U.S. MAGNET DEVELOPMENT PROGRAM

Alternate End Design (OverPass/UnderPass) for Block Coil Dipoles

MDP General Meeting on July 8, 2020

Ramesh Gupta
for PBL/BNL Collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

Contents

Alternate End Design for Block Coil Dipoles

- Why, What, Pros and Cons?
- Working together with CERN & MDP
- Progress and Plans
- Proof-of-Principle Demo in Phase II
  - New End Design
  - Field Quality Coils in Common Coil
- Challenges

Block Coil Nb_3Sn Design (Bill Sampson, BNL, 1980)

- Simple Cross-section
- Flared Ends

U.S. MAGNET DEVELOPMENT PROGRAM

Block Coil Single Aperture Dipoles (lifted ends to clear the beam tube)

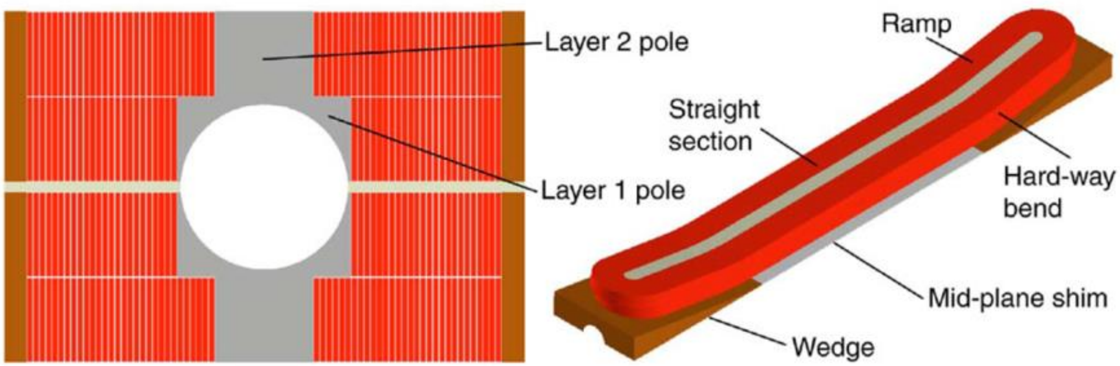
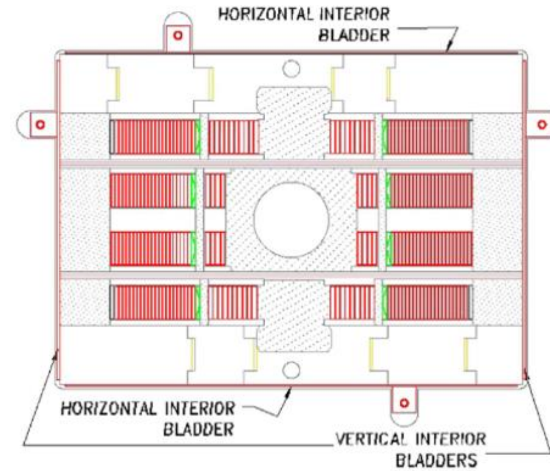


Figure 3: Block coil dipole HD2 designed, built and tested at LBNL.



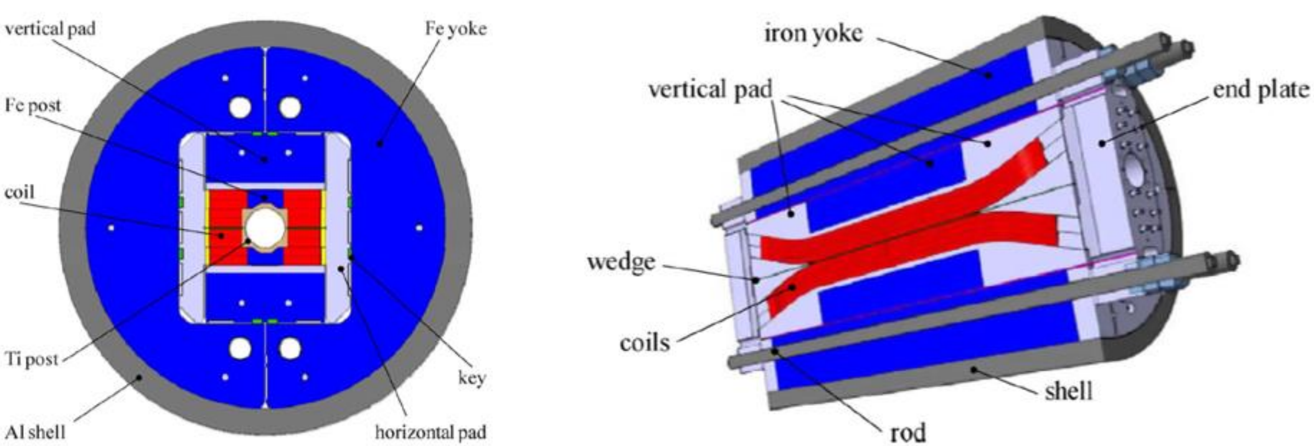
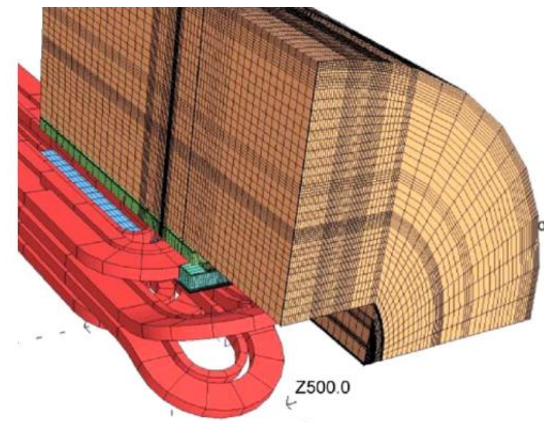
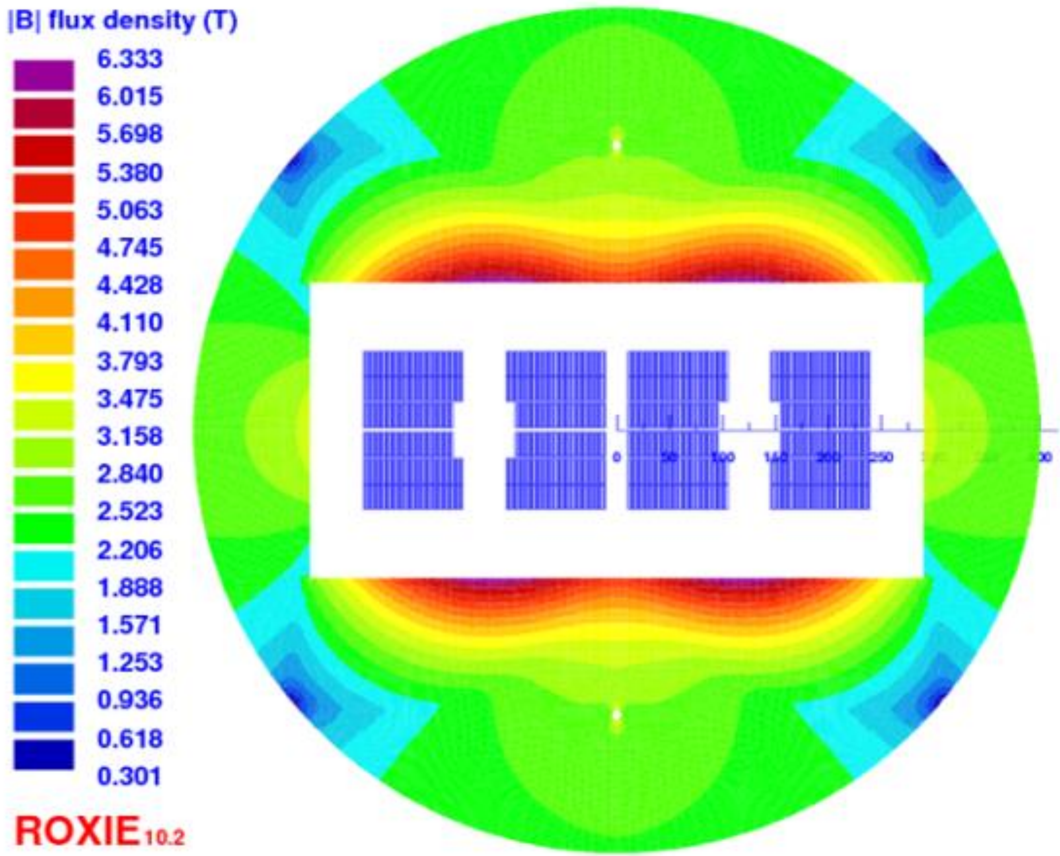


