U.S. MAGNET DEVELOPMENT PROGRAM

BNL HTS magnet experience relevant to accelerator dipoles

MDP Collaboration Meeting, January 16-18, 2019

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Overview

- Key BNL contributions to the current global high field magnet programs
- A variety of HTS R&D magnets and experience at BNL
- Availability of the fast-turn around, low cost magnet R&D factory for the use of community to advance the magnet science and technology
- Possible leverage of BNL assets and experience to US Magnet Development Program on high fields with HTS
- BNL SMD has worked with many institutions worldwide
- Summary and Conclusions

Key Contributions

- BNL has always been a major global player in superconducting magnets
- Next – two of many contributions which are relevant today

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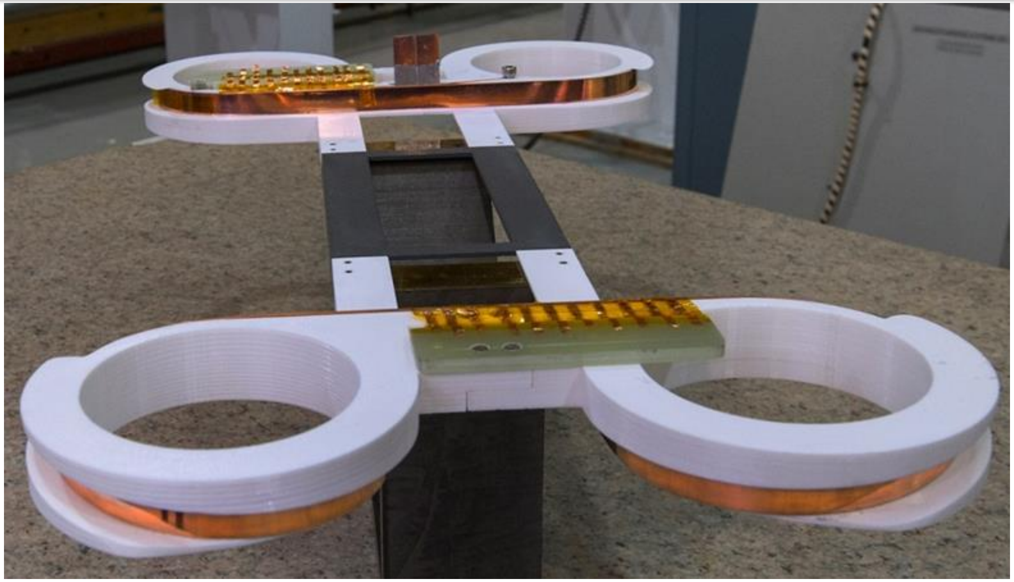
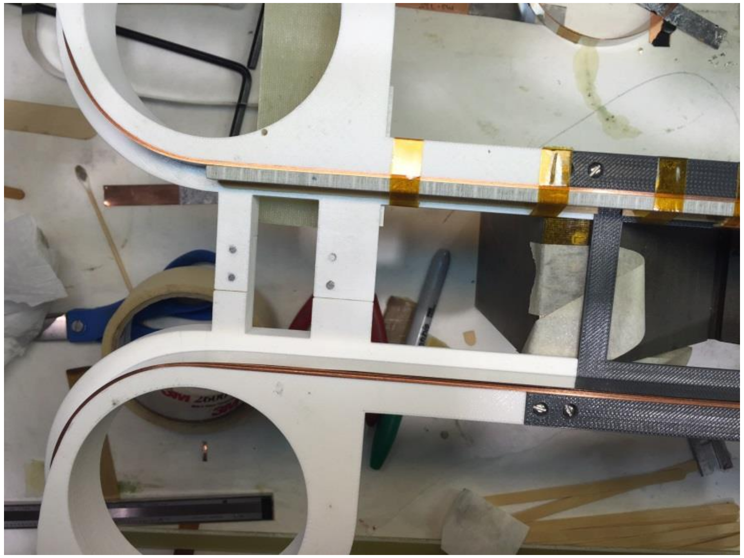
Freeway Overpass/UnderPass (or clover-leaf) Ends

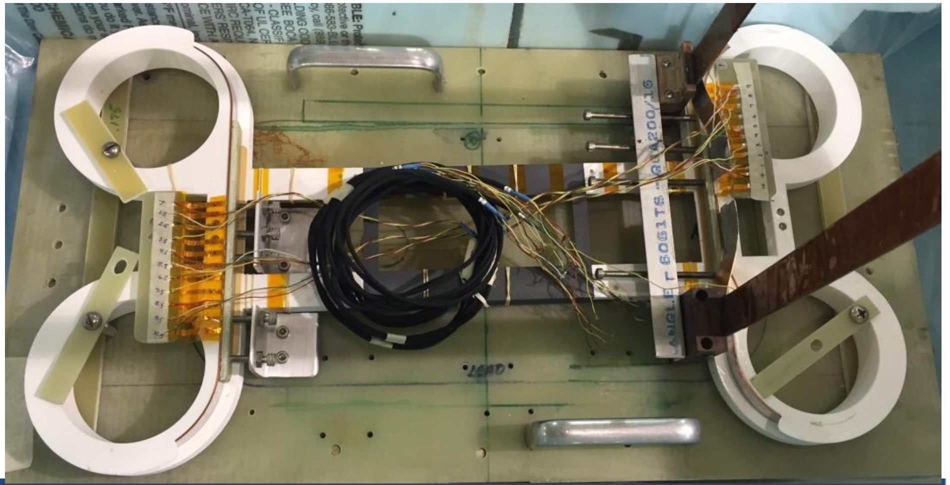
- Presented at ASC 2002
- Design attractive for HTS and block coil dipoles. SBIR with e2P in 2015
- HTS test coil wound in Phase I and produced good technical results
- We collaborated with CERN and they picked it up. Now part of the 20 T design
- BNL can make specific contributions here

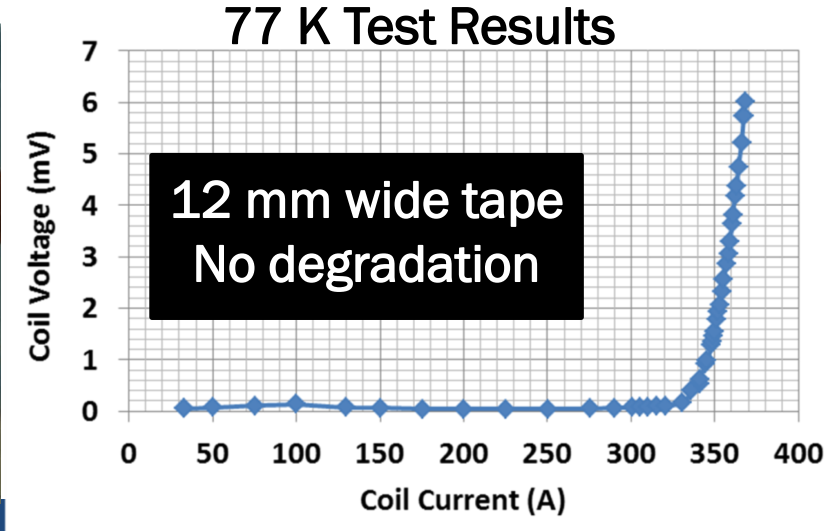
Demonstrations of the Overpass/Underpass in Phase I





SBIR with e2P





Overpass/underpass clover-leaf design

CERN

SEATTLE 2018

SEATTLE, 2018 OCTOBER 28 - NOVEMBER 2

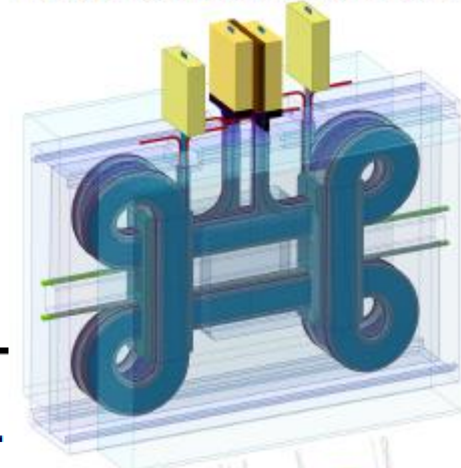
Design and Optimization of a Full HTS Accelerator Dipole for Achieving Magnetic Fields Beyond 20T

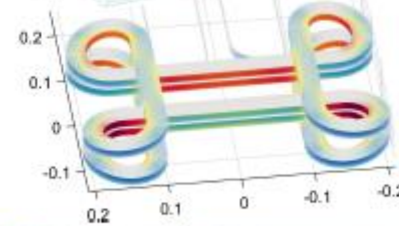
J. van Nugteren, J. Murtomäki, G. Kirby, T. Nes, G. de Rijk, L. Bottura, L. Rossi

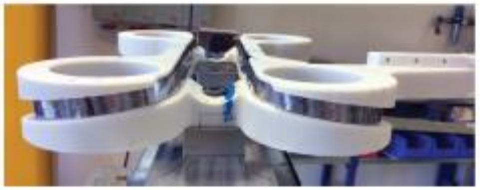
An example of the SBIR Program and of BNL contribution to the high field magnet R&D

9. Cloverleaf Prototype Magnet

Before constructing the large 20 T magnet it is planned to first construct a small coil containing most of the features of the larger magnet. This in order to attain experience with coil winding and impregnation of this relatively new geometry.







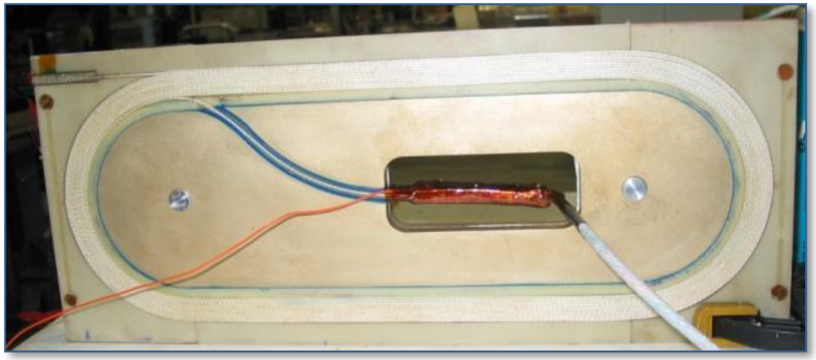
Similar design by wolf about a decade earlier – independent work

HTS/LTS Hybrid Dipoles

- **A key component to HE-LHC**

A Dipole at BNL for Developing Magnet Technology

BNL "React & Wind" Nb_3Sn Dipole



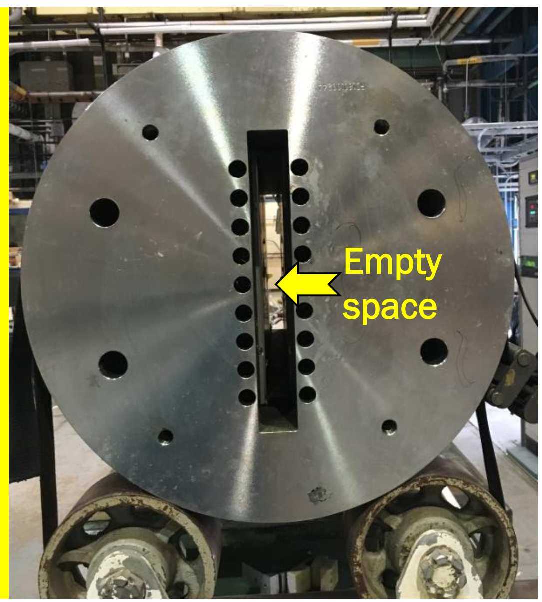
BNL "React & Wind" Bi2212 coil
8 coils, 5 magnets, 4.3kA (10/03)

- **BNL had a magnet development program to demonstrate a high field hybrid HTS/LTS collider dipole.**
- **A Nb_3Sn dipoles was built to produce a record field of >10 T with "React & Wind" technology.**
- **Eight HTS (Bi2212) coils and five magnets were built and tested.**
- **The magnet was designed such that HTS coil can be tested in an hybrid configuration with NO disassembly**
- **This feature can be used by USMDP to systematically test key technologies in high field magnet environment.**

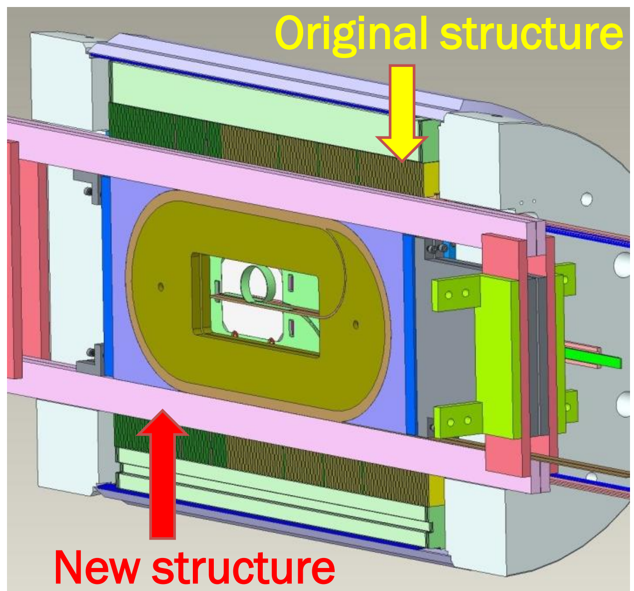
PBL/BNL STTR on HTS/LTS Hybrid Dipole

A unique feature of BNL's common coil dipole: large open space for inserting & testing "coils" without any disassembly (rapid around, lower cost)

