U.S. MAGNET DEVELOPMENT PROGRAM

ReBCO Technology - Part 1

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BNL

USMDP Annual Collaboration Meeting 2021

Acknowledgement

This presentation benefited from the discussions with and direct contributions from the following colleagues:

ACT: Danko van der Laan, Jeremy Weiss
ASC: Ernesto Bosque, Lance Cooley
BNL: Anis Ben Yahia, Michael Anerella, Jesse Schmalzle, Piyush Joshi, …
FNAL: Vadim Kashikhin, Vito Lomardo
LBNL: Xiaorong Wang, Maxim Martchevsky, Reed Teyber, Steve Gourlay

… and more

CONTENTS

- One Slide Summary on the High Field HTS/LTS Hybrid Test Results
  - ➢ A record 12.3 T hybrid dipole field in 2020 following 8.7 T in 2016 PBL SBIR (presentation to review committee was postponed for this year)
- Current Program – High Current CORC coils *"in series"* with the Nb_3Sn coils
  - ➢ MDP: Quench and technology studies – a good multi-lab collaboration
  - ➢ ACT STTR: Demonstration of a high field HTS/LTS hybrid dipole
- Companion Presentation (Friday)
  - ➢ HEP/FES synergistic activities (several programs, including the recently completed CFS test in controlled temperature & up to 1 T/s ramp studies)

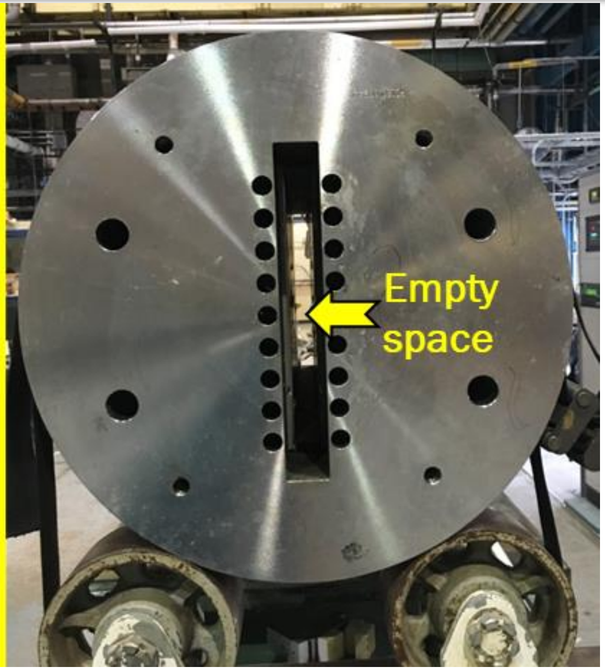
Common coil dipole at BNL offers a novel approach to a low-cost, rapid-turn-around technology development and a unique test vehicle

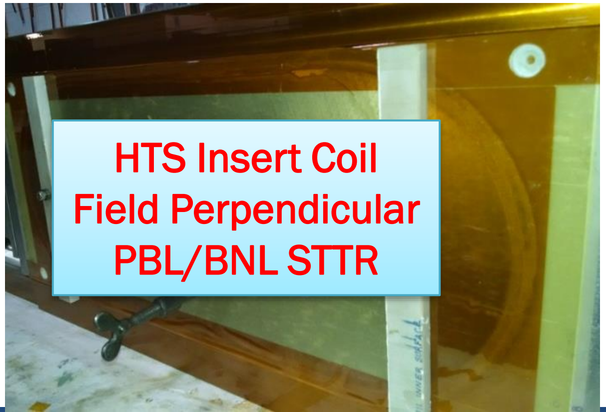
Rapid-turn-around HTS/LTS Hybrid Dipoles

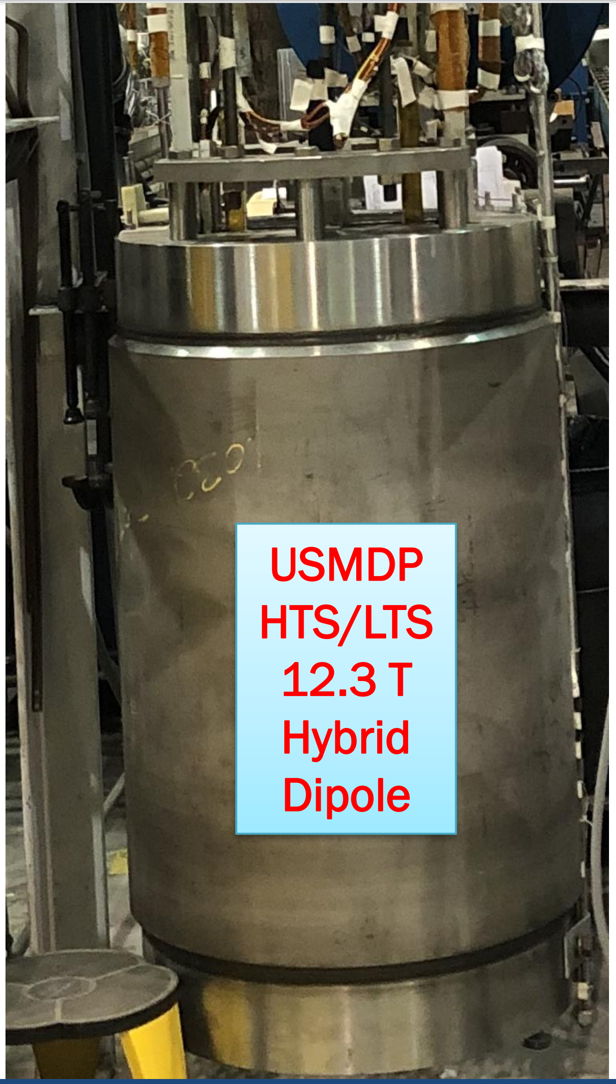
Key components/steps for Rapid-turn-around R&D

- 10 T, Nb_3Sn dipole with a large open space for high field insert coil testing
- New coil(s) in the magnet without any disassembly
- Coils become an integral part of the dipole magnet
- A new coil test essentially becomes a new magnet test

High field technology demo possible in ~1 year and ~$200k



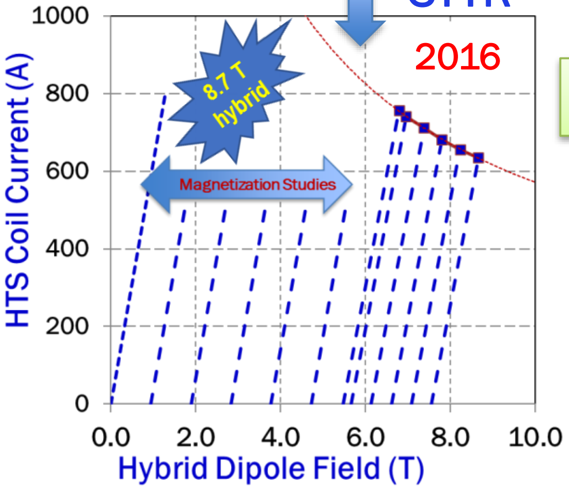


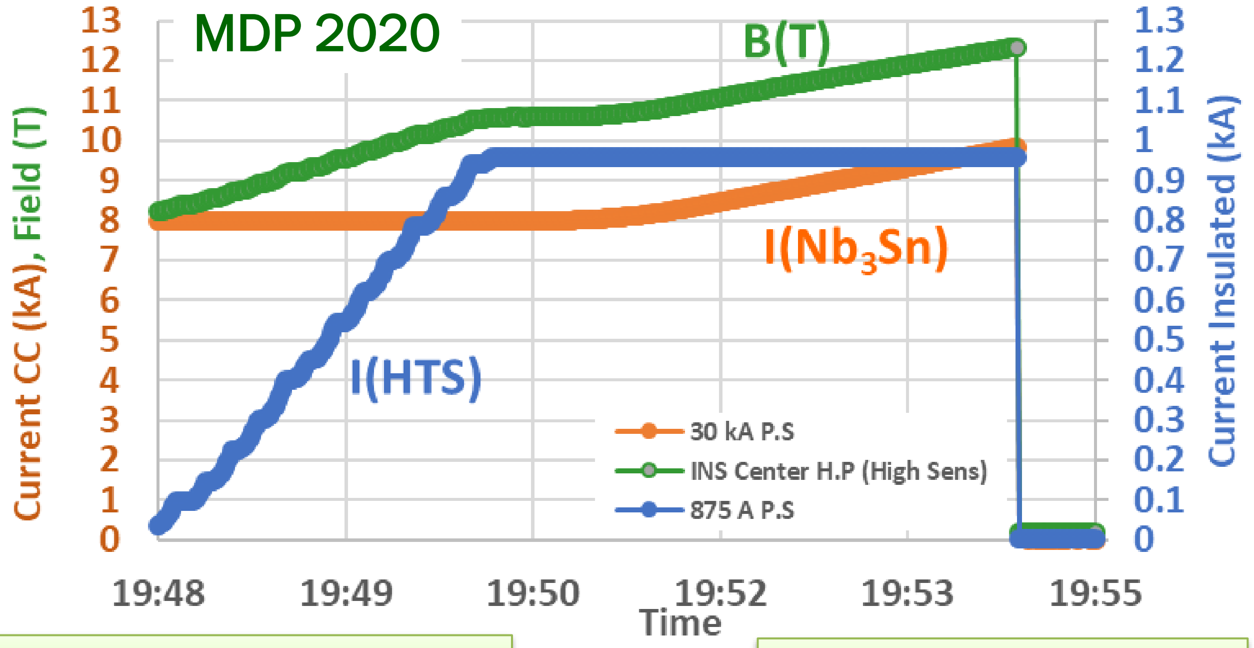


HTS/LTS Hybrid Dipole Tests (with many quenches)