Figure 4: Block coil dipole FRESCA2 built at CERN.



Block coil dipole design at Texas A&M.

Dipoles for Colliders (some blocks must still be lifted in hard direction to clear the bore)



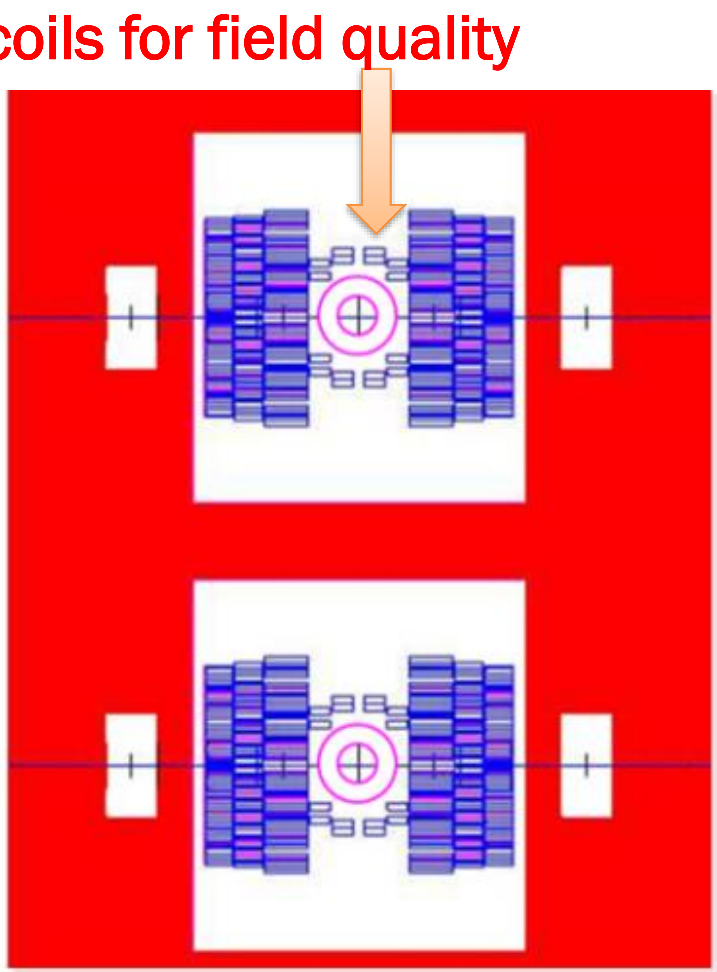


Figure 1: Cross-sections of European 2-in-1 block coil and U.S. 2-in-1 common coil designs.

Good and Bad of Block Coil Designs

GOOD

- Simple cross-section as compared to the cosine theta
- Easier to segment coils for a high field hybrid dipole
- Easier to do stress management
- In common coil design, individual coil layers move as a whole (similar to that as in high-field solenoids made of pancake coils). This allows larger motion without associated large strain on the coils in the end region

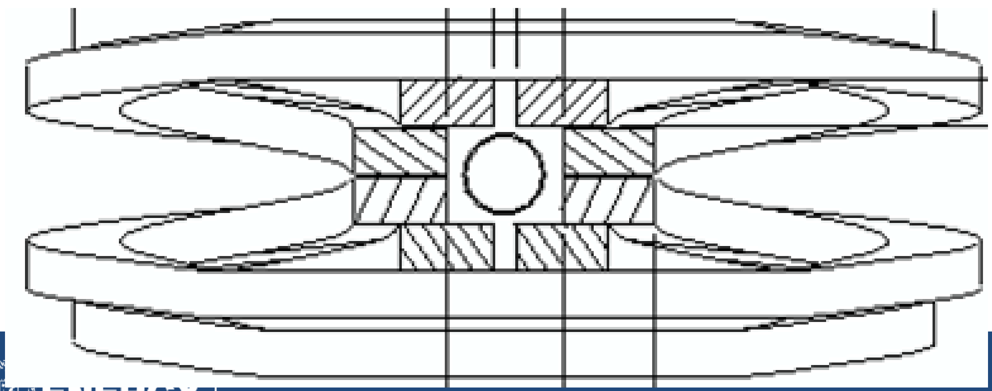
BAD

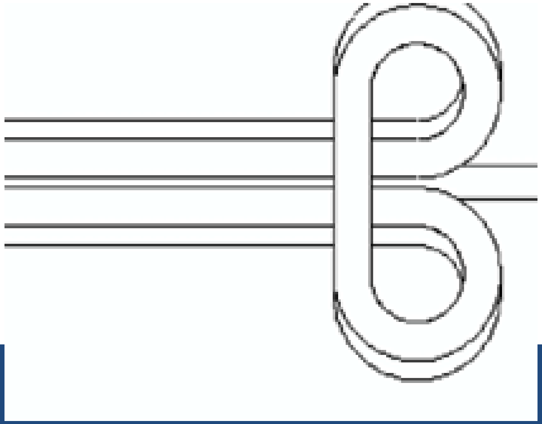
- Conventional ends (at least for certain coil blocks), may be more complex than those of cosine theta dipoles
- Some require lifting in hard direction and some have reverse bends.
- Ends tend to be longer as well.
- The ends + transition region have often limited the magnet performance
- Major challenge in HTS but also in LTS, as well

Overpass/UnderPass End Design

To visualize, imagine driving on a highway when you have to go back

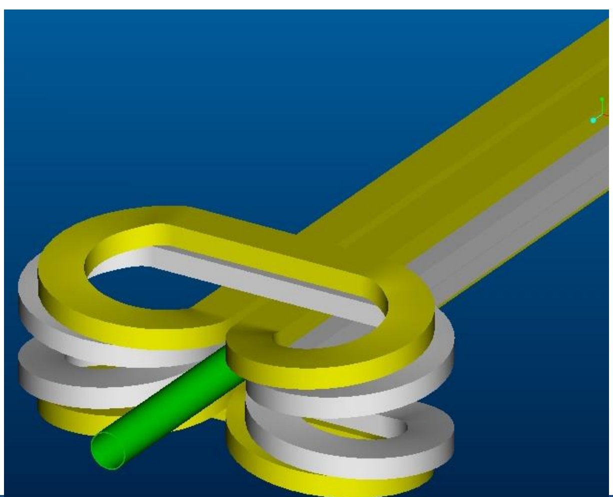
- No reverse or hard way bend
- Conductor friendly design – less strain (primarily tilt)
- Less axial length of ends
- Useful for block coil designs