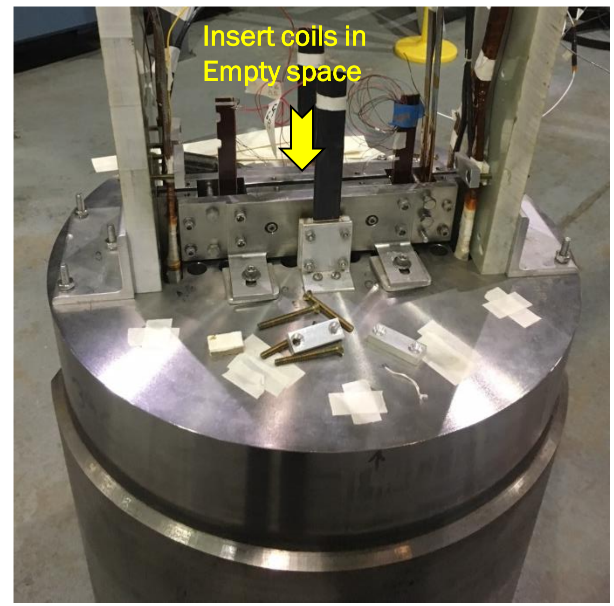
STTR Phase II for (1) Demonstration and protection of High field HTS/LTS hybrid dipole (2) measurement of field ~~parallel and~~ perpendicular field quality



BNL Nb_3Sn common coil dipole DCC017 without insert coils



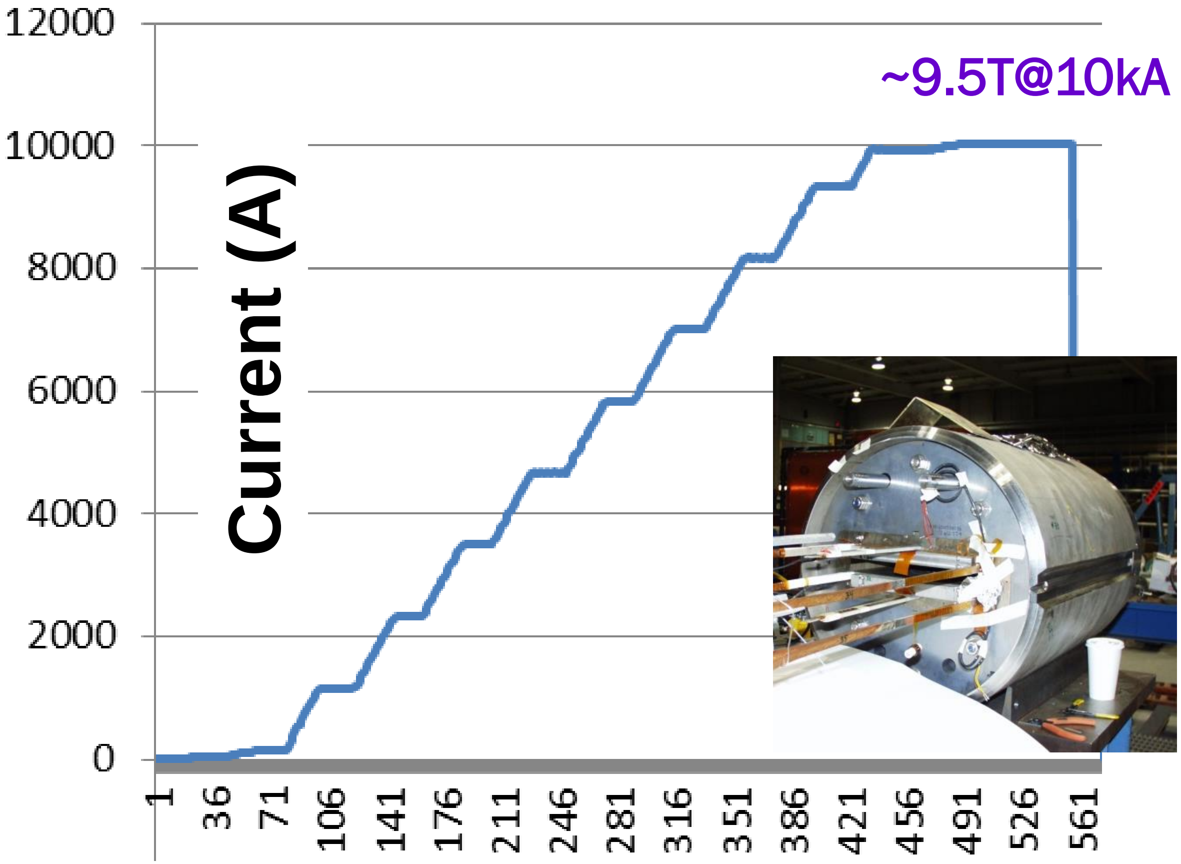
New HTS coils with the existing Nb_3Sn coils and become part of the magnet



HTS coils inside Nb_3Sn dipole - early experience of HTS/LTS hybrid dipole

Retest of Nb_3Sn Common Coil Dipole After a Decade

- **Short Sample: 10.8 kA/10.2 T (reached during 2006 test)**
- **Retest: No quench to 10 kA/9.5 T (>92% of quench, leads limited)**



A reliable magnet for test facility

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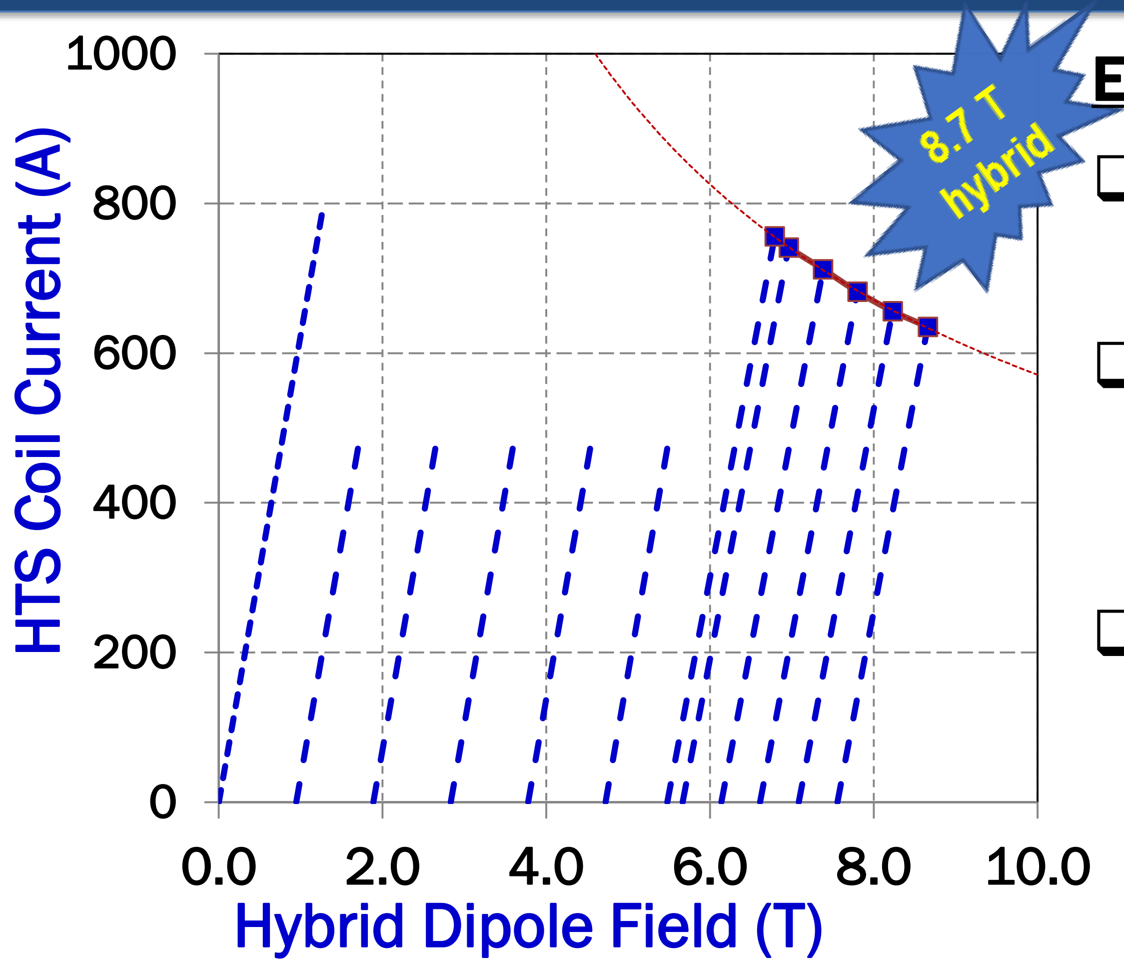
HTS/LTS Hybrid Dipole Test



Encouraging Results:

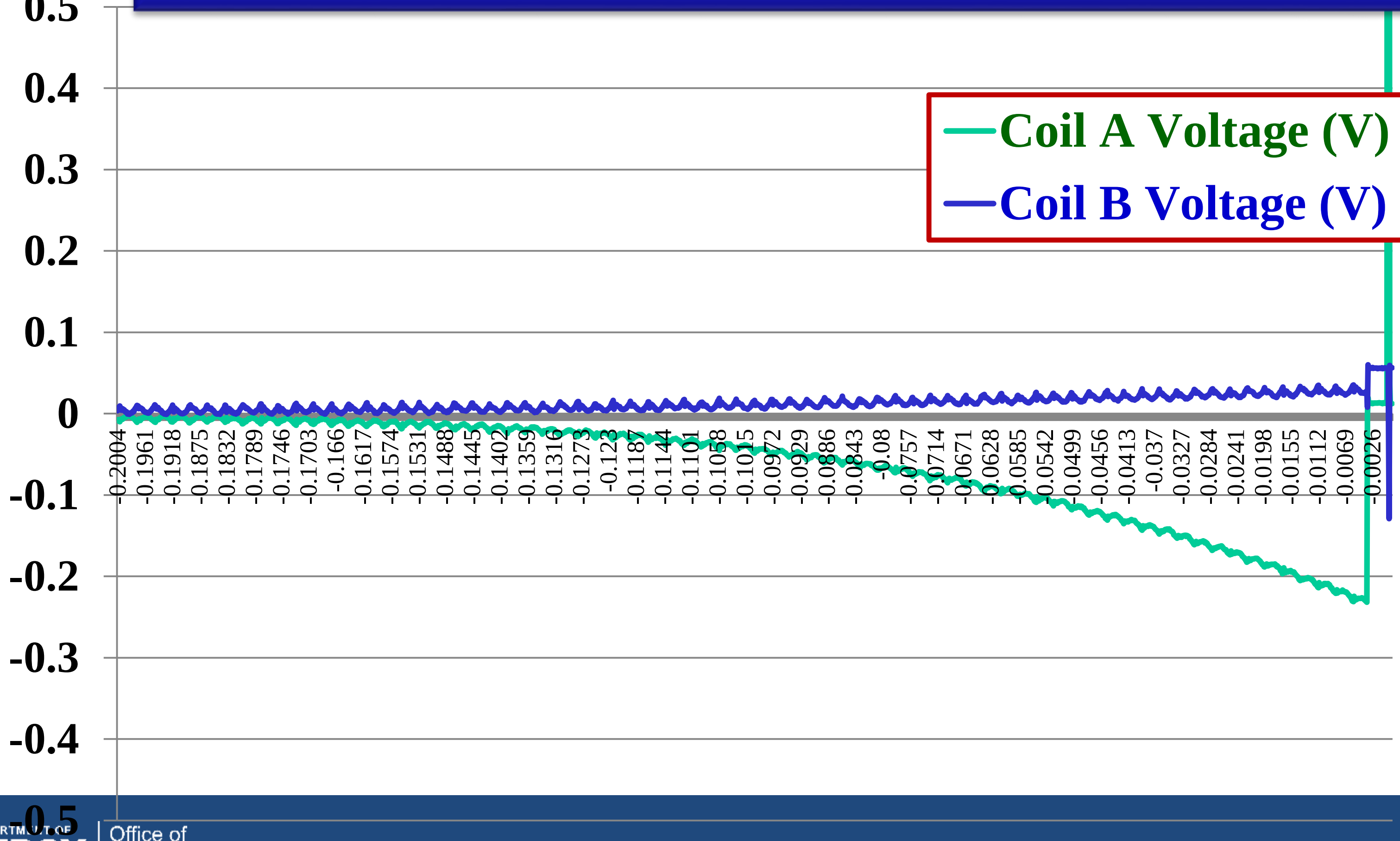
- HTS coils were ramped to quench, just like LTS coils
- No degradation in HTS coils despite a number of quenches
- Significant demonstration. 8.7 T may be the highest field HTS/LTS hybrid dipole magnet

>14 T possible with new HTS tapes in favorable direction

Operation of HTS Coils

HTS coils operated like LTS coils

- Significant voltage in HTS coils: >0.2 Volts

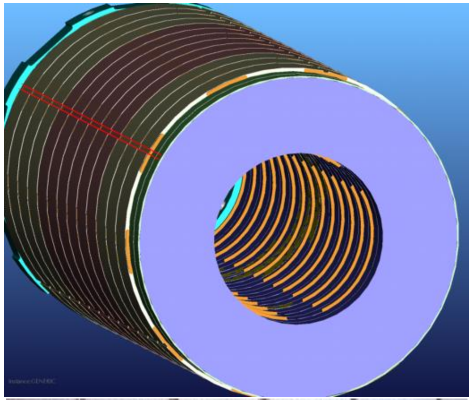


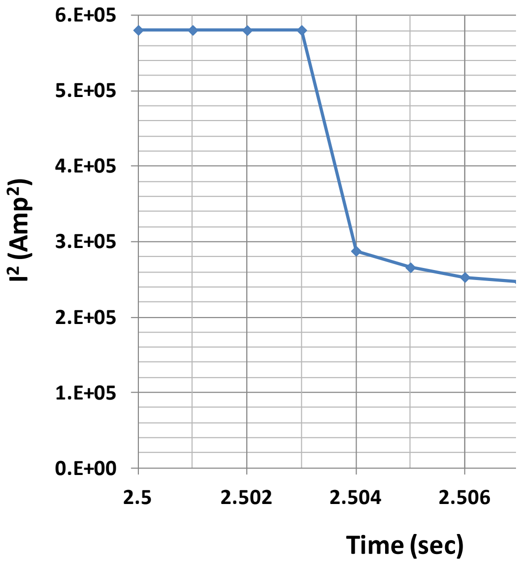
BNL Approach to Quench Protection

Quench protection is a major challenge in using HTS magnets.

