BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

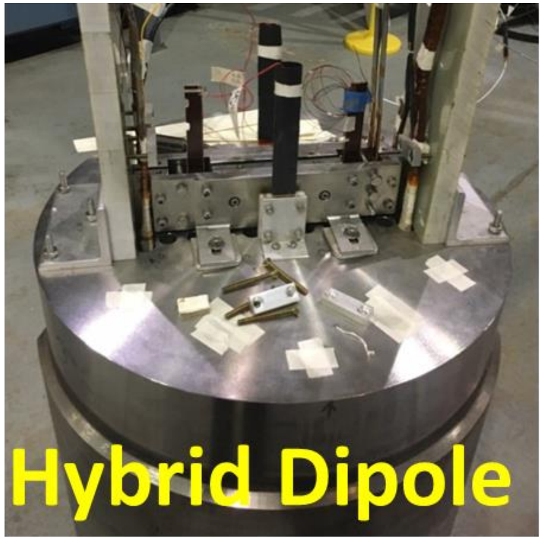
HTS/LTS Hybrid Test Results and Common Coil Design Update

Ramesh Gupta

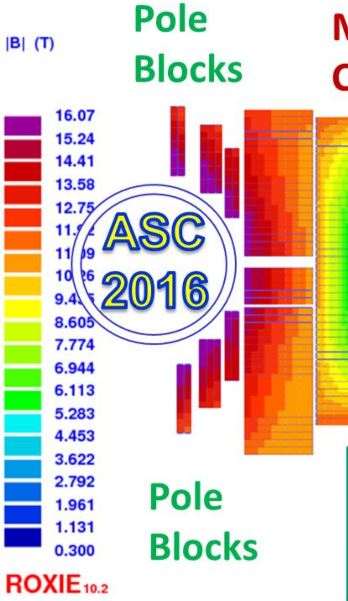
for BNL/PBL Team

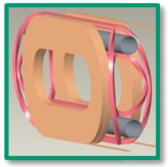
Significant Progress since FCC Week 2016

- **HTS/LTS Hybrid Common Coil Test Results**
  - First test of significant HTS/LTS hybrid dipole
  - Many LTS type quenches in HTS coils (including in hybrid structure). No degradation in HTS coils
  - Nb_3Sn common coil dipole retested after a decade; did not quench up to 92% of the short sample



- **Common Coil FCC Magnet Design Update**
  - Several designs meet FCC field quality specifications
  - Smaller magnet size, lower conductor usage, lower stored energy, improved quench protection, etc., as compared to the designs presented at FCC2016





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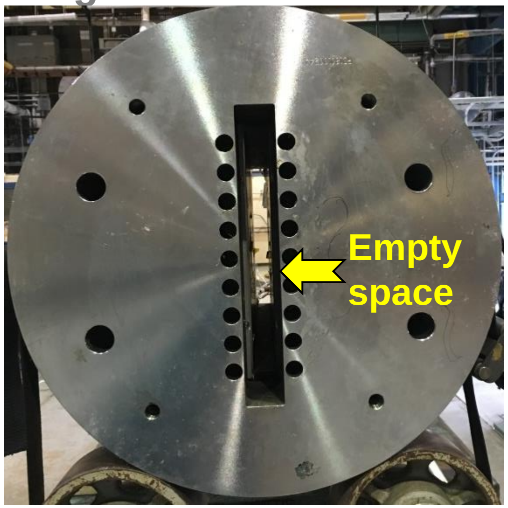
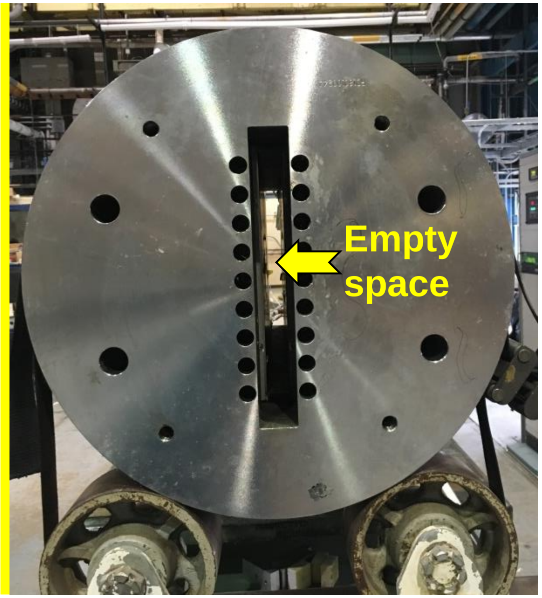
Unique BNL Common Coil Dipole



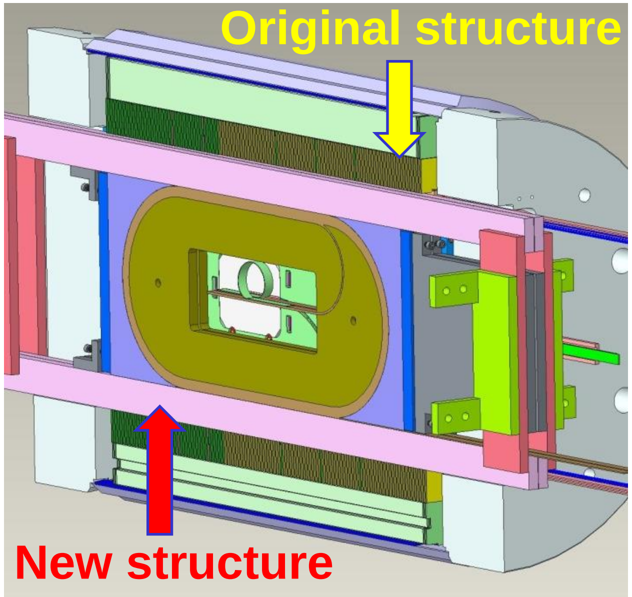
- **Build with "React & Wind" Nb_3Sn Technology**
- **Tested in 2006. Reached short sample of 10.2 T proving "React & Wind" common coil design**
- **Structure specifically designed to provide a large open space (31 mm wide, 338 mm high)**
- **Racetrack coils can be inserted with no need of any disassembly or reassembly of the magnet**
- **New insert coils become an integral part of the magnet. Coil tests become magnet tests**
- **Unique rapid-turn-around facility for novel or systematic R&D which otherwise not possible**
- **Next: Results of HTS/LTS hybrid dipole STTR**

HTS/LTS Hybrid Dipole

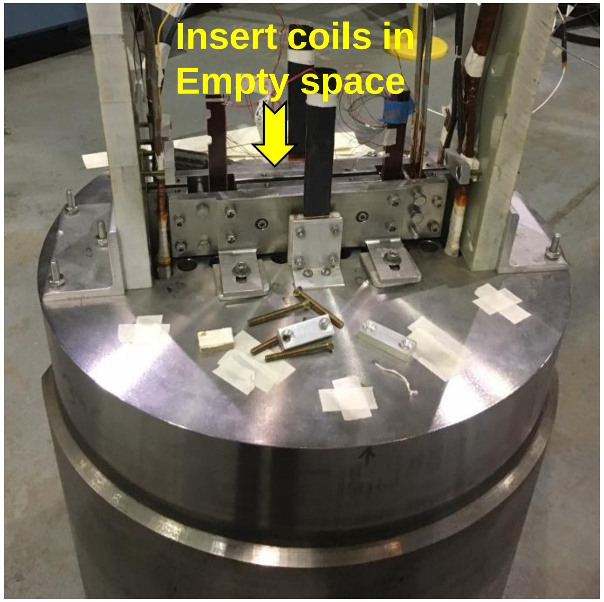
Designed, built and tested: ReBCO/Nb_3Sn hybrid dipole in 2 years



BNL Nb_3Sn common coil dipole DCC017 without insert coils



New HTS coils slide inside the existing Nb_3Sn coils. New coils become integral part of the magnet



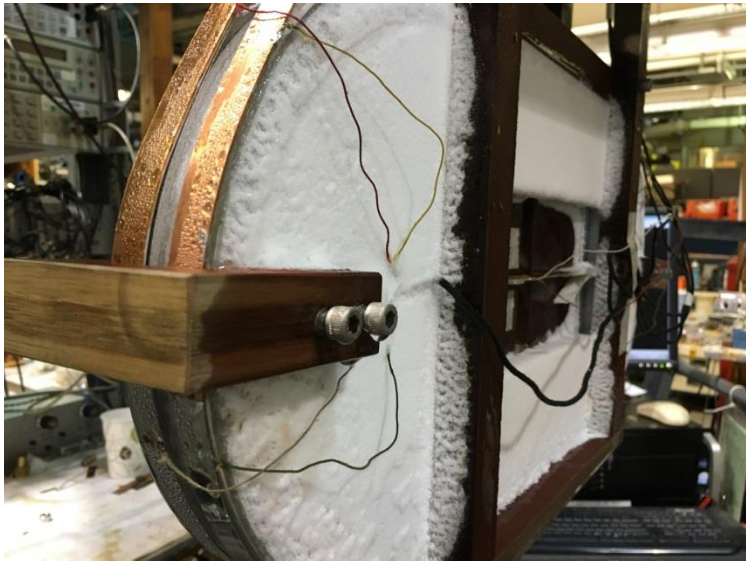
HTS coils inside Nb_3Sn dipole - early experience of HTS/LTS hybrid coils

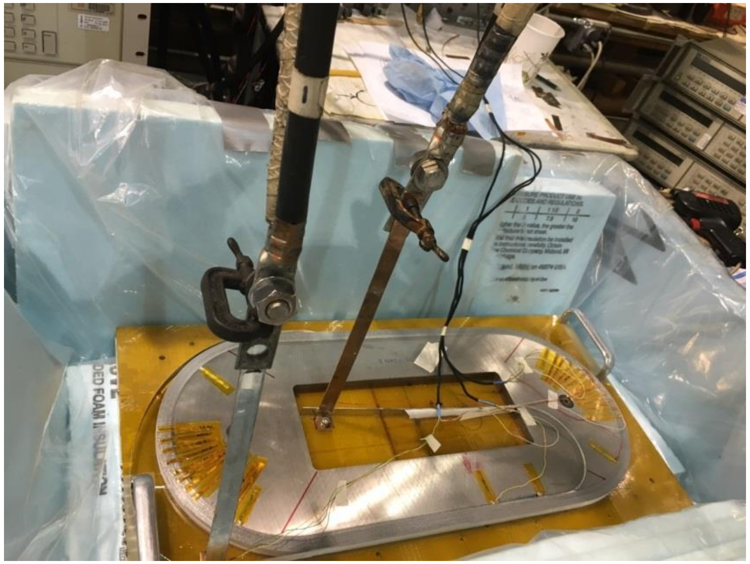
ReBCO HTS Coil with Insulation

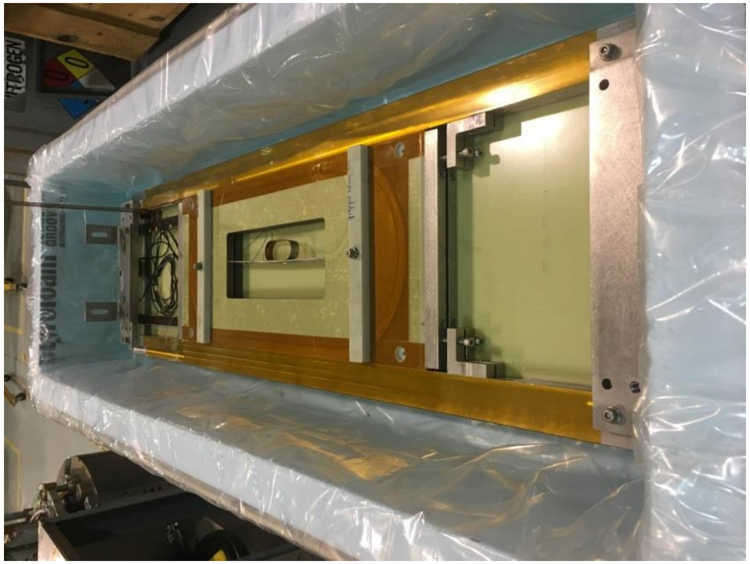
ASC ReBCO 4-ply tape co-wound with Nomex insulation

