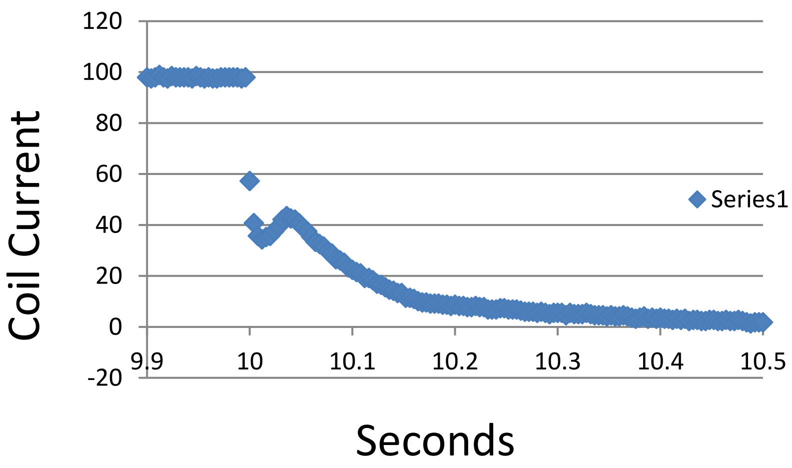
98A at 4.2K



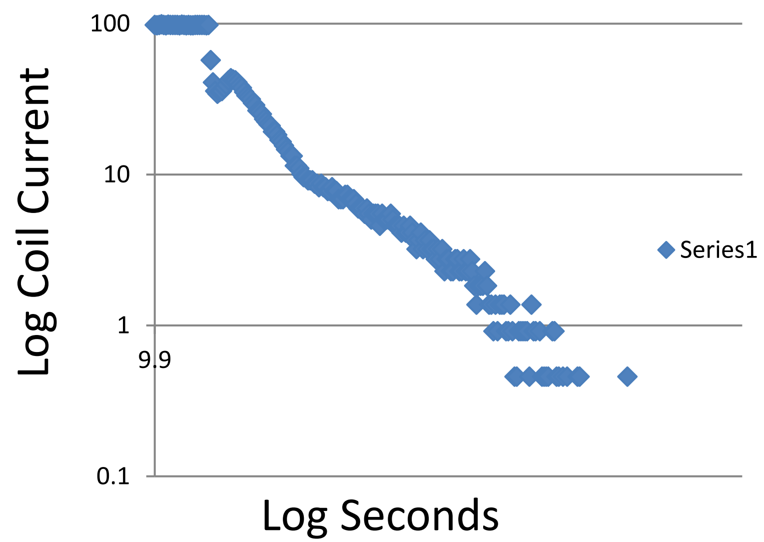
120
100
80
60
40
20
0
-20
8
9
10
11
12
13
Coil Current
Seconds
Series1



1000
100
10
1
0.1
8
Log Coil Current
Log Seconds
Ser...

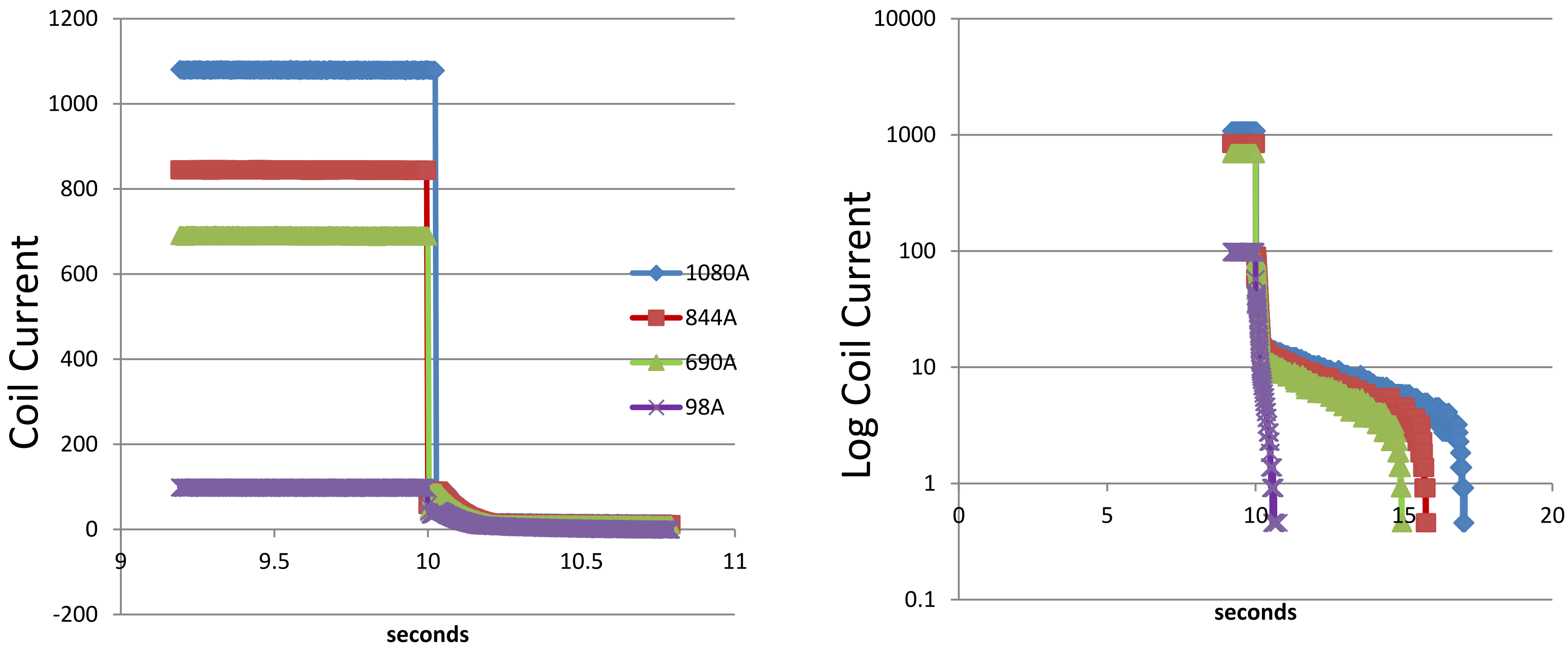


120
100
80
60
40
20
0
-20
9.9
10
10.1
10.2
10.3
10.4
10.5
Coil Current
Seconds
Series1



