Brookhaven National Laboratory
Superconducting Magnet Division

Proof-of-Principle Design of a High Field Overpass/Underpass Nb_3Sn Dipole

R. Gupta, M. Anerella , P. Kovach, J. Schmalzle (BNL); S. Kahn, J. Kolonko, D. Larson, R. Scanlan, R. Weggel, E. Willen and A. Zeller (PBL)

Abstract

- This poster presents the basic design and analysis of a "Proof-of-Principle" overpass/underpass (also called cloverleaf) high field block coil dipole. Block coil configurations are appealing for their simplicity in the body of a magnet, but less so in the ends of the blocks that must be lifted to clear the beam tube. This lifting —which typically is in the hard direction of the broad cable — must be very gradual, to avoid conductor degradation (especially Nb_3Sn or HTS) from excessive strain, making for ends that are undesirably long.
- The overpass/underpass (or cloverleaf) end geometry is designed to overcome the above-mentioned shortcomings. The conductor clears the bore tube at the ends by replacing each hard-way bends by a gentle twist in a 270° turn. The design produces ends that are shorter than those with lifted-end designs. Moreover, the strain on the cable in the ends also is low, although the geometry of the ends becomes more complex.
- This work was carried out under a Phase I Small Business Technology Transfer (STTR) program between Particle Beam Lasers, Inc. (PBL) and Brookhaven National Laboratory (BNL). A plan for the proof-of-principle demonstration was developed for building and testing the pole coils in a 2-in-1 common coil dipole reaching ~11 T. The dipole DCC017 has a large, easily accessible open space in which the new coils can be inserted and tested as an integral part of the magnet without any need to disassemble and reassemble the original magnet.

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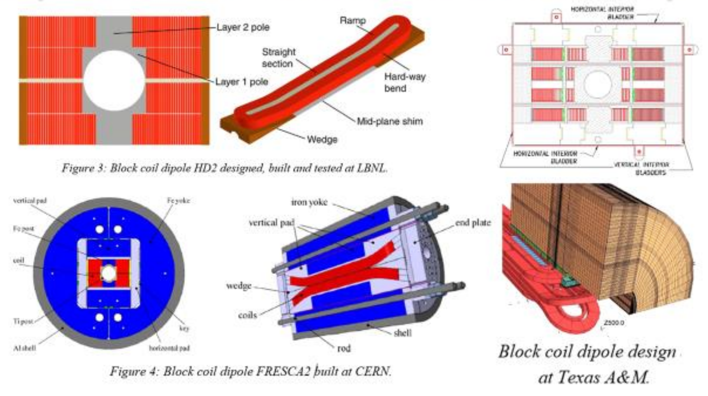
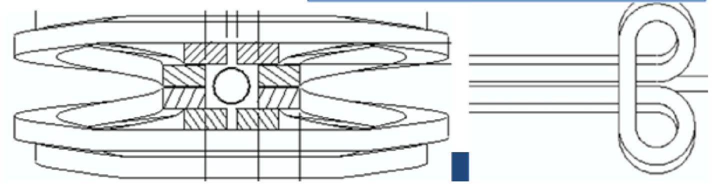
Block Coil Single Aperture Dipoles (lifted ends to clear the beam tube)



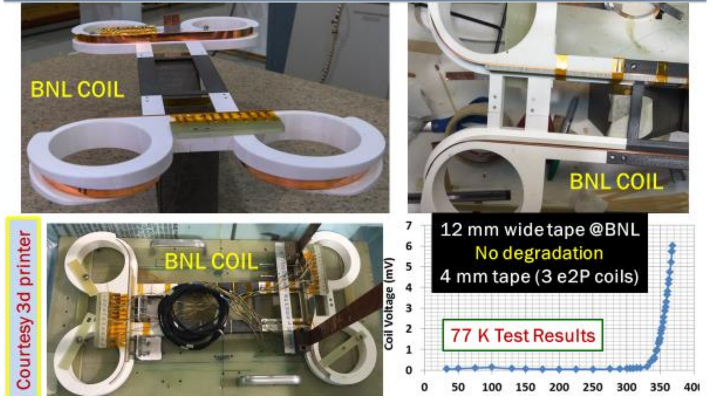
Overpass/UnderPass Approach to End Design

