BNL Magnet Division Tasks

- **Develop a magnetic and mechanical design of a 2.5 MJ HTS Coil**
- **Develop a quench protection system to protect these HTS coils**
- **Build and demonstrate a ~24 T, ~100 mm aperture HTS solenoid**

- **This is a significant undertaking. Nothing close to this has ever been done before**
  - ➢ **A truly high risk, high reward project.**
- **It is important to understand the challenges and develop a systematic and logical R&D program consistent with the budget - right from the beginning.**

Acknowledgements

2.5 MJ, 24 T HTS SMES solenoid is a very demanding and high risk device (just what arpa-e wanted). Successful outcome requires guidance from a number of experts. Following have made key contributions to project already:

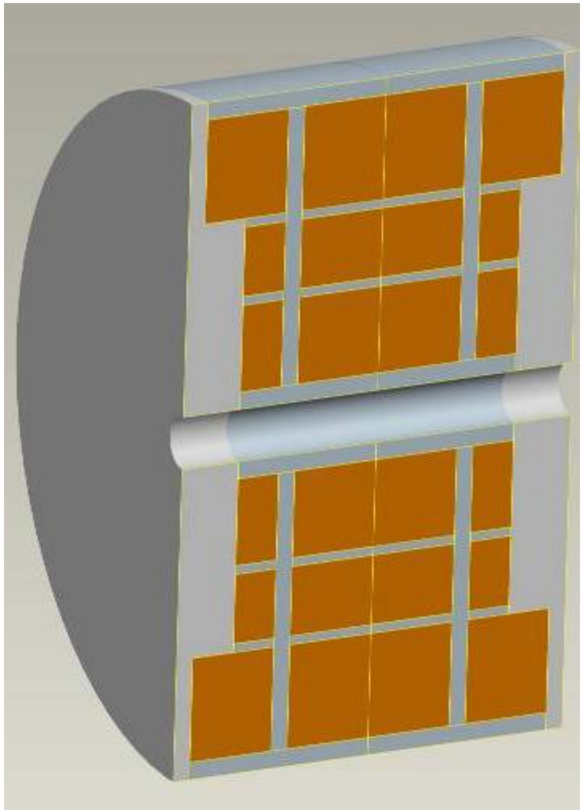
- M. Anerella (Mech Eng)
- F. Teich (Mech Tech)
- G. Jochen (Mech Tech)
- J. Schmalzle (Mech Eng)
- Lakshmi Lalitha (Post doc)
- Y. Shiroyanagi (Post doc)
- W. Sampson (Scientist)

- P. Joshi (Elec Eng)
- G. Ganetis (Elec Eng)
- J. D'Ambra (Testing and Cryo Tech)
- S. Dimaiuda (Elec Tech)
- R. Meier (Elec Tech)
- P. Wanderer (Division Head)
- S. Kahn, Muons, Inc. (Scientist)

Plus me (scientist) and help from several other scientific, engineering, technical and administrative staff

Demo Device

Overall Design of the Demo Device



- A high field (~25 T) magnetic design to give desired stored energy
- Minimize perpendicular component of the field that limits the conductor and hence magnet performance
- A segmented mechanical structure to minimize accumulation of large Lorentz forces
- A magnetic structure that can be developed into an engineering design that can be assembled together with reasonable effort
- Incorporate quench protection scheme in the coil design, right from the beginning

We have reduced radial segments from three to two to simplify and reduce cost. It also reduces stress and strain on the coils and in the support structure.

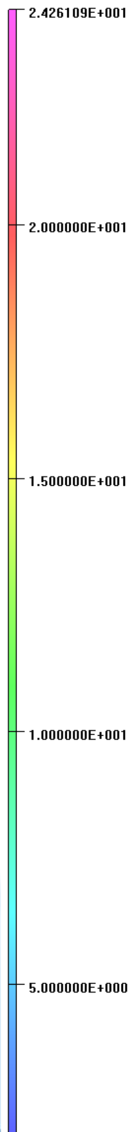
Conductor Specifications

BNL and SuperPower had a lengthy and involved discussion on arriving at conductor specifications for SMES demo device.

Following are the agreed specifications:

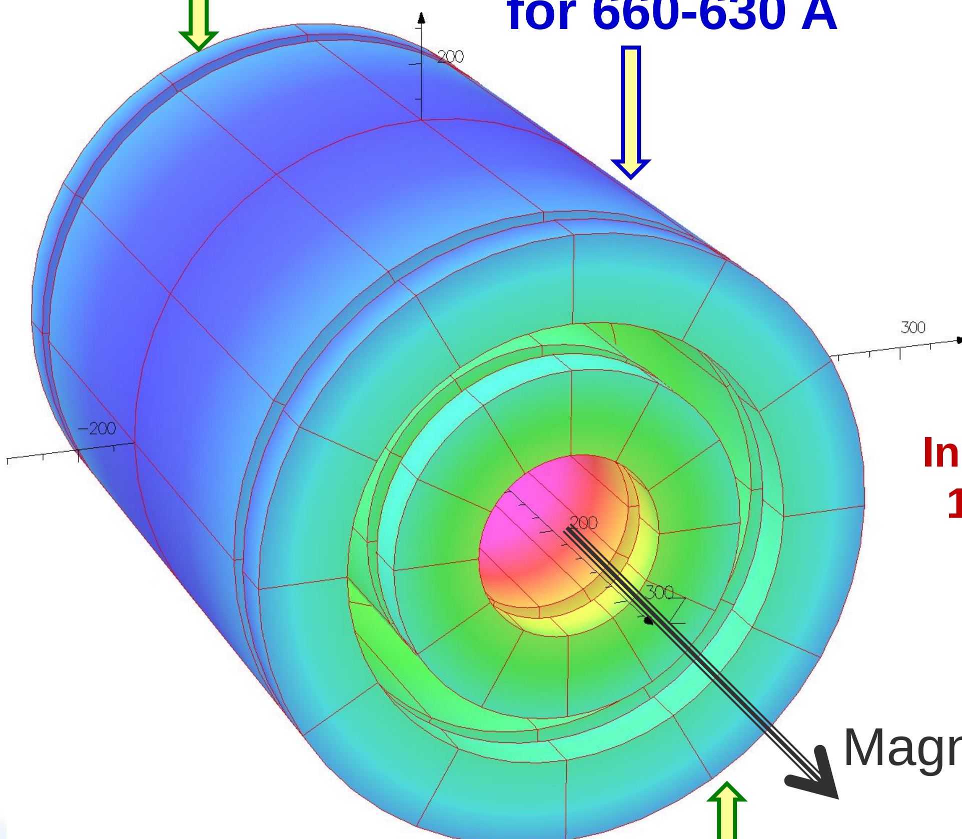
- Min I_c = 700 A at 8 T (in any direction)
- Conductor will be provided in 200 meter length (initially with a maximum two splices but the number of splices are expected to be reduced over time)

Basic Magnetic Design of 2.5 MJ Coil



2 pancakes

28-32 pancakes for 660-630 A



Magnet axis

2 pancakes

Field superimposed on coil (Bmax ~24T)

