HTS in Common Coils

Ramesh Gupta

HFM Forum at CERN

June 25, 2025

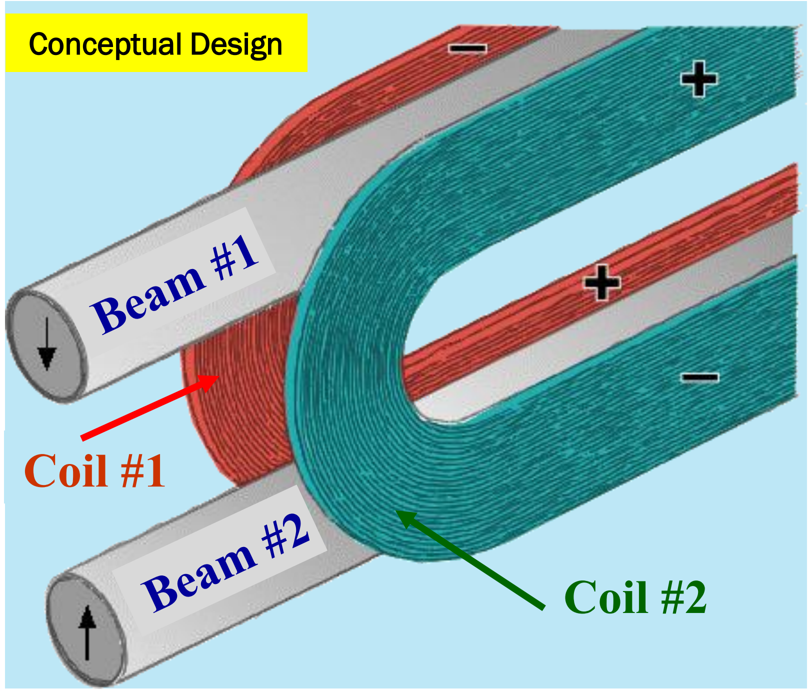
Overview

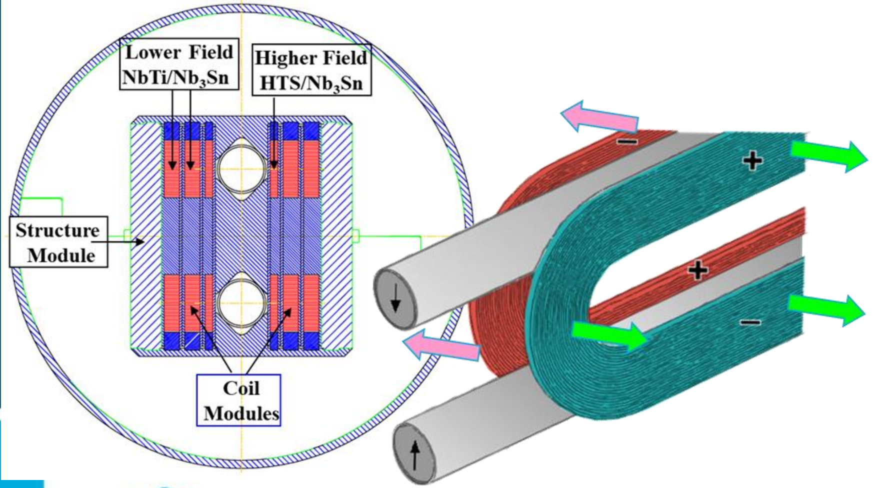
- A few strategic consideration and background of HTS in common coil
- Status of HTS cables and their use in the common coil
- Possibilities of leveraging R&D by fusion in accelerator magnets
- BNL experience with HTS in common coils (including lessons learned)
- Related R&D programs worldwide
- Summary and conclusions

A Few Strategic Consideration

- Given that the next hadron collider is several decades away, the R&D program must have a longer-term vision and a longer-term outlook.
- Need to move away from “incremental” to “game changer” approach.
- We should be mindful, however, that it takes a long time to develop and demonstrate new designs and technologies - no time to wait.
- Facilitate innovative and systematic R&D which is cost-effective with a rapid-turn-around (with demos every few months, not every few years).
- At this stage, we need to develop not only the magnet designs, but the program strategies as well, which set the R&D on a dynamic course.
- Magnet is one of the key part of the accelerator technology. What we demonstrate provides input to future planning (may even change that).

Common Coil Dipole Design and it's suitability for HTS





- ➢Simple 2-d geometry for 2-in-1 collider dipoles
- ➢Large bend radii, determined by the separation between the two borees rather than the bore itself
- ➢Allows use of most ReBCO cables, including high current fusion cables requiring large bend radii
- ➢Allows both "React & Wind" and "Wind & React" Technologies for Nb_3Sn and HTS
- ➢Modular design for mixing HTS, Nb_3Sn NbTi in hybrids, and for lower cost, rapid-turn-around R&D
- ➢Easier incorporation of stress-managed structure
- ➢Allows large horizontal displacement of the entire coil as a whole, without much internal strain

In fact, the common coil design was developed for HTS tapes/cables

PAC'97

(28 years ago)

A COMMON COIL DESIGN FOR HIGH FIELD 2-IN-1 ACCELERATOR MAGNETS*

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Abstract

A common coil design concept for 2-in-1 superconducting accelerator magnets is presented. It practically eliminates the major problems in the ends of high field magnets built with either high temperature superconductors (HTS) or conventional superconductors. Racetrack coils, consisting of rectangular blocks built with either superconducting tapes or cables, are common to both apertures

ReBCO Coils for High Field Accelerator Magnets

- Several accelerator magnet coils have been made with the ReBCO tapes. Also, a few HTS/LTS hybrid dipoles have been tested. This includes ~8.3 T in 2016 and ~12.3 T in 2020. Early tests helped understand issues with a new technology.
- ReBCO cable, rather than the single tape, is desired in magnets (next slide).
- Cables in magnet coils needs to be well supported (in grooves?) and protected.
- Therefore, the structure becomes important part of the design.
- Rectangular cables (including CICC) could be an interesting possibility.
- The overall current density of tape is reduced significantly in a magnet structure
  - ➢ Question: Is the performance of the cable available now sufficient for representative magnet R&D, and will it be sufficient for accelerator magnets in foreseeable future with the progress underway.

Viability of ReBCO in Accelerator Magnets and in Fusion

ReBCO comes in tape form and that poses several challenges:

- A local defect, not always detectable at 77 K QA test of ReBCO tape, could cause an irrecoverable damage to the accelerator magnet coils, when operated at high fields and/or high stresses. This challenge is faced in fusion magnets as well.
- Tape conductors (rather than round wire) create field errors that may be too large for accelerator magnets. Similarly, tape conductors cause large losses that may be too much for fusion devices.
- Quench protection of the large high stored energy HTS magnets is a major issue for the accelerator magnets. This is also a major issue for the large fusion devices.

High current HTS cables are essential to deal with the above issues.

- Will that and other development in technologies be sufficient? Fusion community has made a massive investment and is counting on developing a reliable solution.
- Can/should accelerator community partially align its program to benefit from above?

Emphasizing the Similarities

- Accelerator magnets and fusion applications both need coupled tapes (wires) either to reduces losses or to reduce field errors.
- Both applications need high current ReBCO cables.
- Both applications need significantly longer length cables with more uniform performance along the length.
- Both need the price of the HTS cable to go down by a large amount to make the devices being developed viable.

Pointing out the Differences and Possible Path Forward

The conventional magnet designs need HTS cables that can be bent in small bend radii; fusion cables typically don't require that.

- Can a relatively small strategic investment leverage the development of the cables that can be bent in small radii with a little to no loss in the full potential of REBCO?

----------- AND/OR ------------

- Can accelerator magnet community become open to developing and demonstrating magnet designs that can use fusion cables despite them having large bend radii?

Food for Thought

- There is a large investment on the development of the ReBCO (HTS) cable from the private investors for fusion industry.
- Current HTS wire and HTS cable market (and hence development of the HTS cables) is primarily driven by the privately funded fusion industry; and is likely to remain so for a foreseeable future.
- Several decades ago, private MRI industry benefitted from the development of NbTi superconductors from a large investment from the government agencies on the accelerator magnet R&D.
- Now, can the accelerator magnet community draw similar benefit from the development of the ReBCO cable from an unprecedented funding from the private investors on the fusion R&D?

Suggestion: Accelerator community should use its limited funds strategically to drive the aspects of technology development that are critical to it, rather than try to drive the general development.

A Dialogue Between Users and Manufacturers

Challenge for accelerator magnet designers:

- What can be done to develop and demonstrate new magnet designs that can allow the most efficient ReBCO cables as getting developed now? Example: magnet designs that can use large fusion cables.

Challenge for ReBCO wire/cable manufacturers:

- What can be done to modify cable architect (to the extent possible with incremental funding) to allow their use in a wide variety of magnet designs for accelerators? Example: cables that bends with small radii.

Challenge for both to work jointly to improve the end-product:

- What can be done to find integrated solutions to develop cable and magnet designs together? Examples: dealing with large stresses (CICC?), internal cooling (hole in the middle?), etc..

Update from some Cable Manufacturers

(not a complete list)

Question posed was:

What would be the current density if bending radius requirement is relaxed?

(for HTS in common coil)

CORC® Cable

Re: CORC performance

DV Danko van der Laan <danko@advancedconductor.com>
To Gupta, Ramesh C

Reply | Reply All | Forward | ...

Sun 6/22/2025 4:00 PM

You replied to this message on 6/22/2025 5:33 PM.

Hi Ramesh,

Regarding continuous conductor lengths, currently we could handle about 75 meters for CORC cables of about 8 mm thickness. Expanding to 100-150 meters single piece length could be done in less than a year. The longest cable we've wound was last year: a 56 meter long cable of 11 mm thickness containing 96 tapes.

Regarding performance at 14 T, we currently have the following options, all based on a 48-tape layout at around 7-7.5mm cable thickness:

4 K
SuperPower HM: 30-40 kA
Shanghai Superconductor: about 20 kA
Fujikura: 25-30 kA

20 K
SuperPower HM: 15-20 kA
Shanghai Superconductor: about 10 kA
Fujikura: 12-15 kA

Please let me know if you need anything else.

Best wishes,

Danko

- **J_e@4K,14T: ~900 A/mm^2**
- **J_e@20K,14T: ~450 A/mm^2**

J_o(in structure), may go down by 20-30%

STAR® Cable

AMPeers

High current STAR® cable

Ampeers LLC <contact@
To Gupta, Ramesh C
Cc Selva Kumi
Fri 6/20

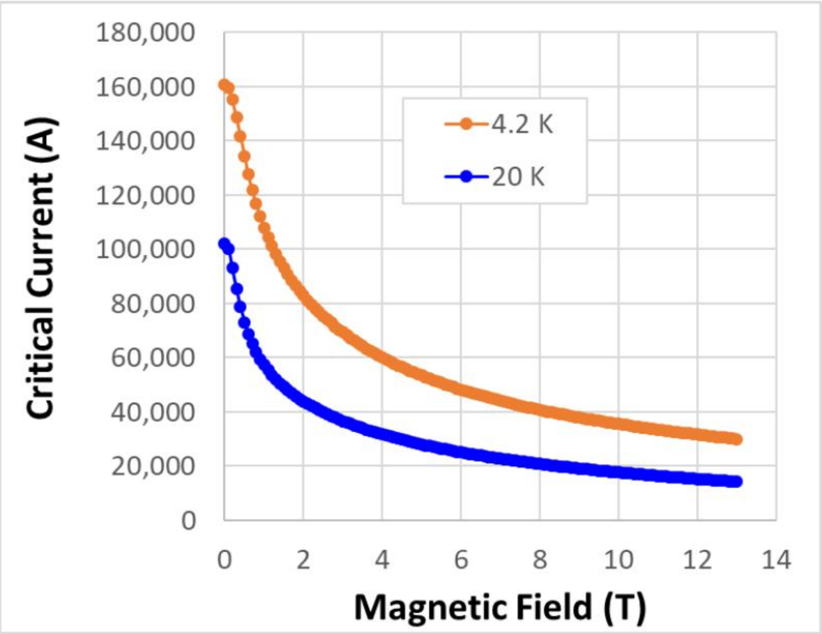
You replied to this message on 6/20/2025 10:21 AM.

High current STAR® cable.pdf
252 KB

We are fabricating a short (2 meter) high current STAR® cable for a customer. I have attached a slide providing the cable specs. If these specs can meet your needs, we can make longer cables (> 5 m) now. Please let me know if any of these specs need to be changed.