To visualize the geometry, imagine turning back via ramp on a highway

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

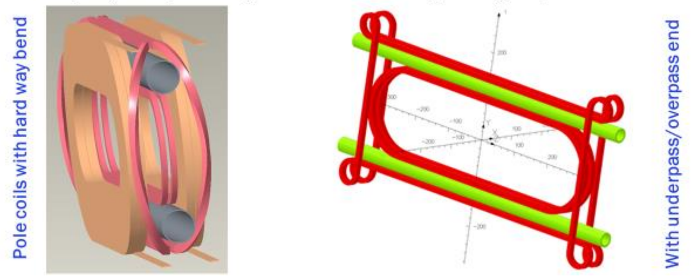


Demonstrations of the HTS Coils made with Overpass/Underpass Design- e2P/BNL SBIR (2015)



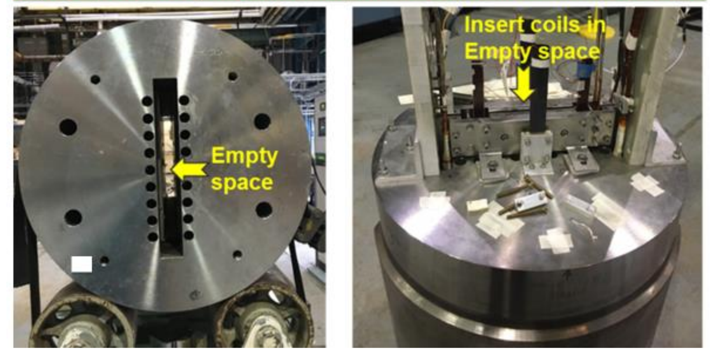
Use of Overpass/Underpass Approach in Common Coil Design for Pole Coils

- Pole coils are needed to achieve good field quality efficiently. Some of them can't be planar
- Several common coil magnets have been built but none with the pole coils
- Test of the pole coil integration remains a major task of the design
- Overpass/Underpass design offers an attractive geometry for pole coils

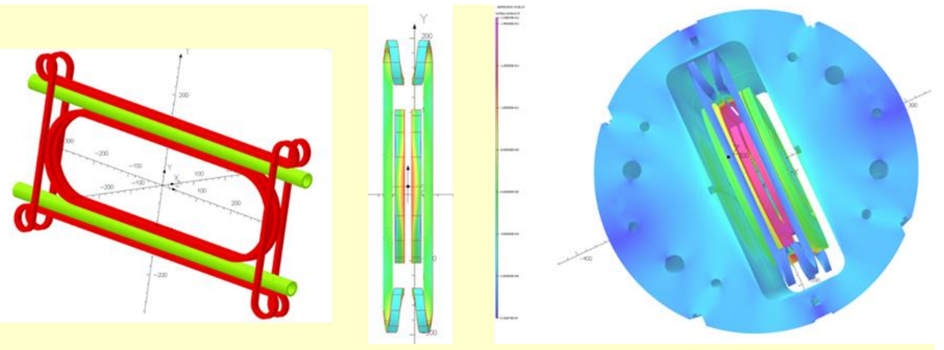


A Candidate Demo in BNL Common Coil Dipole

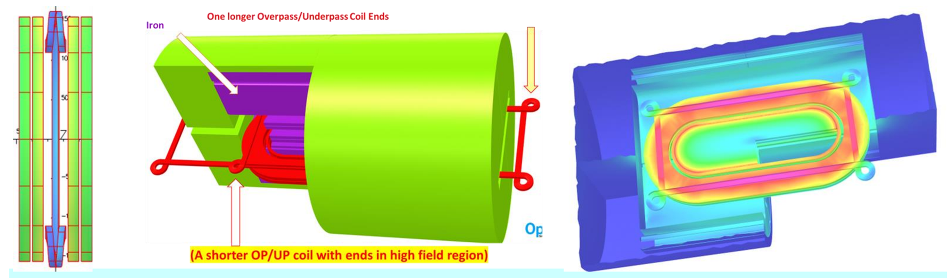
Proposed test with insert coil in magnet DCC017 for demonstration of (a) overpass underpass end design (b) Field quality common coil design



