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U.S. DEPARTMENT OF ENERGY

HTS Magnet R&D Program at BNL

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Key Technical Areas of the Updated MDP Plan at BNL

- **7-8 T all HTS dipole with significant volume (stored energy)**
  - ➢ Take advantage of the existing large HTS coils
- **Flexibility in program for different configurations**
  - ➢ 2-in-1 common coil & single aperture (field parallel & perpendicular)
- **Quench protection of HTS magnets (including cold electronics)**
  - ➢ A major issue in developing HTS magnet technology for accelerators
- **Field quality measurements in HTS magnets**
  - ➢ A major issue in accepting HTS for accelerator quality magnets
- **Study temperature dependent performance of HTS magnets**
  - ➢ Significant discussion on reducing cryogenic and operational cost

✓ Collaboration and contributions welcome

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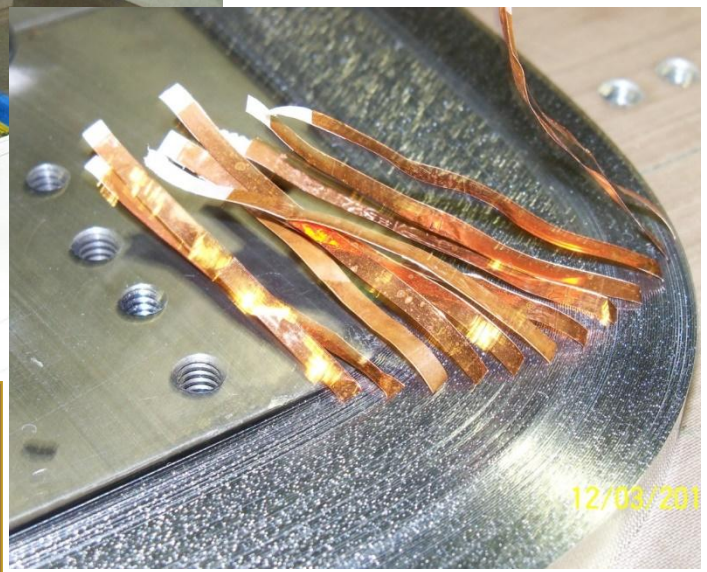
8 HTS Coils for FRIB with the 2nd Generation (2G) HTS Tape

4 coils made with SuperPower Tape

and

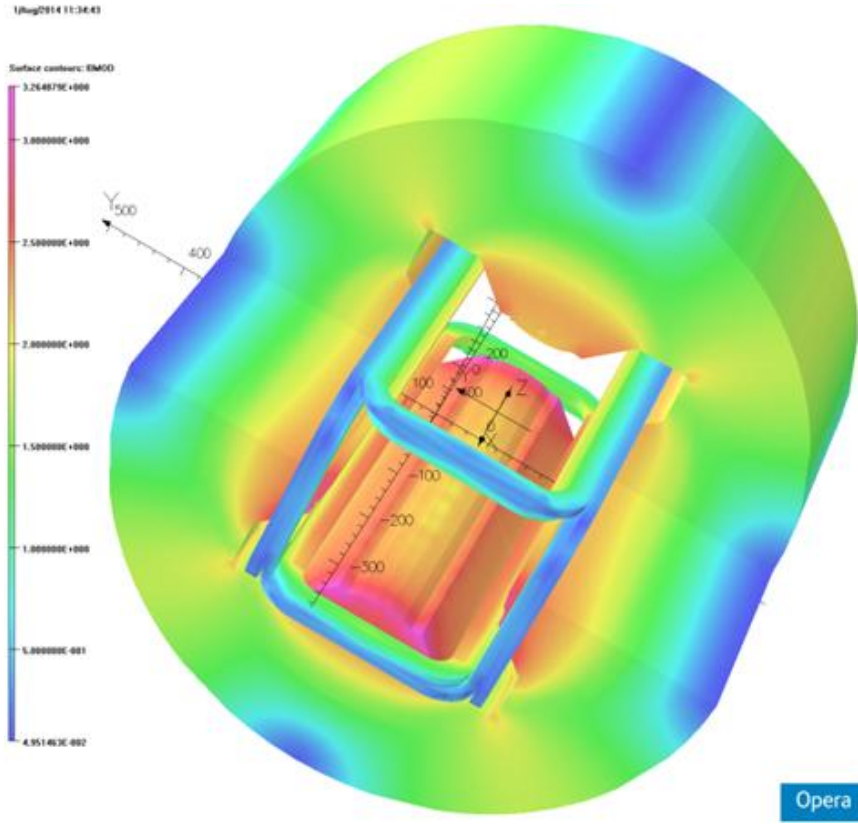
4 coils made with ASC Tape

(~9 km of standard 4 mm equivalent HTS tape used)



Well-instrumented with v-taps

Magnetic Model of the HTS FRIB Quad



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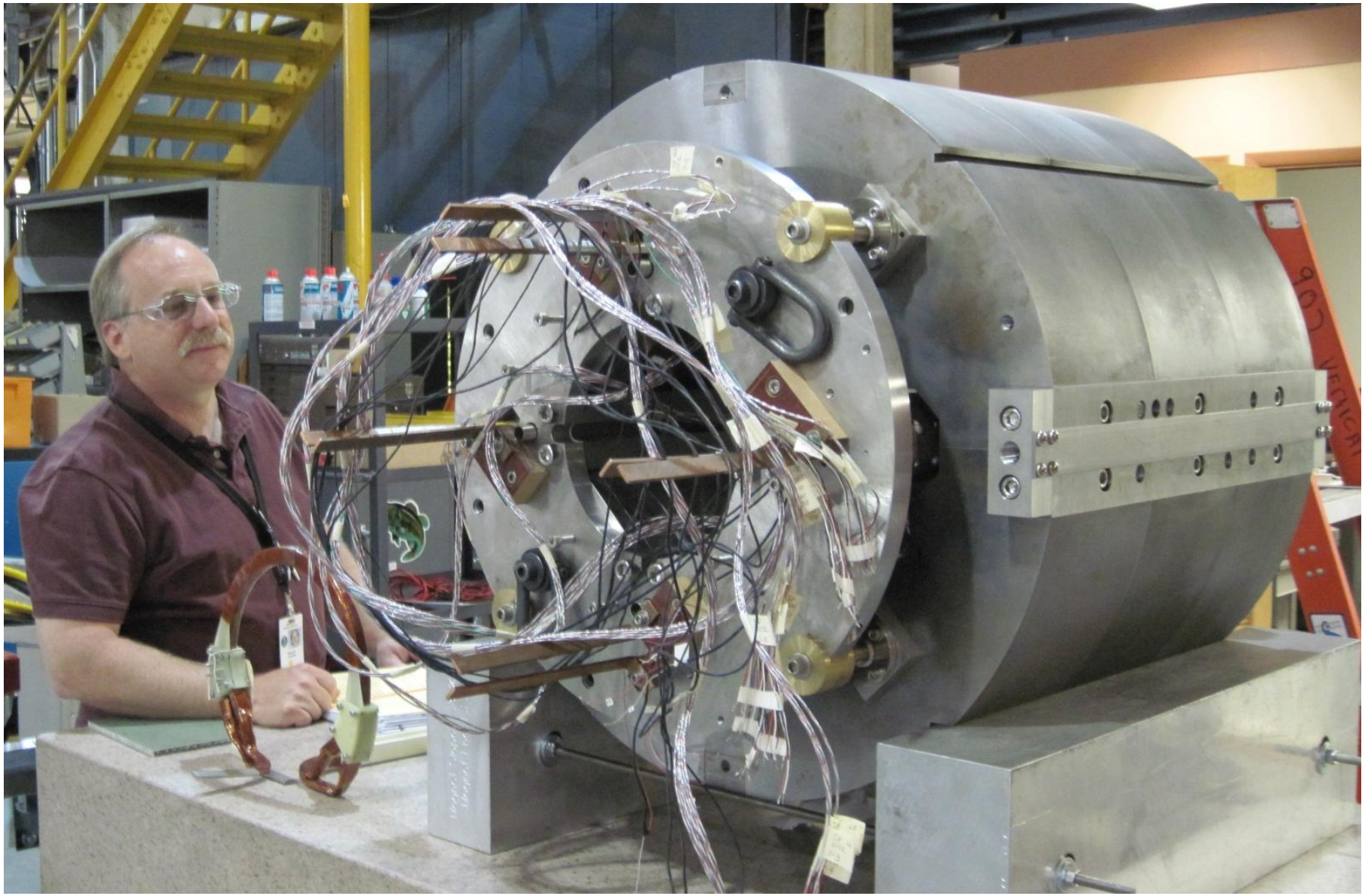
Large HTS Coils from this FRIB Quad will play a Major Role



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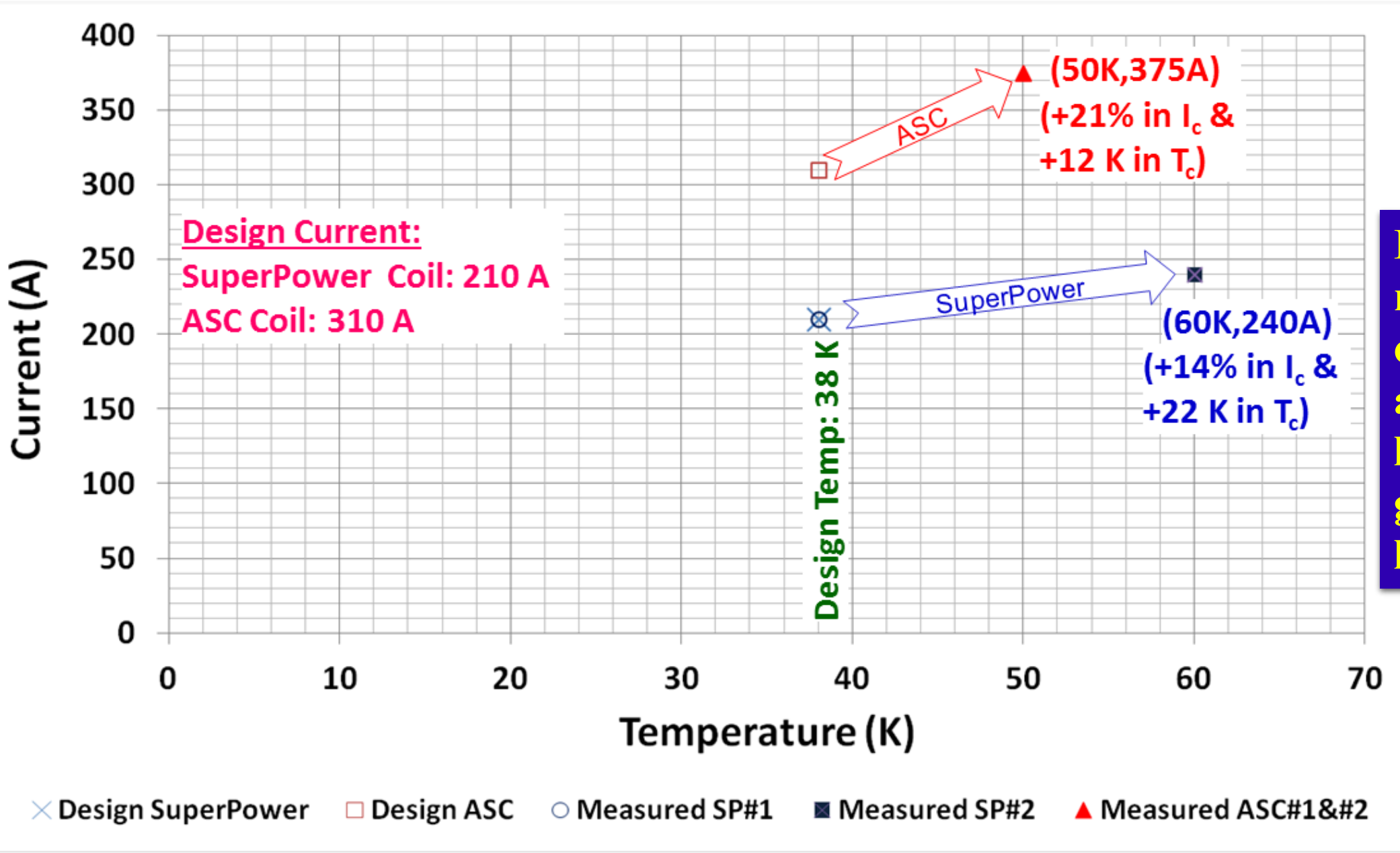
FRIB Quad Test - High Temperature Operation



Provides robust operation against local and global heat loads

FRIB HTS Magnet with Iron and LN_2 Dewar (re-testing now)

Parameter	Value
Pole Radius	110 mm
Design Gradient	15 T/m
Magnetic Length	600 mm
Coil Overall Length	680 mm
Yoke Length	~550 mm
Yoke Outer Diameter	720 mm
Overall Magnet Length(including cryostat)	~880 mm
Number of Layers	2 per coil
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	27 mm, 40 mm
Number of Turns (nominal)	125 (ASC for 40 mm), 220 (SP for 27 mm)
Conductor (2G) width, SuperPower	12.1 mm ± 0.1 mm
Conductor thickness, SuperPower	0.1 mm ± 0.015 mm
Cu stabilizer thickness SuperPower	~0.04 mm
Conductor (2G) width, ASC	12.1 mm ± 0.2 mm
Conductor (2G) thickness, ASC	0.28 mm ± 0.02 mm
Cu stabilizer thickness ASC	~0.1 mm
Stainless Steel Insulation Size	12.4 mm X 0.025 mm
Field parallel @design (maximum)	~1.9 T
Field perpendicular @design (max)	~1.6 T
Minimum I_c @2T, 40 K (spec)	400 A (in any direction)
Minimum I_c @2T, 50 K (expected)	280 A (in any direction)
Nominal Operating Current	~140 A (SuperPower), ~370 A (ASC)
Stored Energy	37 kJ
Inductance	~1 H
Operating Temperature	50 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

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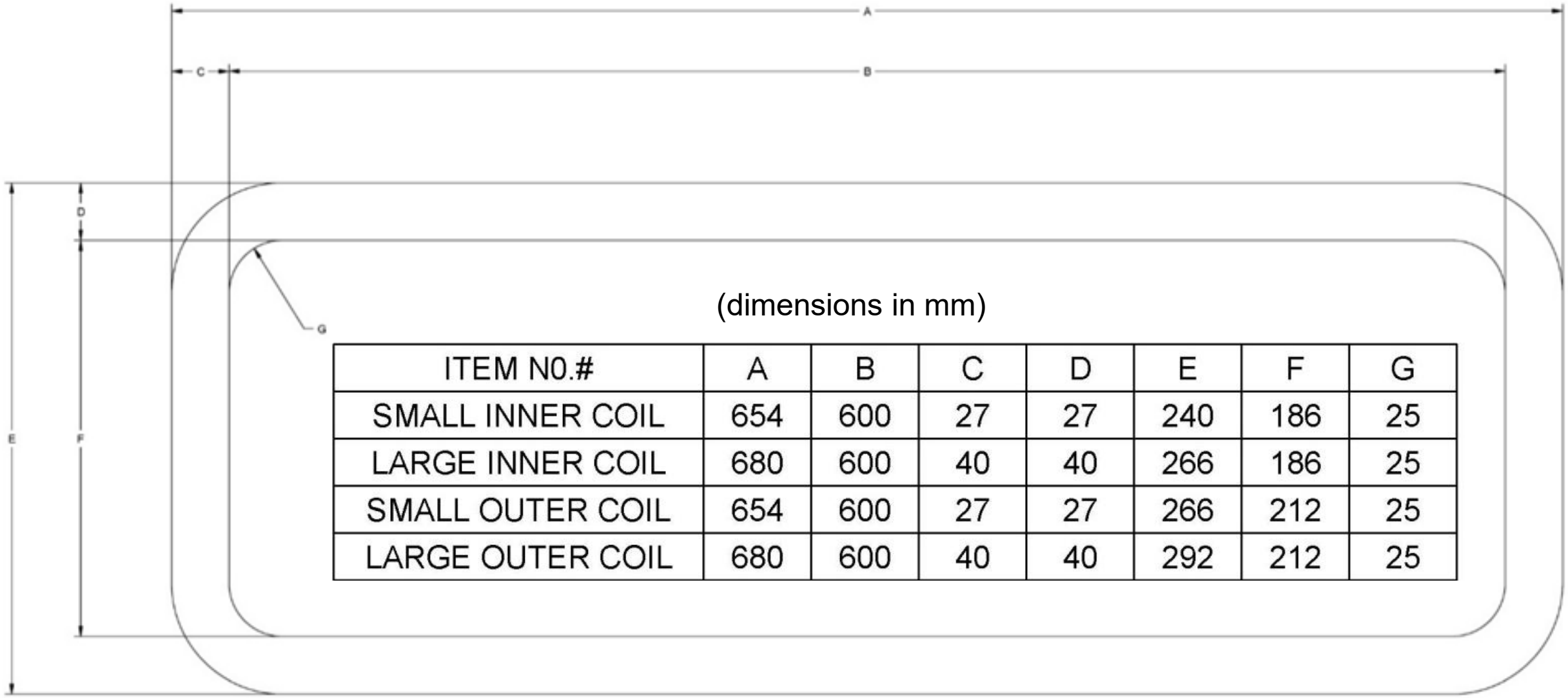
FRIB COILS (four types)