In 2 - 3 years, we could achieve 2x Ic and 10 years, 3x Ic.

Thanks,



- 8 – 9 mm diameter STAR® cable.
- ~ 200 mm bend radius
- Expected I_c
  - 14.2 kA at 20 K, 13 T
  - 30 kA at 4.2 K, 13 T

- J_e@4K,13T: ~440 A/mm^2
- J_e@20K,13T: ~220 A/mm^2

J_o(in structure), may go down by 20-30%

Possible VIPER® Cable for Accelerator Magnets

Possible parameters of a VIPER cable with the state of the art (2022)*:

- **Cable I_c(20T, 4K) = 62 kA**
- **Cable J_e(20T, 4K) = 255 A/mm^2**
- **Cable J_{cu}(20T, 4K) = 420 A/mm^2**
- **Cable outer diameter = 16 mm**
- **Bending Radius = 100 mm**

A cable with a

J_e(20T,4K) of 500-1000 A/mm^2

may be possible within a few years*.

J_o(in structure), may go down by 20-30%

*Zachary Hartwig, MIT, Private communication

Prospects of HTS Cable in Common Coil Dipole

Question posed was:

Is the performance of the cable available now sufficient for representative magnet R&D, and will it be sufficient for accelerator magnets in foreseeable future with the progress underway.

✓ **The answer seems to be positive.**

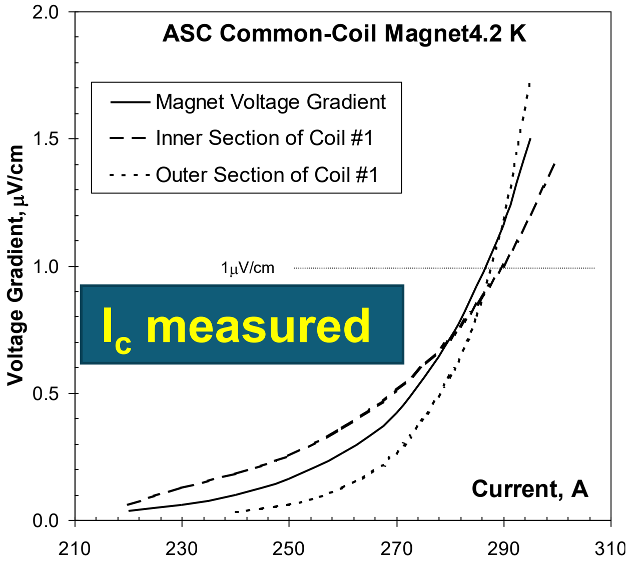
BNL Experience with HTS in Common Coils

Common Coil Magnets With HTS Tapes

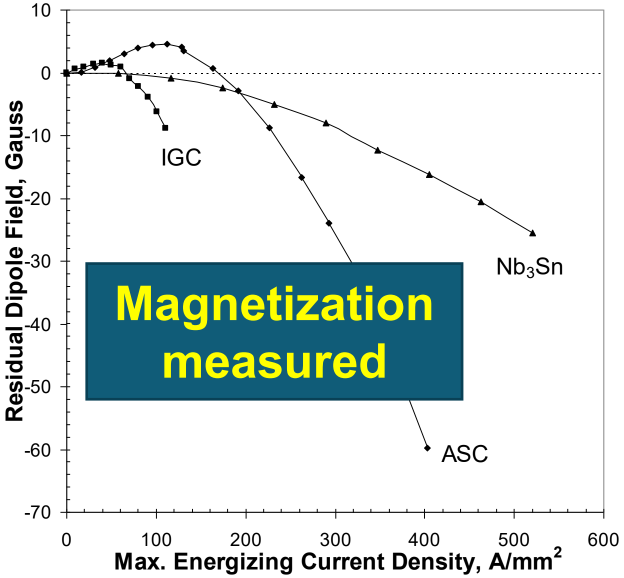
4.2K tests

HTS coils wound and assembled in the common coil geometry

2000



I_c measured



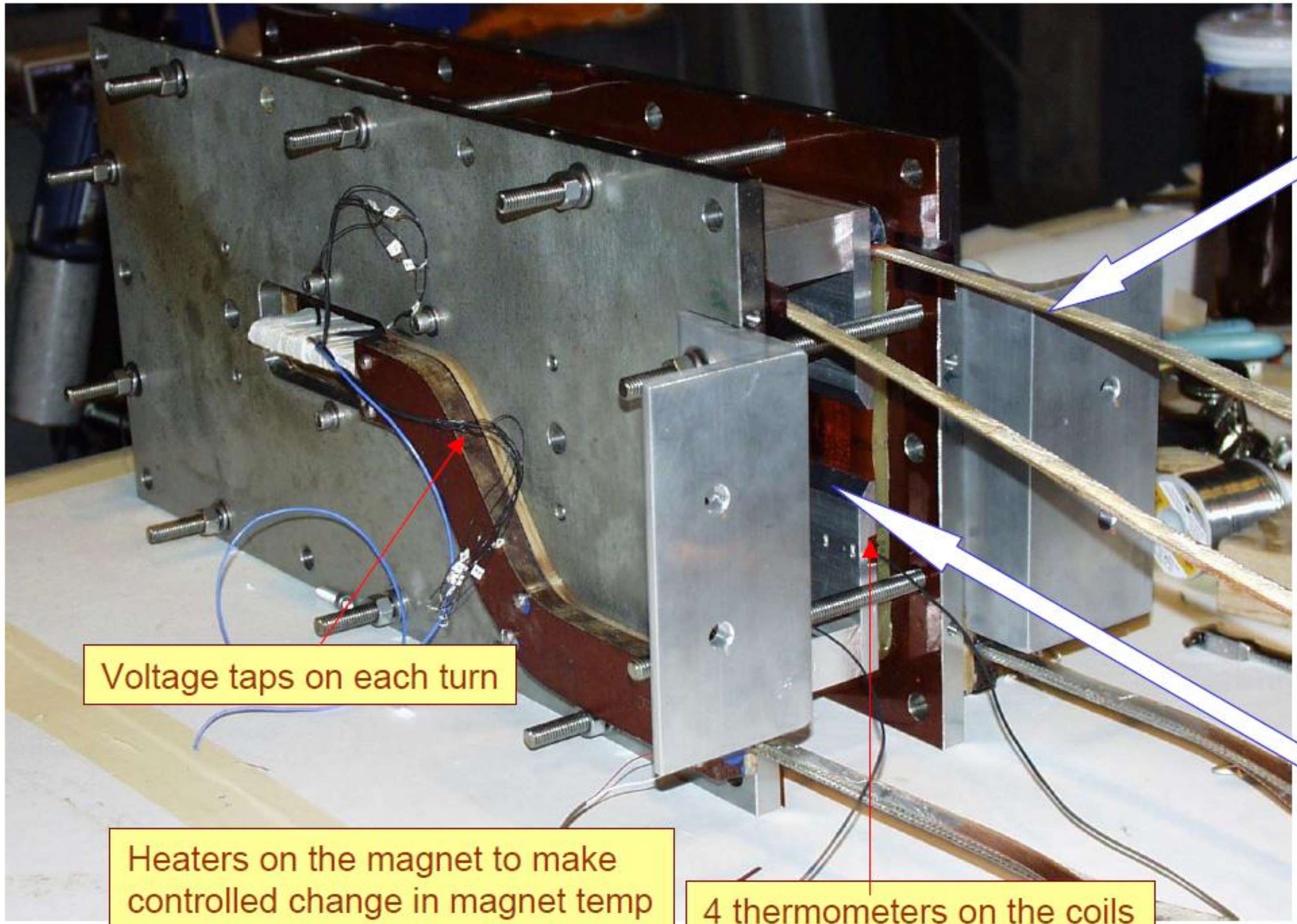
Magnetization measured

Field harmonics measured

BROOKHAVEN NATIONAL LABORATORY

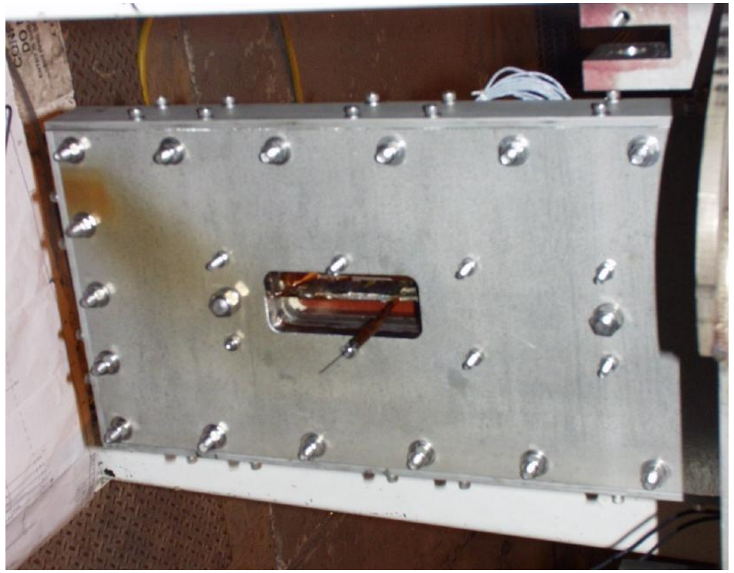
Superconducting Magnet Division

Magnet DCC006: The 2nd HTS Dipole
(Magnet No. 6 in the common coil cable magnet series)

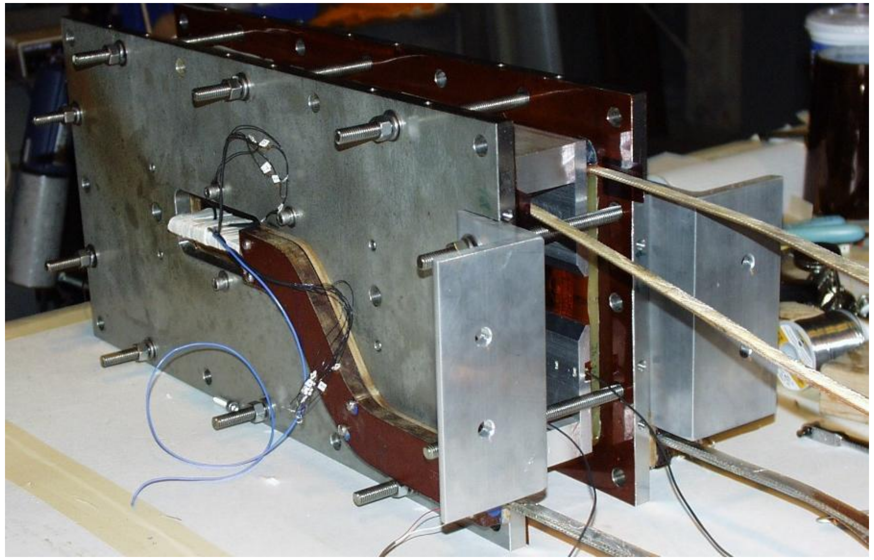


Early Structures for R&D Common Coil Dipoles

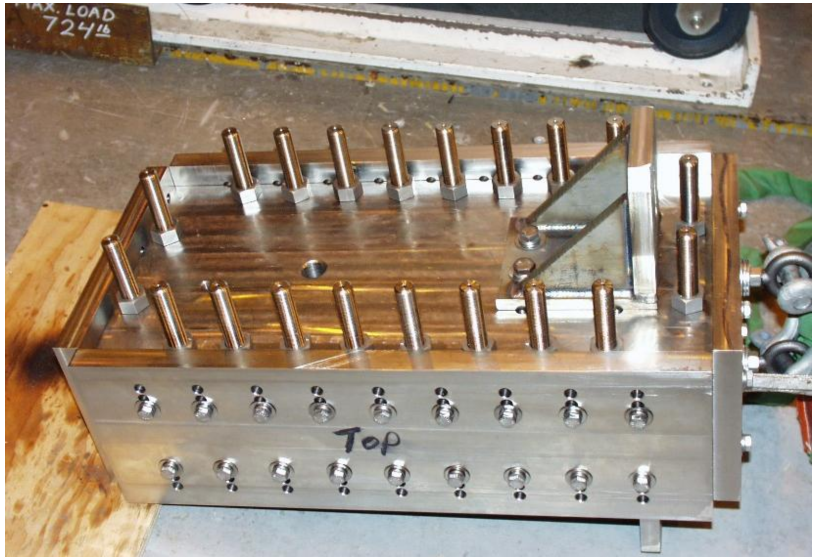
Bolted structures have benefit for easy reassembly (good for early R&D)



