A New Magnet R&D Approach and Test Facility for High Field Magnets

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OVERVIEW

- A new approach to magnet R&D
  - Rapid-turn-around, lower-cost R&D to test innovative ideas and to perform systematic studies
- A unique test facility dipole
- Past, current and future programs
  - Current program: HTS/LTS hybrid dipole
- Future plans for enhancing the test facility

Magnet R&D Approach

- Conventional development of a new technology requires building and testing one or a series of R&D magnets
- Examples:
  - New conductors
  - Coils made with new cables
  - New insulations
  - New epoxies
  - New coil designs
- Building and testing, however, takes several years and a significant budget
  - **NOT** building and testing coils near the desired field level increases the risk, particularly for the high field magnets
- This reality has shaped our thinking

Limitations on Technology Development

- If it takes several years and a significant budget, it puts pressure on the magnet program to demonstrate a success
- That discourages us from deviating significantly from those "*that sort of works*" and limits optimizing of a "*sort of working technology*"
- It limits the development of a new technology "***unless one has to***"
- On the other hand if a magnet doesn't work, we tend to change several things at a time. Then if the magnet starts working, it becomes difficult to distinguish what made it work => incorporate all changes?
- **In summary, the cost and time needed to demonstrate a new technology at high fields has limited the development of new technologies and also optimization of the existing ones**
- **A comprehensive magnet development program ought to develop strategies to overcome above inherent limitations**

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New R&D Approach Concept (rapid turn-around, low cost)

Five Simple Steps/Components

1. Magnet (dipole) with a large open space
2. Coil for high field testing
3. Slide coil in the magnet
4. Coils become an integral part of the magnet
5. Magnet with new coil(s) ready for testing

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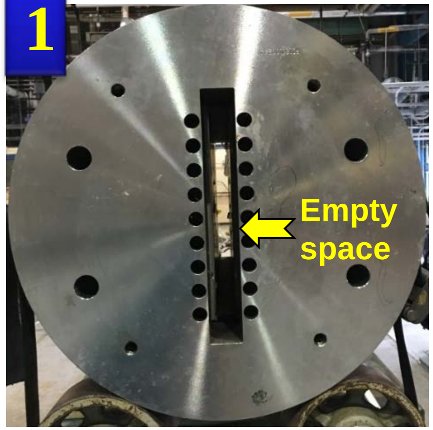

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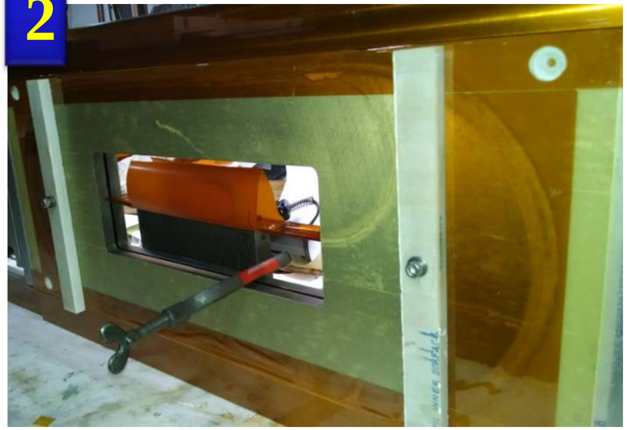

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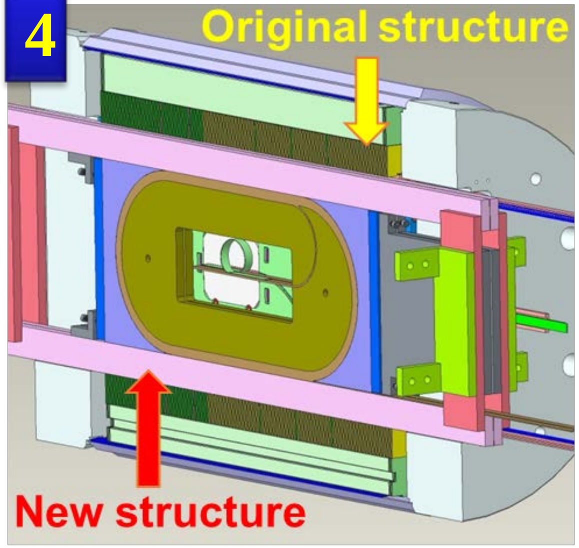

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Guiding Principle of the R&D Approach

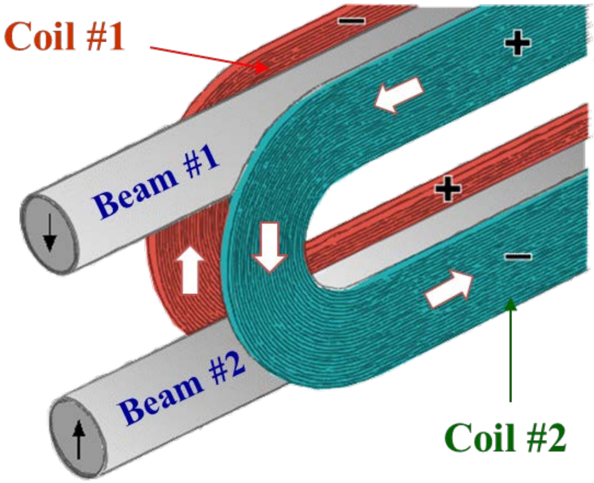
GUIDING PRINCIPLES

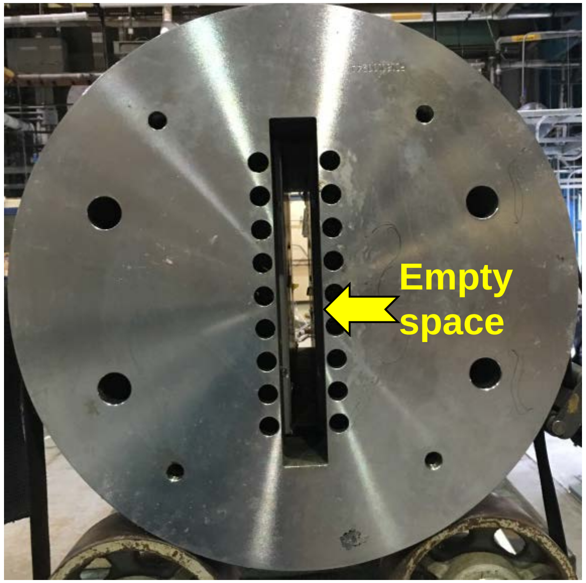
- A test vehicle where new coils can be tested in a short period of time (a few months) and in a reasonable budget (few hundred k$)
- Tests are performed at a significant field (potentially up to 16+ T on coils) making them relevant for the high field magnet technology
- New coils become an integral part of the magnet so that a new coil test can be considered as an R&D test of the new magnet technology

OUTCOME:

- If above works, it changes our thinking on how to plan magnet R&D
- It will allow us to be more enterprising since a potential setback will be failure of a coil, not failure of a magnet (less dramatic)
- Moreover, rapid-turn-around will allow systematic studies

A Unique Background-field Dipole





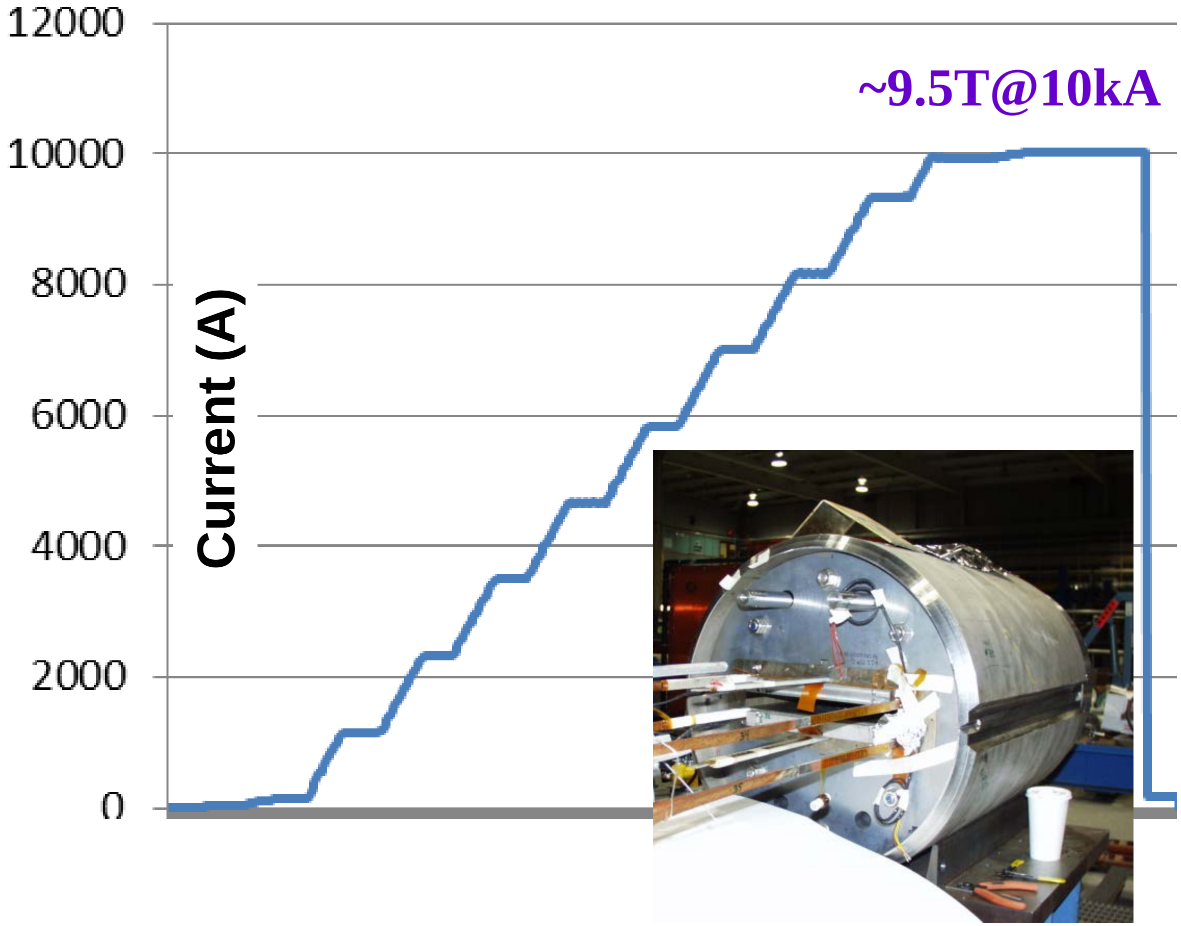
- Nb_3Sn, 2-in-1, common coil dipole
- Structure specifically designed to provide a large open space (31mm wide, 335mm high)
- New racetrack coils can be inserted here for testing them in a background field of ~10 T
- These new insert coils come in direct contact with the existing Nb_3Sn coils and become an integral part of a potential 16+ T magnet
- A new coil test becomes a new magnet test
- A rapid-turn around and low-cost test