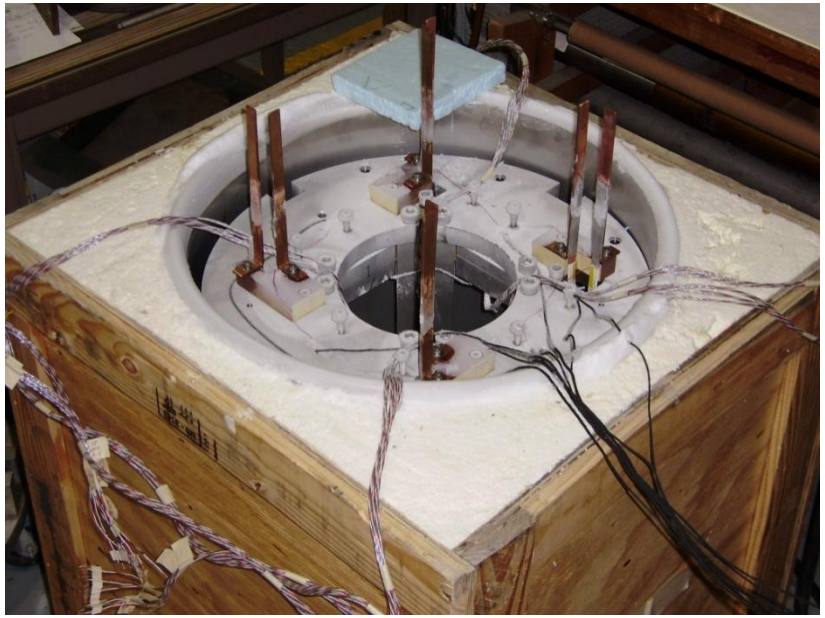
(dimensions in mm)

ITEM N0.#	A	B	C	D	E	F	G
SMALL INNER COIL	654	600	27	27	240	186	25
LARGE INNER COIL	680	600	40	40	266	186	25
SMALL OUTER COIL	654	600	27	27	266	212	25
LARGE OUTER COIL	680	600	40	40	292	212	25

Test of FRIB HTS Quad in a Simple Cryostat

We still have this cryostat.
We will use this to test these coils in various configurations (including field measurements)

- Start by re-testing coil, as configured - yoke removed



Results of previous LN2 tests in extra slides

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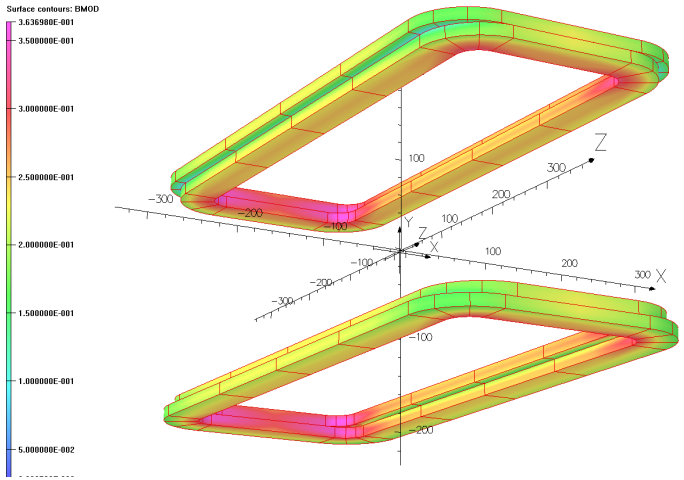
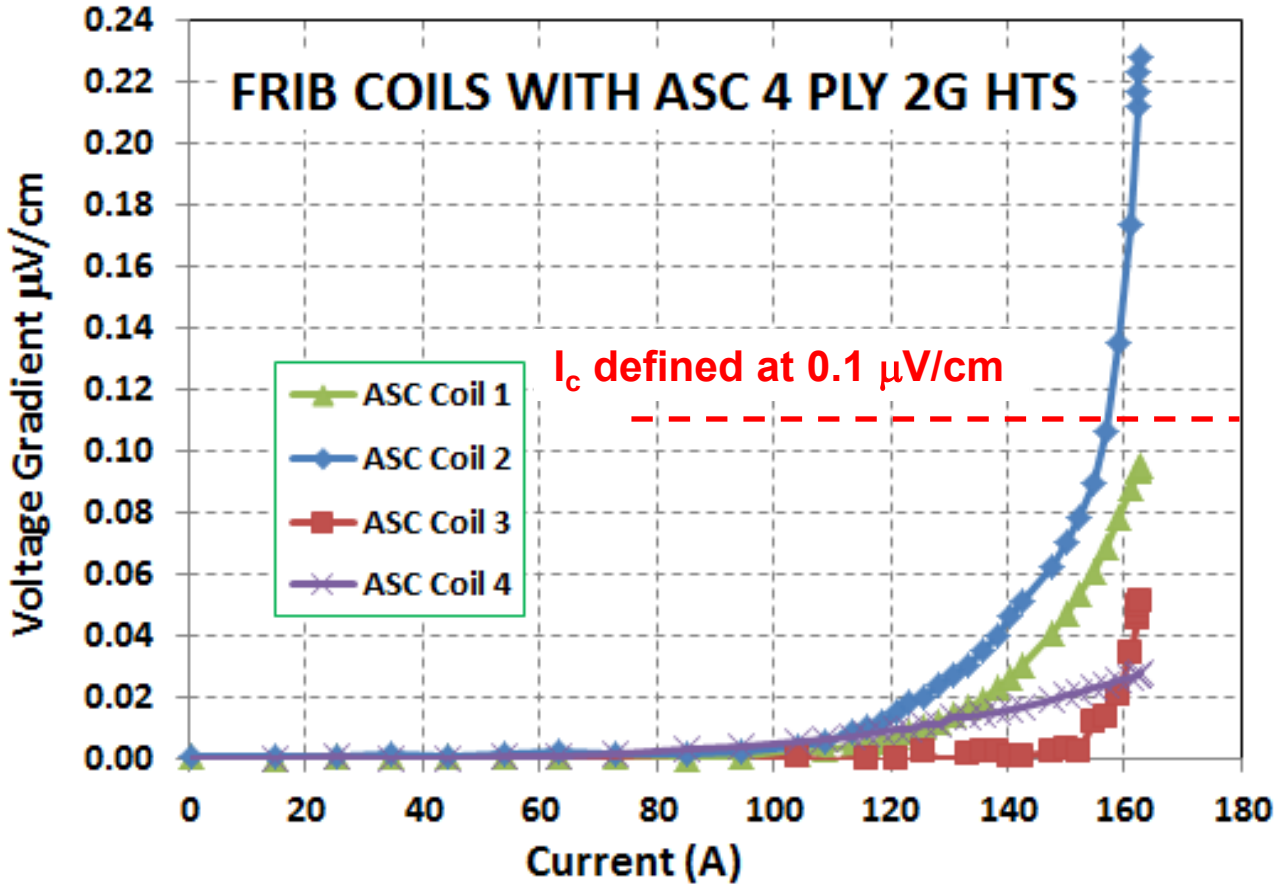
Performance of ASC Coils at 77K (no yoke, four coils of eight powered)

ASC Tape:

2 plies of HTS
and 2 plies of Cu





Field on ASC coils at 100 A

Four SuperPower coils not powered

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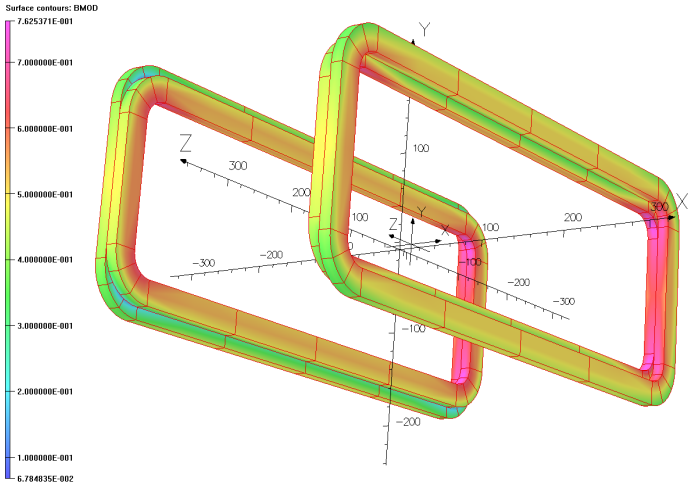
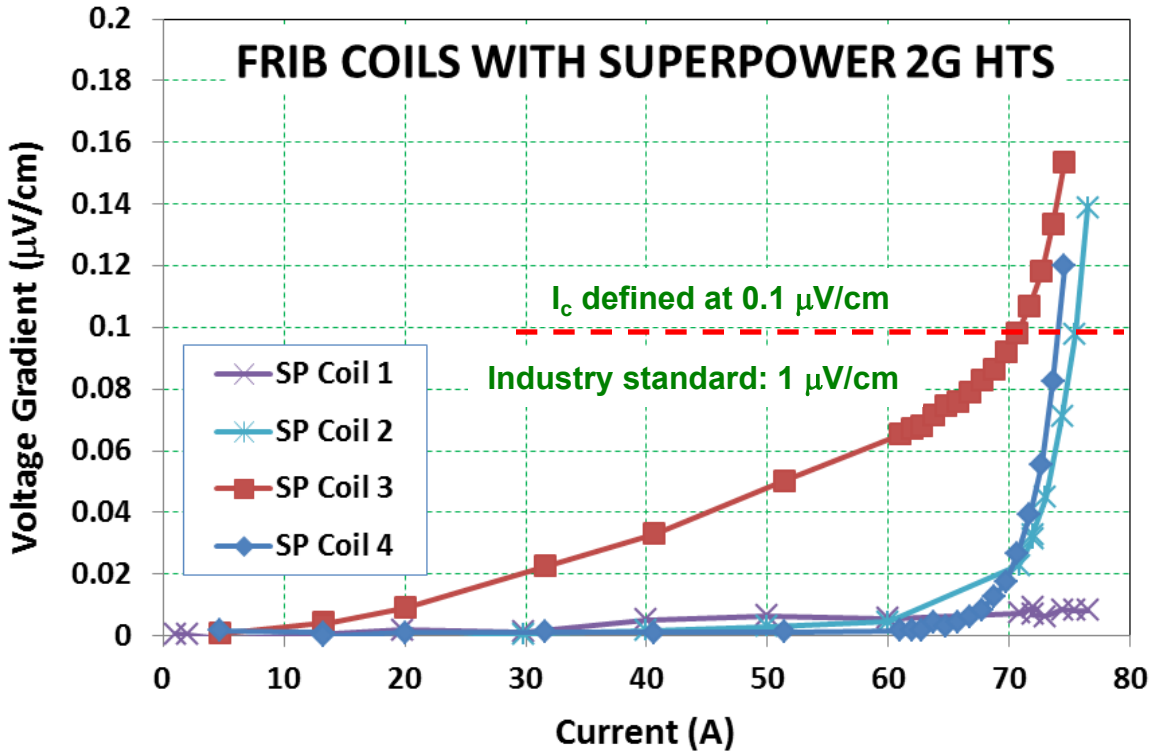
Performance of SuperPower Coils at 77 K (no yoke, four of eight coils powered)

Four ASC coils were not powered



Field on SuperPower coils at 100 A



Internal splice on wrong tape side shows higher resistance. This is not an operational issue as the heat generated is small as compared to the energy deposition.

- **Therefore, the expensive coil was not discarded.**

  Location confirmed with Voltage taps that are typically placed after every 25 turns and on either side of an internal splice

  (slope localized to splice section)

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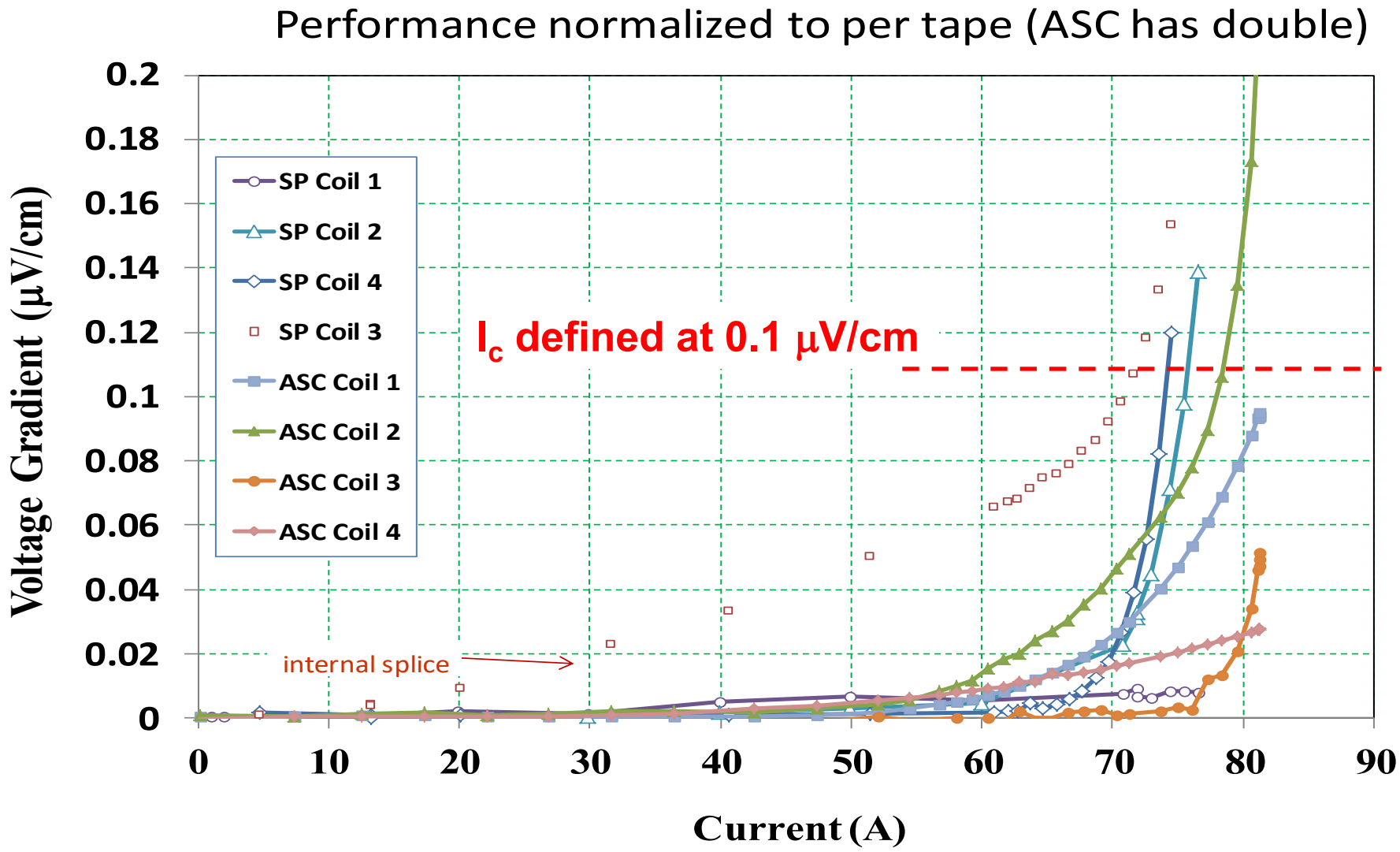
Coils in FRIB Quad Structure @77 K (2G HTS from SuperPower and ASC)

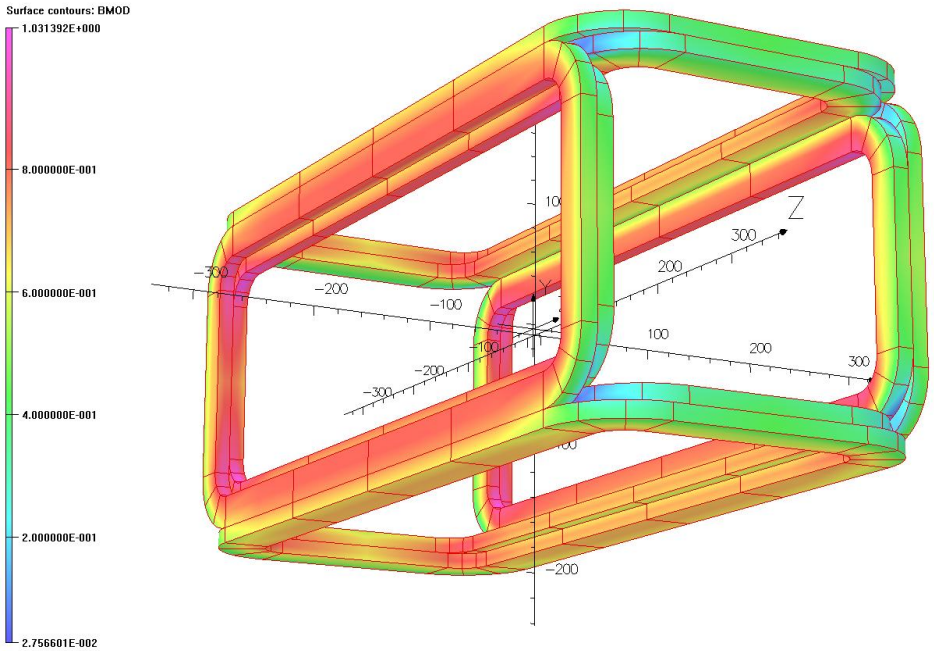


77 K Test in Quadrupole Mode (all eight coils powered)

Currents used for quadrupole mode at 77 K (equal Je)

SP	ASC
40	69.3
50	86.7
60	104

Field with ASC coils at 200A and SuperPower coils at 115.5 A



Note: No iron yoke yet in this structure.