BNL has successfully developed a multi-prong strategy:

1. Inductively coupled copper disks (now being used in CERN HTS program also)
2. Sensitive electronics to detect resistive voltage quickly at the pre-quench phase
3. Fast energy extraction with electronics that can tolerate high voltage stand-off
4. All metallic coil (including insulation)





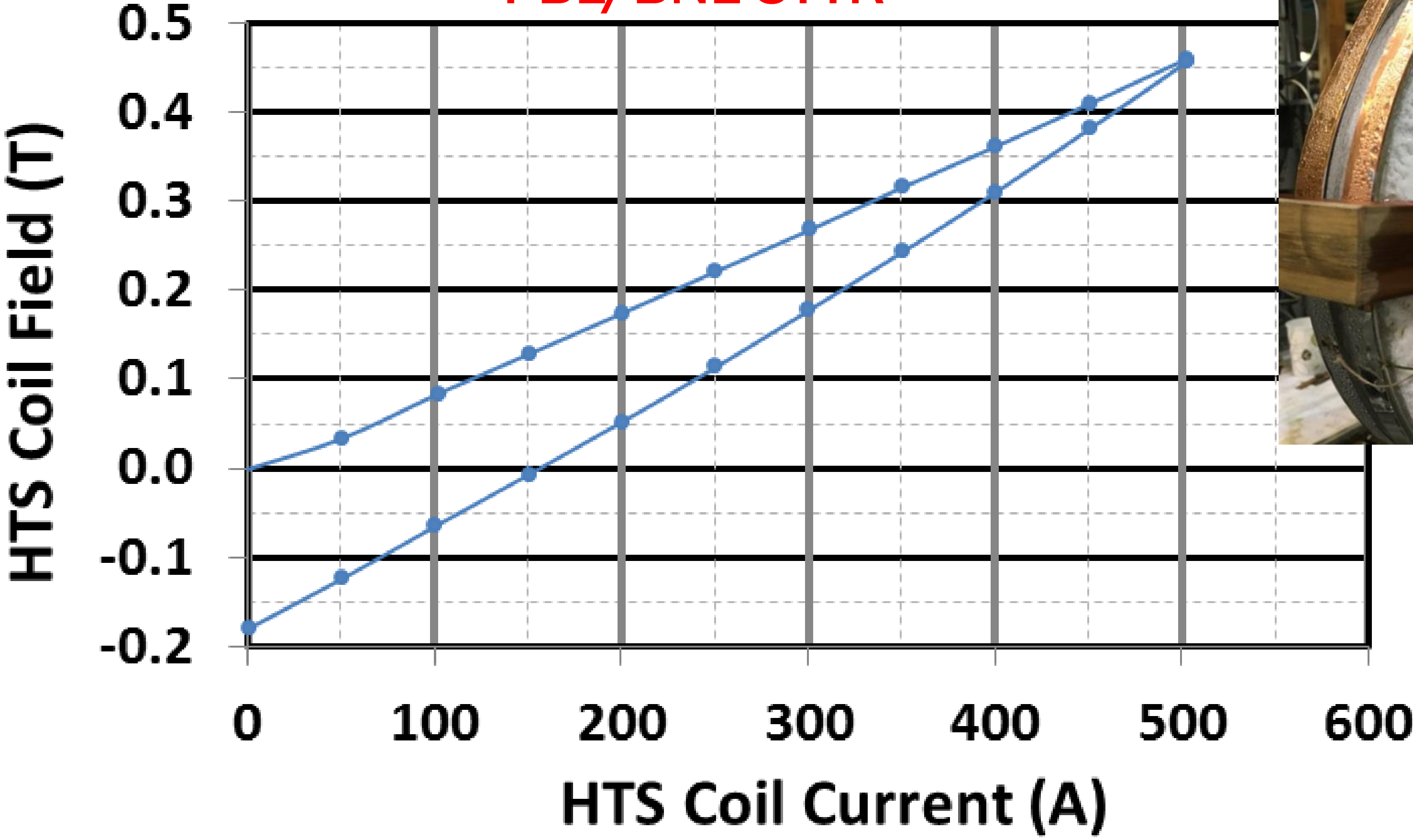
HTS Tape Magnetization – Quantify the issues; Can they be handled?

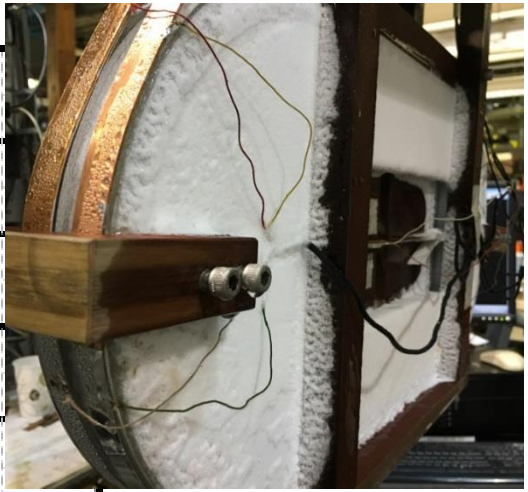
- Key input to machine physicists on dealing with magnetization is to first define the problem.
- This information should be available experimentally, not just computer models (computer model can supplement but they can't replace - initially they must be benchmarked).
- The input should come from an environment that is as close to accelerator magnets as possible
- BNL common coil magnet provides that

Test Run at 4 K (in 2 T background field from Nb_3Sn coils)

Additional field from the HTS coils in up and down ramp (offset to start from zero to start up-ramp)

PBL/BNL STTR





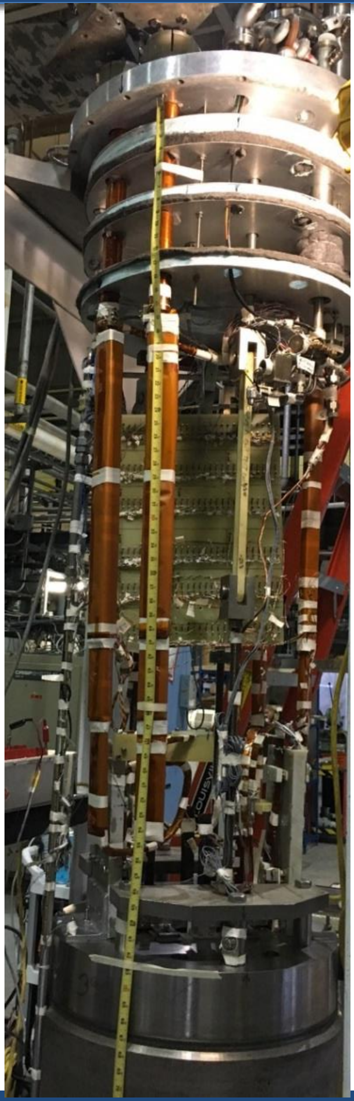
field perpendicular configuration

Summary of BNL HTS Experience

- **BNL has had a long history in development of HTS magnets for science applications**
- **Needs for magnets for various applications, including high field magnets (25 T), magnets for accelerators has driven the areas of research BNL has pursued**
- **Future contributions will continue to develop this focus – e.g. understanding magnetization, HTS/LTS hybrid magnet design and testing**
- **BNL has had 20-30 HTS magnet programs –most are listed in the backup slides**

- **Standout features of BNL magnet program**
  - Develop and demonstrate designs and technology in a cost effective way
  - This should continue together with other partners
- **Standout feature of BNL HTS test facility**
  - A vehicle to demonstrate and study magnet technology in a high field accelerator magnet test environment
  - Unique BNL Nb_3Sn dipole with large opening provides a low cost, rapid-turn around test facility (magnet R&D factory) where R&D insert coils become an integral part of the high field dipole

BNL R&D for International Accelerator Community



- BNL has significant capabilities that can help MDP further address the needs of the global community
- A high field testing capability for HTS coils can be applied immediately to address MDP needs, particularly address the technology issues of interest today
  - CORC hybrid magnet already underway with support from SBIR =>scope can be expanded for quench propagation studies
  - Rapid testing of sample coils at high fields to address/understand coil components impacting quench at high fields in REBCO tape coils, Bi2212 coils (LBNL), Nb_3Sn coils with different epoxies, etc. ...
  - Field parallel magnetization measurements
- Demonstration of unique coil configurations at high fields – e.g. clover-leaf coil
- Note: Insert coil becomes an integral part of the magnet

Summary and Conclusions

- **With it's vast and unique experience with various HTS, BNL can provide a strong contribution to US high field Magnet Development Program, particularly in the area of HTS magnets**
- **With a unique team experienced in large scale magnet productions in partnership with industry for superconducting colliders, BNL can help develop HTS magnets that industry can build**
- **BNL common coil magnet provides immediately a unique fast turn around, low cost magnet development test facility**
- **BNL can make unique and significant contributions by providing answers to key basic science and technology within a year**

Extra Slides

Summary of HTS Magnet Program

- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – solenoid, racetrack, cosine theta, curve coils
- Number of HTS coils/magnets designed built & tested:
  - Well over 150 HTS coils and well over 15 HTS magnets
- Type of HTS used:
  - Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape
- Amount of HTS acquired:
  - Over 50 km (4 mm tape equivalent)
- Our recent activities have been largely on magnets with ReBCO

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Current and Recent HTS and/or High Field Magnet Programs at BNL

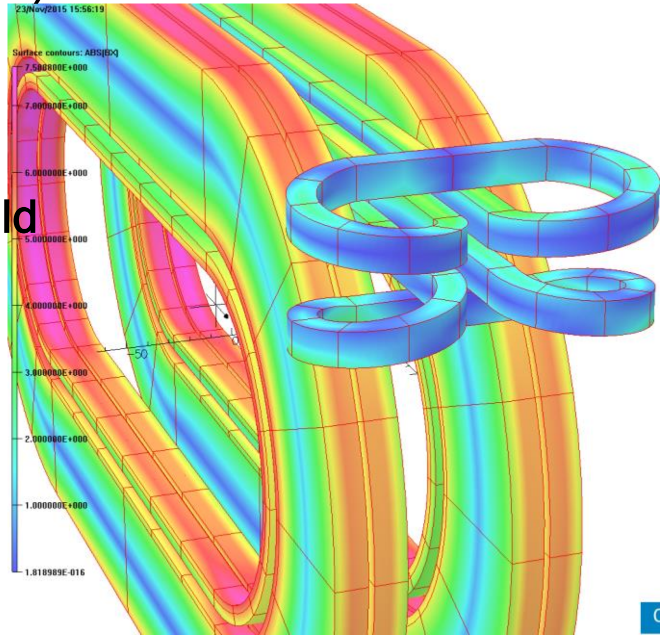
- **25 T, 100 mm HTS solenoid for IBS, Korea (Work for Others)**
- **Hybrid Dipole with CORC® Cable (Phase II SBIR)**
- **High field solenoid for Neutron Scattering (Recent SBIR)**
- **Passive shielding for Electron Ion Collider (Phase I SBIR)**
- **Modular racetrack coil quadrupole for EIC (Phase I SBIR)**
- **100 mm aperture "12.5 T @27 K" HTS SMES solenoid (arpa-e)**
- **High field collider dipole (Phase II STTR)**
- **Curved ReBCO tape dipole (Phase II SBIR)**
- **MgB_2 solenoid (Phase II SBIR)**
- **High field open HTS midplane dipole (Phase I SBIR)**
- **High radiation HTS Quadrupole for FRIB (Collaboration)**

Completed HTS Magnet Programs

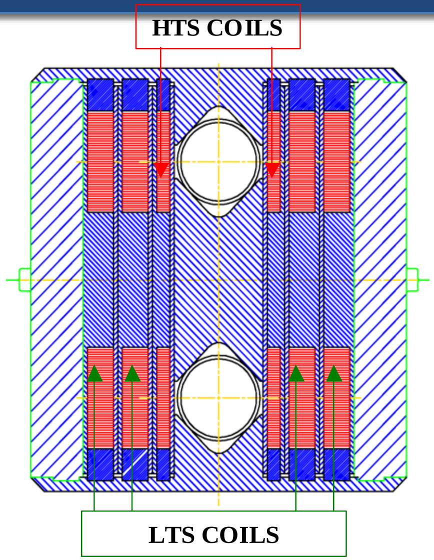
- 25 mm aperture 16 T HTS solenoid (SBIR)
- 100 mm aperture 9 T HTS solenoid (SBIR)
- HTS quadrupole for RIA (Collaboration with MSU)
- Bi2223 HTS tape common coil dipole (funded by DOE)
- Bi2212 Rutherford cable Common Coil Collider Dipole (DOE)
- HTS solenoid for Energy Recovery Linac (BNL project)
- HTS magnet for NSLS (BNL Project)
- Cosine theta dipole with 4 mm YBCO/ReBCO tape (SBIR)
- Cosine theta dipole with 12 mm YBCO/ReBCO tape (SBIR)
- …and a few others.