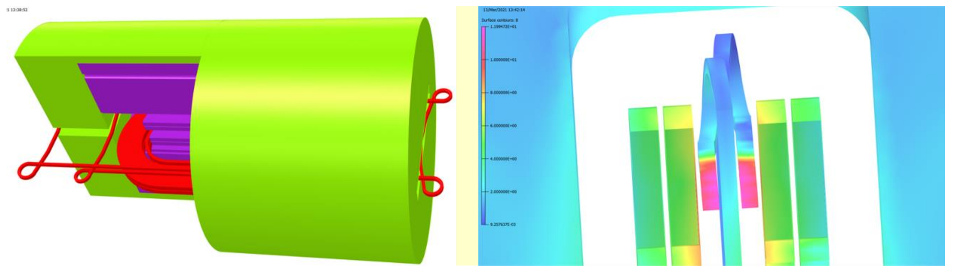
Magnetic Design & Analysis



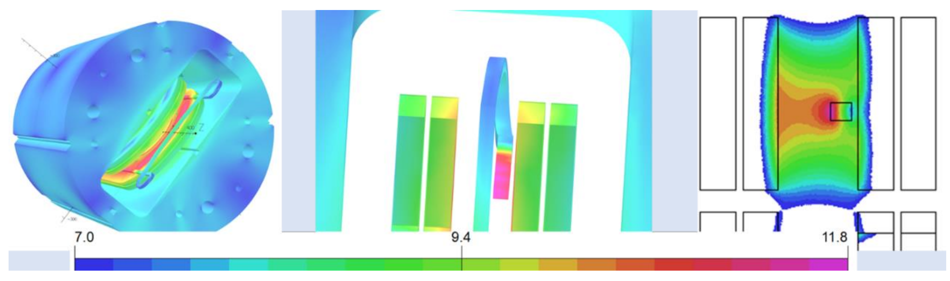
Insert pole coils with overpass/underpass (OP/UP) coils clearing the bore. Model on the left is a side view; in the middle is a view from the magnet axis. Model on the right shows pole coils inside a common coil dipole, along with the main coils.



Left: A view from the end of a proof-of-principle coil assembly, Center: two insert overpass/underpass coils of different lengths are sandwiched between the main racetrack coils. Right: field superimposed on the shorter overpass/underpass insert coils and iron.

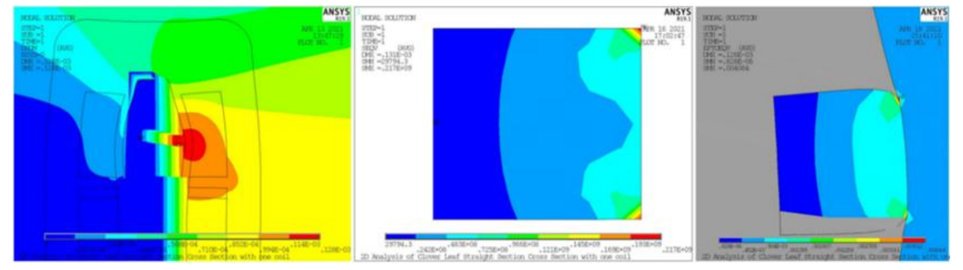


OPERA3d model (left) with three quadrants of the yoke in purple, stainless-steel structure in green and two overpass/underpass coils (having different lengths) in red. Field contours in a cutaway view at 10 kA on the straight section of the overpass/underpass coil block at the center of the magnet (symmetric quadrant only).

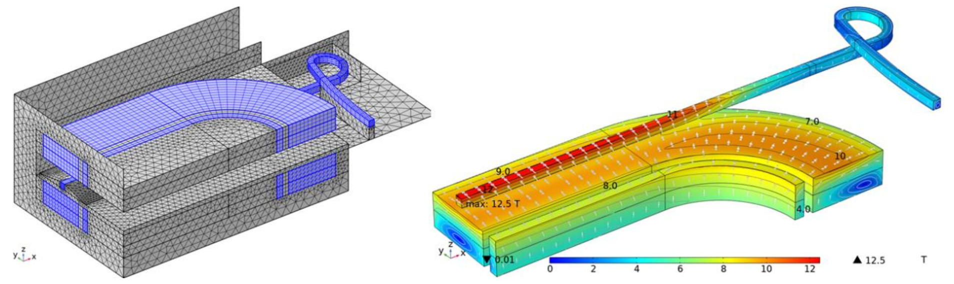


Proof-of-Principle Demo with a single insert pole coil with overpass/underpass coils clearing the bore. Model on the left is a side view; in the middle is a view from the magnet axis. Model on the right shows pole coil inside a rebuilt version considered for magnet DCC017.