Design (38 K): SP coils ~210 A & ASC coils ~310 A (equal Amp-turns).

- **Coils reached about 1/3 of the design current at 77 K itself.**

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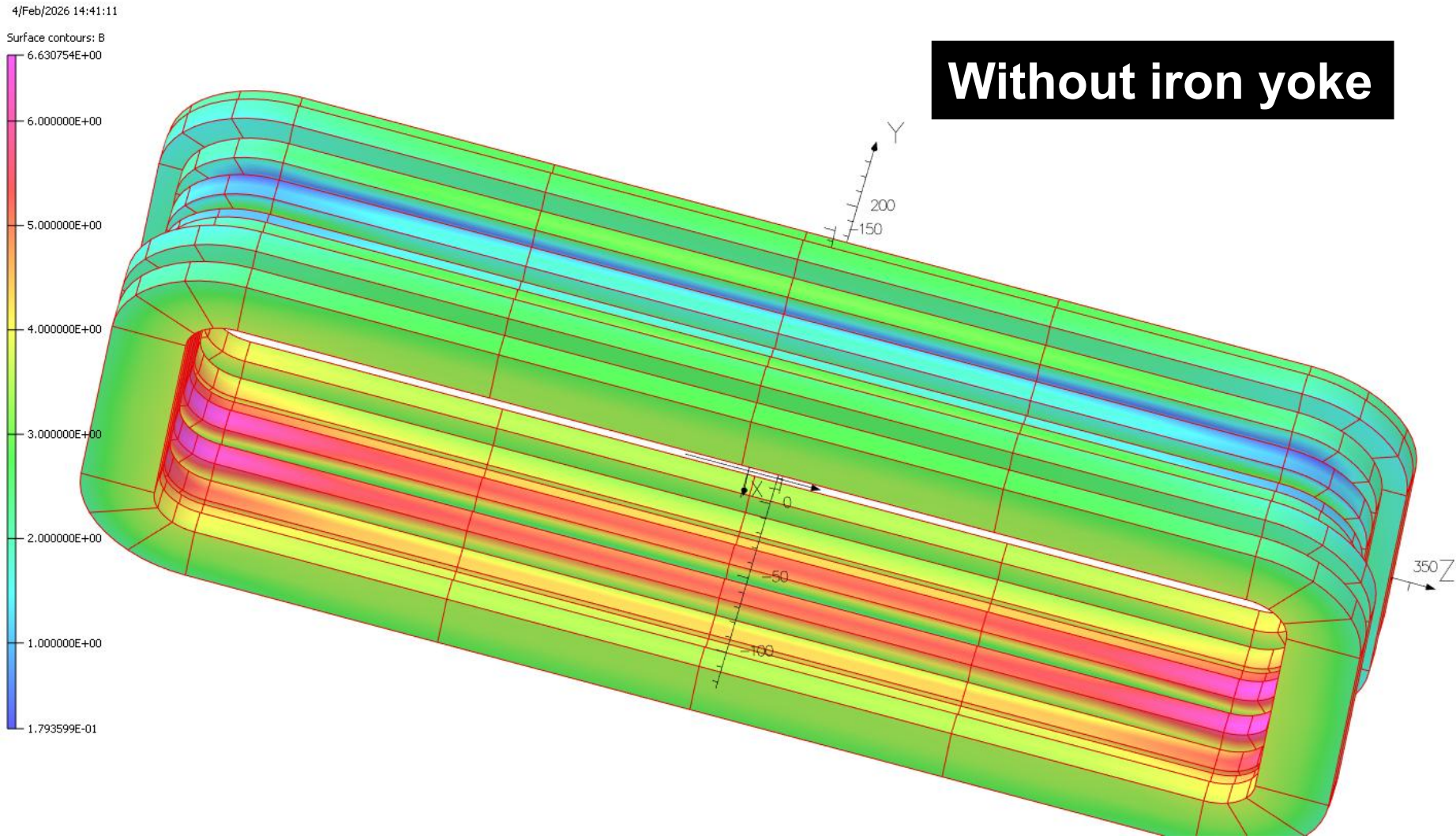
Future Use of FRIB Coils: Put together to create 6-7 T

(Single aperture dipole configuration; Higher field with 2 power supplies)

Reconfigure and assemble the large HTS coils to create 6-7 T dipole.

Need support structure (keep it simple) and perform 77 K tests



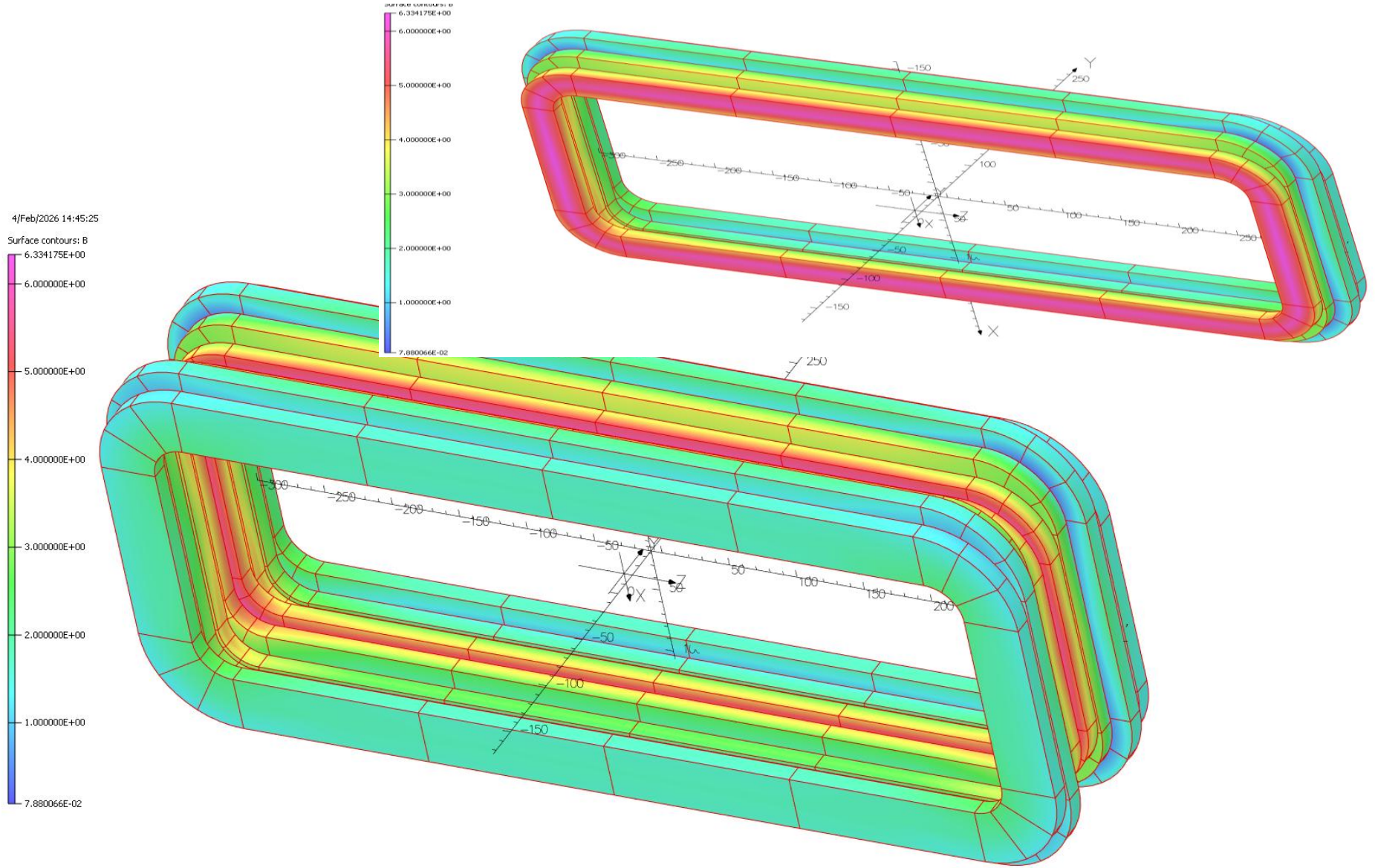
Another Use of FRIB Coils: Put together to create 6-7 T

(2-in-1 Common Coil Dipole Configuration; Higher field with 2 power supplies)

Without iron yoke

Reconfigure and assemble the large HTS coils to create 6-7 T common coil dipole.

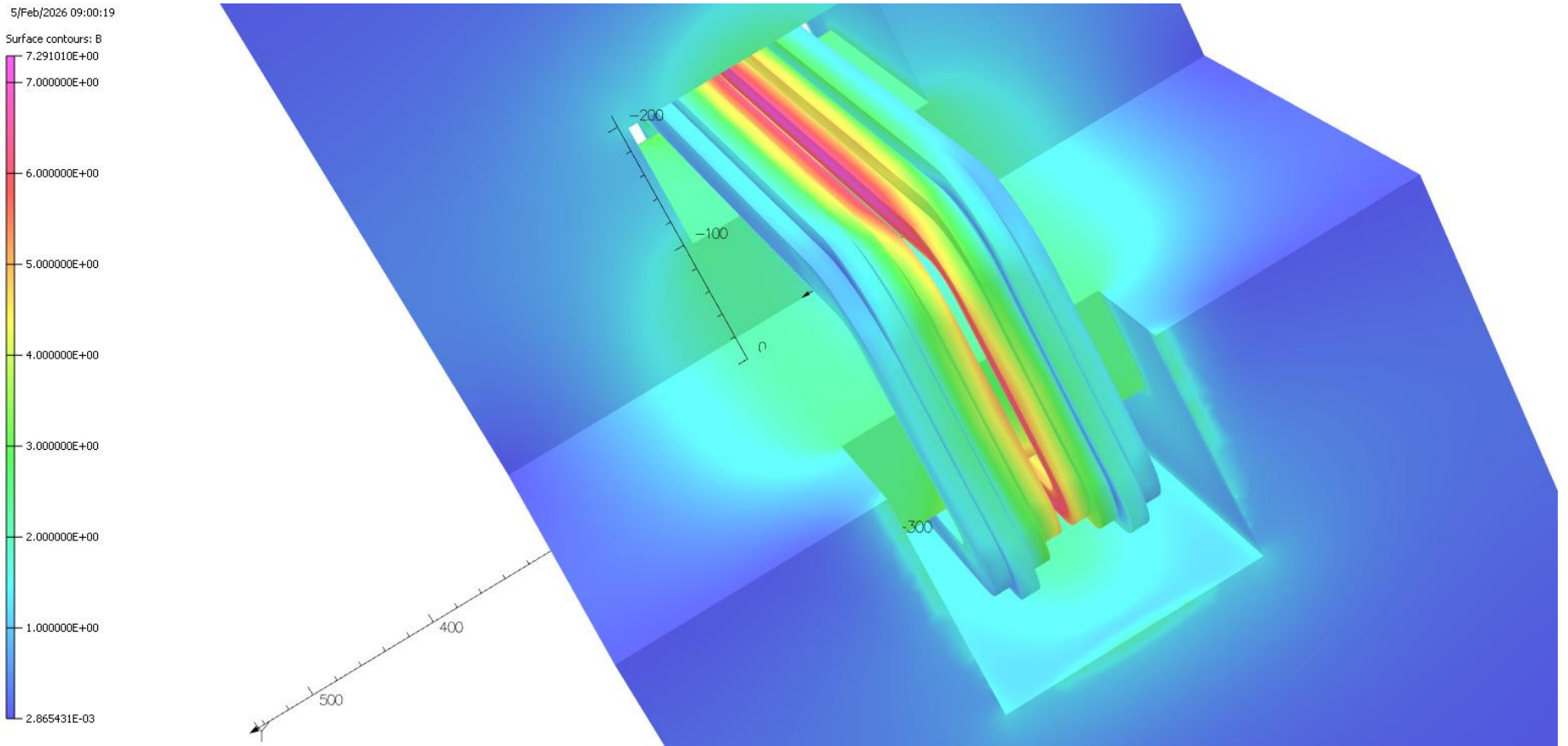
Need support structure (keep it simple) and perform 77 K tests



Future Use: Put together to create 7-8 T Field
(2-in-1 Common Coil Configuration; higher field with 2 PS)

Reconfigure and assemble the large HTS coils in common coil configuration to create 7-8 T dipole at 600 A.

Keep it simple.

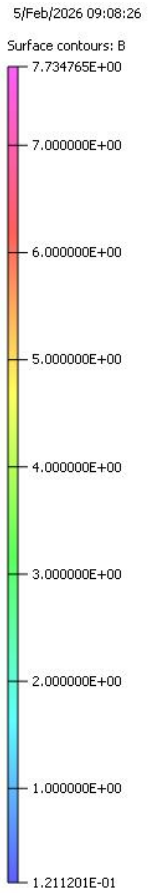


Coils in iron yoke

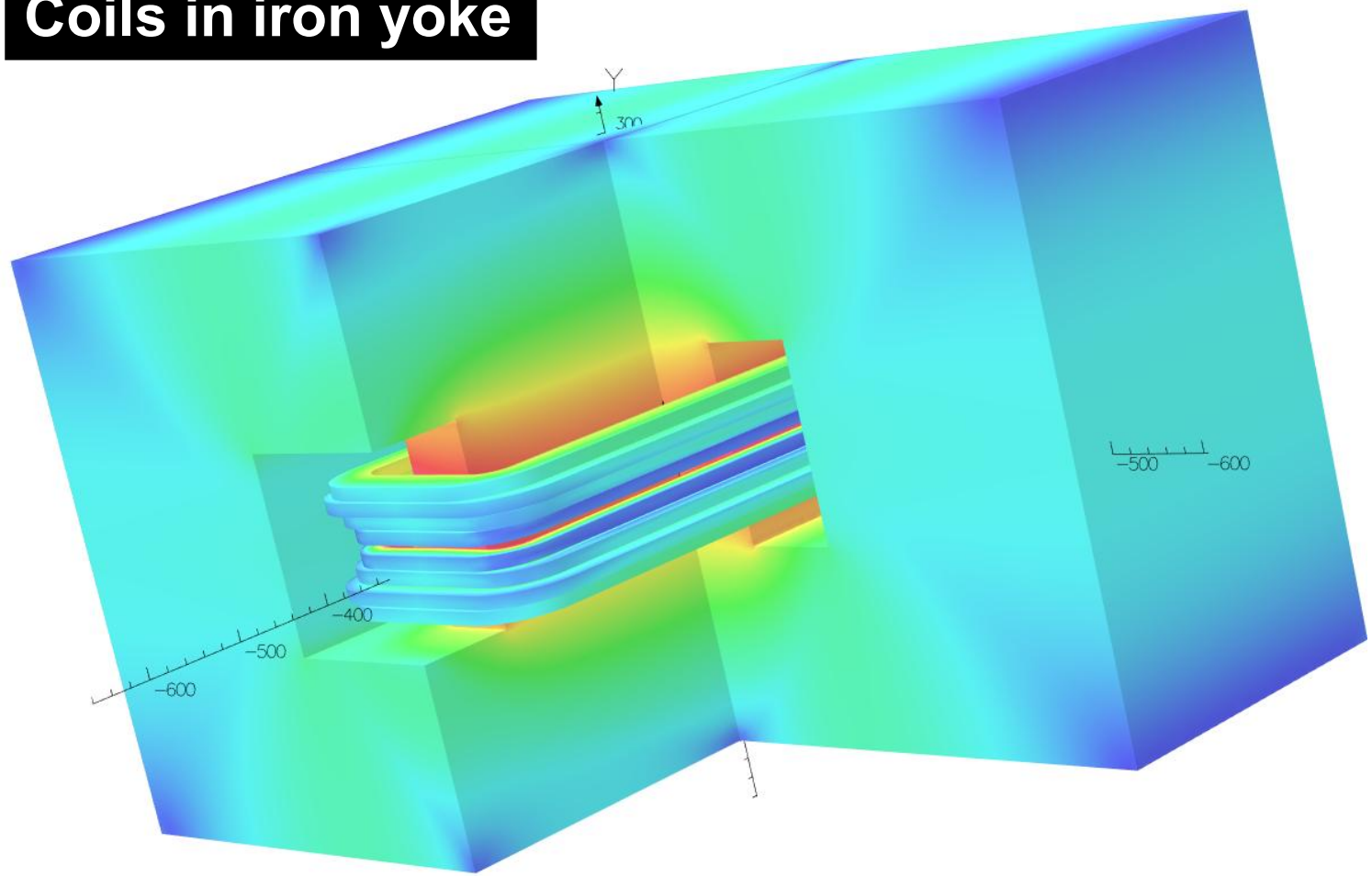
Future Use: Put together to create 7-8 T Field
(Single Aperture Dipole Configuration; higher field with 2 PS)

Reconfigure and assemble the large HTS coils in single aperture dipole configuration to create 7-8 T dipole at 600 A.

Common structure for two configuration.