BNL Common Coil Dipole DCC017
A Robust Magnet for Test Facility

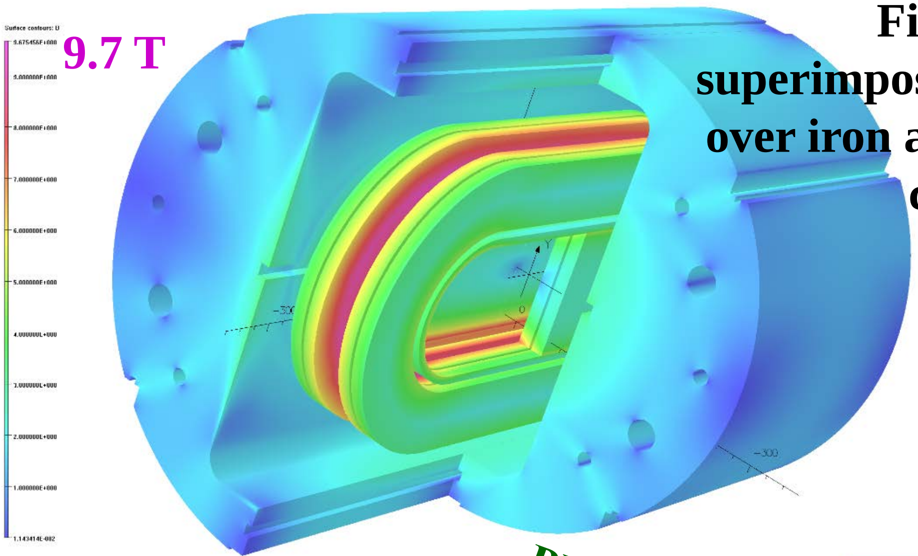
- **Short Sample: 10.8 kA (reached during 2006 test)**
- **Retest (2016): No quench to 10 kA (>92% of SS)**

Worked well when tested after a decade

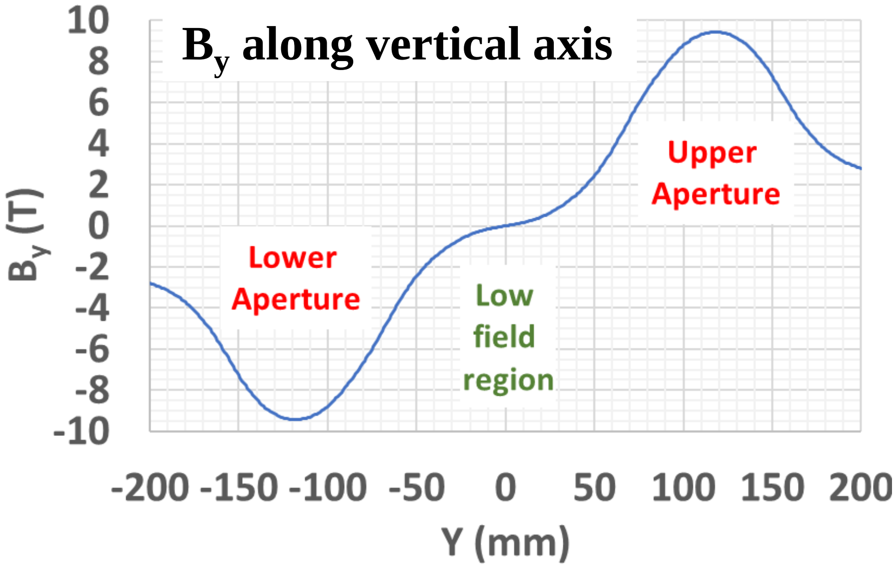
It was a display piece of Nb_3Sn "React & Wind" technology for dipole