(SuperPower tape much better for magnet application)

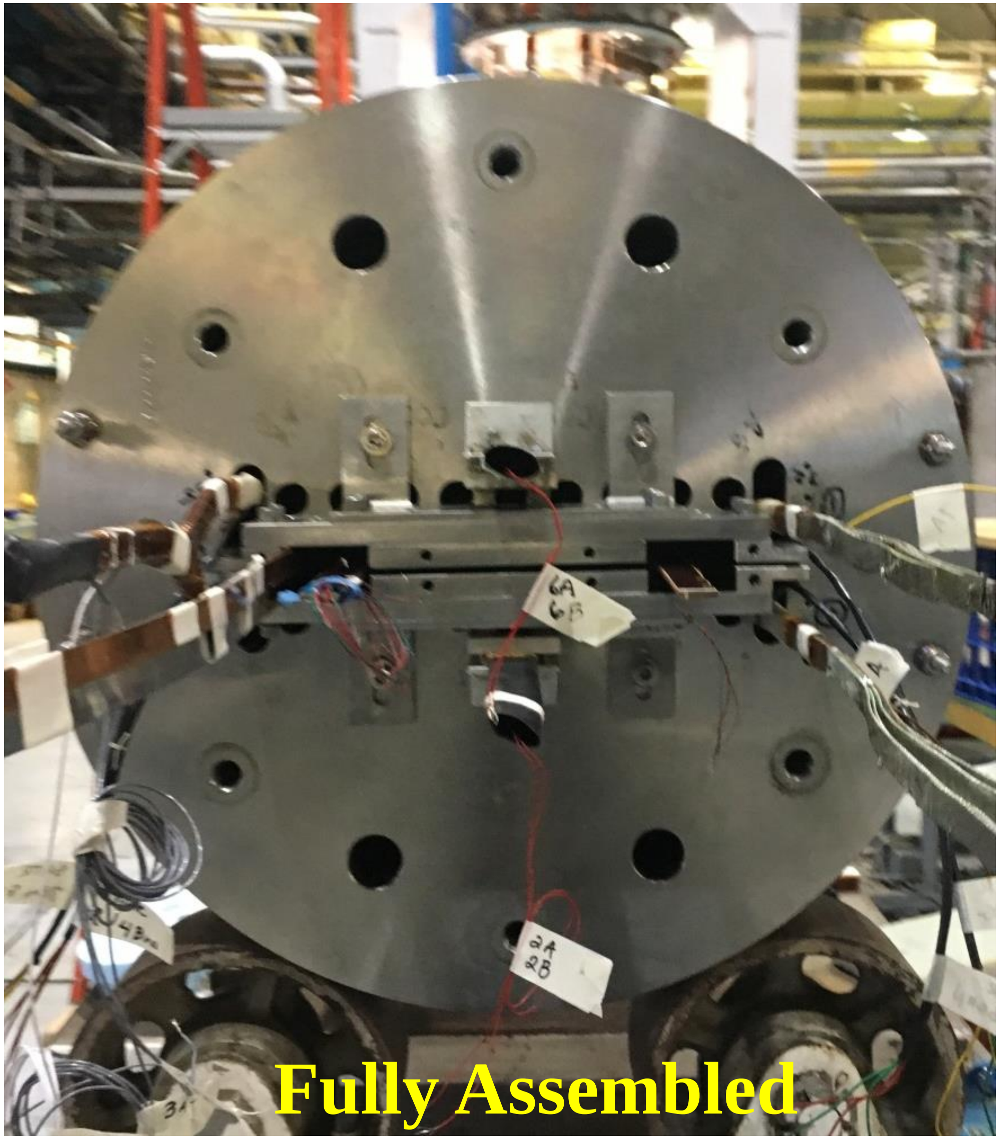
Extensive 77 K Testing of HTS Coils in Various Configurations



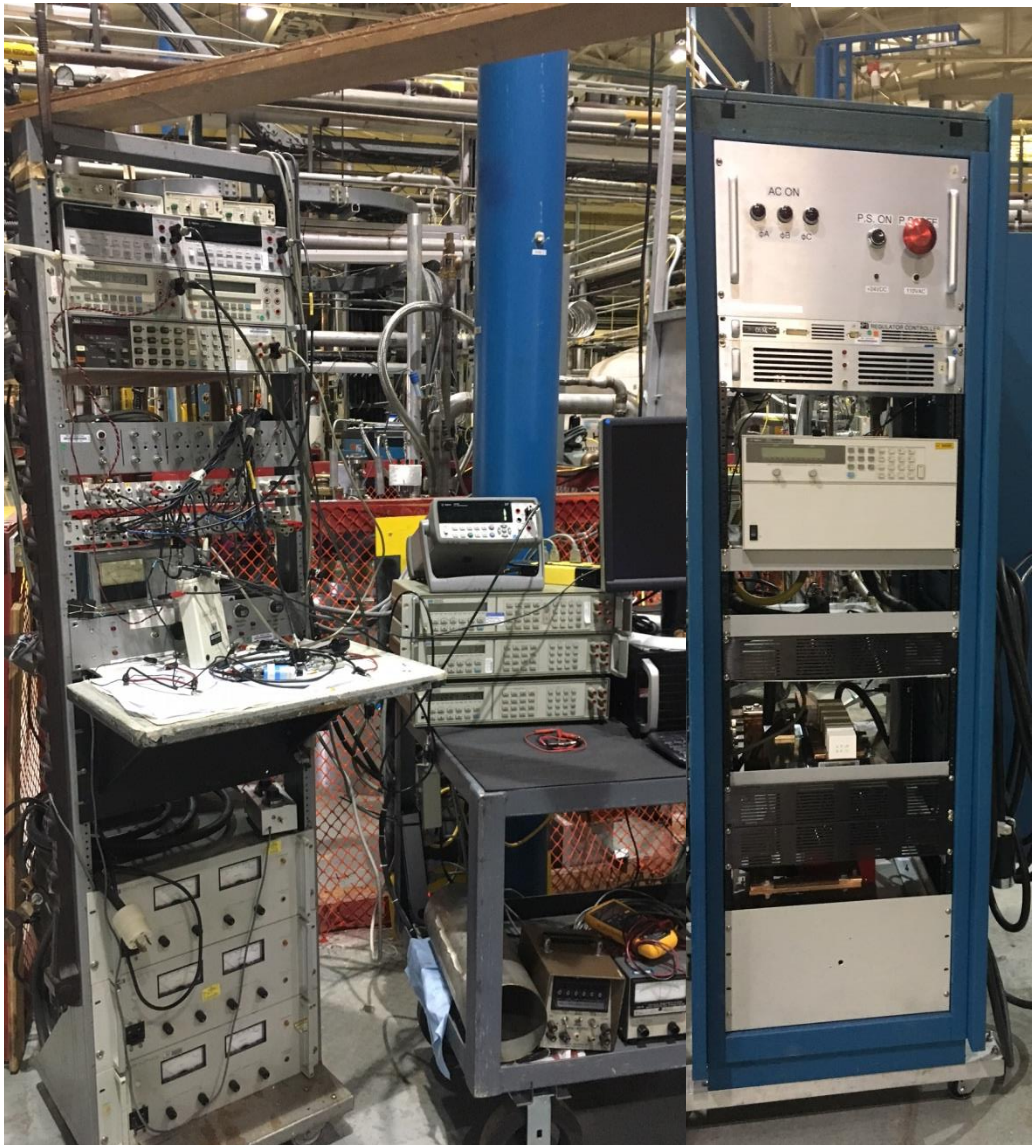




HTS Coil inside LTS Magnet



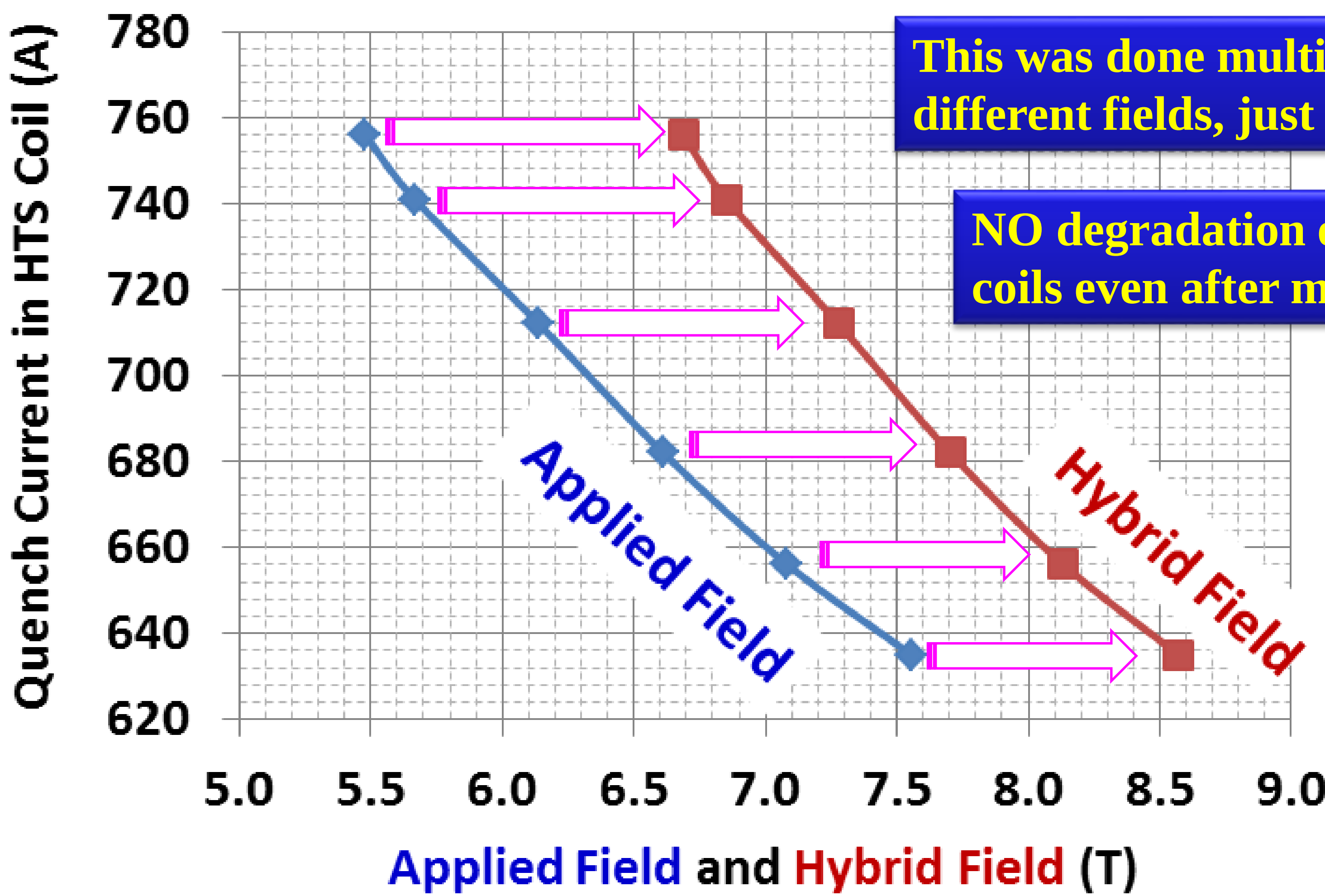
HTS/LTS Hybrid Operation and Quench Protection



- HTS & LTS powered separately
- Tight coupling between them
- Common quench platform; fast energy extraction from both coils
- Quench detection response time: < 5 msec
- Coil current interruption: < 10 micro-second after detection
- HTS coil shut-off: a few msec
- High power IGBT switches
- Isolation voltage: > 1 kV
- Electronic threshold for quench detection: ~100 micro-volts
- HTS Quench threshold planned: 5mV (ran much higher in test)

Safe Quenches in HTS Coils at 4K (highest ever hybrid fields in dipoles)