100
10
1
0.1
9.9
Log Coil Current
Log Seconds
Series1

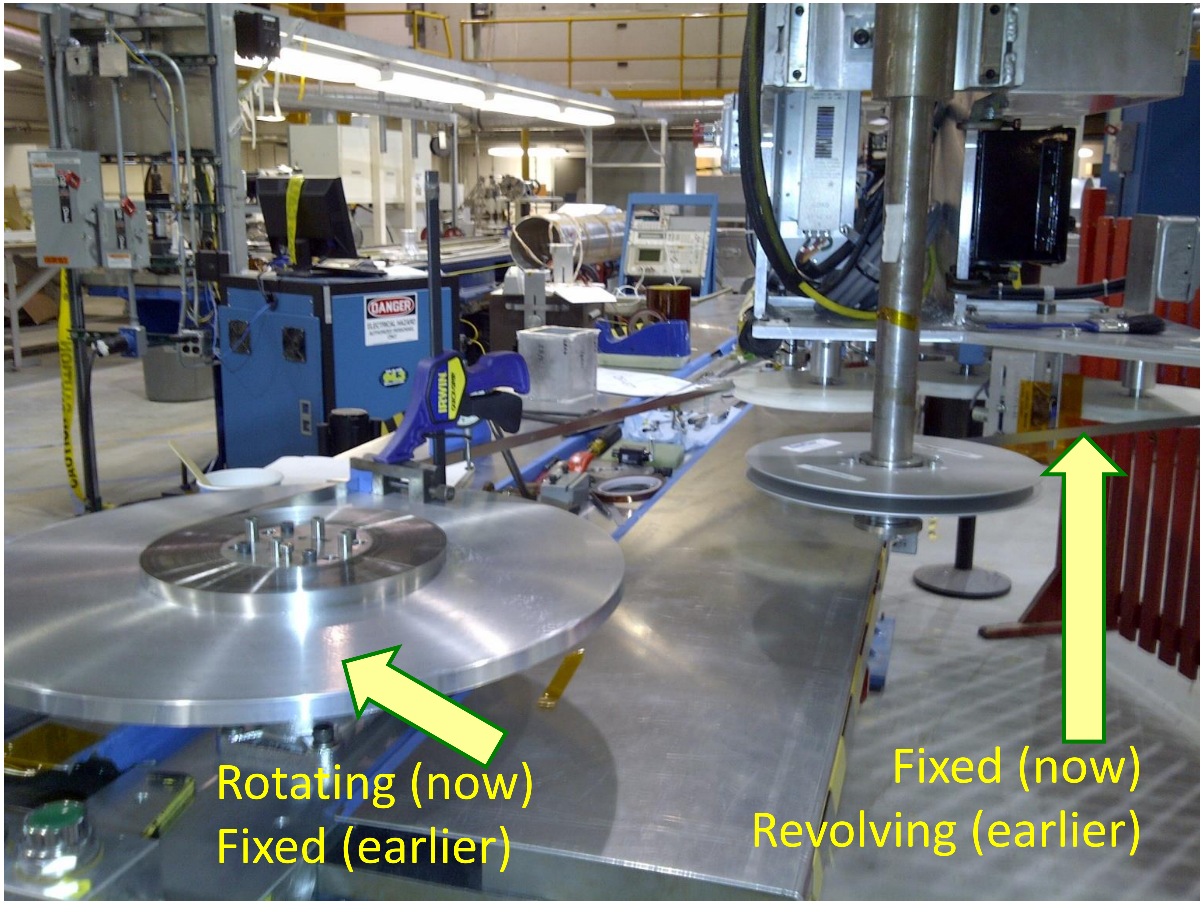
Diff current at 4.2K



Expansion of Quench system to 32 channel

- 32 Channel differential input, 16 bit simultaneous sampling with variable gain and range.
- Synchronization within 10µsec for transient data logging.
- Channel to Channel isolation of 1000V (least delay)
- Channel to ground isolation of 1000V.
- DAQ to withstand at least 2000V for 15sec.
- Software selectable channels for voltage bucking.
- Variable threshold while ramping and steady state and for different coil section combination

Status of Coil Winding



Two practice coils with stainless steel tape have been wound (one mini and one full size inner).

Two full size coils (destined for demo magnet) with 2G HTS have been wound.

Simplification of coil winder is making better quality coils at a faster rate – just what we wanted and expected.

Winder Upgrade

Two independent
Tension controllers

Automated Controls

Status of Q4 Magnet Division Milestones

Milestone	Status
1. Milestone: Small scale test coils fabricated and tested to determine mechanical properties of the conductor that can be used in the design	Test Completed for 4K-77K (original goal was for 77 K only)
2. Milestone: Demonstrate a cross-section section design with deflection < 200 micron	Completed (last review)
3. Milestone: Magnet design complete to produce coil with 2.5 MJ stored energy	Completed (last review)
4. Milestone: Tooling Design	Completed

We have completed all Q4 milestones

- In addition by testing coil at 4 K (in addition to at 77 K), we obtained useful information, etc. that reduces risk in future

- **Magnet Division does not have any Q5 milestone and is on track to Q6 GO/NOGO milestone subjected to inflow of funds**

Major Accomplishments

- Coil technology is demonstrated to well beyond the Q4 milestone:
  - Tests performed to 4 K (milestone required only 77 K)
  - Coils tested to 1140 A (design required only ~650 A)
- Basic quench protection is demonstrated in detecting small resistive voltage in presence of large noise and in protecting coil well beyond the design current
- The basic joint technology is successfully applied to real coils. Joint construction has been found robust in high current 4 K tests. Joint with a resistance of ≤ 1 nΩ built and tested (specification ≤ 5 nΩ)