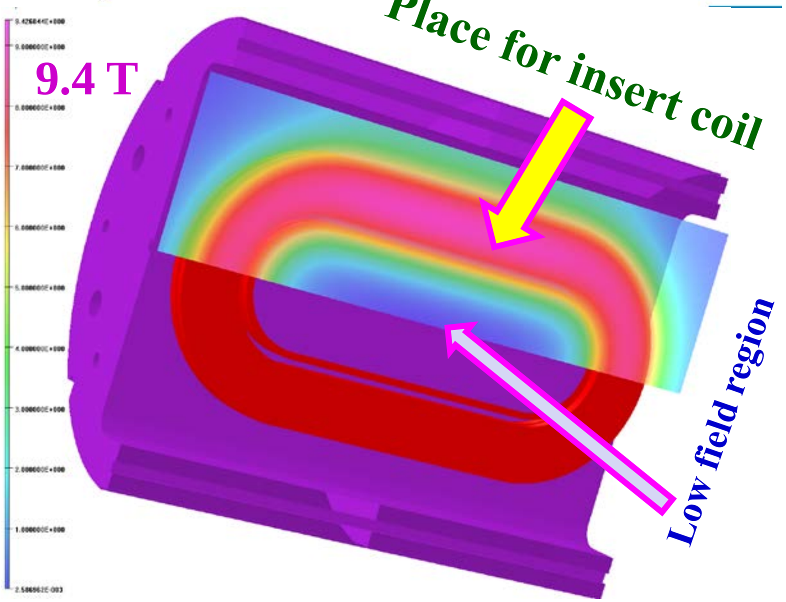
Magnetic Fields at 10 kA

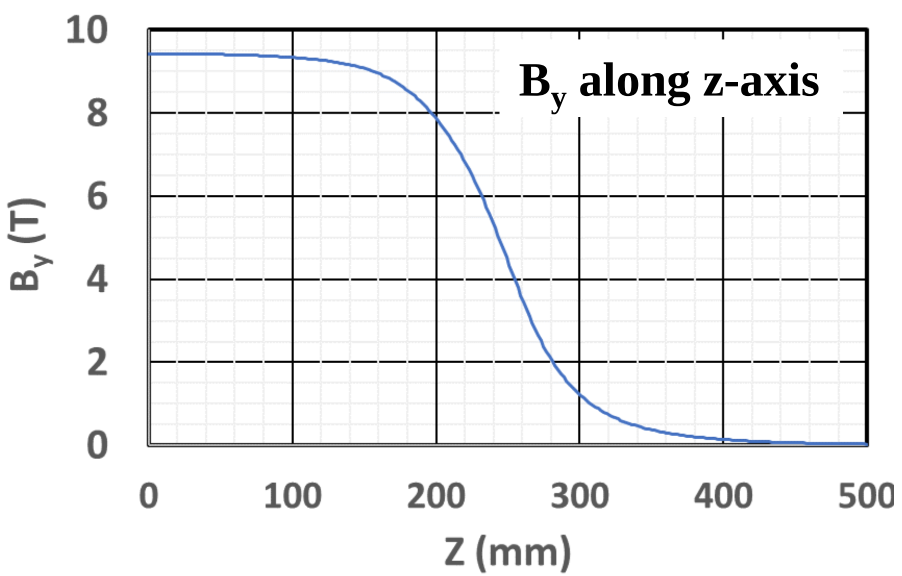


Field superimposed over iron and coil

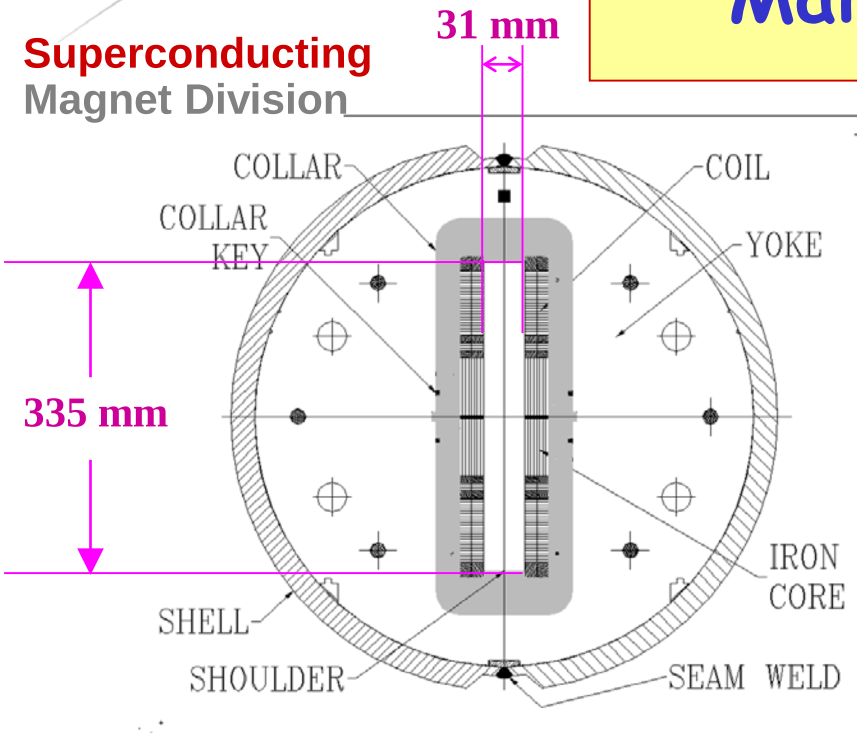


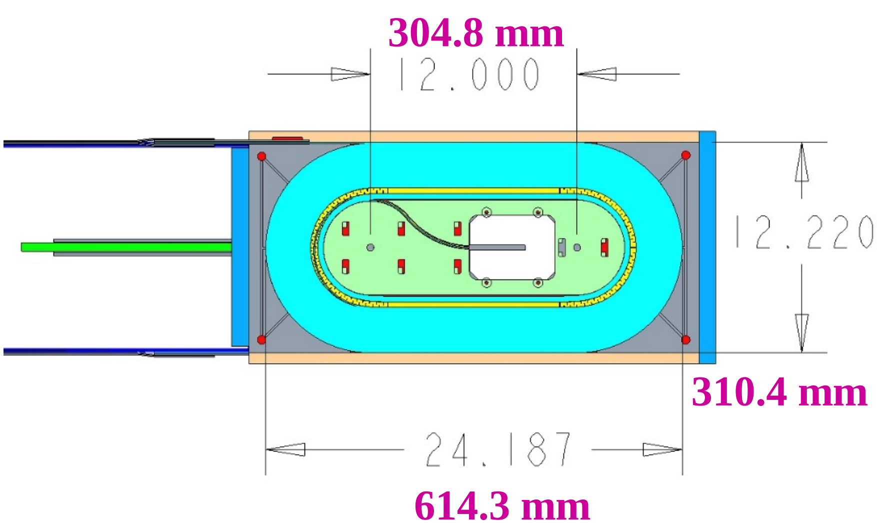
Field @ x-z plane





Main Parameters of DCC017

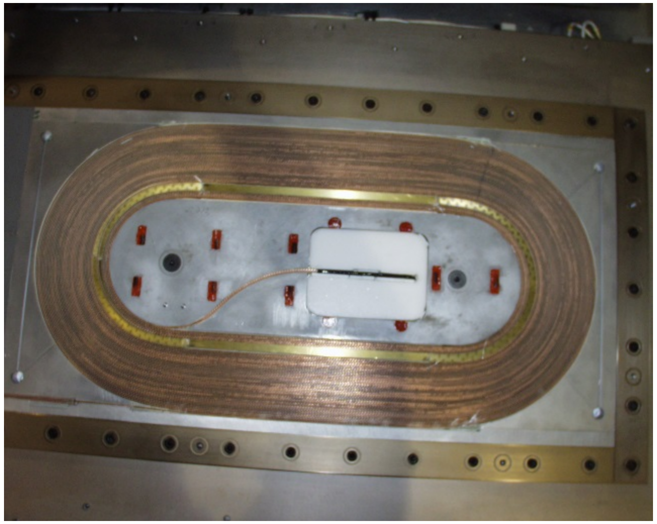


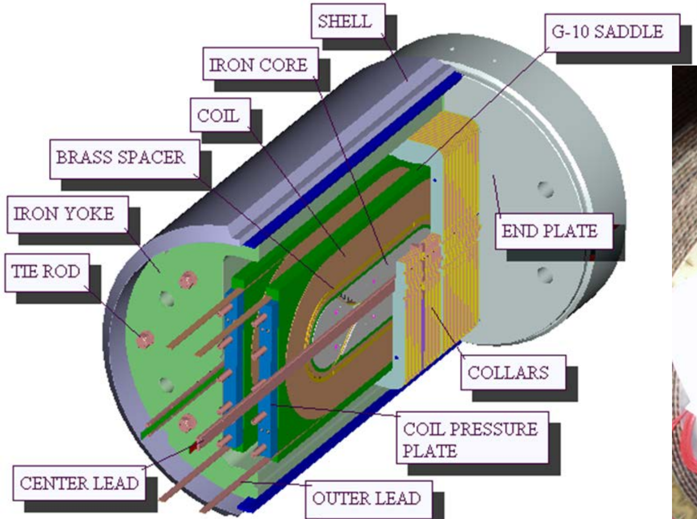


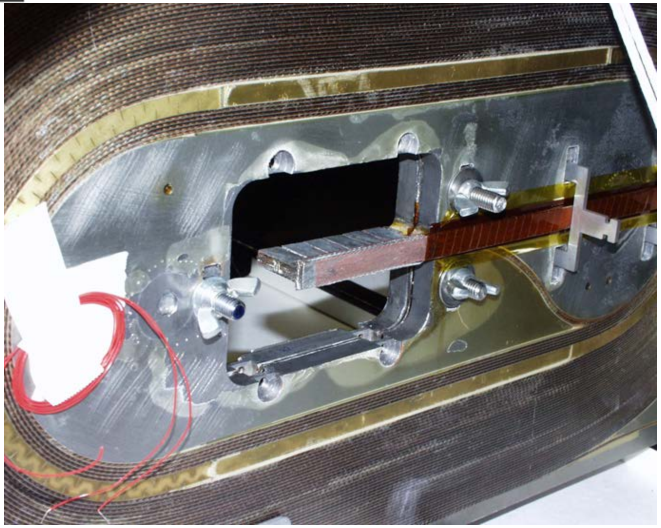
- Nb_3Sn, R&W, dual aperture dipole
- Short sample current: 10.8 kA
- Maximum current reached: 10.8 kA
- Bore field: 10.2 T
- Peak field: 10.7 T
- Horizontal opening: 31 mm
- Vertical opening: 335 mm
- Coil height in each aperture: 85 mm
- Straight section: 305 mm
- Coil length: 614 mm
- Center-to-center btw 2 aperture: 118 mm
- Stored Energy @ Quench: ~0.2 MJ
- Inductance: 4.9 mH

Details of the Magnet DCC017
(React & Wind Dipole with Low Pre-stress)

Magnet design	2-in-1 common coil dipole
Conductor type	Nb_3Sn
Magnet technology	React and wind
Horizontal coil aperture (clear space)	31 mm
Vertical coil aperture (clear space)	338 mm
Separation between upper and lower aperture	220 mm
Number of layers	Two
Number of turns per quadrant of single aperture (pole-to-pole)	45 turns in each layer
Coil height (pole-to-pole)	85 mm
Wedge(s) (size and number)	8.5 mm, one in each layer (inner & outer)
End-spacer(s) (size and number)	8.5 mm, one in each layer (inner & outer)
Wire non-Cu J_{sc} (4.2 K, 12 T)	1900 A/mm^2
Strand diameter	0.8 mm
Number of strands in inner and outer cable	30
Cable width in inner and outer layer	13.13 mm
Cu/Non-Cu ratio in the wire of inner and outer cable	1.53
Computed quench current	10.8 kA
Computed quench field @4.2 K (including cable degradation)	10.2 T
Peak field at quench in inner, outer Layer	10.7 T, 6.1 T
Coil bobbin (core) material	Carbon steel
Coil length (overall)	620 mm
Coil straight section length	305 mm
Coil inside radius in ends	70 mm
Coil outside radius in ends	155 mm
Coil curing preload - sides	0 N
Coil curing preload – ends	0 N
Cable insulation thickness	180 µm thick Nomex®
Potting agent	CTD-101K
Thickness of the collar	26.6 mm
Stainless steel shell thickness	25.4 mm
Thickness of the end plates	127 mm
Yoke outer radius	267 mm
Yoke length	653 mm







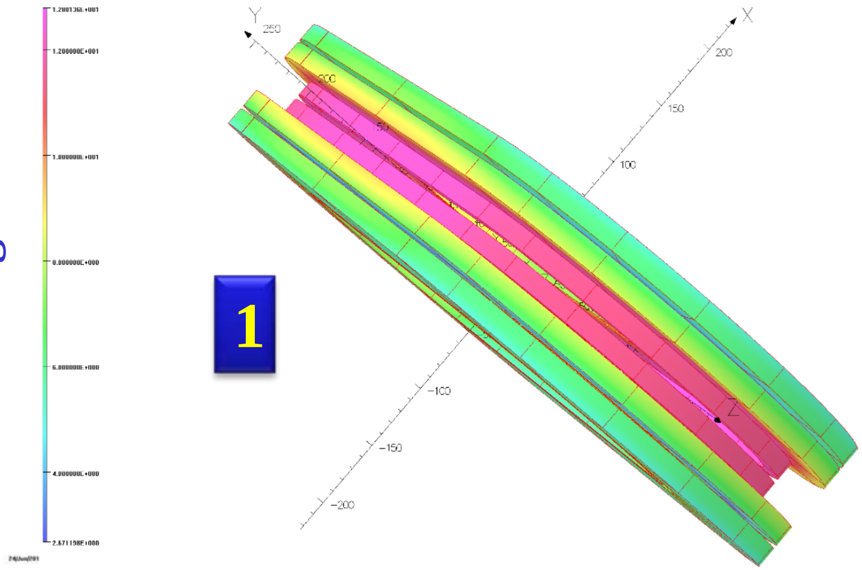
Benefits of the Rectangular Opening in Common Coil Structure

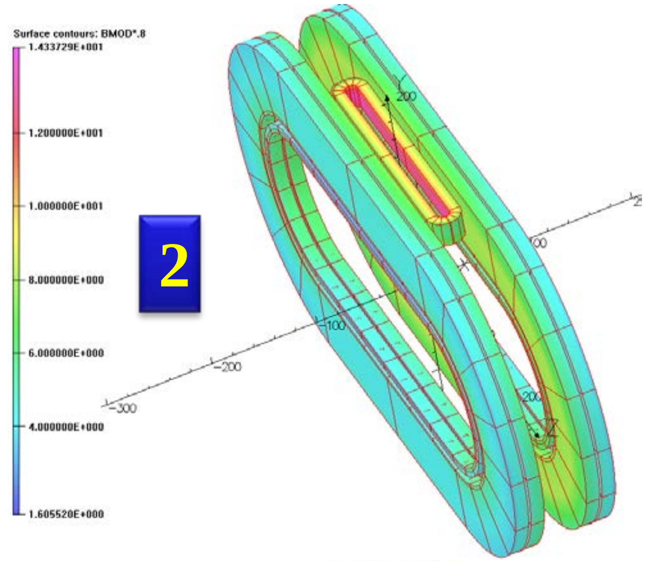
Rectangular opening has several inherent advantages:

- **It provides a flexible structure to allow a different number of insert coils. These coils can have different height/width and their relative position can be changed, as long as they fit in the opening**
  - **One generally doesn't have similar flexibilities in a cosine theta magnet with circular bore**
- **These coils can be made of different materials**
- **The same opening can be used to test cables - even those cables that can't be bent in small radius**
  - **Furthermore, these cables can be looped for a longer length cable test in a high field region**

Four Possible Configurations for Insert Coils and the Cable Tests

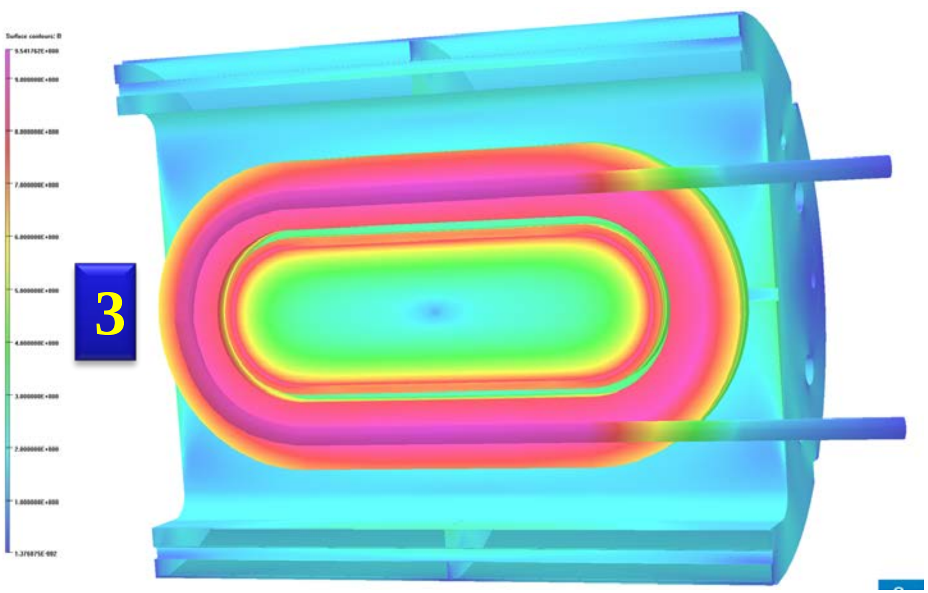
Standard insert coil test configuration

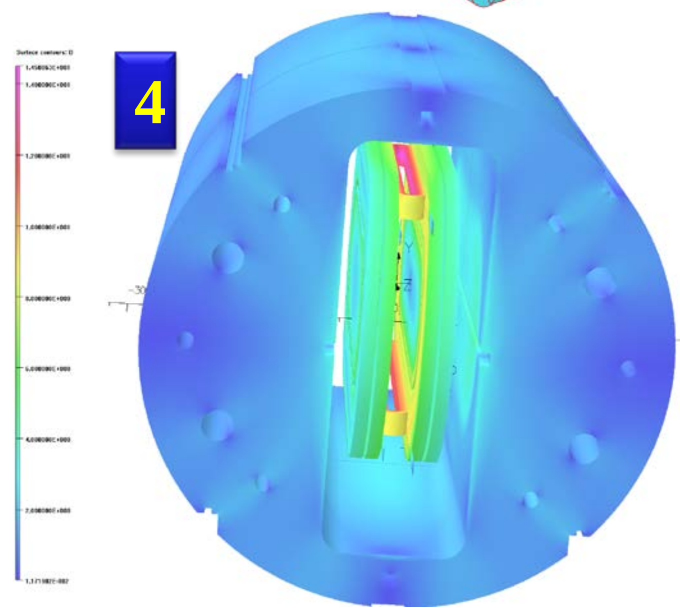




One insert coil in one aperture

Cable test configuration



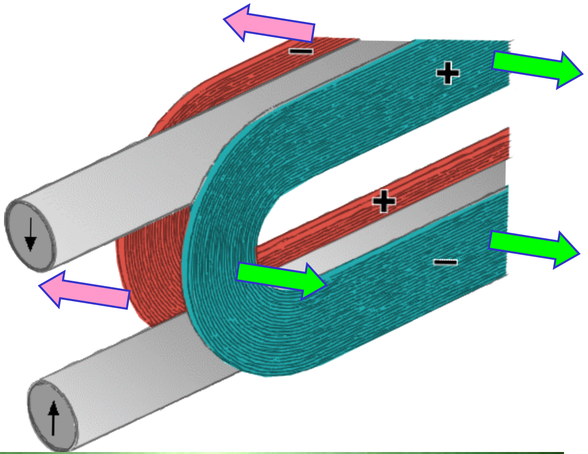


Two independent insert coils in two aperture

Key steps and Considerations

Making Insert Coils an Integral Part of the Magnet

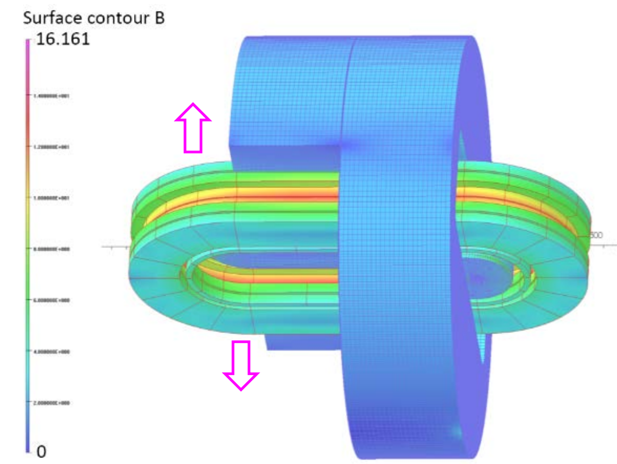
- Insert a pair of new coils in the opening. There has to be some tolerances
- These coils move apart under Lorentz forces and make contact with the existing magnet coils. This makes the insert coils an integral part of the magnet
- A flexible splice between two coils has been developed which allows this motion. It stays in the low field region of the common coil
- The insert coils can be operated with an independent power supply or in series with the main magnet coils