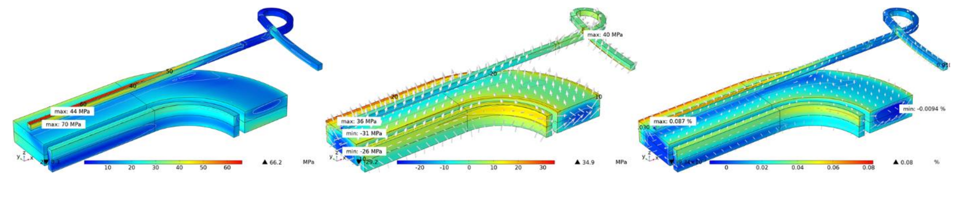
Mechanical Design & Analysis



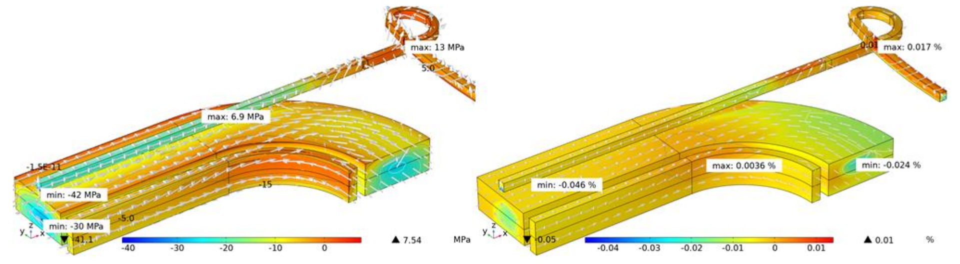
2-d Analysis with ANSYS. Left: Contour plot of the displacements, Middle: Contour plot of von Mises stress over the op/up coil, and Right: Contour plot of the von Mises strain.



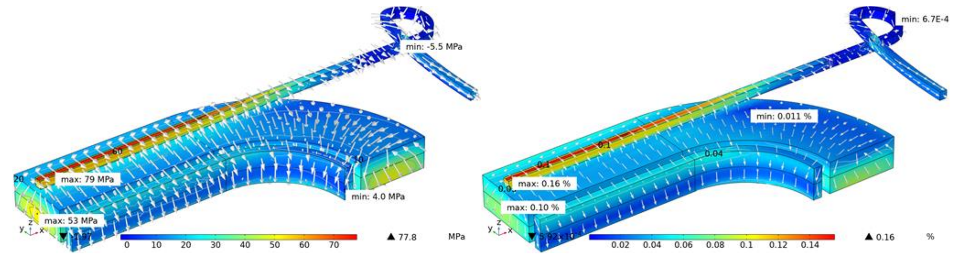
3-d Analysis with COMSOL. Insert pole coils with overpass/underpass coils clearing the bore. Model on the left is a side view and on the right is a view from the magnet axis.



3-d Analysis with COMSOL. Left: von Mises stress contours. Middle: 1st principal stress contours. Right: 1st principal strain contours.