Can change aperture

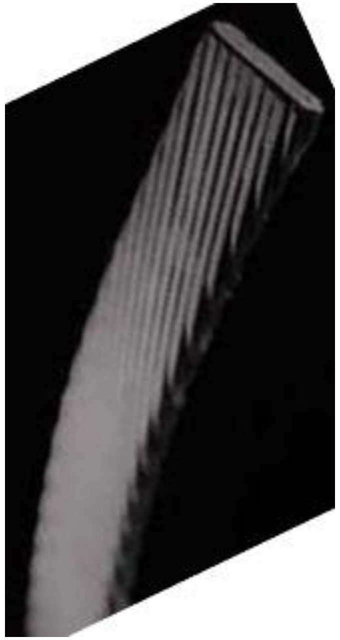


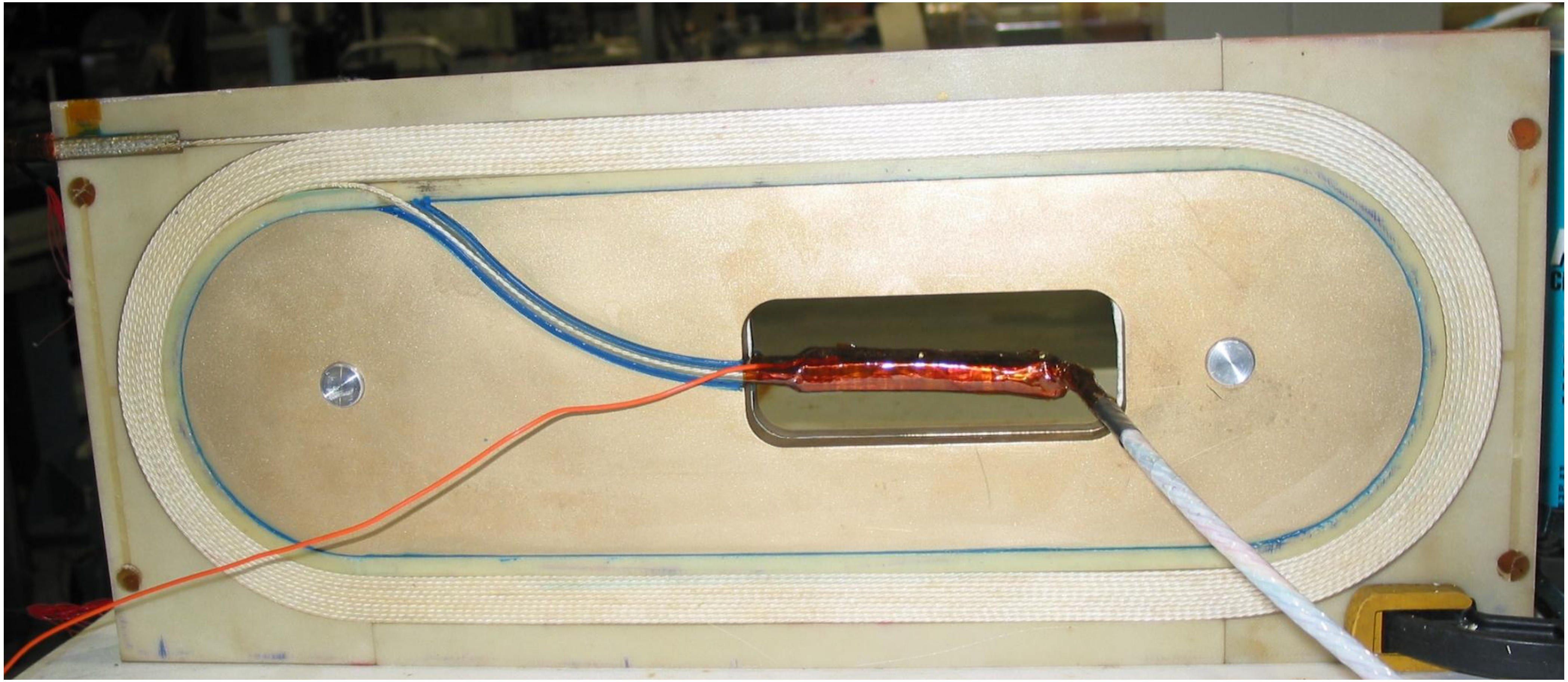
Can change number of coils (2 to 6) and can change pre-stress



(later high field common coil magnets had more traditional structure with SS shell)

Racetrack coil made with *React & Wind Bi2212* Rutherford cable for the common coil dipole

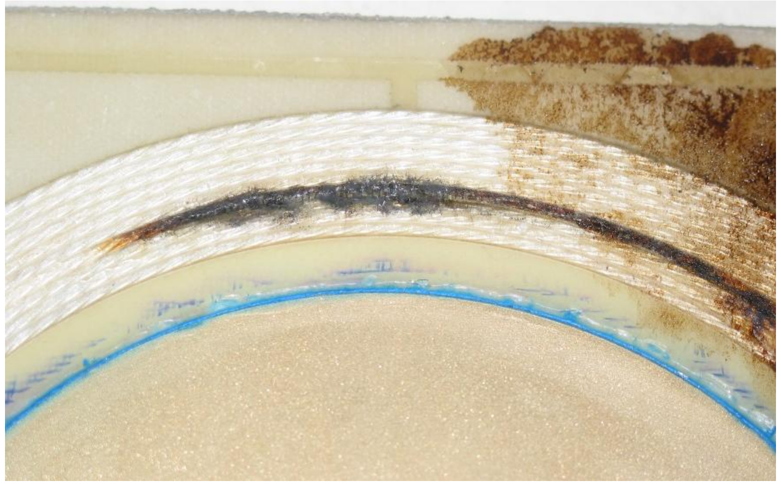




Most of this presentation will focus on ReBCO though

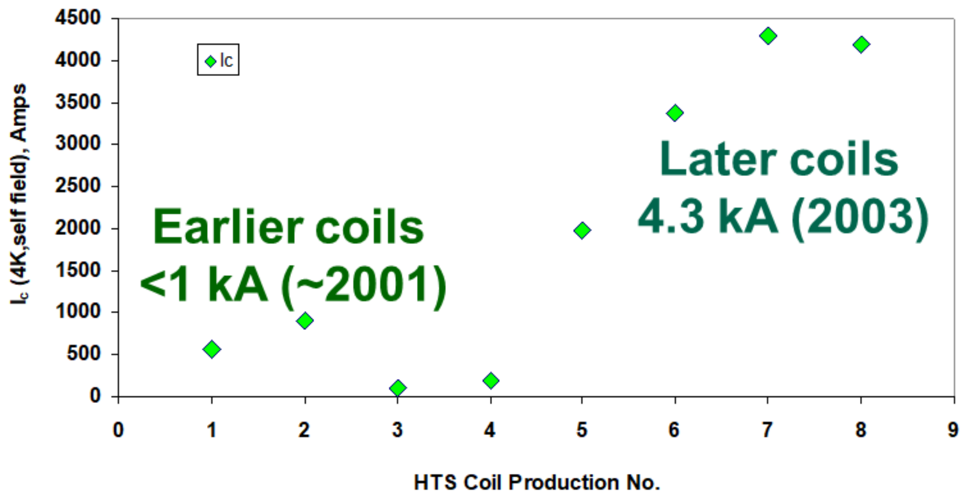
A Learning Experience

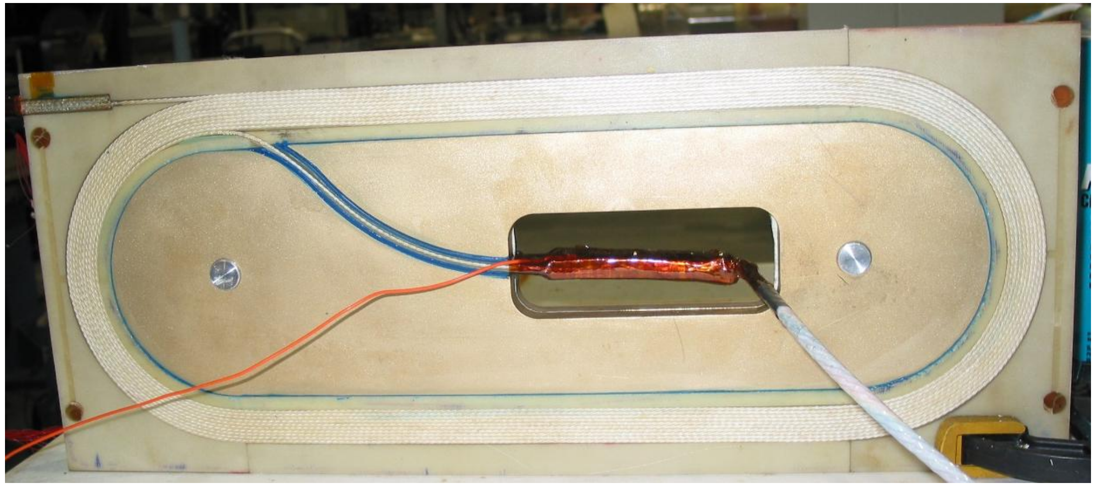
- To learn, perhaps one has to burn! … and we certainly did that!!
- In magnet DCC014 one of the two HTS coils was damaged (burnt-out) during the test after two quenches.
- The quench protection (as used in LTS coils) was unable to protect the high current HTS coil at 4K.
- Now, of course, we do things very differently.



Presented at MT13 in 2003

Before Test





After Test

High Field HTS/LTS Hybrid Dipole

(with ReBCO)

HTS/LTS Hybrid magnet R&D is desired and useful at this stage for practical reasons
(even if the ultimate goal is not hybrid magnets)

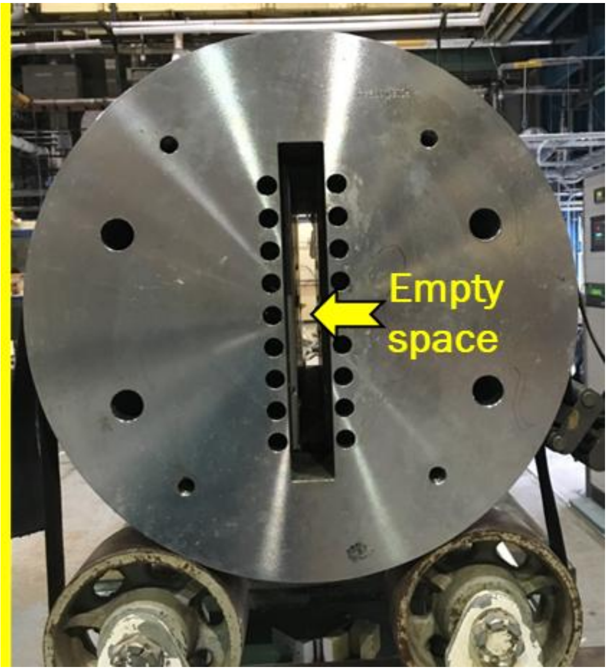
This provides a less expensive way to perform high field HTS coil and magnet R&D
(without building a very expensive and too risky all HTS magnet at this stage)

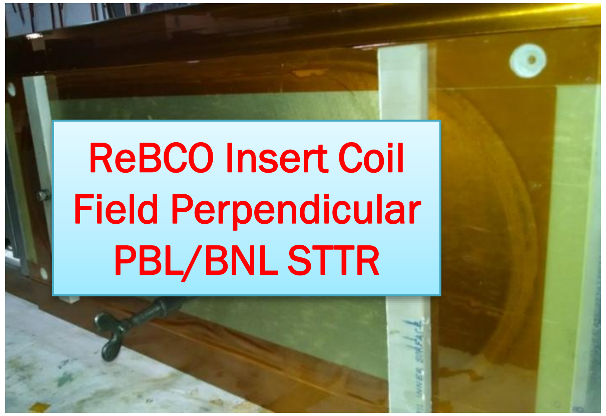
BNL common coil dipole as a test bed for high field magnet R&D