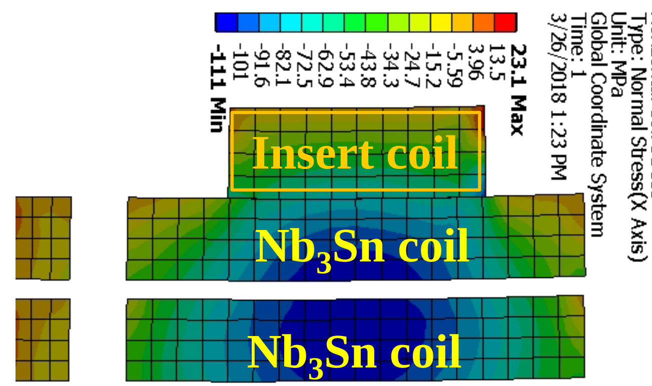


A flexible splice

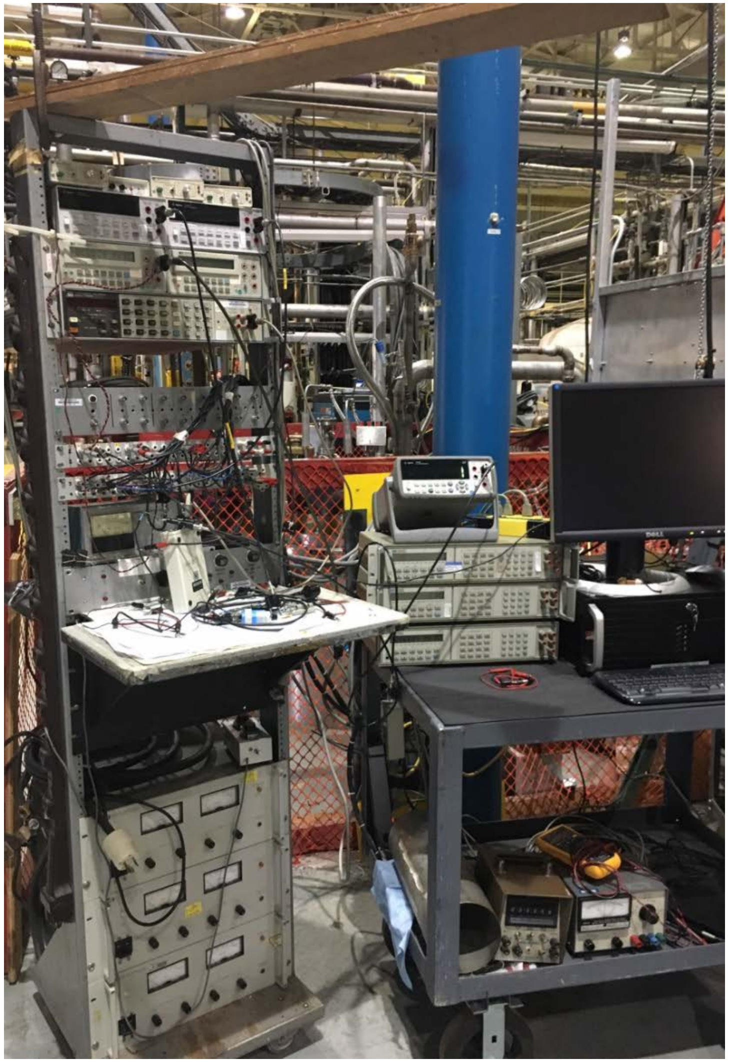
Capability of Magnet Structure

- Structure of DCC017 is designed to deal with much higher loads than that of Nb_3Sn coils only
- The additional forces from the insert coils cause additional deflections on the support structure and additional stress/strain on the NB_3Sn coils
- Calculations show that the DCC017 structure may accommodate a field of 16 T generated by the combination of the insert coil and the Nb_3Sn coils
- Computed stress and strain on the Nb_3Sn coils remain within acceptable limit





Quench Protection



- Quench protection system is designed to protect both the main magnet coils and the insert coils
- The insert coil may be HTS or LTS
- BNL advanced quench protection with fast energy extraction has protected both HTS and LTS coils
- The impact of inter-coil coupling (specially in the event of quench) is an important consideration

Projects Using New R&D Approach and Test Facility at BNL

- **Experience with the successfully completed project**
  - HTS/LTS hybrid dipole (funded by an SBIR/STTR)
- **Current project underway with a significant progress**
  - HTS/LTS hybrid dipole (funded by the Magnet Development Program or MDP)
- **Projects already funded with some progress**
  - CORC coil magnet with HTS and LTS cable coils running in series (funded by SBIR/STTR)
  - CORC cable quench studies in a short coil (funded by the MDP)
- **Proposals (not yet funded)**
  - Quench studies in twisted-stack-cable (may be funded by INFUSE)
  - HTS/LTS hybrid dipole (may be funded by US/Japan collaboration)
  - Bi2212/Nb_3Sn hybrid dipole (LBL/BNL collaboration to be funded by MDP)
  - Texas A&M high current cable test (may be funded by MDP or INFUSE)

First Demonstration of DCC017 to Carry out New R&D Approach

Design, build and test a respectable field HTS/LTS hybrid dipole for PBL with the budget of an SBIR

- **Insert coil made with the HTS tape**
- **Assure quench protection**
- **Perform magnetization measurements**

SBIR to Demonstrate a Significant Field HTS/LTS Hybrid Dipole

- SBIR have a limited budget and limited time scale
- So it has to be a low-cost, rapid-turn-around Program

- **SBIR with Particle Beam Lasers, Inc. (PBL) to design, build and test a respectable field HTS/LTS hybrid dipole**
  - Wind HTS coils with the ReBCO tape
  - Integrate a pair of HTS coils with Nb3Sn dipole DCC017
  - Assure quench protection
  - Perform magnetization measurements

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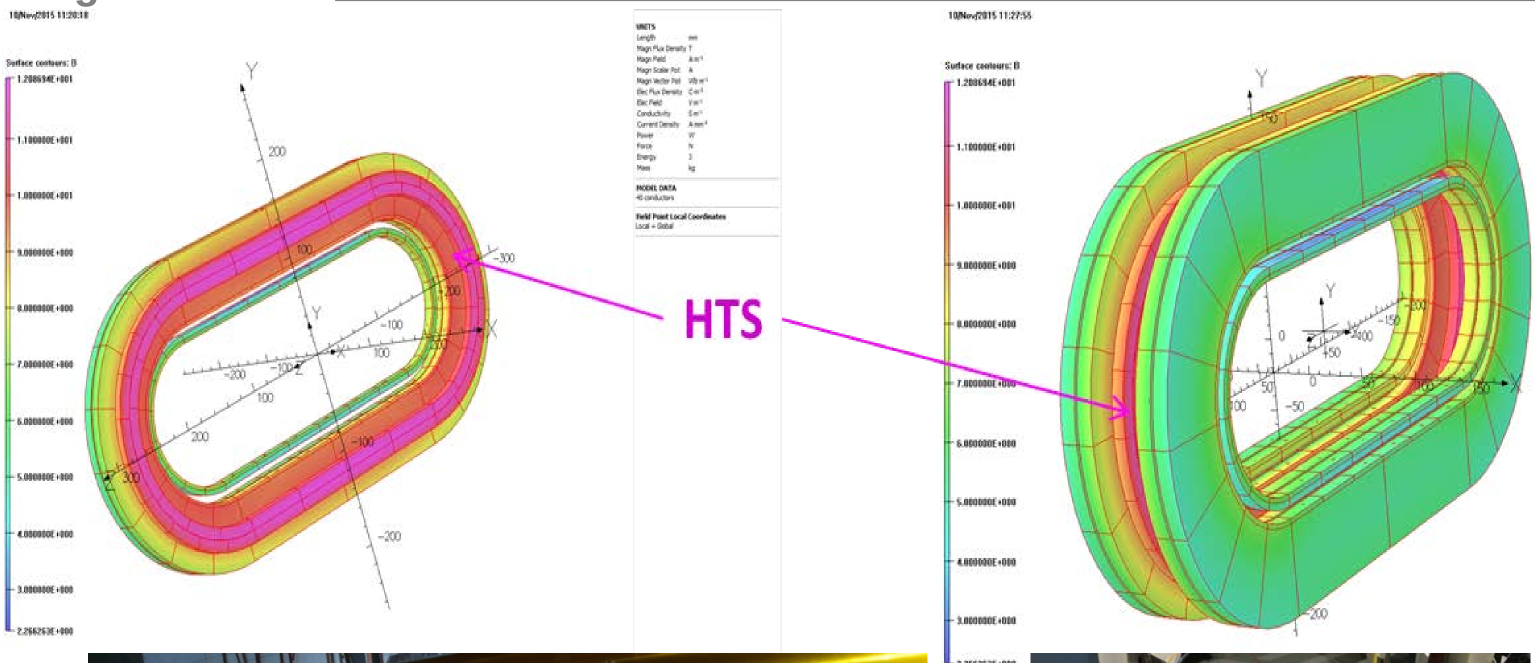
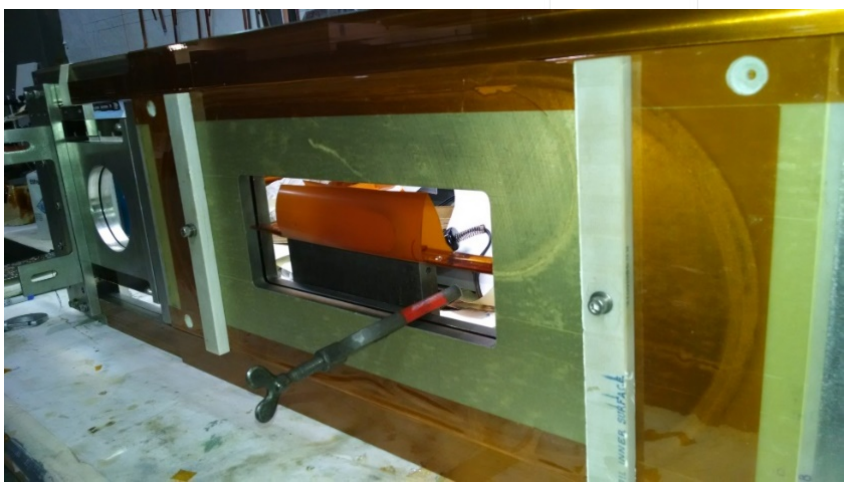
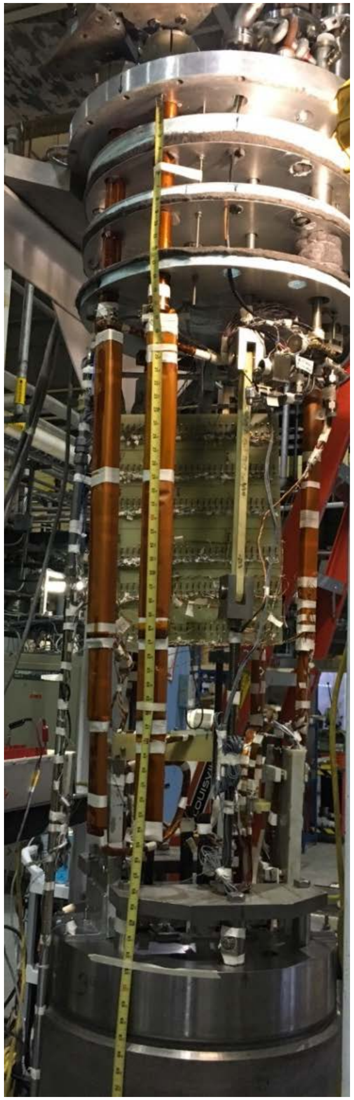
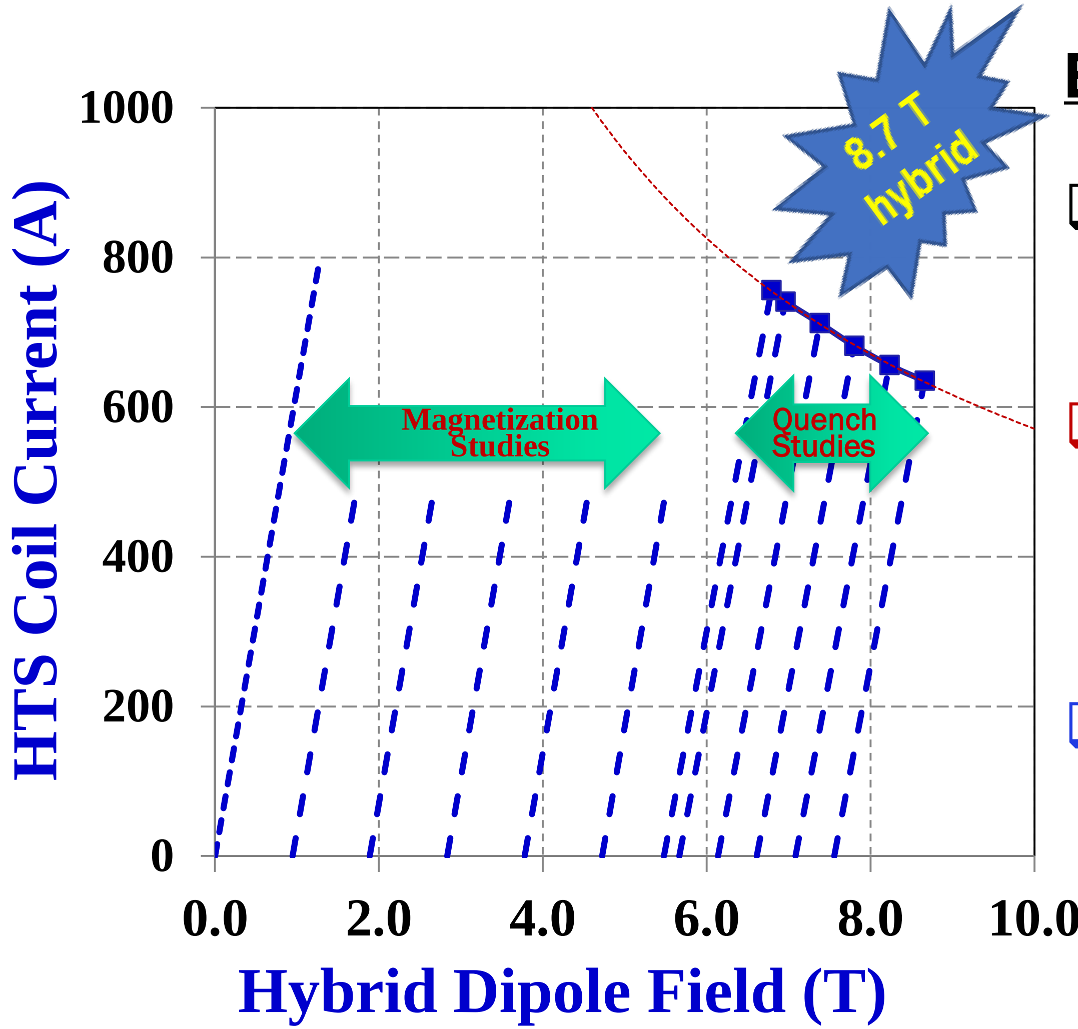
HTS/LTS Hybrid Dipole (field on HTS coils primarily perpendicular)