Coils in iron yoke



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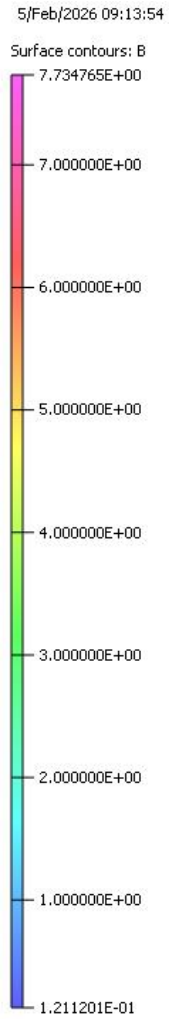
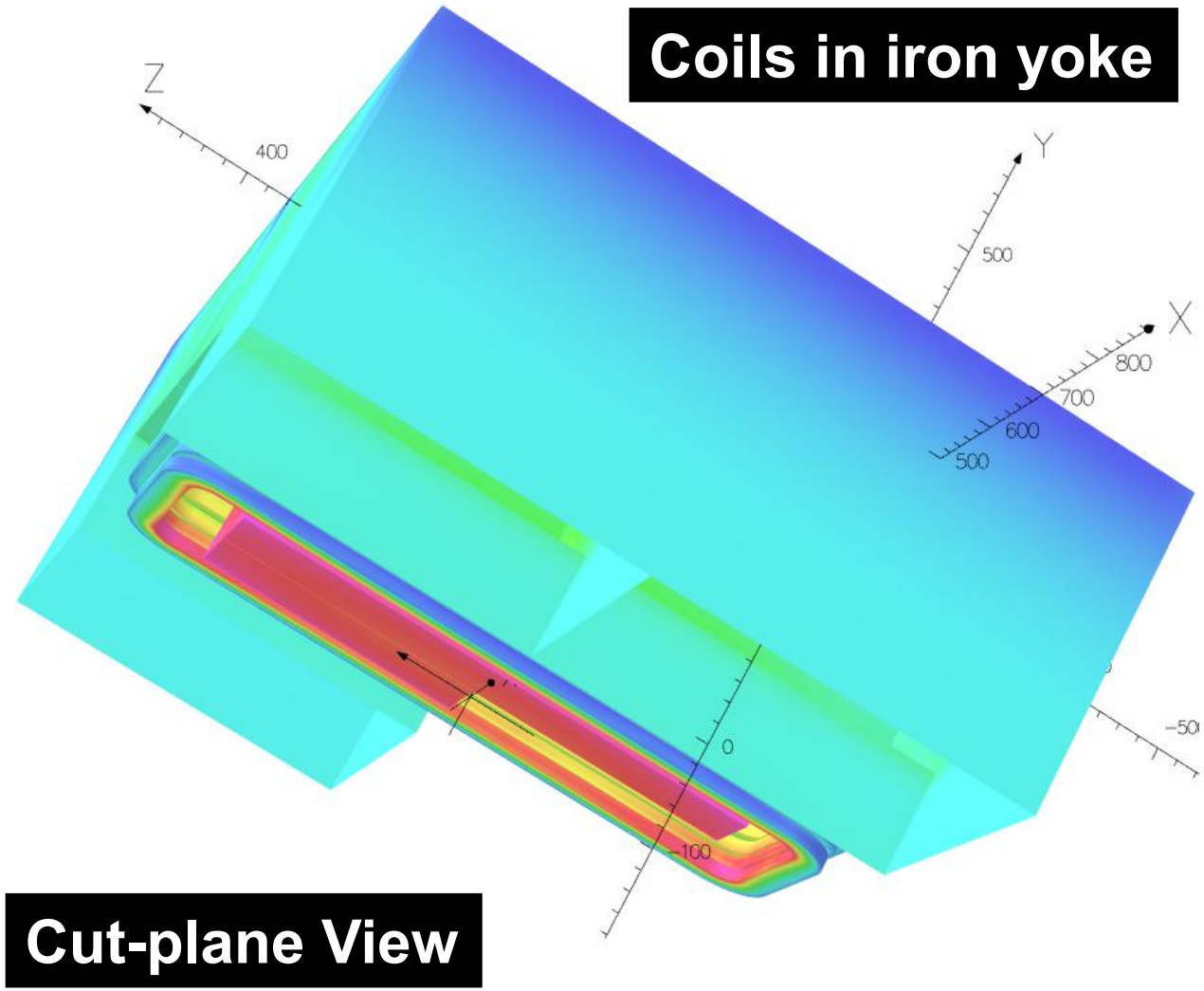
Future Use: Put together to create 7-8 T Field
(Single Aperture Dipole Configuration; higher field with 2 PS)

Reconfigure and assemble the large HTS coils in single aperture dipole configuration to create 7-8 T dipole at 600 A.

Higher current may be possible since higher value of field is primarily parallel.

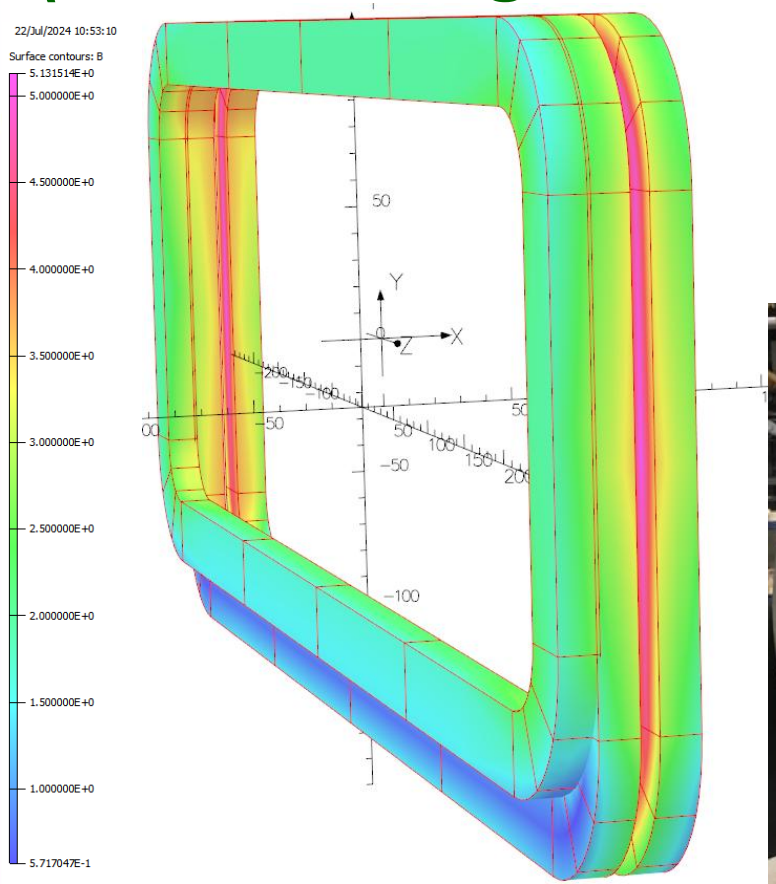
Try to make a common structure for two configuration.



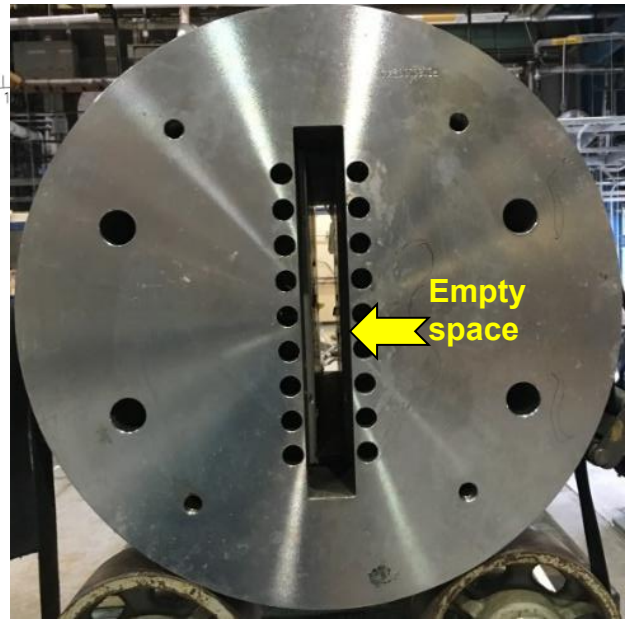


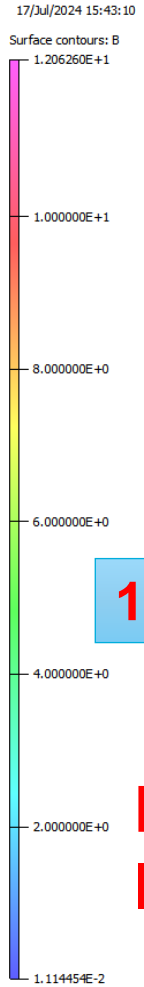
Moving to HTS/LTS Hybrid Test with Larger Coils

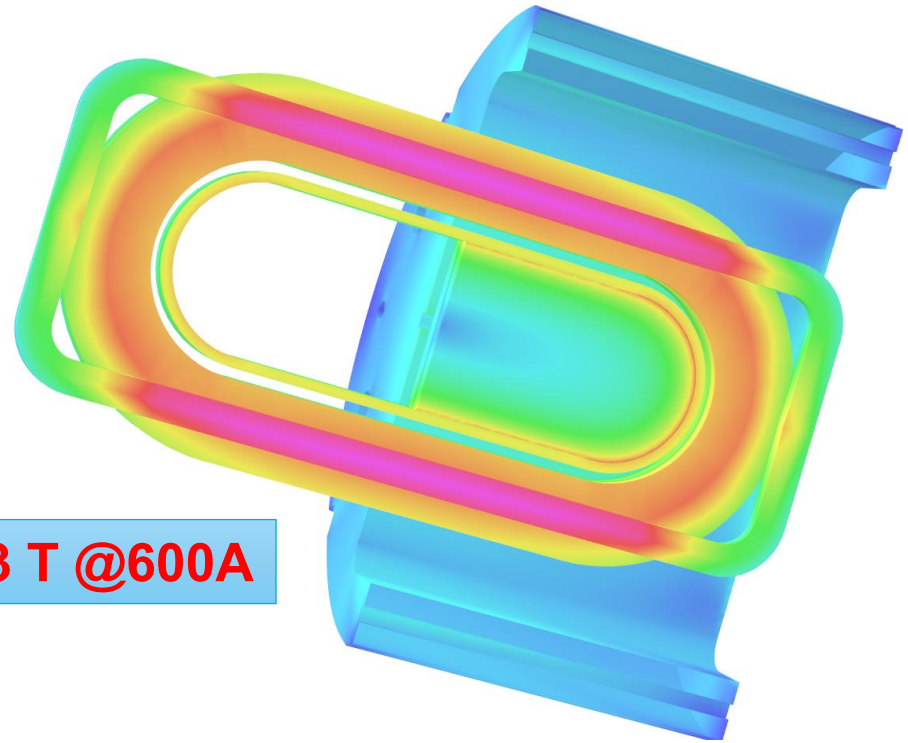
(Use existing FRIB coils for a quicker and lower-cost program)



Insert FRIB HTS coils in the BNL Common Coil DCC017 Dipole for HTS/LTS Hybrid Dipole







13 T @600A

Field perpendicular, larger coils than tested before

4 FRIB HTS coils @520 A made with 12 mm HTS tape from SuperPower for 5T standalone

~7 T when 4 ASC coils are also added

FRIB HTS coils made with 12 mm HTS tape from SuperPower in the background field of DCC017 @420 A for HTS/LTS hybrid test

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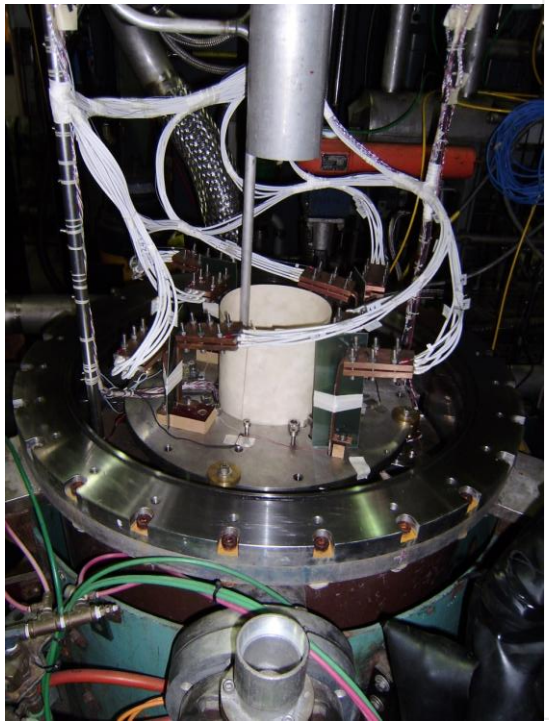
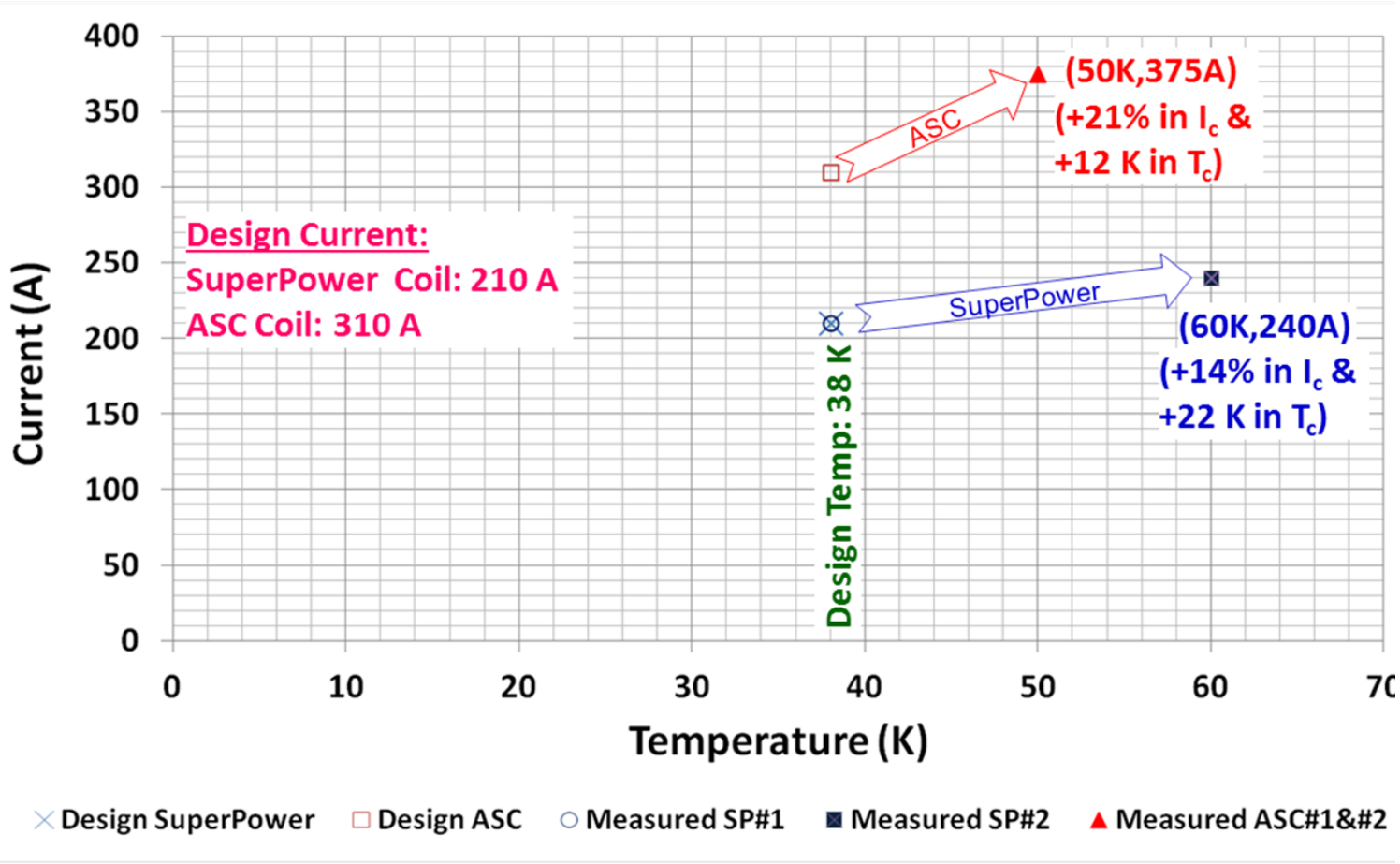
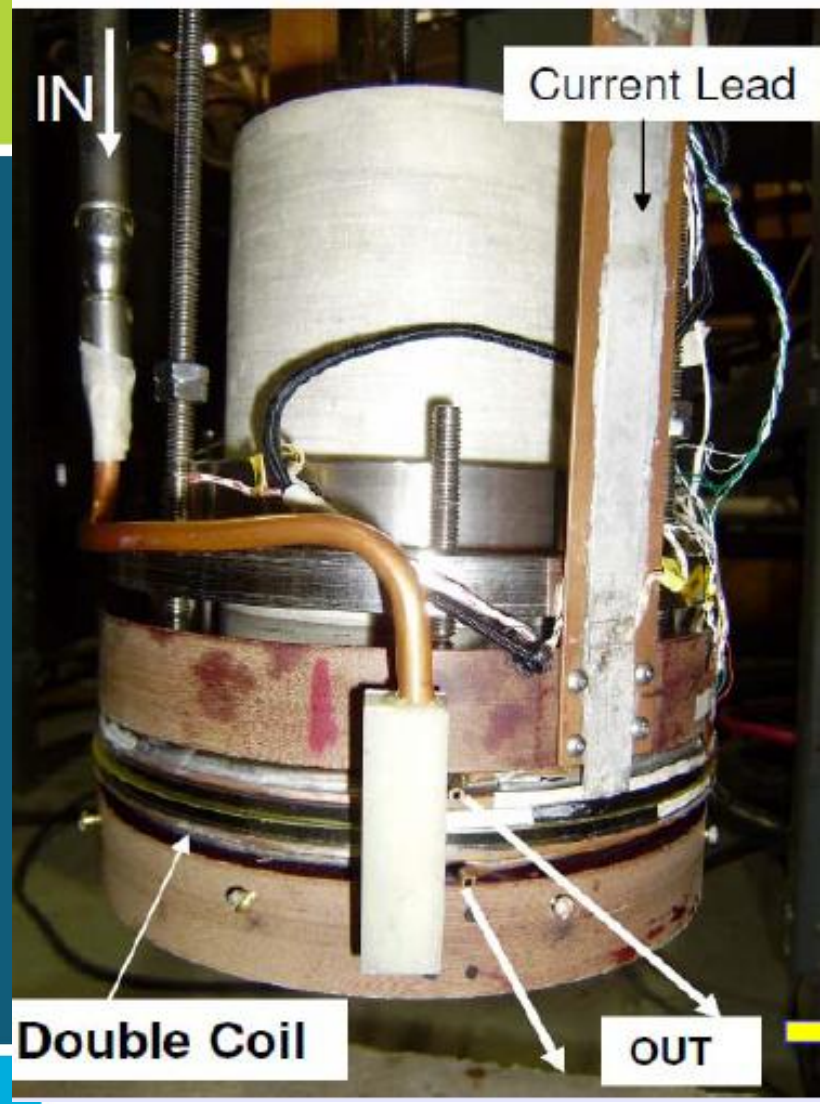
Intermediate Temperature Tests: Past Experience and Future Planning