HTS coils were ramped up and allowed to quench at their limit



This was done multiple times and at different fields, just like in LTS coils

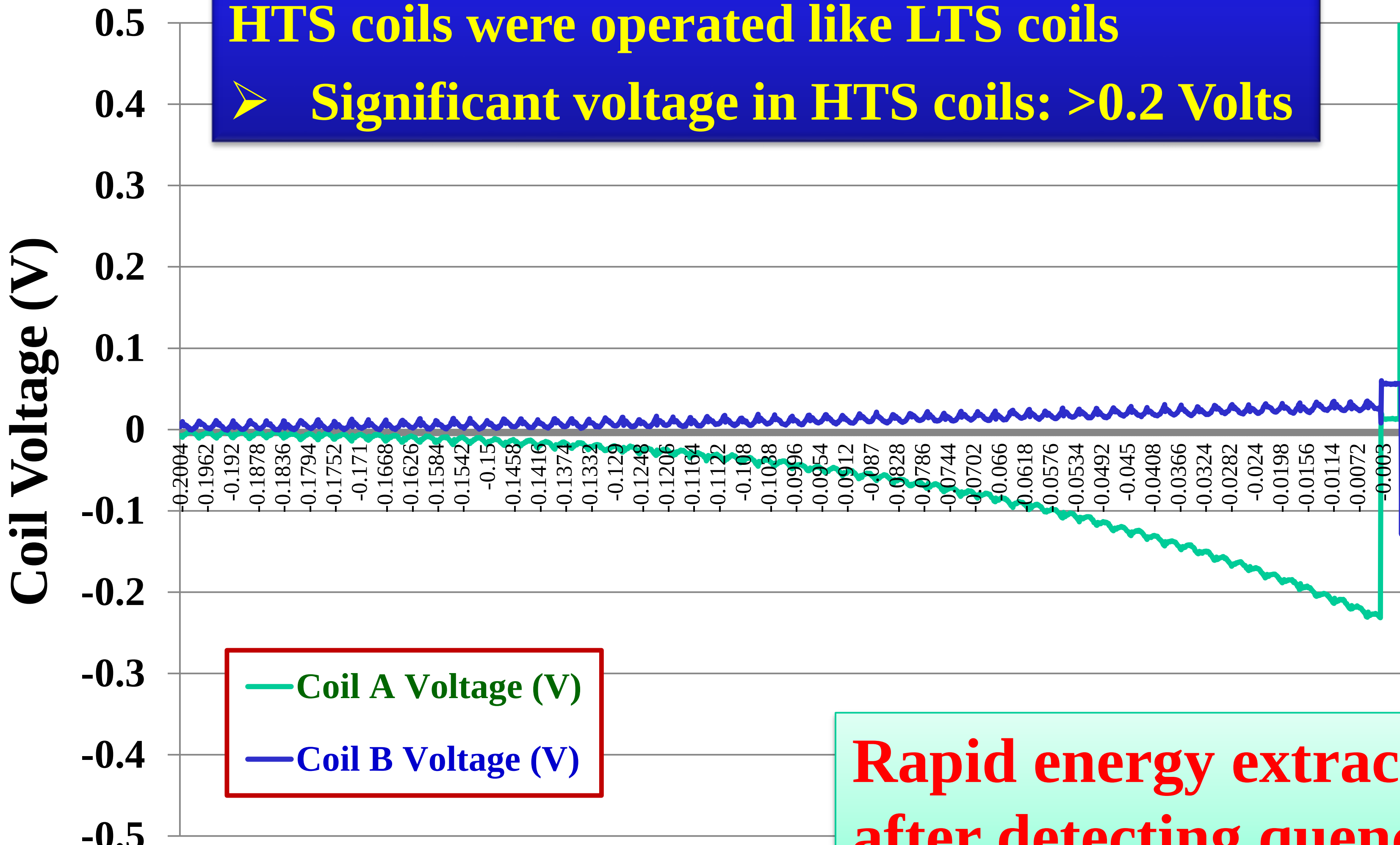
NO degradation observed in HTS coils even after many quenches

The maximum field achieved was limited by the leads

HTS Coil Voltages at Quench

HTS coils were operated like LTS coils

- Significant voltage in HTS coils: >0.2 Volts



Rapid energy extraction after detecting quench

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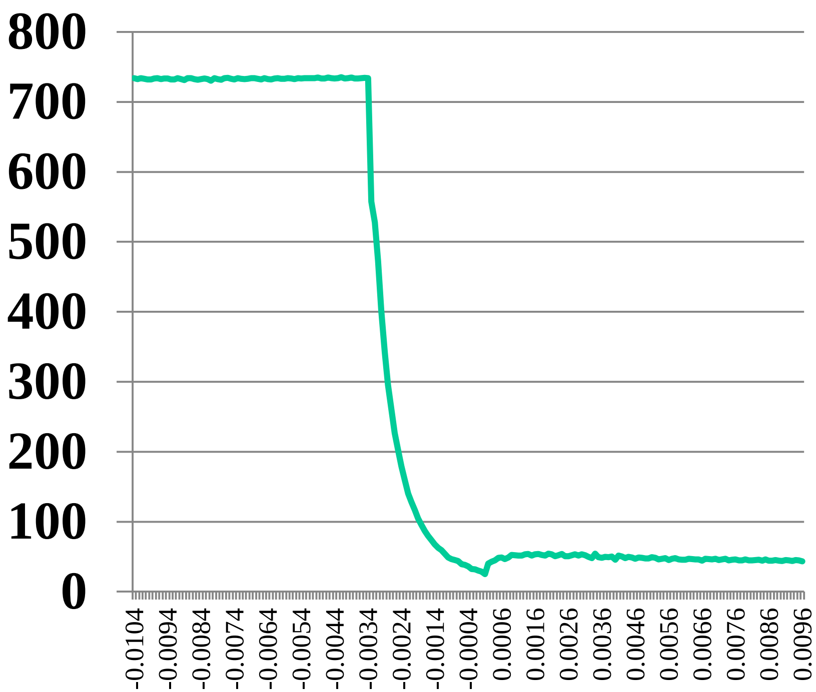
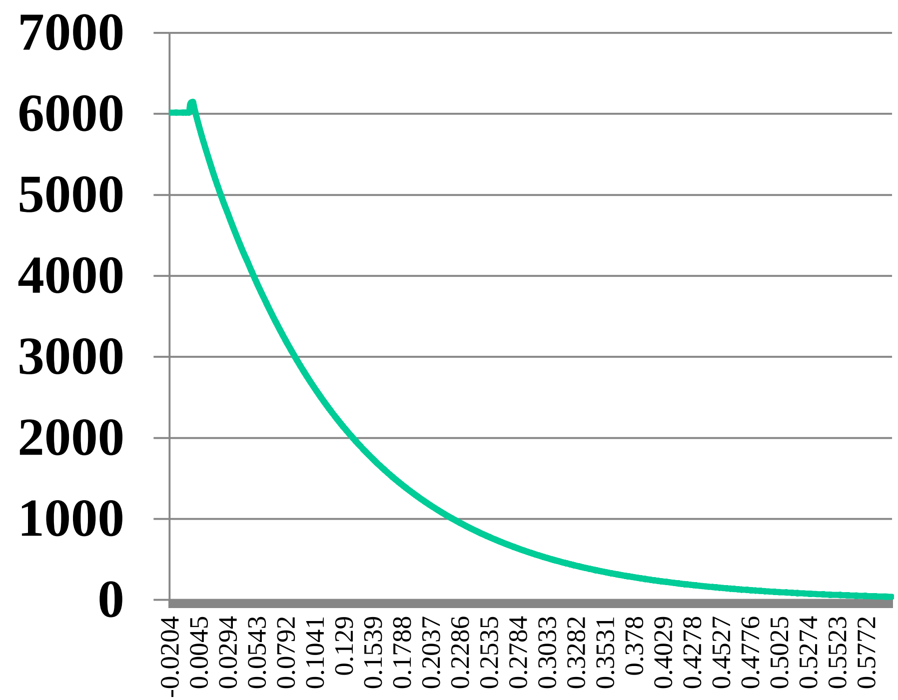
HTS and LTS Currents (just before and after the quench)

HTS Current (A)



LTS Common Coil Current (A)

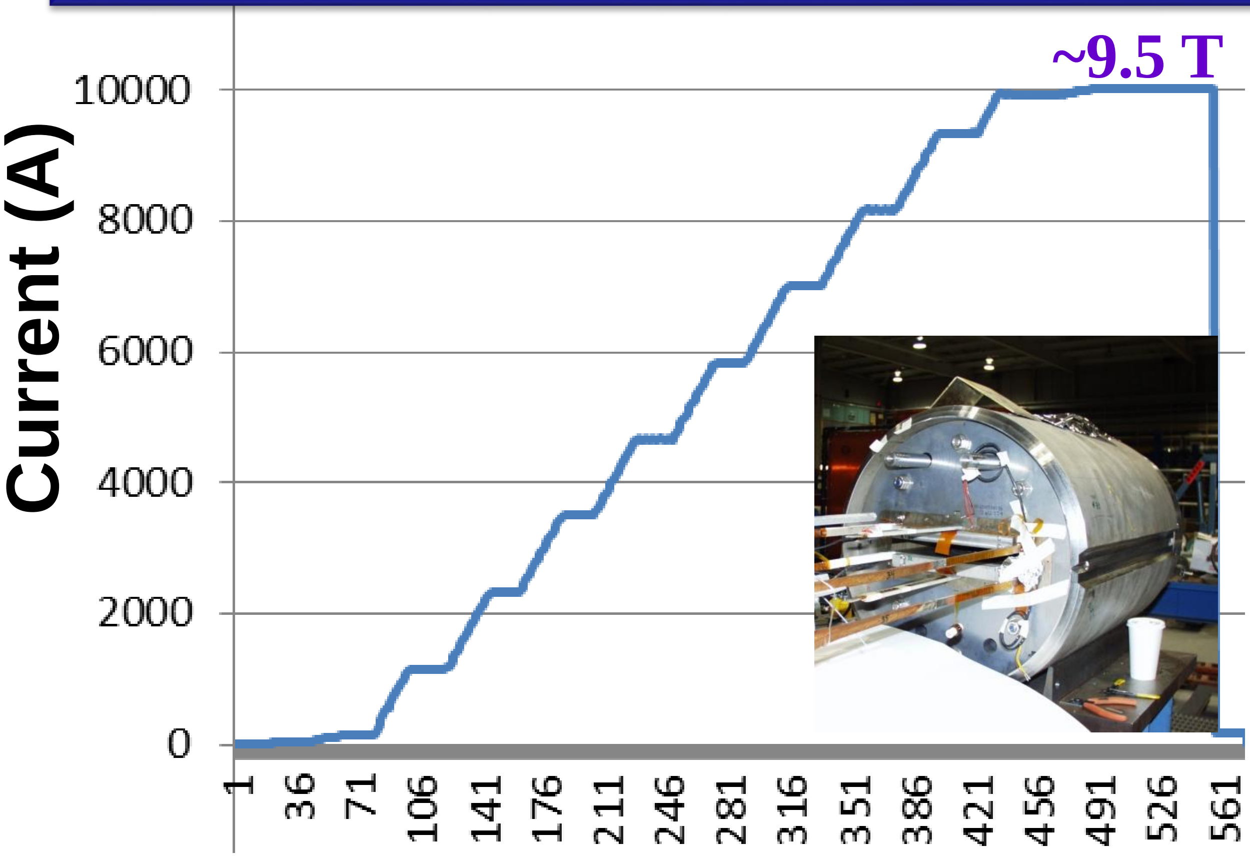


Separate power supplies and separate energy extraction for HTS and LTS coils

HTS and LTS coils have different inductances and different characteristics

Performance of BNL Nb_3Sn Common Coil Dipole (tested after a Decade)