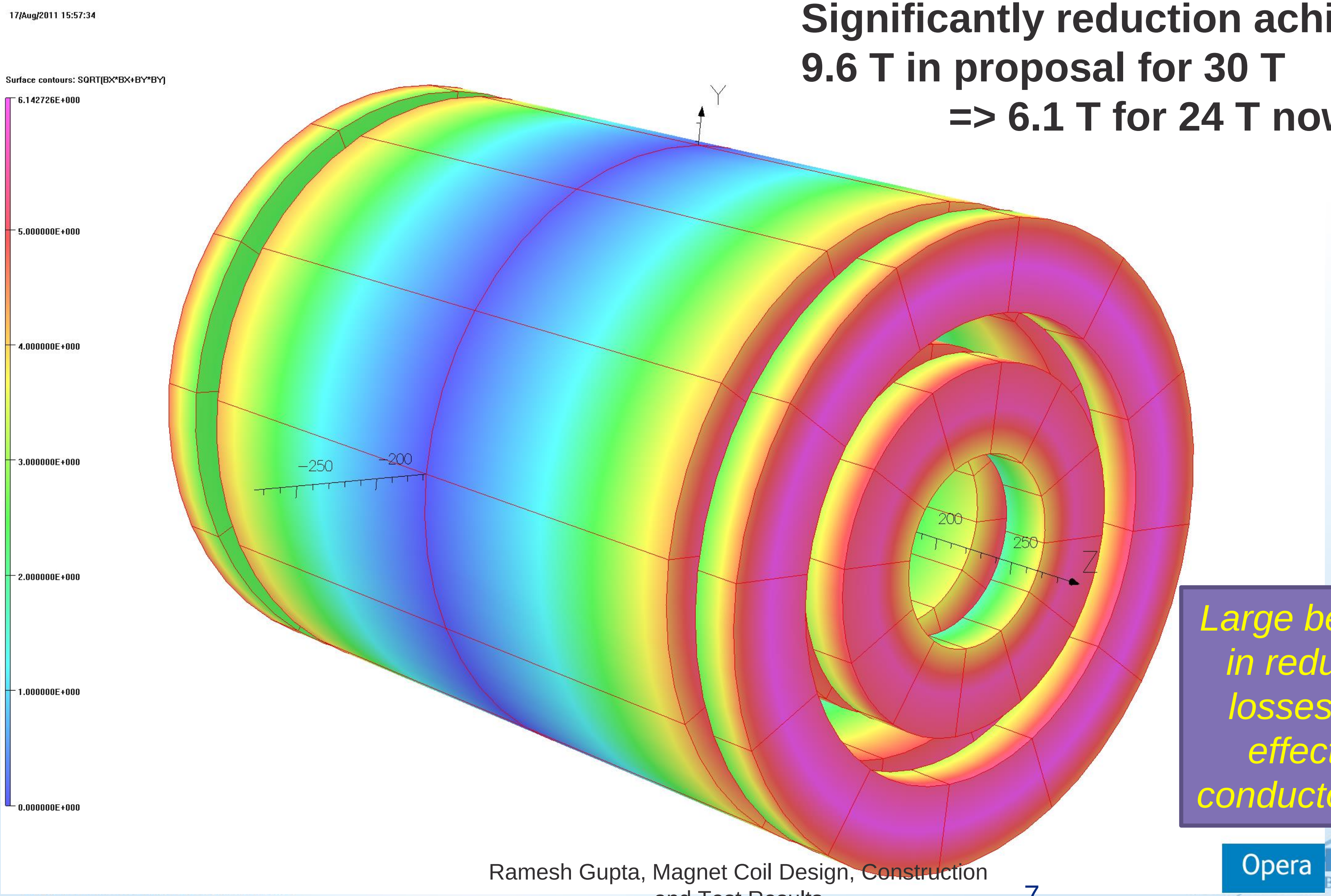
Inductance: 11-12 Henry

Magnet axis

2-d axi-symmetric model

Perpendicular Component of the Field

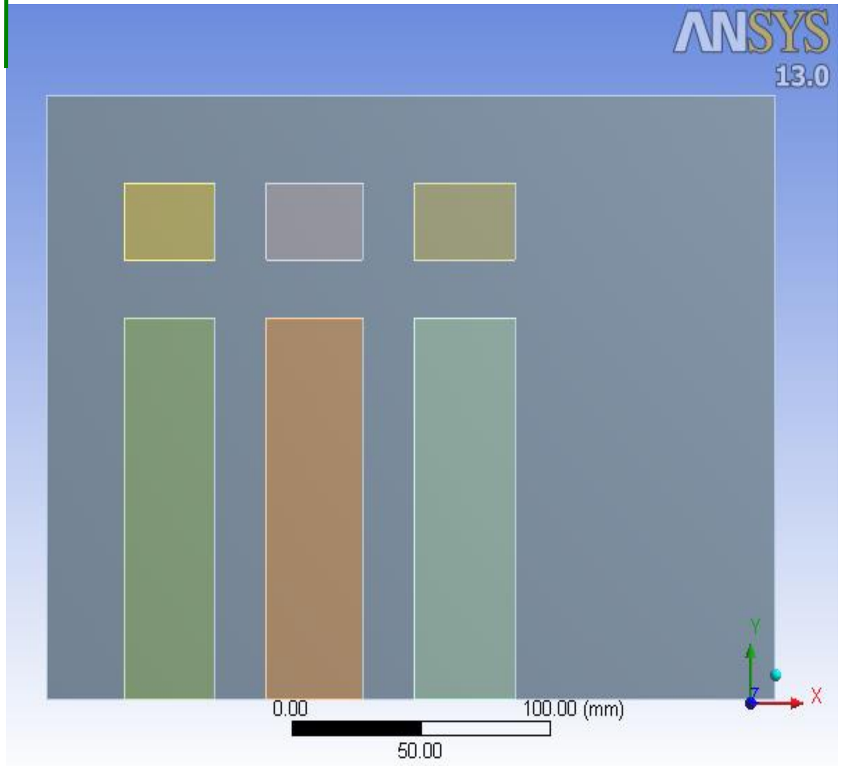
Significantly reduction achieved:
9.6 T in proposal for 30 T
=> 6.1 T for 24 T now



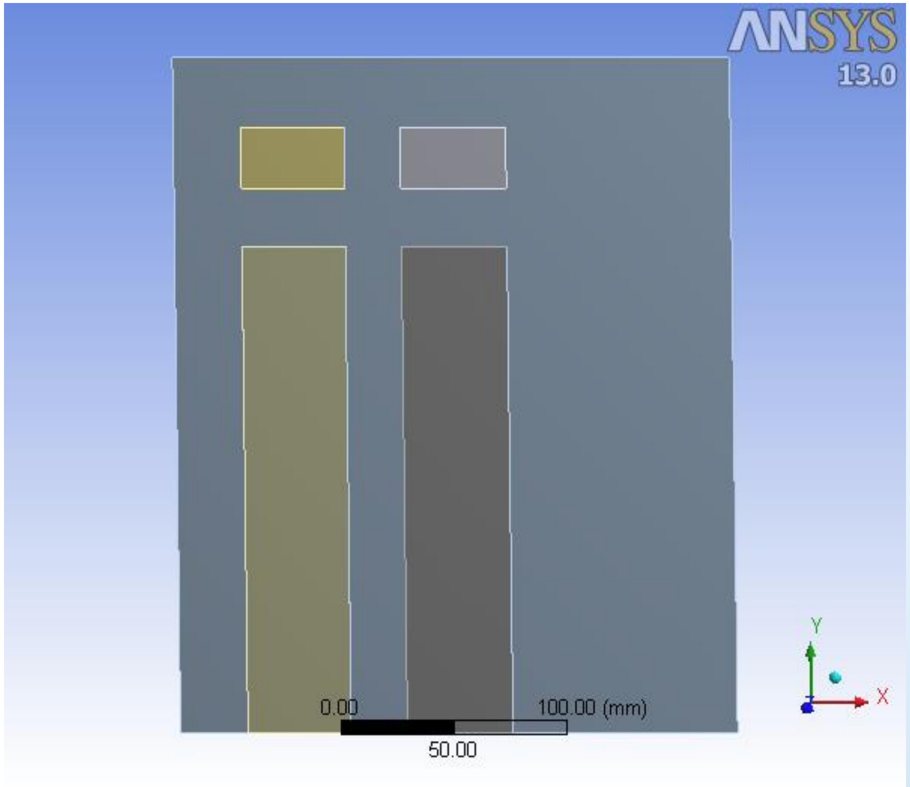
Large benefits in reducing losses and effective conductor cost

Mechanical Analysis

Line of symmetry



3 radial blocks



2 radial blocks

We preferred 2-radial block design

Courtesy: S. Lakshmi

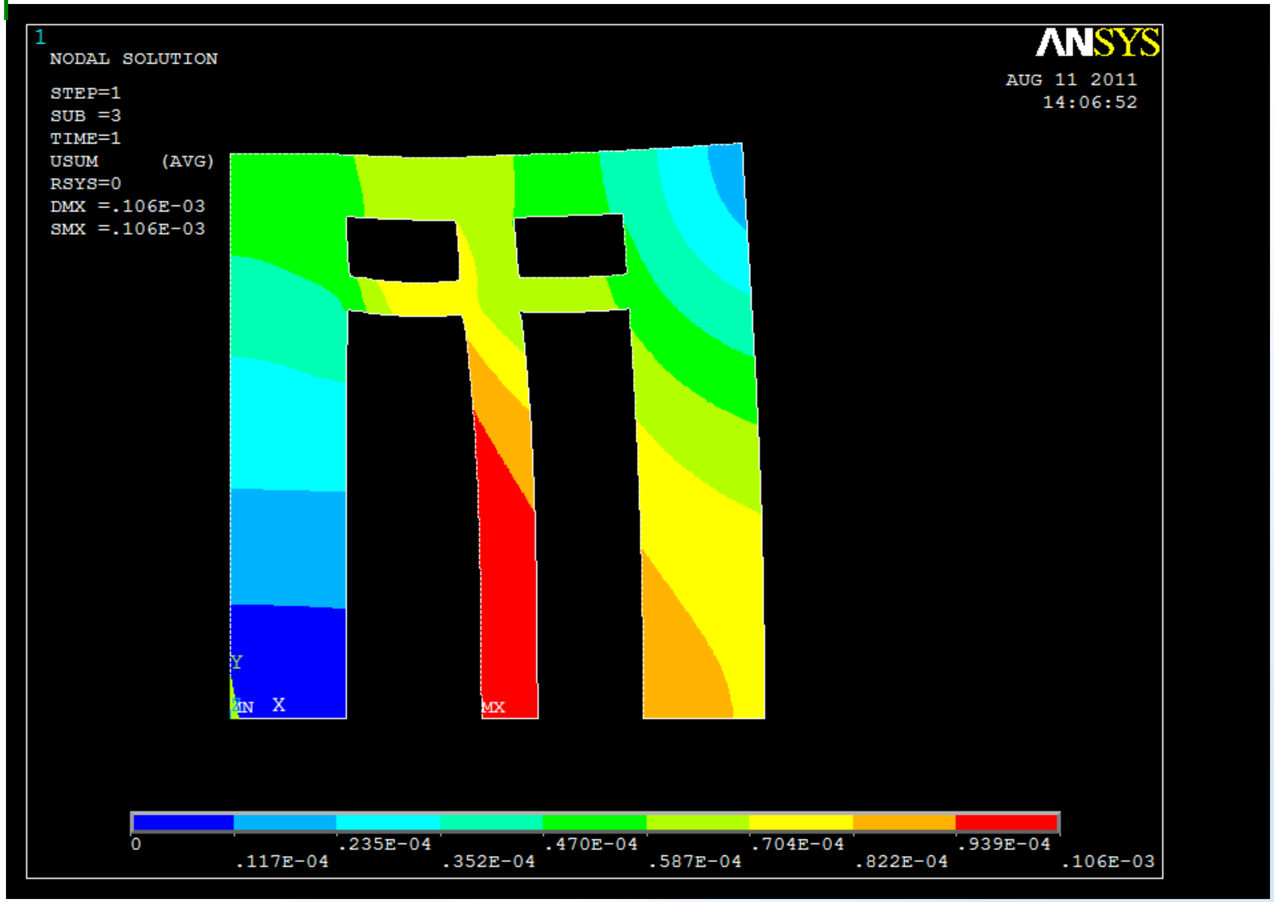
Mechanical Analysis with Solid SS Structure (optimistic)

Line of symmetry

Deformation in SS structure shown (coils hidden)

Deformation in SS ~110 micron

Courtesy: Steve Kahn, Muons, Inc.