Remaining Magnet Division Tasks

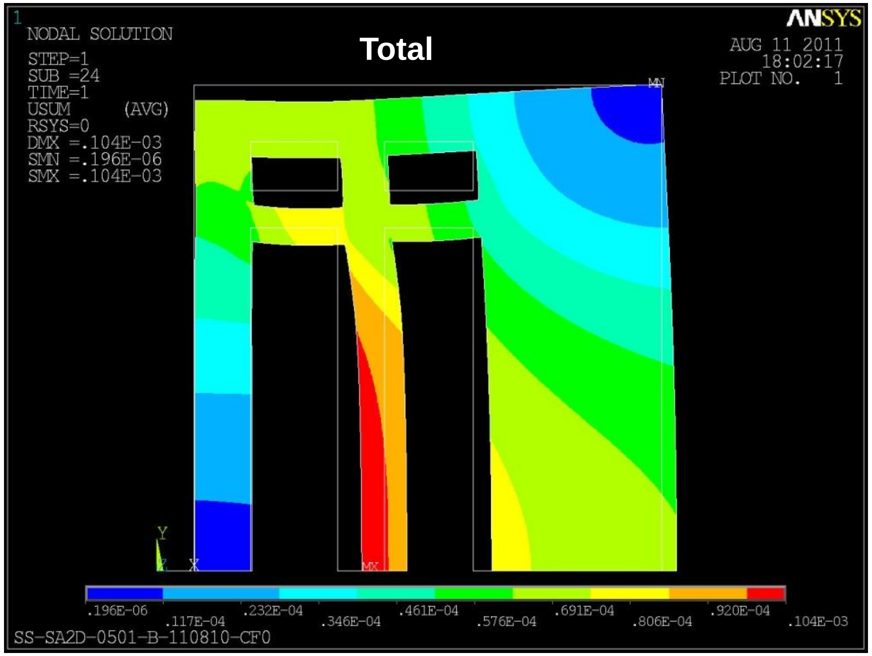
- **Complete detailed engineering design**
- **Complete construction of advanced quench protection hardware with 32 channels (significant work based on the basic system that was demonstrated in this quarter for two coils)**
- **Start series production of remaining coils**
- **Do 77 K QA test of each double pancake coil**
- **Construct and test 10 T magnet for Q6 GO/NO GO milestone with intermediate support structure**
- **Construct 24 T magnet with advanced support structure**

SUMMARY

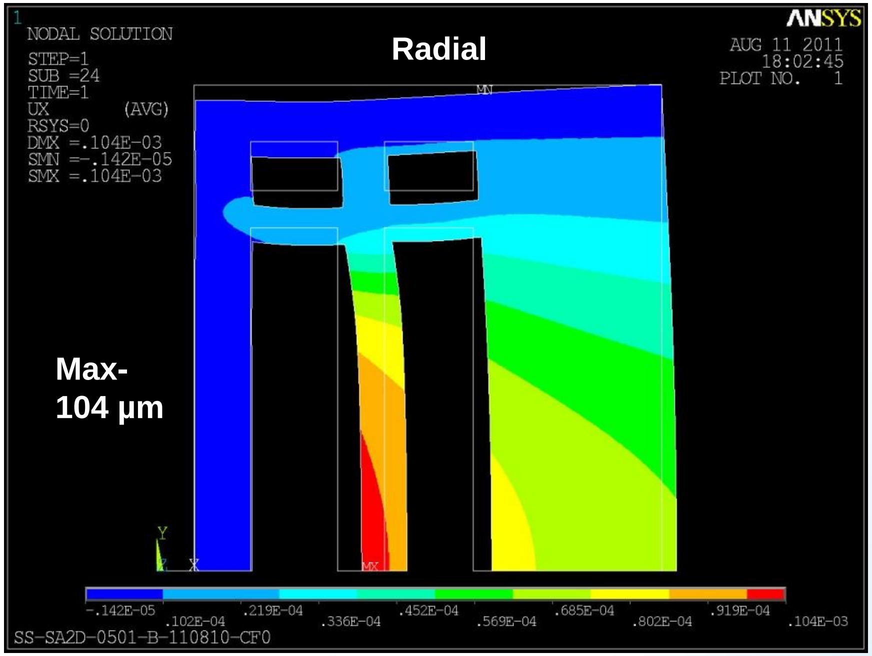
- First GO/NOGO milestone has been successfully completed.
- With basic technology (coil winding, splice joint, quench protection, etc.) demonstrated, we are moving to a series production of coil.
- Important iteration in the design of demo is proposed so that we apply our limited resources in solving those issues that will be relevant in the GRID scale device.
- We are pleased with the progress made so far, but are mindful of the number of challenges ahead.