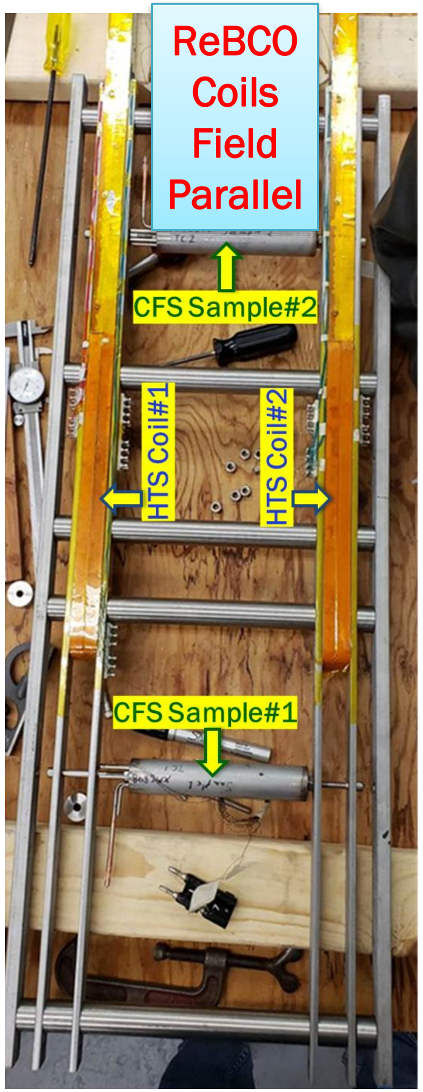
Key components/steps for Rapid-turn-around R&D

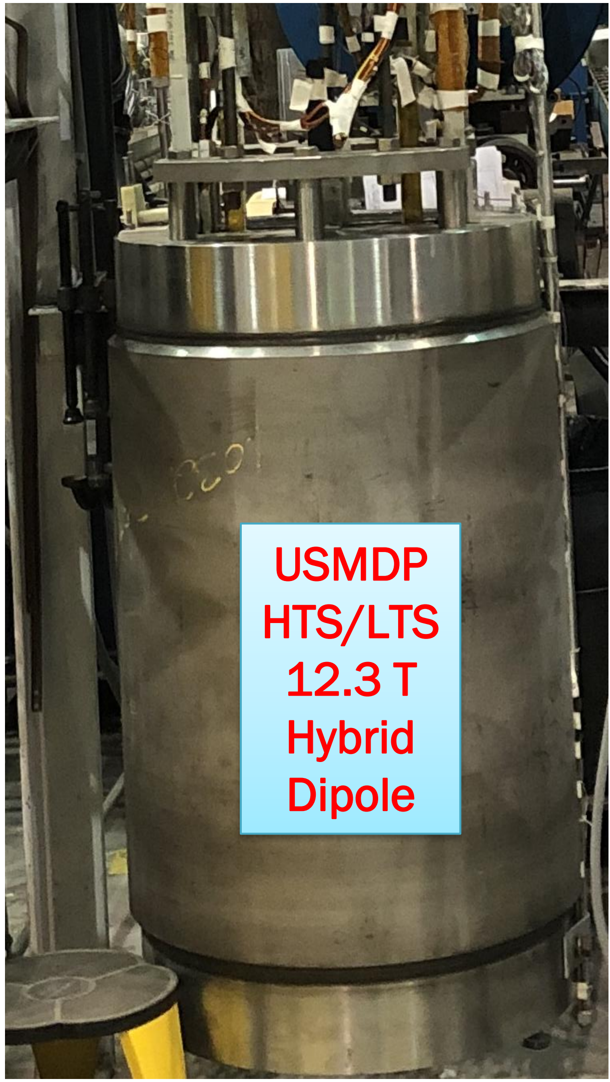
- 10 T, Nb_3Sn R&W dipole with a large open space for high field insert coil testing
- New coil(s) in the magnet without any disassembly
- Coils become an integral part of the dipole magnet
- A new coil test essentially becomes a new magnet test

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





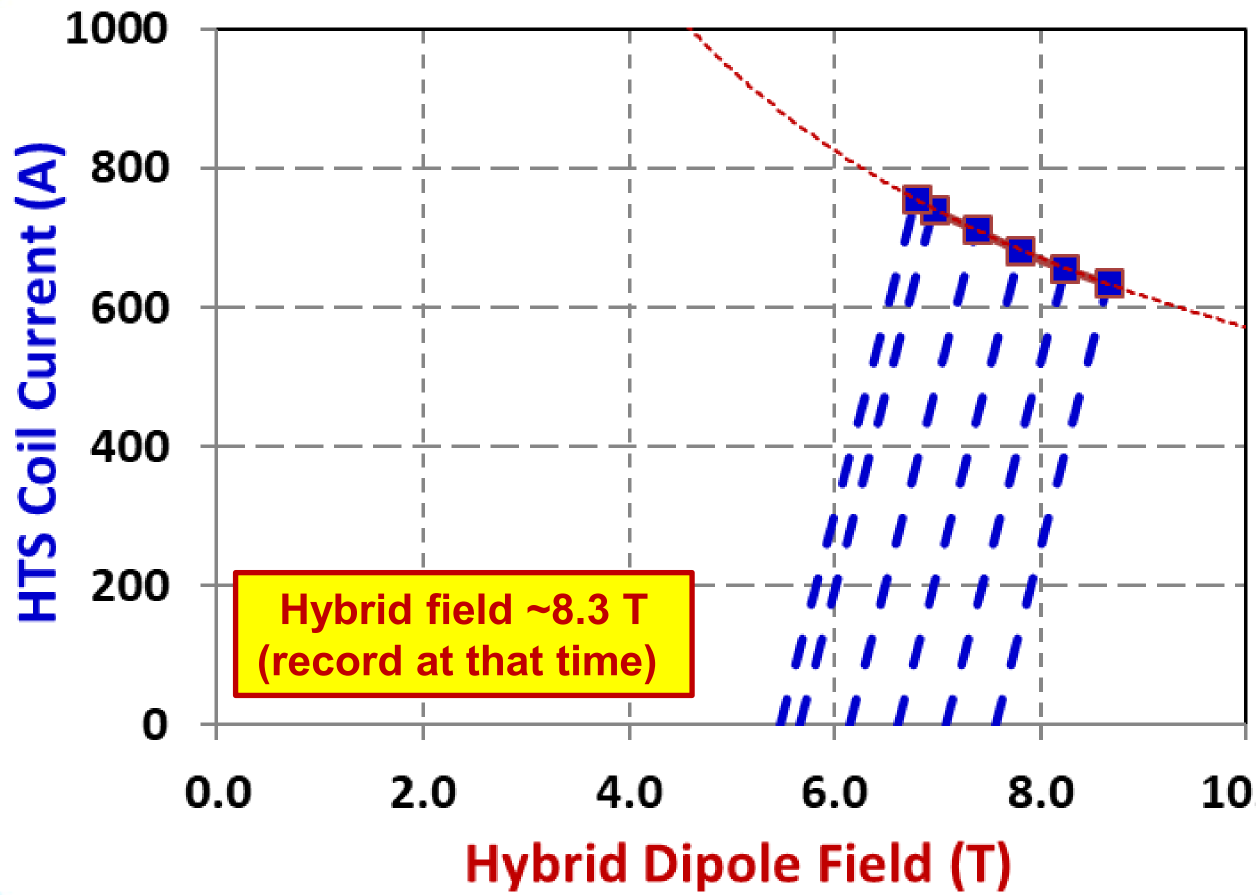


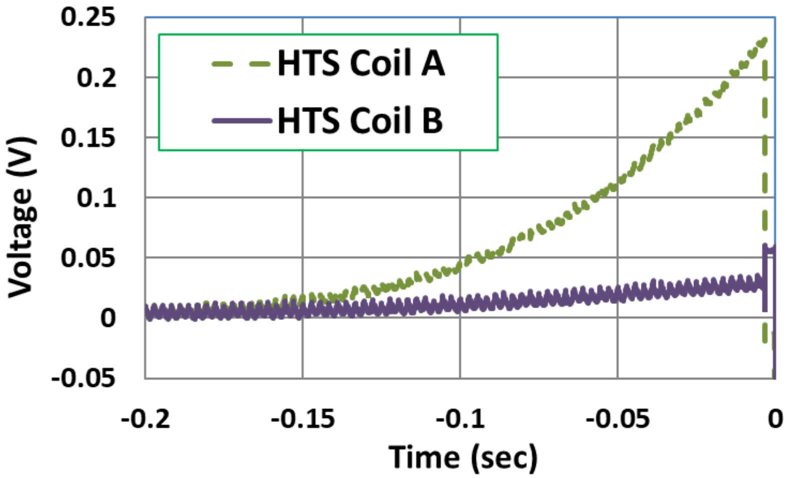


Positive experience with a variety of programs. Suggest that CERN and other laboratories consider a similar approach as an integral part of R&D for proof-of-principle magnet tests.

HTS/LTS Hybrid Dipole Test (2016)

ReBCO coils were ramped till they quenched (different background field from Nb_3Sn coils)





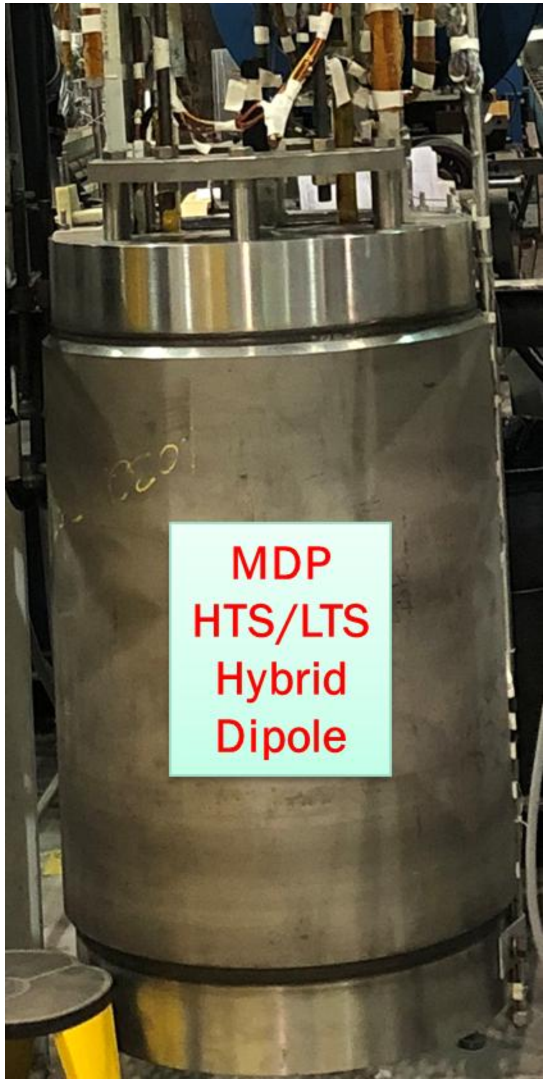
Quench threshold 200mV (just like in LTS)

- **No training: different from LTS**

No damage, no degradation despite many quenches with high threshold

Note: These coils were made with two HTS tapes soldered together. Did that make a difference? Perhaps.

