8. Project Narrative

Cover Page

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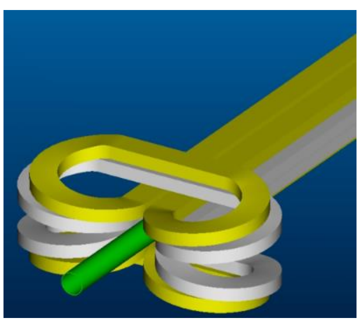
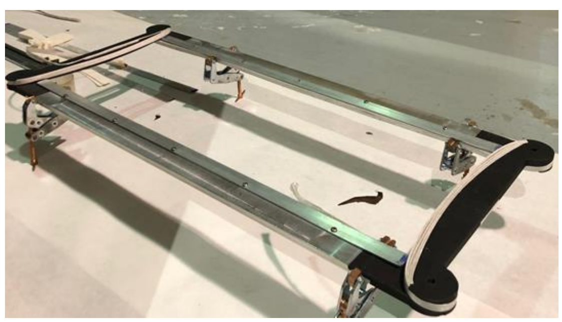
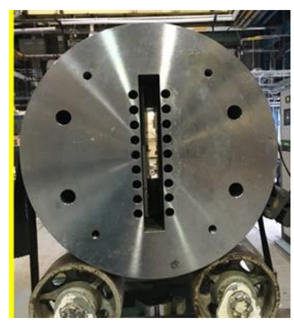

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1.0 Introduction

1.1 Identification and Significance of the Problem or Opportunity

The High Energy Physics Advisory Panel (HEPAP) subpanel on Accelerator R&D has recommended to "Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider" [1]. The 2014 Particle Physics Project Prioritization Panel (P5) recommended that the United States Department of Energy (DOE) research efforts should "Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders and continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs".

Block coil dipole designs are appealing for their simplicity in the body of a magnet, but less so in the ends where, to clear the bore tube, cable in certain blocks must be lifted or bent in the hard direction to clear the beam tube. To avoid excessive strain, particularly for brittle conductor such as Nb_3Sn or HTS, this bend must be very gradual, making the ends very long and inefficient. The overpass/underpass end geometry [2, 3] keeps ends short without introducing excessive bending strain.

Our Phase I work, the basis for this strong Phase II proposal, has included engineering design work well beyond that promised in the Phase I proposal. The overpass/underpass design, upon successful demonstration, will be applicable for any block coil dipole, either single aperture [4-7] or dual aperture common coil [8], made of NbTi, Nb_3Sn and/or High Temperature Superconductors (HTS). This technology will be important for high energy accelerators, such as the proposed Future Circular Collider (FCC). The design is well suited for the next generation high field dipoles built with Nb_3Sn and high field superconductors which are brittle in nature.

1.2 Technical Approach

In Phase II, the PBL/BNL collaboration will develop and demonstrate an innovative overpass/underpass coil design [2, 3] for the ends of high field block coil dipoles of Nb_3Sn Rutherford cable [4-7]. The block coil dipole design is an alternative to conventional cosine theta dipoles, with a goal of increasing performance and/or reducing costs. Block coil geometries have the virtue of simplicity in their cross-section. Several magnets based on various block coil designs have been designed, built, and tested. These include (a) single-aperture, or conventional 2-in-1 block coil designs with two independent coils and (b) 2-in-1 common-coil designs [8], in which the same coil is shared between the two apertures. In both designs, to clear the bore tube, the ends of several blocks must depart from the simplicity of the flat racetrack coil design. The cable in the ends of those blocks needs to be splayed--lifted in the hard direction (edgewise)--and/or have a reverse bend [2], as in dog-bone ends, which is difficult to support during the coil winding and during assembly. Also, it is difficult to maintain winding tension or apply pre-stress without damaging the conductor. The complications in the end geometry may contribute degraded performance of block coil magnets, particularly those built with Nb_3Sn, which is brittle. The overpass/underpass design addresses this issue for high field magnet coils. Another major disadvantage of the conventional block coil magnet has been that their ends are much longer than those of conventional cosine theta designs. The overpass/underpass design (also called the cloverleaf end design) overcomes that disadvantage.

1.2.1 Conventional Block Coil Designs with Lifted Ends

Photos of an early block coil design by Sampson at BNL are given in Fig. 1.1, with the coil cross-section shown on the left, and the magnet ends, with Rutherford cable gently lifted, shown on the right [4].

Figure 1.1: Nb_3Sn block coil dipole with cross-section (left) and lifted ends (right).

Since the early block coil work, several more Nb_3Sn block coil designs with lifted ends have been designed, and a few have been built: (a) a 13.8 T, 36 mm aperture dipole (named HD2) at Lawrence Berkeley National Laboratory (LBNL) [5], (b) a 13 T, 100 mm aperture dipole (FRESCA2) at CERN [6], and (c) a high field block coil magnet at Texas A&M [7]. The ends of these magnets are shown in Fig. 1.2, showing how the cable is lifted to clear the bore tube.

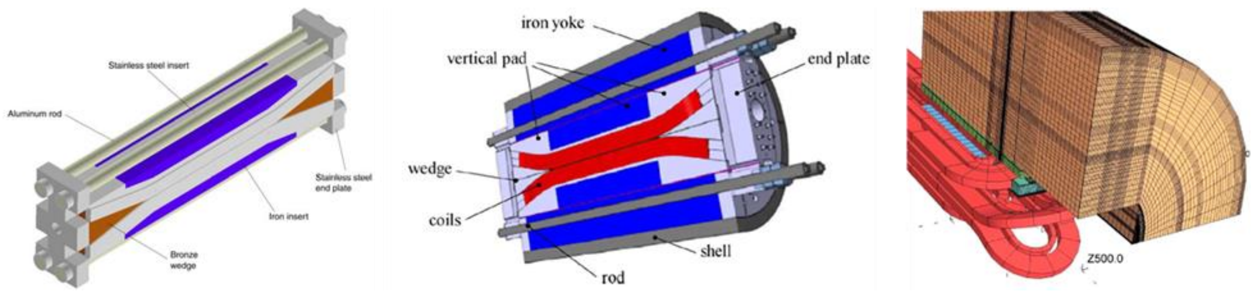


Figure 1.2: Models of block coil dipoles with lifted ends to clear the bore tube: (a) HD2 at LBNL on the left, (b) FRESCA2 dipole at CERN in the middle, and (c) Block coil dipole at Texas A&M on the right.

Issues with Lifted Hard-way Bends in Block Coil Dipoles

All block coil dipole designs presented above require the cable to be bent in the *hard*-way (edgewise) on each side of the mid-plane to clear the bore tube at the ends (see Fig. 1.2). Although most Nb_3Sn coils are fabricated using the react-after-winding (*"wind and react"*) approach, a hard-way bend of the unreacted cable can cause strands to become dislocated and thus sensitive to damage when the coils are handled and after the reaction heat treatment. In addition, it is difficult to provide adequate support of the turns in this hard-way bend transition area, and this may contribute to excessive magnet training. To avoid *excessive strain*, the ends are typically much longer in block coil designs than those in their counterpart cosine theta designs. This increase in end length decreases the overall field integral of the magnet for a given length, which is undesirable.

Issues with the Ends of Pole Blocks of Common Coil Dipoles

Some of the issues of concern in the several single-aperture block coil cross-sections are also of concern in most designs of the pole blocks of a 2-in-1 common coil dipole [8]. Although most turns in the common coil geometry have simple racetrack coil ends (referred to as the main coils, as shown by the golden-brown color in Fig. 1.3, left), some need to be lifted sideways to clear the bore tube (referred to as the pole coils – shown by the pink color in Fig. 1.3, left). Another design option is to have turns of some pole blocks return away from the aperture as shown in Fig. 1.3 (center) for the cross-section and Fig. 1.3 (right) for the ends. This keeps the design simple; however, it is at the expense of wasteful use of the conductor and an increase in yoke size to accommodate the turns on the return side. As explained later, the proposed overpass/underpass design also offers a design option for pole blocks to clear the beam tube in the common coil design.