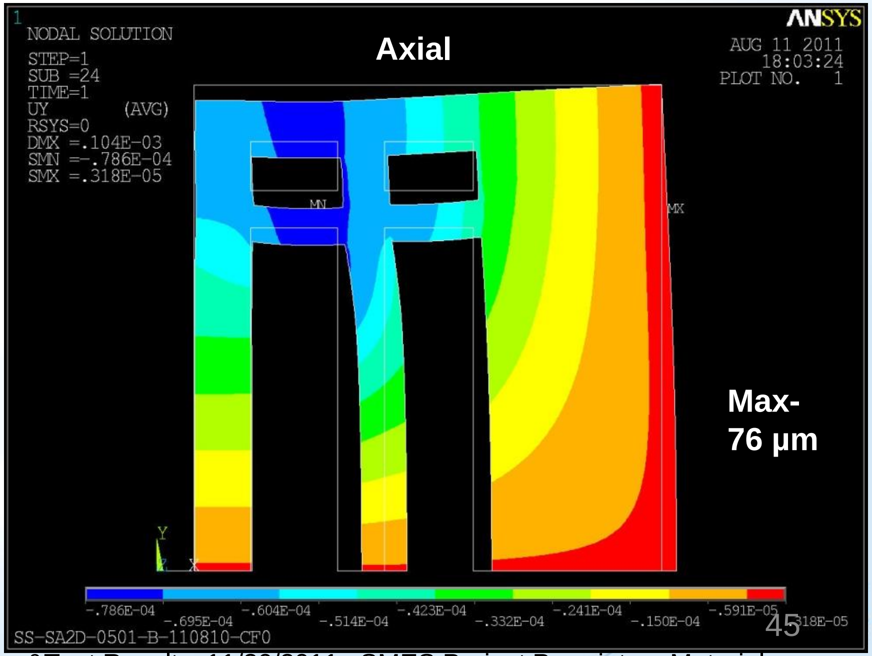
Back-up Slides

MECHANICAL DEFORMATION IN SS STRUCTURE



Maximum deformation- 104 μm

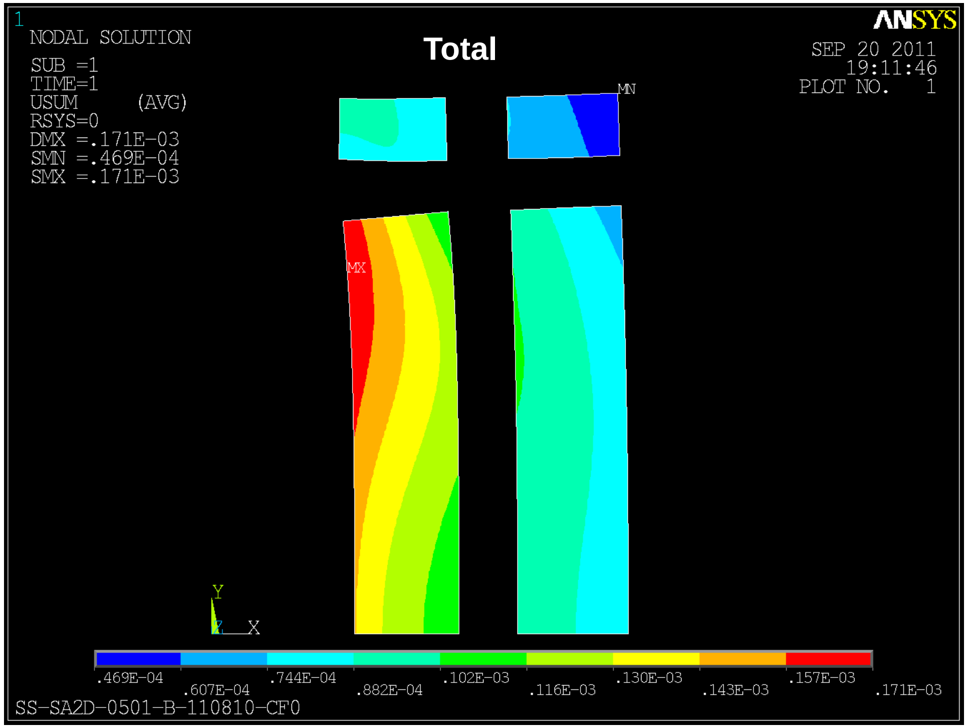




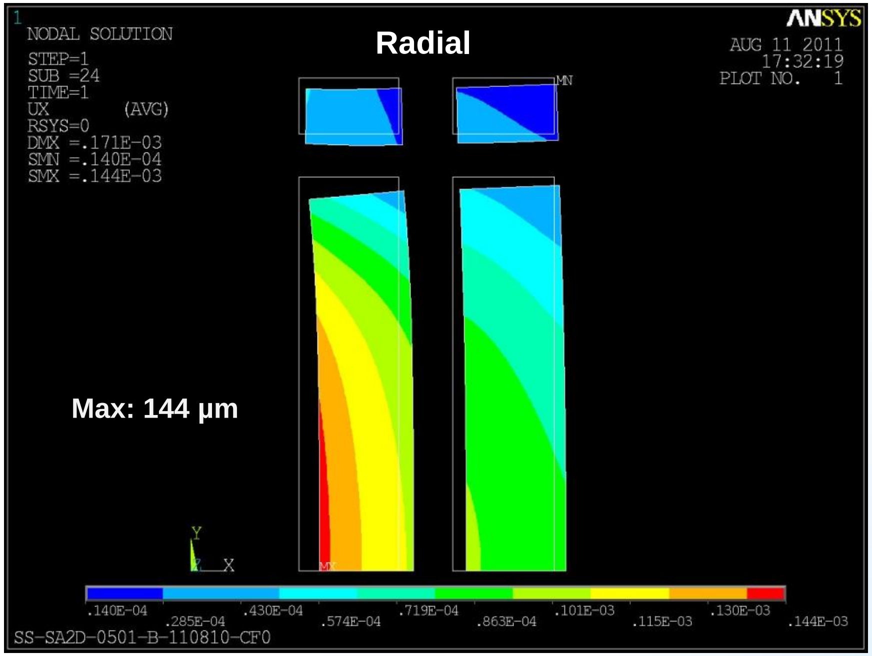
Note: HTS coils are not shown

Lakshmi

MECHANICAL DEFORMATION IN HTS COILS



Maximum deformation- 171 µm

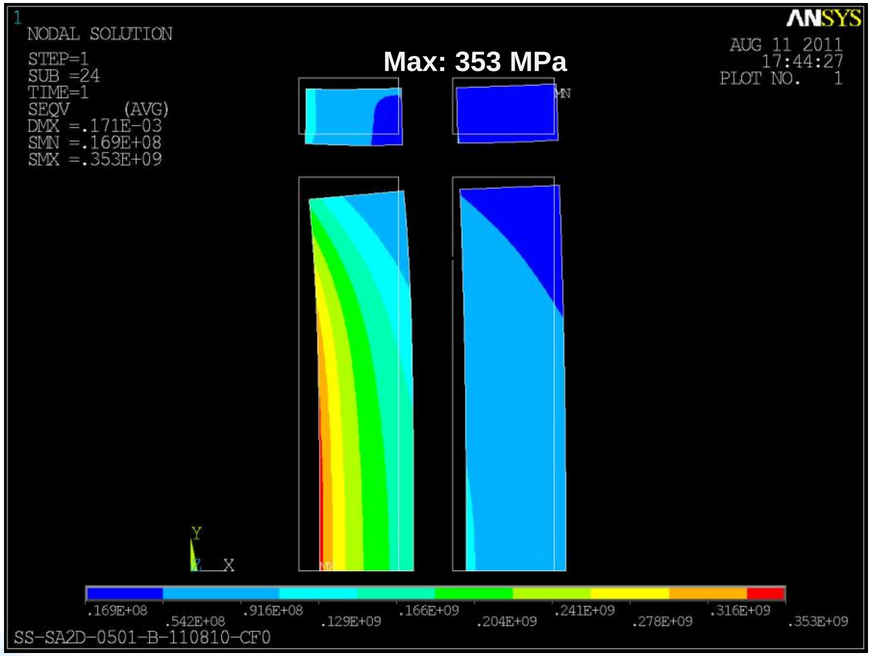


Lakshmi

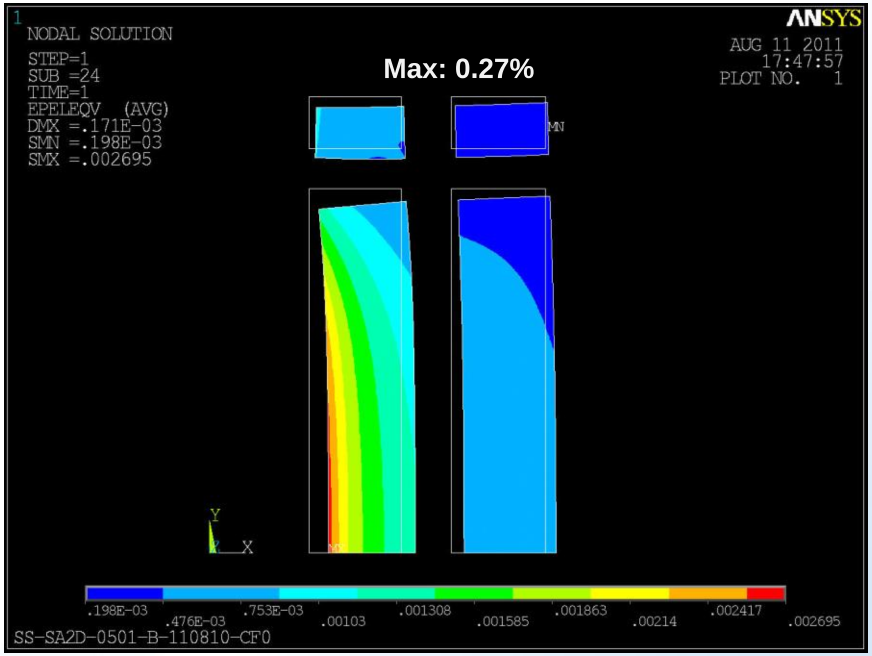
Note: SS structure is not shown

STRESS and STRAIN WITHIN HTS COILS

EQUIVALENT STRESS IN HTS COILS



EQUIVALENT STRAIN IN HTS COILS



Lakshmi

Expected Values of Joint Resistances

Diagonal splice between two pancakes (6.2 cm long chosen):

- ~6 nΩ@77K and ~4.5 nΩ@4K
- This will disappear if we wind coils as double pancake

Internal splice within pancake (15 cm long chosen):

- ~2 nΩ@77K and ~1.5 nΩ@4K
- This will disappear as long length conductor become available

Field dependence of joint is expected to be measured by AEM

Best splice joint (may be used to join two double pancakes):

- ≤ 1 nΩ@77K and ≤ ¾ nΩ@4K