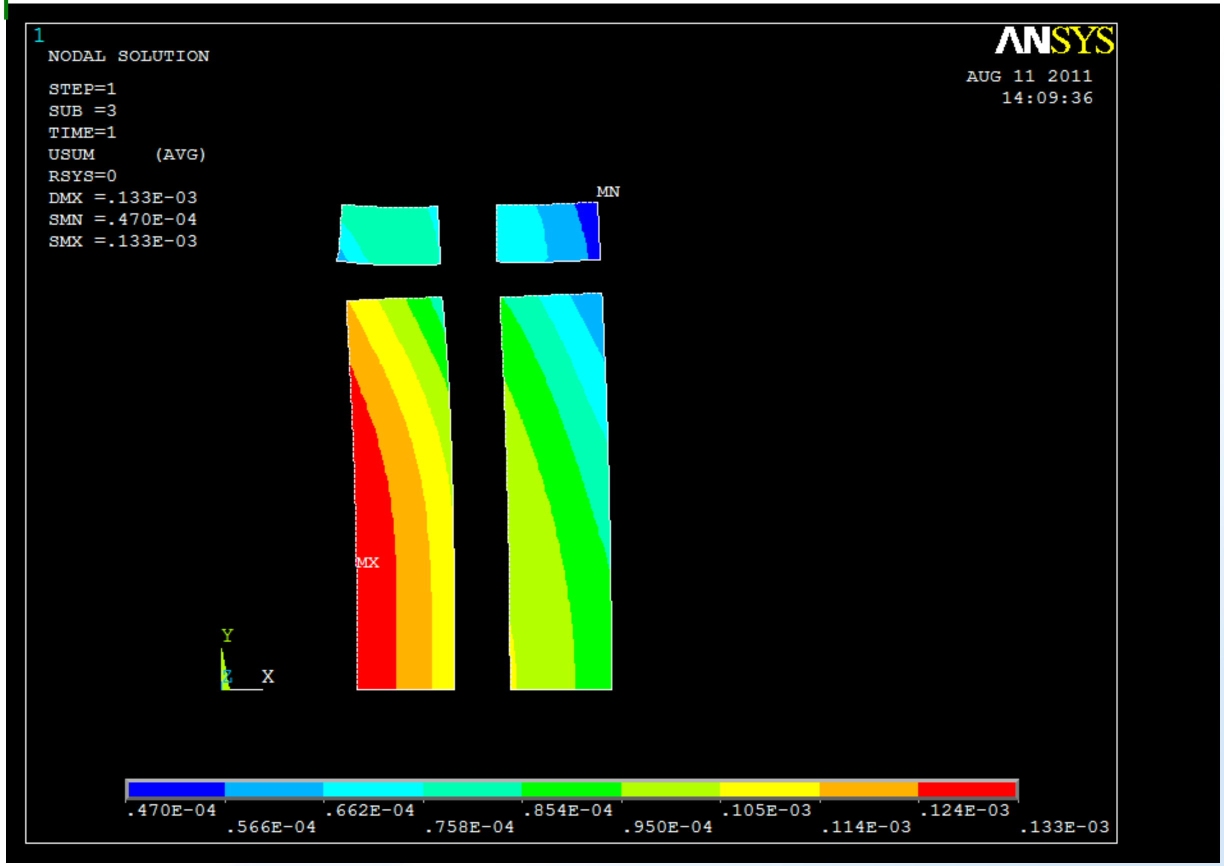
Will be higher in the actual structure made up of several components. However , it is well below the target of 200 microns.

Mechanical Analysis with Solid SS Structure (optimistic)

Deformation in coils shown (SS structure hidden)

Deformation in HTS coils ~140 micron

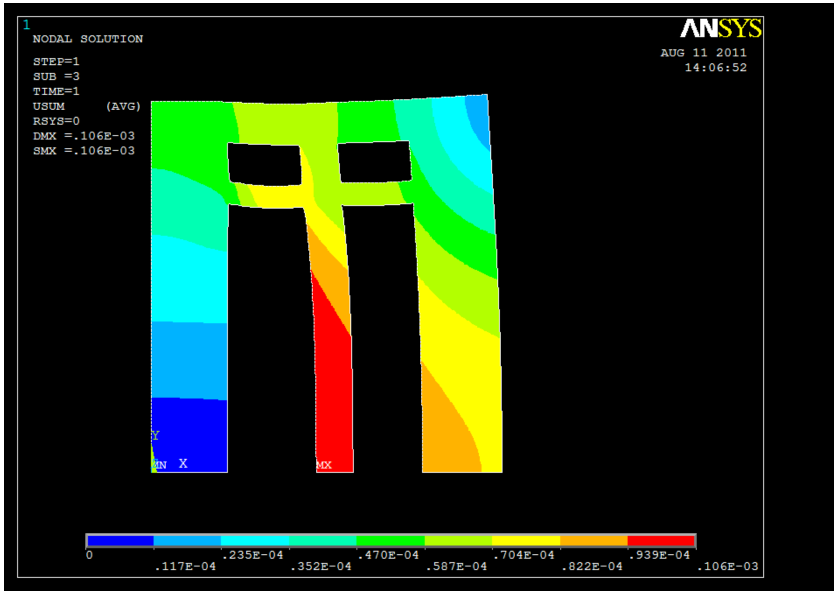
Line of symmetry



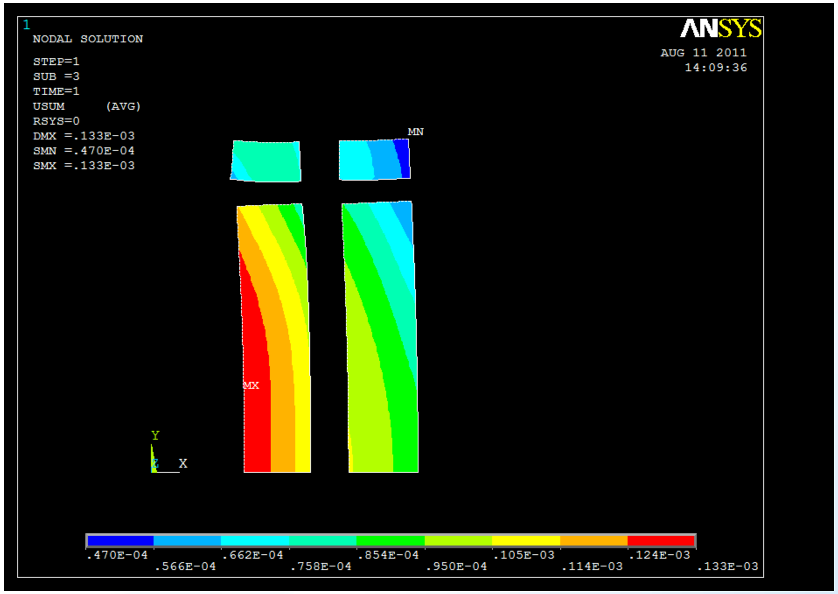
Courtesy: Steve Kahn, Muons, Inc.

Mechanical Analysis with Solid SS Structure (optimistic)