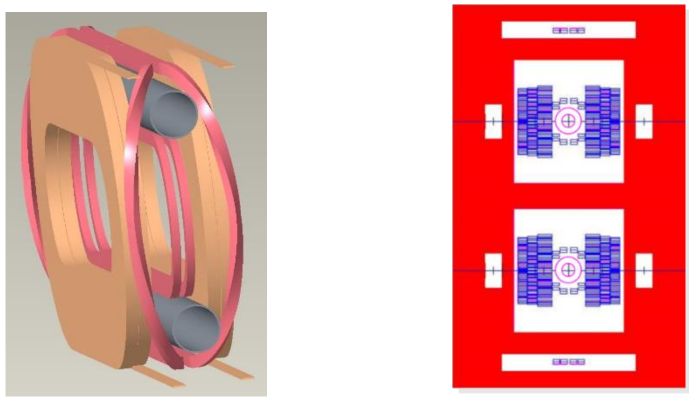


Figure 1.3: Common coil design with the turns of pole blocks lifted sideways to clear the bore tube (left), common coil cross-section that allows all coils to be simple racetrack coils (middle), but that requires some turns to return away from the aperture (right).

1.2.2 Novel Overpass/Underpass (Cloverleaf) Design

To overcome excessive strain and associated concerns regarding magnet performance, an alternative end geometry, called the overpass/underpass (or cloverleaf), has been proposed [7, 8]. The overpass/underpass design, as explained below, replaces the *hard-way* bend by a *gentle twist* like that in solenoid. This greatly reduces the strain on the cable. Another major benefit of this design, as discussed more in the next section, is a major reduction in the length of the ends of the block coil designs. The design may also allow Nb_3Sn magnets to be fabricated using a wind-after-reacting approach since the strains are much reduced.

In an example considered here, total strain in the ends of overpass/underpass design (a combination of strain from the twisting and from the bending) is smaller by approximately a factor of five despite a five-fold reduction in the length of the overpass/underpass ends as compared to that of the conventionally lifted ends. This estimate is made for a cable having a width of 15 mm and thickness of 2.0 mm and the length/radius of the overpass/underpass ends being 50 mm compared to 250 mm for conventional lifted ends. A more detailed and complete modelling of these strains will be carried out as a part of the Phase II effort.

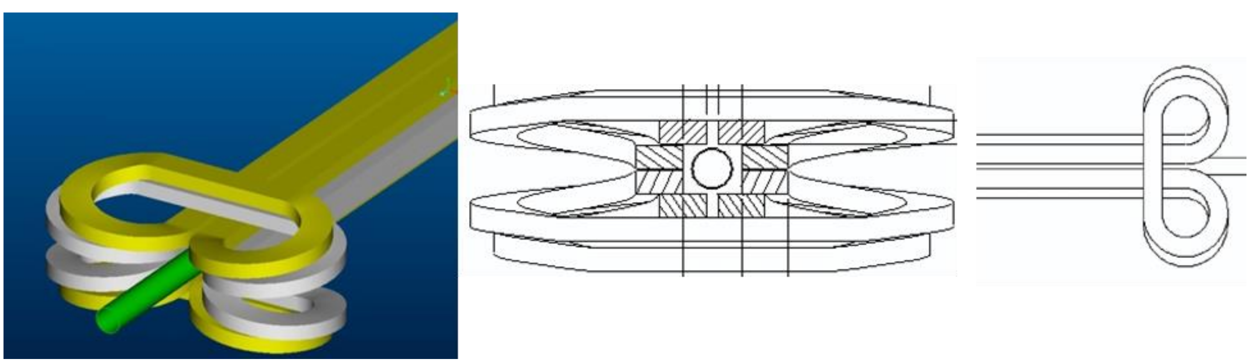


Figure 1.4: Overpass/Underpass design concept [7] for clearing the bore tube (left) in racetrack coil dipoles (left). A view from the end (middle) and top (right) show the cross-section and coils (including ends) of the overpass/underpass design.

Fig. 1.4 illustrates the concept [2] of a block-coil dipole based on the overpass/underpass design for the magnet ends. An easy way to understand this concept (the path of the cable) is to imagine the cable as tracing the path of an automobile reversing direction via an overpass/underpass bridge (see Fig. 1.4, right). The cable (or automobile) clears the beam (traffic) via the overpass/underpass, returning to its original highway with reversed direction of travel, as desired. The coil ends clear the beam tube without a hard-way bend. Moreover, unlike in dog-bone ends [4], no reverse curvature is involved. The cable traverse involves a twist or tilt, as typical on an overpass/underpass of a high-speed expressway. This twist is much gentler than in a "Twisted Stacked-Tape Cable [9]" made with HTS tape and should not degrade the Nb_3Sn.

For winding the coil, the turns are wound outside-in (i.e., the turn furthest away from the center is wound first), with successive turns layering naturally. The cable clears the bore tube as it first traverses away from the aperture and moves up or down over the mid-plane the same way the cable does in layer wound solenoidal coils. The bend radius can be chosen independently of the bore radius (perhaps limited by other constraints such as the size of the coldmass) to obtain the desired reduction in the strain. The cable will tend to have a constant-perimeter end (i.e. the total length of the tape is invariant across the width of the tape).

The primary purpose of the proposed Phase II project is to develop and demonstrate the overpass/underpass design for a high field Nb_3Sn racetrack coil block made with Rutherford cable. Two designs of interest are: (a) coils at or near the mid-plane of the single-aperture block coil dipoles and (b) pole blocks of the 2-in-1 common-coil dipoles. In both cases conductors in the ends of some coil blocks need to be lifted-up to clear the bore. The proposed design would not only avoid severe bends in the hard direction but would also eliminate reverse bends and greatly shorten the ends.

Shorter Ends of Overpass/Underpass Coils

A major disadvantage of lifted ends in block coil designs is that they are excessively long. This must be done in order to keep the strain low when the cable is bent in the hard direction. Fig. 1.5 compares the length of the coil (for the same length of the magnet straight section) for the overpass/underpass end design (the lower coil in Fig. 1.5) against the lifted end design (the upper coil in Fig. 1.5).

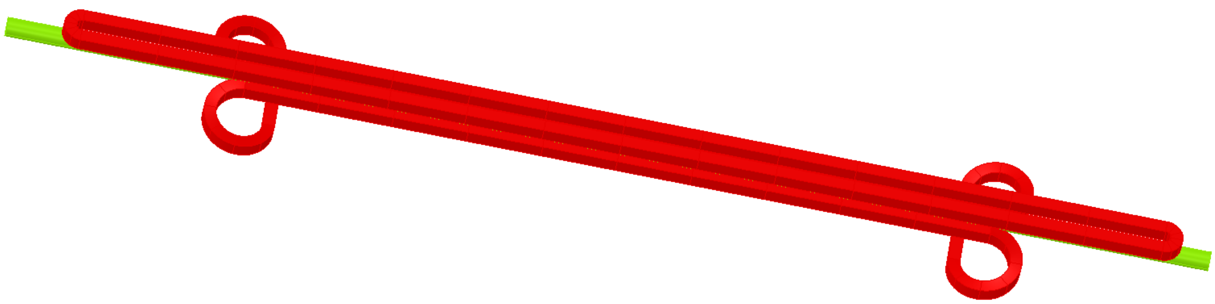


Figure 1.5: A comparison of the length of the ends in a coil with overpass/underpass ends (the lower coil) and a coil with lifted ends (the upper coil). Both coils have the length needed to clear the bore tube (green).