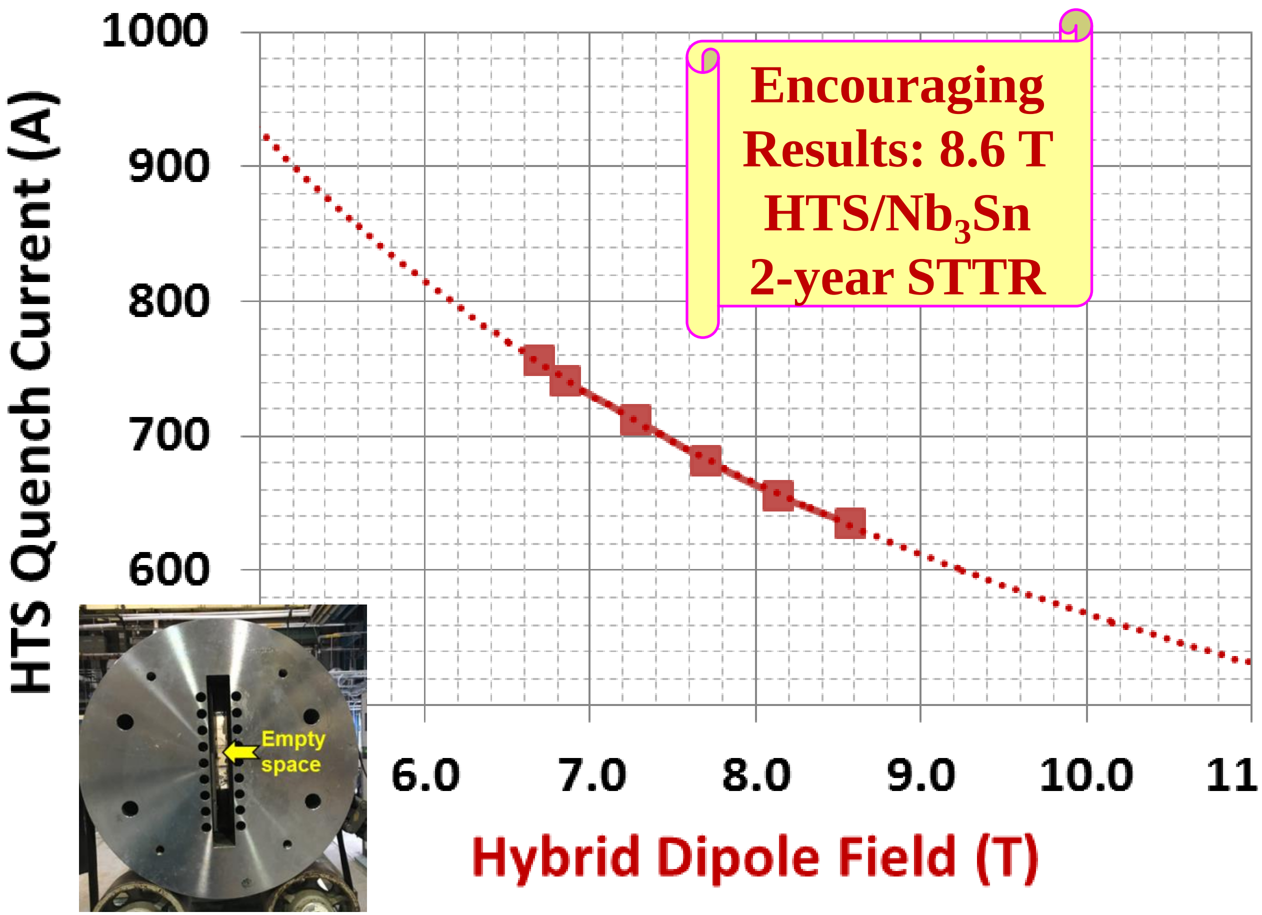
- Short Sample: 10.8 kA (reached during 2006 test)
- Retest: No quench to 10 kA (>92% of short sample)
- Despite over 200 μm displacement & magnet out for a decade



Nb_3Sn magnet test limited by the leads

Similarly, the maximum background field was limited by the stable operation of the leads in the top-hat 8 kA (~7.5 T)

Next Logical Step
Small Investment, Significant Results



- **Simple replacement of the leads in top hat will allow 11 T hybrid test**
- **New HTS coils with SuperPower tape would allow ~15 T hybrid test**
- **Big Bang for little money – such is what we need to do in the present environment: show noticeable results in short regular intervals**

BNL has proposed to commission this unique facility (with minimum upgrade required for a user facility) under GARD (USMDP). This background field coil/magnet test rapid-turn-around facility can be used for the high field development of Bi2212 coil, Nb_3Sn coils, etc.

Next Major HTS Project at BNL for IBS (Korea)

25 T, 100 mm Cold Bore User Solenoid

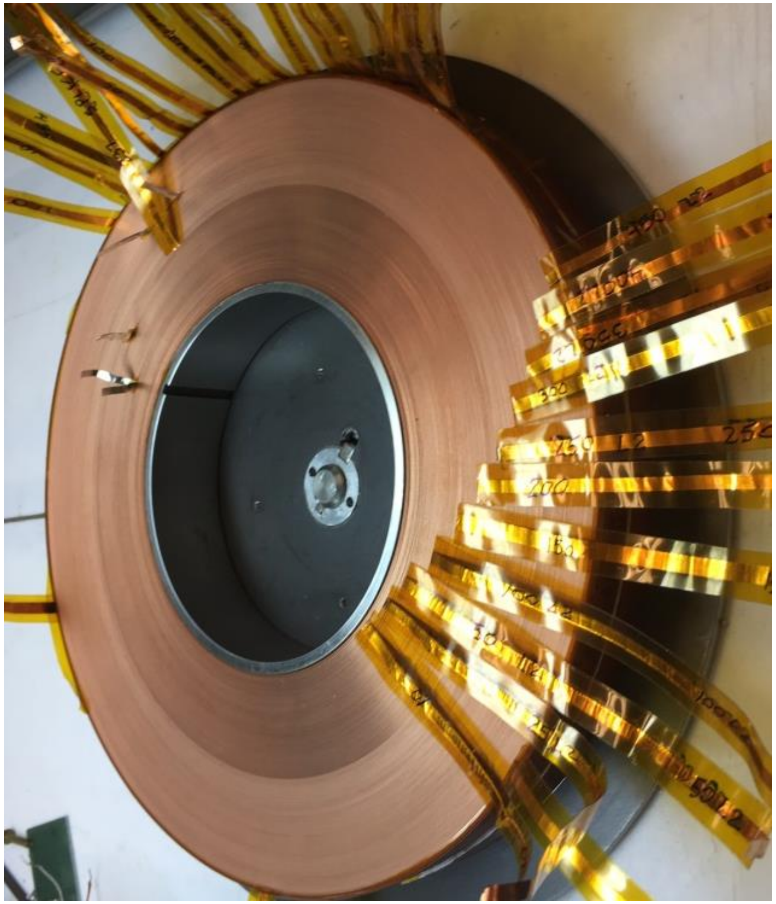
(would use 9-10 km of 12 mm wide ReBCO)

Status of the IBS Program

BNL has previously designed and built 25 T HTS solenoid with 100 mm coil id for SMES as a high risk, high reward program (no margin)

Margins for this user solenoid:

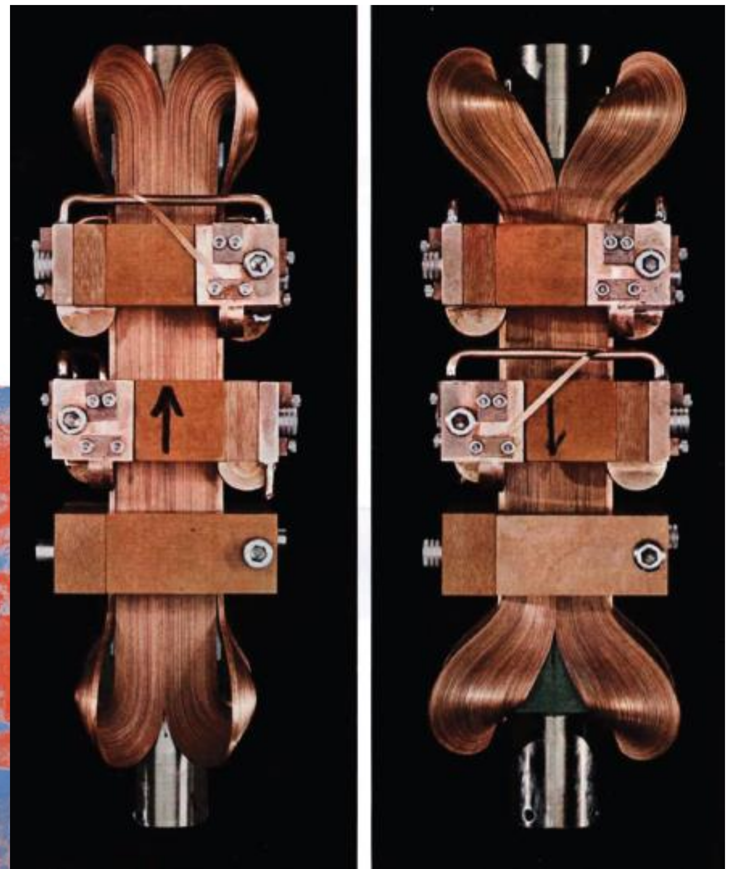
- **Electrical (I_c): > 50%**
- **Mechanical (stress/strain): > 50%**
- **Quench protection: No-insulation (ok to use since the field quality and ramping time are not critical)**



100 mm bore double pancake coil wound with 550 m of 12 mm wide ReBCO tape (to be tested at 4K)

Fifty Years of "No-Insulation" Superconducting Tape Magnets

Bill Sampson 1967



SUPERCONDUCTING MAGNET was designed by one of the authors (Sampson) as a prototype of a class of magnets that will be used to focus the beam of protons from the 33-billion-electron-volt accelerator at the Brookhaven National Laboratory. The device, called a rectangular quadrupole magnet, consists of four mutually perpendicular current sheets made of superconducting niobium-tin ribbon encased in copper. The direction of the current (pointed *black arrows*) is opposite on adjacent sheets, two of which are visible in these two side views. The magnet is shown approximately actual size. When it is in use, it is immersed in liquid helium.

Nb_3Sn Tape Quadrupole (still available to touch)

Advances in Superconducting Magnets

In the past five years superconducting magnets have developed from a laboratory curiosity into the most practical means of generating intense magnetic fields for a growing number of research projects

by William B. Sampson, Paul P. Craig and Myron Strongin

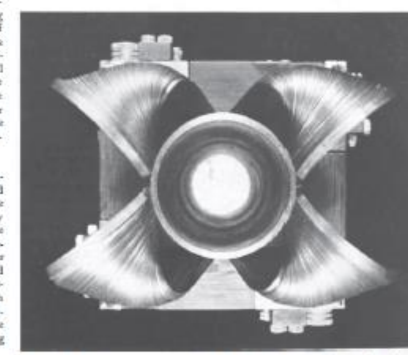
Five years ago superconducting magnets were a laboratory curiosity. An adequate supply of superconducting wire was available, and experimental magnets capable of generating fields as high as 70,000 gauss had been built and operated successfully [see "Superconducting Magnets," by J. E. Kunzler and Morris Tanenbaum; SCIENTIFIC AMERICAN, June, 1962]. Nevertheless, numerous technical difficulties remained, and in spite of their widely recognized potential such magnets were held to be economically impractical for most purposes in competition with conventional electromagnets.

Today this situation has changed drastically. Considerable progress has been achieved in the past few years in the design and fabrication of superconducting magnets. For a substantial number of applications superconducting magnets now perform better and more economically than comparable conventional magnets. Moreover, it seems probable that in the not too distant future the growing need for stronger and cheaper magnetic fields in many areas of science and technology will be filled by superconducting magnets.

At the Brookhaven National Laboratory we are engaged in building and testing superconducting magnets for use primarily in the fields of high-energy physics and solid-state physics. We have also begun to use such magnets for specific experiments in these fields. Other investigators have recently speculated on some potential uses of superconducting magnets in space research. Although the space applications seem much further in the future, they do not require any unreasonable extension of existing knowledge.