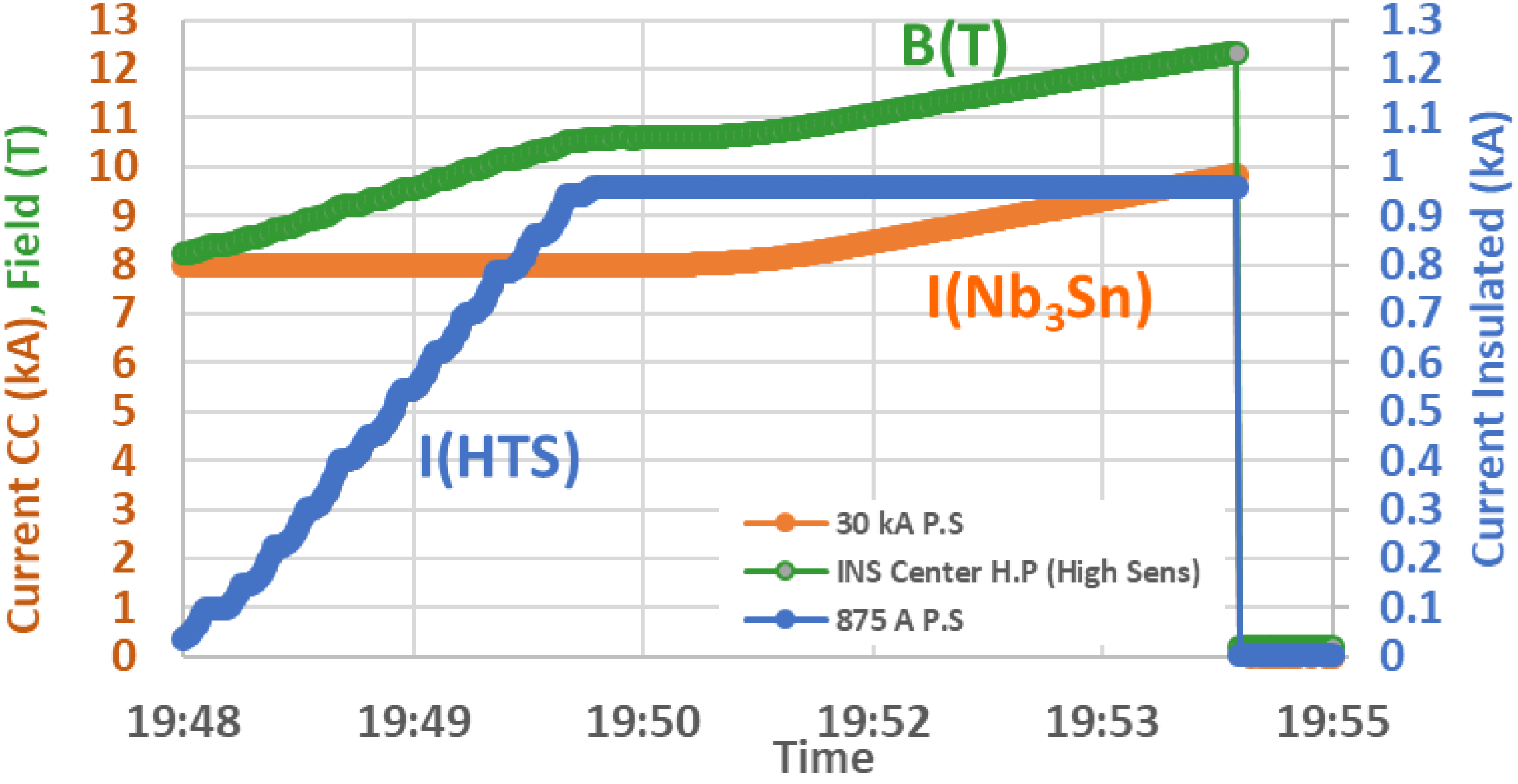
HTS/LTS Hybrid Dipole Test (2020)



~12.3 T hybrid field (still a record)

(~3 T from HTS)

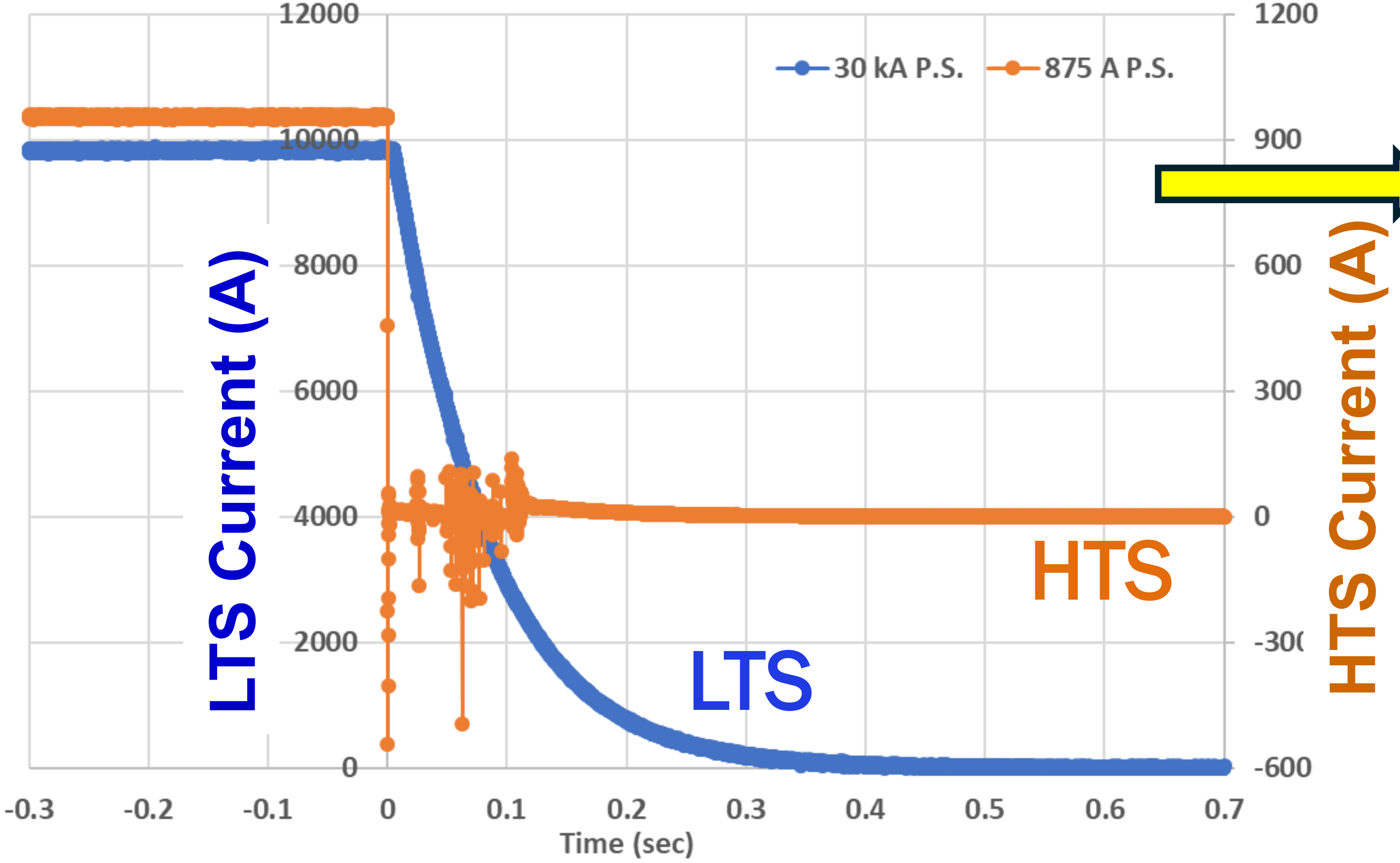
HTS Insulated Coil & Common Coil

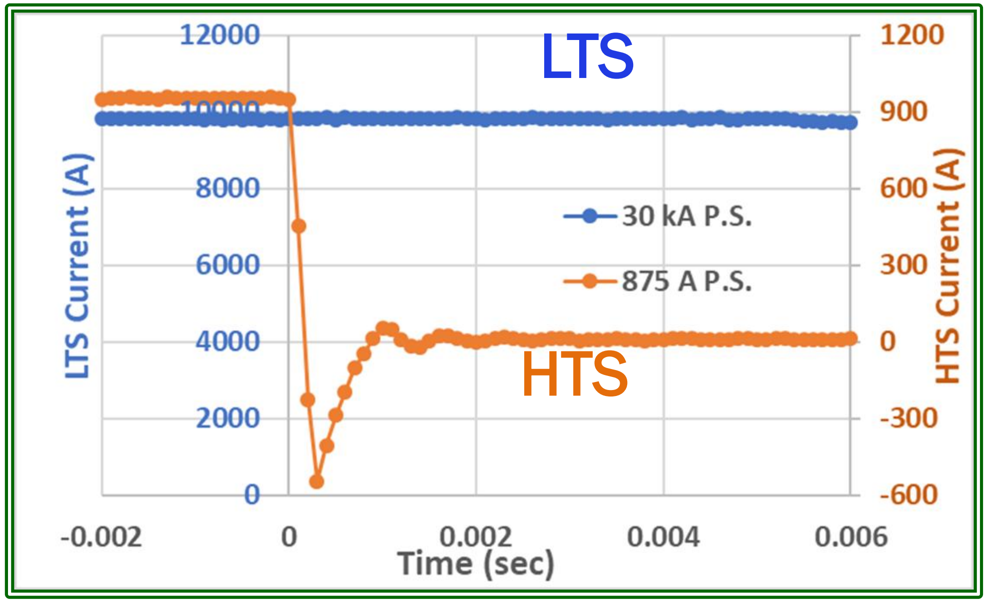


Quench Protection of HTS/LTS Hybrid Dipole when LTS Quenches

Major concern was: what will happen if LTS coil quenches, and dumps large energy on inductively coupled HTS coil? Will HTS coil survive?

Courtesy: Piyush Joshi



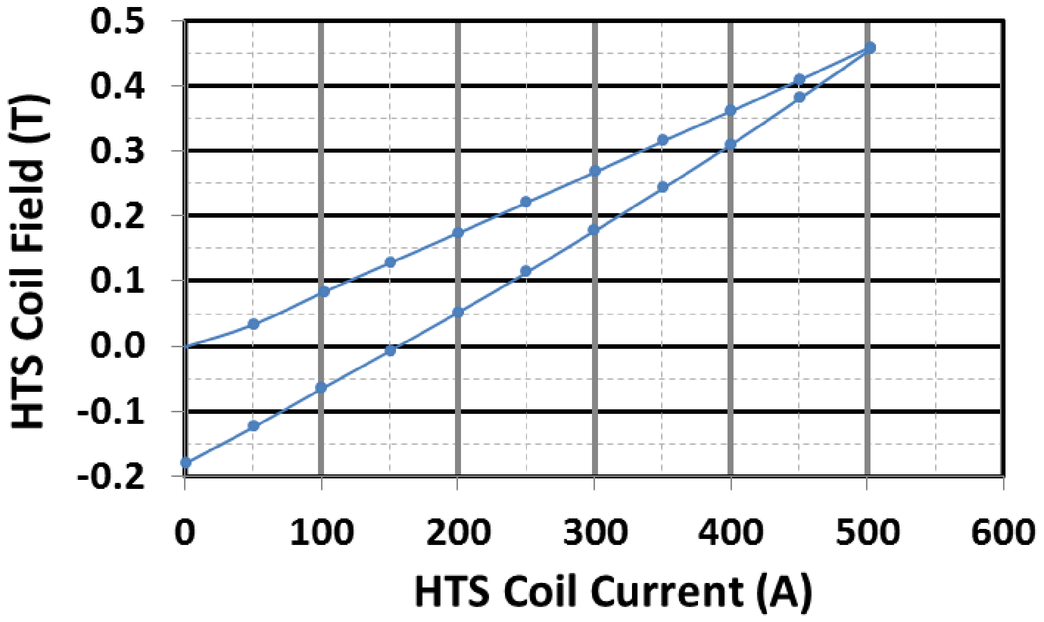


- LTS coils are powered down after the HTS coils are deenergized.
- Much less energy to dump from smaller HTS coils on LTS coils (situation changes when HTS coils become larger).