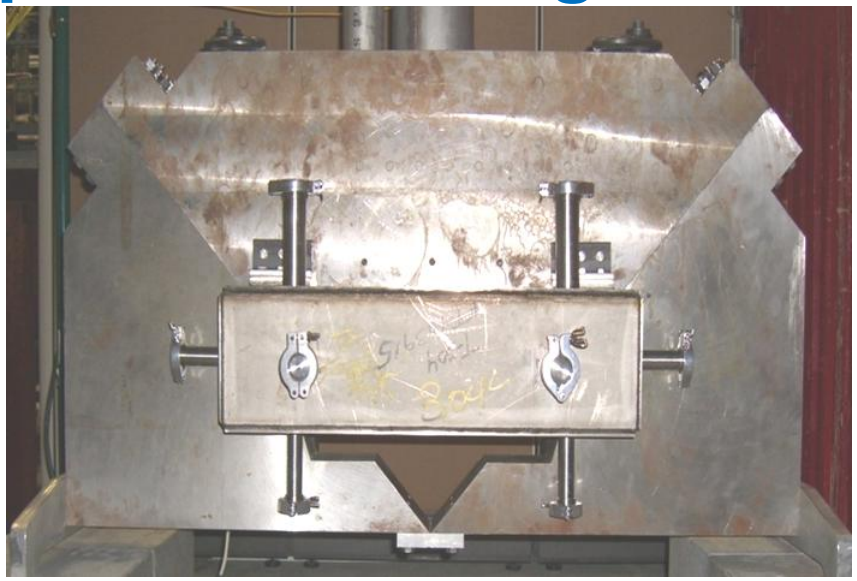
- Use HTS tape to carry the current from coil to leads at the top-hat for Ic Vs T tests
- ➢ Start with US-Japan - do as before, HTS soldered on thin Cu (He Gas, manual adj)
- **Need to develop feedback loop to regulate Helium flow to dial the temperature**
- Helium gas cooled structure (designed for this and other FRIB magnets, where used)

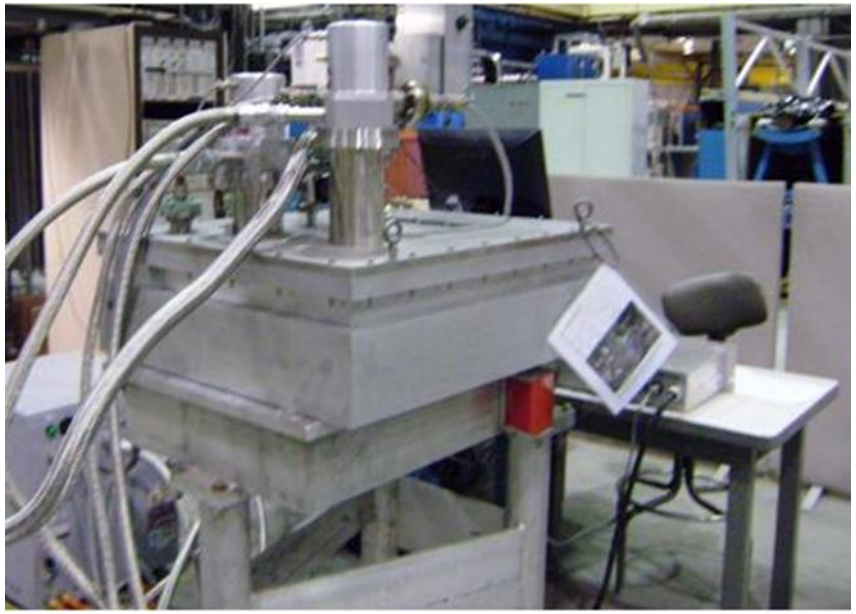


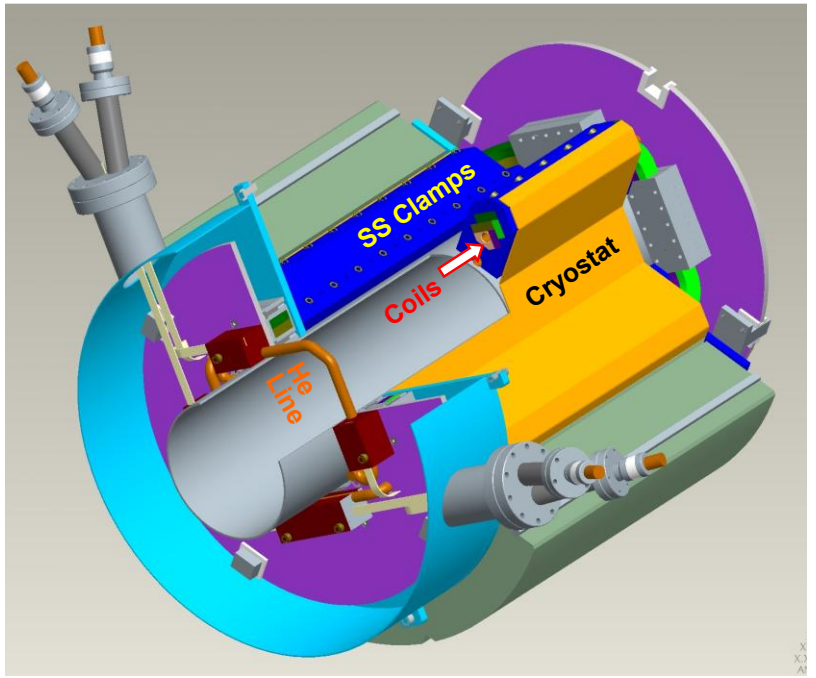


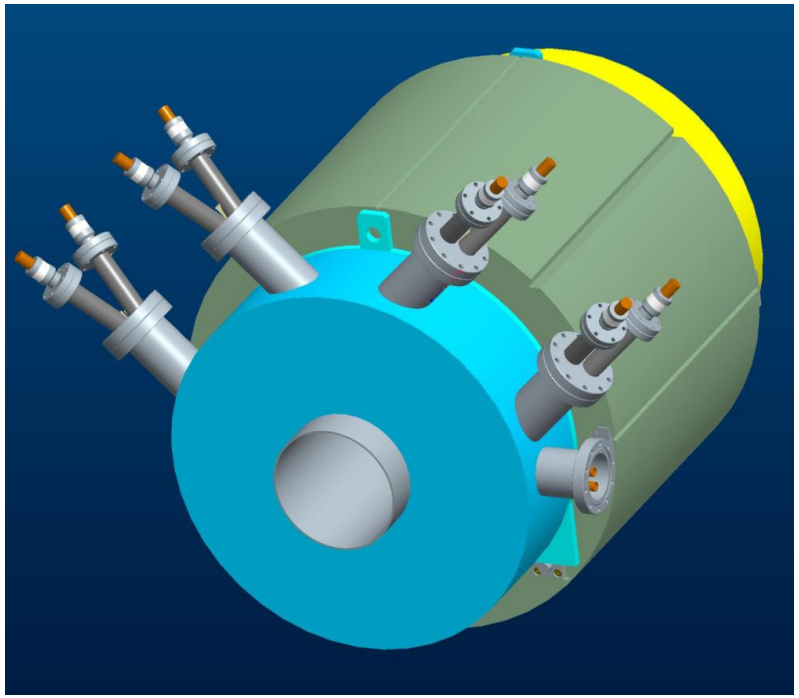
Previous He Gas/Cryo-cooled Structures for Intermediate Temperature Testing











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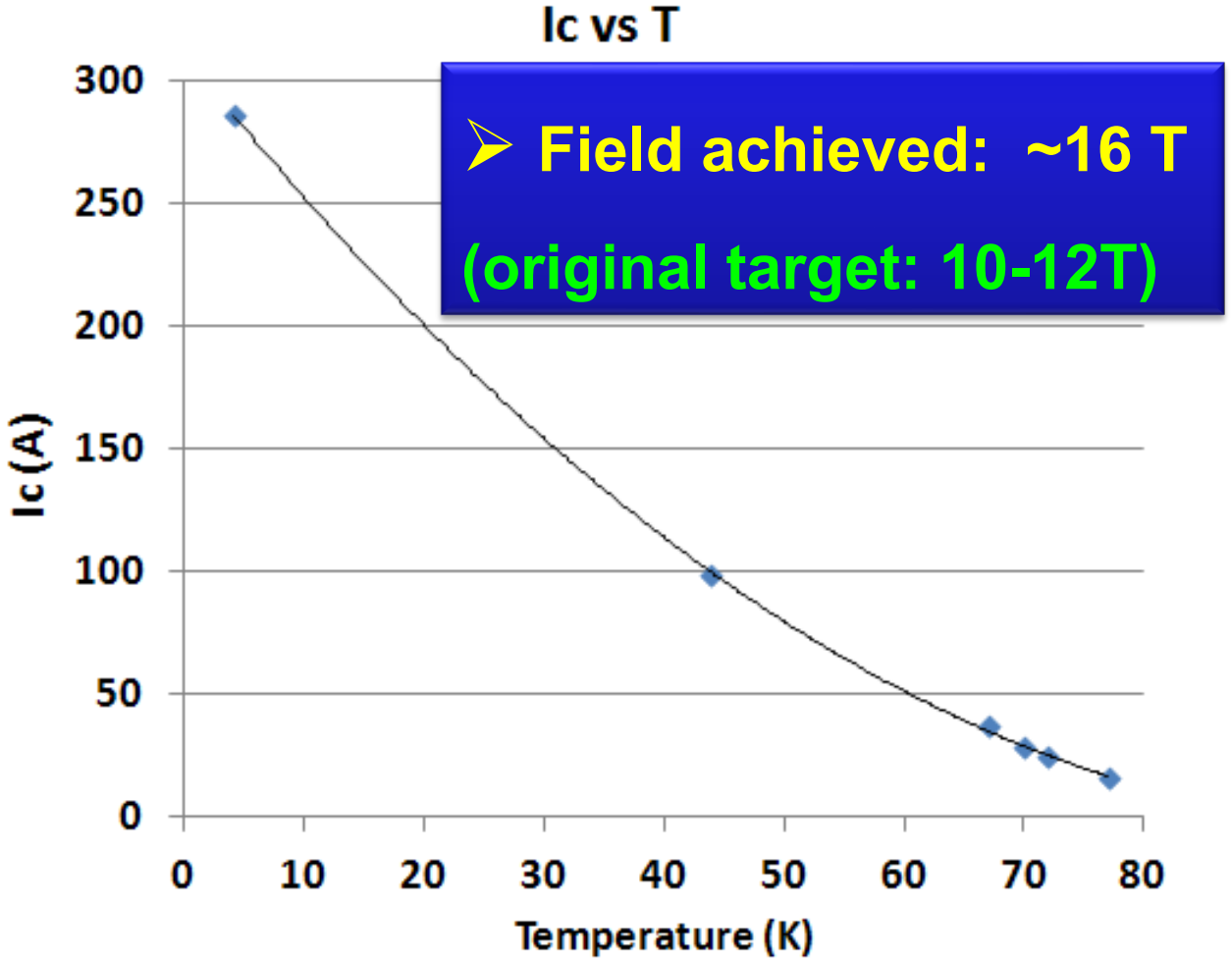
HTS 16 Tesla Solenoid (Record in 2012) and Ic Vs T

Make measurements at intermediate temperature with controlled cooling by adjusting the flow of helium (for future feedback loop on controlling valve?) or perform measurements during the warm up.

HTS solenoid

Must use HTS leads from the HTS coil to the top-hat



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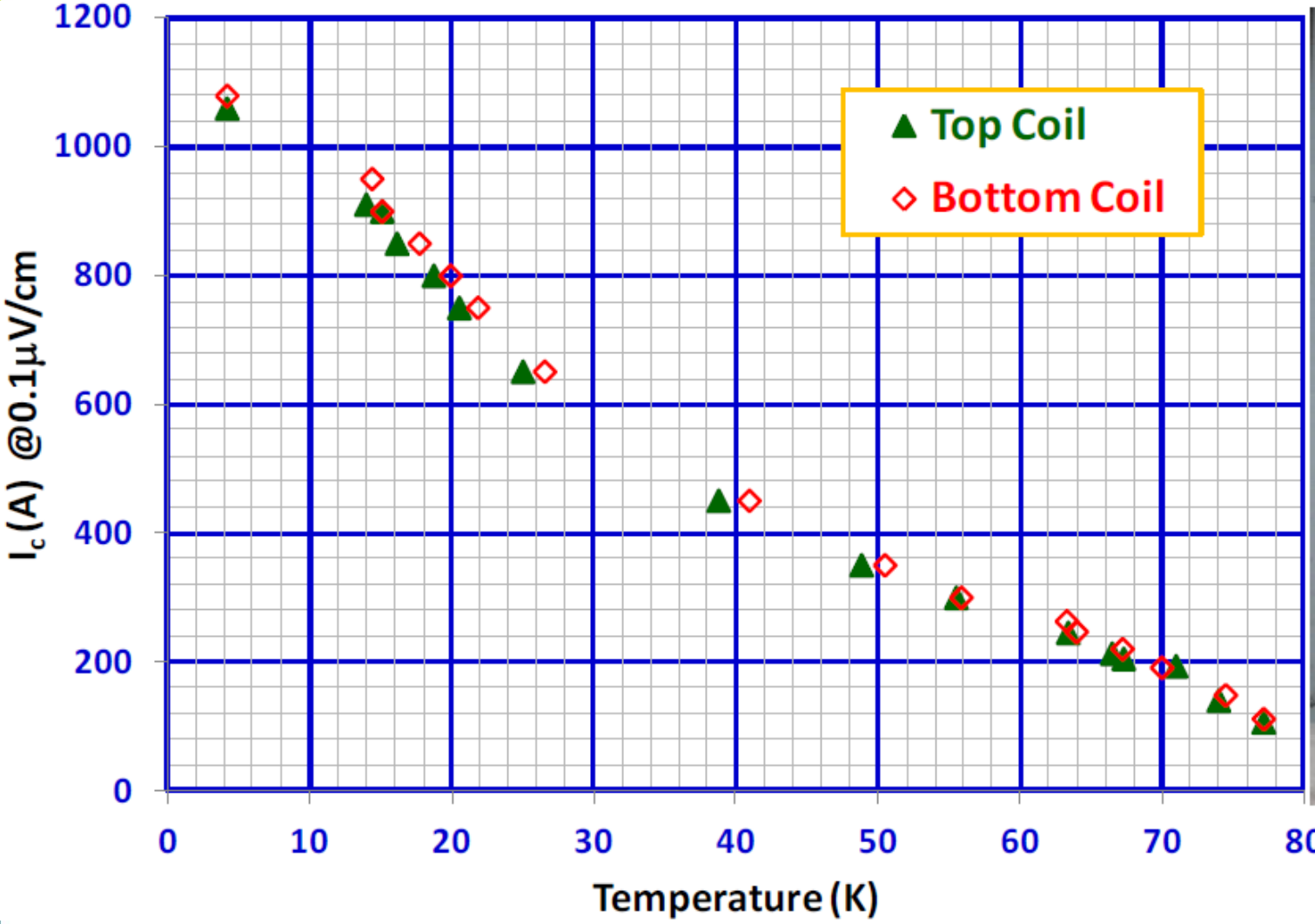
Another Test at Different Temperature in Gaseous Helium Environment