The most important property of superconducting materials from the point of view of a magnet designer is their complete lack of resistance to an electric current at temperatures near absolute zero. This property, discovered by the Dutch physicist Heike Kamerlingh Onnes in 1911, makes it possible in principle to build an extremely strong magnet that requires no input of power. (Permanent iron magnets also produce magnetic fields with no power input, but the strongest fields they can attain are only about 10,000 gauss.) The vast amount of power consumed by a conventional high-field electromagnet appears in the form of heat as a result of electrical resistance in the current-carrying coils. This power input produces no useful work and must be carried away by some cooling agent, usually large quantities of water. At the National Magnet Laboratory in Cambridge, Mass., continuous fields as strong as 250,000 gauss have been achieved with a conventional electromagnet, but the electric power consumed by the magnet is about 16 million watts—approximately the power requirement for a town of 15,000 inhabitants [see "Intense Magnetic Fields," by Henry H. Kolm and Arthur J. Freeman; SCIENTIFIC AMERICAN, April, 1965].

Since there is no electrical resistance in the current-carrying coils of a superconducting magnet, no power is dissipated as heat, and strong fields can be



END VIEW of the superconducting quadrupole magnet on the opposite page shows the rectangular array of current sheets around the bore, which is slightly more than an inch across.

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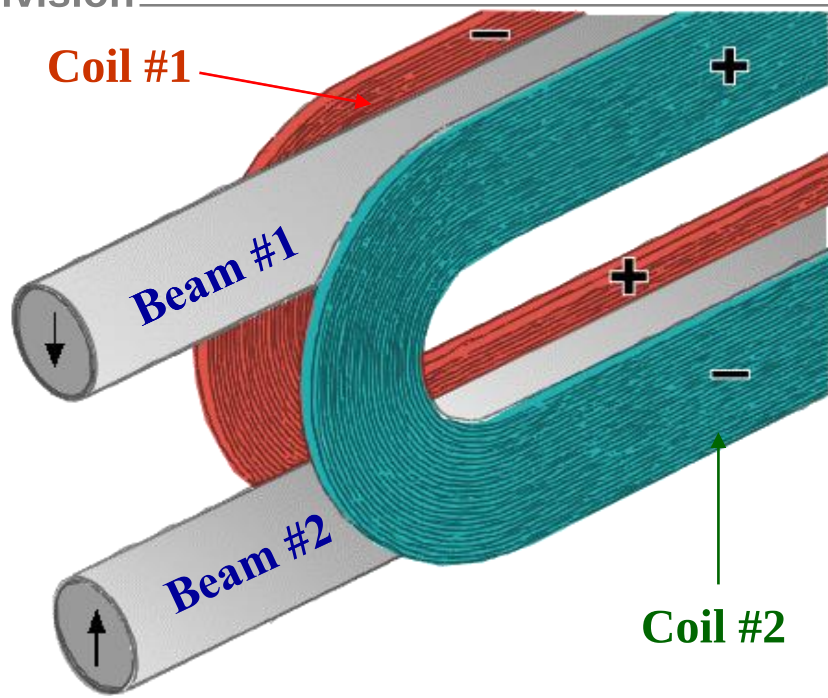
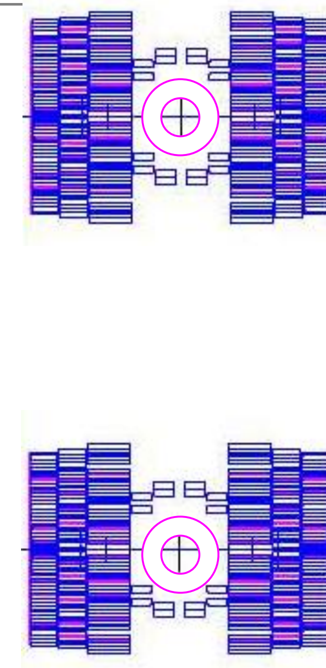
Common Coil Design Update

Common Coil Design

Main Coils of the *Common Coil Design*



Bend radius is determined by the aperture spacing (much larger), not by the aperture (much smaller)



Good Field Quality *Common Coil Design*

- **Simple coil geometry with large bend radii: lower cost expected; suitable for both "Wind & React" and "React & Wind" technologies**
- **Same coil for two aperture: Manufacturing cost should be lower as the number of coils required for 2-in-1 magnet is half**
- **Rapid turn-around for systematic and innovative magnet R&D**
- **Tolerates larger deflections without causing strain on the conductor**

Basic Guidelines

Examine if a common coil cross-section is possible that satisfies the key FCC 50 mm, 16 T design requirements

- Harmonics (geometric & saturation): well within specifications
- Conductor usage: similar or less than in the other designs
- Stored energy: similar or less than in the other designs
- Inductance: much less than in the other designs
- Intra-beam spacing: 250 mm
- Yoke outer diameter: 700 mm
- Structure: able to hold pole (auxiliary) coils
- Conductor: standard filament/strand, wider cable (next slide)

Choice of Cable/Conductor

- **Filament : Same as in EuroCirCol Common Coil**
- **Strand : Same as in EuroCirCol Common Coil**
- **Cable: Wider (reach 16 T @~16 kA)**

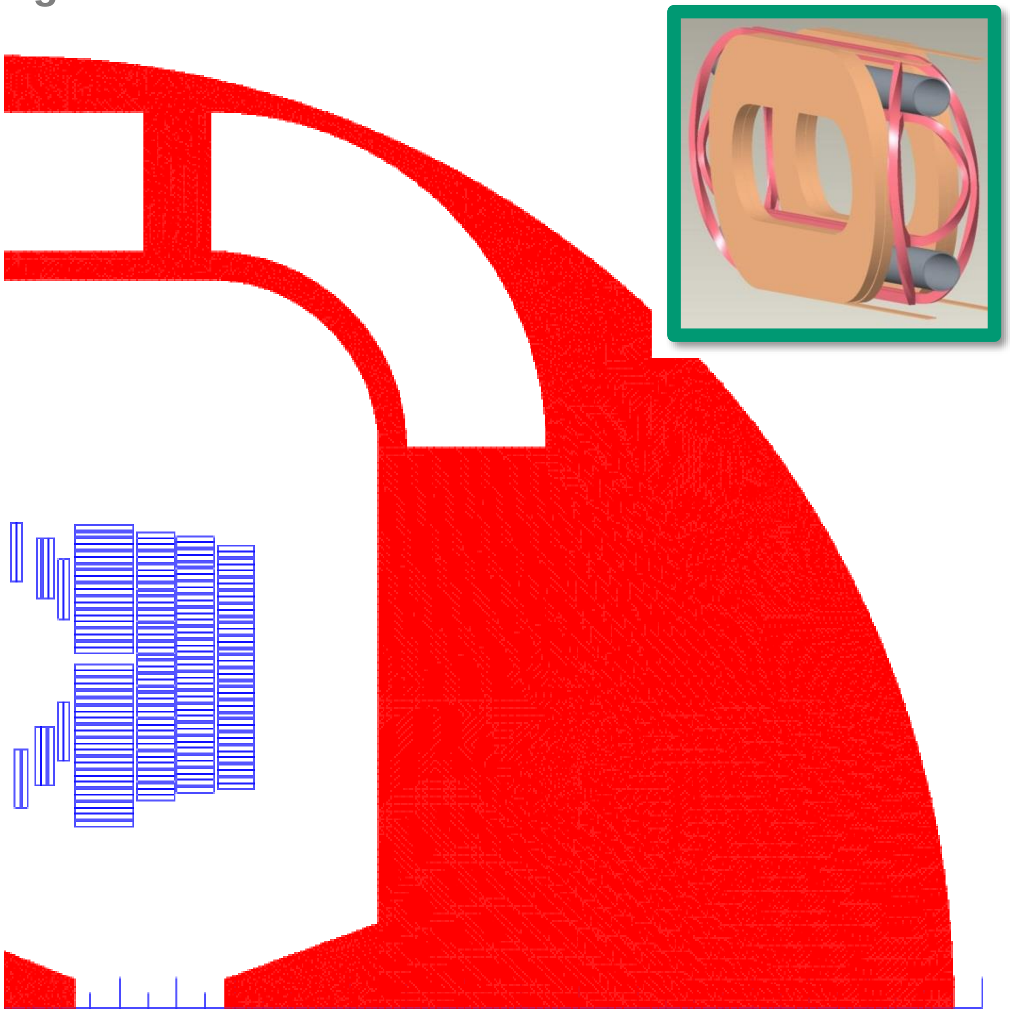
  OK in conductor friendly common coil design

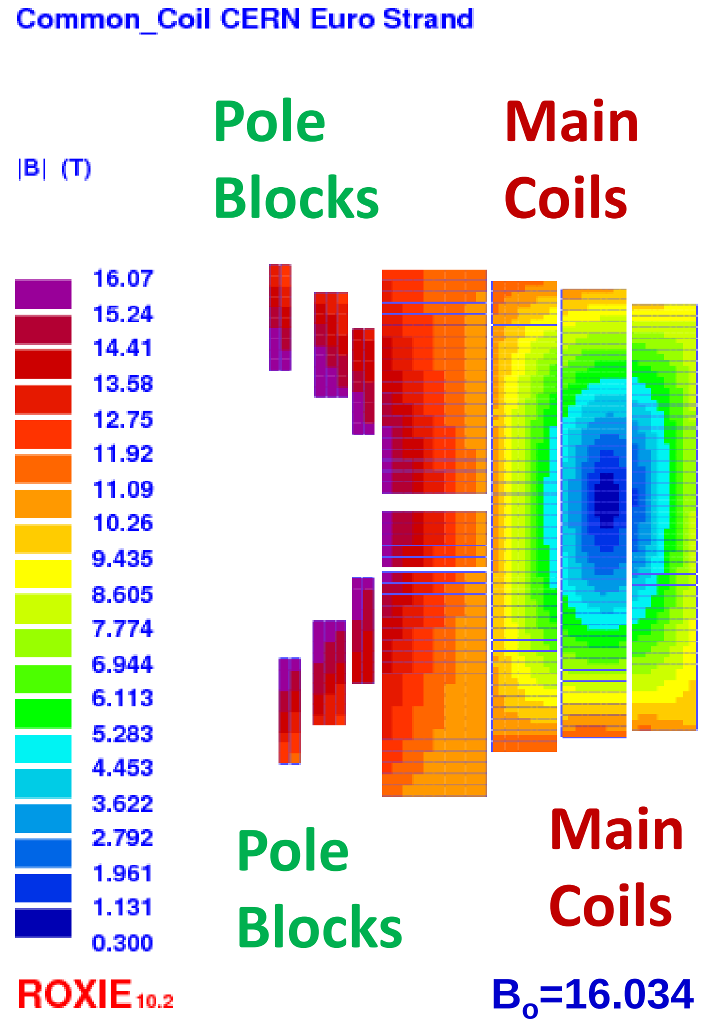
  - **Reduces inductance (helps quench protection)**
  - **Fewer coils (helps in reducing cost)**

Perhaps only design which works easily with 20 kA cable

Larger diameter strand for inner layer will significantly reduce conductor usage as it will allow better grading and by changing the aspect ratio of the cable

Magnet Cross-section (one of several types optimized)