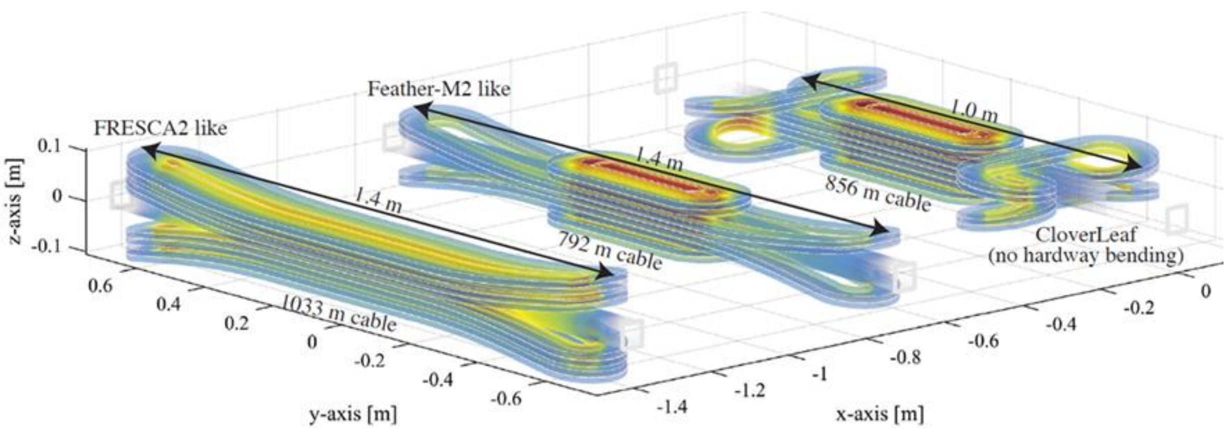


Figure 1.6: Comparisons of the length of the ends in coils with lifted ends (left & center) and a coil made with overpass/underpass ends (right) to clear the bore tube [10].

This virtue was also noted by J. van Nugteren, et al., and presented by a CERN group in several publications [10-13]. Regular updates on this program are available at the "researchgate site", see "Project log" https://www.researchgate.net/project/Dipole-HTS-Magnets-at-CERN [14]. An illustration from the EUCAS paper [10] is shown in Fig. 2.6. In the FRESCA2 design, the length was about 400 mm for each end (the end-to-end coil length is about 1400 mm, but the straight section is only about 700 mm).

Despite the advantages mentioned above, the end geometry itself is more complicated for winding the coils than that in a simple racetrack coil and will require a more complicated support structure. Furthermore, the strain, though expected to be lower than that in a lifted end-design and in other designs, will require careful calculation. Much work was performed during Phase I to address these issues. Initial 2-D and 3-D magnetic and mechanical analyses of the design have been performed, along with the preliminary engineering design, and winding of the practice coil.

In summary, the overpass/underpass end design is expected to produce a block coil magnet design where (a) the strain on the conductor is expected to be significantly less than that in conventional lifted-end designs, and (b) the length of the end region is much less than that in conventional lifted-end designs. It is also expected that the coil performance will be better than that of conventional lifted-end designs, particularly at and near the end regions. The primary purpose of this proposal is to demonstrate this technology for Nb_3Sn coils.

2.0 Anticipated Public Benefits

The block coil designs (two single aperture coils for the 2-in-1 or inherently 2-in-1 common coil design) are expected to provide a lower cost and technically attractive solution to the high field dipoles that are being developed for the next generation high energy colliders, such as the proposed Future Circular Collider (FCC) [15]. Lower costs and better performing magnets may be expected because of the simpler geometry of the block coil designs. The block coil designs are also considered technically attractive for high field magnets with large Lorentz forces. Overpass/underpass ends are expected to provide a technically attractive solution to lift the ends of the blocks that don't naturally clear in a shorter length. The benefit of such a design may be applicable to a "High Field Vertical Magnet Test Facility for Conductor, Cable" magnet design that is currently being proposed for a joint High Energy Physics (HEP) and Fusion Energy Science (FES) program. This STTR offers an opportunity for the U.S. to remain engaged with this attractive block coil design in a high field dipole magnet program based on Nb_3Sn and HTS.

The public benefit from HEP may prove to be great, but it is hard to specify in advance. It is the nature of the enterprise that advances cannot be predicted; one can only speculate. Greater knowledge over the particles and forces that make up our world may be used to enable devices that are noy yet foreseen. Past experimentation led to understanding and control of the electromagnetic force, with revolutionary benefits accruing to mankind. Future experimentation may lead to understanding and control of other forces, such as the nuclear and gravitational forces, and such gains could be revolutionary as well. One thing is certain – if we stop experimenting, progress in these areas will stagnate.

The overpass/underpass or cloverleaf design for high field dipoles is also being currently pursued at CERN [10-14] among others, as the values and benefit of overpass/underpass ends in block coil geometries are now being globally recognized. Two coils based on this geometry were built with pre-reacted HTS tape a few years ago as a part of a Phase I SBIR with Energy to Power Solutions (e2P) as the principal contractor collaborating with Brookhaven National Laboratory (BNL) as a subcontractor. The HTS coils were tested at 77 K. Those test results, as partially presented at the 2016 Low Temperature Superconductor Workshop (LTSW16), showed no measurable degradation in the overpass/underpass geometry [16].

3.0 Demonstration of Technical Feasibility and Significant Engineering Design during Phase I

This section gives a summary of the Phase I work. More details can be found in the complete Phase I report, which is submitted along with this proposal. In order to demonstrate the technical feasibility of the overpass/underpass ends, the Phase I effort included a design of a high field proof-of-principle dipole that can be tested in Phase II. A strategy was chosen to ensure that there would be no showstoppers. To achieve this, Phase I tasks included performing magnetic and mechanical analysis for the proof-of-principle dipole, winding a practice coil and completing a conceptual design. We exceeded the original goals of Phase I by developing a preliminary engineering design with significant details (rather than just a conceptual design). The Phase I project has resulted in a strong Phase II proposal for a proof-of-principle test of overpass/underpass coil ends in ~11 tesla magnetic field conditions.

This is an ambitious and aggressive goal, one that generally would not be possible in the budget of a Phase II SBIR/STTR. It is possible here thanks to the unique design of the common coil dipole DCC017 which has a large open space [17-19]. (See section 4.1 (Technical Objectives) for more details). The project also benefitted from collaboration with a CERN team which is pursuing this design [10-14] for their 20 T dipole design with Roebel cable.

We wound two practice coils rather than one, using printed-part technology. The original design with a straight connection between two overpass/underpass (or cloverleaf) sections was superseded by the CERN-style convex connection [14] for the second coil. The convex connection is being adopted for our proposed Phase II work. We were also able to locate Nb_3Sn cable (left over from previous projects), which is often a long lead-time item. This is a proven cable and is well suited for our Phase II effort.

3.1 Selection of the Conductor for Phase II

Selection of the superconducting cable for Phase II received considerable attention. The cable width must be narrow enough to fit inside the dipole DCC017, and its critical current must be high enough to run in series with the main coil. Moreover, it should be available soon, to fit the schedule of the SBIR/STTR program. Fortunately, the Nb_3Sn Rutherford cable developed for the LARP Long Racetrack Series (LRS) magnet program [20] satisfies all these requirements. The LARP LRS001 magnet reached a nominal "plateau" at 9596 A, at a peak field in the coils of 11 T. This is what we desire, based on our calculations. The cable used the Rod-Restack Process (RRP) wire from Oxford-Instruments Superconducting Technology (OI-ST). The strand diameter was nominally 0.7mm, with a 54/61 design. The average Cu/non-Cu ratio of the strands was 0.87, and when reacted at 650C/48hours it has a RRR greater than 200. Leftover pieces of this cable have been secured to satisfy the above requirements.