Ramp rate up to 10 A/s

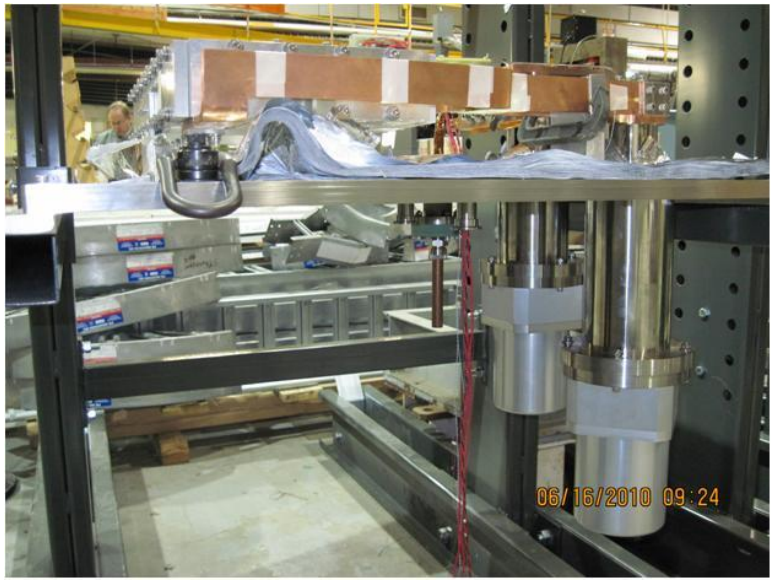
Testing at different temperature by letting it warm up slowly in Dewar after Helium has exhausted

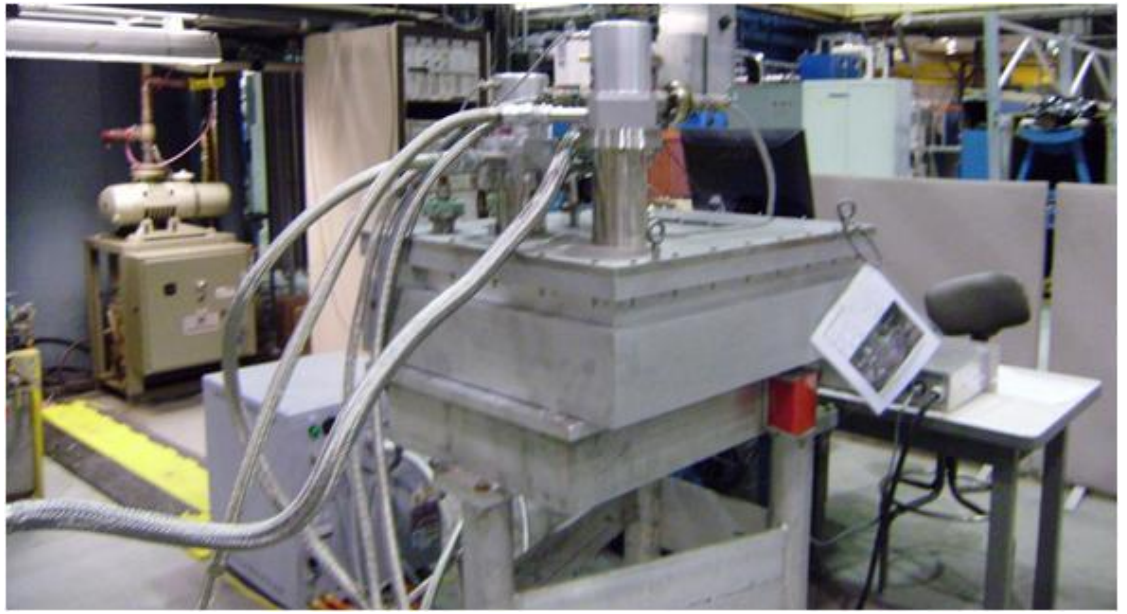
Testing at different temperature by adjusting Helium flow rate

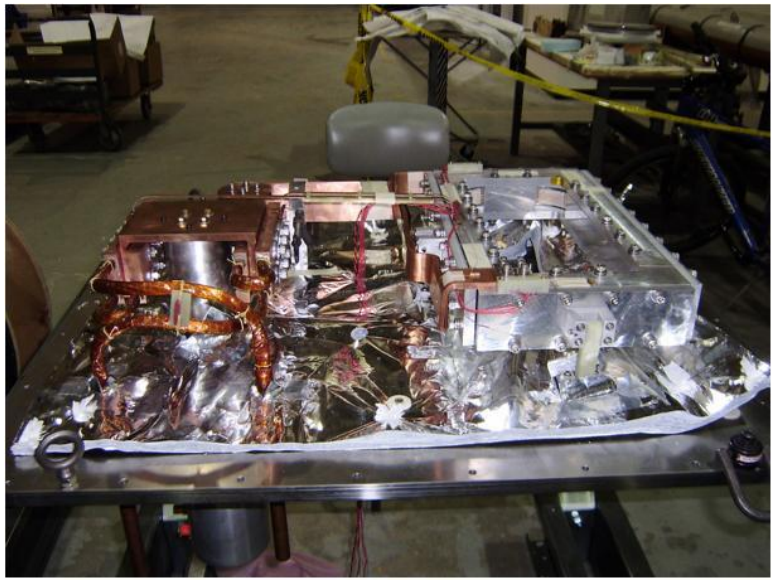
Must use HTS leads from the HTS coil to the top-hat

Cryo-cooler based structure

An easy to open & close simple Cryo-cooler based structure







Up to six coils were tested in various configurations.

Cutout in the middle for warm iron or other warm measurements.

- **Coils reached <40 K (goal was 40-50 K)**
- **Cryo-coolers turned-on at 5 pm and left unattended. Coils reached the desired temperature at 8:30 am next day.**
- **Experiment starts early morning (saving in cost & time).**
- **Good test bed for HTS coil technology – No Helium, no personnel, turn on cryo-cooler the evening before and start the actual experiment in the morning…**

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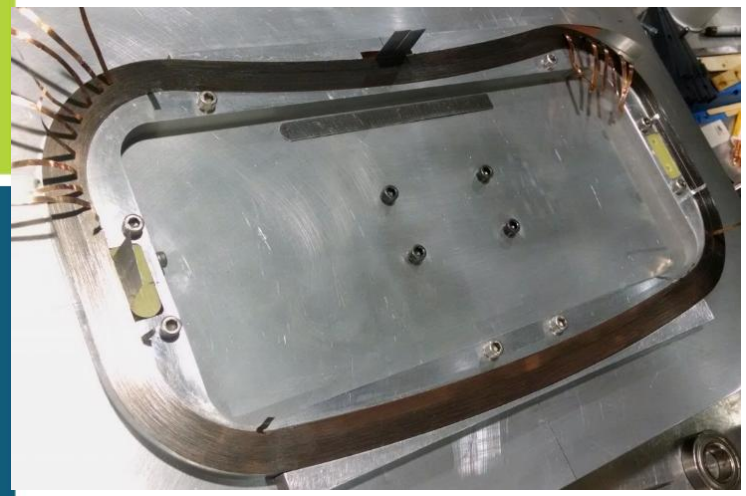
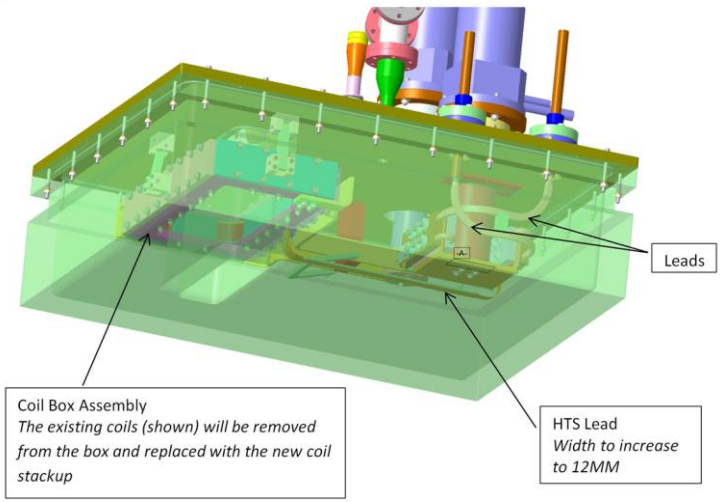
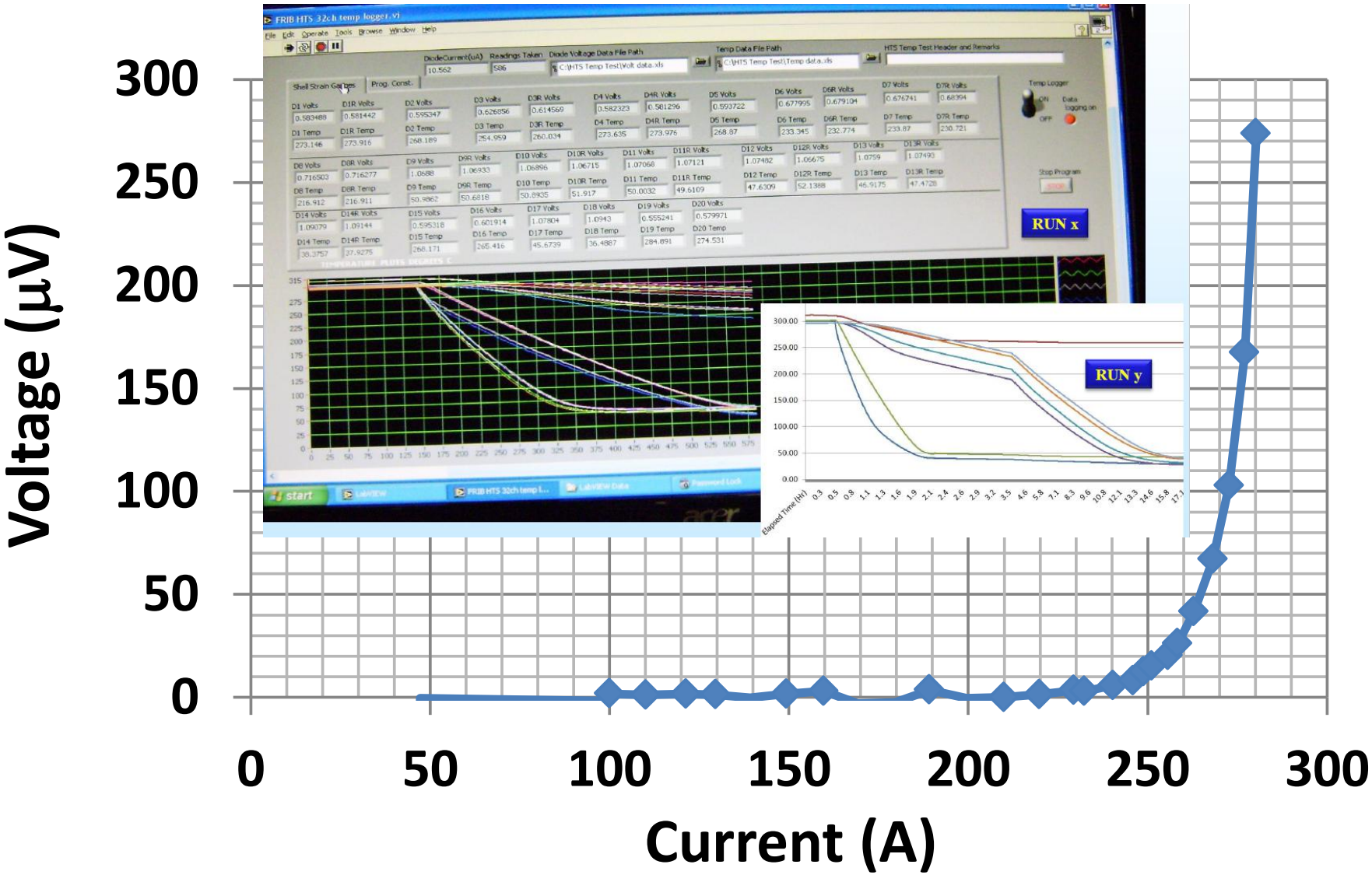
HTS Coil Test @48K reached overnight with cryocoolers

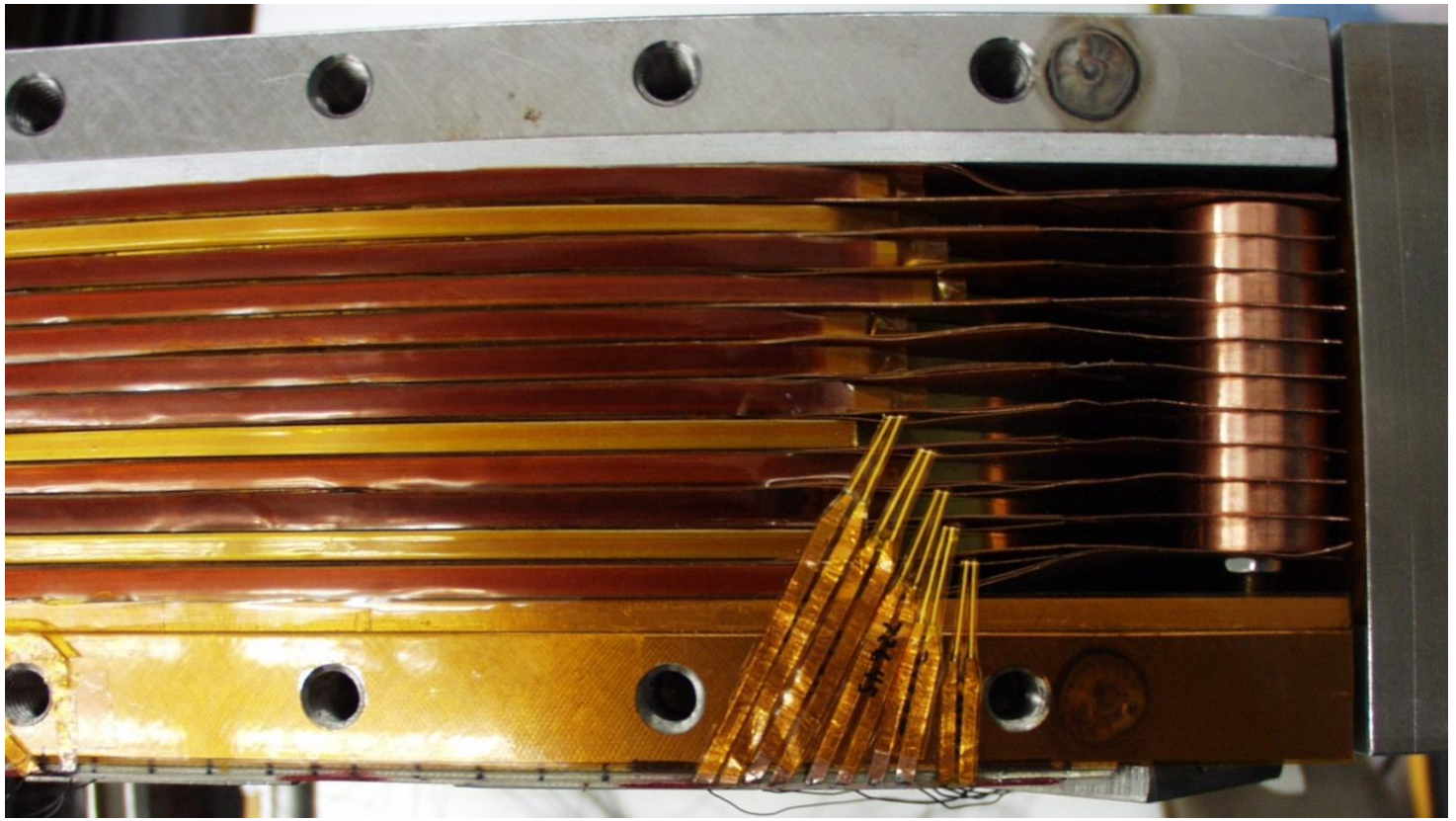






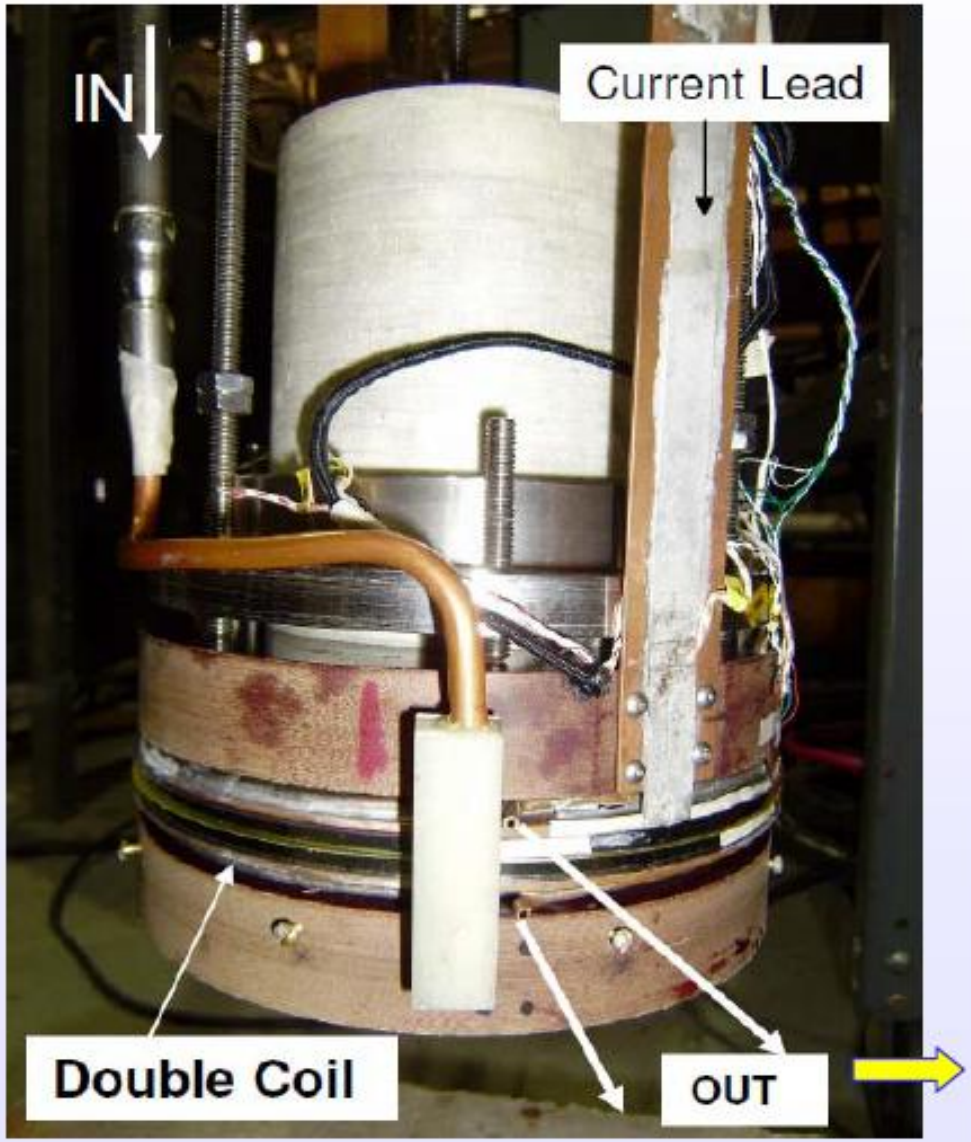
Energy Deposition and Cryogenic Experiments