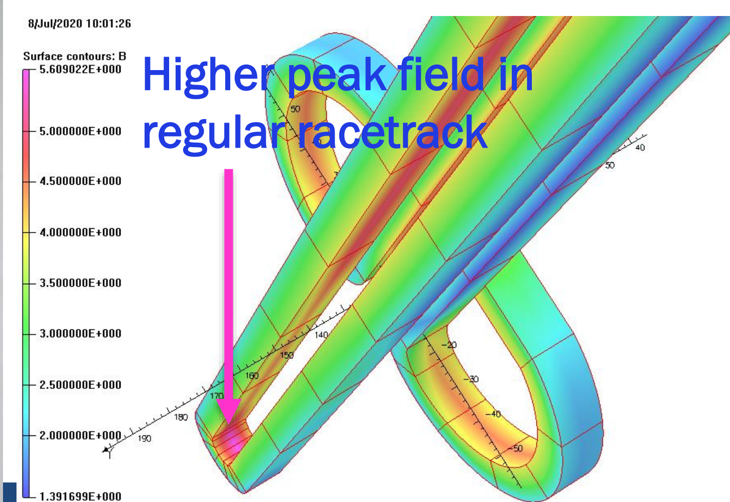




Some Interesting Features of OverPass/UnderPass Coil

- Overpass/Underpass coils can be viewed as a combination of straight section and solenoid. Moving up is a ¾ turn layer-wound solenoid
- This is a conductor friendly geometry with essentially no hardway bend which is present in most block coil ends– instead there is a tilt, as in solenoidal turns
- Bending radius in the ends can be much larger than the coil aperture
- Strain in the conductor in the end is much lower (analysis supports that)
- Peak field from the end can be eliminated (it will be in the body of the magnet)
- These all in principle should improve the performance (yet to be proven)
- However, the coil winding, which must be wound outside-in, is more complicated

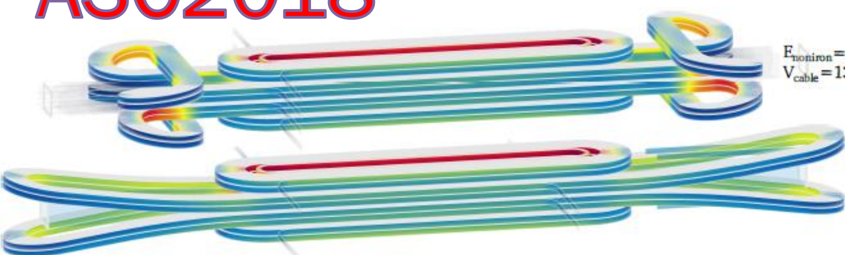




U.S. MAGNET DEVELOPMENT PROGRAM

Overpass/UnderPass End Design (or clover-leaf design @CERN)

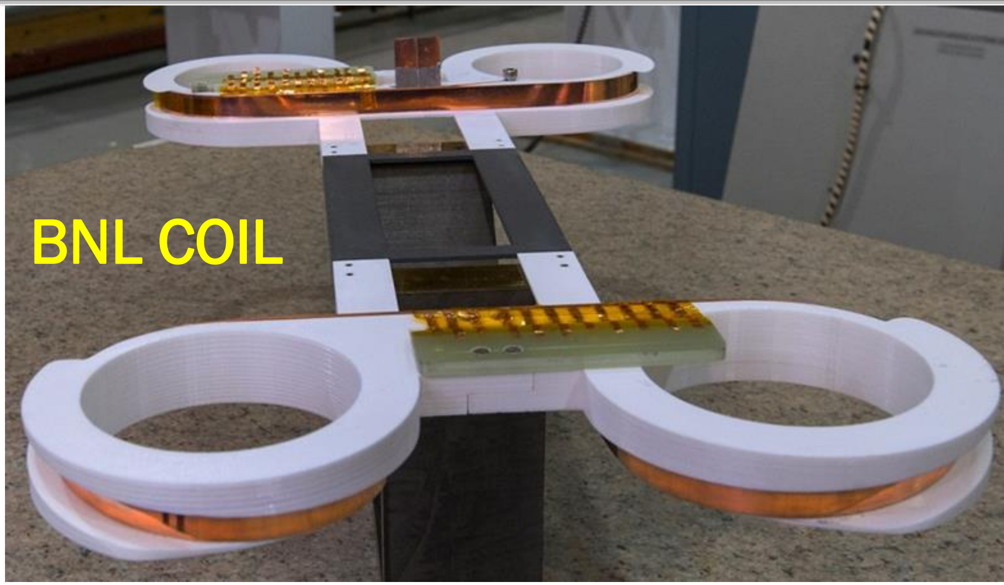
ASC2018

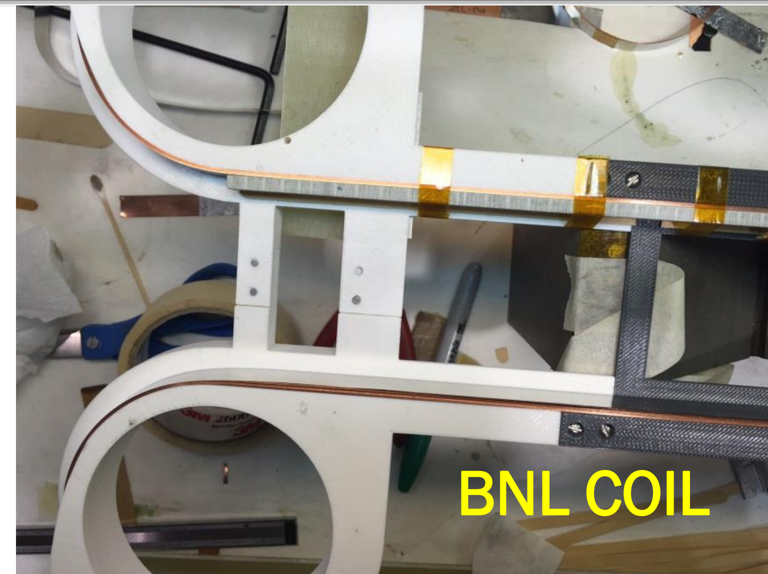


CERN

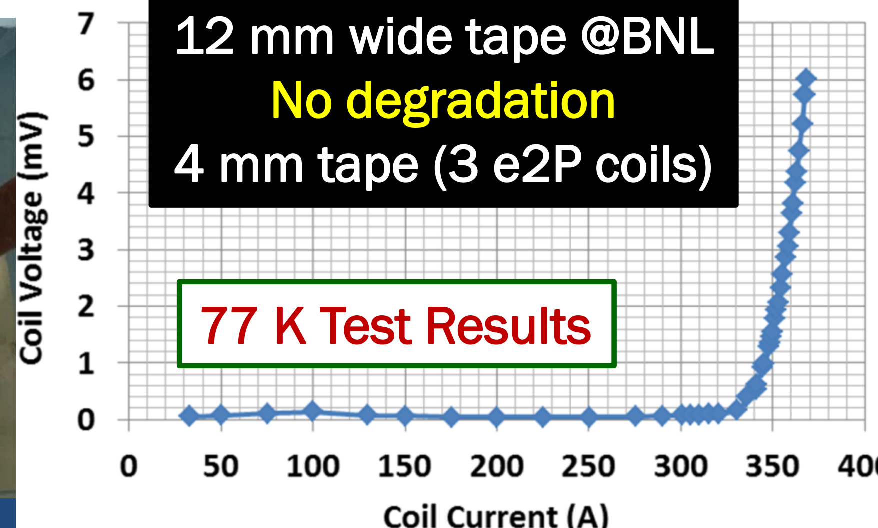
- Presented at ASC 2002
- Design attractive for the HTS and for the block coil dipoles
- SBIR Phase I with e2P in 2015
- *HTS* test coil wound in Phase I and produced good technical results
- CERN picked it up, made large invested and made significant progress - part of the 20 T design
- STTR Phase I with PBL in 2020
- Proof-of-principle *Nb_3Sn* demo in Phase II with common coil dipole