- This can't be avoided but ≤ 1 nΩ is perhaps the best achieved

✓ All of above are below the project milestone of 5 nΩ.
✓ Contribution to losses from these joints should be relatively small.

SMES Coil Design for GRID

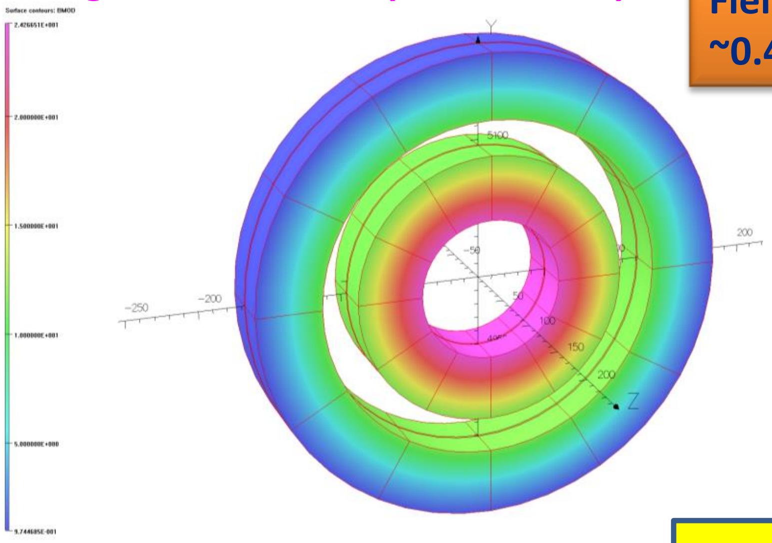
Guiding Principles

Conductor is the cost driver in the high field HTS SMES. In fact, in the present design, the conductor cost determines the cost of the SMES coil. Therefore, minimizing this must be the major goal of this R&D.

Demo model should be as much in sync with the likely SMES system for GRID as possible/practical. At minimum, we should not spend major resources in solving/optimizing something that is specific only to demo.

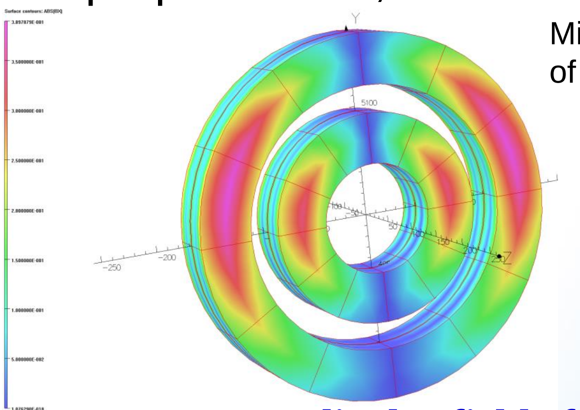
Field on Conductor in 2 Layer Coil of 2 GJ System

Magnitude of B (24 T max)



Field Parallel ~24 T; Field Perpendicular: ~0.4 T (NOT 6-10 T)

B-perpendicular, 0.4 T max



Lower perpendicular field effectively increases I_c and reduces losses.

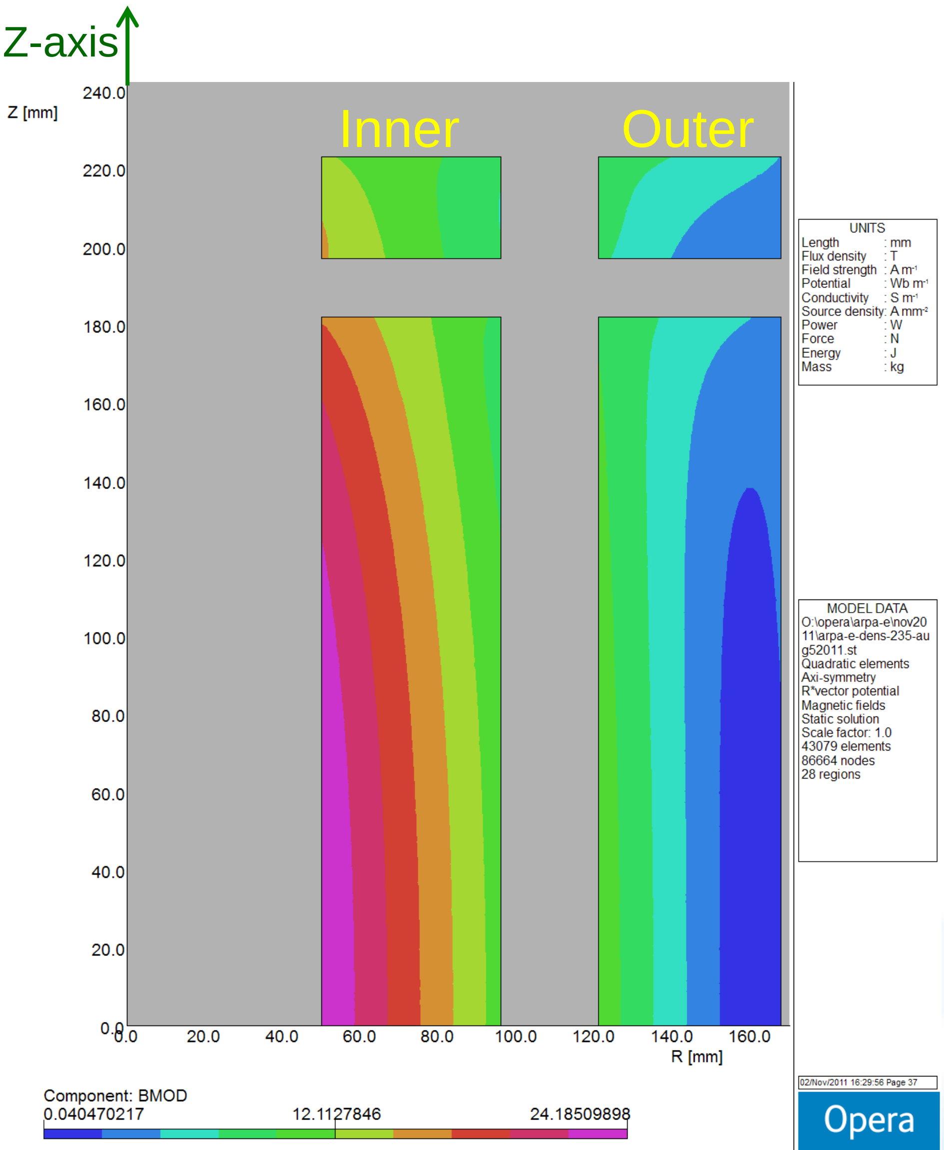
- B_{max} (inner coil): ~24 T
- B_{max} (outer coil): ~11 T