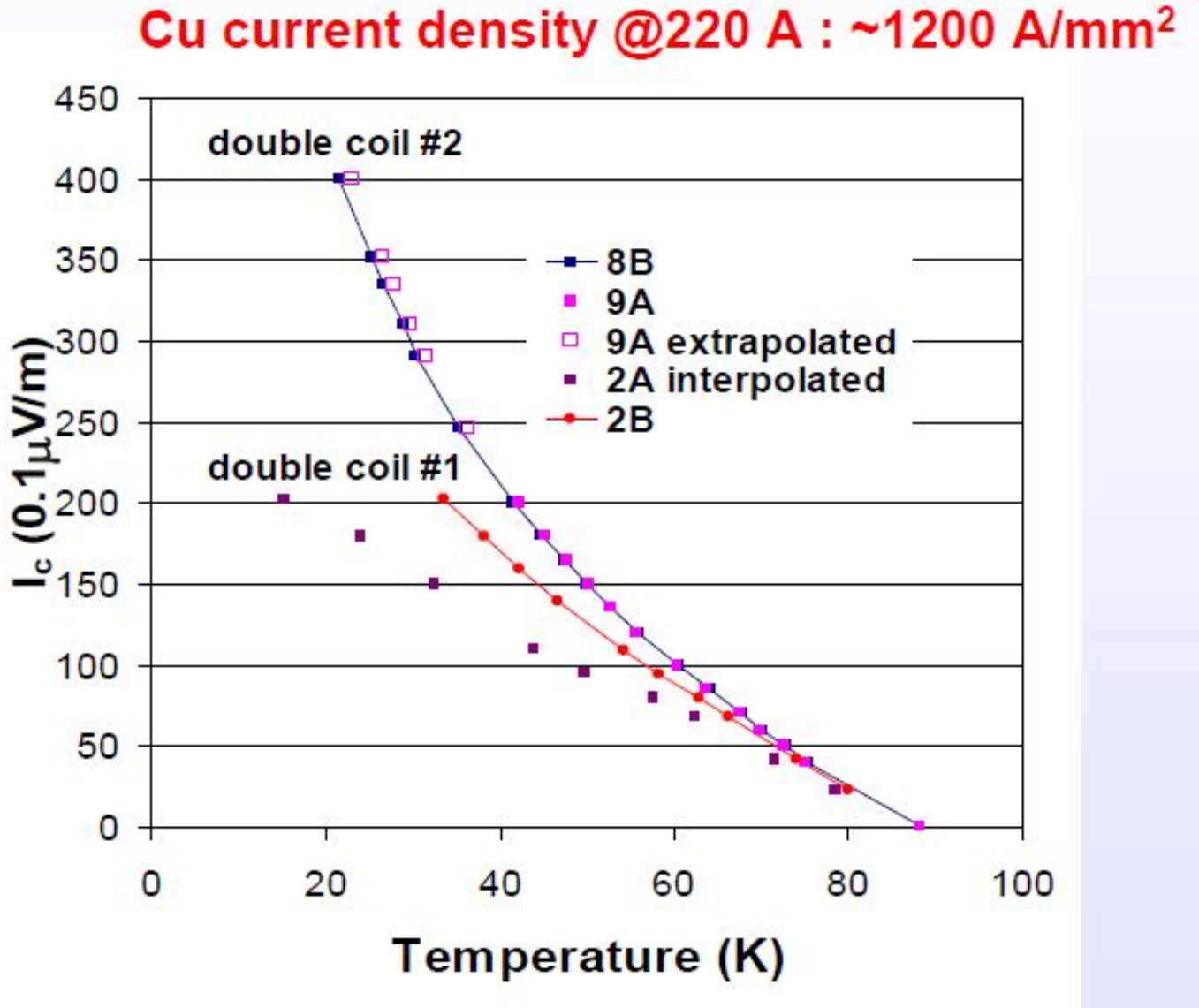
Stainless steel tape heaters for energy deposition experiments or for changing the temperature of the coils by adding heat load on the outer plates



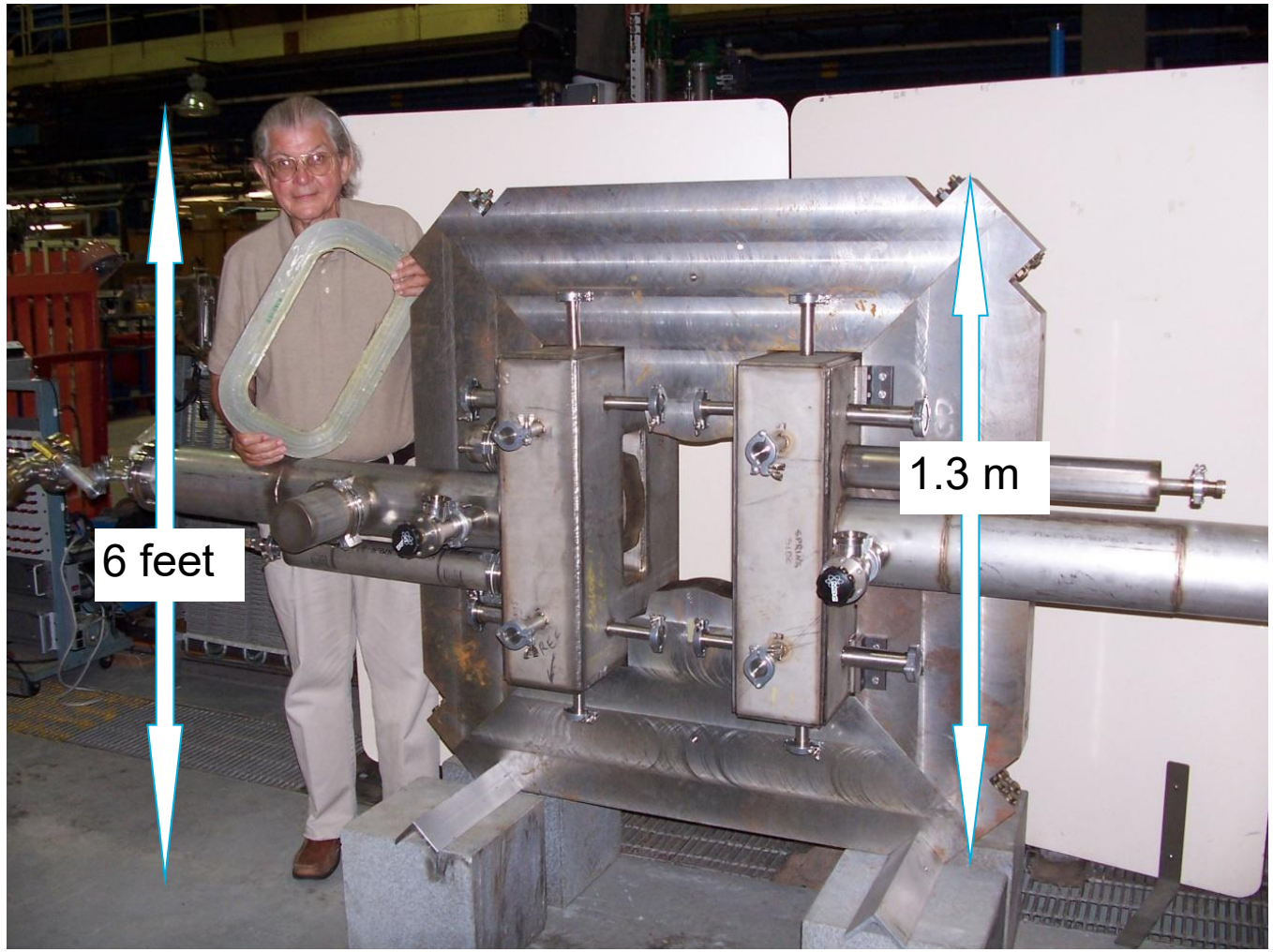
Cover Plates Cooled by Helium Gas

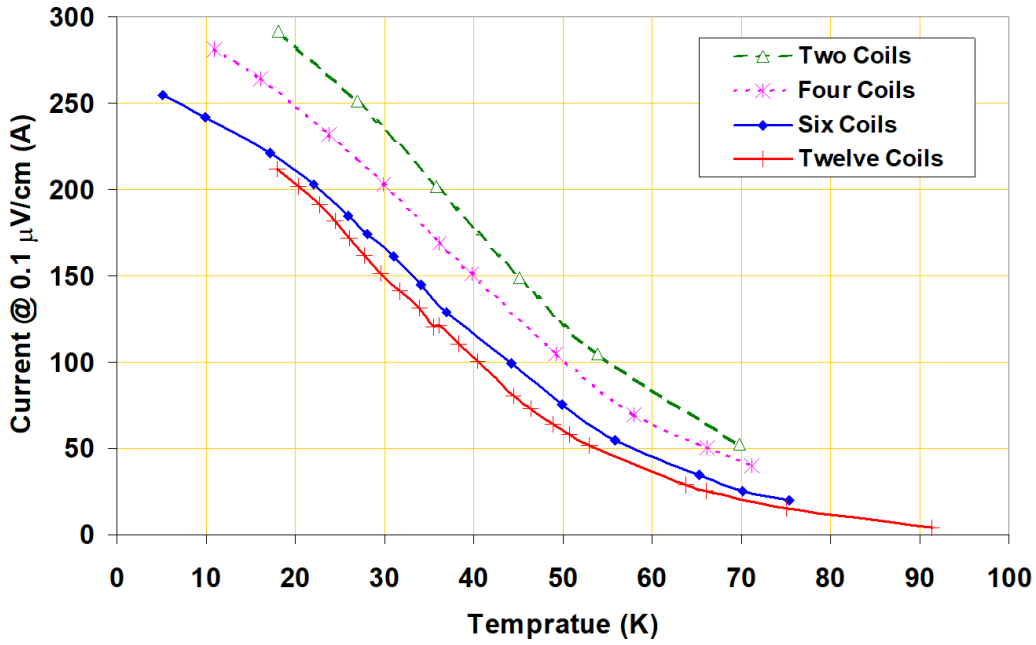
An example of how HTS coils were tested





Temperature Adjusted with Helium Flow Rate





Was part of a major program at BNL RIA/FRIB

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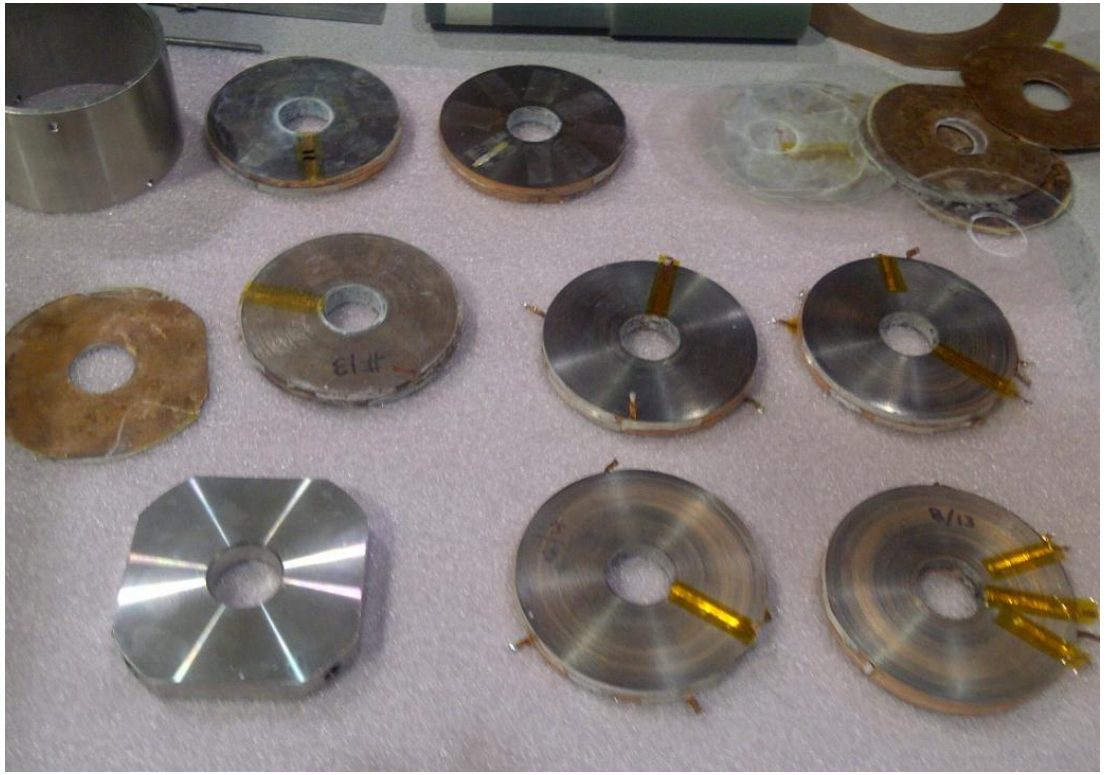
Quench studies with a large number of expensive HTS coils leftover from the previous R&D programs

(No fear of destroying them for a "burn to learn" approach)




Continue development of BNL's Advanced Quench Protection Electronics

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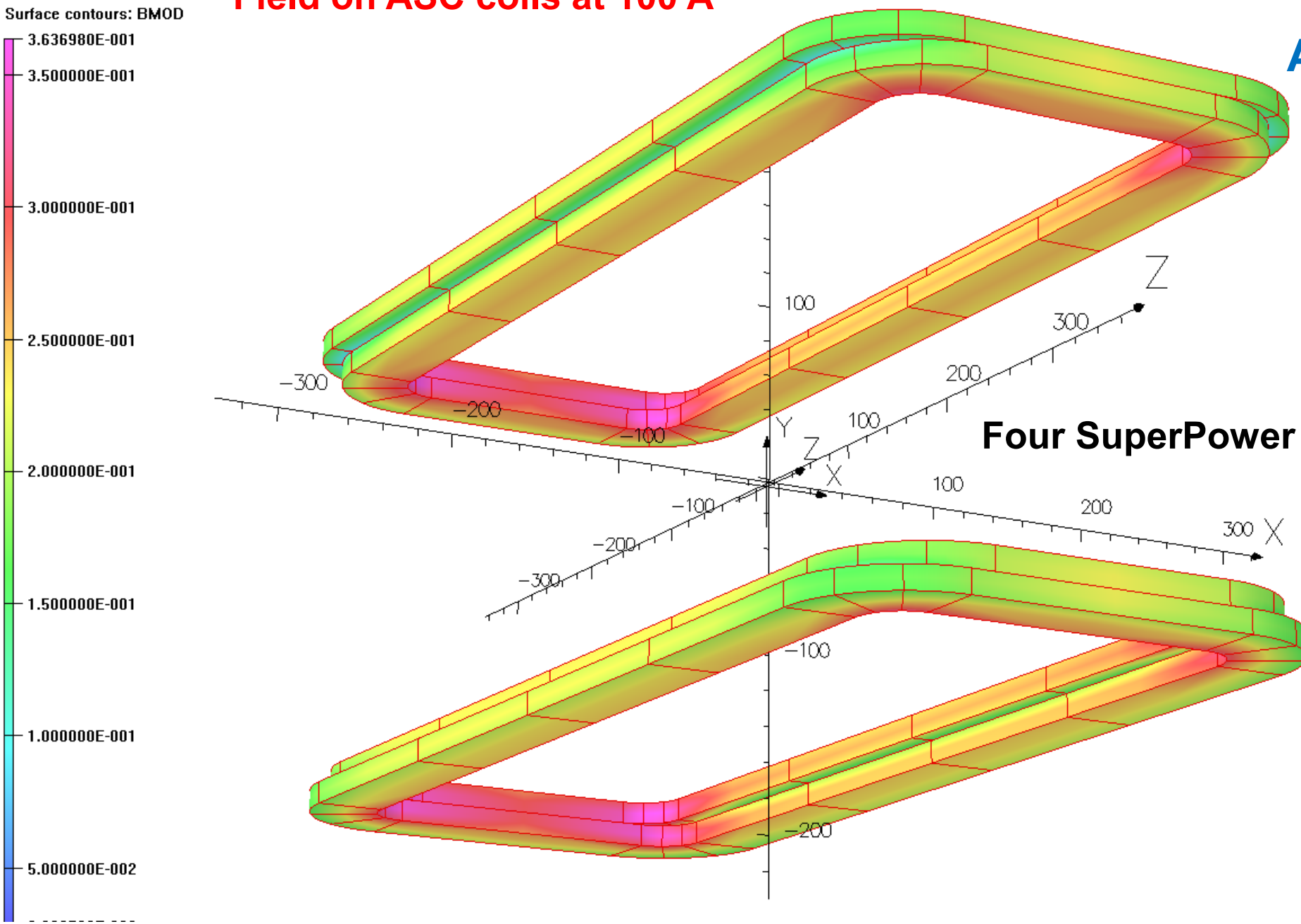
Extra Slides