HTS/LTS Hybrid Dipole Test Results
(new HTS insert coils with existing Nb_3Sn magnet coil)



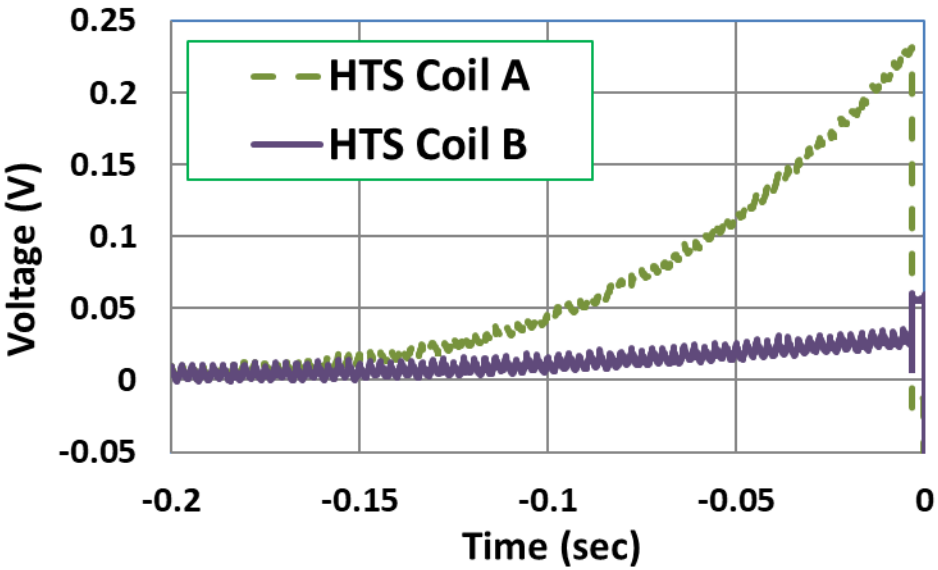
Encouraging Results:

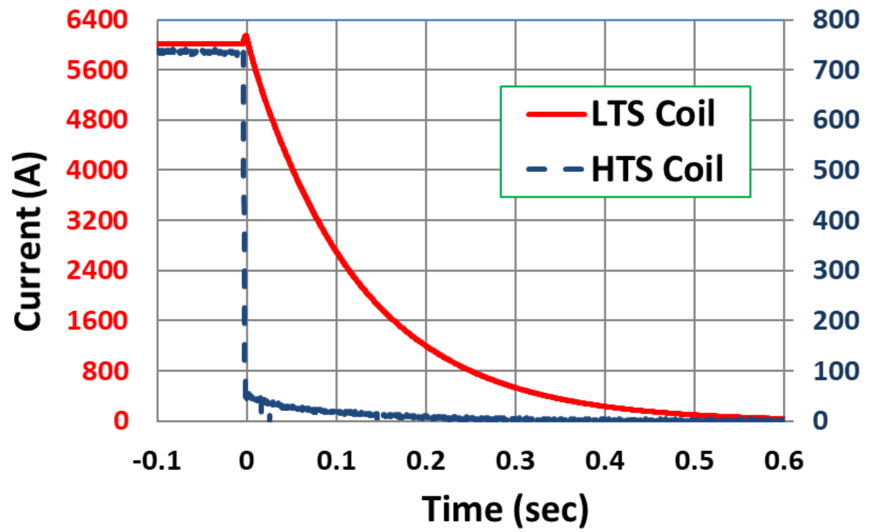
- HTS coils were ramped to quench, just like LTS coils
- HTS coils had no training, no degradation despite a number of quenches
- Field error studies with wide face of the HTS tape aligned primarily perpendicular to field

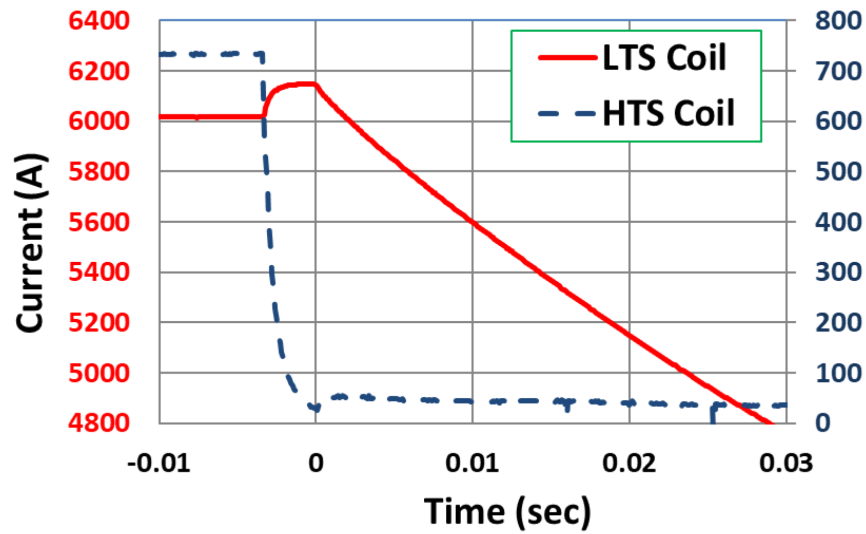
Reported at MT25

Quench Protection of HTS Coils in HTS/LTS Hybrid Magnet

HTS coils operated like HTS coils
Significant voltage in HTS coils







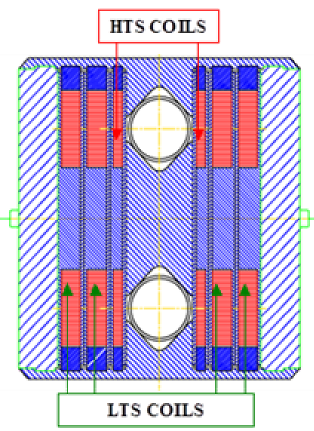
- HTS and LTS coils were operated with different power supplies and had separate energy extraction under a common platform
- Coupling between HTS & LTS