Deformation in SS ~110 micron



Deformation in coil ~140 micron

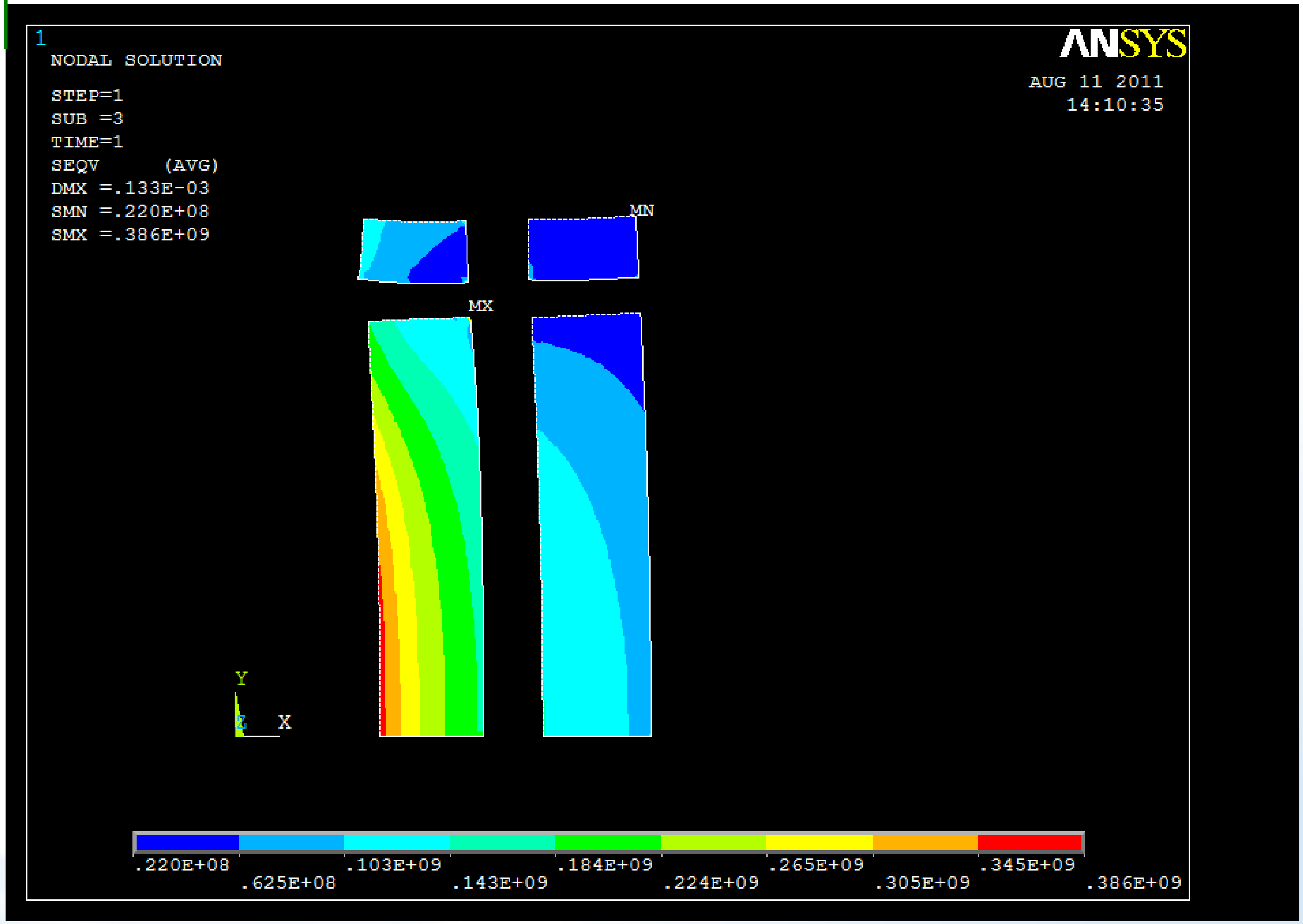


Will be higher in the actual structure made up of several components. However , it is well below the target of 200 microns.

Computed Stress in HTS Coil

Line of symmetry

Max stress ~400 Mpa (acceptable)



Significant Reduction in Magnetization Losses

- Based on certain models, there has been a significant concern about the magnetization loss.

- ~0.4 T in the 2GJ system instead of ~10 T in the design in proposal, means that the magnetization loss issue now becomes a non-critical issue.

Construction and Test Results

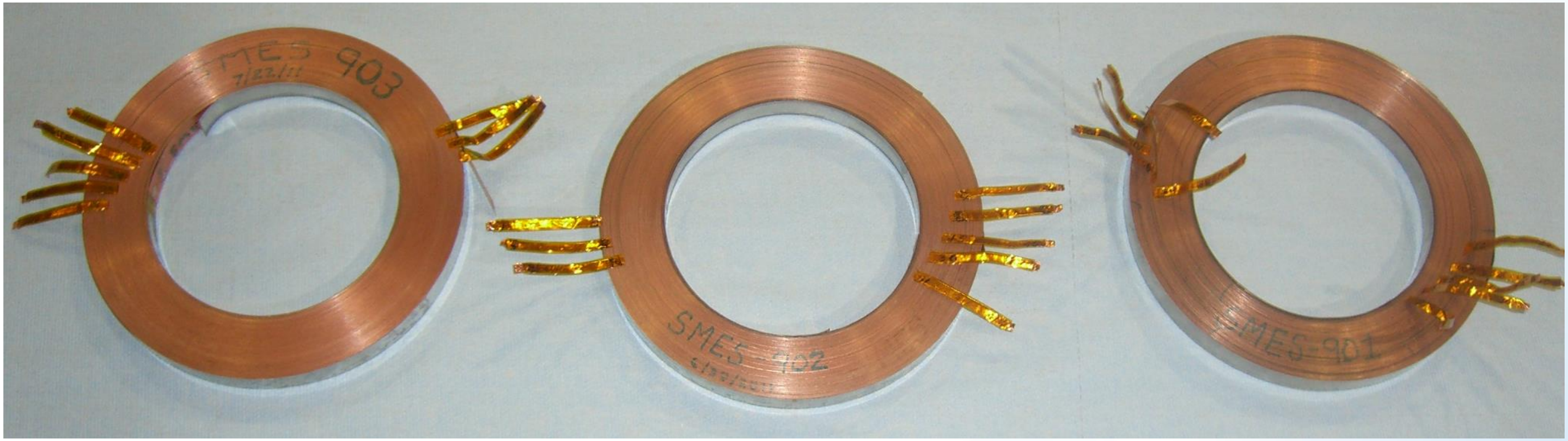
Test Plan for Quench Protection

- We are developing a novel quench protection system (most advanced ever and radically different from previous one).
- This system will detect very small resistive signal in presence of large noise.
- Initial plan was to build and test a double pancake coil at 77 K that reaches ~100 A and perform a quench detection and protection test.
- We decided to do a more demanding quench protection test at 4 K early on with current in coil reaching 700 A.
- This required development of high current test set-up much earlier than originally planned.
- Thus we put our basic quench protection system for 2 coils to most demanding requirements now. We are doing it before we multiply this system for 36 coils.
- In our opinion, this is the best way to deal with an item that is rated at the highest risk level. We want to do every thing we possibly can to protect an expensive coil.

SMES R&D Coils

SMES R&D coils for addressing critical questions early on

• These coils have a large number of voltage taps for detailed studies.

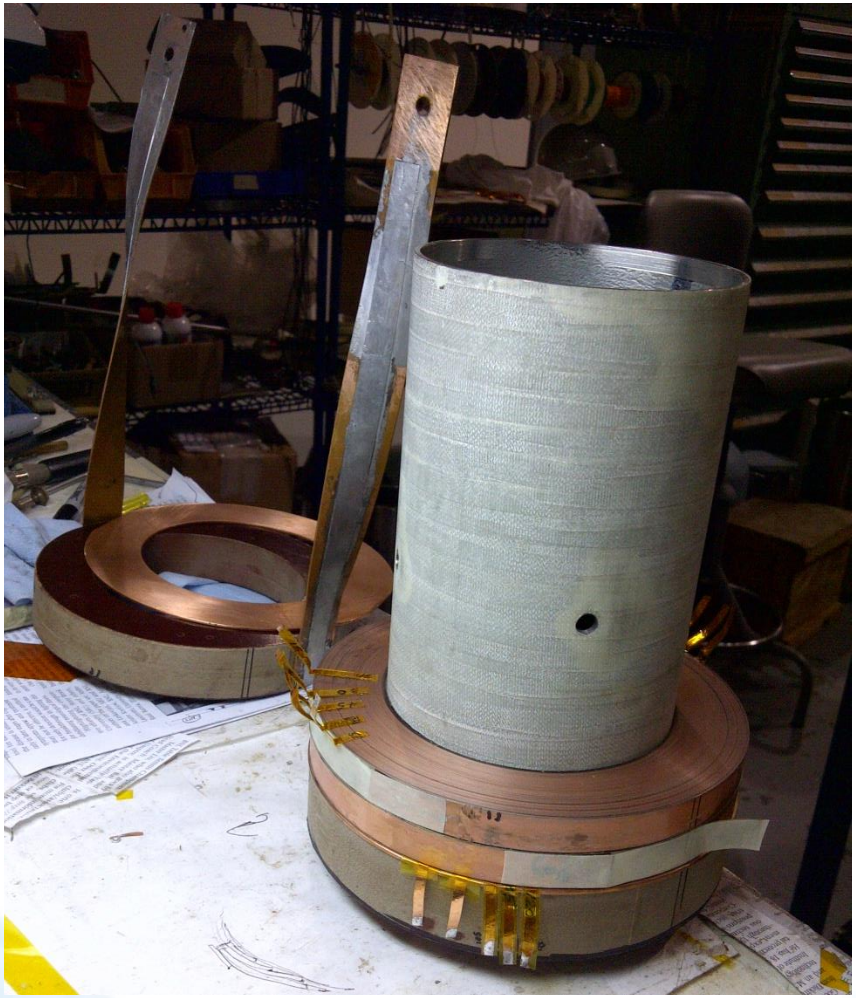


• Coil #2 and #3 are identical (made with the same conductor and stainless steel insulating ribbon and are being used in the double pancake coil test.

• These are single pancake coils and would require a joint at inner radius.
• We are also planning to wind a double pancake coil that avoids this joint.