Possible Demonstration of Clover-leaf hybrid

- A successful demonstration of this technology will open the door for many new possibilities
- In HEP high field magnets, it can be used for Roebel (CERN) with field in right direction
- It can also be used in Nb_3Sn magnets
- Phase II for more automated coil winding & insert high field coil testing inside BNL dipole



Common Coil Dipole for High Current CORC® Cable



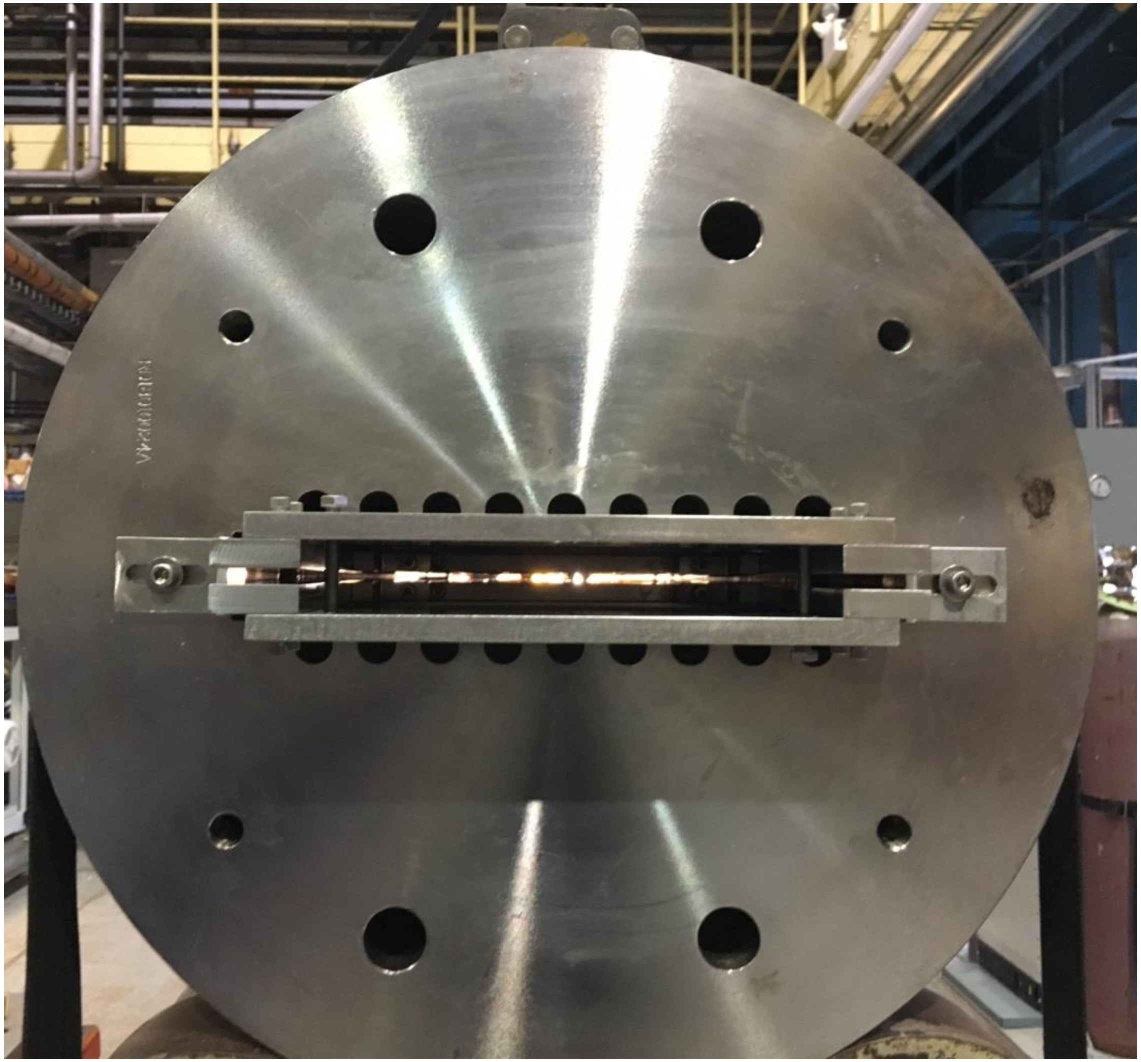
- CORC® cable offers a promising option for high performance, high strength ReBCO tape for making high field magnets
- Partially transposed CORC® cable reduces the field harmonics associated with the tapes
- 6 mm diameter offers a relatively robust CORC® cable with a measured J_e(4.2 K, 17 T) = 344 A/mm^2; I_c = 7,030 A, and is ready for use in common coil with practically no R&D required
- CORC® cable based HTS insert coils running at 10 kA in series with BNL Nb_3Sn common coil DCC017 produces a proof-of-principle 13 T hybrid dipole within the budget of Phase II SBIR
- High current HTS coils running in series with Nb_3Sn coils provides a magnet with easier operation and easier protection
- Larger diameter cable requires magnet designs with large diameter coils – common coil design offers that
- 6 mm CORC® cable is a factor of 2 higher in J_e than the smaller 3 mm diameter cable, has less wastage, lower cost, …
- Phase 2 J_e > 600 A/mm^2 at 20 T in 5-6 mm thick CORC® cables
- CORC® based common coil offers a promising hybrid option

Dry Run for Final Assembly

Dry run to see that the metal frame structure will fit inside the common coil magnet opening

Metal part fabrication was coordinated and purchased by PBL (saves on overhead)

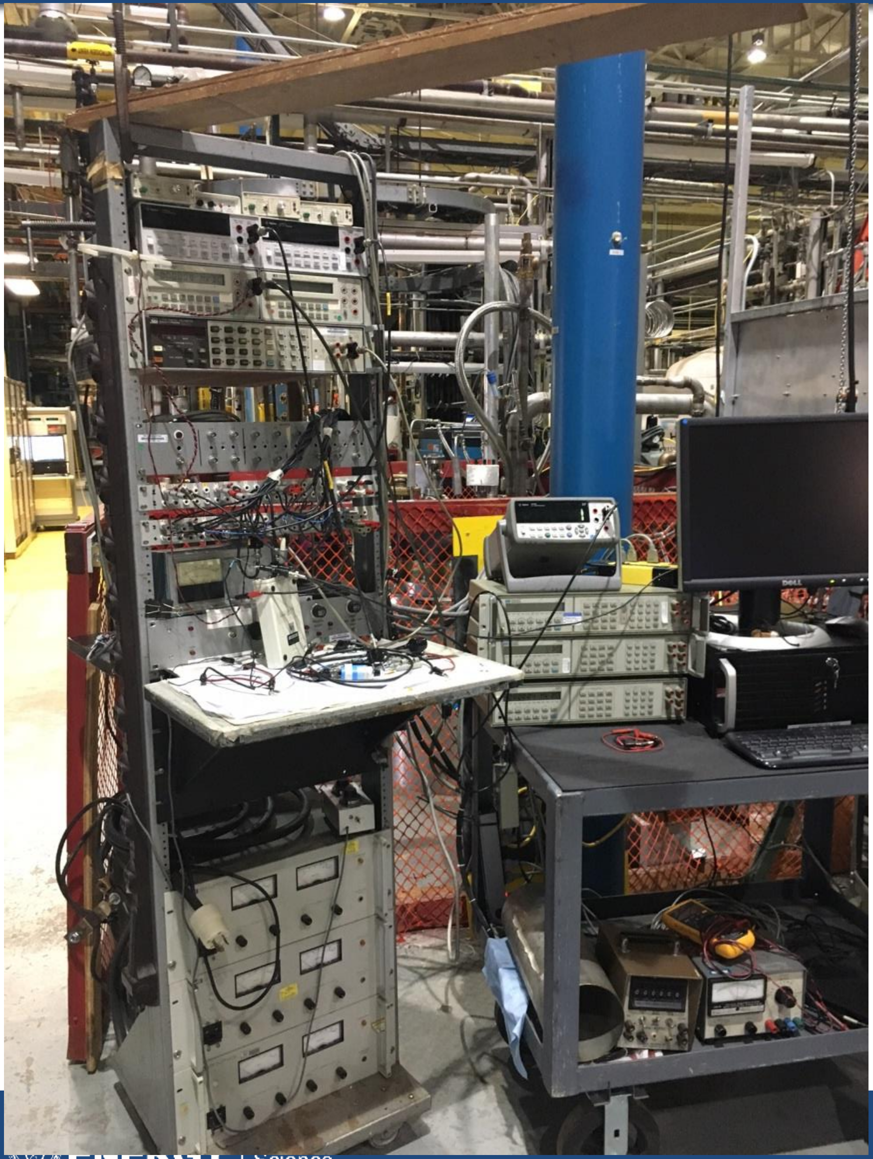
Metal Structure Inserted



Further check to see that the two pancake coils can be separated out by ~1/16” after the installation

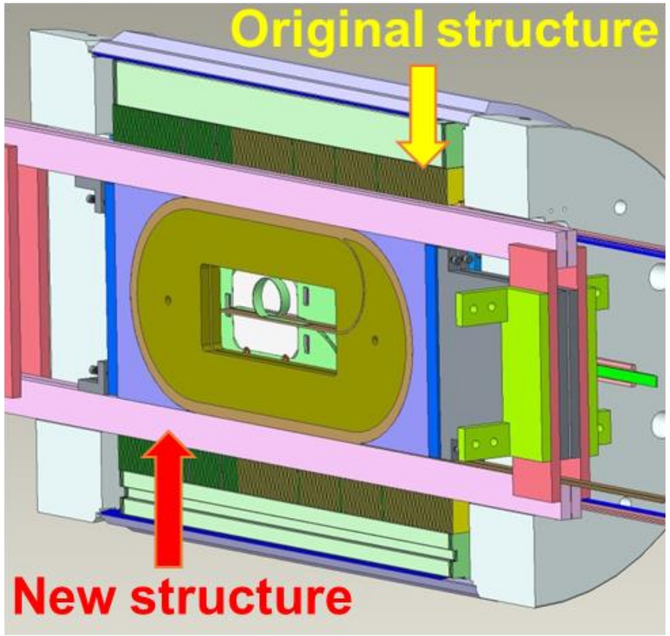
(now you can see light at the end of the tunnel)

HTS Quench Protection



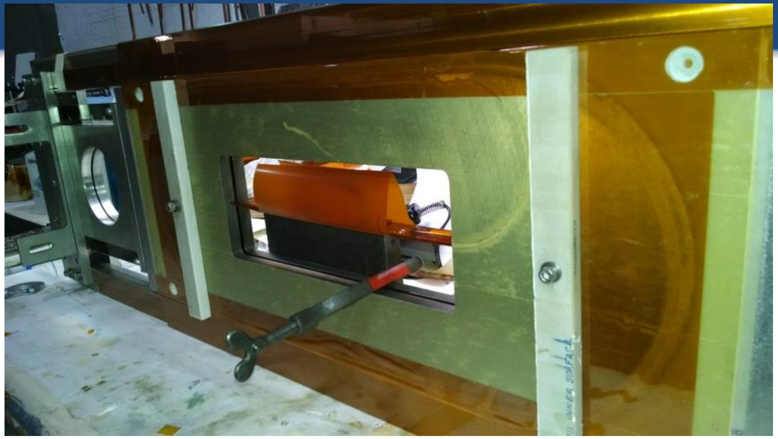
HTS/LTS Hybrid Dipole Structure

Design

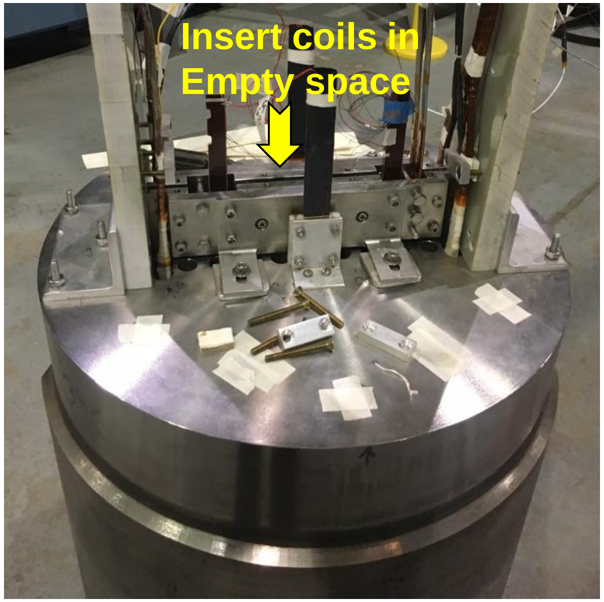


New HTS coils slide inside the existing Nb_3Sn coils and become an integral part of the structure

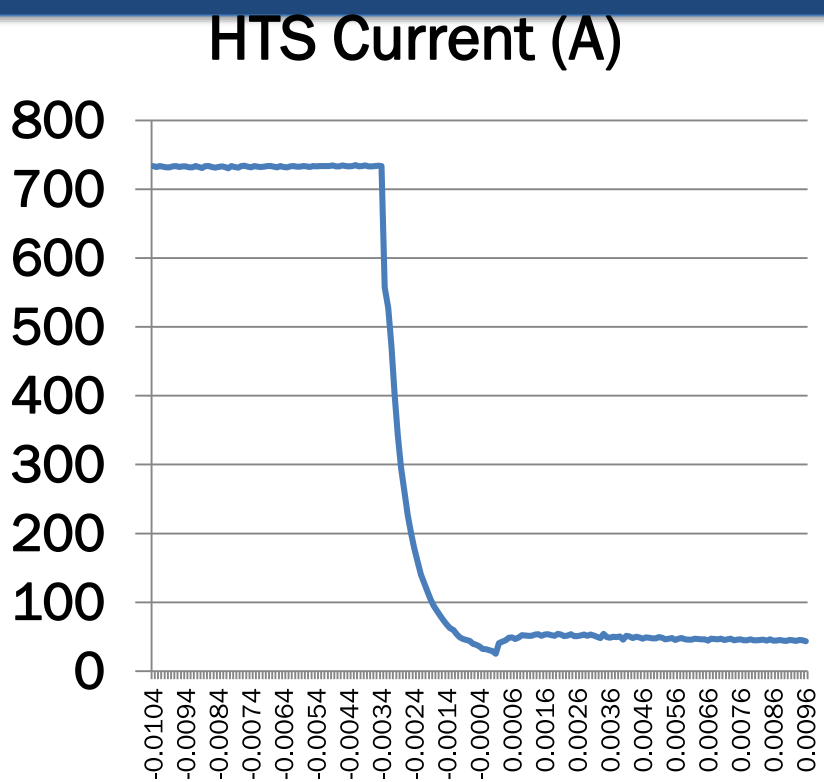
HTS coils get pushed inside the LTS coils