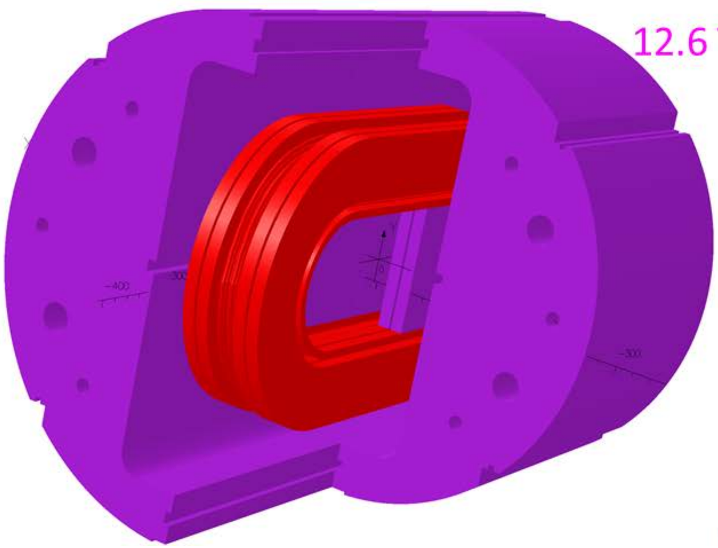
Second Funded Project Using DCC017

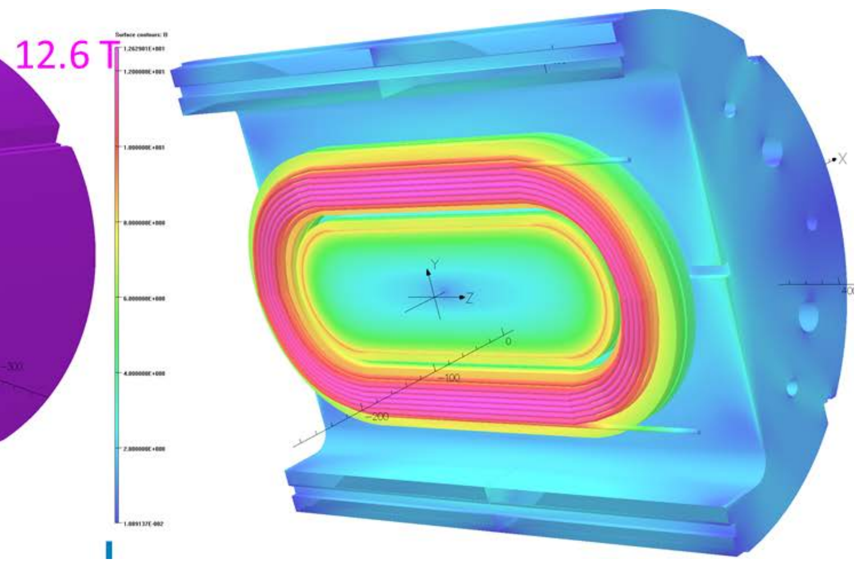
(Phase II STTR with Advanced Conductor Technologies LLC)

Coils made with high current CORC® cable inserted in DCC017 to "operate in series with Nb_3Sn coils" (it has many advantages)

Courtesy: Danko van der Laan



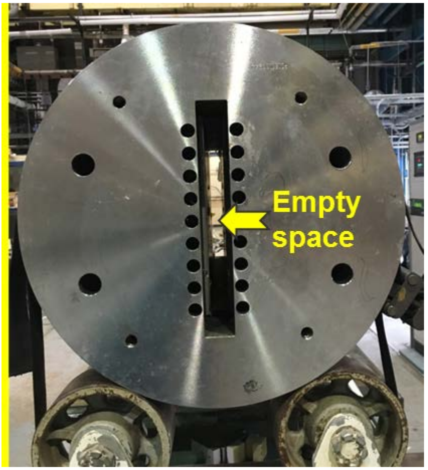




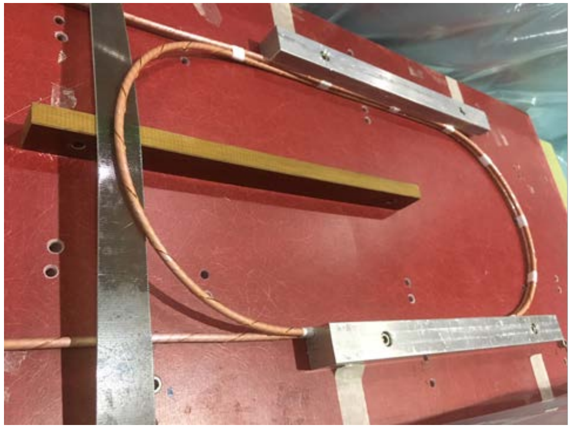
Common coil design accommodates high current CORC cable with large bend diameter in racetrack coil geometry

Test of High Current CORC®

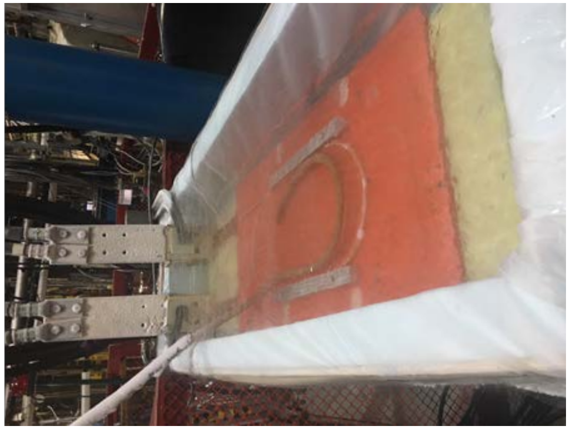
Dipole DCC017



Cable bent and lifted (as per the design of DCC017)

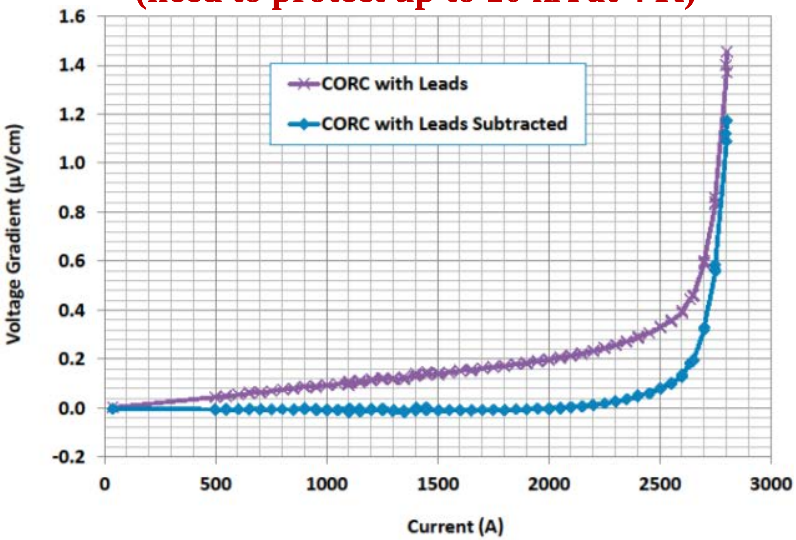


High current test in LN_2

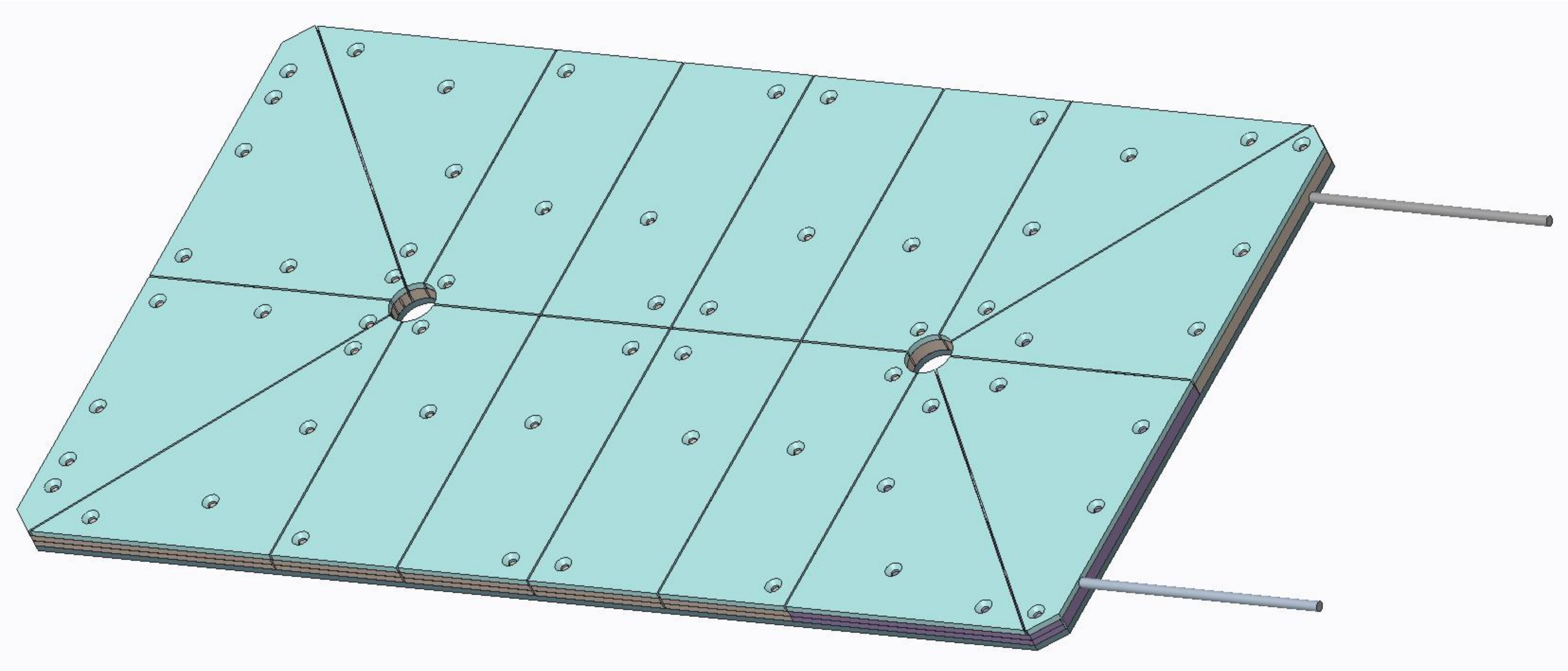


Advanced control and quench protection system

No degradation from quenches at ~2.8 kA (need to protect up to 10 kA at 4 K)



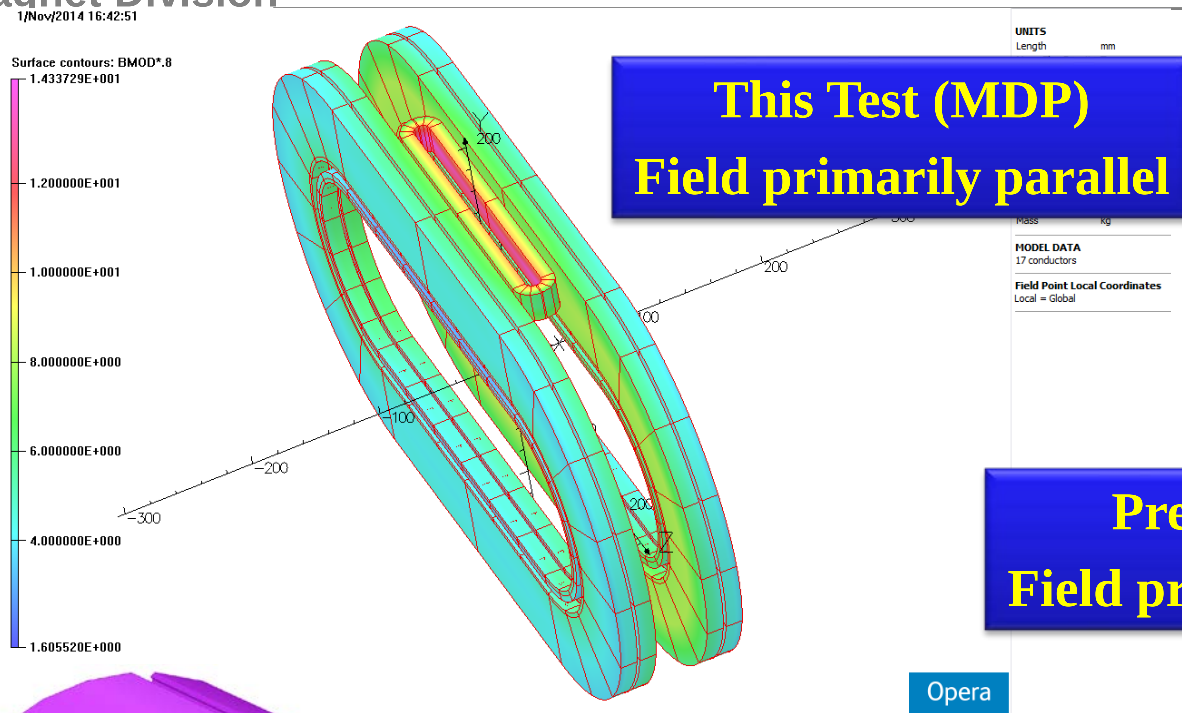
A Possible Structure of CORC Coil Module that can be inserted in DCC017