Two coils Being Prepared for Test with Internal Splice

Preliminary Test Results of the Double Pancake Coil



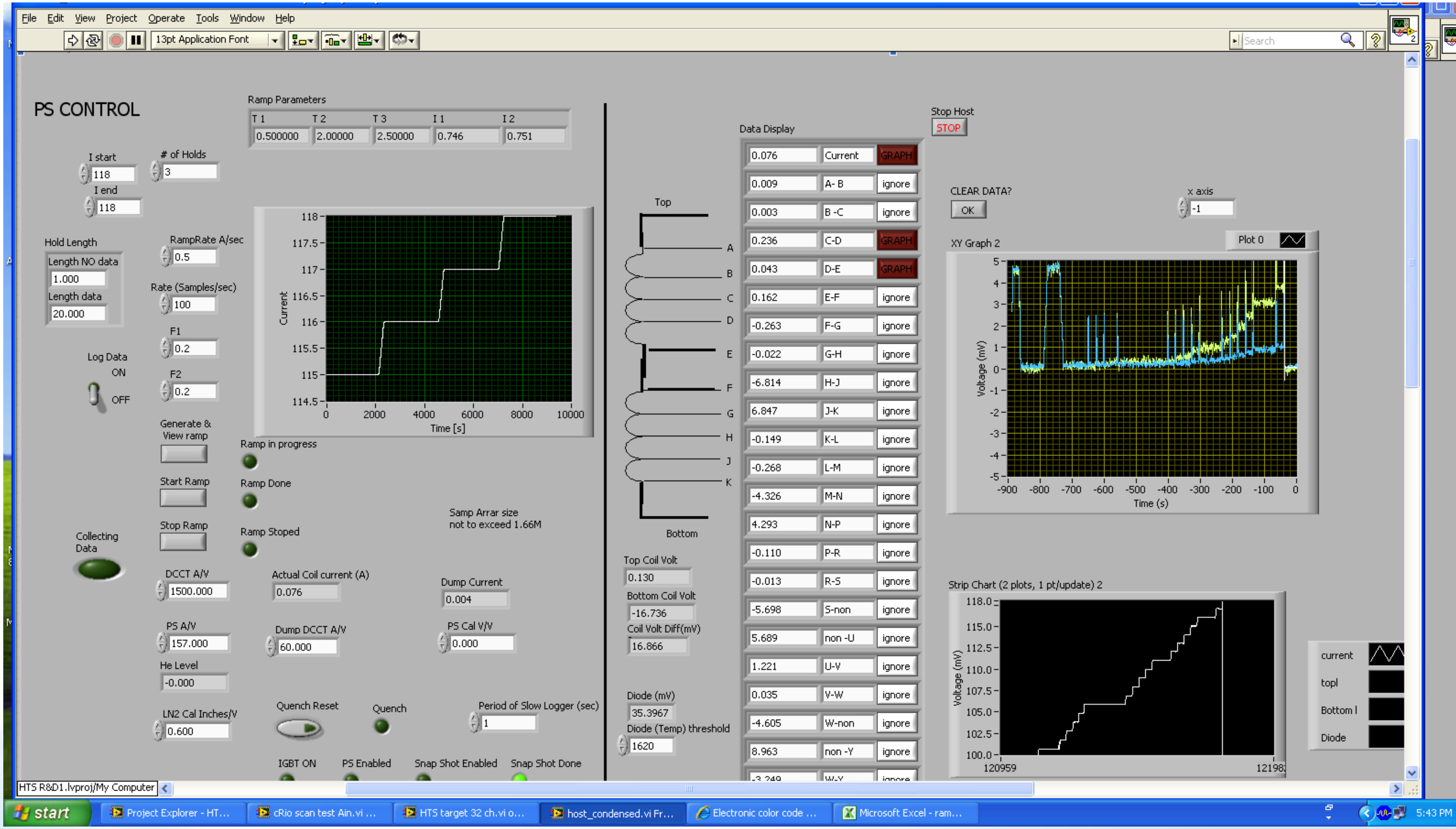
- The coil was tested at 77 K with our previously working standard system
- Performance was good. Critical current was limited by inner turns, as expected, where the field is highest.
- The coil reached over 114 A

➢ Able to protect the coils @77 K; <5 mV milestone achieved (next talk)

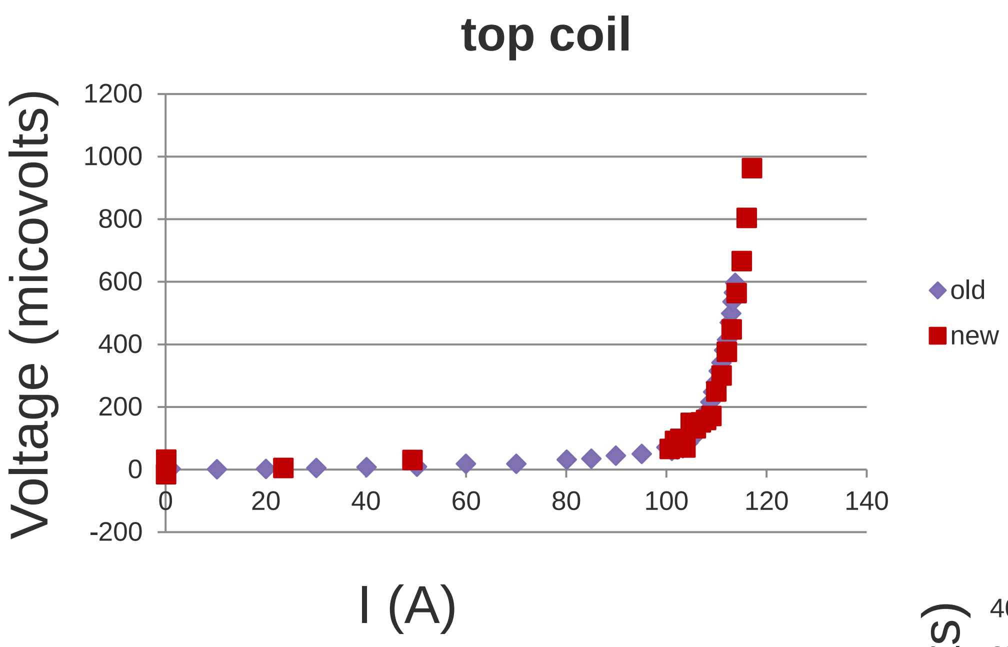
Next Step:

- Do complete system test (including driving the coil, data acquisition, quench protection, etc) with full setup at 77 K
- Do above tests with new setup at 4 K – confirm that system is able to protect the coils at high currents (up to 700 A).

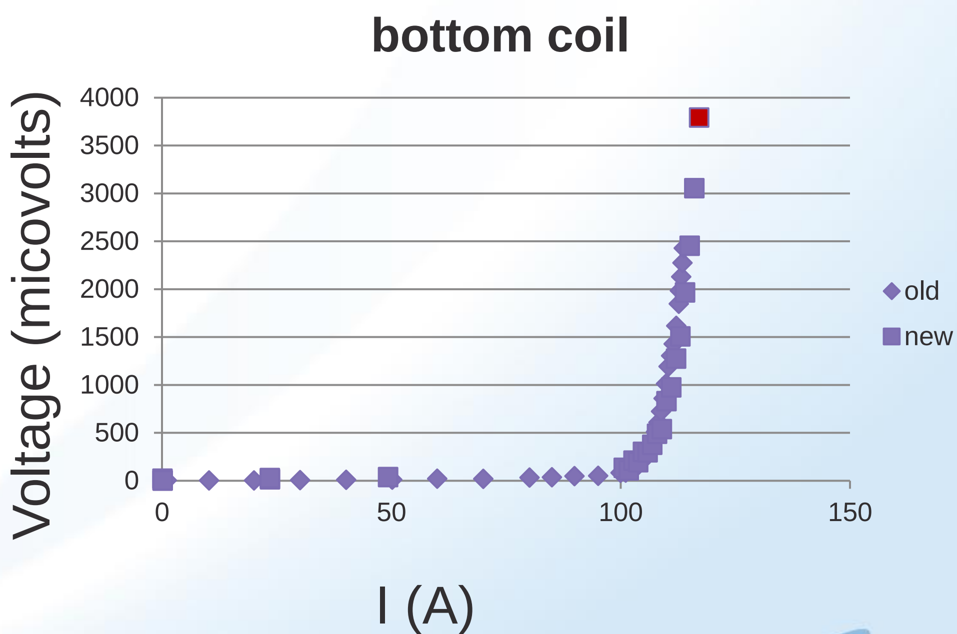
New Console for Quench Protection and Data Acquisition (LabView based)



Test Results (Full Coil)

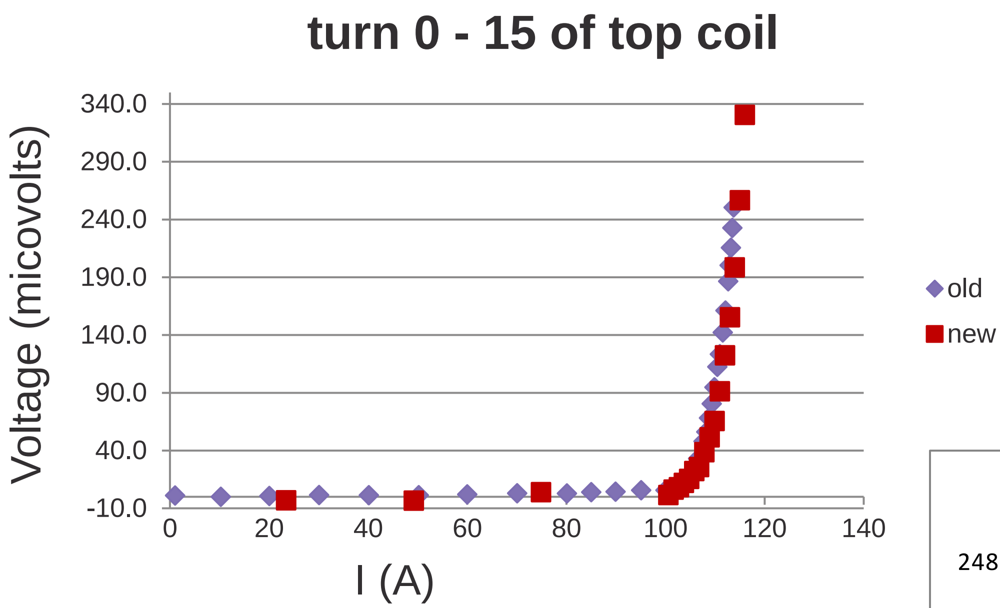


- **Old system has a proven high resolution low noise voltmeter.**
- **These results show that new system is as good in performance as earlier one.**