USMDP *"Record"* HTS/LTS 12.3 T Hybrid Dipole (2020)

PBL/BNL STTR



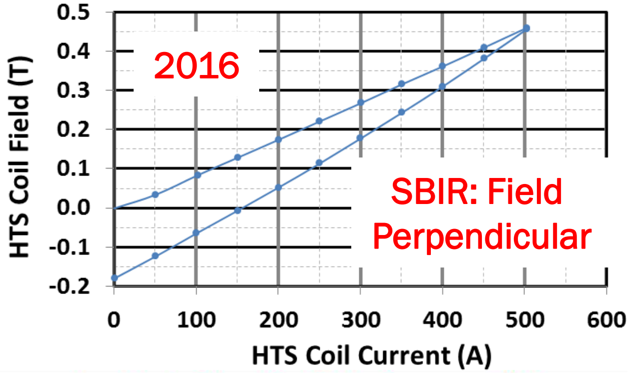


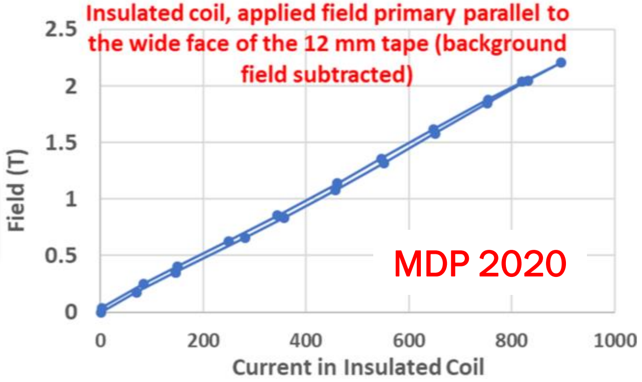
Survived Many Quenches

14.5 T hybrid possible

DATE	TIME	HTS COIL	Nb3Sn Coil (A)	HTS Coil (A)	B, hybrid (T)	B, Nb3Sn + trapped
13-Feb-20	1955	Nomex	9830	955	12.3 Tesla	9.39 Tesla
14-Feb-20	1157	Nomex	9617	955	11.96 Tesla	9.87 Tesla
14-Feb-20	1652	NI	10120	955	12.09 Tesla	10.37 Tesla
15-Feb-20	1318	NI	9171	1000	11.53 Tesla	9.34 Tesla
15-Feb-20	1336	NI	-	1590	4.23 Tesla	0.27 Tesla
15-Feb-20	1414	NI	8000	1110	10.74 Tesla	8.1 Tesla
15-Feb-20	1502	NI	9000	910	11.23 Tesla	9.2 Tesla

Magnetization Studies

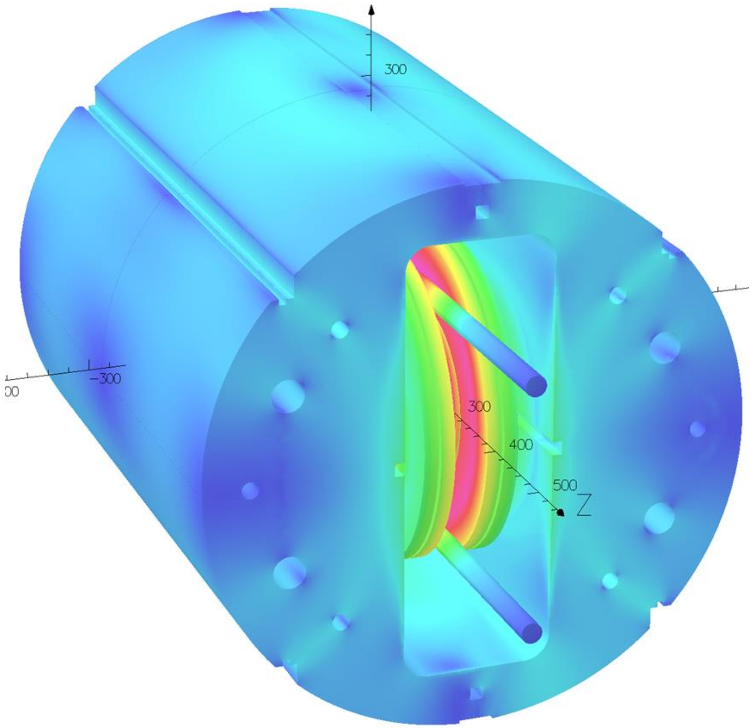


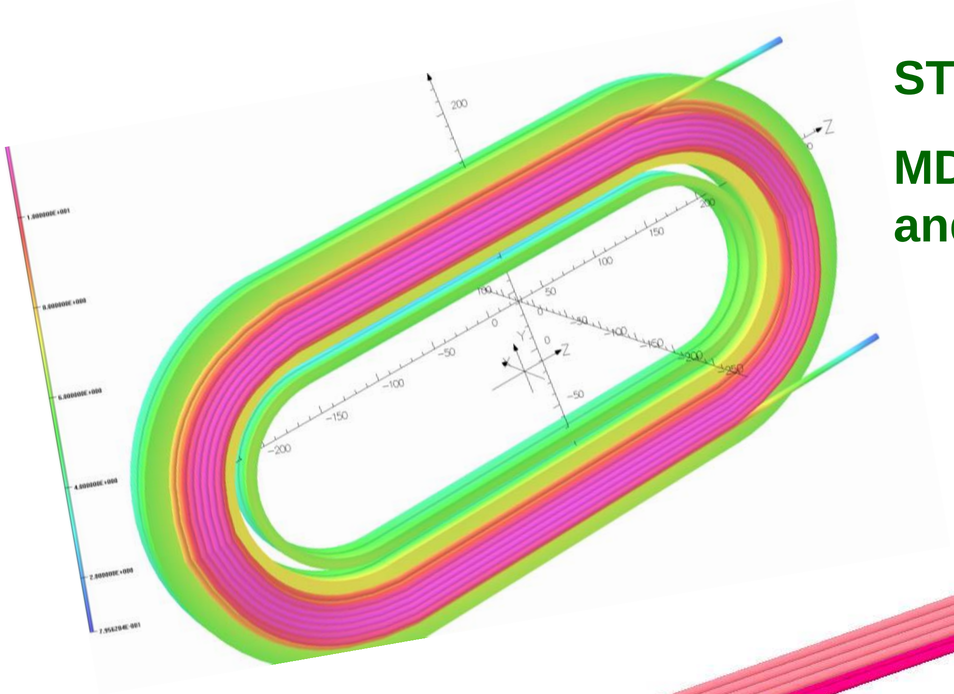


Significant reduction in magnetization from HTS coils when field is primarily parallel to the wide face