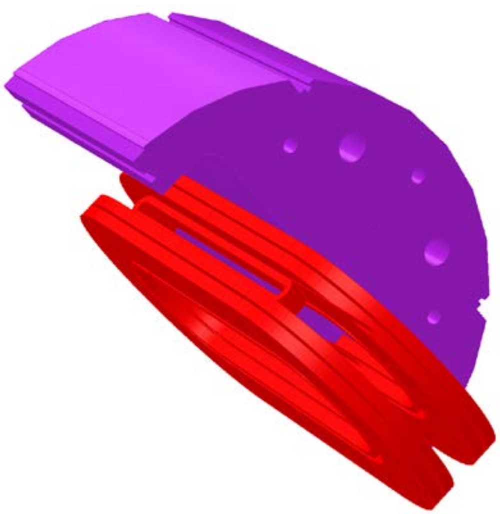
Third Funded Program (getting ready for testing)

- HTS/LTS Hybrid by the US Magnet Development Program (MDP)
- The primary goal of this program is to perform field error measurements of the HTS coils with the wide face of HTS tape aligned primarily parallel to field
- Another important goal is to perform quench protection studies of HTS coils in HTS/LTS hybrid structure (coupling between the HTS/LTS coils in the event of quench)

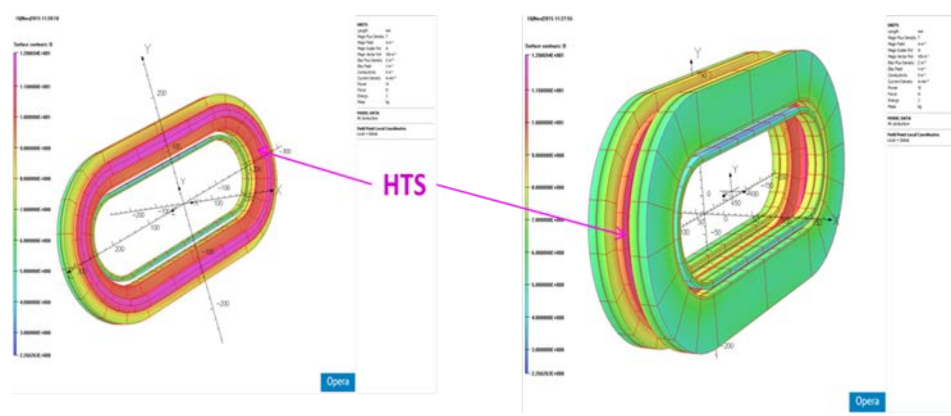
Insert Coil Configuration



This Test (MDP)
Field primarily parallel



Previous Test (SBIR)
Field primarily perpendicular



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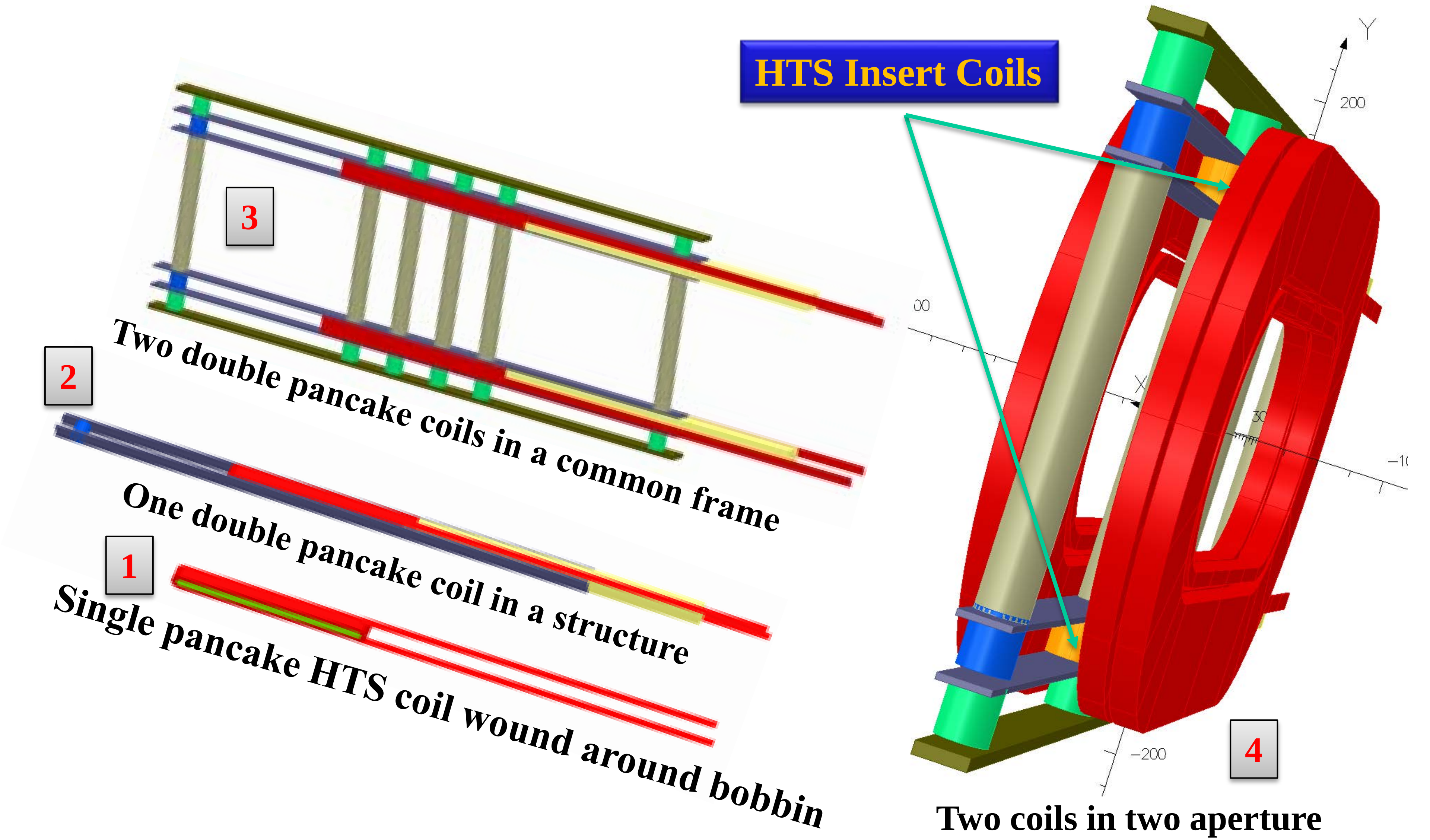
HTS Coils in Different Stages of Construction

HTS Coil Structure Concept (two inserted between Nb_3Sn coils)



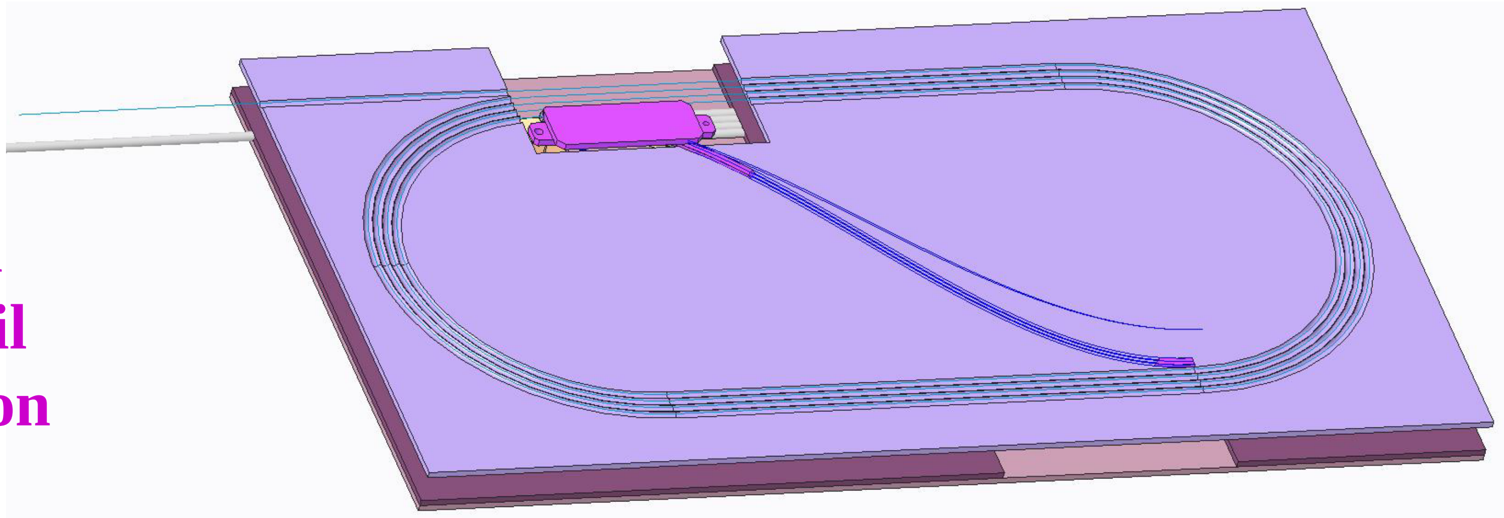
Two coils in two aperture

Other Collaboration

4-turn Double Pancake CORC® Coil in support Structure (to be funded by MDP for quench studies)

Double pancake with current in the 2 pancakes in opposite direction and a gap in between for field measurements and quench diagnostics

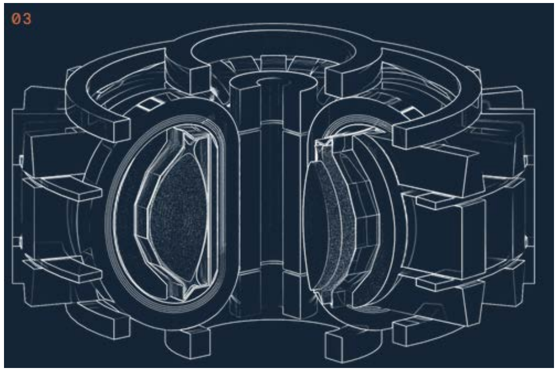
Two pancakes in common coil configuration



Conductor Courtesy: Advanced Conductor Technologies LLC

- **S-turn in transition region changes the direction of the current between the two pancakes.**
- **It should tolerate some horizontal motion (as was the case for the splice during the last test).**

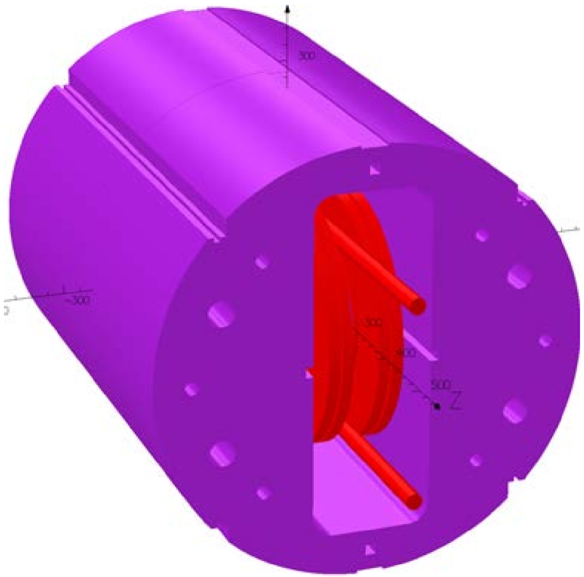
Quench Studies on the Stacked Tape Cable for Fusion