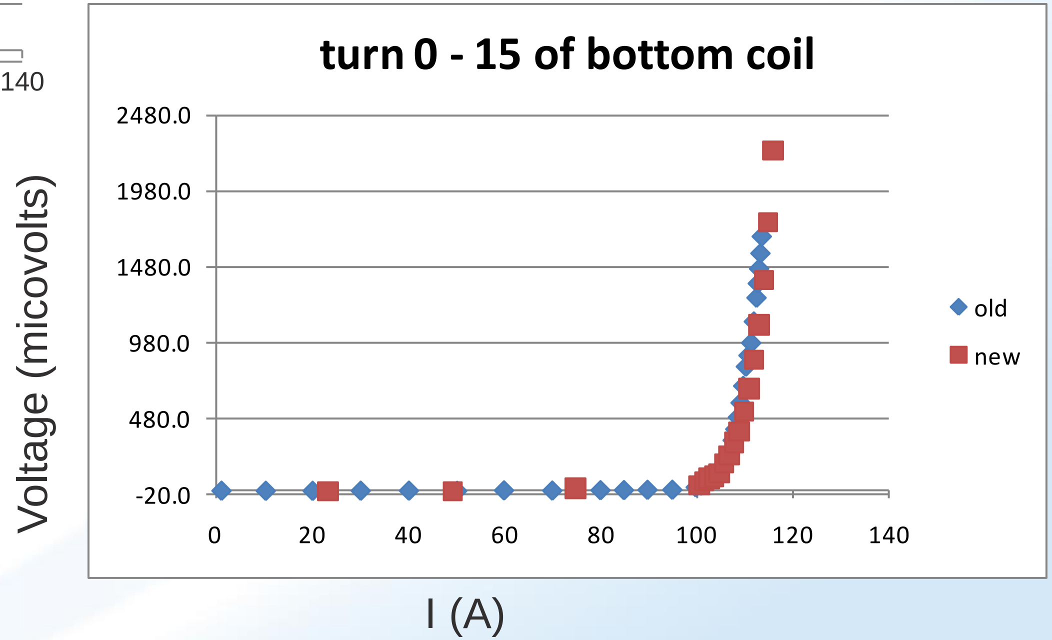
- **New system has modern control , data acquisition and new quench detection system.**
- **Two coils, made with the same conductor, are slightly different (see Piyush's presentation)**

Test Results (High Field Turns)



• Old system has a proven high resolution low noise voltmeter.

• These results show that new system is as good in performance as earlier one.

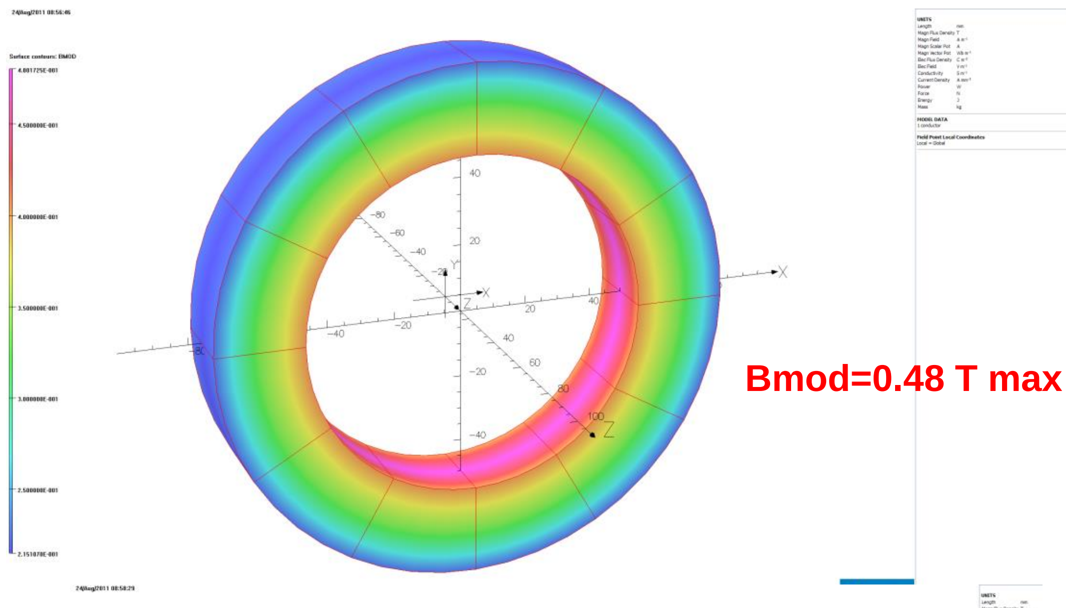


• New system has modern control , data acquisition and new quench detection system.

• Two coils, made with the same conductor, are slightly different (see Piyush's presentation)

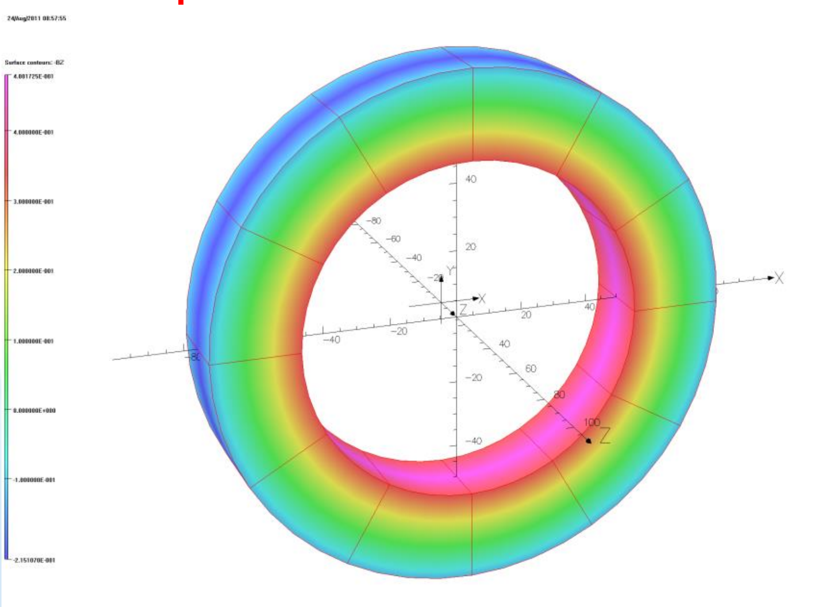
Distribution of Field Across the Double Pancake Coil

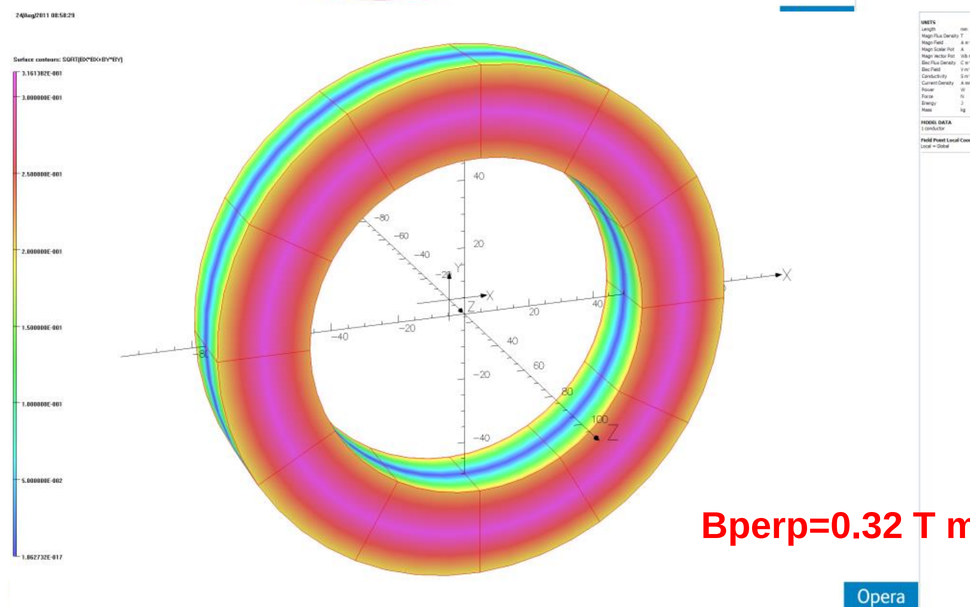
- Computed Field at 100 A
- 125 turns per pancake
- Maximum field at coil i.d.
- Bperp max in the middle (but lower value)