Higher I_c => less conductor => reduced system cost

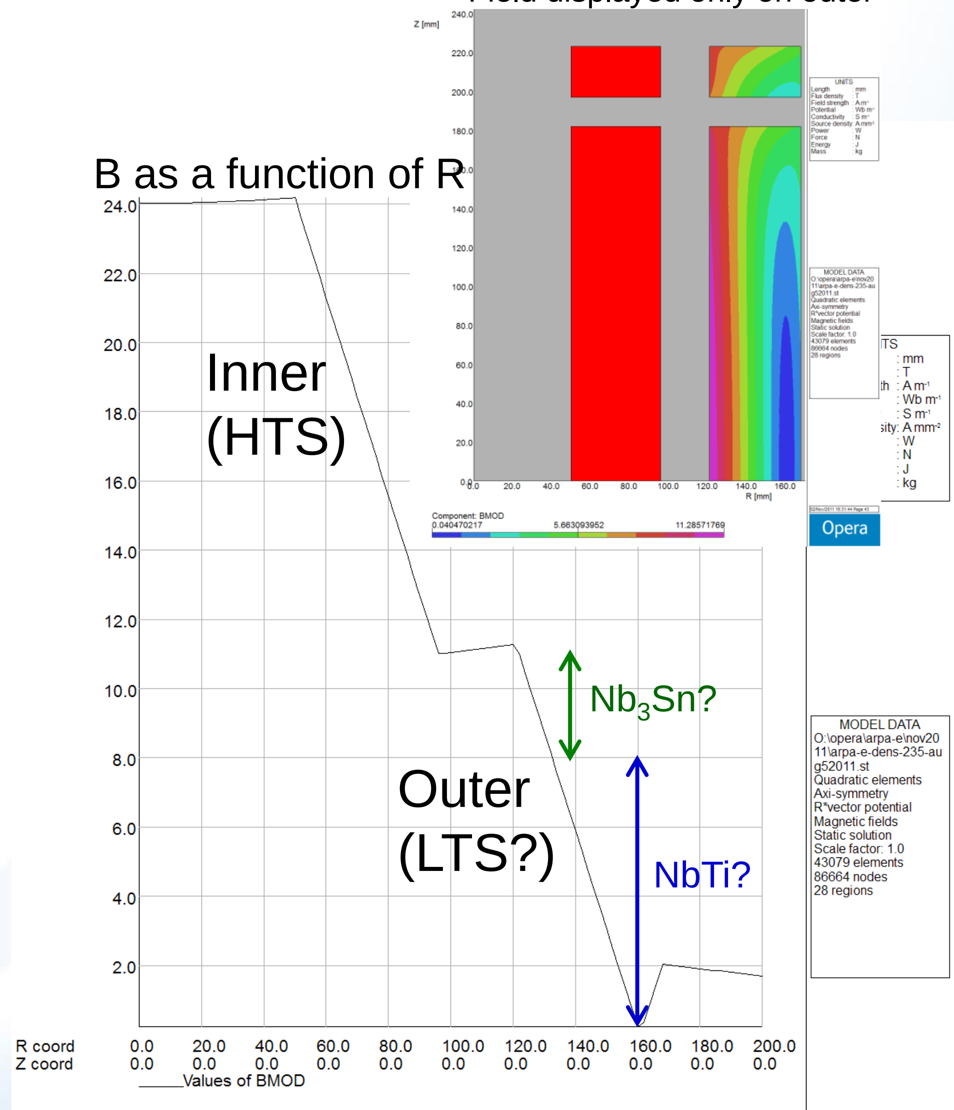
At 12 T, HTS is order of magnitude more expensive in kA.meter than LTS (Nb_3Sn).

- Is HTS the right choice of conductor for outer?
- Since outer coil uses twice as much conductor as inner, the impact is even more dramatic.