Comparison of Residual fields between Field Perpendicular and Field Parallel as an indication of Persistent Harmonics (concern because of coils made with tape, not round wire)

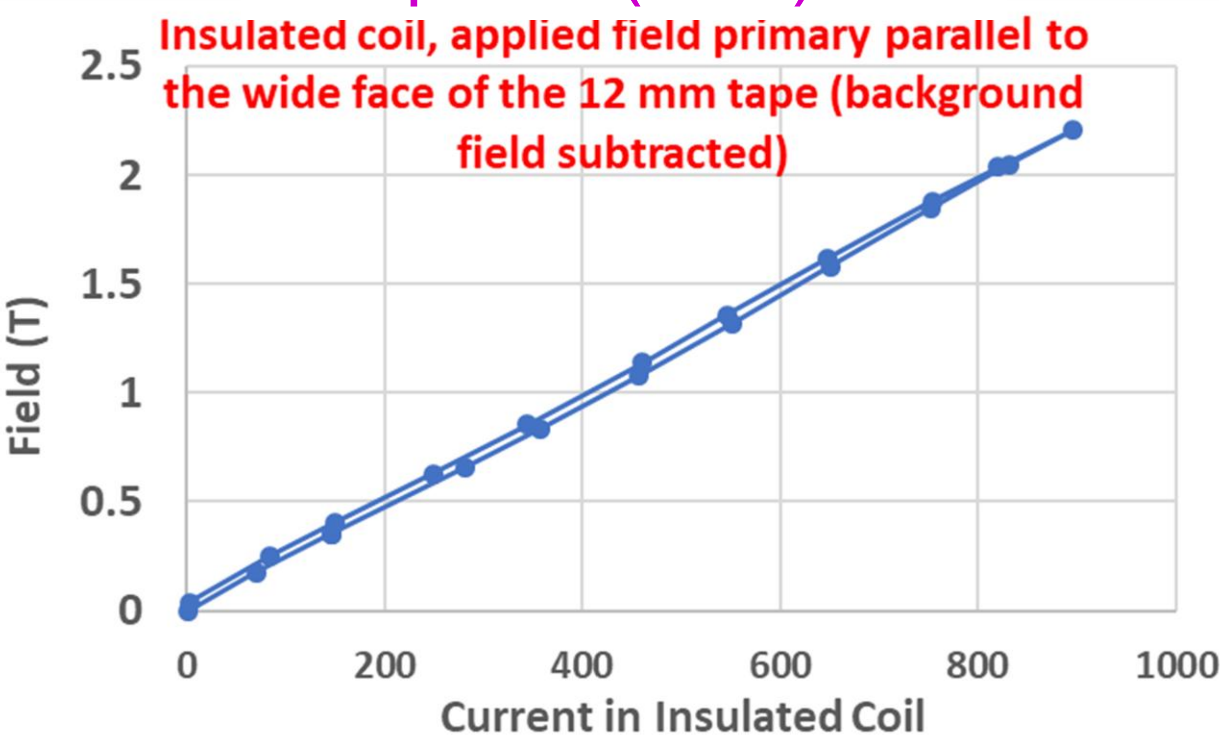
Field perpendicular (2016)

Additional field from the HTS coils in up and down ramp (Field from LTS coil subtracted)



A large remnant field (-0.2 T) due to magnetization in tape

Field parallel (2020)



Order of magnitude reduction in the magnetization when the field is primarily parallel to the HTS tape

Related Worldwide R&D Programs

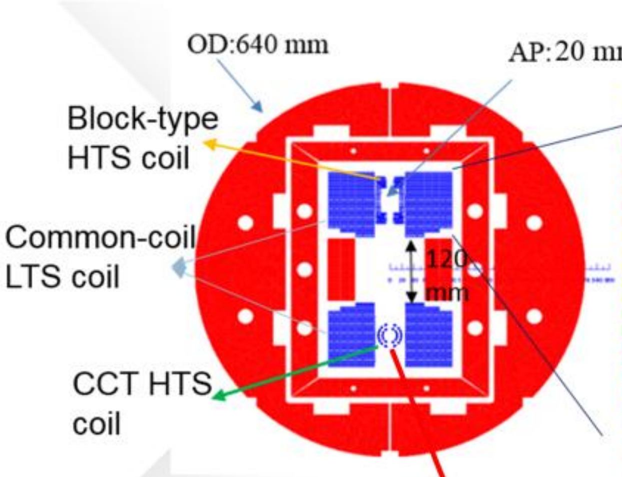
(a quick tour)

IHEP

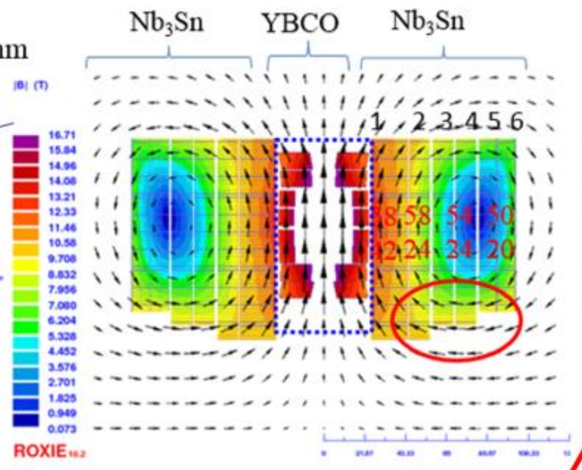
Development of LPF3 magnet

- Aiming at 16 T: 13 T (LTS) + 3 T (HTS)

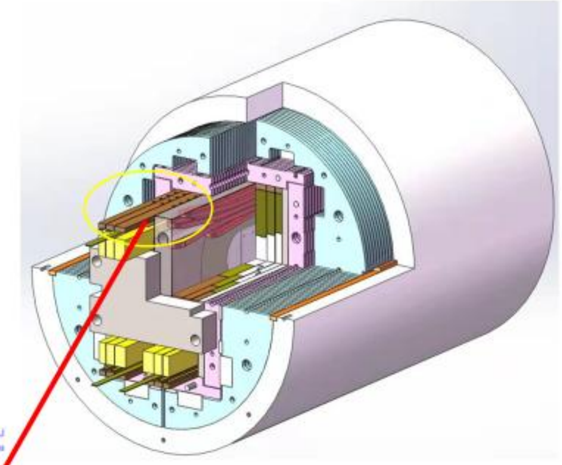
To be 16 T



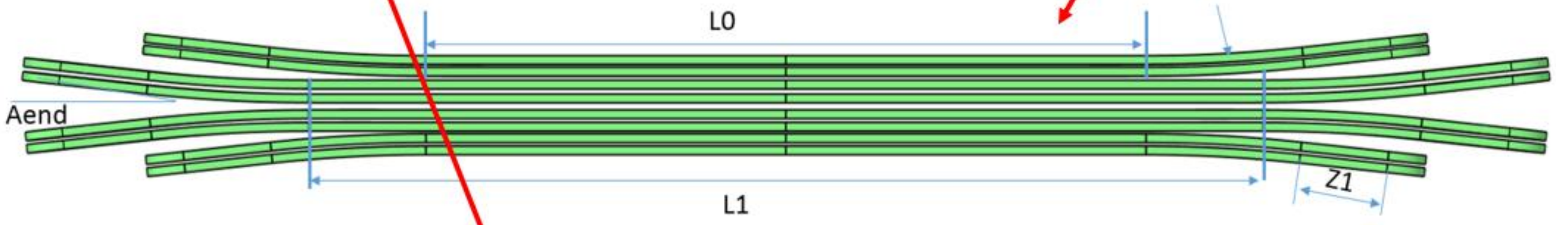
Cross-section of LPF3



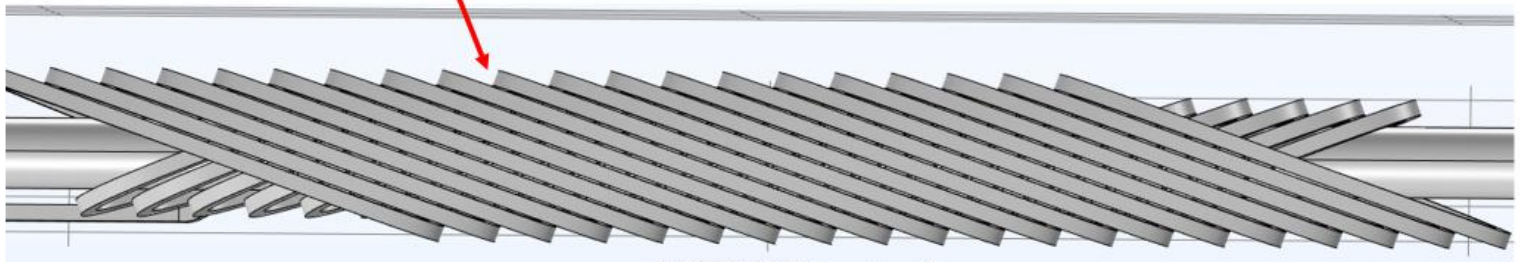
Field and flux distribution (1st and 2nd quadrant)



Schematic of LPF3



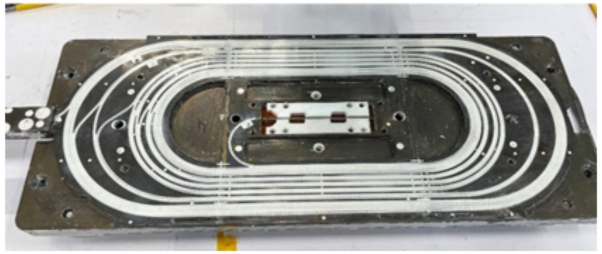
ReBCO Block-type insert coil

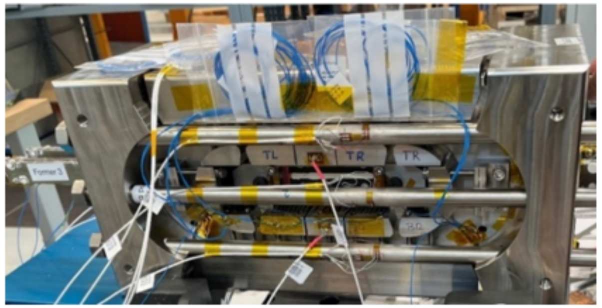


ReBCO CCT insert coil

REBCO-based Racetrack Technology: One Step Closer to REBCO Subscale magnet 1 (RS1)

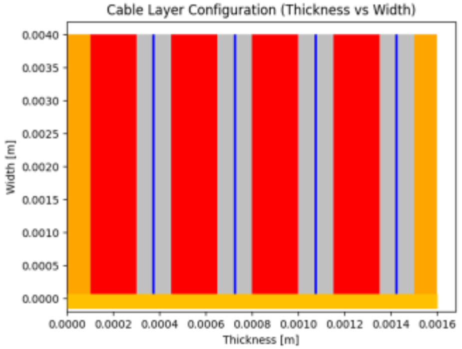
Re-use of the subscale SMCC 1 (Nb_3Sn) coil shape, winding tooling, instrumentation and magnet structure

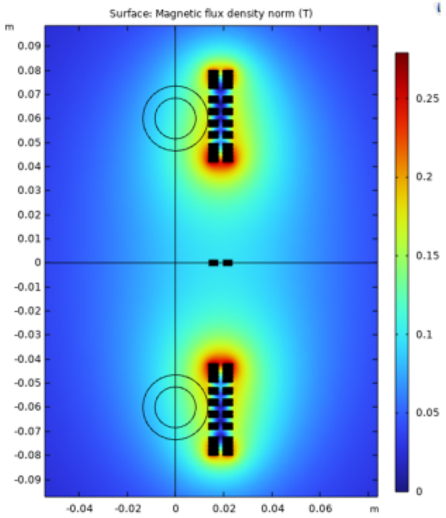




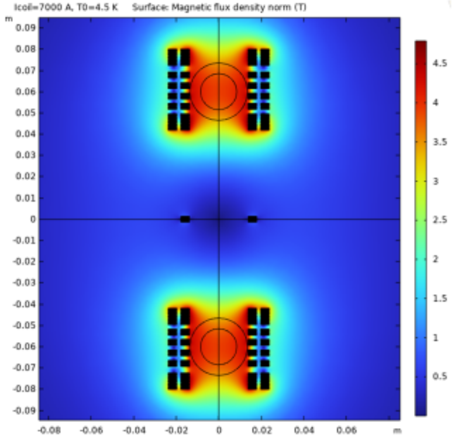
Subscale SMCC 1 and 2 magnet structure

- The coil is being manufactured from an insulated HTS cable, consisting of stacked ReBCO and copper tapes.
- The thickness of the soldered cable is consistent with that of the subscale SMCC 1 cable.
- Two single layers are connected and assembled together with inner splices, forming one side of the common-coil configuration.