CORC Coil Programs with the Common Coil Dipole

STTR Coils two sets:
Each with 6 and 8 turns

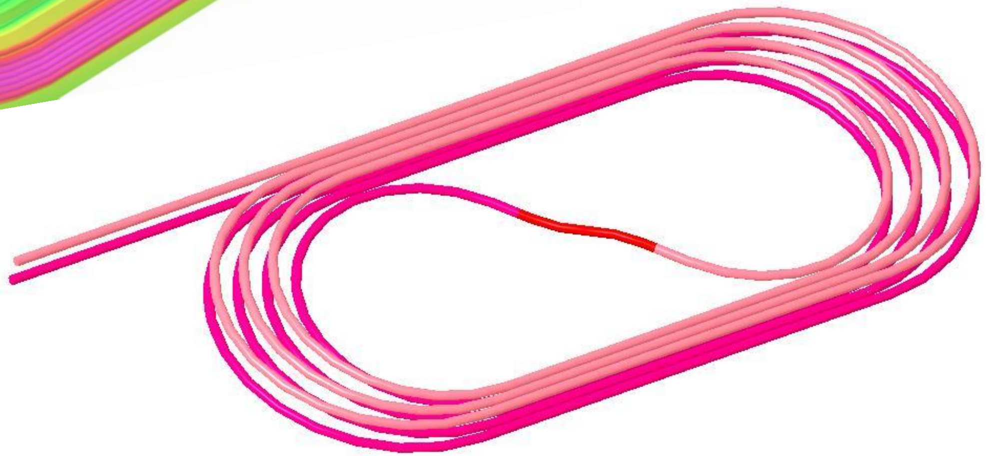




STTR: High field Demo

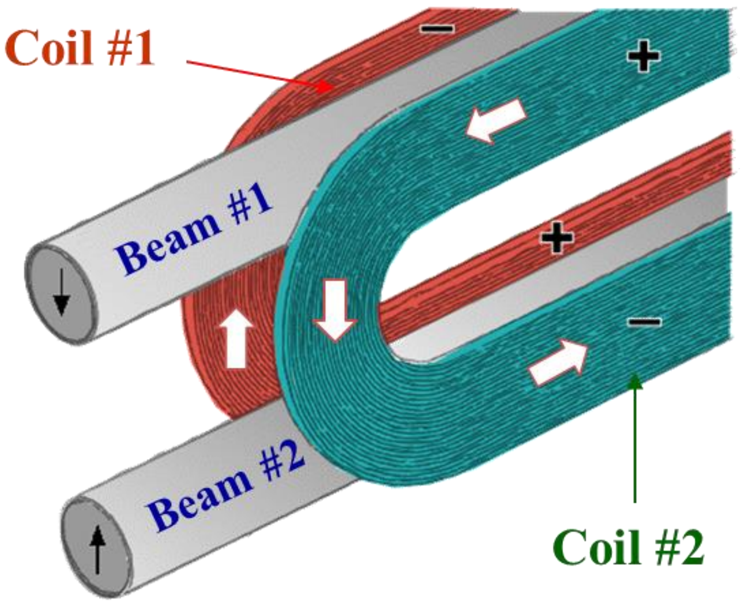
MDP: Quench studies and technology demo

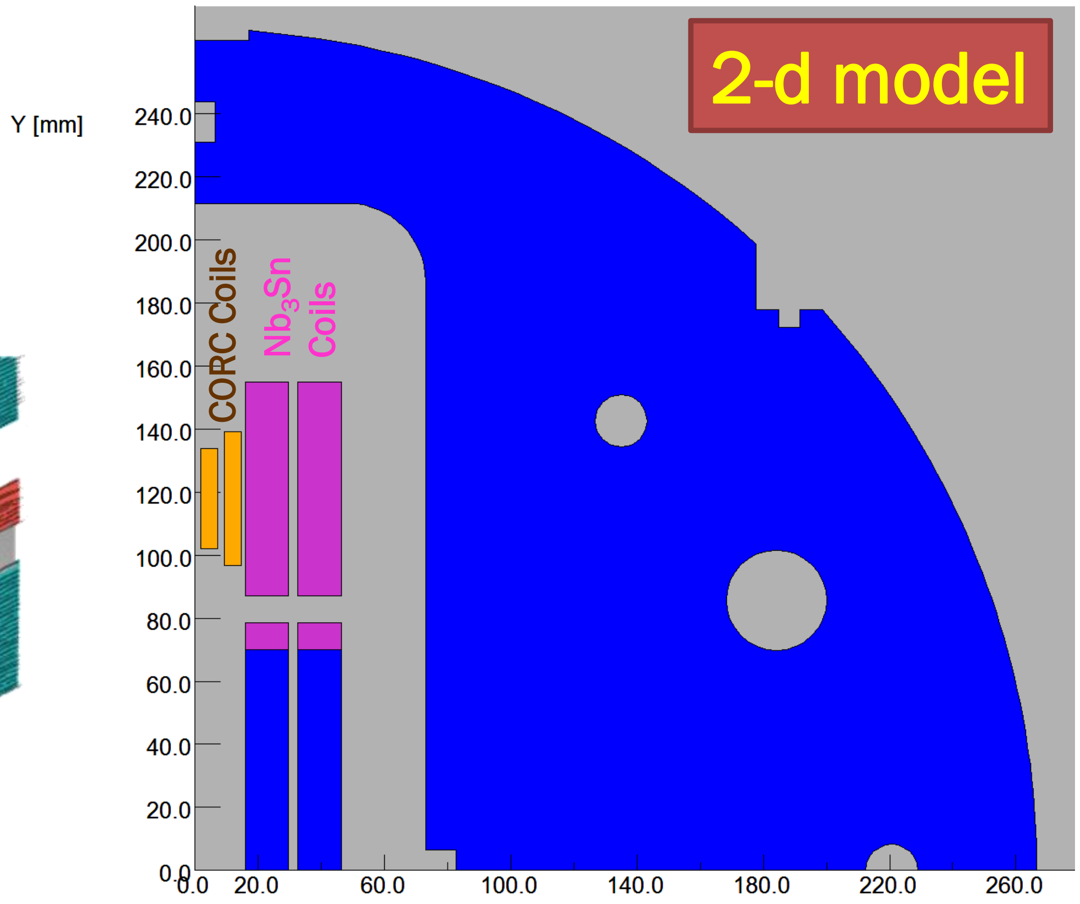
MDP Coil
4+4 turns
with an S-turn



CORC Coil based HTS/LTS Hybrid Dipole STTR

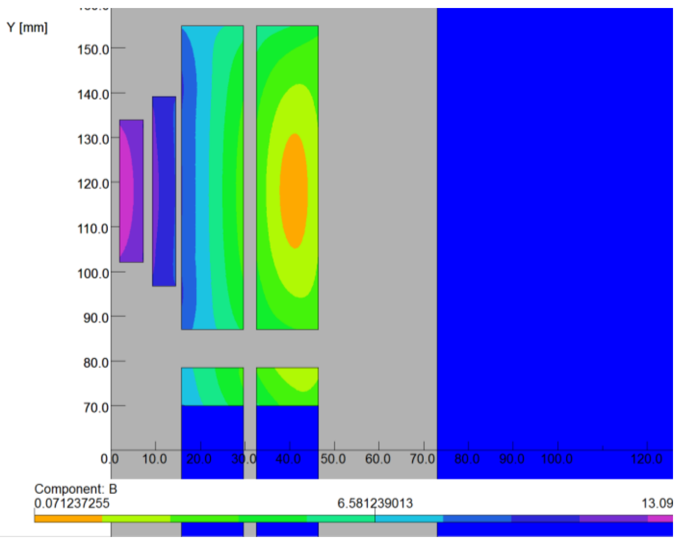
- High current CORC coils in series with the Nb_3Sn coils
- Desired for quench protection
- Large radii of common coil allows high J_e CORC cables





CORC coils:
6 and 8 turns, running in series with Nb_3Sn coils

Hybrid field: 13.1 T @10 kA
: 14.4 T @11 kA
(peak field in Nb_3Sn coils reduced by CORC coils)



Status of the MDP CORC Program

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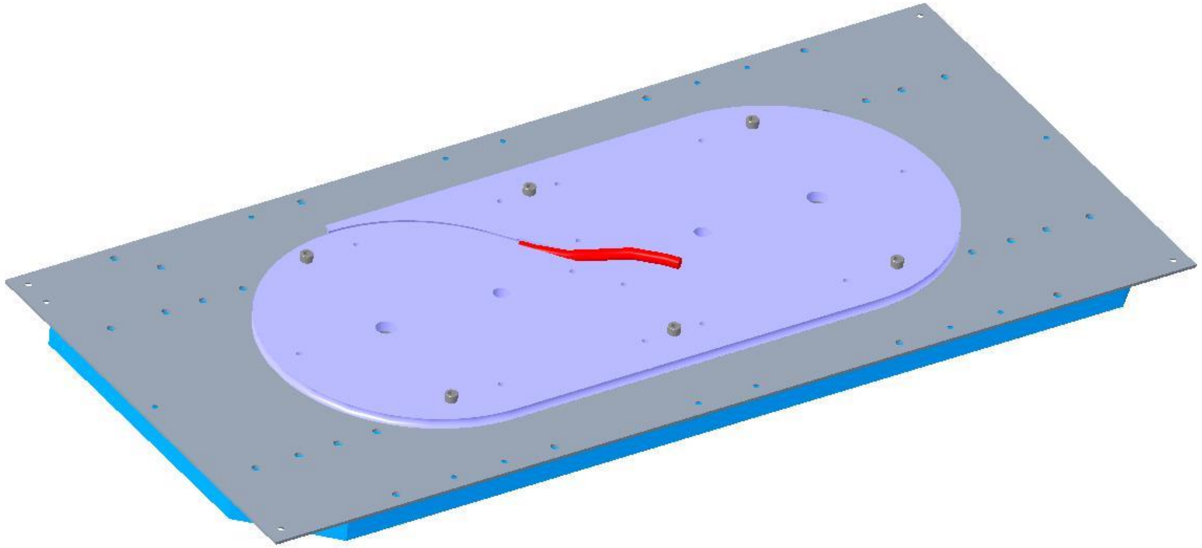
- ➢ Regular meetings to create a good though out R&D program
- ➢ Conductor from ACT, significant help in design & ordering parts also
- ➢ Most instrumentation to be provided by LBNL
- ➢ Engineering design and magnet test to be carried out by BNL
- ✓ Status: All drawings made. Parts ordered. Test expected in 2021.
  - ❑ Next few slides is a rapid walk through on the design and proposed construction process (Courtesy: Jesse Schmalzle)