The rectangular cable was fabricated with 20 strands. After cabling, the cable was annealed for 8 hours at 200C and subsequently re-rolled to a width of 7.793 ± 0.050 mm and a mid-thickness of 1.276 ± 0.010 mm. Low field stability measurements show that strands reacted with an optimized heat treatment had a minimum critical current I_c (12T, 4.2K) of 560 A. We will follow the same heat treatment that was optimized for the LARP cable.

3.2 Magnetic Design Analysis

Extensive magnetic analyses were performed to evaluate several designs and their variations. This included (a) a completely rebuilt dipole DCC017, integrating its Nb_3Sn coils with new overpass/underpass coils, (b) a dipole in which new overpass/underpass coils are inserted and integrated with DCC017 without taking the DCC017 apart, (c) several variations of (b) with a range of overpass/underpass coil numbers and geometries, and (d) other magnet designs in which all coils are built new. Assembling new overpass/underpass coil(s) and integrating them with DCC017 without disassembly provides the least expensive proof-of-principle magnet, but also will also be the most complicated, as it involves several restrictions in the geometry.

3.2.1 DCC017 Rebuilt with Overpass/Underpass Coils

A field-quality rebuild of the common coil dipole DCC017 will require pole coils in addition to the main coils that have simple racetrack coil geometry. One possibility of the new additional pole coils is shown in Figure 3.1 (left) and Figure 3.1 (center). The design contains some pole coils that can be simple racetrack coils, as their ends do not interfere with the beam tube, and some other coils use the overpass/underpass design to clear the beam tube. Fig. 3.1 (right) shows the magnetic model of DCC017 with these pole coils added. The overpass/underpass design brings the end into the plane of the main racetrack coils.

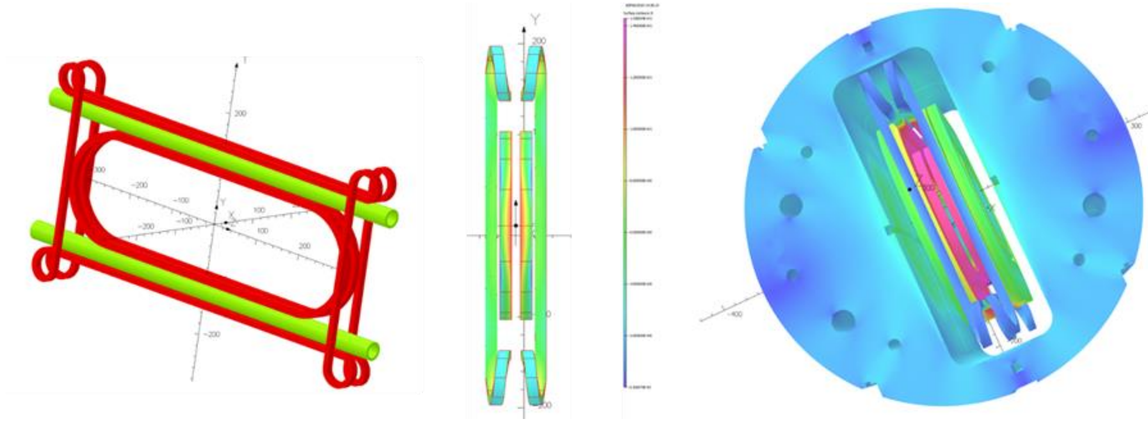


Figure 3.1: Insert pole coils with overpass/underpass coils clearing the bore. Model on the left is a side view; in the middle is a view from the magnet axis. Model on the right shows pole coils inside a rebuilt version considered for magnet DCC017.

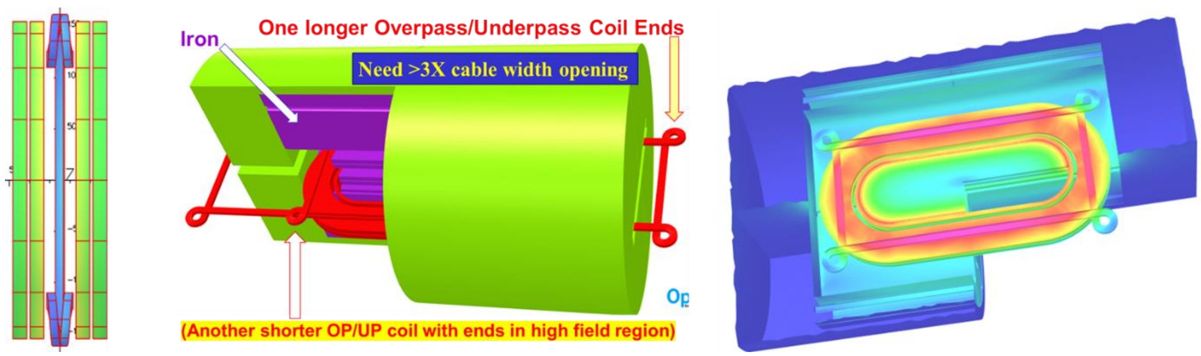


Figure 3.2: Left: A view from the end of one version of a proof-of-principle coil assembly, Center: two insert overpass/underpass coils of different lengths are sandwiched between the main racetrack coils. Right: field superimposed on the shorter overpass/underpass insert coils and iron.

3.2.2 Overpass/Underpass Coils in DCC017 with Straight Connect

In the proposed proof-of-principle demonstration, the overpass/underpass coils are inserted without disassembling the magnet. Since the straight section is closer to the main coils, the ends connecting the two overpass/underpass coils must be in the middle. One of the overpass/underpass coils is longer than the other coil, to be able to use an available cable (which is wider than ¼ the horizontal space in DCC017, details explained in the full Phase I report). Fig. 3.2 shows views of this configuration. Fig. 3.2 (right) shows the cutaway view of the field superimposed over the coils and iron. One can see that the field is lower in the cross-over region, with a relatively more complex shape than it is in the straight section of the magnet. This lower field means that the stress/strain on the conductor will be lower as compared to that in the straight section. This provides an extra safety margin in the coil section where the shape is more complex.

3.2.3 Overpass/Underpass Coils in DCC017 with Convex Connect

A convex connection is preferred over the straight connection between the two overpass/underpass ends for better winding. A magnetic model is shown in Fig. 3.3 for a five-turn pole-winding with the cable chosen in section 3. To fit two overpass/underpass coils inside DCC017, the length of the two overpass/underpass coils are designed to be different (Fig. 3.3, left). One can see that the field is maximum on the straight section of the insert coil (Fig. 3.3, right).