Demonstrations of the HTS Coils made with Overpass/Underpass Design- e2P/BNL SBIR (2015)





Courtesy 3d printer



Overpass/UnderPass End Design for Cable Magnets

Rutherford Cable
(PBL/BNL STTR)

Roebel Cable

<u>Courtesy</u>:
Glyn Kirby, CERN

Overpass/underpass clover-leaf design

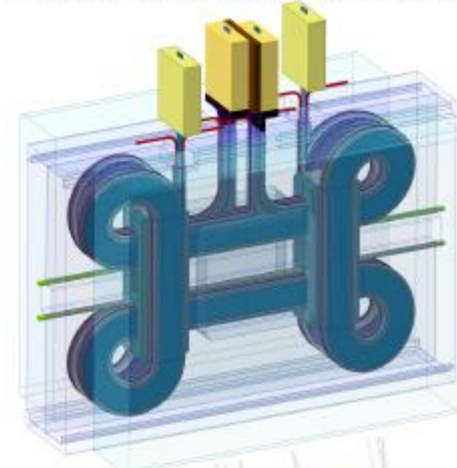
SEATTLE 2018
SEATTLE, 2018 OCTOBER 28 - NOVEMBER 2

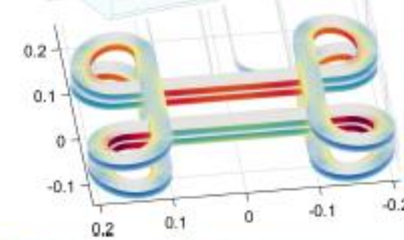
Design and Optimization of a Full HTS Accelerator Dipole for Achieving Magnetic Fields Beyond 20T

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

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.

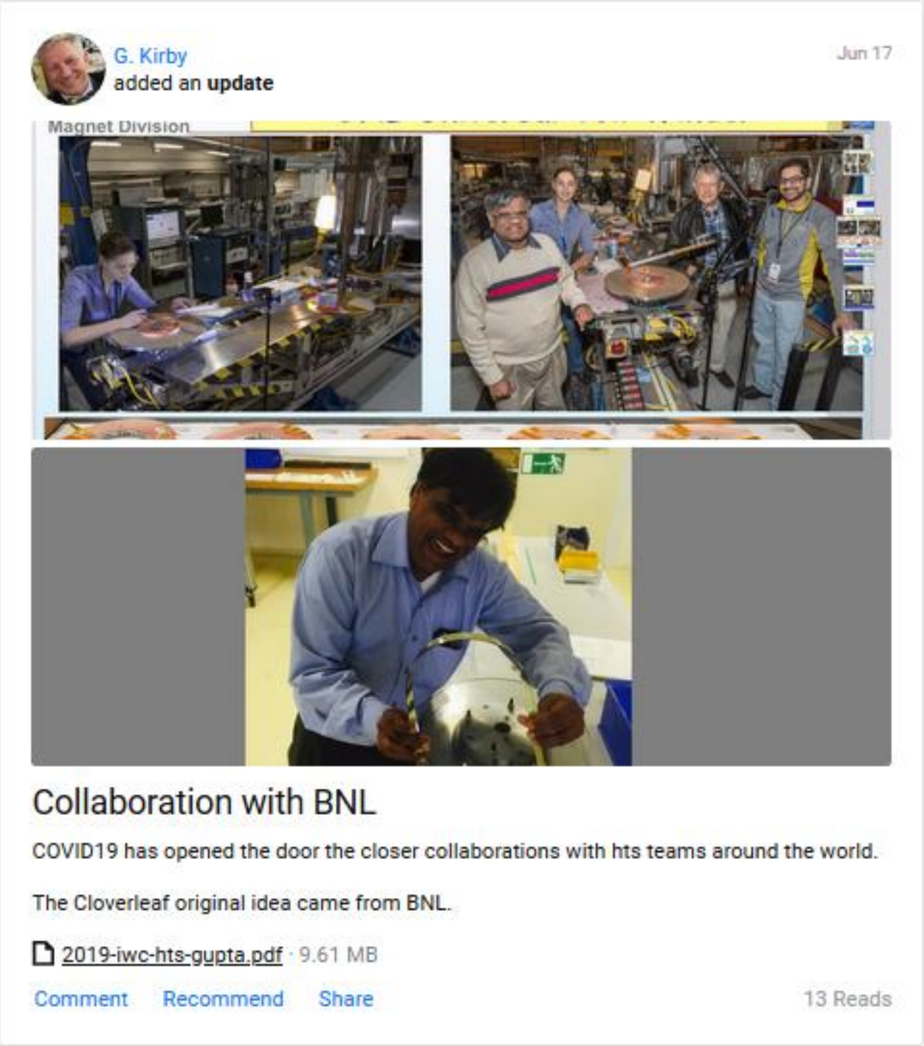




Another significant contribution of the US SBIR Program to the world wide high field magnet R&D

Similar design by wolf about a decade earlier – independent work

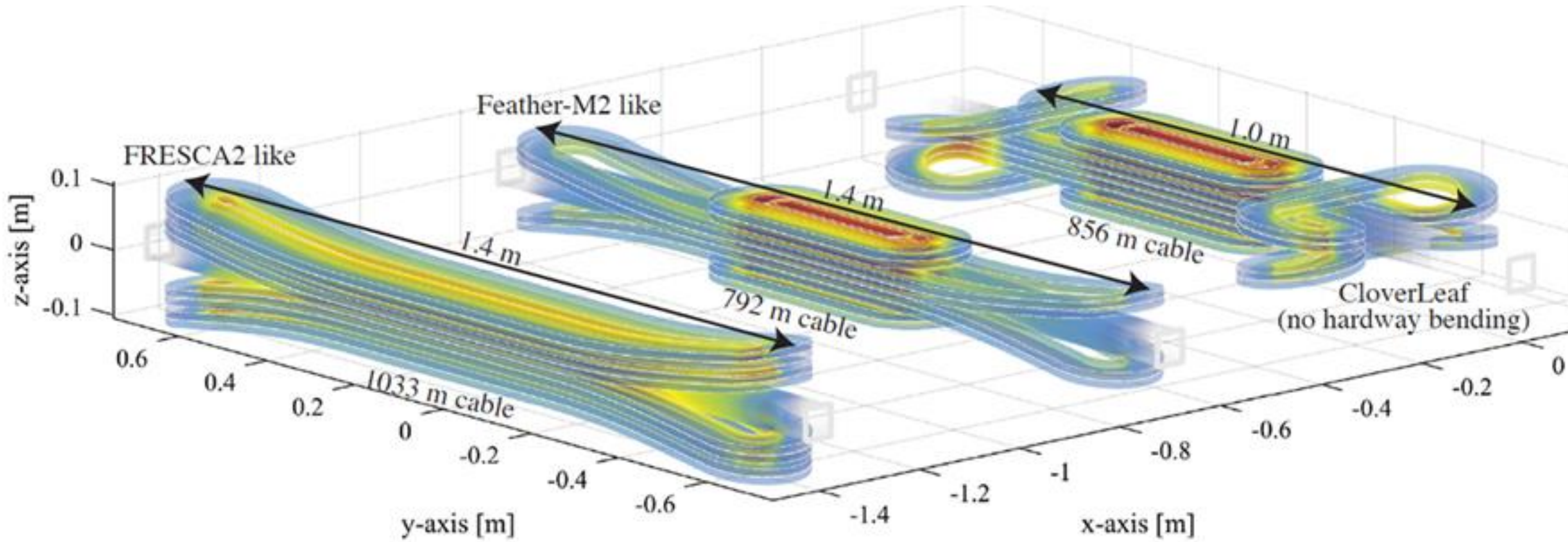
Collaboration with CERN



U.S. MAGNET DEVELOPMENT PROGRAM

Work at CERN (1)