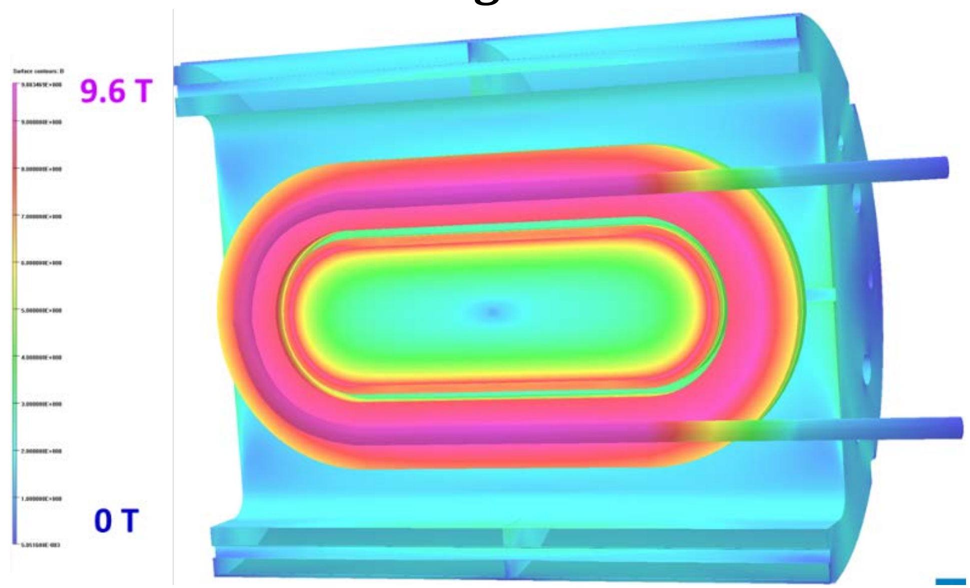


Commonwealth Fusion System https://cfs.energy/

INFUSE Innovation Network for Fusion Energy

- Commonwealth Fusion System (CFS) is developing a revolutionary fusion technology based on HTS magnets
- It uses Stacked Tape Cable
- Funding request from Innovation Network for Fusion Energy (INFUSE) program to perform quench studies in the background field of DCC017
- Common coil magnet DCC017 accommodates a large bend radius within the background field of the magnet





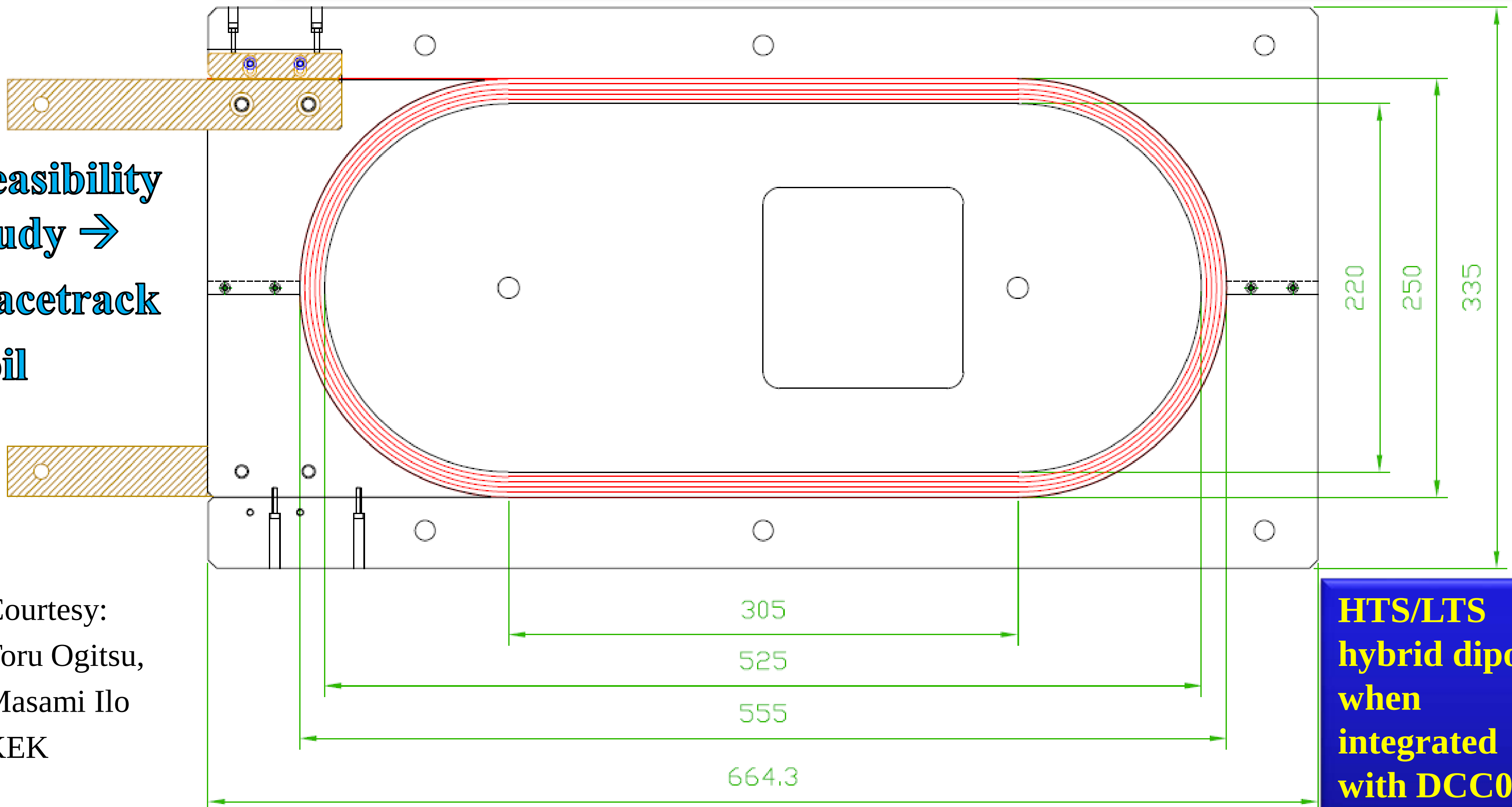
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Future US Japan Collaboration

R&D of mineral insulated REBCO coils applying ceramic coating and ceramic bonding technology

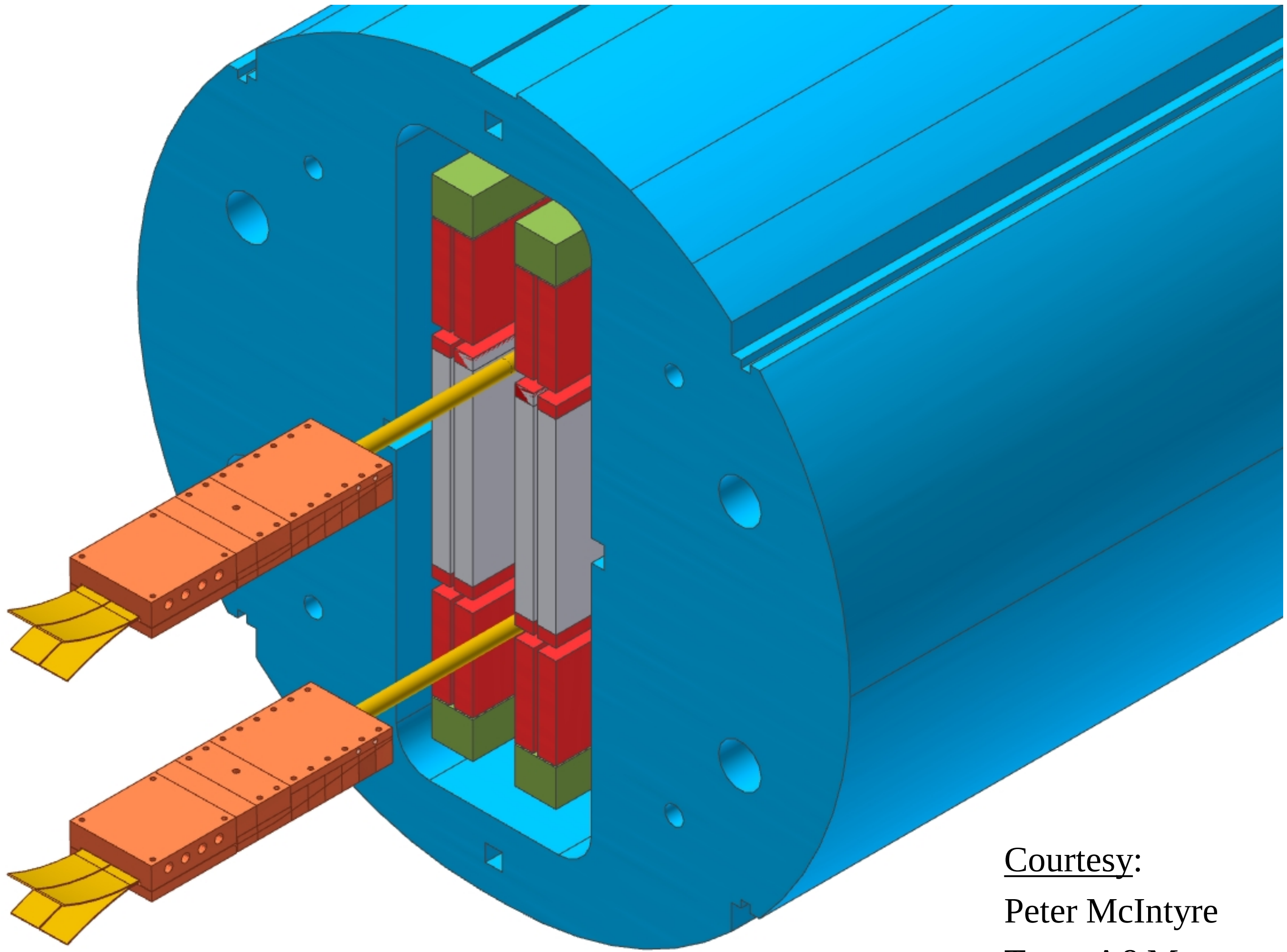
Feasibility study → Racetrack coil



Courtesy:
Toru Ogitsu,
Masami Ilo
KEK

HTS/LTS hybrid dipole when integrated with DCC017

Texas A&M Proposal



Courtesy:
Peter McIntyre
Texas A&M

Nb_3Sn Coil Block R&D Tests for Understanding the Loss in the Performance of Many Nb_3Sn Magnets

- As an another example, one can test a Nb_3Sn coil block (say pole block), reacted and impregnated in 10 T field. It should fit in the available space with appropriate structure.
- A series of such simulated tests may help us identify the cause of the loss in the performance of Nb_3Sn magnets.
- Perhaps the consequences of not doing such investigative R&D is the large number of Nb_3Sn magnets with poor performance. Result: spending a large sum of money, time and potential loss in the confidence of Nb_3Sn technology.
- A systematic, lower cost, faster turn-around focused R&D may allow us to get at the bottom of it.

Future Upgrades

Current setup is for

- Insert coil/cable up to 4.5 kA for any background field up to 10 T
- Insert coil/cable up 10 kA, if in series with common coil

Future upgrades planned for

- Insert coil/cable to 7.5 kA for any background field up to 10 T
- Insert coil/cable up to 15 kA, if in series with common coil with added shunt allowing variation in current in insert coil/cable
- Transformer inside cryostat allowing up to 100 kA for cable test with any background up to 10 T
- Use existing shunt between inner and outer layers of Nb_3Sn coils to push field from 10 T to 11 T

SUMMARY

- An alternate approach for performing high field R&D
  - Time frame: a few months; Cost: a few hundred k$
- It could transform the way we plan and do magnet R&D
- BNL dipole DCC017 with large opening is available to facilitate this rapid-turn-around, lower cost R&D
- We welcome it's use and collaboration. Please take advantage of this unique facility to develop and test new technologies or optimize the existing ones