Field on the Coil



Field displayed only on outer

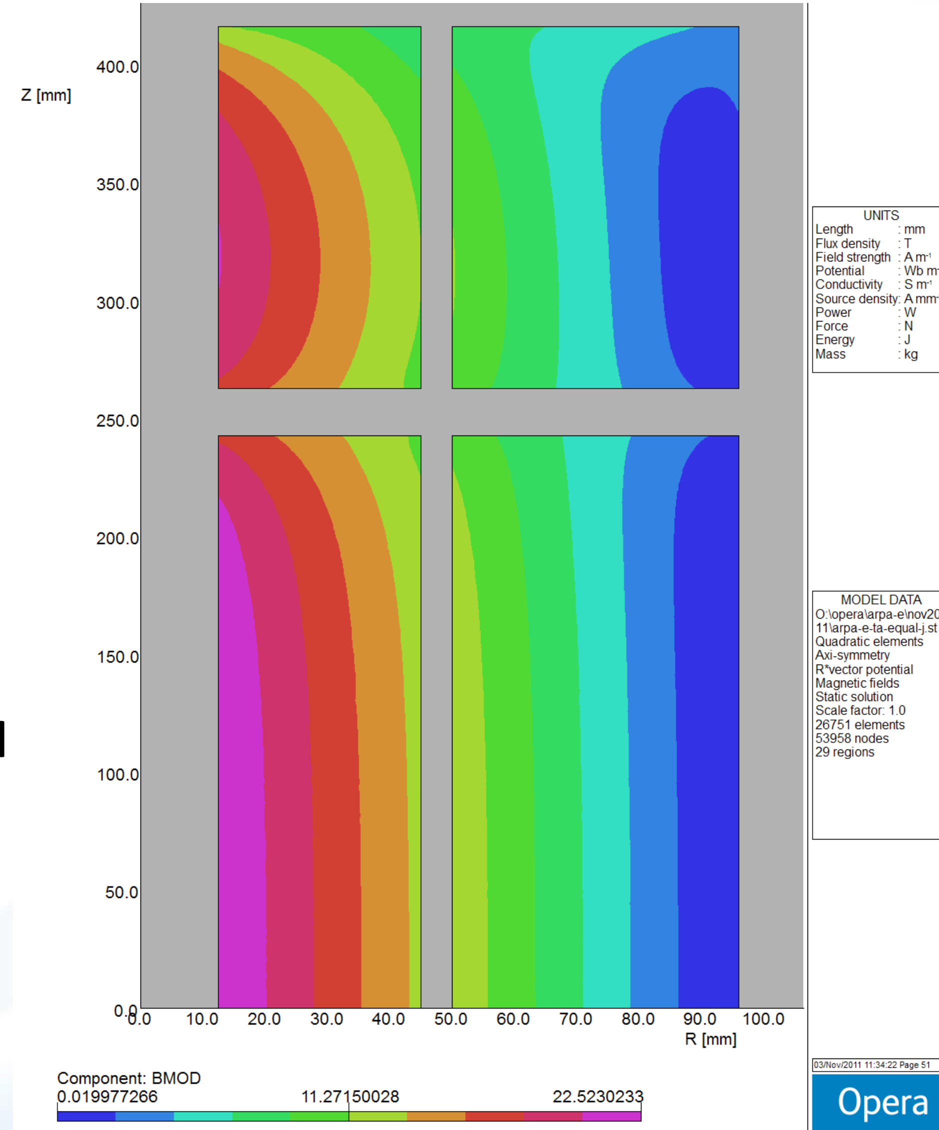


Possible Scenario
Longer Length and Insert Coils

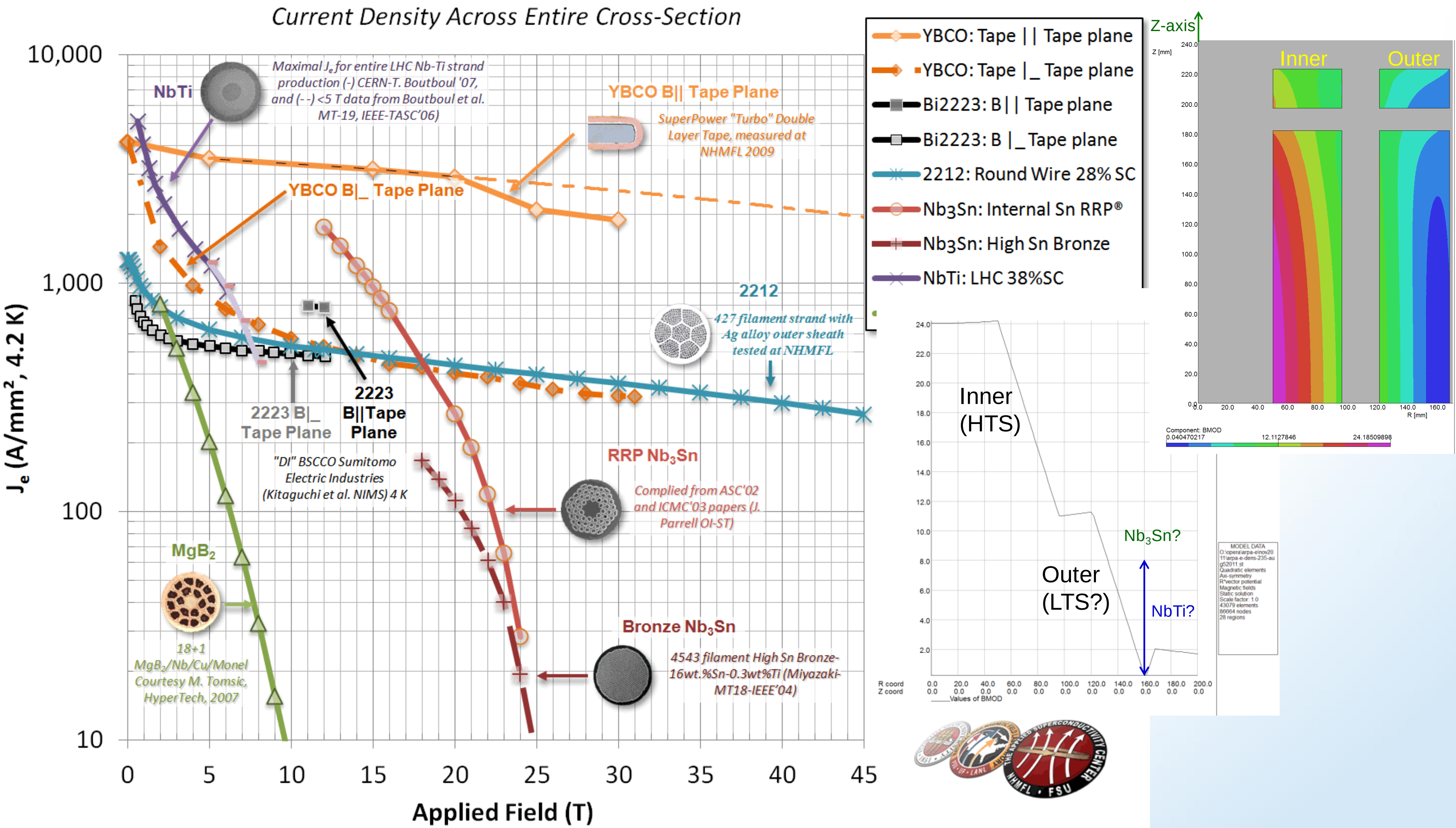
- **What if we use the same amount of conductor and make (a) demo device longer and (b) make second coil with smaller radius to go as insert instead of making with larger radius to go as outsert?**