A comparison of the length of the ends in a coil with lifted ends (left) and a coil with overpass/underpass ends (right) to clear the bore tube



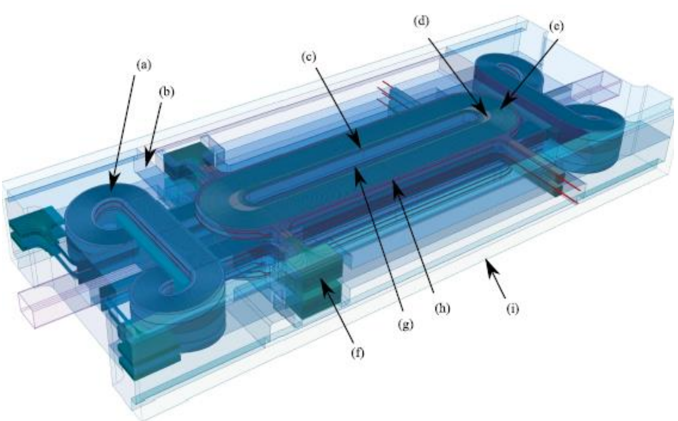
J. van Nugteren, G. Kirby, J. Murtomaki, G. de Rijk, L. Rossi and A. Stenvall, "Towards REBCO 20+ T Dipoles for Accelerators," presented at the European Conference on Applied Superconductivity (EUCAS 2017), September 2017

Work at CERN (2)

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 29, NO. 5, AUGUST 2019 4004608

3-D Mechanical Modeling of 20 T HTS Clover Leaf End Coils—Good Practices and Lessons Learned

Jaakko Samuel Murtomäki, Jeroen van Nugteren, Antti Stenvall, Glyn Kirby, and Lucio Rossi, *Fellow, IEEE*



l design of a 20 T magnet with a clover leaf end coil. (a) Clover leaf end coil (b) Top lid (c) Inner race-track coil (d) Spacer (e) Outer race ea (g) Inner cooling ring (h) External cooling ring (i) Side lid.

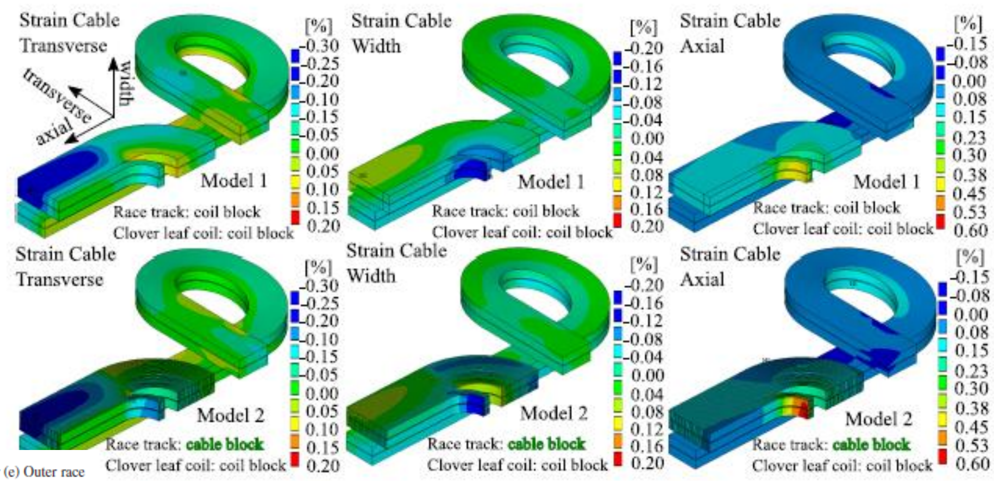
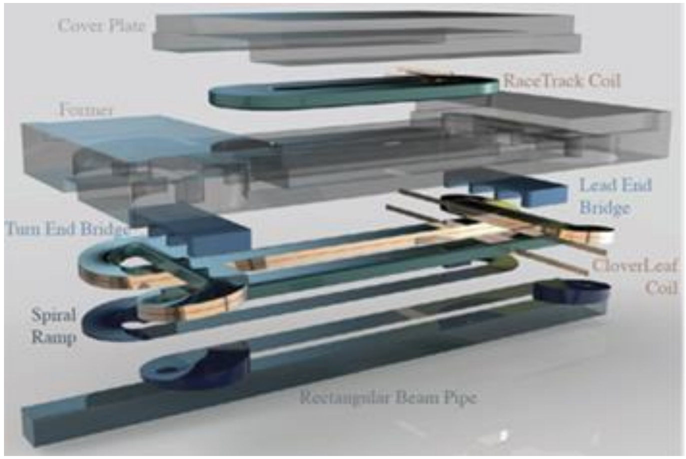
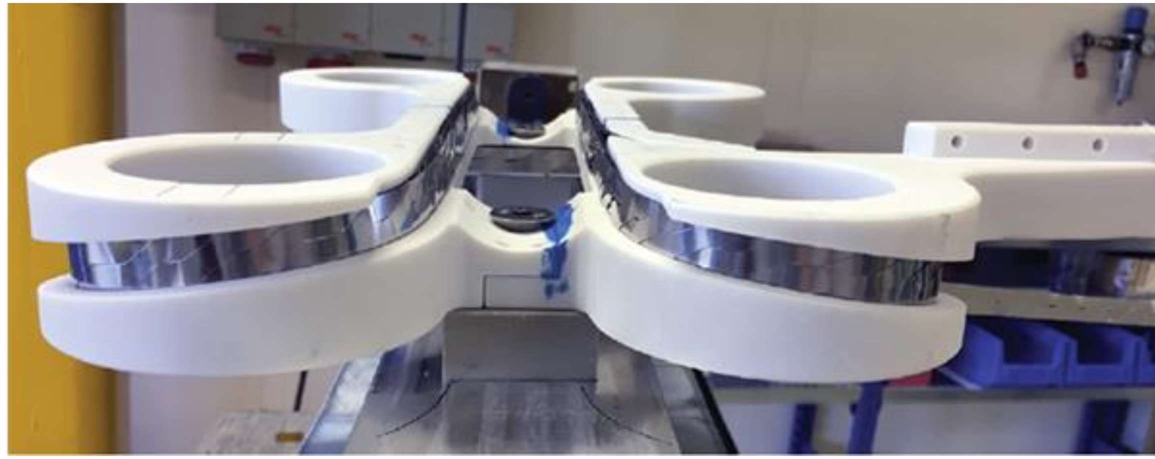


Fig. 6. Strain fields of the coils for the Model 1 and Model 2 at 20 T. The clover leaf end coil is modelled as a coil block in both the two Models, but race track is modelled as a coil block only in the Model 1. The strains are plotted in the inner surfaces of the turns for the cable block model. Coil block strains are plotted at the surface of the solid. The coil shape is plotted in undeformed state. The tapes of the race track coil in cable block model are modelled like in Case 2.