Bmod=0.48 T max

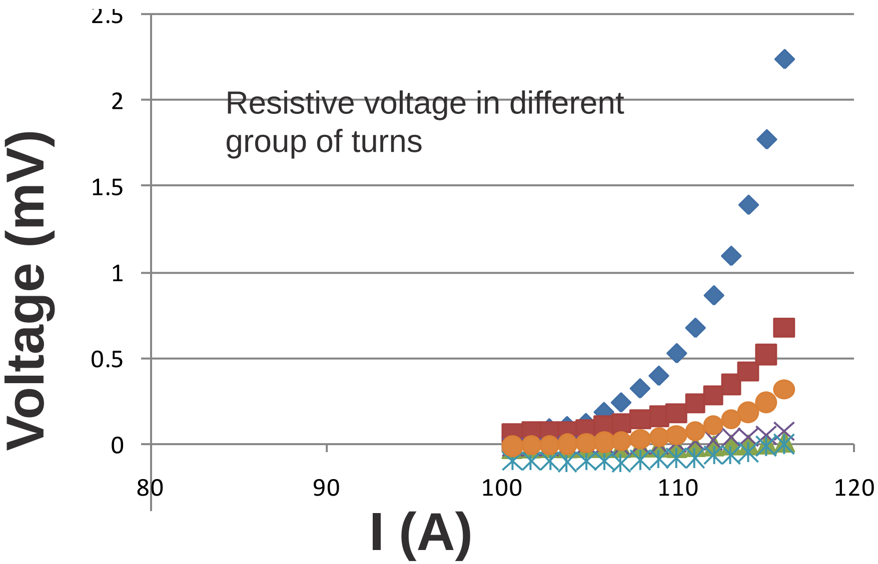
Bpara=0.48 T max





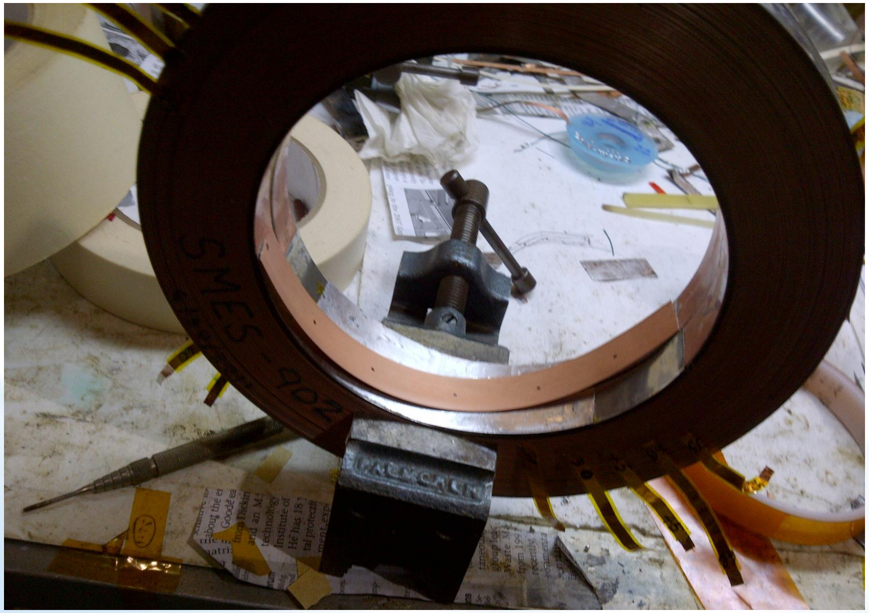
Bperp=0.32 T max

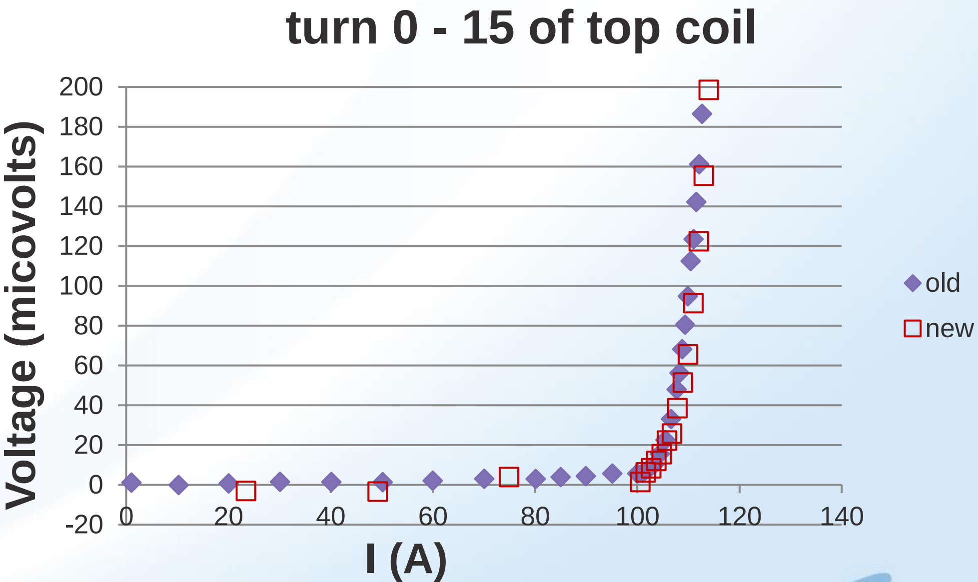
Distribution of Voltage Across the Coil



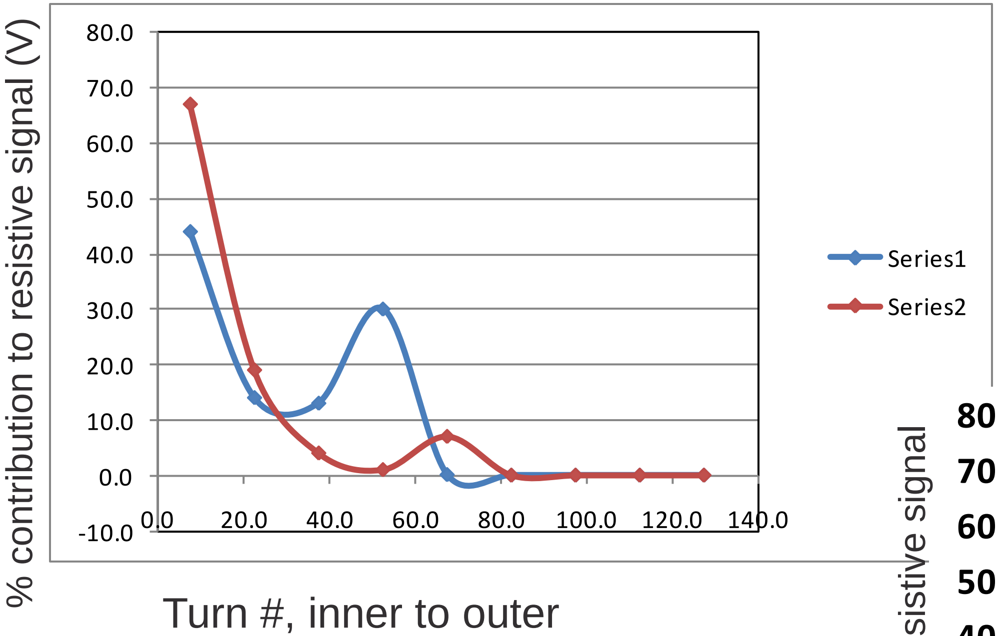
- Turns at coil i.d. have high field and thus would generally be first to show resistive signal.

- Good agreement between old and new system (at μV level).

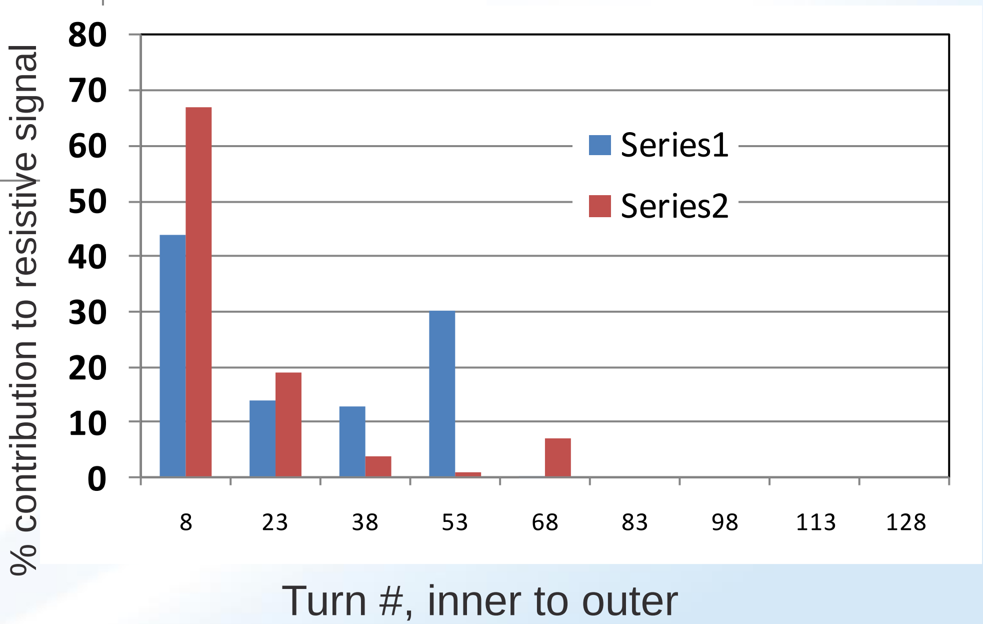




Analysis of the Conductor Used in the Coils



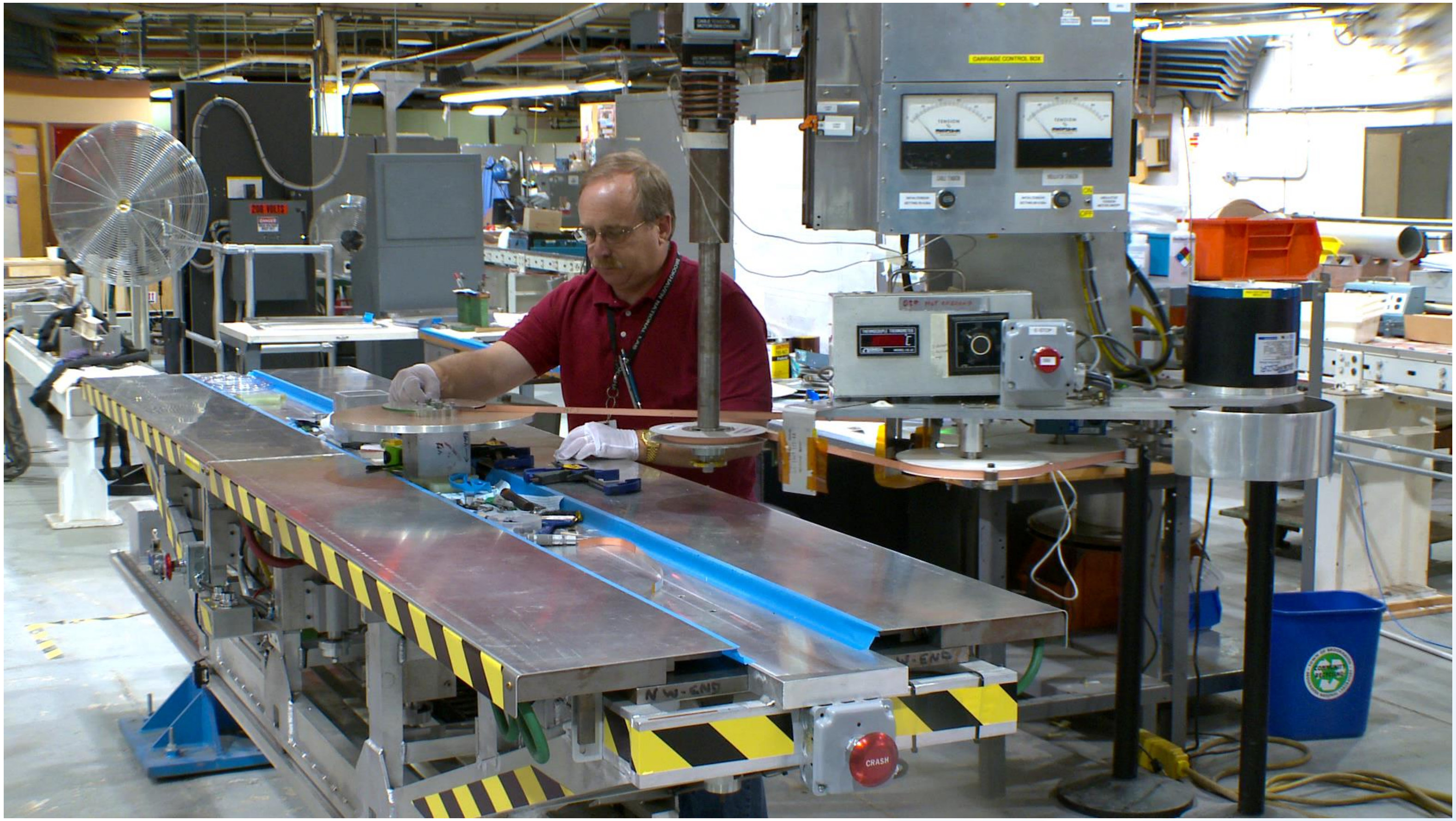
- **Series 1: Lower coil**
- **Series 2: Upper coil**