¼ of a 2-in-1 magnet, ½ of one aperture

Intra-beam spacing = 250 mm; yoke od =700 mm; wider cable

Geometric Harmonics

SKEW AND NORMAL HARMONICS AT 17 MM RADIUS AT 16 T IN DESIGN #1

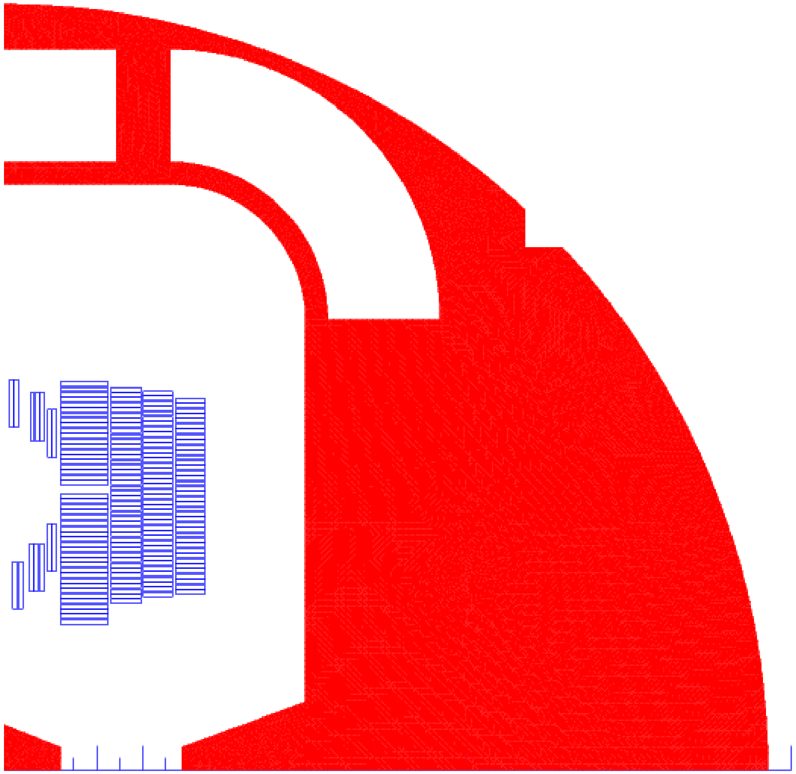
a_2	a_4	a_6	a_8	a_{10}	a_{12}	a_{14}	a_{16}
0.00	0.00	0.00	0.27	0.21	-0.07	-0.31	0.07
b_3	b_5	b_7	b_9	b_{11}	b_{13}	b_{15}	b_{17}
0.00	0.00	0.01	-0.16	-0.10	-0.35	-0.32	0.03

Specifications < 3 unit

- **Above are about an order of magnitude better**
- **Errors to be determined by magnet construction**

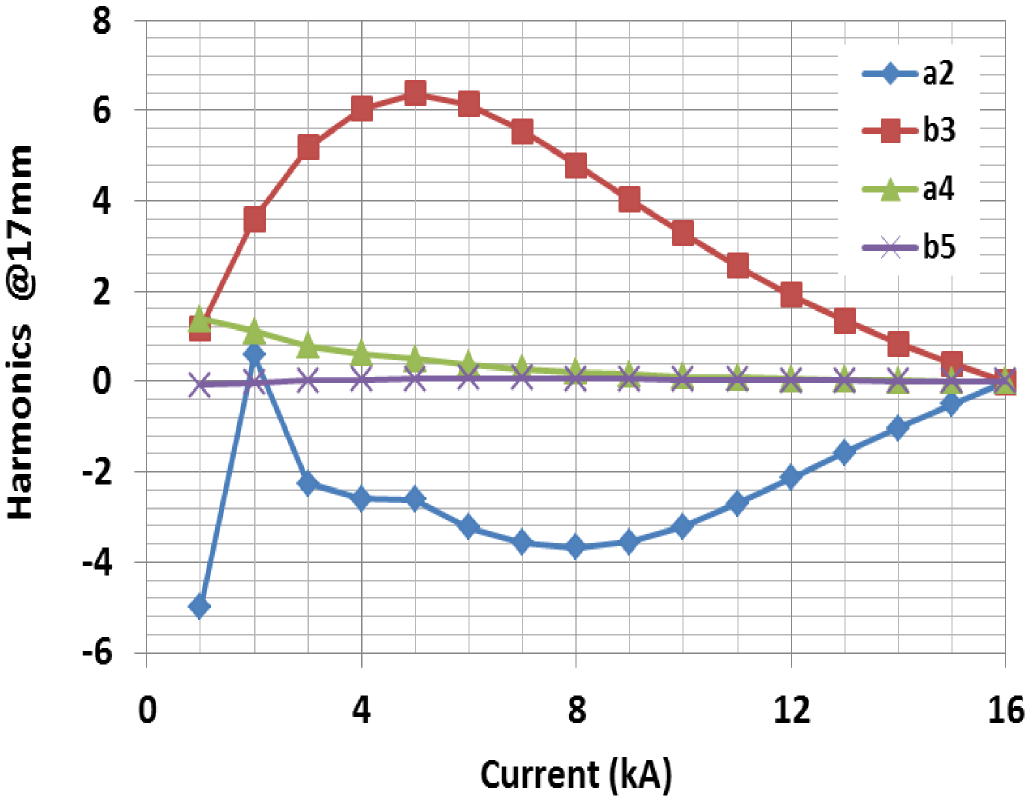
Iron Saturation

Yoke od = 700 mm
Intra-beam = 250 mm



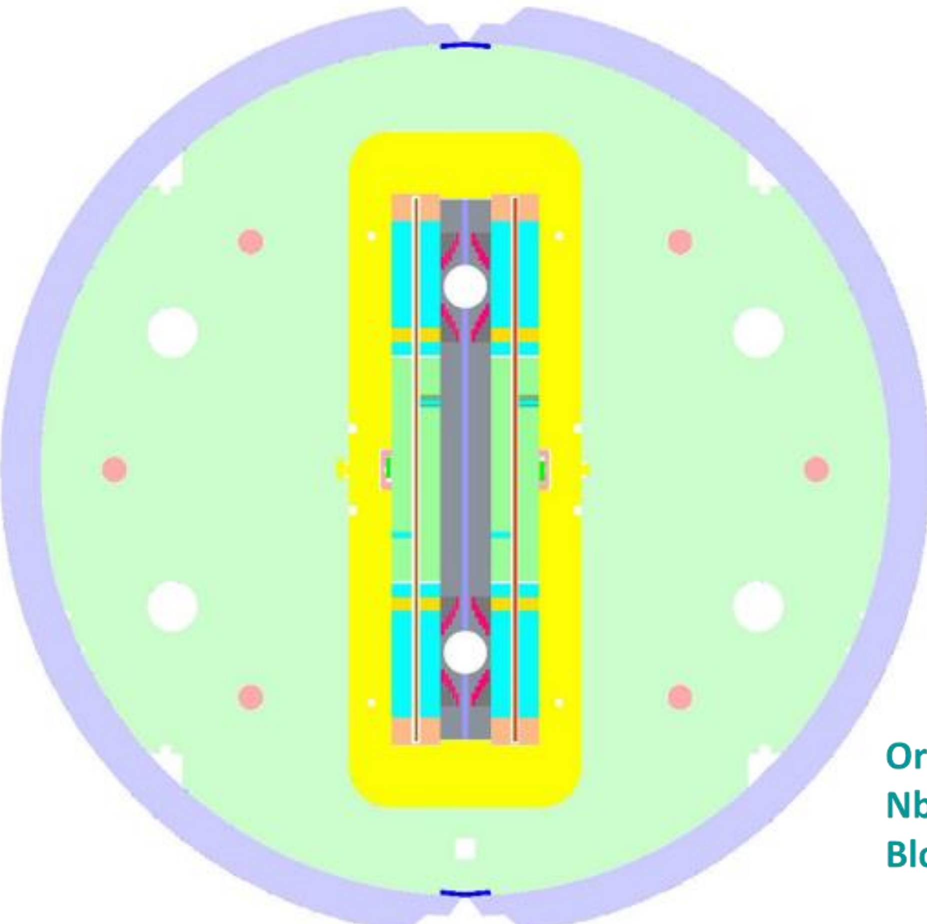
Well below specification:

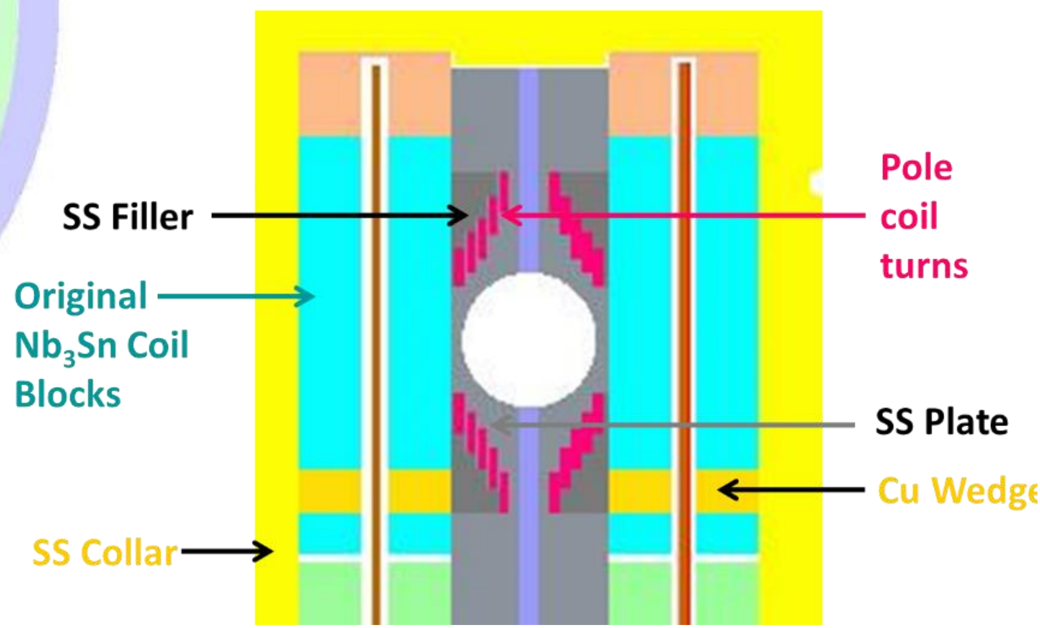
- ❑ b_3 < 7 units (spec <10 units)
- ❑ a_2 < 6 units (spec < 20 units)