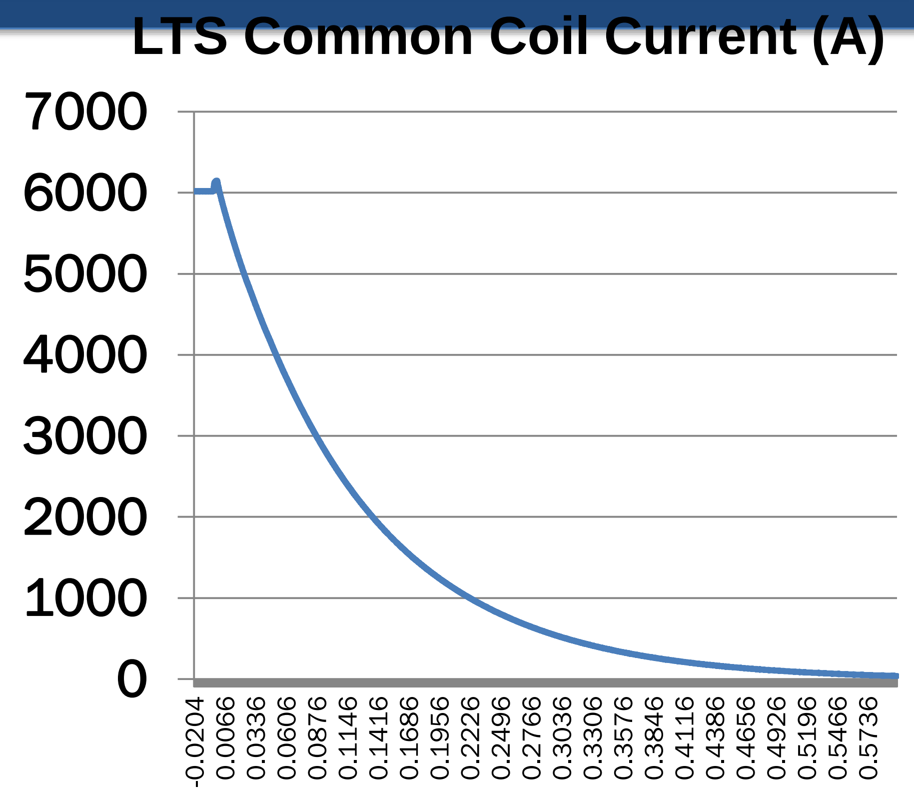


Assembly of a pair of insert coils



HTS and LTS Currents
(just before and after the quench)



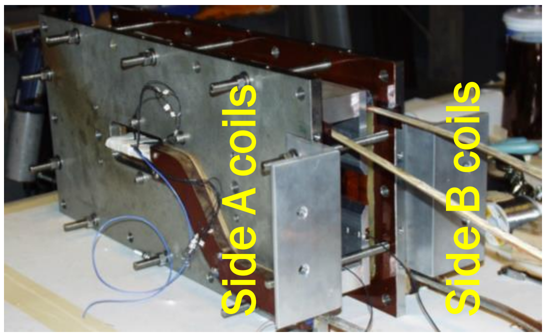


Separate power supplies and separate energy extraction for HTS and LTS coils

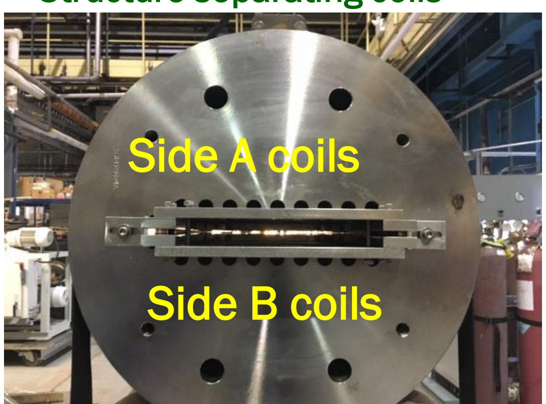
HTS and LTS coils have different inductances and different characteristics

Relevance of Aperture in Magnet R&D

All coils in a single structure



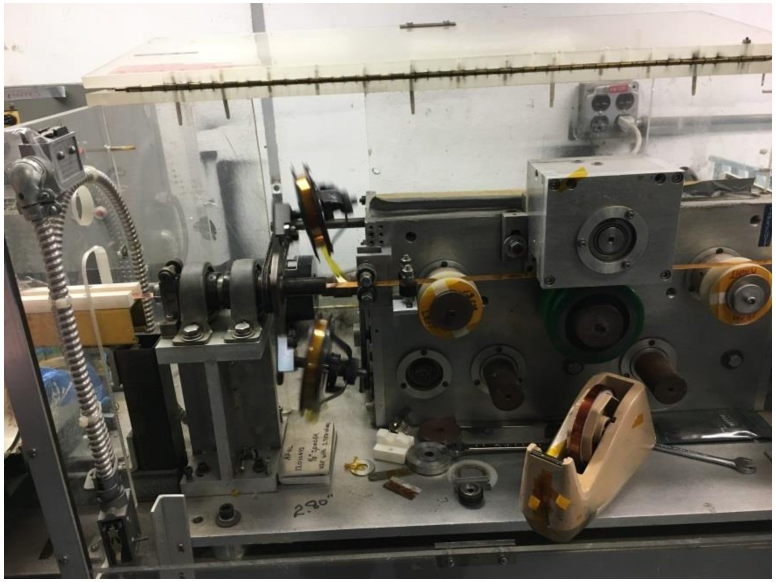
Structure separating coils

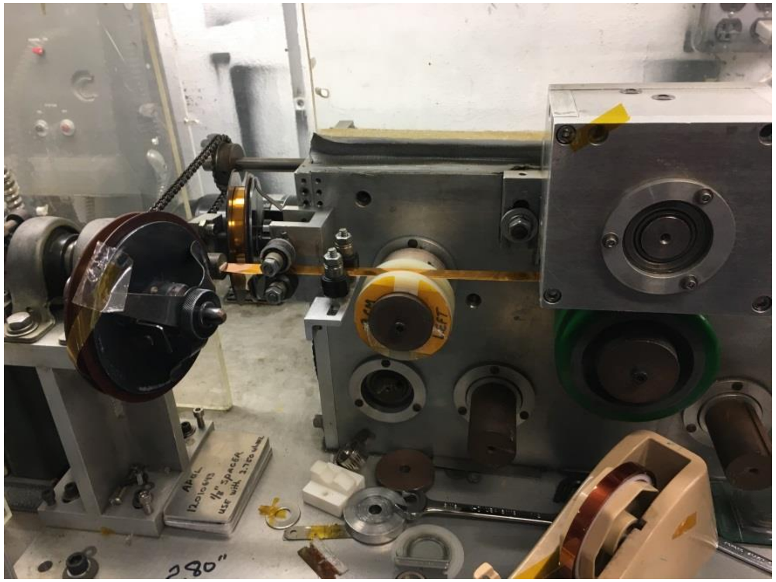


Visible space between left and right insert coils inside DCC017

- The modular common coil design offers an option where the aperture can be made smaller to do initial evaluation of high field magnets R&D at a lower cost
- Natural question: what is the applicability of these results in "magnets with real aperture?"
- If a design is such that one side of the coils are independent of the other side of the coils, then how much does it matter that how far they are, as long as the individual set of coils are subjected to the same level of field & stresses.
- Compare this with using the results of magnet R&D between the long magnets and the short magnets
- Yes, long magnets give complete results. But if we were relying only on them then what would have been the cost of developing technology; or examine different options; or how much R&D we would have been able to do?
- Common coil design with an option of doing R&D with smaller aperture takes the value of subscale magnet R&D to the next dimension

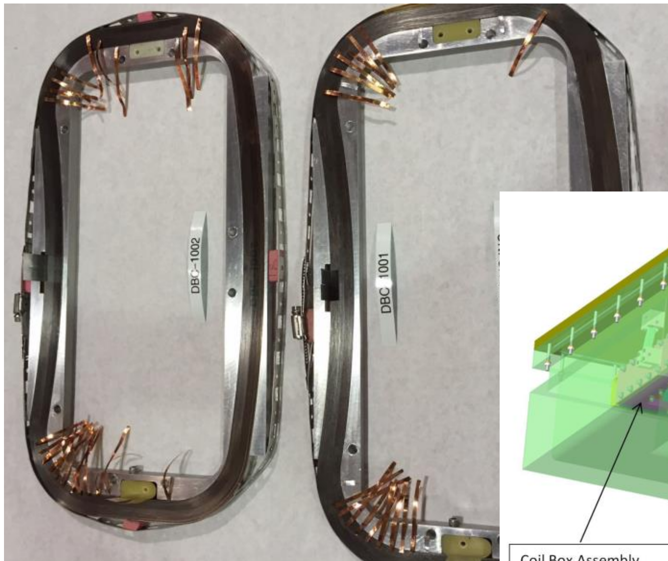
Kapton-Ci Insulation on ReBCO Tape (and Making a NbTi Type Cured Coil)





Part of the same STTR

77 K tests show no degradation in conductor performance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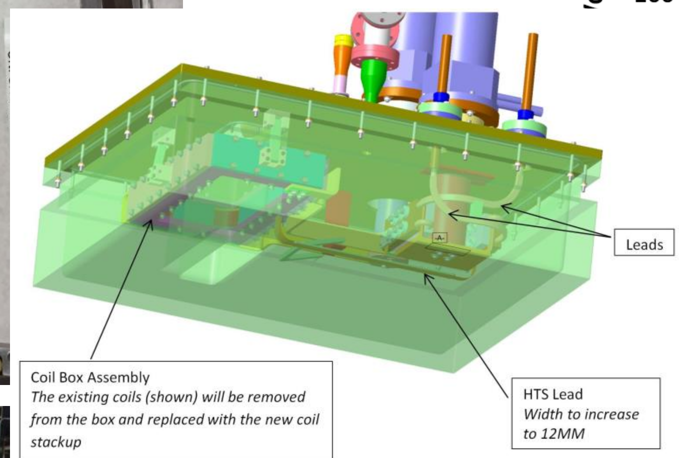
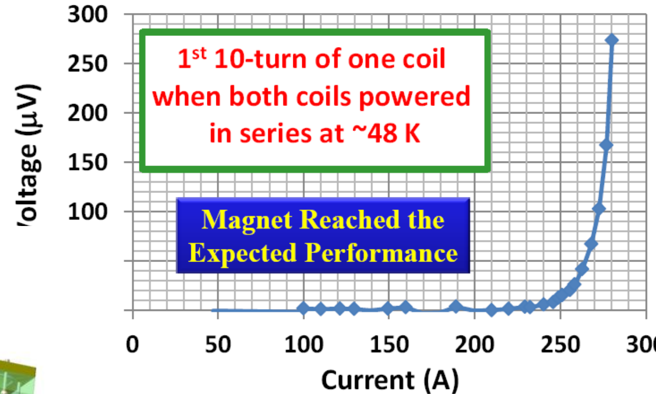
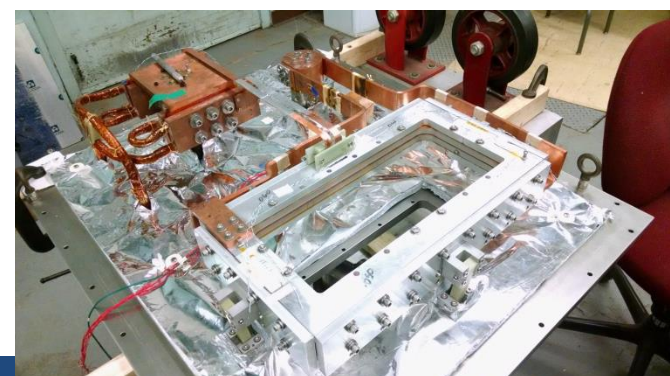
DBC 1001


Leads
Coil Box Assembly
The existing coils (shown) will be removed from the box and replaced with the new coil stackup
HTS Lead
Width to increase to 12MM


300
250
200
150
100
oltage (μV)
0
50
100
150
200
250
300
Current (A)
1st 10-turn of one coil when both coils powered in series at ~48 K
Magnet Reached the Expected Performance



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Magnetization studies in high field at 4 K in magnets made with the HTS tapes

(Hall probe measurements)