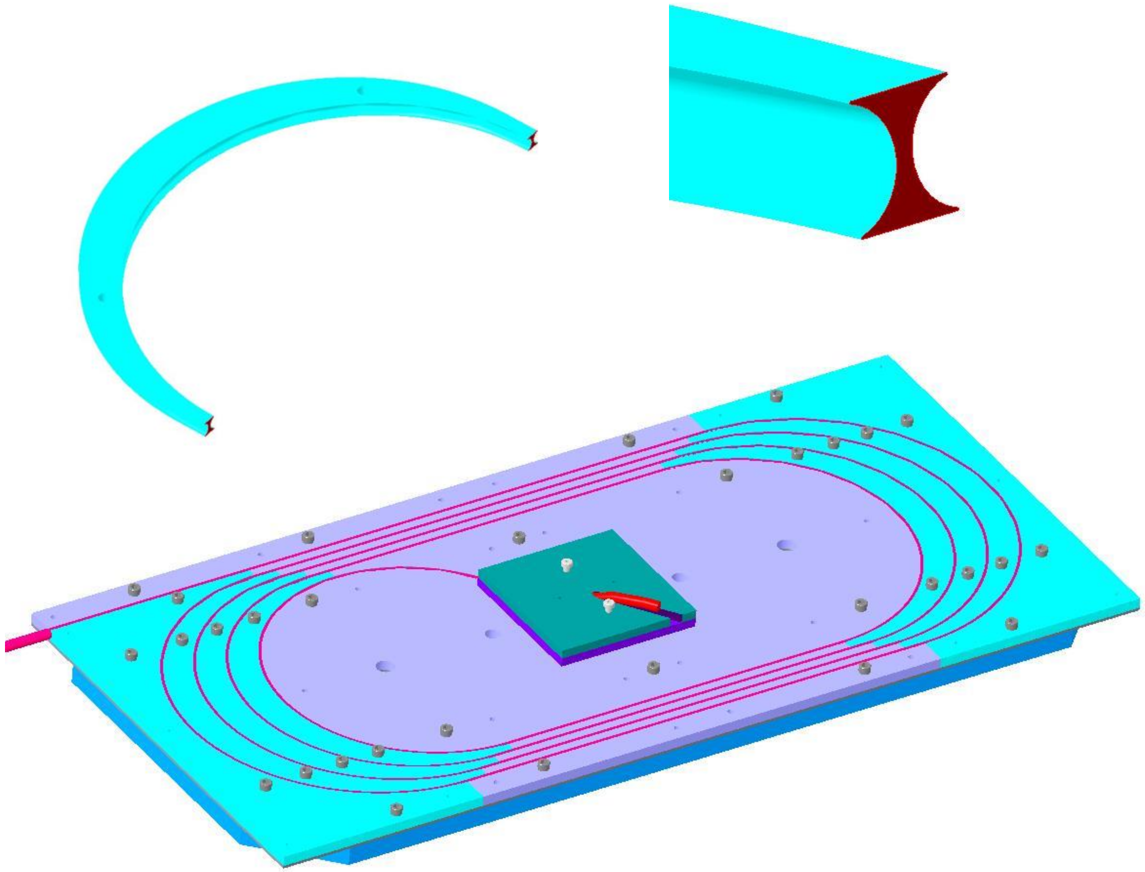
    Note: Cable and many design features of the MDP and STTR program will be as similar as possible to allow better comparison and analysis

Coil Winding Process (1)

- Outer plate and inner spacers mounted on winding plate.
- Conductor split onto 2 spools – Layer 2 spool mounted above coil.

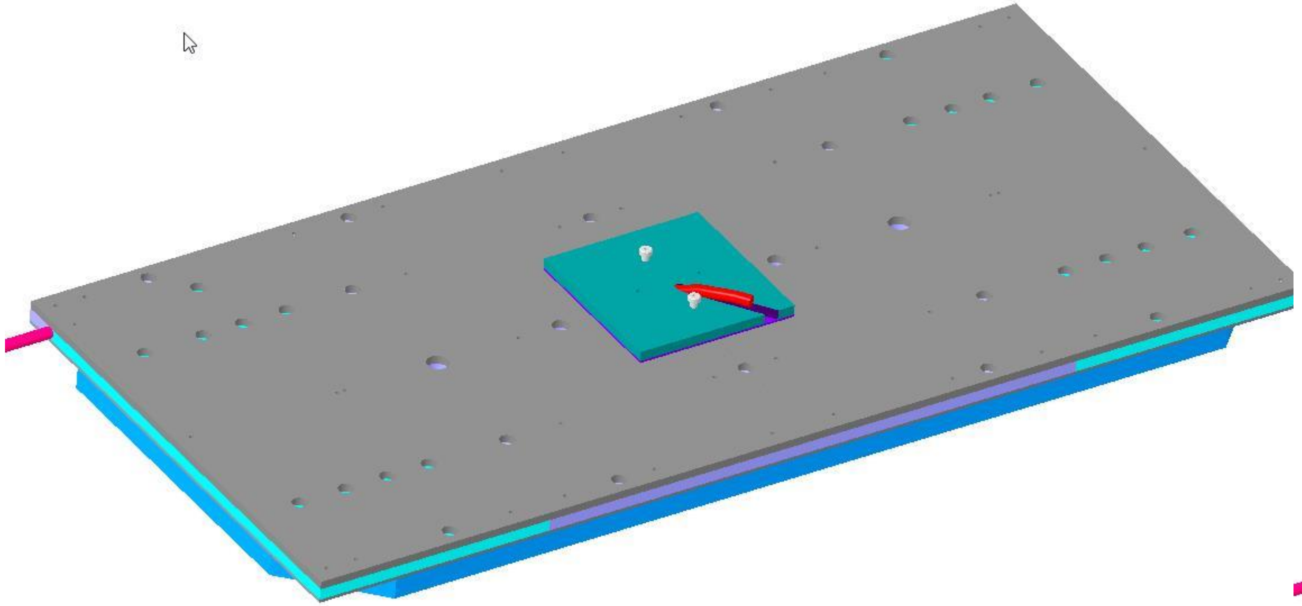


- Wind Layer 1, apply epoxy over coil turns.

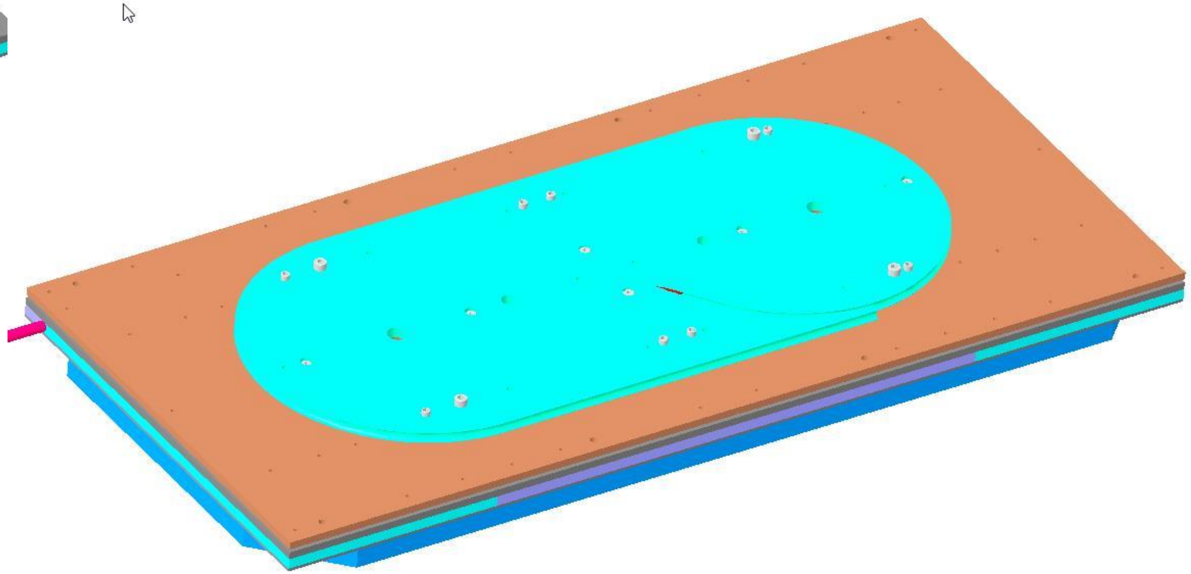


Coil Winding Process (2)

- Install L1 inner support plate.