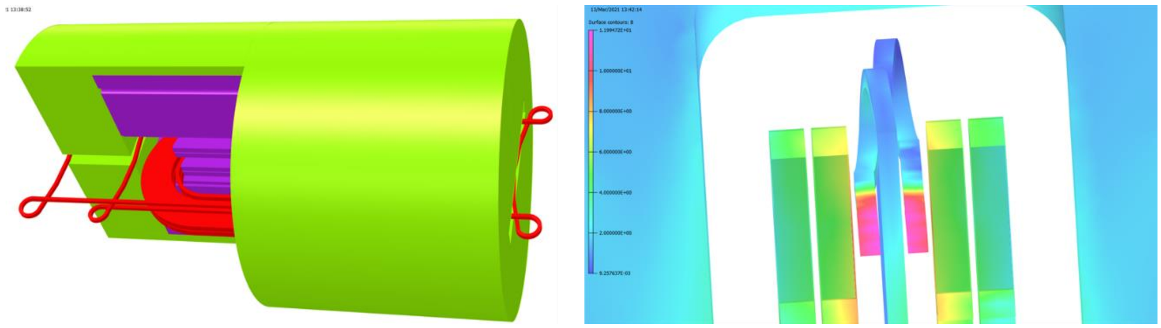


Figure 3.3: OPERA3d model (left) with ¾ model of the yoke in purple, including two overpass/underpass coils with different lengths. Field contours in a cutaway view at 10 kA on the straight section of the overpass/underpass coil block at the center of the magnet (one symmetric quadrant only).

3.2.4 Proof-of-Principle Overpass/Underpass Dipole for Phase II

Since the two-coil insert is beyond the Phase II budget, a one coil option was chosen. The one-coil test will demonstrate all the key features of the overpass/underpass design, as it will be subjected to similar fields and stresses. We chose the coil that was subjected to a relatively higher field at the magnet ends. Fig. 3.4 (left) shows a view of the field contours from the end of the magnet, Fig. 3.4. (middle) a cutaway view, and Fig. 3.4 (right) the field contour from an OPERA2d model. The maximum computed field at 10 kA is 11.8 T.

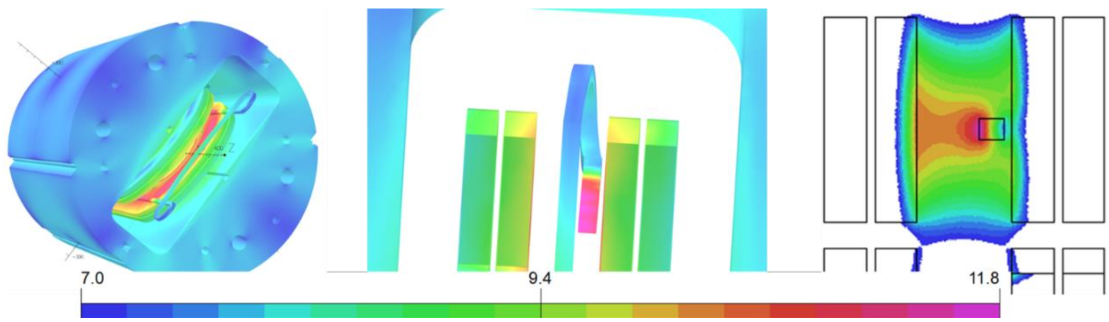


Figure 3.4: On the left the field contours are shown superimposed over the coils and iron from the end of the magnet. In the middle is a cutaway view of the field contour highlighting the high field (purple) in the straight section region of the insert coil. On the right is the field contour from an OPERA2d model.

3.3 Mechanical Design Analysis

The clover leaf is being designed to allow coil blocks to lift up (or down) to pass over (or under) the beam pipe in such a way as to minimize the strain on the conductor. A detailed mechanical analysis of the overpass/underpass coil and its support system is important for the design of the magnet. We have performed two mechanical analyses: (1) A 3D analysis using COMSOL that models the magnet end region, which includes the clover leaf. The field from the DCC017 coils falls off, which reduces the Lorentz forces. The 3D simulations are important for the design of the support structure for the complex end coil. (2) A 2D analysis using ANSYS models a cross section of the DCC017 magnet with the coil in the straight section, where the field is maximum. The coil strain in the straight section will limit the performance of the coil. Both of these analyses depend on the mechanical properties of the materials used. Of particular importance is the modulus of the epoxy impregnated Nb_3Sn coils. We are using the magnet and Nb_3Sn coil material properties that were used in the US LARP [21].

3.3.1 ANSYS Analysis

The straight section of the overpass/underpass (op/up) coils is in the high field region and subject to large Lorentz forces. The strain in the coil conductor will potentially limit the performance of the coil. A mechanical simulation of the 2D cross section was performed to evaluate the design. A magnetic simulation is first performed to predict the field and Lorentz force at each node, to generate input for the structural calculation. In the second phase of the simulation, stresses and strains are calculated from the Lorentz forces previously saved. Figure 3.5 (left) shows a contour plot of the displacement as a result of the forces. The maximum displacement, 128 μm, is in the vicinity of the op/up coil and the adjacent DCC017 coil. A contour plot of the von Mises stress over the op/up coil is shown in Fig. 3.5 (middle). The peak von Mises stress is 217 MPa; the goal was to limit the Nb_3Sn stress to 200 MPa. The peak stress is localized and may be an artifact of the simulation rather than reality. Fig. 3.5 shows the von Mises strain at the op/up coil.

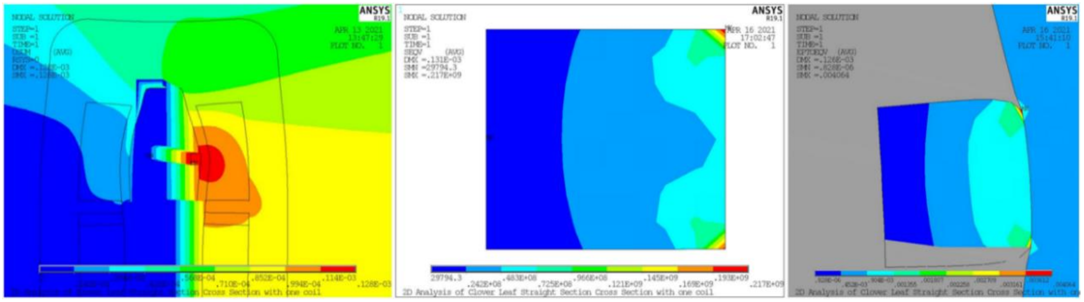


Fig. 3.5: Left: Contour plot of the displacements, Middle: Contour plot of von Mises stress over the op/up coil, and Right: Contour plot of the von Mises strain.

3.3.2 COMSOL 3-D Analysis: Phase II Dipole Field, Displacements, Stresses & Strains

A major goal of the structural analysis described below was to minimize any augmentations of strain in the Nb_3Sn of DCC017. Important also, of course, was that the overpass/underpass coil itself is not at significant risk of conductor degradation. Lorentz forces from the insert coil may raise the strain in the DCC017 Nb_3Sn and risk conductor degradation. Therefore, the insert-coil support structure includes a stainless-steel pad, as in Fig. 3.6 (left), which spreads the Lorentz load from the insert coil onto a much larger surface of DCC017. Besides the mesh, Fig 3.6 (right) also shows the field contours at 10.8 kA (The COMSOL calculations described in this section were carried out at 10.8 kA rather than 10 kA as elsewhere in this proposal.)