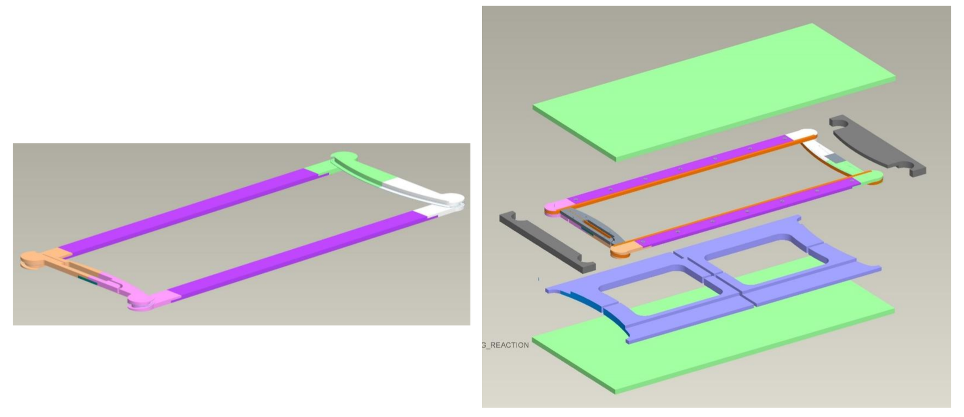


3-d Analysis with COMSOL. . Left: 2nd principal stress contours. Right: 2nd principal strain contours.

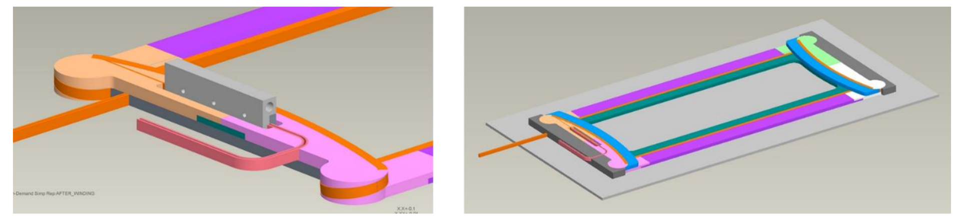


3-d Analysis with COMSOL. Left: Negative 3rd principal stress contours; Right: Negative 3rd principal strain contours.

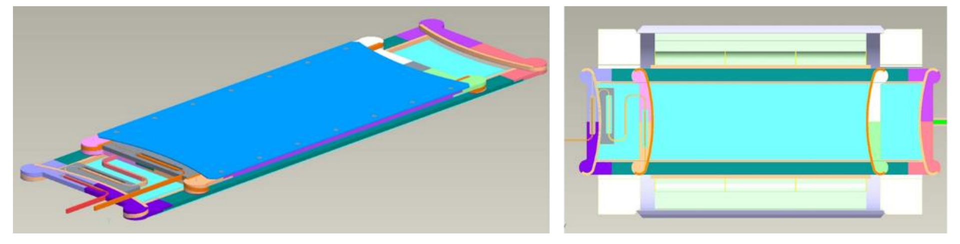
Preliminary Engineering Design



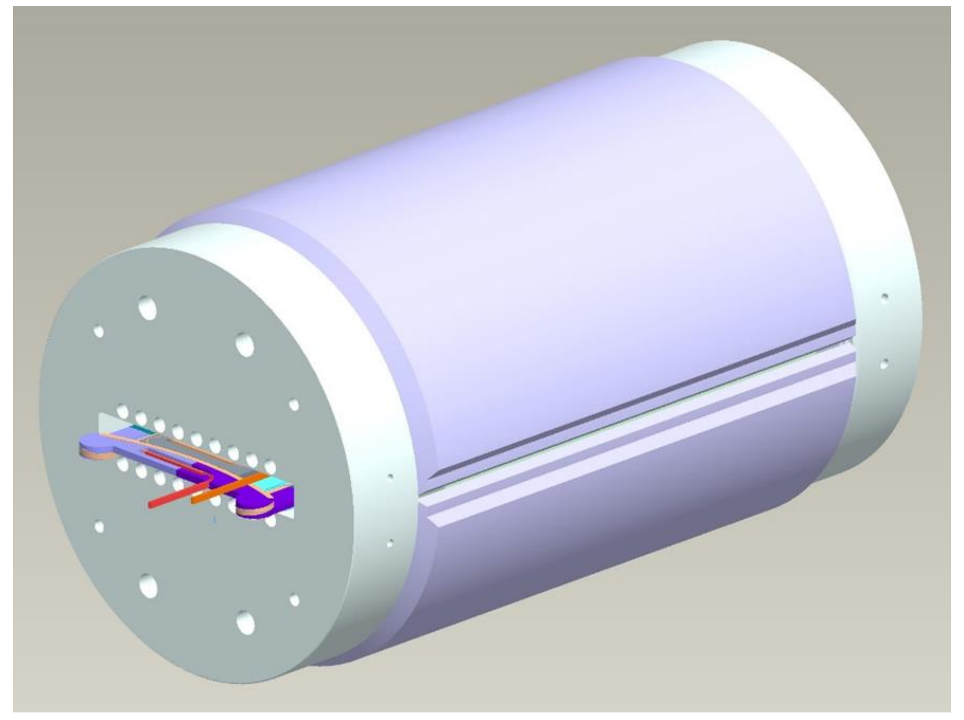
Coil winding form (left) and exploded view of tooling showing gaps in (blue) reaction frames (right).