- **We get 22.5 T**

  ... close but not 24 T that we promised



Conductor Choices

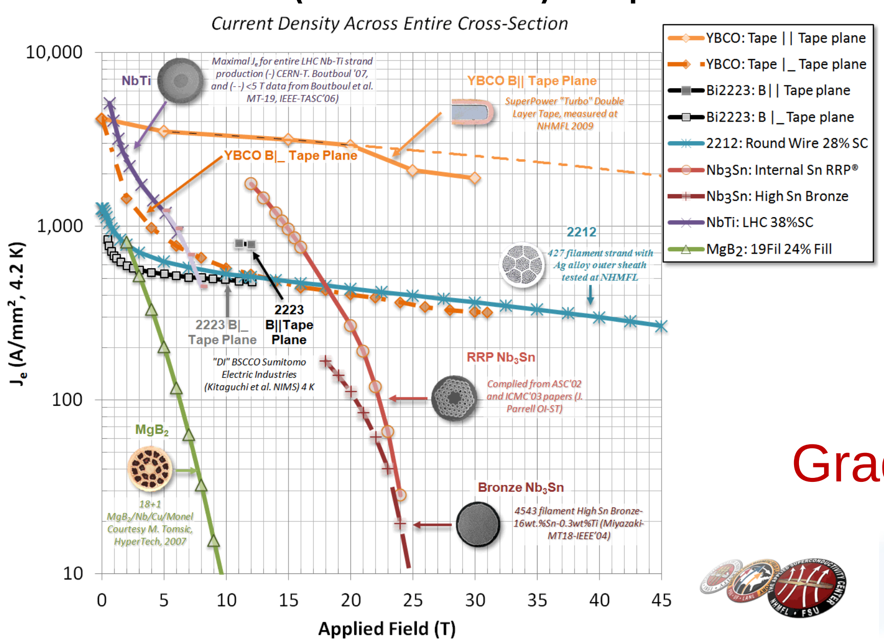


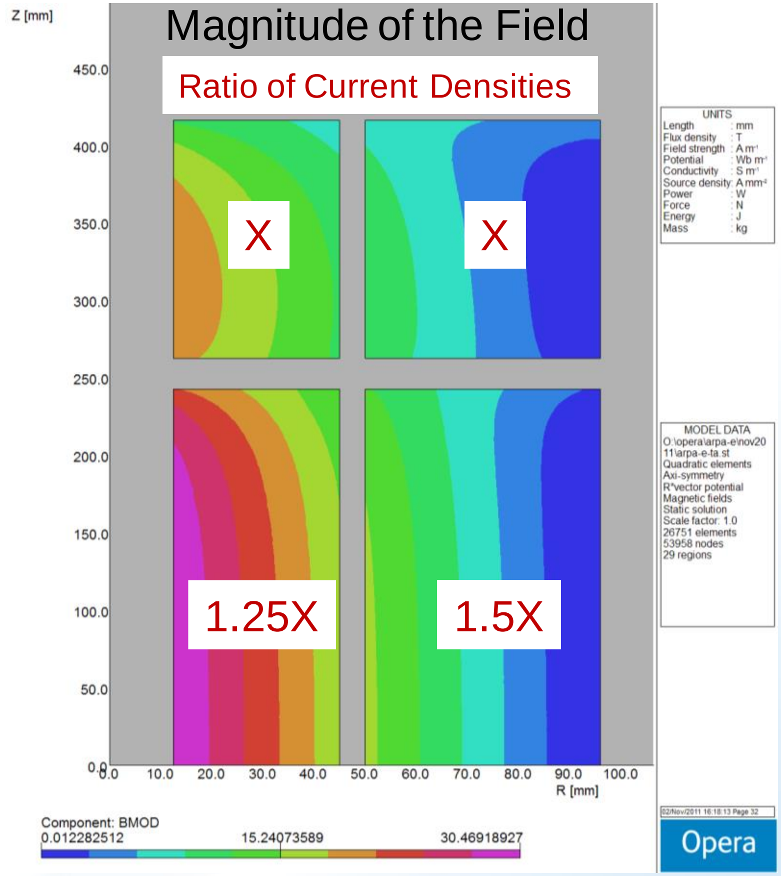
HTS must be used in high field regions. But cheaper NbTi/Nb_3Sn become more attractive in low field regions.

Possible Scenario

Grading to Make SMES Demo Coils with Field up to 30 T

- Considering grading: means use higher current density where the field is low or more parallel, i.e. where the conductor is under-utilized (without grading ~22.5 T).
- Grading increases the field (hence stored energy) while reducing the amount of conductor (hence cost) required.



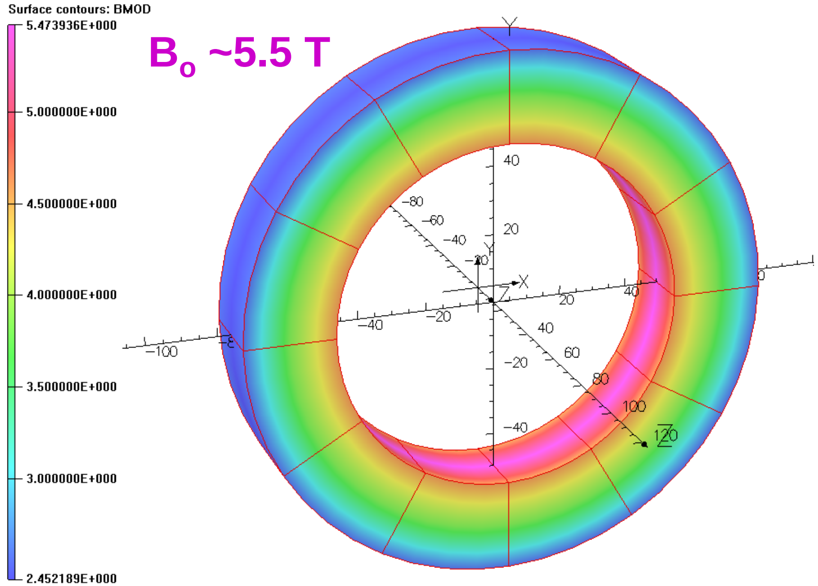


Grading may be obtained with:

- ➢ different width of tapes (real system)
- ➢ different power supplies (demo system)

New HTS SMES goal in a range of 24-30 T (TBD)

Parameters and Field in GO/NOGO COIL at 1140 A



Coil Parameters:

- Coil i.d./o.d. = 100/153 mm
- Coil width = ~26 mm
- Number of turns = 250
- Length of HTS wire used= ~110 m
- Conductor thickness = ~165 micron
- Insulation (SS) thickness = ~50 micron