2 layers in LN2



2 layers in LHe

Simulation: D. Sotnikov

2 Paul Scherrer Institute PSI 25.06.2025

REBCO-based Racetrack Technology: One Step Closer to REBCO Subscale magnet 1 (RS1)

HFM High Field Magnets Programme

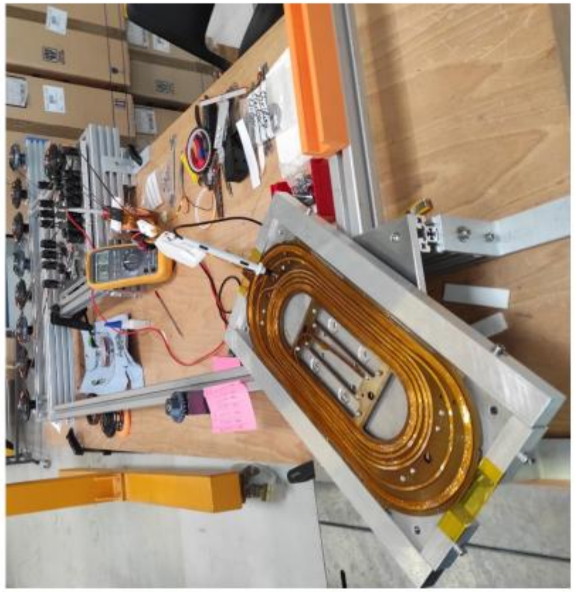
CHART Swiss Accelerator Research and Technology

PSI

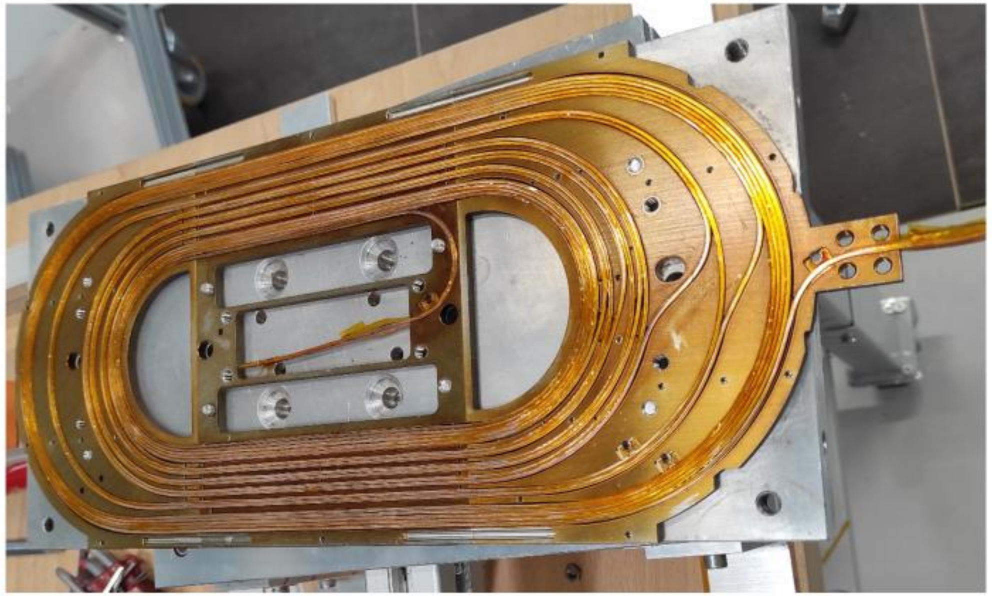
Design and construction of the winding/cabling machine. Ongoing winding and soldering trials using dummy tapes.

PSI

Winding: the insulated cable Is assembled during the winding process



View of the coil, HTS & Copper spools, insulating tool and former



View of the coil before the soldering process

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HFM plans at CIEMAT

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CDTI Centro para el Desarrollo Tecnológico Industrial

CERN

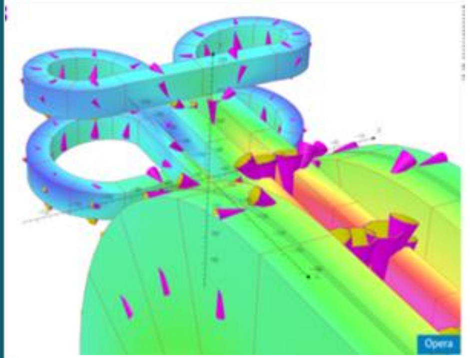
- **CIEMAT** is contributing to the **High Field Magnet (HFM)** program led by **CERN**.
- CIEMAT is working on high field magnets based on **common coil** topology, profiting from the lessons learned from EuroCirCol collaboration.
- The target is to develop a prototype magnet able to provide **14 T** at the aperture.
- In a first step, CIEMAT is working on a model magnet (**ISAAC**) using existing coils produced by CERN. The aim is to learn about mechanics of high field magnets in common coil configuration. **ISAAC** means **I**nvestigating **S**uperconducting **A**ssembly to **A**ddress **C**ommon coil mechanics.
- In a second step, we are developing **DAISY**: **D**emonstrator for **A**ssembly **I**nnovations in **S**uperconducting common coil technolog**Y**. It honours Margarita Salas, an outstanding Spanish biologist (*daisy* is translated into Spanish as *margarita*).
- DAISY coils will be the first ones made with Nb_3Sn cable in the new CIEMAT magnet laboratory (**SMART-Lab**: **S**uperconducting **MA**gnet **R**esearch and **T**echnology **Lab**oratory).

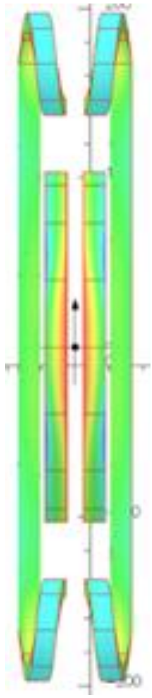
HFM High Field Magnets | 22th May 2025 | FCC Week 2025

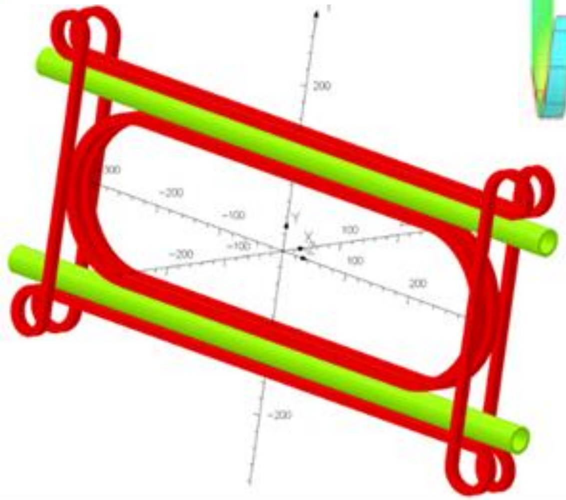
A Few Possible Layouts of Pole Coils Clearing the Bore

Also Clover-leaf Program at CERN

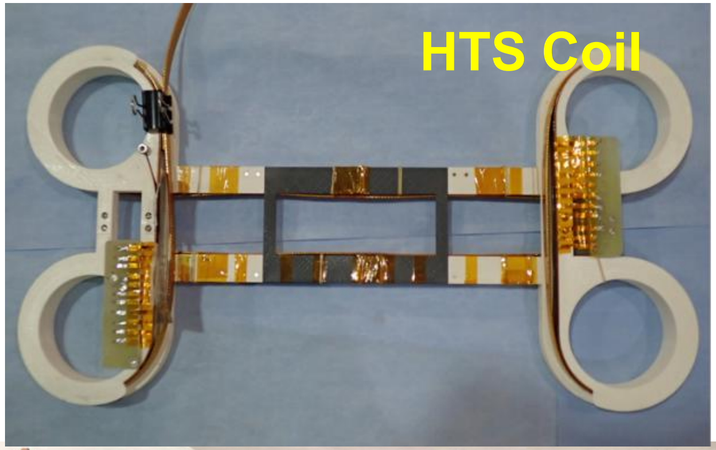
Overpass/underpass (cloverleaf) design

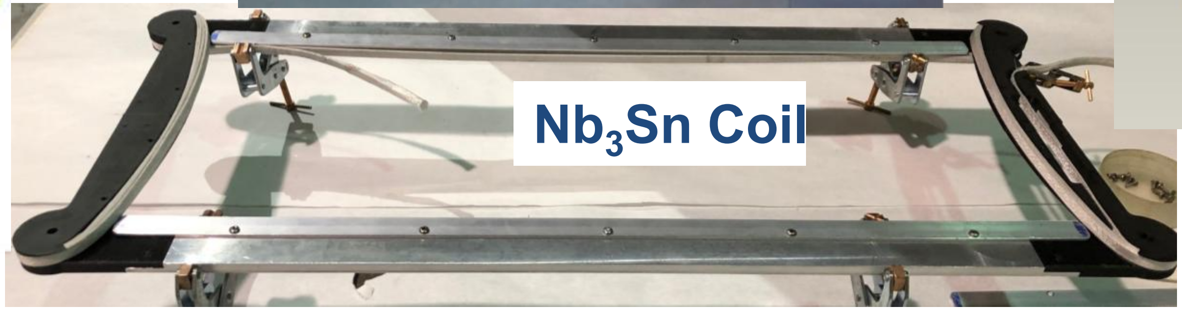


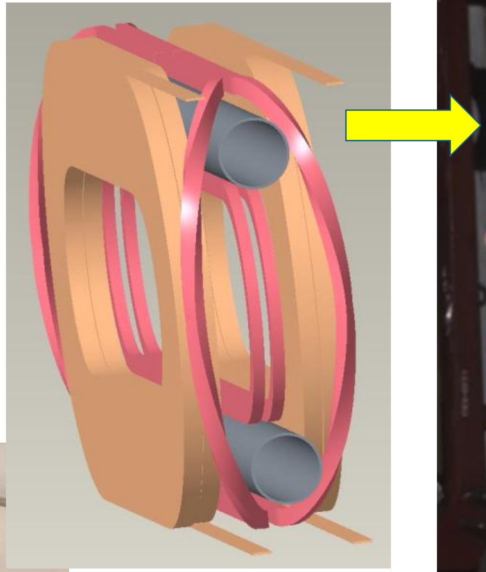




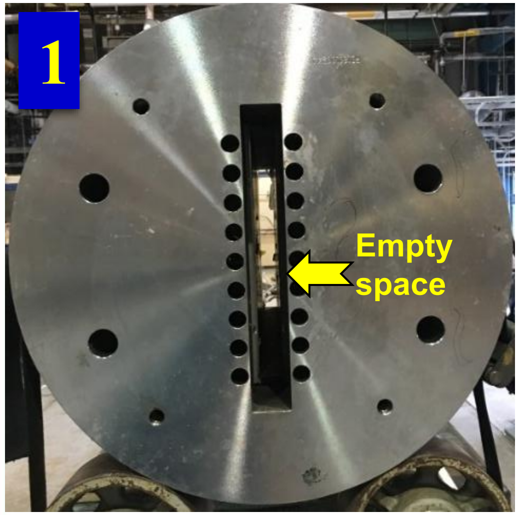
Pole coil windings and preliminary designs of coils that can be built and tested at 10⁺ T field.