Planned Addition to MDP Program at BNL

- **There are very few HTS R&D accelerator type magnets built with large coils. It is important to evaluate the impact of moving to larger scaler as sometimes there are surprises in scaling up (including quench protection, etc.).**
- **Also, there is a significant interest in the higher temperature operation (20 K or so) of fusion and accelerator magnets in future.**
- **MDP Plans at BNL take advantage of the existing large HTS coils (cost and schedule driver for most programs) that were earlier built for R&D program for FRIB.**
- **Ongoing other programs will continue. Overall progress will depend on the budget.**

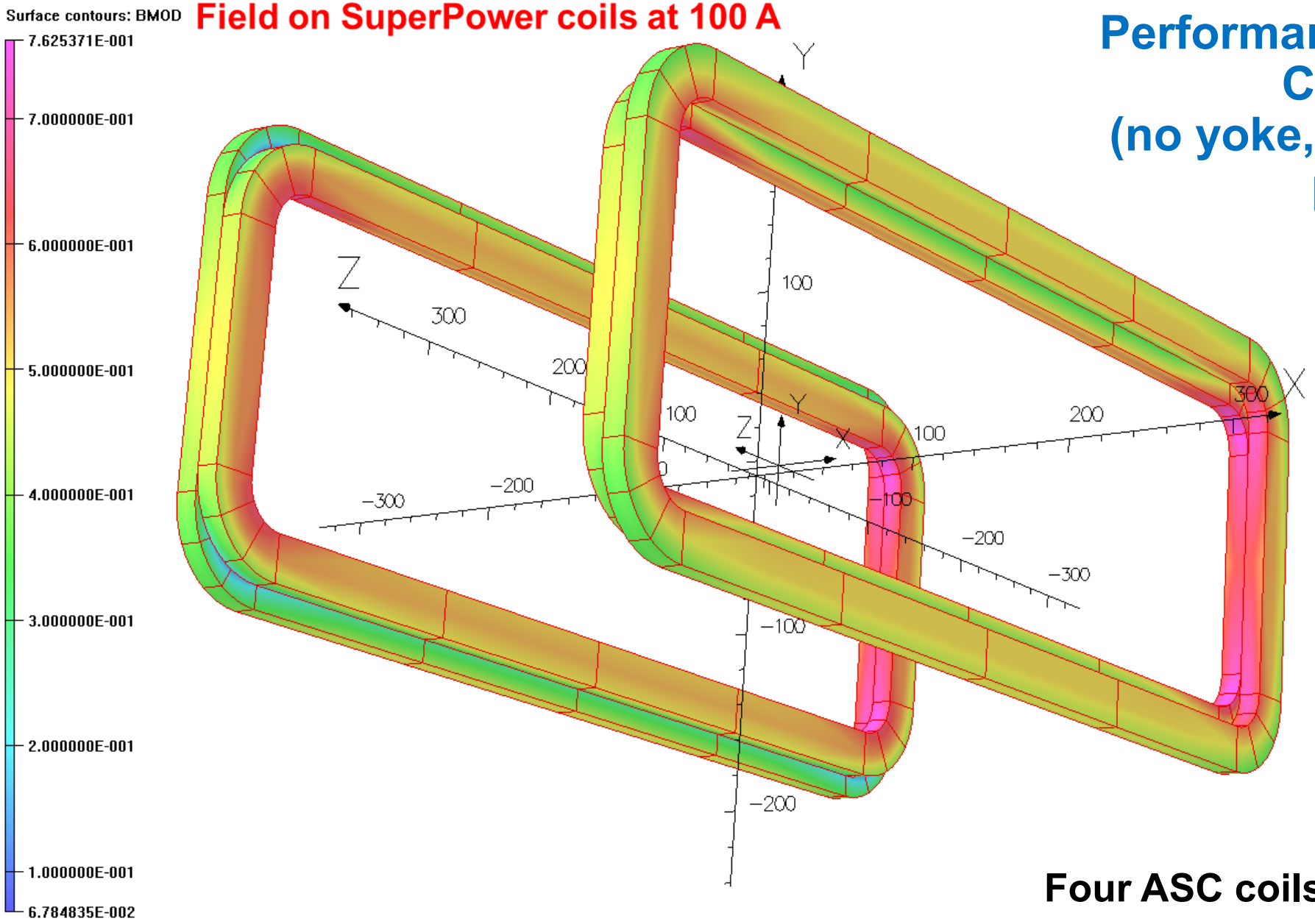
Field on ASC coils at 100 A



Performance of ASC Coils at 77K (no yoke, four coils of eight powered)

Four SuperPower coils were not powered

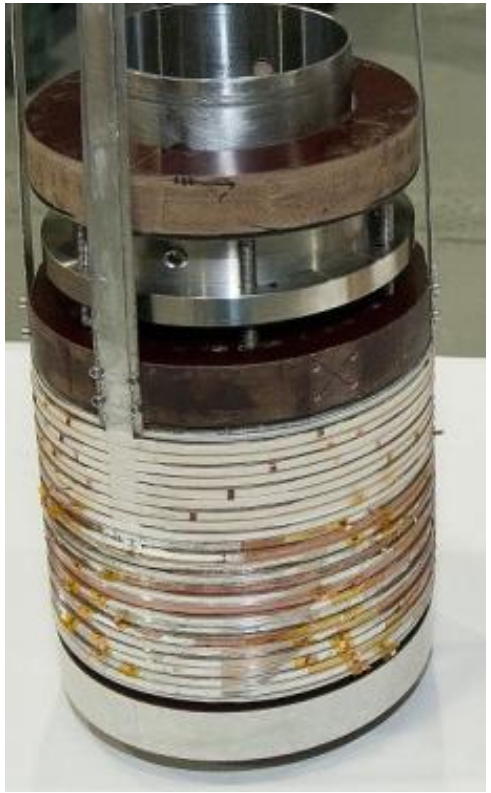
Performance of SuperPower Coils at 77K (no yoke, four coils of eight powered)



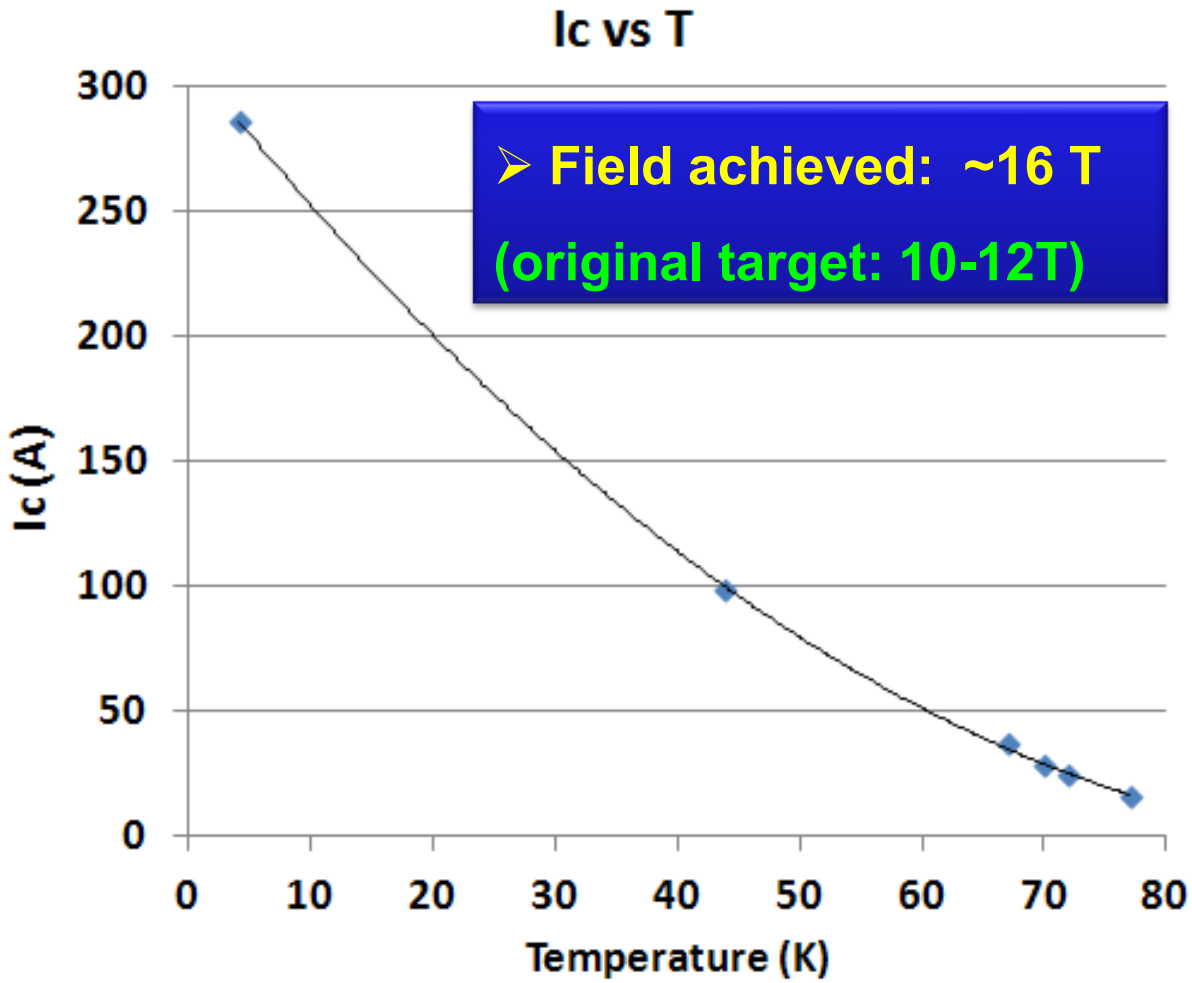
Four ASC coils were not powered

HTS 16 Tesla Solenoid (Record HTS field in 2012)

Insert solenoid



Outsert solenoid

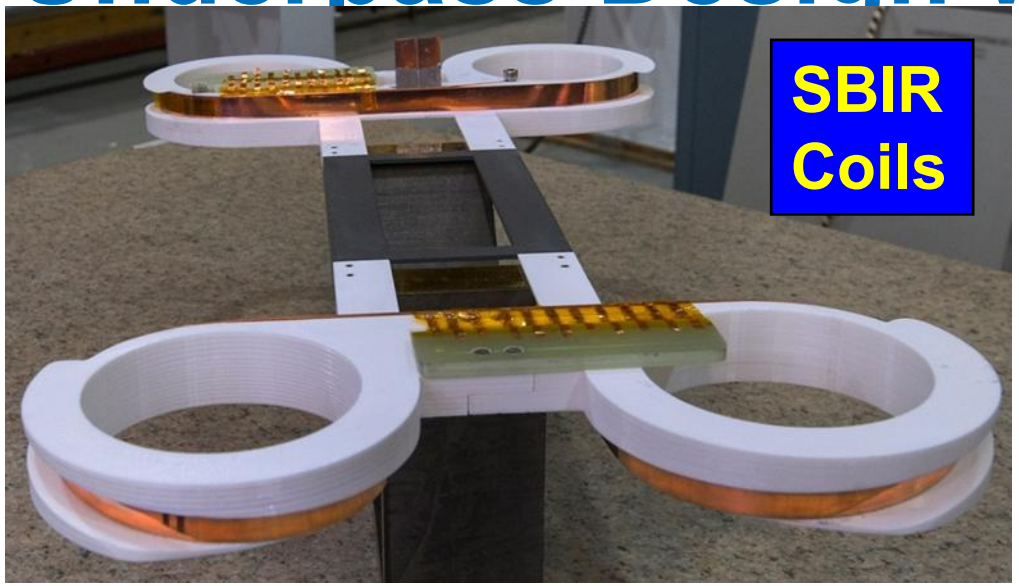


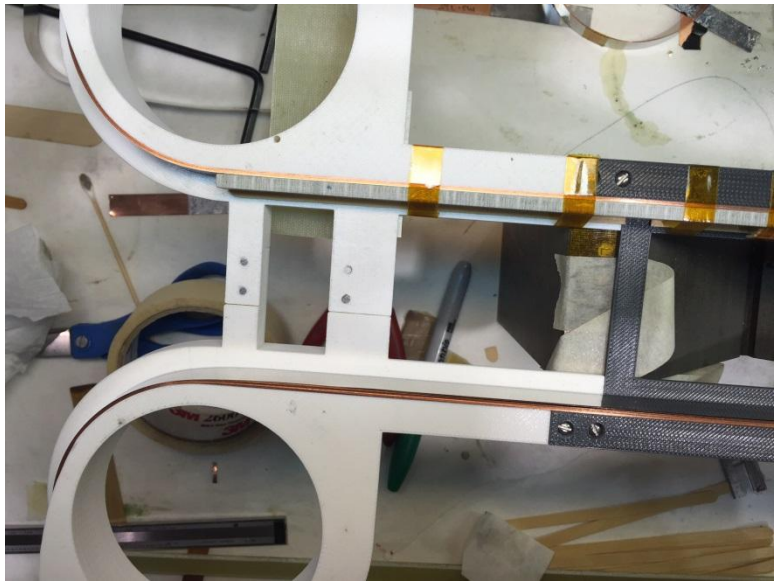
Overall Current Density (J_o) in the coil: >500 A/mm^2 @16 T

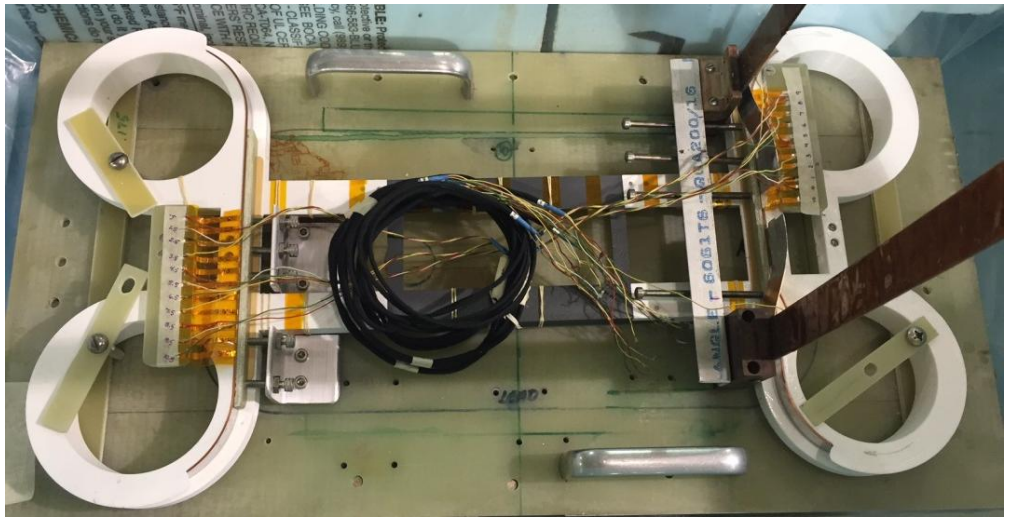
Demonstrations of the Overpass/Underpass Design with HTS Coils

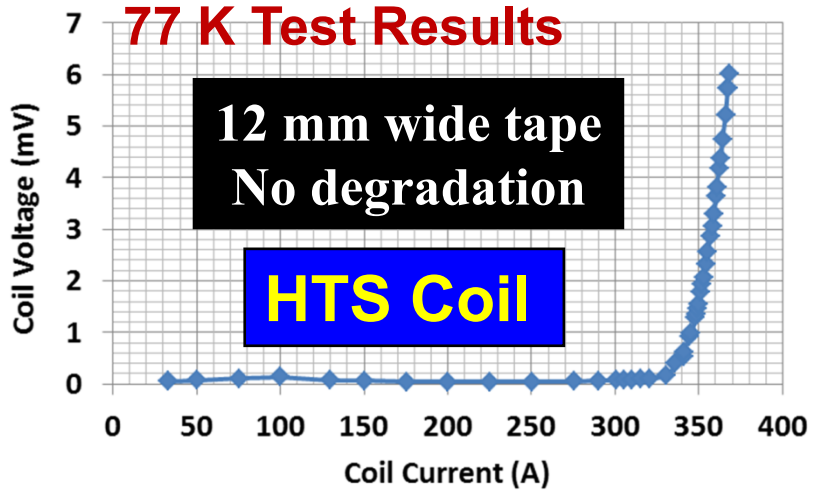
Another Innovative Design from BNL developed at BNL under previous GARD program. Followed by two SBIRs- e2P & PBL

Adapted at CERN for its earlier 20 T HTS program. Coils built & tested CERN









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FRIB HTS QUAD - Magnetic Design