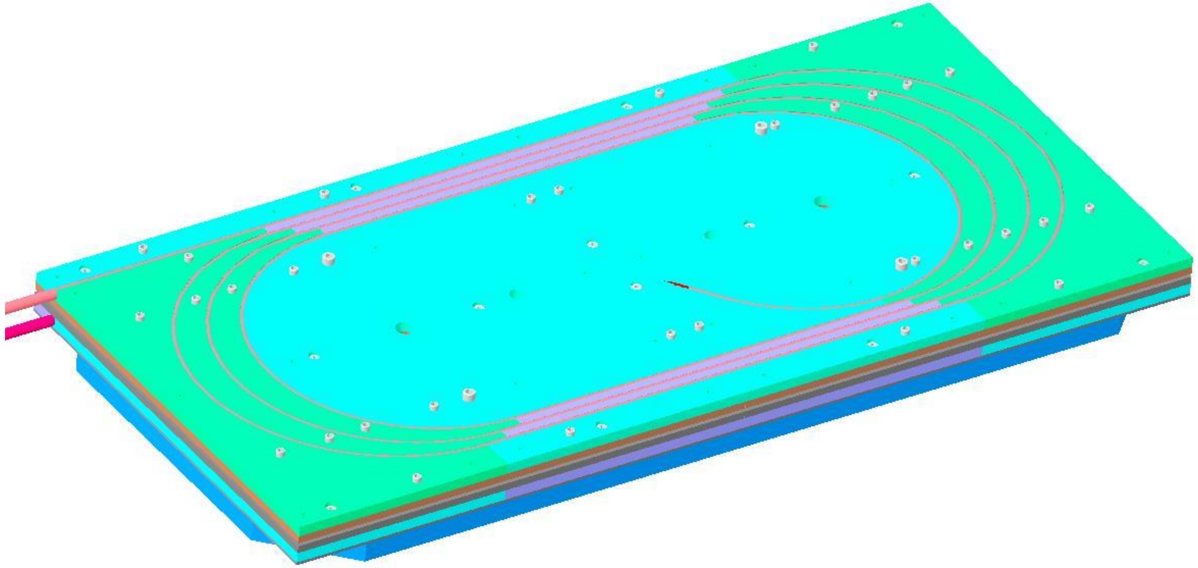


- Install L2 inner support plate and coil spacers.

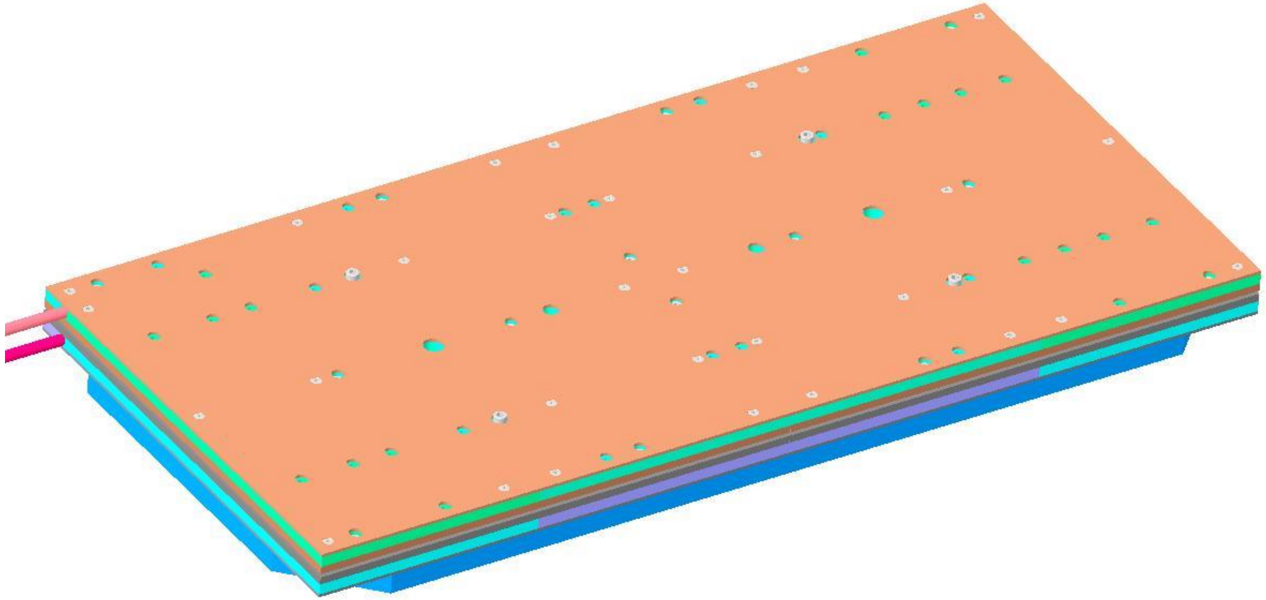


Coil Winding Process (3)

- Wind layer 2, apply epoxy over coil turns.

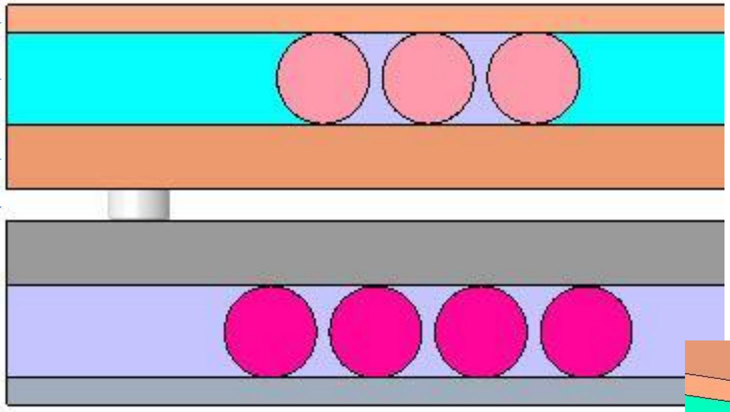


- Install L2 outer cover plate.