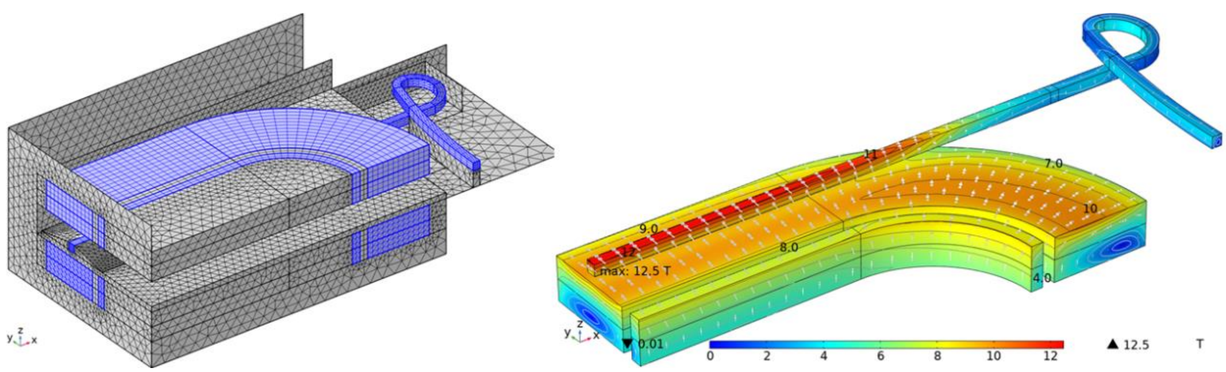


Figure 3.6. Left: Mesh of quadrant of DCC017 coils & collar, five-turn overpass/underpass coil, and stainless-steel support blocks. Blue is Nb_3Sn. Right: Magnetic field direction (arrows) and magnitude (color & contours) with 10.8 kA in all coils.

Figure 3.7 shows the von Mises stress contours, 1st principal stress contours and 1st principal strain contours.

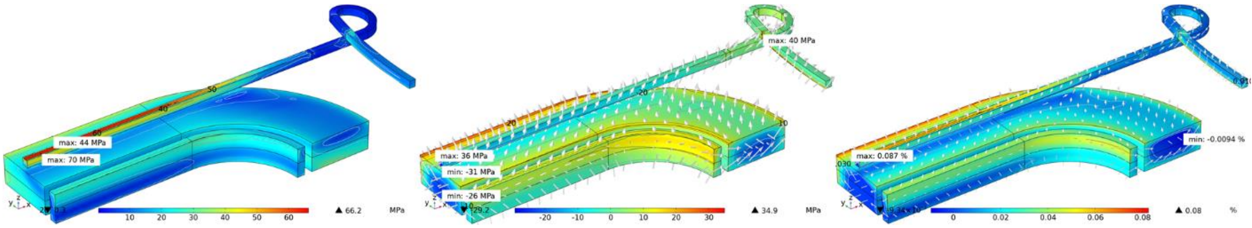


Figure 3.7. Left: von Mises stress contours. Middle: 1st principal stress contours. Right: 1st principal strain contours.

Figure 3.8 shows the 2nd principal stress contours and 2nd principal strain contours.

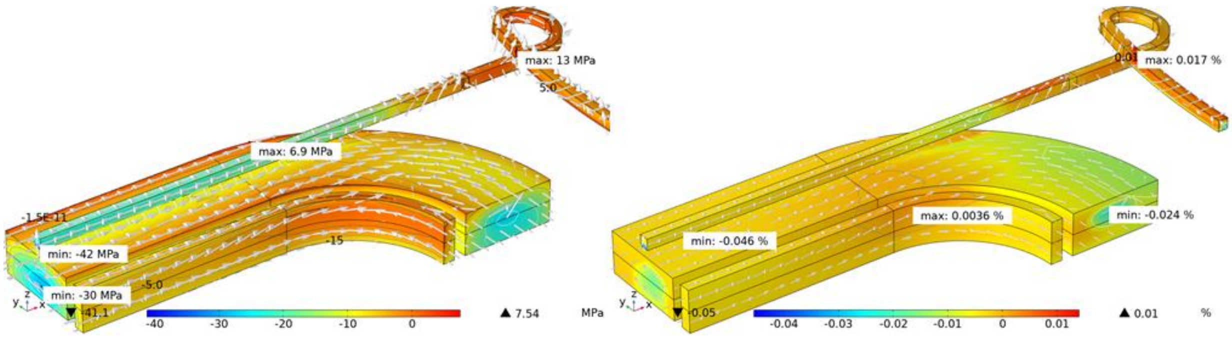


Figure 3.8. Left: 2nd principal stress contours. Right: 2nd principal strain contours.

Figure 3.9 shows the negative 3rd principal stress contours and negative 3rd principal strain contours.

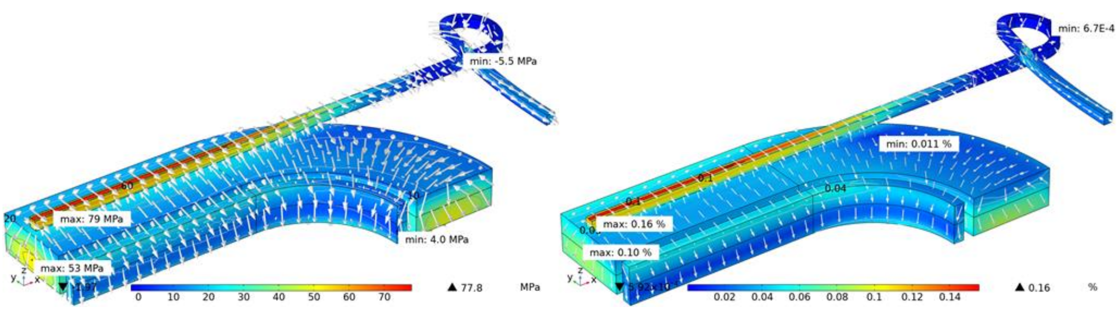


Figure 3.9. Left: Negative 3rd principal stress contours; Right: Negative 3rd principal strain contours.

3.4 Preliminary Engineering Design of the Proof-of-Principle Coil for Phase II

The preliminary mechanical engineering design for the fabrication and installation of a Nb_3Sn "Overpass/Underpass" insert coil in the aperture of the DCC017 magnet was completed. The coil design followed the magnetic model. The ends of the coil were located beyond the central field of the magnet, to reduce the magnetic forces in the end regions. The transverse ends of the final design between the "cloverleaves" of the coil were designed with a convex curve, as in the CERN OP/UP coil, to facilitate conductor contact with the winding surface in these regions.

The design is based on a continuous winding form, to ensure the proper dimensions and shape of the completed coil. This form, as is seen in Figure 3.10 (left), becomes a permanent part of the coil support structure; as such, it needs to be compatible with all the fabrication steps involved. Because the niobium tin coil is being fabricated using the wind-and-react process, the coil form must be compatible with the 665 C reaction temperature. Therefore, all components are designed to be made from titanium, including the 3-D end shapes, which will be fabricated using additive machining, and which survives the heat exposure and is well matched to the thermal expansion of the conductor during reaction. Nonetheless, gaps are still required between mating titanium frame components, as is seen in Figure 3.10 (right). Gaps will also be present in the straight sections and convex sections of the ends to allow for the differential thermal expansion between various metals and the conductor during reaction.

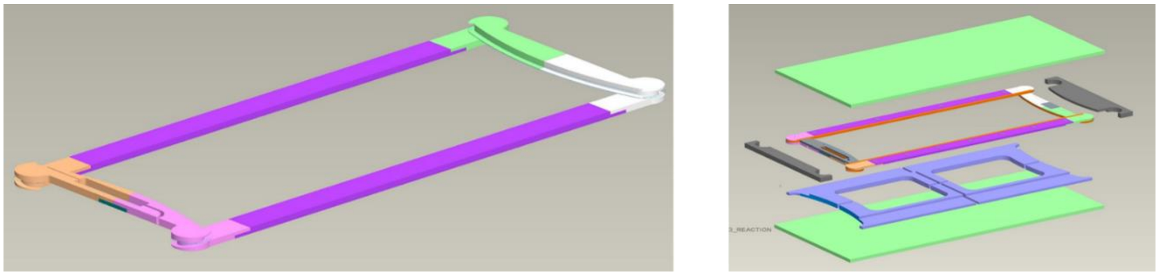


Figure 3.10: Coil winding form (left) and exploded view of tooling showing gaps in (blue) reaction frames (right).