Test Coil Winding at CERN



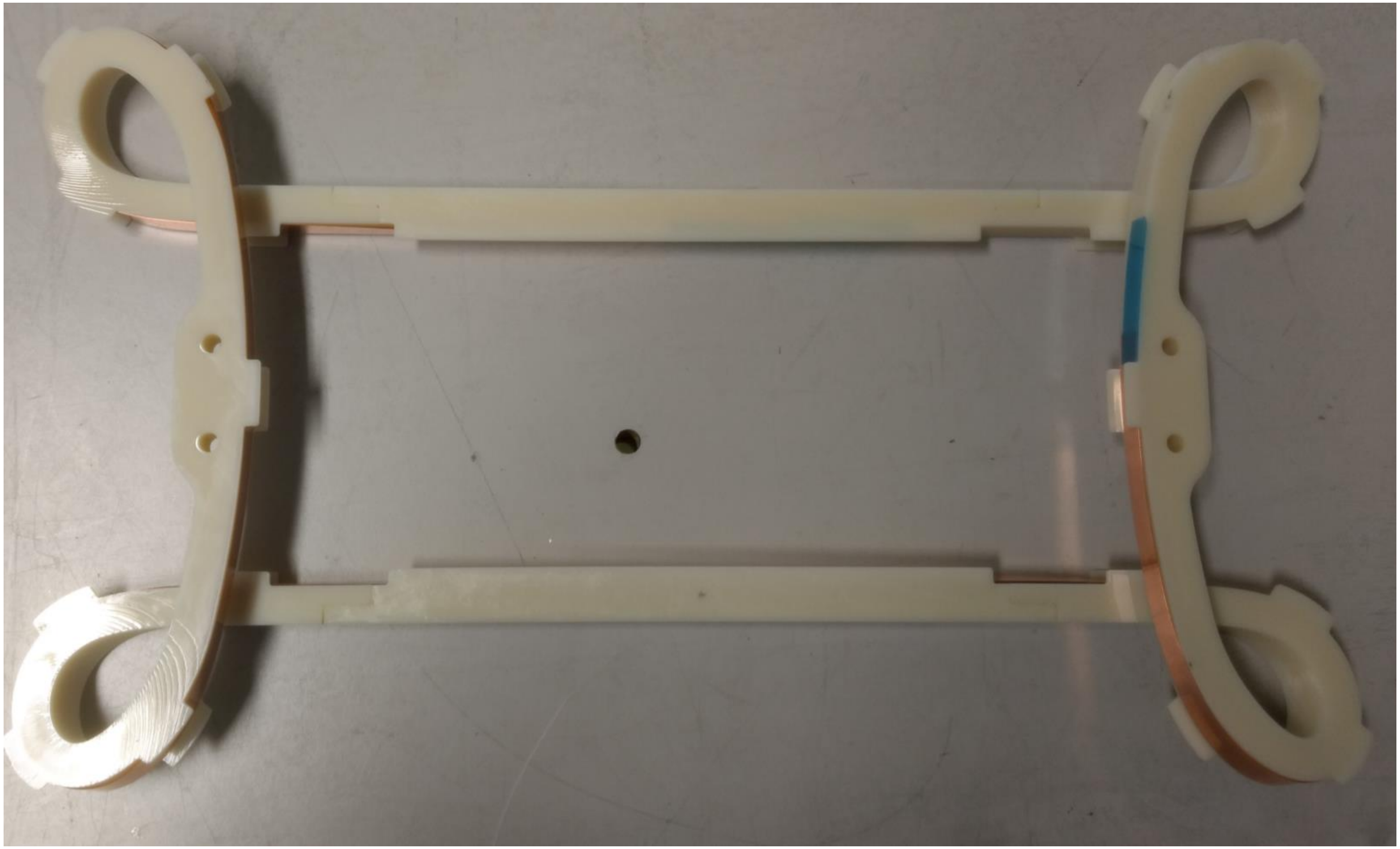


https://www.researchgate.net/project/Dipole-HTS-Magnets-at-CERN

Test Coil Winding at CERN (downloaded today)

https://www.researchgate.net/project/Dipole-HTS-Magnets-at-CERN

Test Coil Winding at CERN (downloaded today)

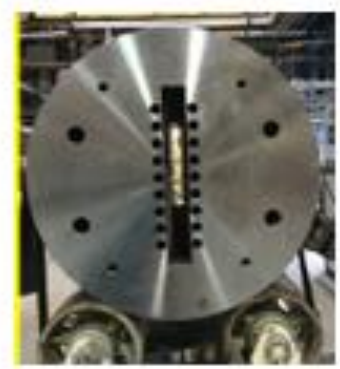


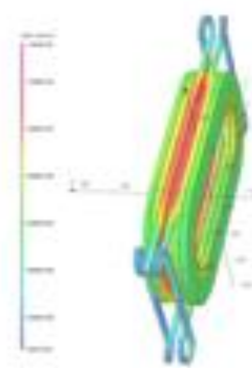
https://www.researchgate.net/project/Dipole-HTS-Magnets-at-CERN

Recently Funded PBL/BNL STTR (work to start soon)

Cover Page

Company Name & Address:	Particle Beam Lasers, Inc. 8800 Melissa Court Waxahachie, TX 75167-7279
Principal Investigator:	Ramesh Gupta Brookhaven National Laboratory Upton, NY 11973
Project Title:	Overpass/Underpass coil design for high field dipoles
Topic No: 33	Superconductor Technologies for Particle Accelerators
Subtopic: (b)	Superconducting Magnet Technology





PBL Team

Current staff of Particle Beam Lasers, Inc. (PBL)

- James Kolonko (President)
- Delbert Larson (Vice President)
- Steve Kahn (Senior Scientist, BNL retiree)
- Ron Scanlan (Senior Scientist, LBNL retiree)
- Bob Weggel (Senior Engineer, MIT retiree)
- Erich Willen (Senior Scientist, BNL retiree)

Previous participants

- Bob Palmer (BNL)
- David Cline (UCLA)
- Harold Kirk (BNL)
- Al Garren (LBL)
- Shailendra Chouhan (FRIB)

PBL/BNL team has worked on several SBIRs/STTRs and has made important contributions in areas such as high field HTS solenoid, common coil dipole, hybrid dipole, open midplane dipole, etc.

Phase I TASKLIST

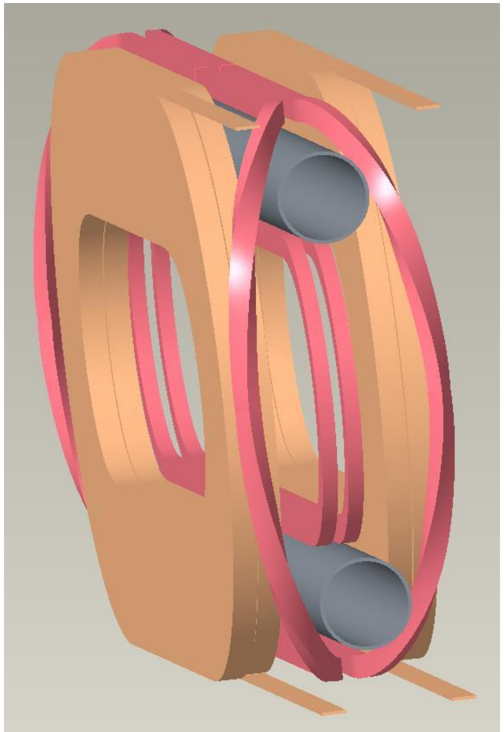
- **Perform 2-d and 3-d magnetic design for the proof-of-principle Nb_3Sn dipole**
- **Perform 2-d and 3-d mechanical design for the proof-of-principle Nb_3Sn dipole**
- **Perform coil winding test**
- **Perform mockup assembly test**
- **Selection of conductor and cable for the proof-of-principle magnet**
- **Plan for proof-of-principle tests in Phase II**
- **Develop a conceptual design for the assembly and test of the overpass/underpass coils in the proof-of-principle dipole**
- **Develop a conceptual design of a 16 T, 50 mm aperture dipole for a future proton collider and a background field test facility magnet for HEP and FES**
- **Phase I Final Report and identify the key components for a Phase II proposal**