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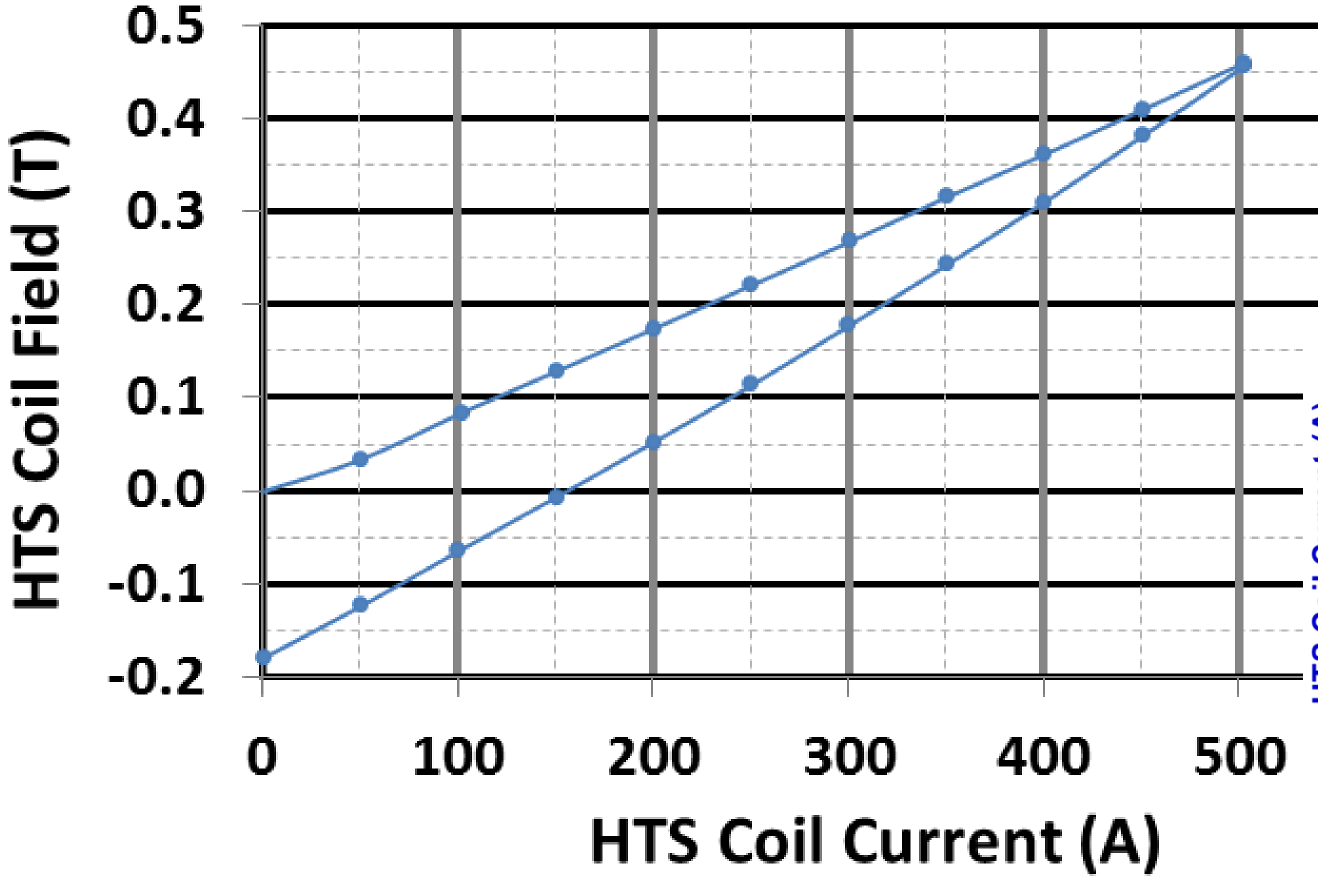
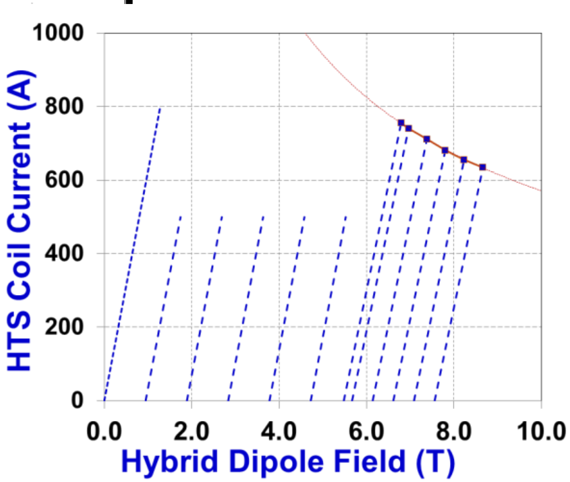
Test Run at 4 K (in 2 T background field from Nb_3Sn coils)

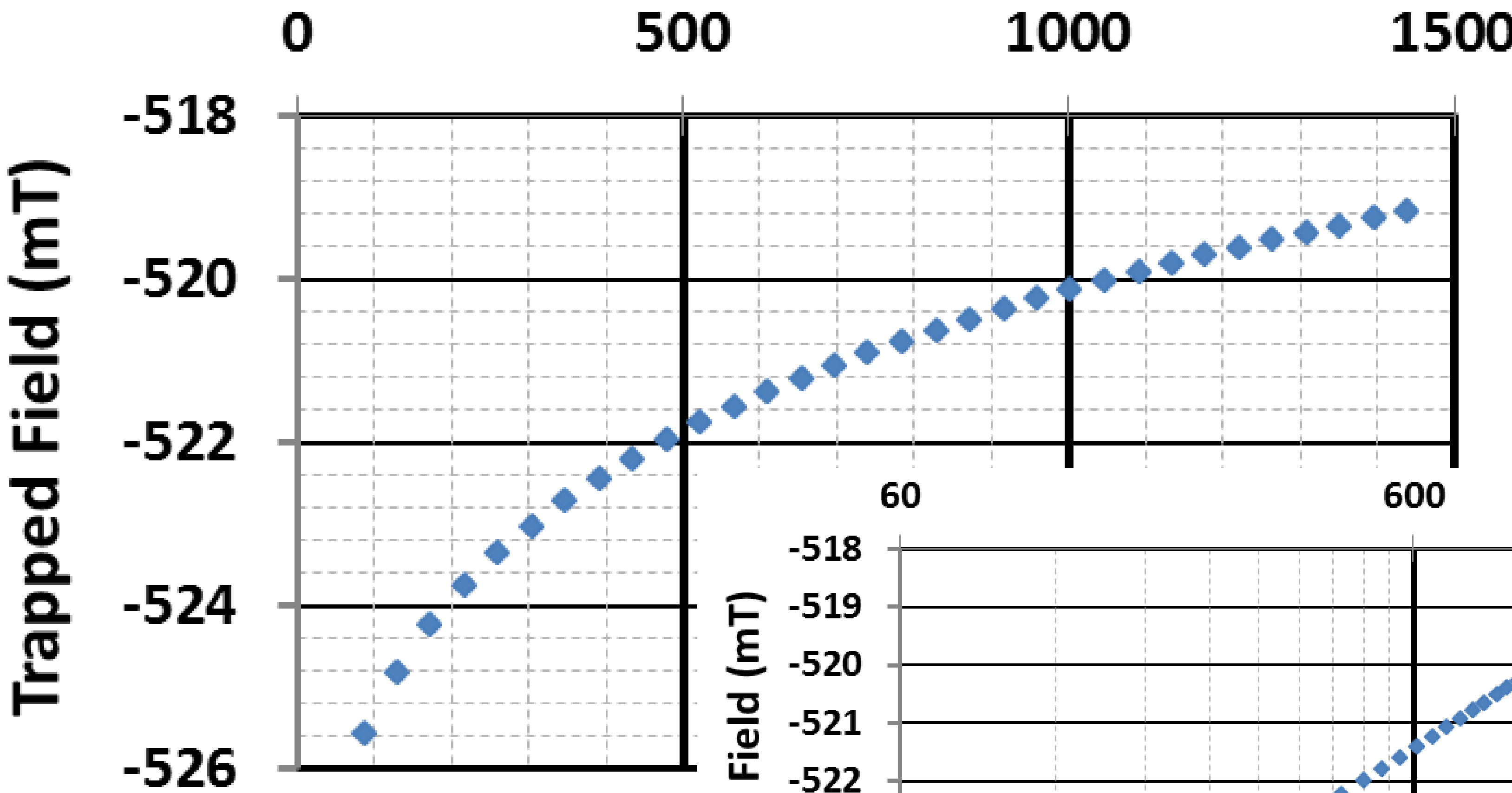
Additional field from the HTS coils in up and down ramp (offset to start from zero to start up-ramp)

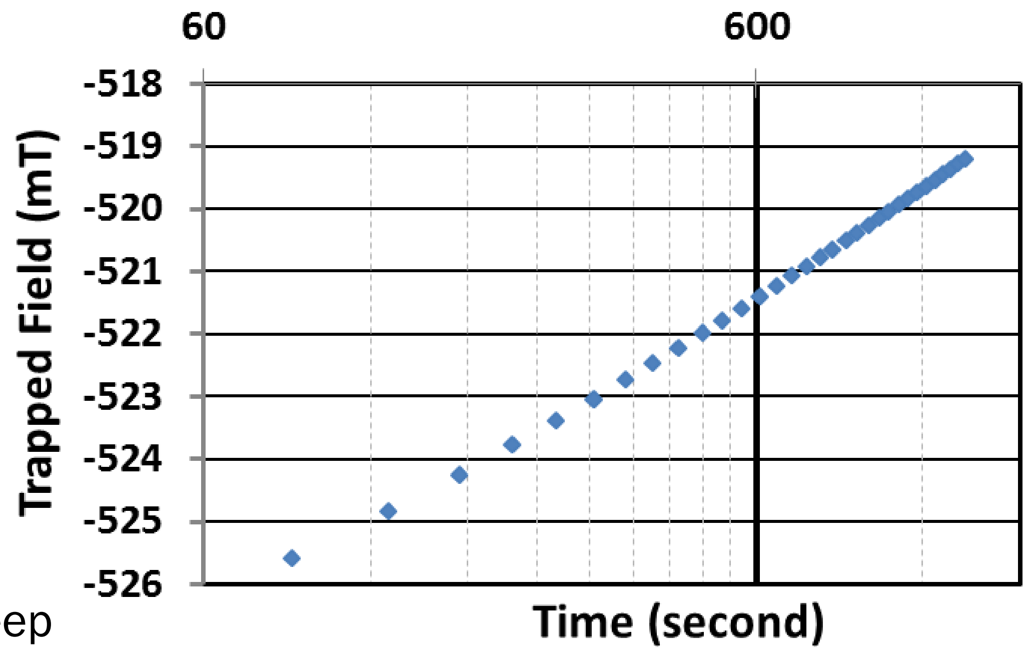




Decay of Trapped Field

(after the final run to ~8.7 T hybrid field @ 4 K)



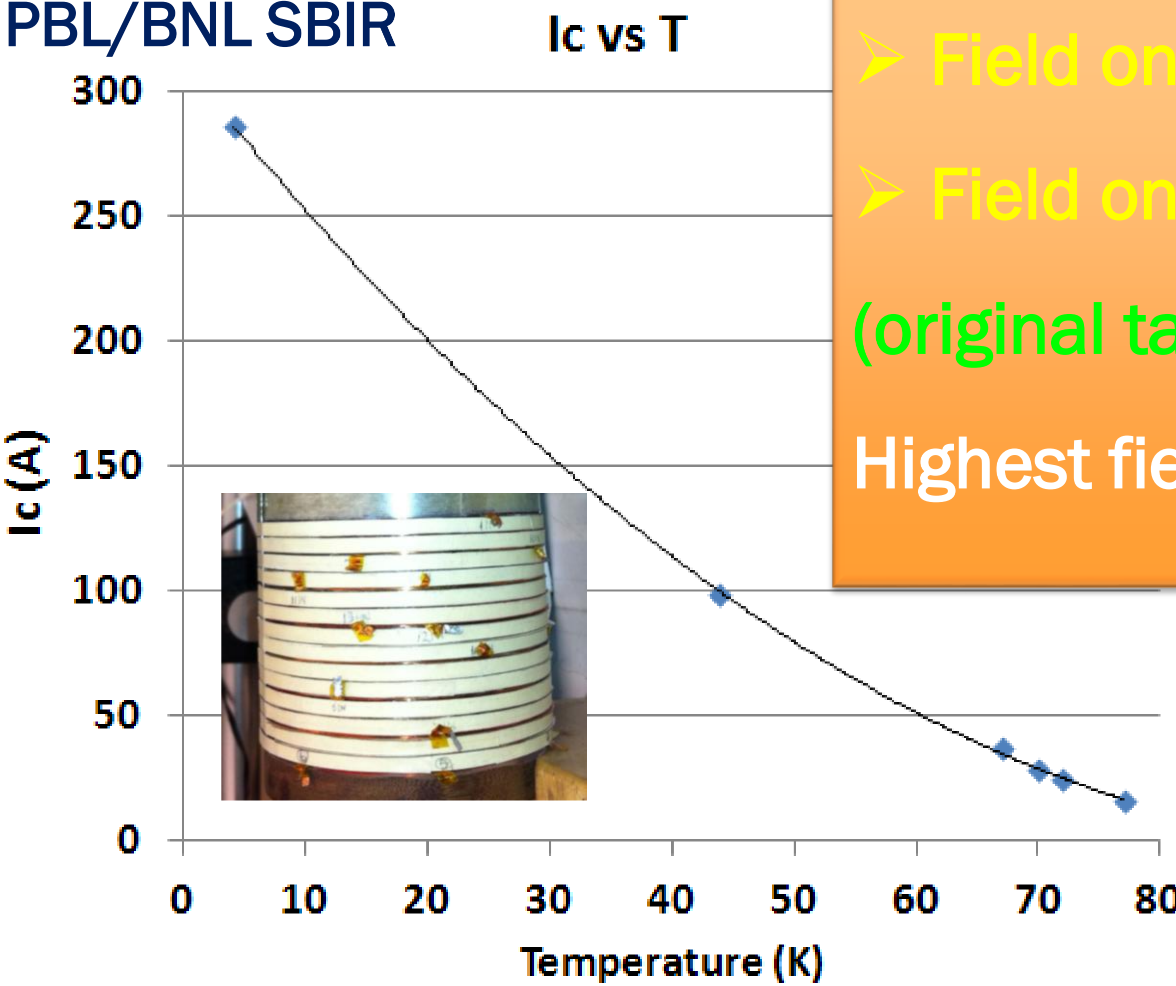


Flux creep

U.S. MAGN
DEVELOPM
PROGRAM

16T HTS Solenoid
(a wide range of operating temperature)

PBL/BNL SBIR



- Field on axis: 15.7 T
- Field on coil : 16.2 T

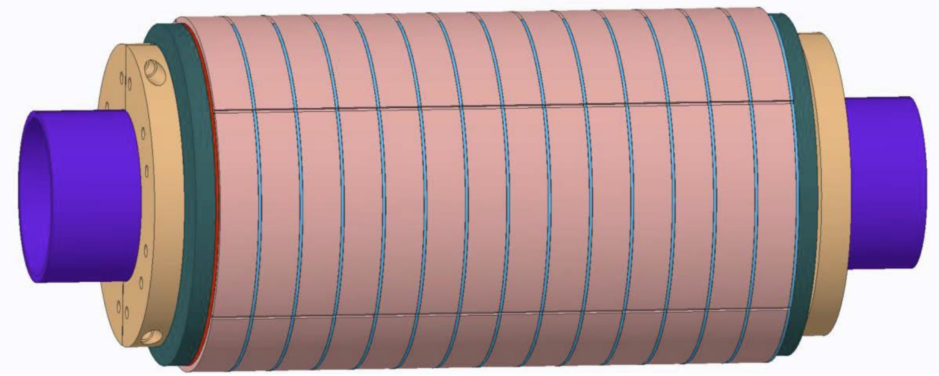
(original target: 10-12T)