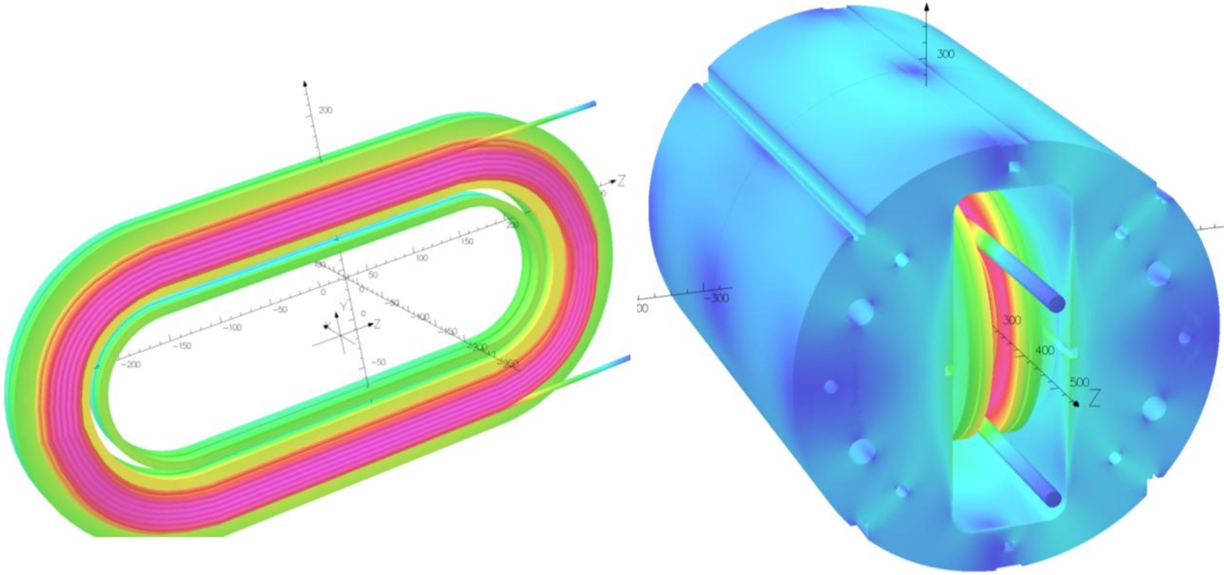


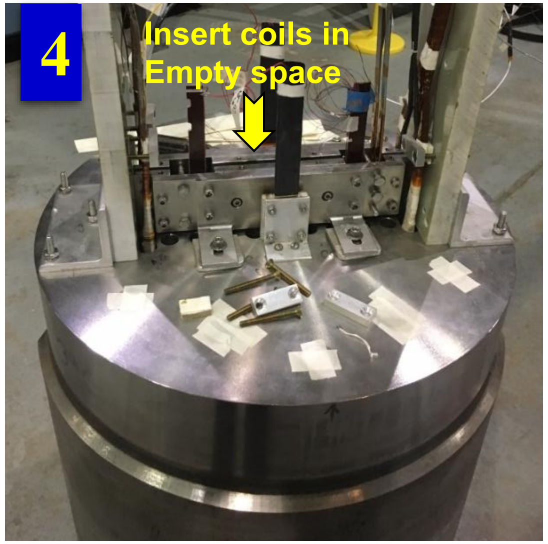


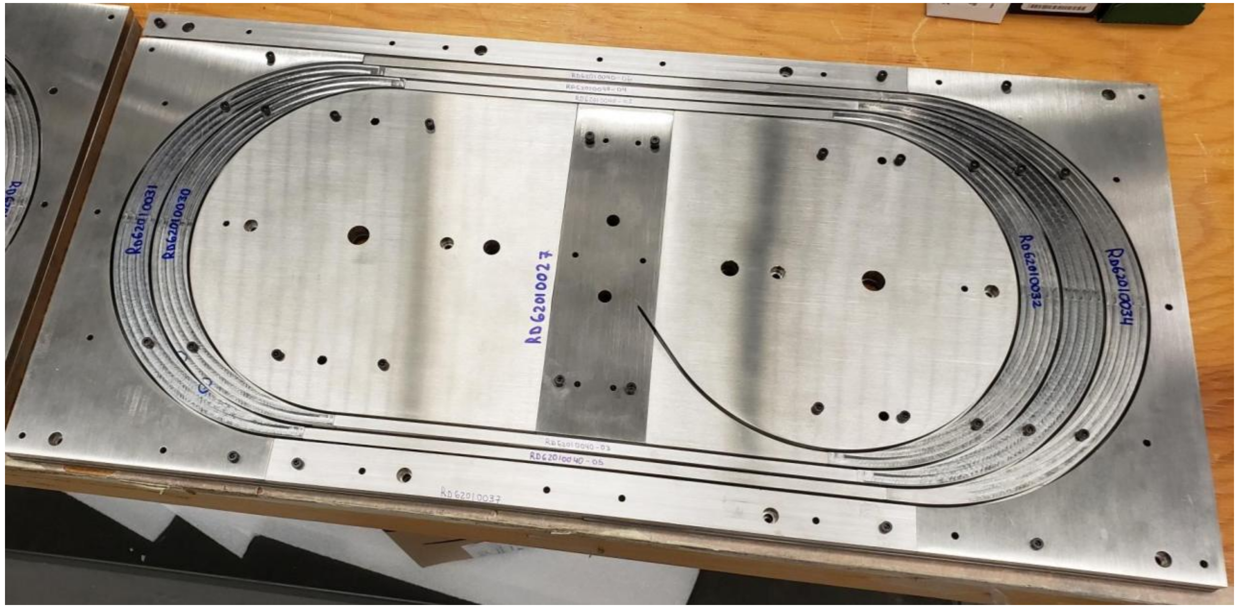


Common Coil Hybrid R&D with ACT with CORC® Cable

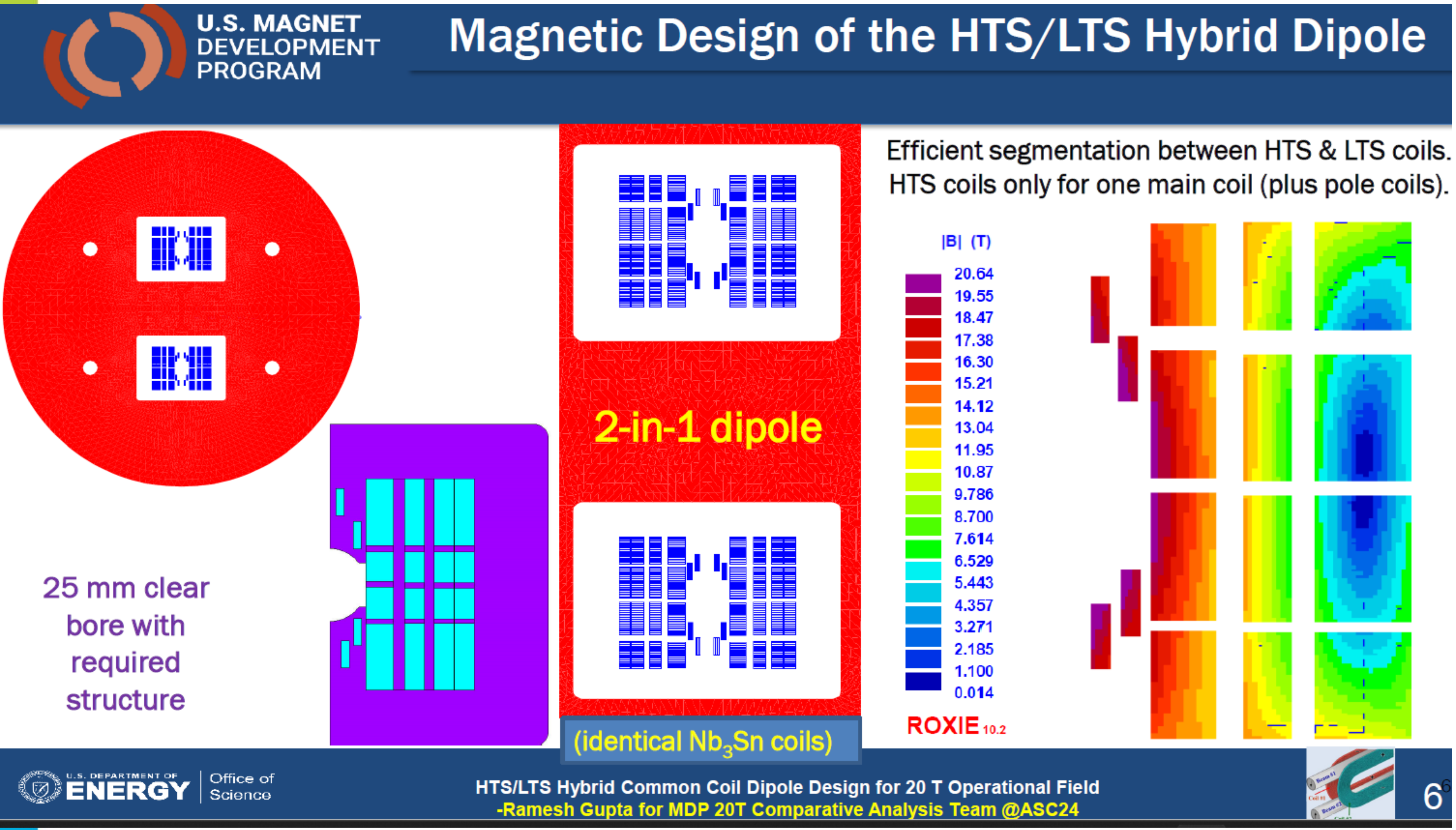




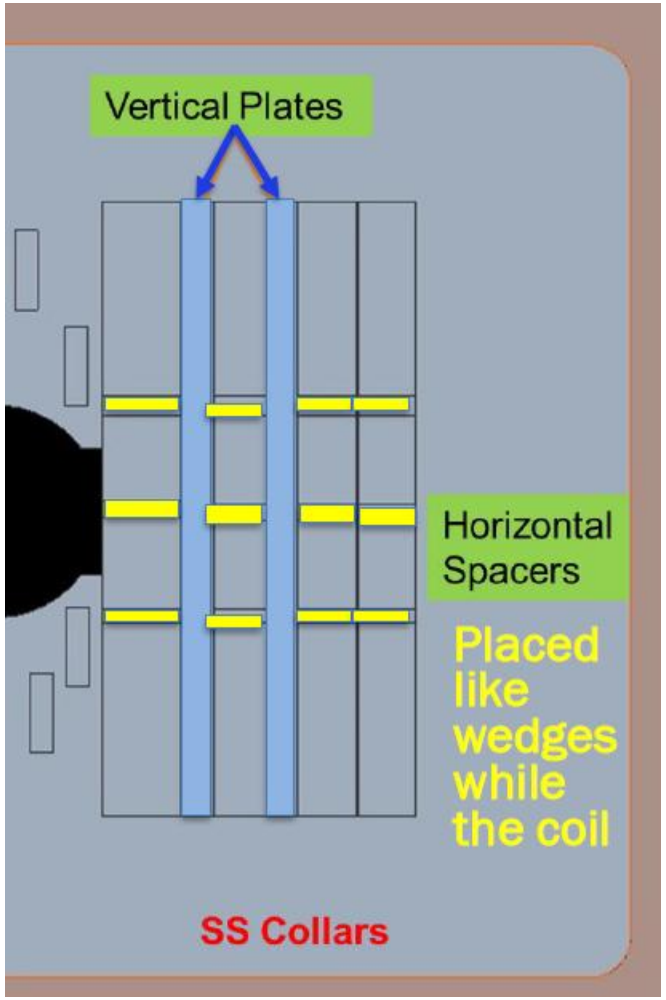




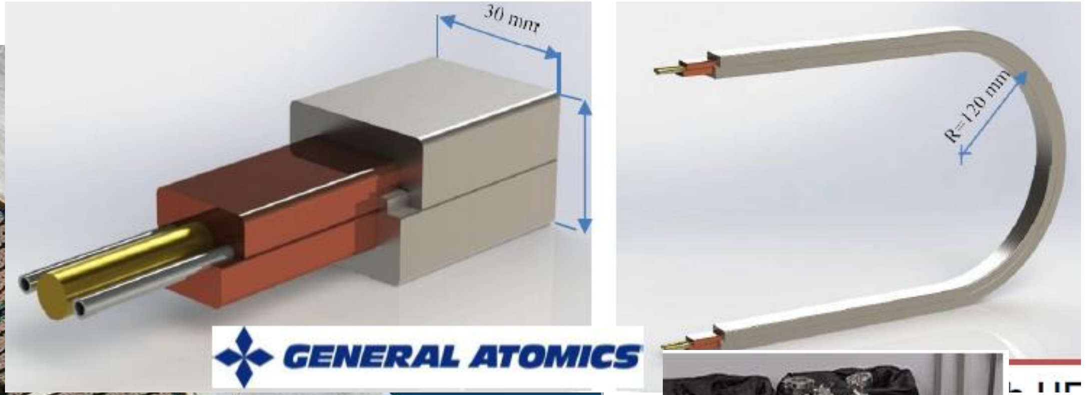
Initial Design Studies of 20 T Hybrid Common Coil (BNL)



25 mm clear bore



Test of various fusion cables at the BNL common coil dipole



React & Wind Approach and its Advantages

(since design and techniques needs to be developed for pre-reacted ReBCO cable, why not consider this for Nb_3Sn)

- In the "React & Wind" approach, the coil and associated structures are not subjected to the high temperature reaction. This allows one to use a variety of insulation and other structural materials in the coil modules.
- "React & Wind" approach appears to be more adaptable for building production magnets in industry by extending most of present NbTi manufacturing techniques. Once the proper tooling is developed and the cable is reacted, most remaining steps in industrial production of magnets remain nearly the same in both Nb-Ti and Nb_3Sn magnets.
- Since no specific component of "React & Wind" approach appears to be length dependent, demonstration of a particular design and/or technique in a short magnet, should be applicable in a long magnet in most cases.

Summary and Conclusions

- HTS coils for high field accelerator magnets must be built with the HTS cable.
- Common coil geometry, allowing large bend radii, offers unique advantage for using high current HTS cables, including similar to those being developed for fusion.
- Present HTS cable market (and hence development of most HTS cables) is primarily driven by fusion applications; and it is likely to remain so for a foreseeable future.
- Can accelerator magnet community benefit from that in designs such as common coil and use the available resources more strategically for a few focused enhancement?
- If we can, then both accelerator and fusion technologies could benefit in many ways.
- HTS/LTS hybrid and low cost, rapid-turn-around approach should encourage both innovation and systematic approaches. We should be looking for technical results with a proof-of-principle demos once every few months, rather once every few years.
- HTS coils with high current cables in a modular common coil structure should be a platform for an exciting R&D for the next generation magnet scientists and engineers.