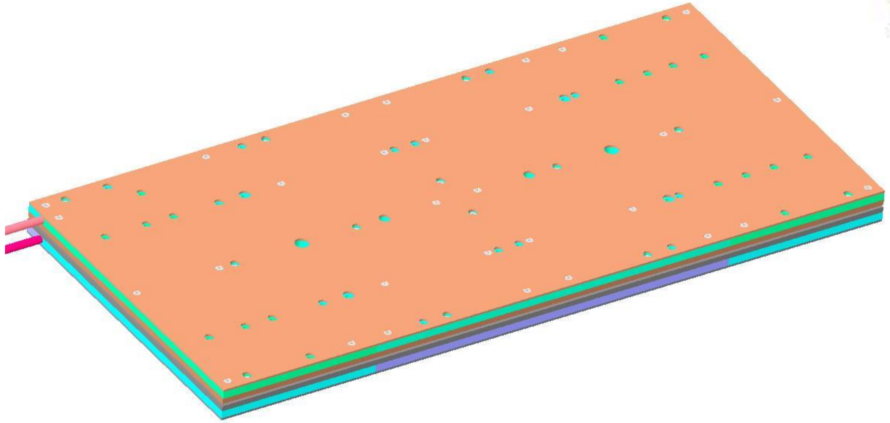


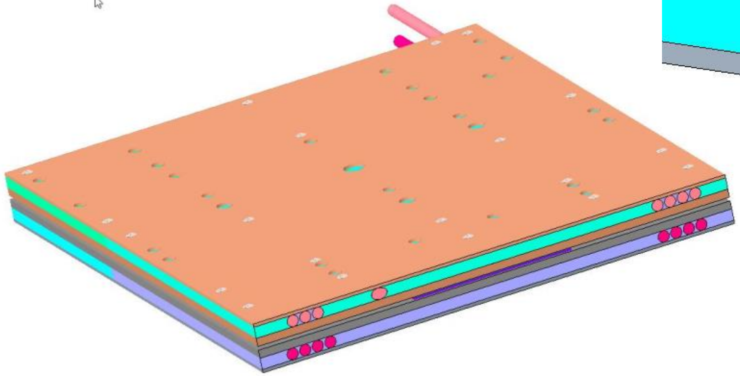
Overall Coil Package

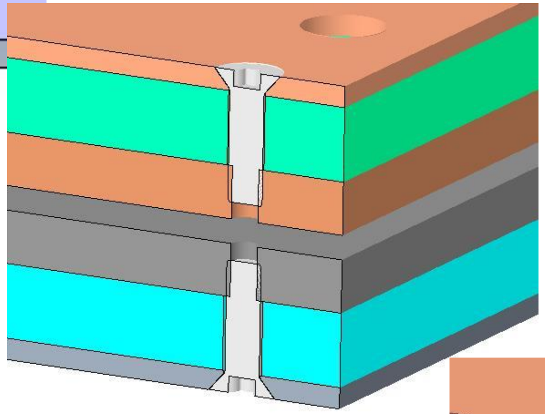
- Overall thickness – 30.3 mm
- Outer plates – 2 mm
- Coil spacers – 7 mm
- Inner plates – 5 mm
- Gap between layers – 2.3 mm

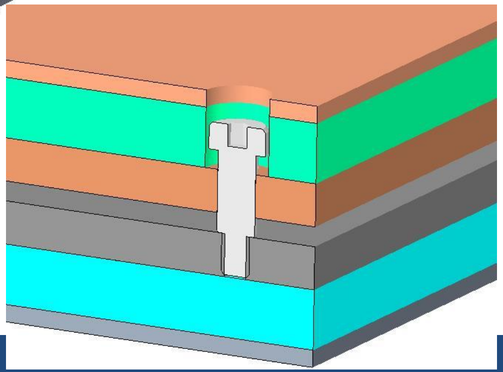


- Each layer held together with flat head screws
- Assembly held with shoulder screws to allow separation of layers.





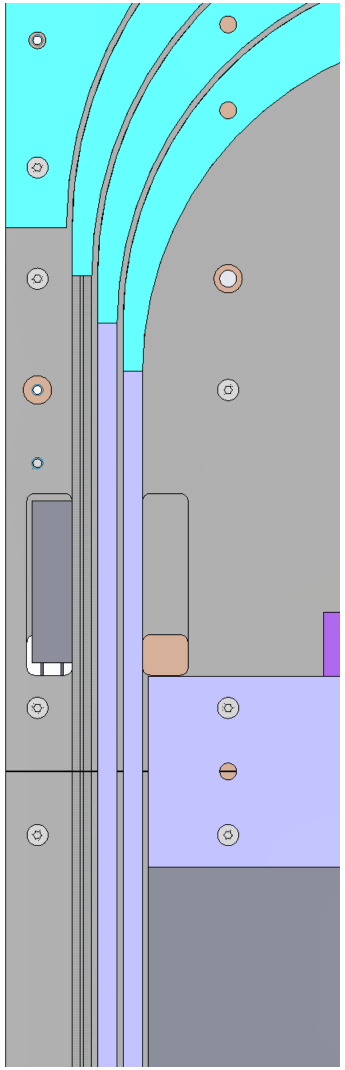




Instrumentation

A series of instrumentation are being discussed during the regular working group meetings (organized by Xiaorong). They include

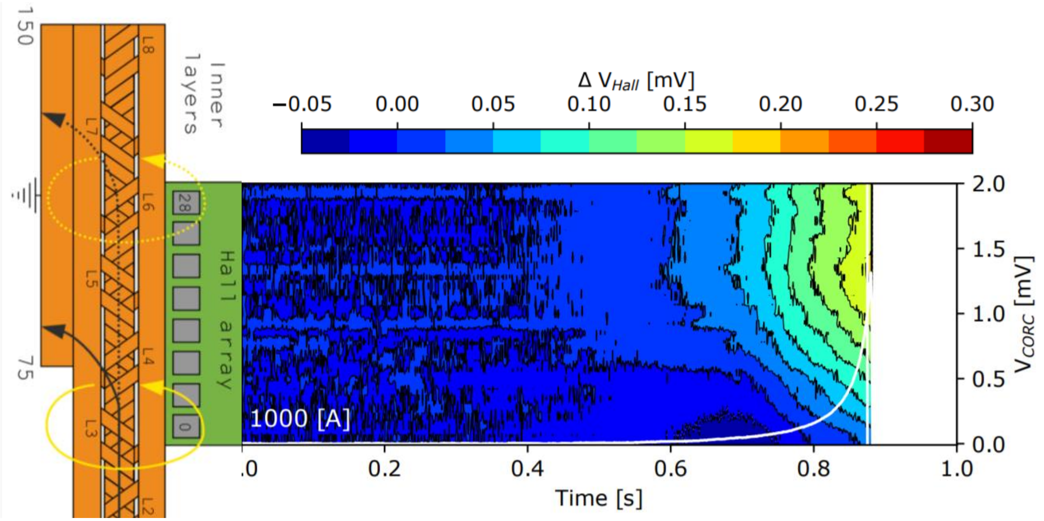
- Voltage taps
  - Can only be on the terminals (became part of the design discussion to allow voltage taps to follow the cable in the groove). Courtesy: Danko and Jeremy
- Quench heaters
  - To induce quench / normal zone for diagnostics R&D. Courtesy: Reed
  - Groove will be machined on the flat plates for the heater installation
- Acoustics
  - To be placed between the two layers of CORC coils. Courtesy: Maxim
- Hall probe arrays
  - Details in the next slide



Hall Probe Arrays

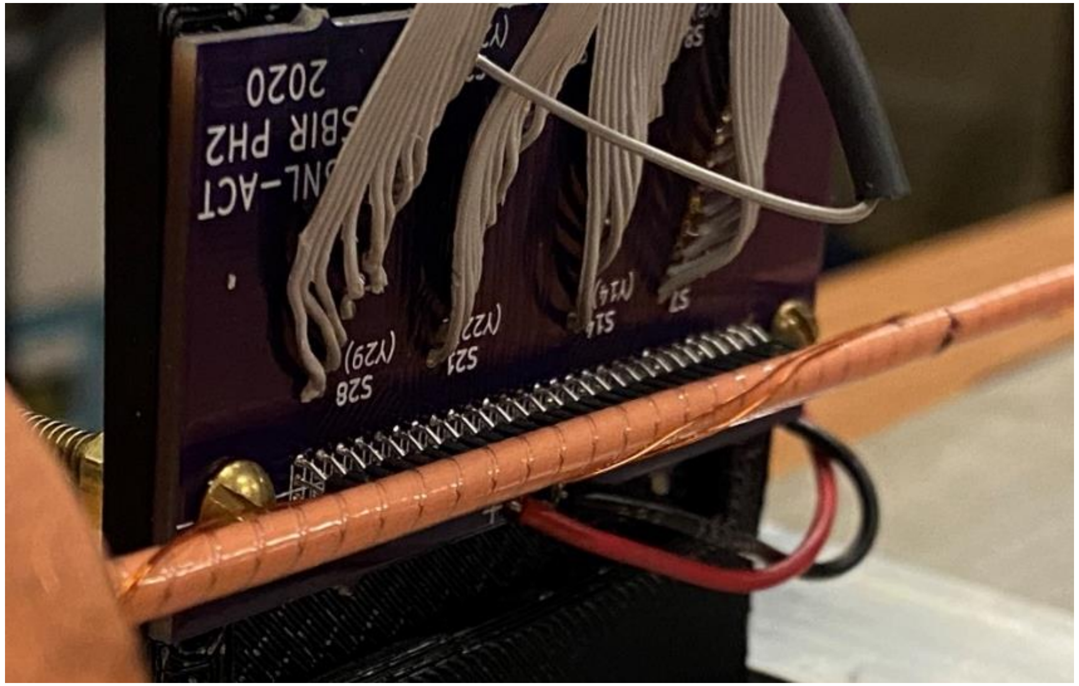
- Maxim & Reed (LBNL), Danko & Jeremy (ACT) have been developing Hall arrays for CORC quench detection and diagnostics (FES SBIR)
  - See Thursday talk for more details
- Latest Hall probe arrays (bottom right) will be integrated into BNL common coil test
  - Will provide real-time current redistribution monitoring, as well as test diagnostic method
  - Meeting regularly & collaborating for integration