Highest field all HTS solenoid

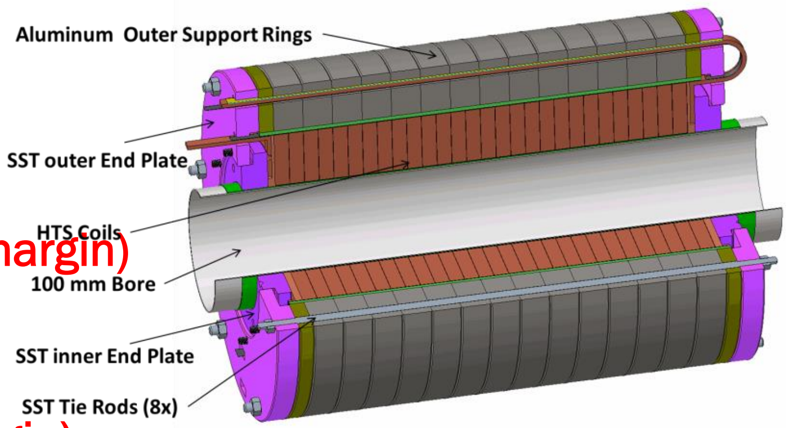
Overall J_o in coil:
>500 A/mm^2 @16 T

Insert solenoid: 14 pancakes, 25 mm aperture

IBS 25 T, 100 mm HTS Solenoid Design Summary



- Design Field: 25 T
- Operating Temperature: ~4 K
- Cold Bore: 100 mm
- Coil i.d.: ~105 mm
- Coil o.d.: ~200 mm
- Single Layer
- Conductor: 12 mm wide ReBCO (50 µm Hastelloy, 20 µm Cu)
- Conductor per Pancake: ~300 m
- Number of Pancakes: 28
- Current: ~450 A
- Overall Current Density: ~500 A/mm^2 (+ >50% margin)
- Stored Energy: ~1.3 MJ
- Inductance: ~13 Henry
- Maximum Hoop Stress: ~480 MPa (+ >50% margin)
- Maximum Axial Stress: ~180 MPa
- Outer Support Ring: 40 mm High Strength Aluminum



U.S. MAGNET DEVELOPMENT PROGRAM

Summary of the 3rd (of 4) 4 K Test Campaign

- **Three quenches at ~850 A, B_{peak} ~17 T, ~450 MPa (similar hoop stress and stored energy/pancake as in full 25 T solenoid)**
- **Many shut-offs at different currents**
- **Survivability against unusual events : Out of Helium, sudden jump in current, sudden loss of power, runaway**

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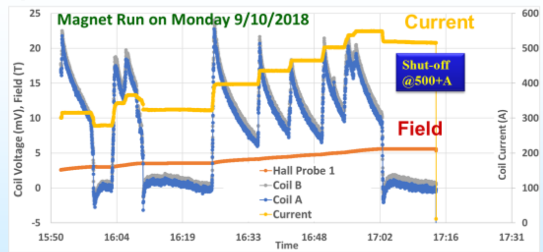
Monday Run Summary



Shut-off may cause an eventual thermal runaway (quench)

- As a part of the study a large number of shut-off (30-50) performed. This gives an early indication, depending on whether coil runs away or not, that we are close to the limit (more discussion in the next slide).

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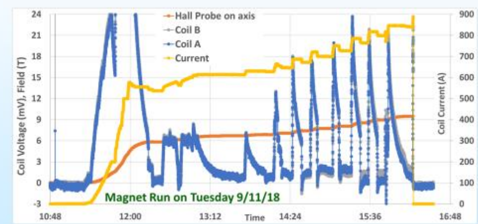
Tuesday Run Summary

- Continue increasing current to the maximum it could go
- Quenched in going from 850 A to 900 A (design: ~450 A)
- It reached maximum field in bore ~9 T and in coil ~17 T



850 Amp in a double pancake, creates similar hoop stresses and similar stored energy per pancake as in the 25T solenoid

- Quench discussed in more details in the next slide

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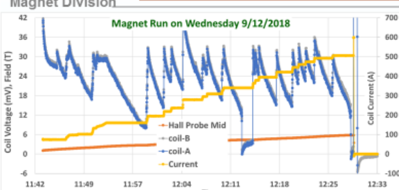
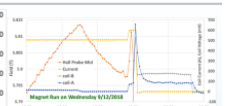
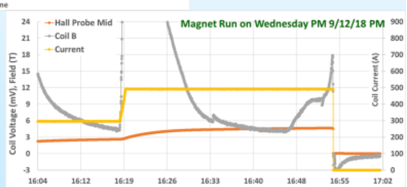
Wednesday Run Summary

(unusual events – not expected during normal operation)





1. Sudden increase in current due to coupling of two power supplies
2. Running out of Helium at the end of the day



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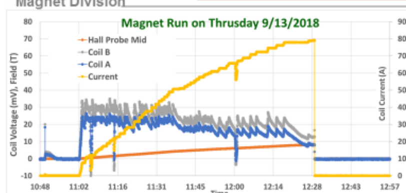
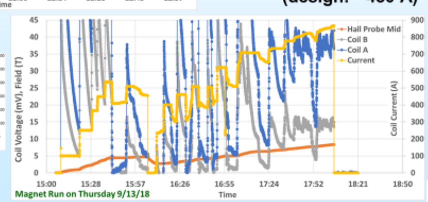
Thursday Run Summary



Second quench at ~800 A (design: ~450 A)

Third quench at ~850 A (design: ~450 A)

Shut-off near design current



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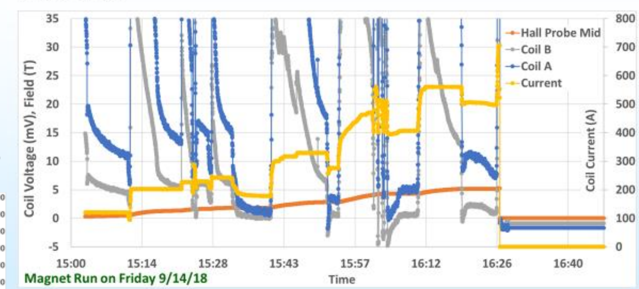
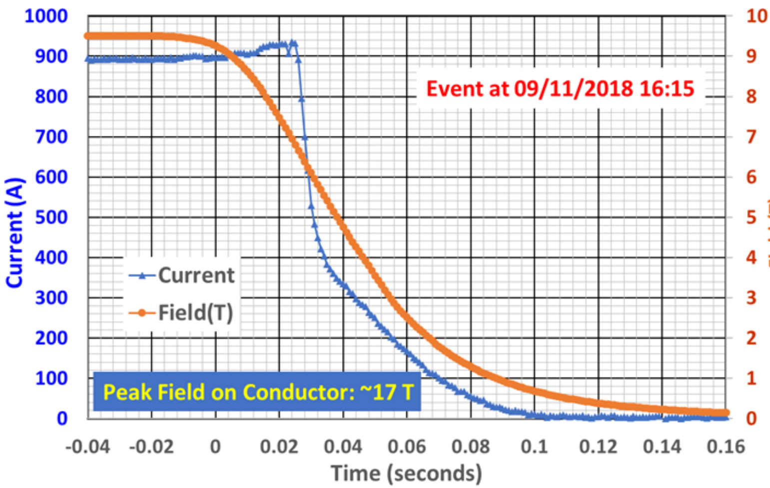
Friday Run Summary

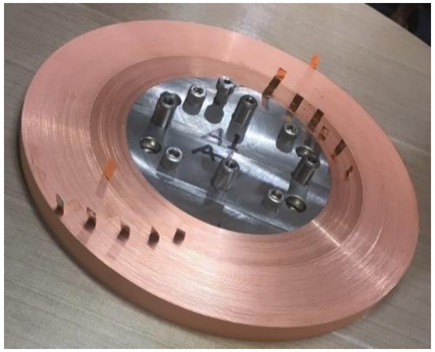


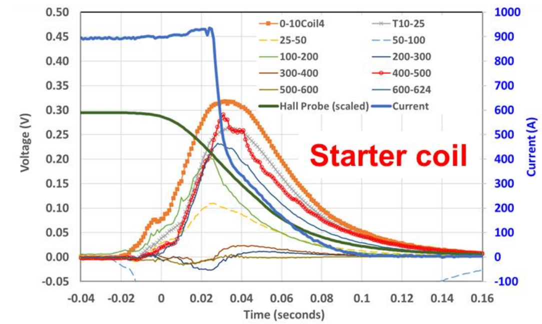
- Higher temperature operation mostly in Helium gas environment

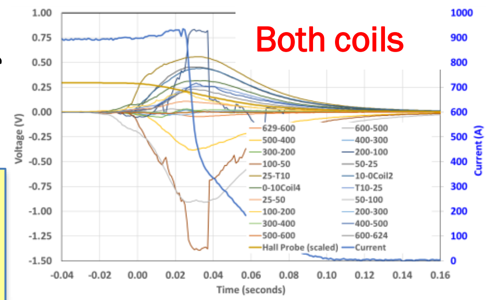
A Typical Quench Propagation in IBS Double Pancake at 4K
(a significant number of v-taps provides a good insight)

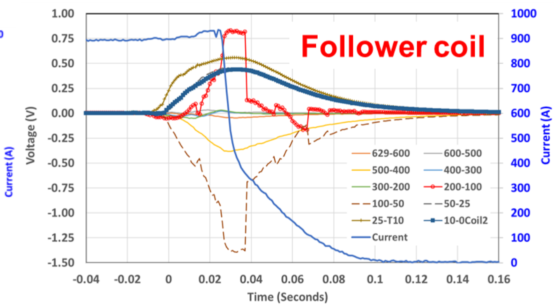


Many v-taps for detailed study







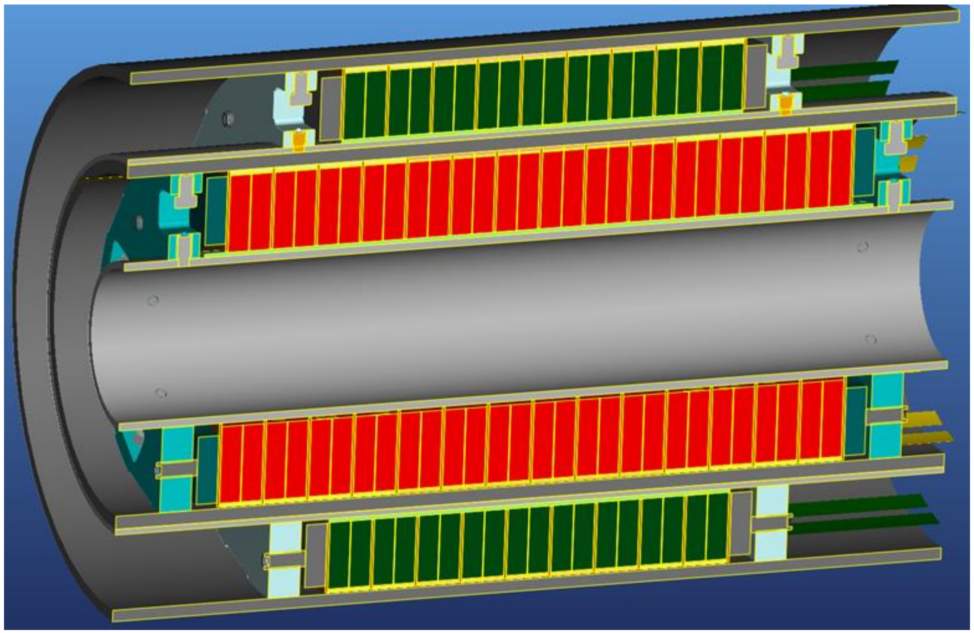


IBS coil became normal in < 200 msec (even faster than in many LTS magnets)

- Within a pancake: fast propagation due to resistive heating through contact resistance between turns in a “No-insulation” coil when the current goes across (not circulating)
- Pancake to pancake: fast propagation due to inductive coupling - local change in field

The Basic Demo Module

Aggressive parameters:

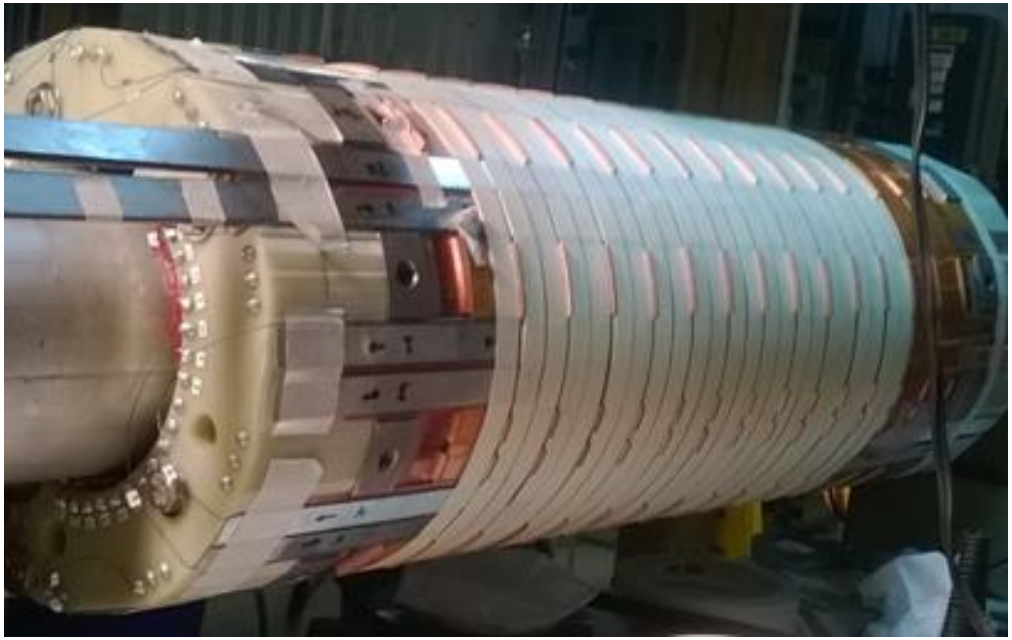


- Field: 25 T@4 K
- Bore: 100 mm
- Stored Energy: 1.7 MJ
- Hoop Stresses: 400 MPa
- Conductor: ReBCO