The winding form does include some temporary components, namely lateral guide plates, which are subsequently removed. After winding, additional clamping is introduced to the exposed edges of the wound coil to ensure proper dimensioning and positioning of the coil block during reaction, and the coil is installed in an oven and heated using a prescribed cycle to a plateau of 210C for 48 hours, then 395C for 48 hours, and then finally 665C for 50 hours for the reaction to be completed. The coil is then cooled using a similar prescription.

After reaction, cleaning and testing are performed, after which instrumentation and niobium titanium exiting leads are spliced within the coil structure, as seen in Figure 3.11 (left). In this way, after impregnation, the brittle niobium tin conductor is protected within the impregnated coil volume, and only ductile niobium titanium and copper conductors exit the coil structure. Additional final coil components are added as shown in Figure 3.11 (right), and then the coil is vacuum pressure impregnated using CTD-101K epoxy at elevated temperature.

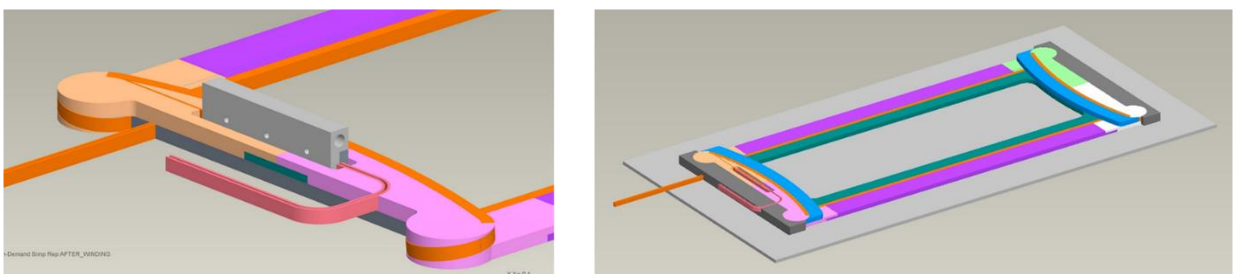


Figure 3.11. Nb_3Sn coil lead to NbTi exiting lead splice within the impregnated coil structure (left) and Nb_3Sn coil in the impregnation fixture (right).

After impregnation, final structure plates are added to connect and support coil blocks together, and at installation additional load distribution plates are added between the coil and the DCC017 main coils to reduce contact stress experienced by the main coils.

Even though the Phase II budget allows for only the fabrication and installation of one coil in DCC017, considerable effort was made to ensure that the design was compatible with the installation of two similar overpass/underpass insert coils as a pair into DCC017 in a future program. This involved strategically shifting the ends of the coils in the axial direction, as discussed in the magnetic design section, to enable the coil ends to be nested laterally, as shown in Figure 3.11. Additionally, changes to the design of the single coil lead were required to be able to connect the two coils in series. Figure. 3.11 (right) shows the 3-d rendering of the two such overpass/underpass coils inside the magnet DCC017.

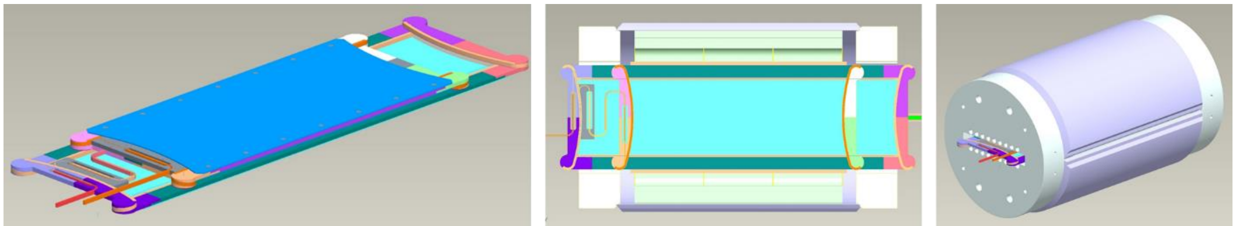


Figure 3.11. Two OP/UP coils with staggered ends nested together (left); section view of two OP/UP coils in DCC017 (middle); and rendering of the two OP/UP coils assembled in the magnet DCC017. The design allows installation of two insert coils in a future follow-on program.

3.5 Construction of Parts and Winding of the Overpass/underpass Coil

An important part of the Phase I plan was to practice-wind a coil having a new shape. Use of the 3-d printer purchased during an earlier PBL SBIR allowed a series of relatively complex parts to made and iterated. Fig. 3.12 shows different views of overpass/underpass printed parts and one turn wound, including the initial practice run of how the cable will lay in the overpass/underpass section. Fig. 3.12 (left) shows the 3-d printed parts for the overpass/underpass section; Fig. 3.12 (middle) shows an initial study of how the cable is going to lie in the overpass/underpass section; and Fig. 3.12 (right) shows the first turn of the lower dipole coil based on the overpass/underpass geometry. The arrow shows the beam path and an illustration of how the overpass/underpass block coil geometry clears the beam tube.

We performed two distinct styles of practice windings. As mentioned earlier, CERN is also pursuing the overpass/underpass design (generally referred to there as the cloverleaf design) for their 20 T dipole design [14]. Both projects are benefitting from ongoing discussions and collaboration. A specific feedback from the CERN team is described here. Fig. 3.13 (left) shows the one-turn coil wound as per the original design; Fig. 3.13 (right) shows the HTS tape wound at CERN, as per the modified geometry developed there. The convex shape between the two cloverleaves or underpass/overpass sections allows the cable to lie nicely. Therefore, we are adopting that general shape for Phase II.

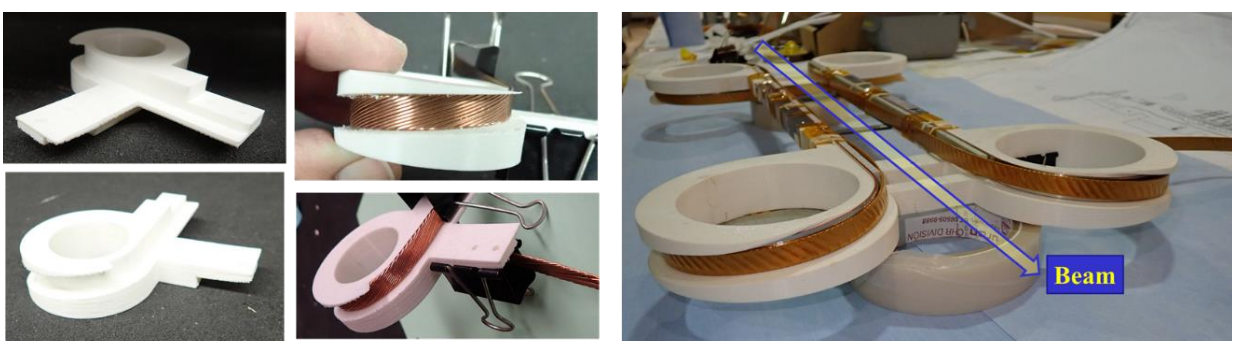
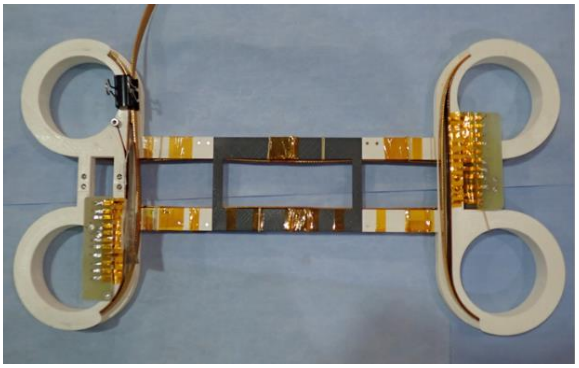


Figure 3.12. Left: 3-d printed parts for the overpass/underpass section; Middle: initial study of how cable is going to lie in the overpass/underpass section; and Right: first turn of the lower dipole coil based on the overpass/underpass geometry.