Optimized by : Nick Maineri
2nd year undergrad student
6 week DOE SULI program

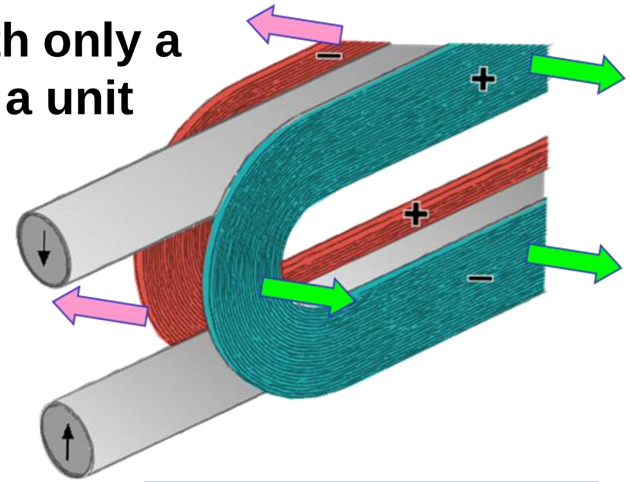
Initial Design for Pole Coil Assembly

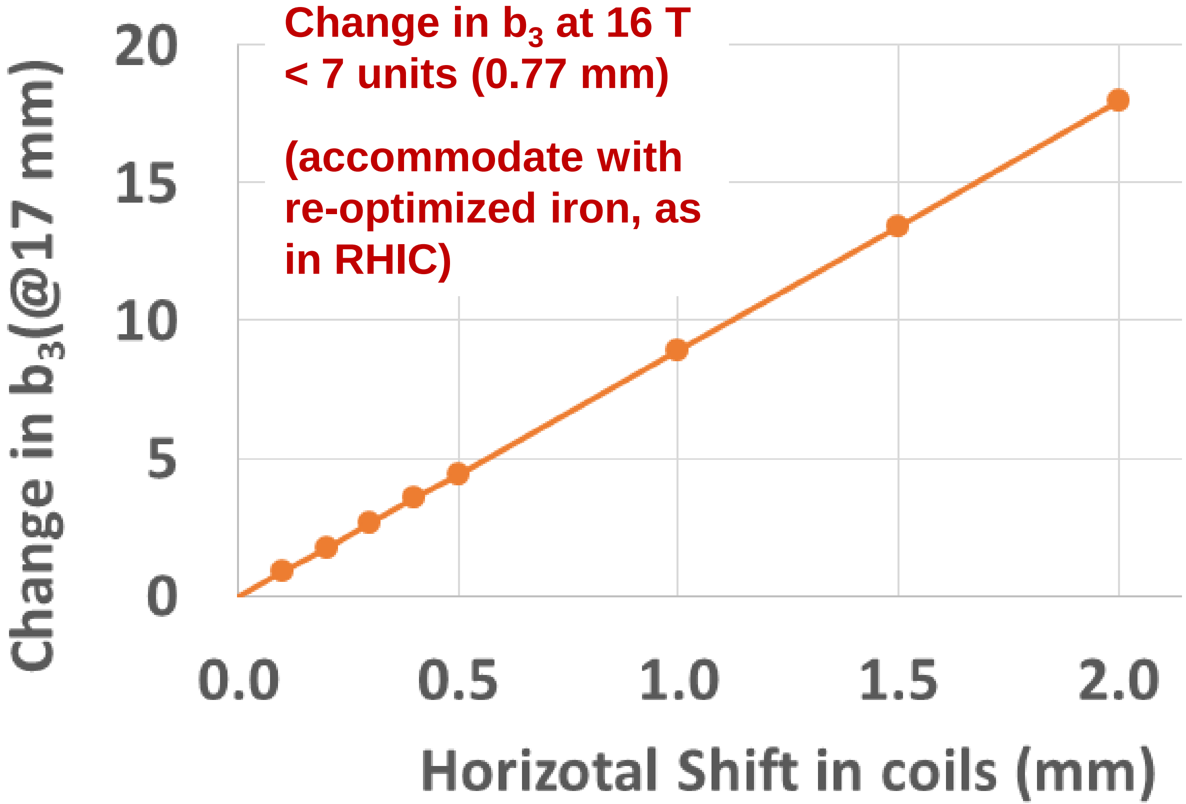




Influence of Coil Deflections due to Lorentz Forces on the Field Quality

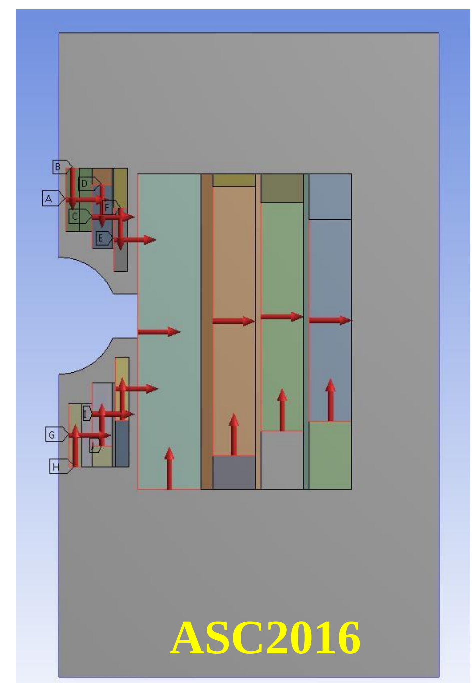
- **Common coil design can tolerate large deflections with only a small strain on the conductor since the coils move as a unit**
- **Large deflections found in horizontal direction**
- **Significant change in b_3 harmonic only**





Change in b_3 at 16 T < 7 units (0.77 mm)

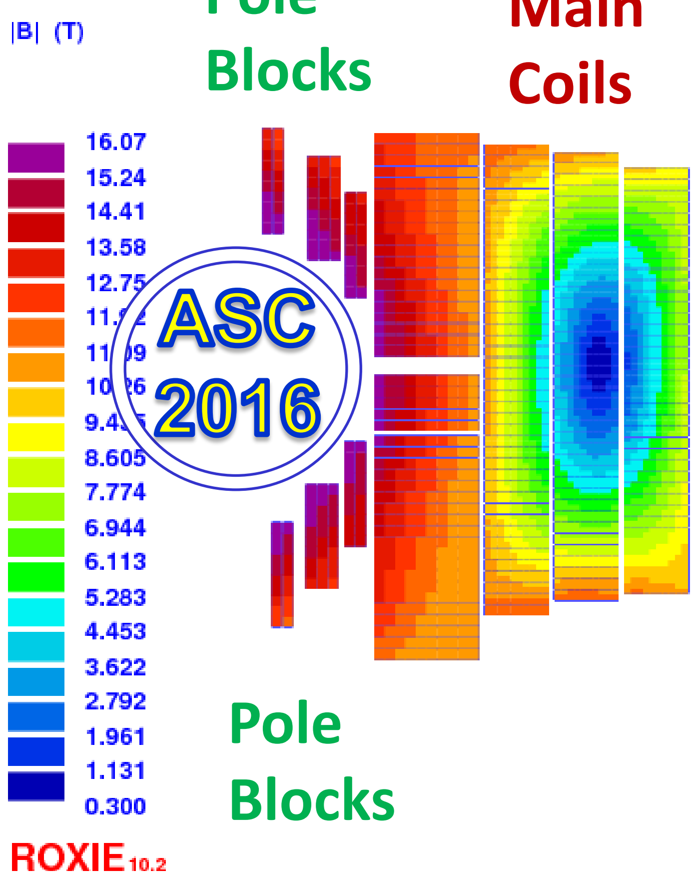
(accommodate with re-optimized iron, as in RHIC)

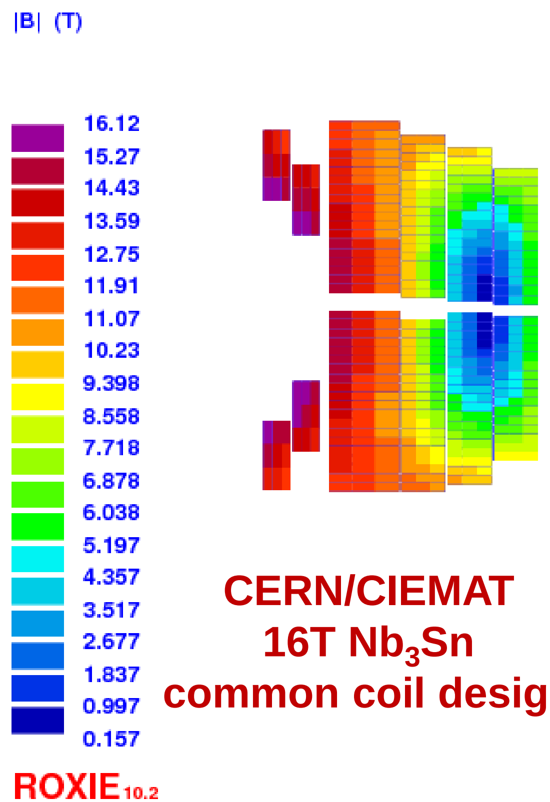


Basic Design Parameters (ASC2016)

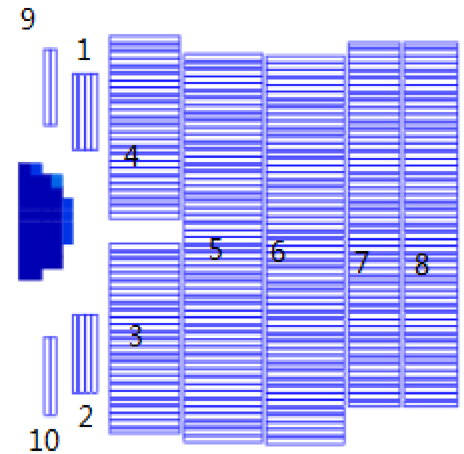
Operating current	(kA)	15.96
Field in the aperture	(T)	16.0
Margin at 1.9 K	%	19.3
Intra-beam spacing	(mm)	250
Yoke outer diameter	(mm)	700
Stored energy per unit length/aperture	(MJ/m)	1.7
Inductance/aperture	(mH/m)	13
Strand diameter (inner and pole layer)	(mm)	1.1
Strands/cable (inner and pole layer)	-	36
Cu/Non-Cu (inner and pole layer)	-	1.0
Strand diameter (outer layers)	(mm)	1.1
Strands/cable (outer layers)	-	22
Cu/Non-Cu (outer layers)	-	1.5
Total number of turns per aperture		179
Total area of Cu/aperture	(mm^2)	5029
Total area of Non-Cu/aperture	(mm^2)	4026
Total weight of conductor for all FCC dipoles	(tons)	10300

A Few Common Coil Designs





CERN/CIEMAT 16T Nb_3Sn common coil design



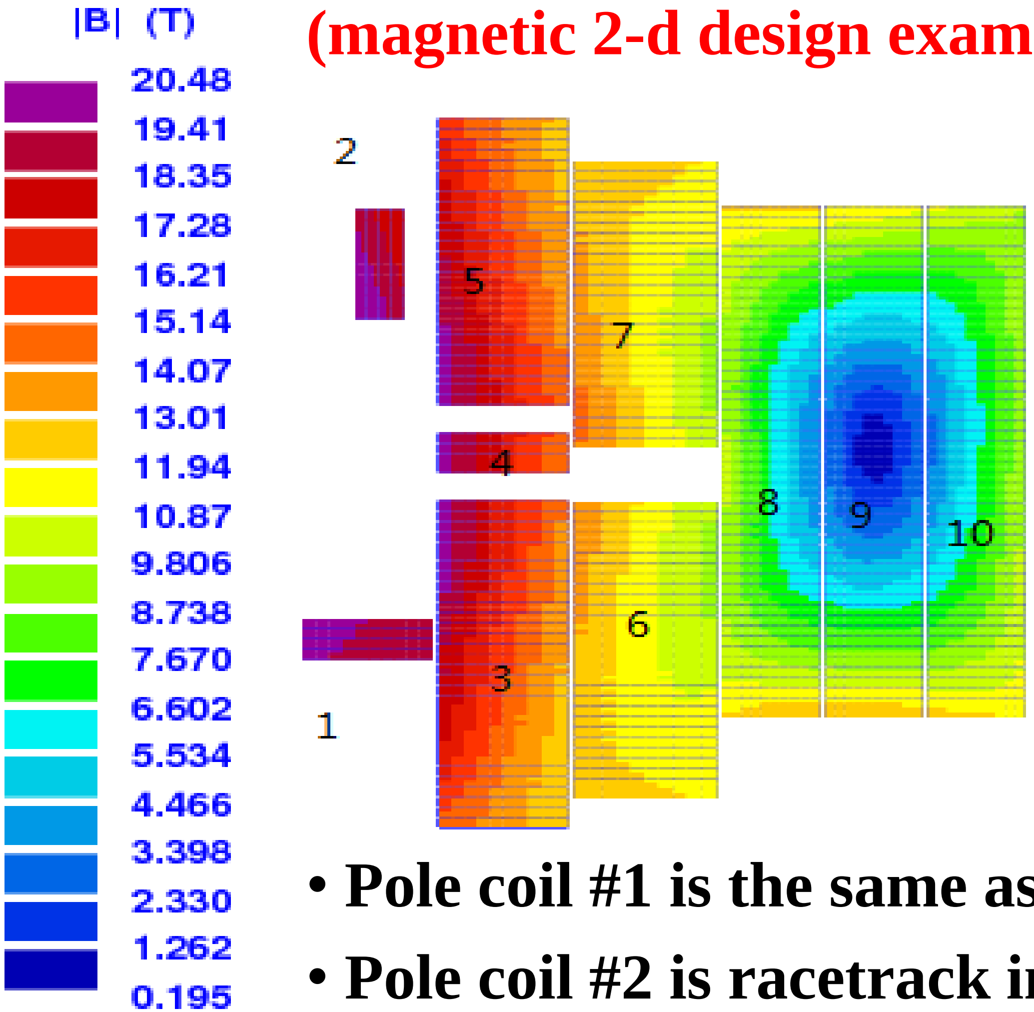
SppC 20 T hybrid common coil design

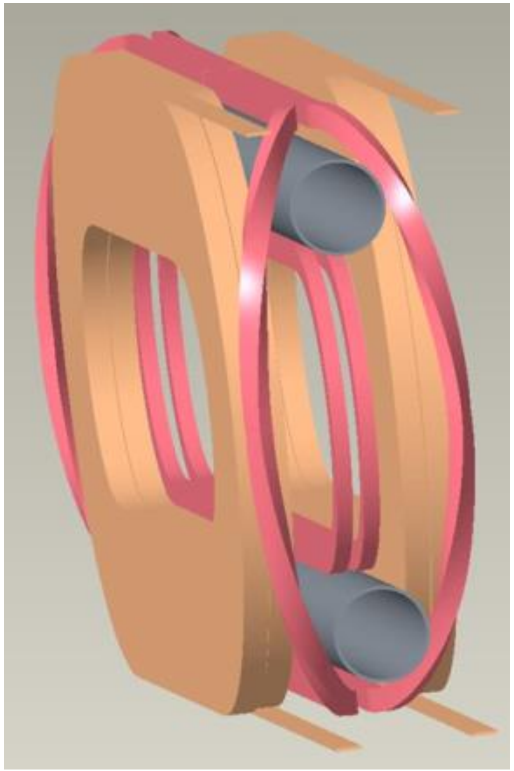
BNL/PBL Nb_3Sn 16 T Nb_3Sn Design

Informal Exchange/Collaboration with CERN and IHEP

Another Configuration for Pole coils

(magnetic 2-d design examined with IHEP visitor at BNL)