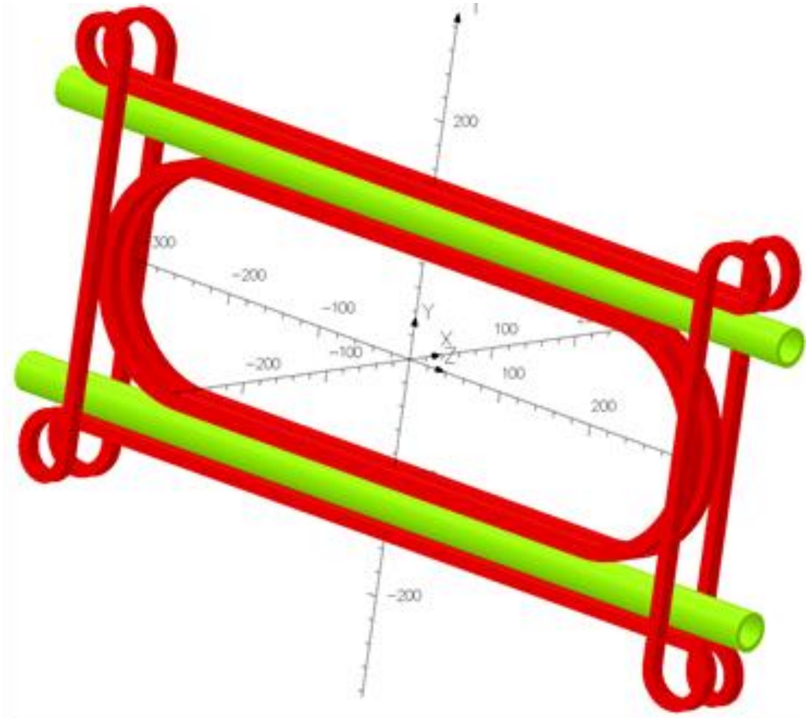
(PBL sent a letter to welcome participation and collaboration with all USMDP partners)

Field Quality Pole Coils for Common Coil Design

- Pole coils are needed to achieve good field quality efficiently. Some of them can't be simple planar racetrack
- Several common coil magnets have been built but none with the pole coils
- Test of the pole coil integration remains a major remaining task of the design
- Phase II will have a dual goal – demonstrate OP/UP and demonstrate pole coils

Pole coils with hardway bend





With underpass/overpass end

Proof-of-Principle Field Quality in DCC017

U.S. MAGNET DEVELOPMENT PROGRAM

BNL common coil dipole DCC017 was not built with field quality consideration. However, surprising the addition of pole coils makes all but one harmonics $<10^{-4}$

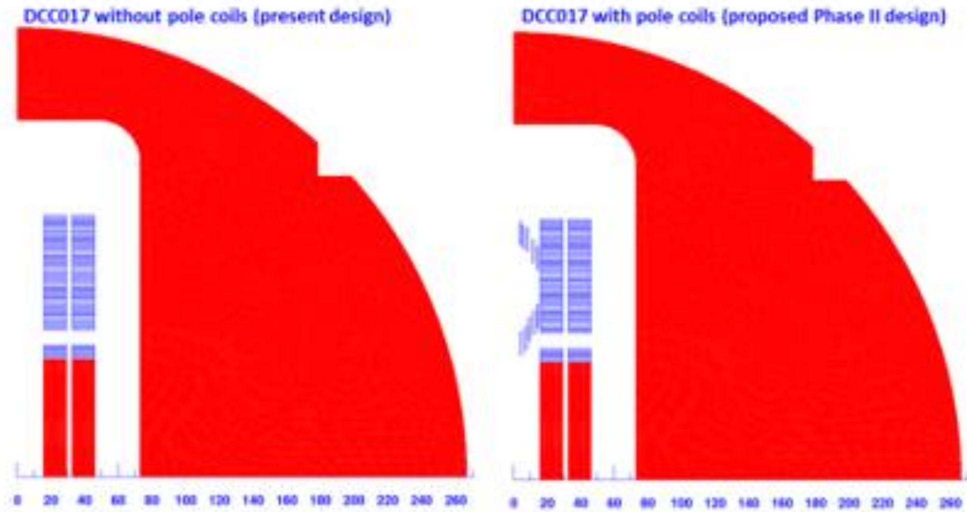


Figure 6: DCC017 as-built, without pole coils (left), and with pole coils to improve field quality (right).

New Pole Coils

Table II. Left-calculated multipoles in as-built DCC017, showing a large values for b_3 (180 units) and a_2 (-192 units). Right-calculated multipoles with pole coils added, showing all values below 3 units.

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	

DCC017 with pole coils (proposed Phase II design)

MAIN FIELD (T) 1.065409
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:	2.69509	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:	0.00000	b18:	0.00000
b19:	0.00096	b20:	0.00000	b	

Goal of Phase II, if funded (1)

Insert coil test in BNL DCC017 for a “Proof-of-Principle” demonstration of (a) overpass underpass end design (b) Field quality common coil design

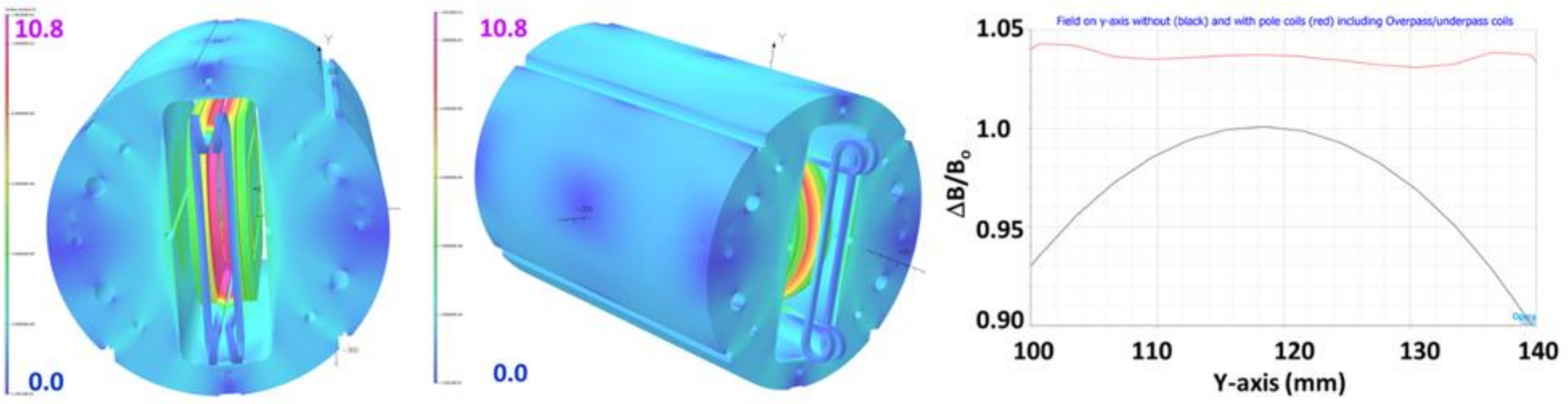


Figure 10: Initial magnetic model (left and middle) with magnetic field superimposed over the coils and the yoke of the BNL common coil dipole DCC017 with field shaping coil which include overpass/underpass coils (proposed to be built in Phase II). Improvement in field uniformity is clear from the picture on the right where the relative field uniformity is plotted with (above) and without field shaping coils.