Slide Courtesy
Reed Teyber



LBNL + ACT - Supercond. Sci. Technol. 33 (2020) 095009

ACT + LBNL - Supercond. Sci. Technol. 33 (2020) 105011

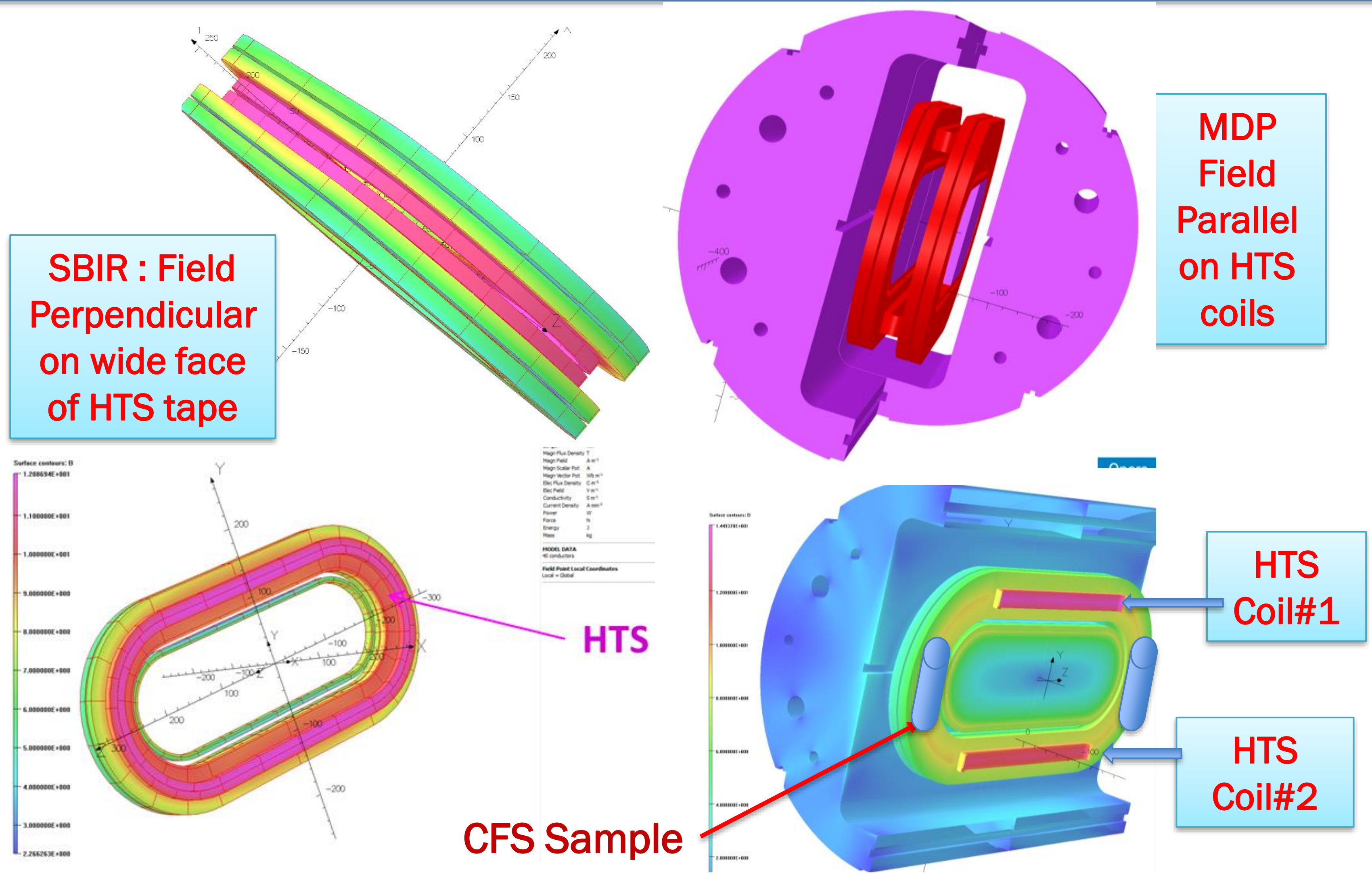


Summary

- Common coil dipole provides a useful rapid-turn-around and low-cost vehicle for developing and testing hybrid dipole technology. USMDP produced 12.3 T HTS/LTS hybrid field within a year of BNL joining it.
- HTS coils were subjected to many quenches in LTS coils during the MDP test (and by themselves at their short sample during the PBL/BNL SBIR test).
- CORC MDP R&D is well underway for quench studies and for diagnostics technology development. Test expected by the end of this year.
- CORC STTR program follows above test for a high current CORC coil in series with the Nb_3Sn coil for an expected field of 13-14 T.

EXTRA SLIDES

HTS/LTS Hybrid Dipole Key Test Objectives



Key test objectives (*besides demonstrating high fields*)

- Magnetization studies: (a) field parallel and (b) field perpendicular on the wide face of the HTS tape
- Quench studies: survival of HTS coils in high field environment when (a) HTS coil quenches near its short sample limit and (b) LTS coil quenches with a significant stored energy (LTS/HTS strong inductive coupling)

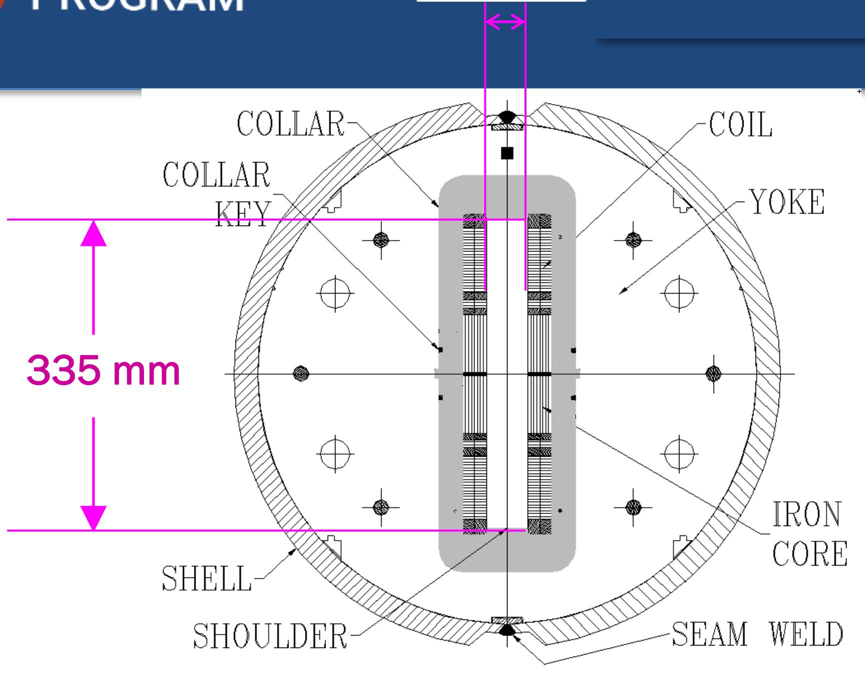
An Alternate Approach to Magnet Technology Development

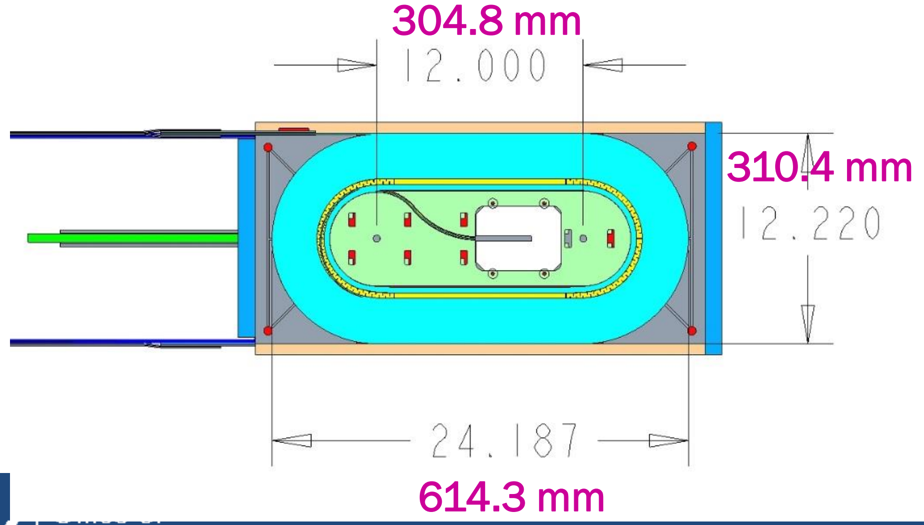
When there were more funds to develop and demonstrate magnet technology (SSC and RHIC days), we used to argue about the applicability of short magnet test results in building long magnets