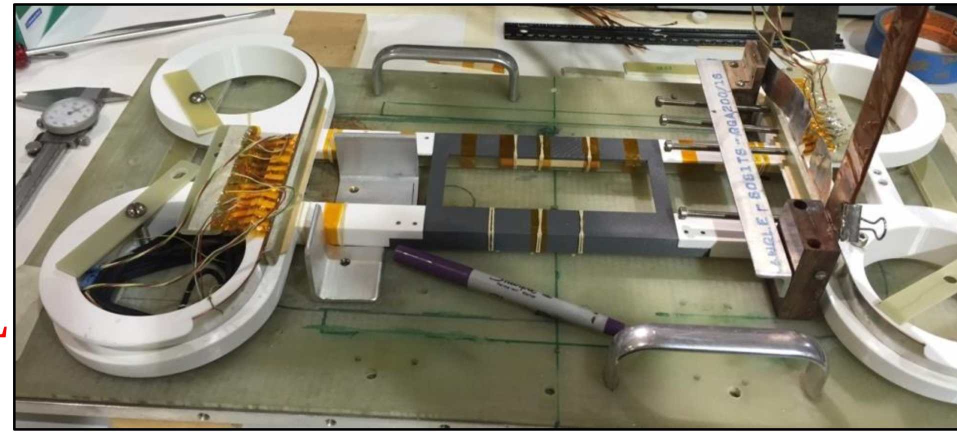


- **Pole coil #1 is the same as all other main coils**
- **Pole coil #2 is racetrack in the other orientation with space for support between pole coils and main coils**

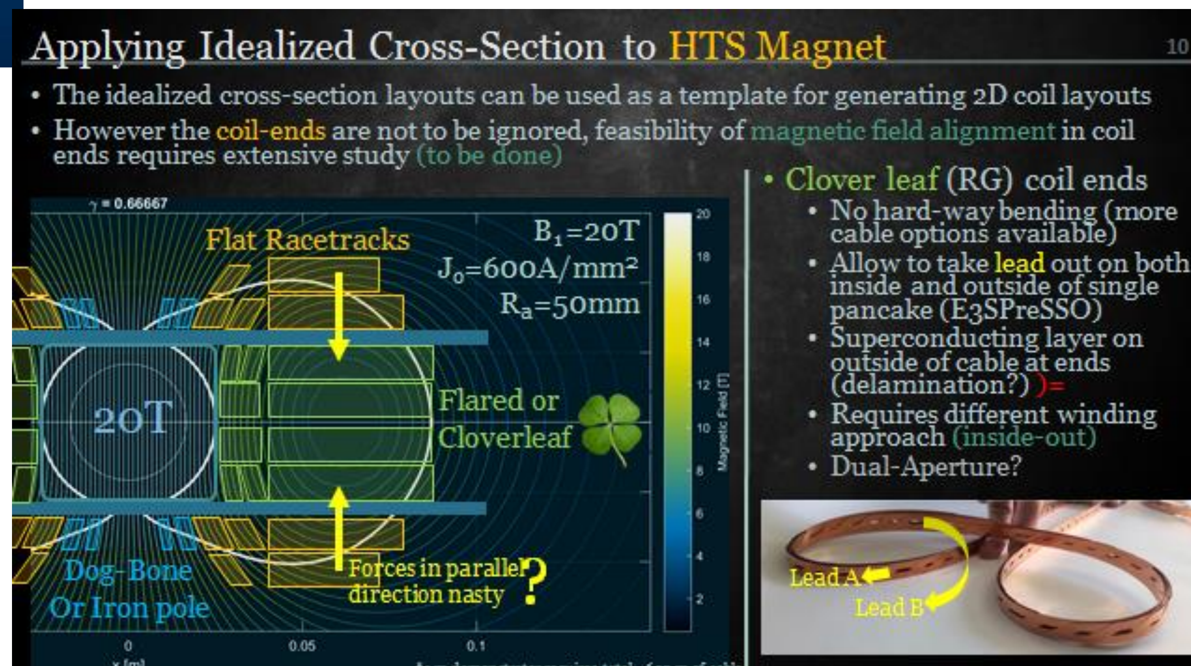
End Design for Block Coils

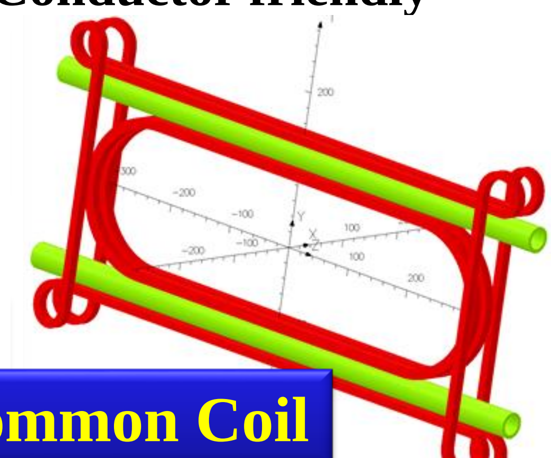
HTS Coils made with e2P/BNL

Phase I SBIR



- Shorter ends
- Conductor friendly



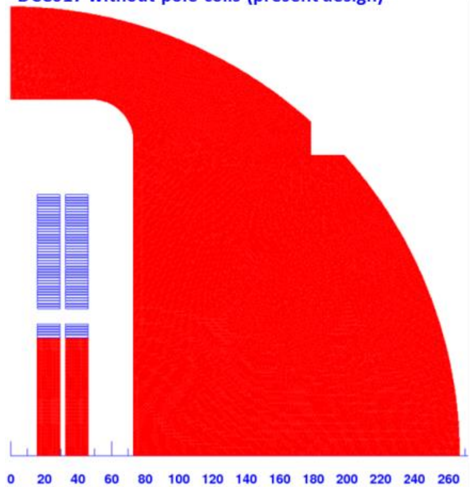


Common Coil

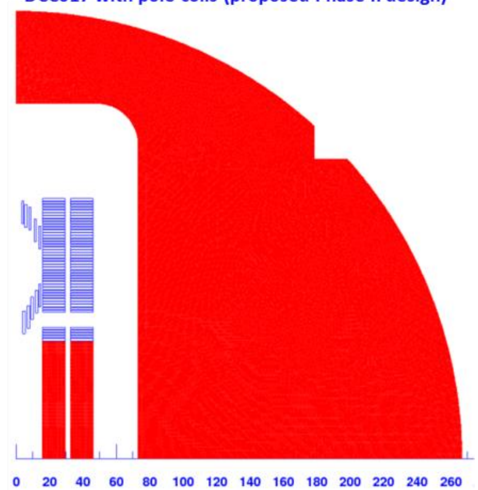
Pole Coil Integration for Demonstrating Accelerator Quality Common Coil Design

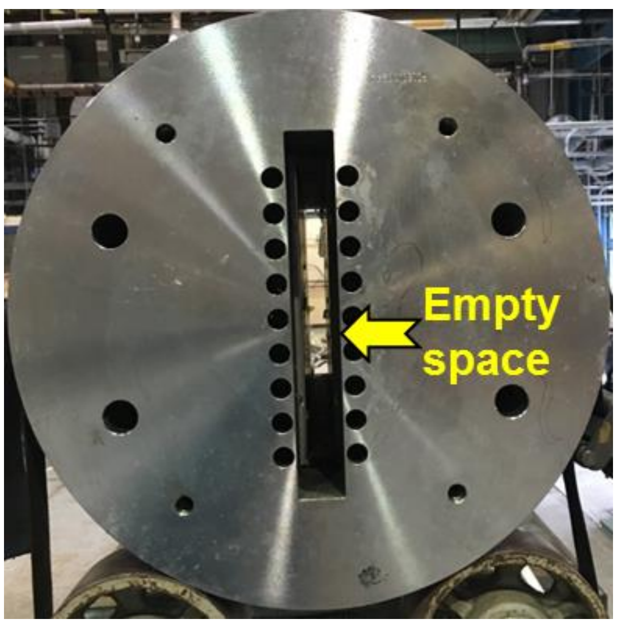
- Several options for pole coils for a proof-of-principle common coil
- Insert coil test facility magnet is an ideal platform for evaluating them
- A design that converts common coil DCC017 to a field quality magnet
- Topic of Phase II SBIR with PBL

DCC017 without pole coils (present design)



DCC017 with pole coils (proposed Phase II design)





DCC017 without pole coils (present design)

MAIN FIELD (T) 0.995409
MAGNET STRENGTH (T/(m^(n-1)) 0.9954

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	0.00000	b 3:	187.58719
b 4:	-0.00000	b 5:	-2.01358	b 6:	0.00000
b 7:	-0.13995	b 8:	-0.00000	b 9:	0.00365
b10:	0.00000	b11:	0.00136	b12:	-0.00000
b13:	-0.00014	b14:	0.00000	b15:	-0.00000
b16:	-0.00000	b17:	0.00000	b18:	0.00000
b19:	-0.00000	b20:	-0.00000	b	

SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	-0.00000	a 2:	-192.09501	a 3:	0.00000
a 4:	6.49804	a 5:	-0.00000	a 6:	0.33413
a 7:	0.00000	a 8:	-0.03499	a 9:	-0.00000
a10:	-0.00209	a11:	0.00000	a12:	0.00053
a13:	-0.00000	a14:	-0.00002	a15:	0.00000
a16:	-0.00000	a17:	-0.00000	a18:	0.00000
a19:	0.00000	a20:	0.00000	a	

DCC017 with pole coils (proposed Phase II design)

MAIN FIELD (T) 1.065489
MAGNET STRENGTH (T/(m^(n-1)) 1.0655

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	-0.00000	b 3:	0.00071
b 4:	-0.00000	b 5:	0.00045	b 6:	-0.00000
b 7:	2.69589	b 8:	-0.00000	b 9:	0.38260
b10:	-0.00000	b11:	-0.06197	b12:	0.00000
b13:	-0.02446	b14:	0.00000	b15:	-0.00522
b16:	0.00000	b17:	0.00080	b18:	0.00000
b19:	0.00096	b20:	0.00000	b	

SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	0.00000	a 2:	0.00049	a 3:	0.00000
a 4:	-0.00002	a 5:	0.00000	a 6:	0.30753
a 7:	-0.00000	a 8:	0.26673	a 9:	-0.00000
a10:	-0.01777	a11:	-0.00000	a12:	-0.01224
a13:	-0.00000	a14:	-0.00849	a15:	-0.00000
a16:	0.00121	a17:	-0.00000	a18:	0.00129
a19:	0.00000	a20:	-0.00004	a	

Summary

- Encouraging Test Results of HTS/LTS Hybrid Dipole
- Many LTS type quenches in HTS coils with no degradation

- Common Coil Magnet Design Update for FCC
  - Several designs meet FCC field quality specifications
  - Smaller magnet size, lower conductor usage, lower stored energy, improved quench protection, etc.

- Commissioning of a rapid-turn-around, low-cost facility
  - Insert coil become integral part of the magnet
  - This could play a major role in performing both systematic studies and trying novel ideas in the present limited budget environment where it is important to show progress regularly