It will be interesting to see the behavior at 4 K

Related Technologies

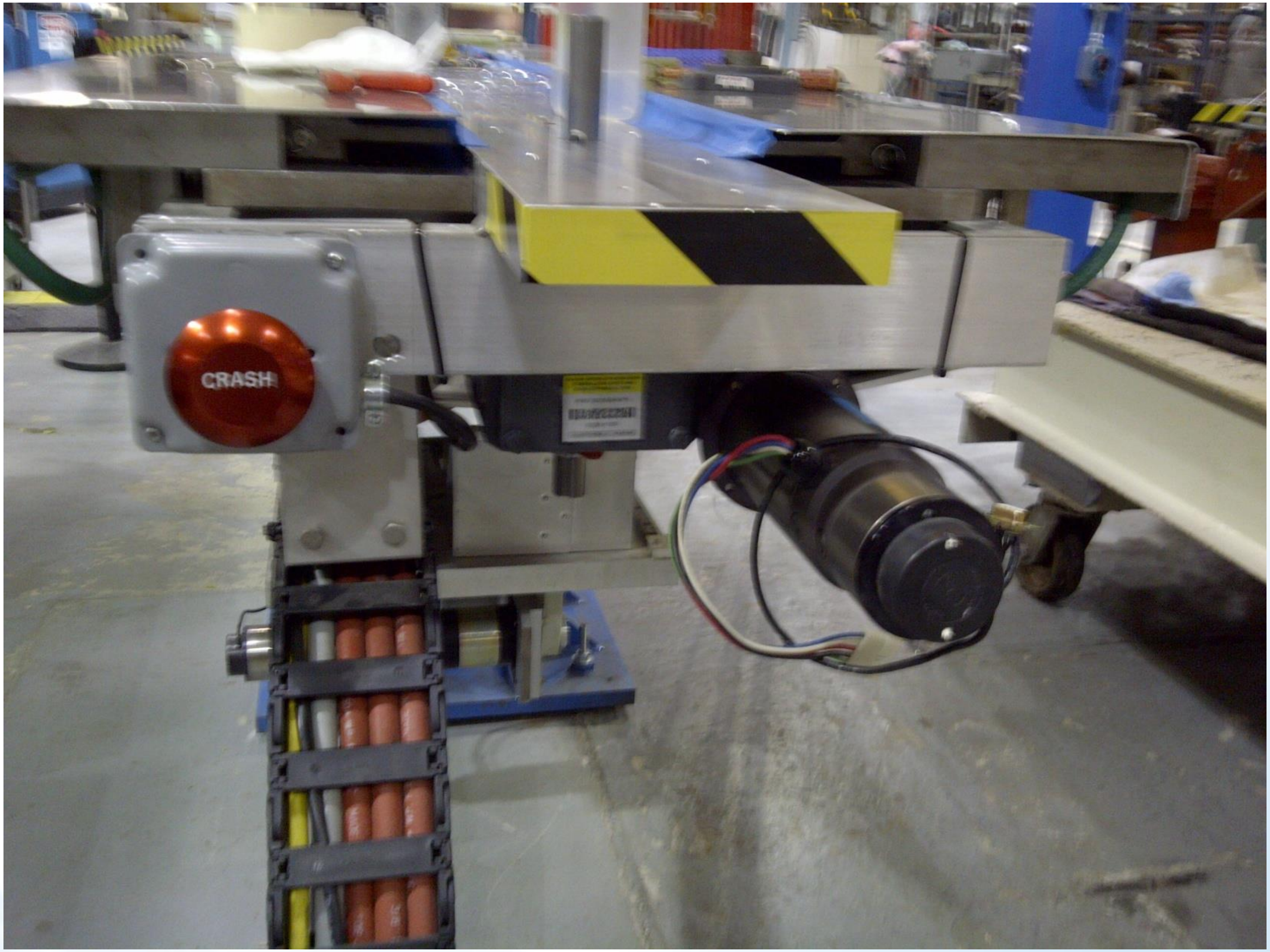
Reducing Winding Costs



• We have a very sophisticated winding machine - too sophisticated for this purpose and it takes several days to a week to make a completed coil.

• We want to simplify it. That will reduce cost and time needed to wind 36 coils.

Status of Simplifying the Coil Winding Tooling for Efficiency



Upgrade of High Current Test Setup Completed




Status of Q3 Magnet Division Milestones

- We have achieved all accelerated Q3 milestones.

Milestone	Status
1. Milestone: Initial quench protection system design complete	Completed
2. Milestone: 1st phase of quench protection. Develop electronics to detect resistive voltage signal < 5 mV despite large inductive and noise voltage.	Completed

Status of Q4 Magnet Division Milestones

- We are well on track for all accelerated Q4 milestones
    - We should complete one next week.
- Additional achievements in low resistance *"coil joint"* area

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.	Next week (completed @77 K)
2. Milestone: Demonstrate a cross-section section design with deflection < 200 micron.	On Track
3. Milestone: Magnet design complete to produce coil with 2.5 MJ stored energy	On Track
4. Milestone: Tooling Design.	On Track

Remaining Magnet Division Tasks

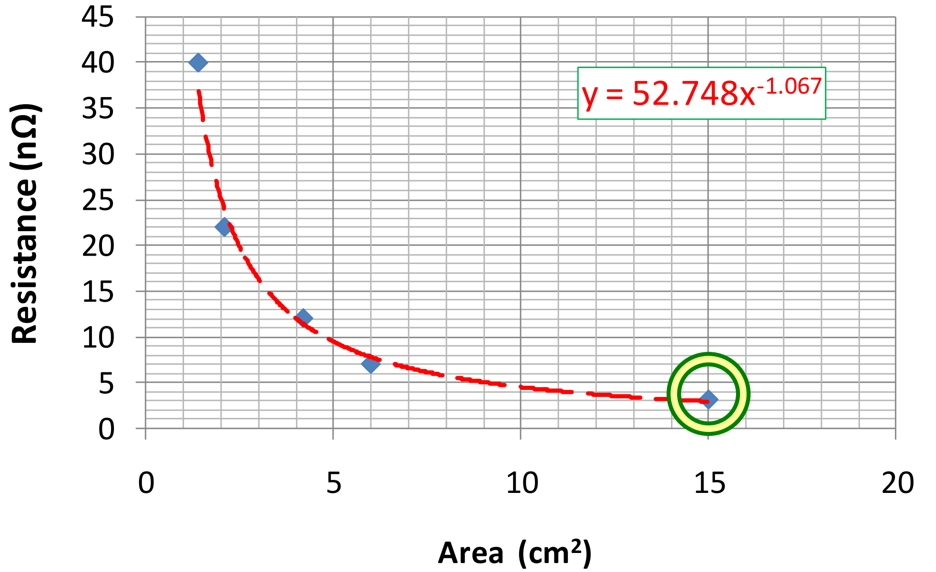
- Complete magnetic and mechanical design
- Complete engineering design
- Complete quench protection analysis of the coils and decide on the protection scheme
- Complete construction of coil winding tooling
- Complete development of advanced quench protection hardware
- Incorporate low resistant splice with the coils
- Construct 32/36 coils with intermediated support structure and number of splices
- Construct double pancake pairs and do intermediate testing of the coils
- Construct and test 10 T magnet for GO/NO GO milestone
- Construct 24 T magnet with advanced support structure

Summary

- 2.5 MJ, 24 T large aperture all HTS solenoid is perhaps the most ambitious such magnet ever proposed.
- We have a well defined plan in action with a team of world class engineering, scientific and technical staff in place.
- We have met all accelerated milestones.
- A large number of tasks are yet to be completed. However, the test results and design analysis performed indicate that so far we have been meeting all goals.

Back-up Slides

Joint Resistance As a Function of Area



Simulation of splice between two coils

Simulation of splice joint within coil