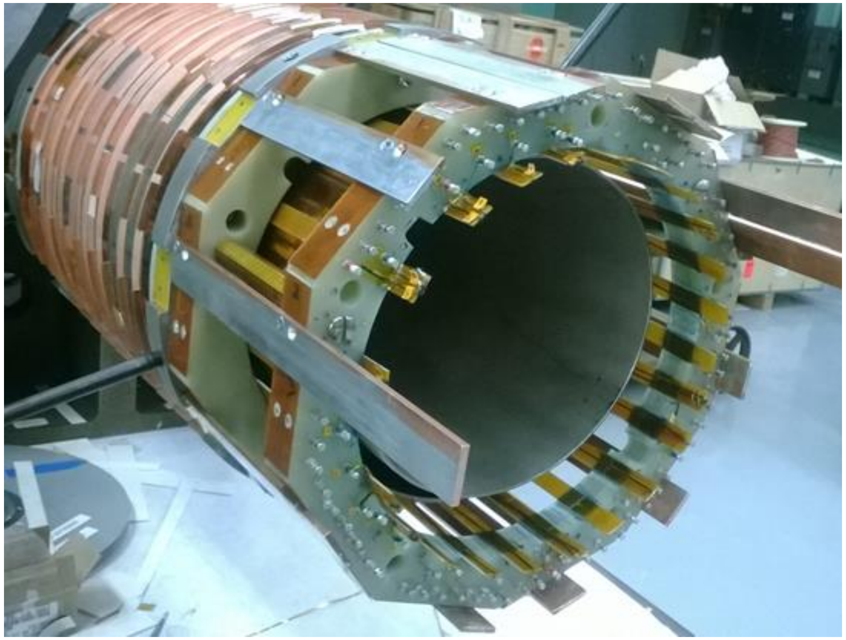
Amount of ReBCO used: >6 km, 12 mm wide

Significant use of HTS in a high field application

Inner and Outer Coils Assembled with Bypass Leads



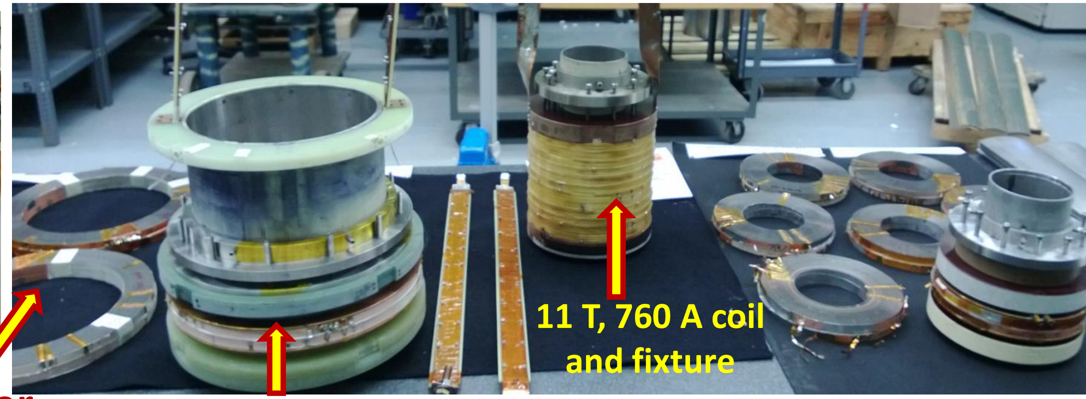
Inner Coil
(102 mm id, 194 mm od)
28 pancakes



Outer Coil
(223 mm id, 303 mm od)
18 pancakes

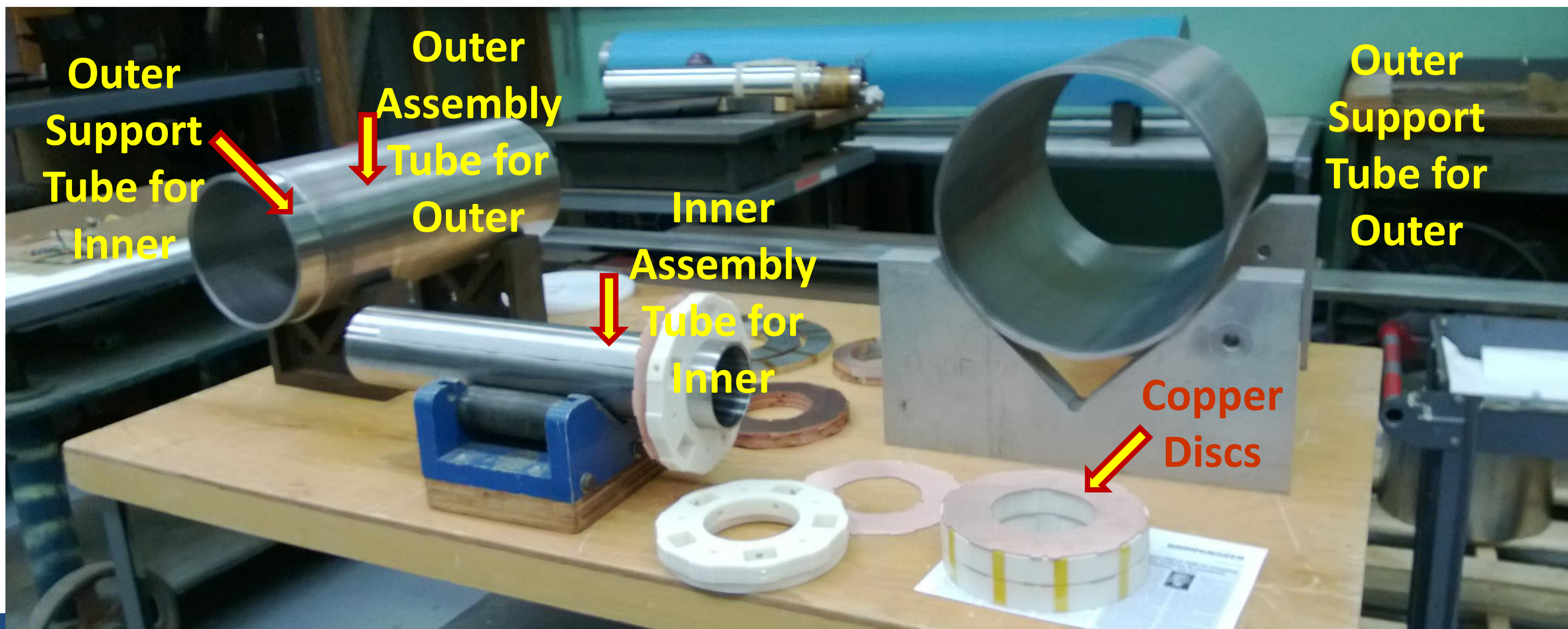
Total: 46 pancakes

Coils, Test Fixtures and Support Structure

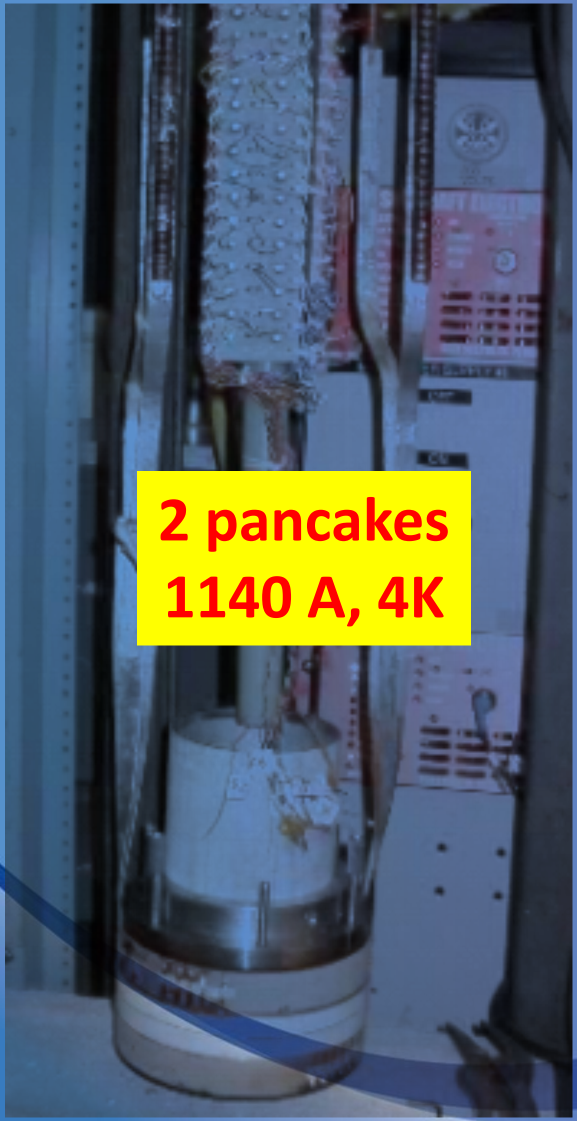


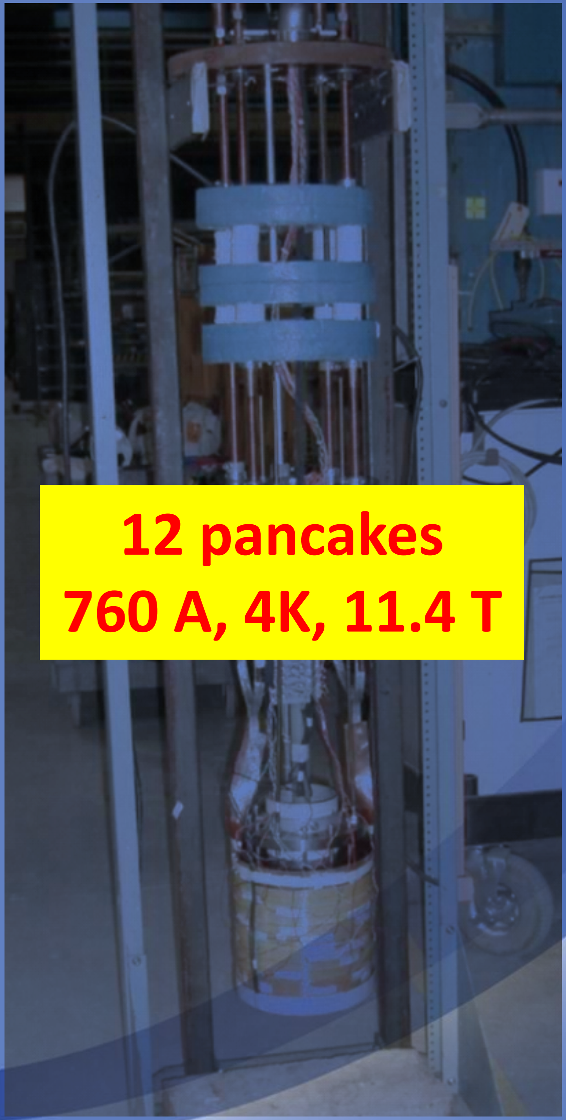
Pancake coils: inner and outer

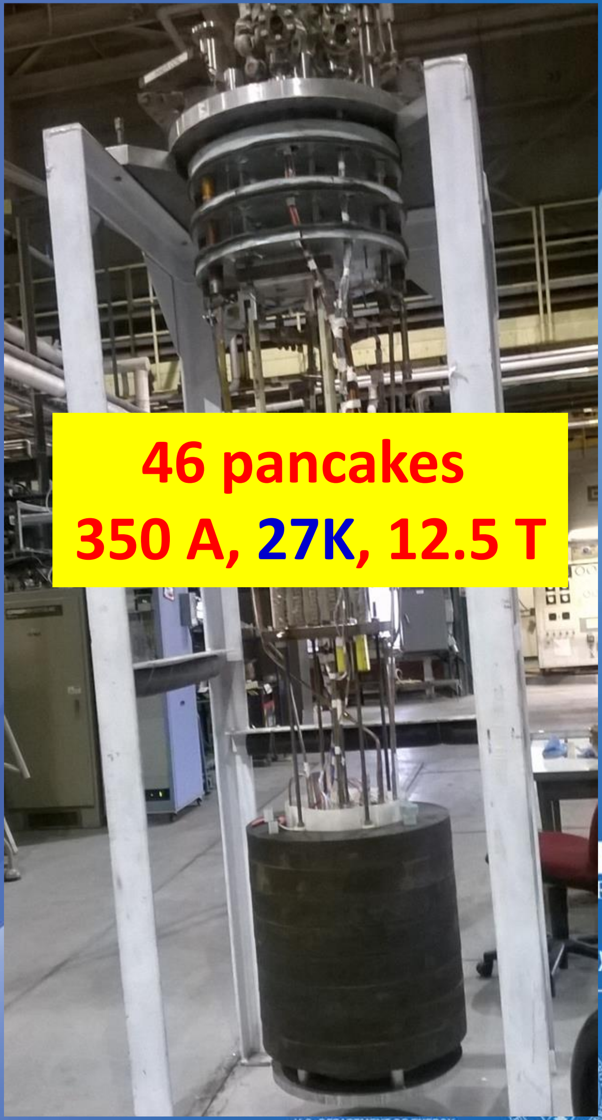
77 K Test Fixture for outer



HTS SMES Coil High Field Tests







Peak fields higher