- We accepted the benefits of short magnet R&D as they could be built and tested cheaper and faster (relatively speaking) and we could afford to change one or fewer parameters at a time to identify issues and to develop magnet technology
- Now short high field R&D magnets take so long and are so expensive to build (relatively speaking) that we can't afford even them. Then we have to find an alternate R&D approach

The results of the alternate approach should be largely (even if not completely) applicable to real magnets and the test vehicle be robust

Parameters of BNL Dipole DCC017



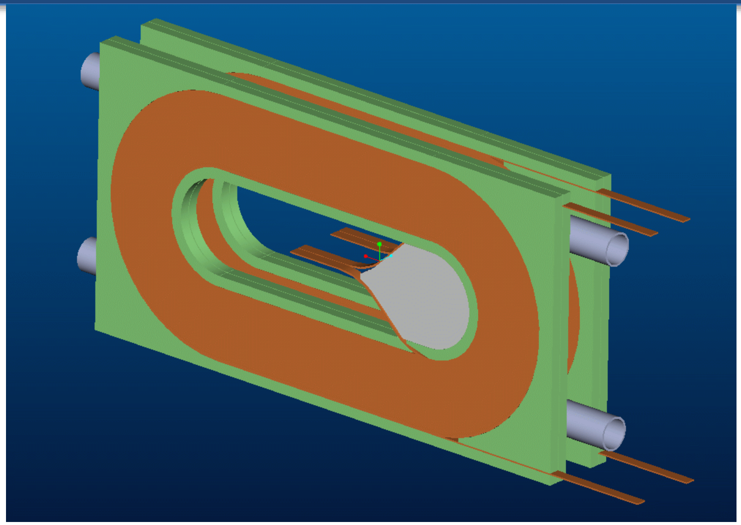


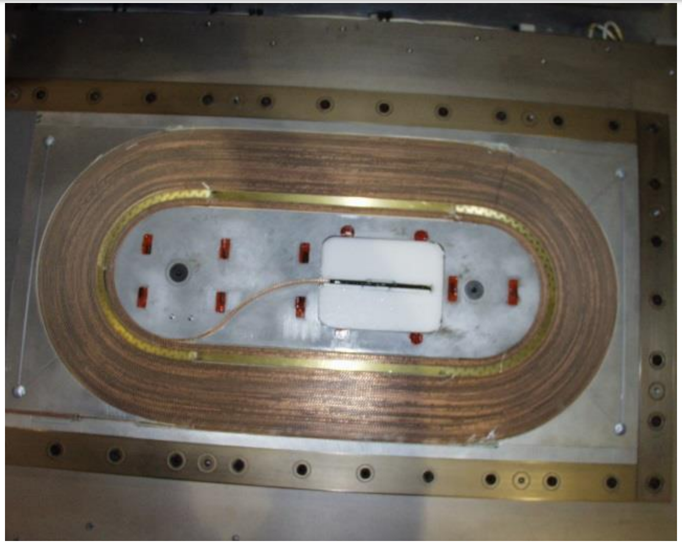
- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- **31 mm horizontal aperture**
- **335 mm vertical aperture**
  - **A unique feature for insert coil or cable testing**
- 0.8 mm, 30 strand Rutherford cable
- 70 mm minimum bend radius
- 85 mm coil height
- 614 mm coil length
- One spacer in body and one in ends
- Iron over ends
- Iron bobbin
- Stored Energy@Quench ~0.2 MJ

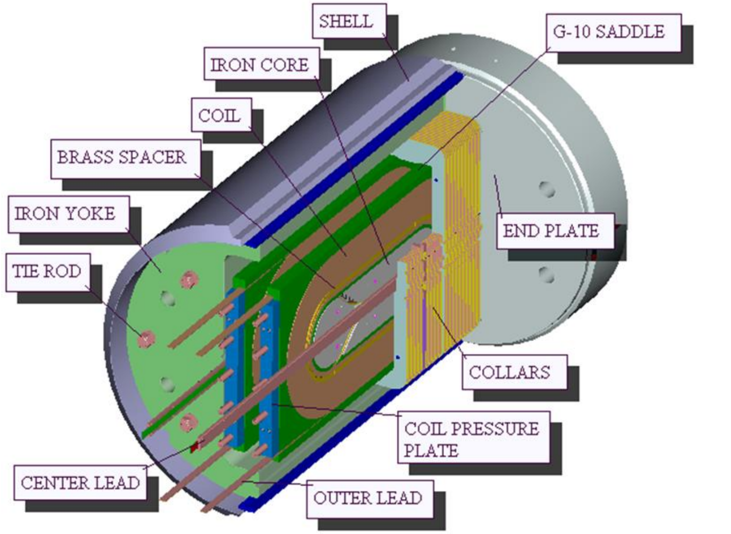
Performance Parameters of DCC017

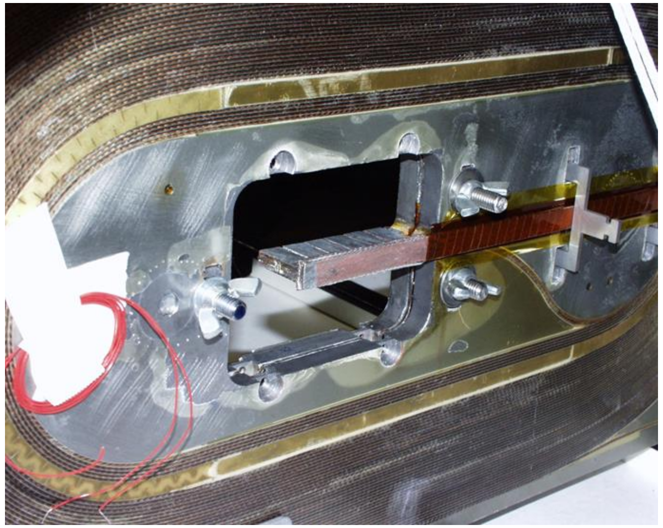
MAJOR PARAMETERS OF REACT & WIND COMMON COIL DIPOLE DCC017

Magnet design	2-in-1 common coil dipole with racetrack coils
Conductor type	Nb_3Sn
Magnet technology	React and wind
Horizontal coil aperture (clear space)	31 mm
Vertical coil aperture (clear space)	335 mm
Separation between the magnetic center of the upper and lower aperture	236 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 (inner and outer layers)	13.13 mm
Cu/Non-Cu ratio in the wire (same for both inner and outer cables)	1.53
Computed quench current (limited by inner)	10.8 kA
Computed quench field @4.2 K	10.2 T
Peak field at quench in inner, outer Layer	10.7 T, 6.1 T
Special electrical feature (not used)	Shunt between layers
Computed stored energy at quench	0.2 MJ
Computed inductance	4.9 mH
Coil bobbin (core) material	Carbon steel
Coil length (overall)	614.3 mm
Coil straight section length	304.8 mm
Coil height (overall)	310.4 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
Insulation thickness between turns	180 μm thick Nomex®
Potting agent	CTD-101K
Thickness of the collar	26.6 mm
Thickness of stainless-steel sheet between inner and outer layers	1.65 mm
Vertical pre-stress applied	17 MPa (low)
Horizontal pre-stress applied	Essentially none
Computed horizontal stress on structure	59 MPa at 10.2 T
Design maximum for horizontal stress	75 MPa
Stainless steel shell thickness	25.4 mm
Thickness of the end plates	127 mm
Yoke outer radius	267 mm
Yoke length	653 mm
Quench protection strip heaters (no energy extraction available during the tests)	25 μm X 38.1 mm, each quadrant, between layers









MDP HTS/LTS Hybrid Magnets Design

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Aperture #1

HTS coil size: 9 mm X 25 mm
HTS No. of turns: 92 (2 X 46)
Insulation: Nomex

LTS coil size: 27 mm X 85 mm
LTS No. of turns: 90 (2 X 45)
Insulation: Nomex

Bore size: 13 mm X 25 mm

Aperture #2

HTS coil size: 9 mm X 25 mm
HTS No. of turns: 142 (2 X 71)
Insulation: No Insulation (NI)

LTS coil size: 27 mm X 85 mm
LTS No. of turns: 90 (2 X 45)
Insulation: No Insulation

Bore size: 13 mm X 25 mm

NI coils were wound with "low tension" and this test was partly meant to simulate multi-tape cable providing added protection by current sharing. It was also meant to test if "field" can be made to track the "current".