Nb_3Sn coil lead to NbTi exiting lead splice within the impregnated coil structure (left) and Nb_3Sn coil in the impregnation fixture (right).

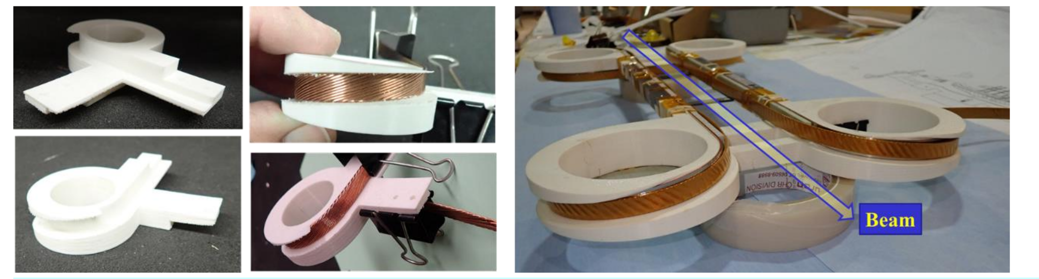


Two OP/UP coils with staggered ends nested together (left); section view of two OP/UP coils in DCC017 (right).

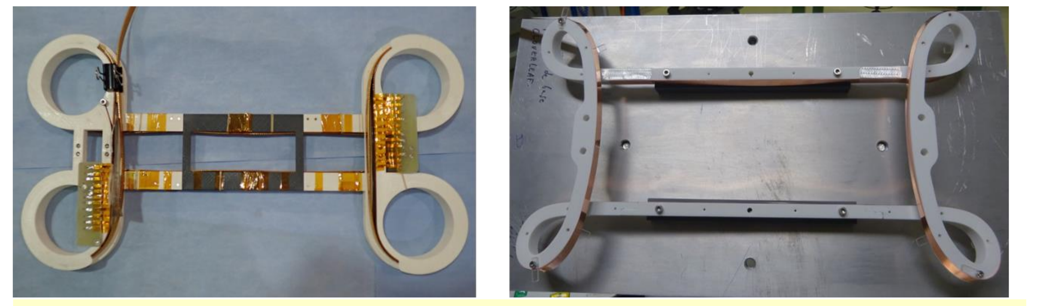


Rendering of the two OP/UP coils assembled in the magnet DCC017. The design allows installation of either one or two insert coils in the magnet.

Practice Coil Winding & Fitting



Left: 3-d printed parts for the overpass/underpass section; Middle: initial study of how cable is going to lie in the overpass/underpass section; and Right: first turn of the lower dipole coil based on the overpass/underpass geometry.



Left: Rutherford cable coil wound by the PBL/BNL team in the early part of the Phase I proposal, with a straight connection between the two overpass/underpass (cloverleaf) sections in the end. Right: HTS tape coil wound by the CERN team, with a convex connection between the two cloverleaves (overpass/underpass) sections in the end.

Phase I winding of the overpass/underpass coil with a Nb_3Sn Rutherford cable similar to that which will be used in winding the of the proposed coil. Two pictures on the left and right side are of the same coil turned over to show the other side.

BNL common coil dipole DCC017 with a large open space (left), with an insert coil for a previous PBL/BNL STTR (middle), and a view of the mockup insertion test of the overpass/underpass coil wound under this SBIR (right).

Summary

Several advantages of the Overpass/Underpass design have been outlined. A magnetic, mechanical and preliminary engineering design of a "proof-of-principle" for a demonstration of this design has been developed. This can be tested at a relatively low cost (< 2 million dollars) at a field of about 11 T.