Goal of Phase II, if funded (2)

Insert coil test in BNL DCC017 for a "Proof-of-Principle" demonstration of (a) overpass underpass end design (b) Field quality common coil design

Figure 12: BNL common coil dipole with a large open space (left), with insert coil for another PBL/BNL STTR (middle), and the magnetic model of the proof-of-principle test (right). Similar to the design of the pole blocks of a high field common coil dipole, the overpass/underpass ends of the proof-of-principle design will be in a relatively lower field region, pointing to another advantage of the design.

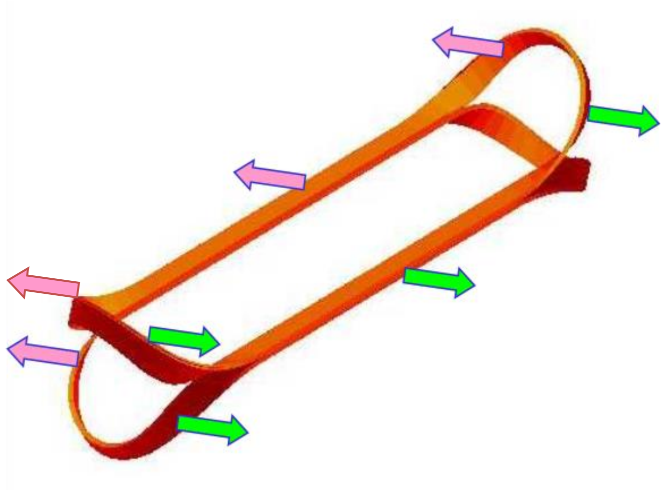
Lorentz Forces in High Field Magnets

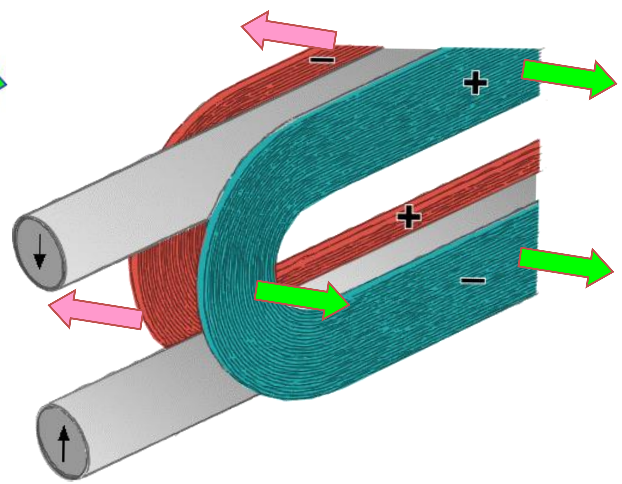
A key technical and cost issue in high field magnets is structure

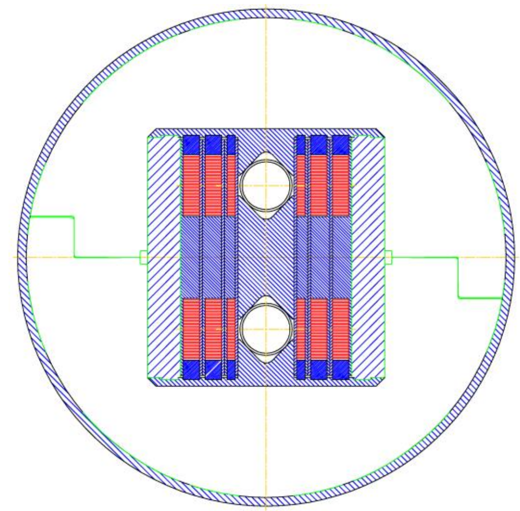
In conventional block coil design (and also in cosine theta designs), large forces put excessive stress/strain on the conductor in the end region

In a common coil design, coils move as a whole - much smaller stress/strain on the conductor in the end region

One can have structure in between the pancakes to manage forces so that stresses don't accumulate (still want coil layers to move as whole)



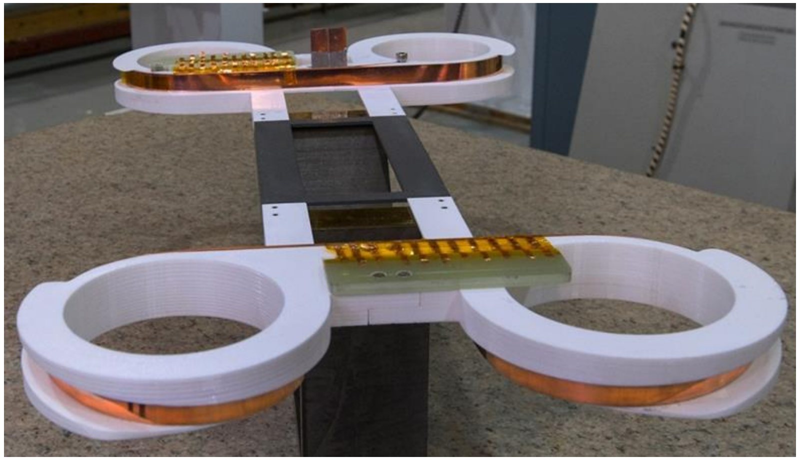


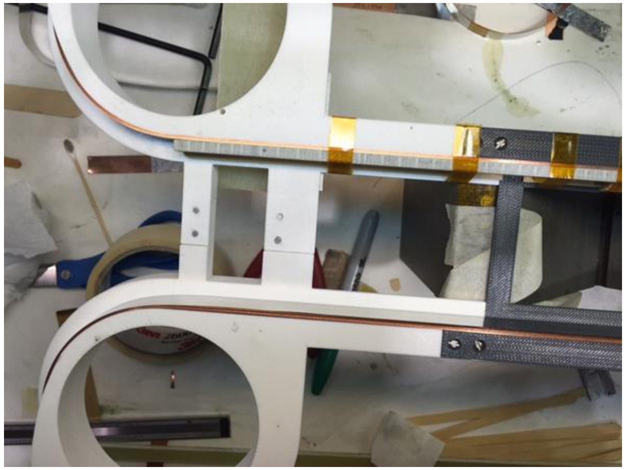


BNL common coil dipole tolerated ~200 microns motion (typical ~25-50 μm)

Challenges (incomplete list)

- New Design – any new design, until demonstrated, has potential issues not fully appreciated initially
- Coil winding – coils are wound outside in, with no clear path, regular winding techniques don't work
- Mechanical design and analysis of the new end design





U.S. MAGNET DEVELOPMENT PROGRAM

Summary

- A new conductor friendly end design for block coils dipoles to reduce strain and length of the end region
- Relevant to Nb_3Sn and HTS and therefore relevant to high field 20 T design study
- May also be interesting for FES block coil design option
- Magnet ends and body to end transition region has often limited the performance of block coil dipoles. This new design has a potential of improving that performance.
- New designs typically comes with new challenges. All are invited to collaborate/participate in this PBL/BNL STTR.