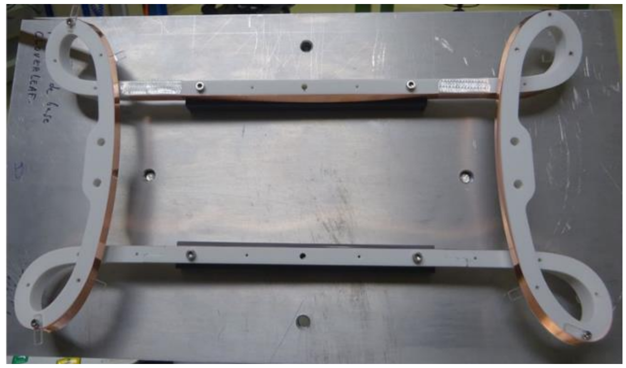


Figure 3.13. Left: Rutherford cable coil wound by the PBL/BNL team in the early part of the Phase I proposal, with a straight connection between the two overpass/underpass (cloverleaf) sections in the end. Right: HTS tape coil wound by the CERN team, with a convex connection between the two cloverleaves (overpass/underpass) sections in the end.

Fig. 3.14 shows the winding of the Phase I overpass/underpass practice coil, with cable similar to the Nb_3Sn Rutherford cable that will be used in winding the actual coil in Phase II. Printed curved parts (black) and machined straight parts made with aluminum (gray) make a frame for winding the overpass/underpass practice coil with a convex connection between the cloverleaf sections. The two pictures show views of the same coil turned over to show the other side.

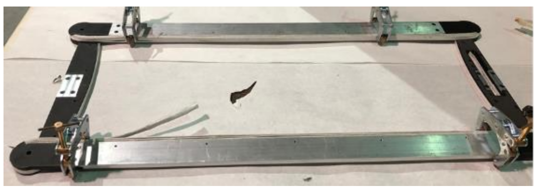


Figure 3.14. Phase I winding of the overpass/underpass coil with a Nb_3Sn Rutherford cable similar to that which will be used in winding the Phase II coil. Two pictures on the left and right side are of the same coil turned over to show the other side.

A view of the mockup insertion test of this coil is shown in Fig. 4.1 (page 17). The Phase II coil will be enclosed in a support structure before it is inserted inside the magnet DCC017.

4.0 The Phase II Project

4.1 Technical Objectives

The key goal of the Phase II proposal is the construction and test of the novel overpass/underpass (or cloverleaf) geometry in a proof-of-principle demonstration with Nb_3Sn Rutherford cable at a field of ~11 T. Such a demonstration is possible within the budget of a Phase II, thanks to the unique capabilities of BNL's dipole DCC017. It has a large, easily accessible open space in which new coils can be inserted and tested as an integral part of the magnet without any need for disassembly and reassembly. These new insert coils make direct contact to the main coil (or to added structure in between insert coil and main coil to manage stresses) under Lorentz forces [19, 22].

A side benefit of the proposed Phase II test will be the first demonstration of field shaping coils in a common coil dipole, a design which was investigated for field quality in another PBL/BNL SBIR [23].

The Phase II proposal is built upon the significant progress in Phase I, summarized in the previous section and abstract submitted at MT27-International Conference on Magnet Technology [24], which included considerable engineering design work. We also chose, located, and secured the Nb_3Sn cable that will be used in the Phase II coil. This is leftover Nb_3Sn cable that has achieved good results when used in previous magnets.

In addition, at the end of Phase II, preliminary designs of the 16 T dipole for both (a) a 2-in-1 common coil and (b) a single aperture block design will also be made. This will allow us to pursue this technology beyond Phase II, into an effort of model magnet production either at a laboratory or by industry. Participation of General Atomics (GA) in Phase II is a significant part of our planning for Phase III and beyond. GA will provide valuable insight into industrial production and commercial application of this design and technology for High Energy Physics (HEP) and other applications.

4.2 Phase II Work Plan

The detailed work plan will involve a series of tasks with roles assigned to PBL, BNL, and General Atomics (GA). (Please see letter of support from GA uploaded with this proposal in Field 12 "Other Attachments", and also please see the overview in section 10.1). The Phase II tasks are:

Task 1: Perform practice winding of coils under tension. Phase I coils were wound by technicians with no tension applied to the cable. An initial task of Phase II will be to make a few more practice windings with tension applied through the winding machine. This will help in making a more controlled winding (with cable better laid out and secured) for the proof-of-principle magnet. We are planning to use some adapter with the universal coil winder at BNL. The BNL technical staff, with input from the PBL team, will take the primary responsibility for this task.

Task 2: Complete the engineering design. Even though a significant engineering design was completed during Phase I, detailed engineering will be carried out during Phase II to complete remaining tasks and to make the drawings required to order the parts. This will be a joint task between the PBL and BNL teams, with PBL taking the lead. Input from General Atomics will be considered.

Task 3. Continue the mechanical and magnetic analysis. The magnetic design has been completed in Phase I, and that is unlikely to change in Phase II. However, additional mechanical analysis is expected for the final engineering design completed in task 2 for the new structure that will get integrated with the existing structure of DCC017. This task will involve the use of design and analysis tools such as ANSYS and COMSOL. We will also perform more complete calculations of the strain on the conductor in the ends. More magnetic analysis may be required if the winding layout gets iterated. PBL will have primary responsibility for this task, with support from BNL.

Task 4. Procure the parts for coil winding, reaction, impregnation, and support structure. Once the engineering design is completed, purchase orders will be placed to procure the parts for (a) coil winding and (b) for reaction, impregnation, and support structure. PBL will have primary responsibility for this task, with support from BNL.

Task 5: Final Selection of cable for the proof-of-principle insert coil. One of several remaining cables will be used for making the overpass/underpass proof-of-principle coil. Final selection will make use of a particular lot of cable. This task will be primarily carried out by PBL.

Task 6. Winding of the overpass/underpass coil for the proof-of-principle magnet. Final winding of the overpass/underpass coil will be done using the universal coil winder, with optimized tension on the cable. A few trial runs with a few turns may be required before the final winding is made. This task will be led by BNL with input from the PBL and GA teams.

Task 7: Reaction, impregnation, and assembly of the overpass/underpass coils in DCC017. The Overpass/underpass Nb_3Sn coil will be placed in the reaction fixture, reacted, and heat treated as per the prescription outlined earlier. After reaction and cleaning, instrumentation and niobium titanium exiting leads will be spliced within the coil. The coil will then be vacuum/pressure impregnated using CTI-101K epoxy at elevated temperature. After impregnation, final structure plates will be added to hold the coil blocks together and additional load distribution plates will be added between the coil and the DCC017 main Nb_3Sn coils to reduce the contact stress experienced by the main coils. Then the overpass/underpass coil will be installed in the empty space of DCC017 (Fig. 4.1 left). Fig. 4.1 (middle) shows a previous installation of insert coils under a previous PBL/BNL SBIR [18], and Fig. 4.1 (right) shows a view of the mockup insertion test of the overpass/underpass coil wound under this SBIR (right). Insert coil leads will then be connected to the main Nb3Sn coil leads as the two coils will be powered in series with the same power supply. A rendering of a similar magnet design with two overpass/underpass coils at the return end is shown in Fig. 4.1 (right). This task will be led by BNL with input from PBL and GA teams.

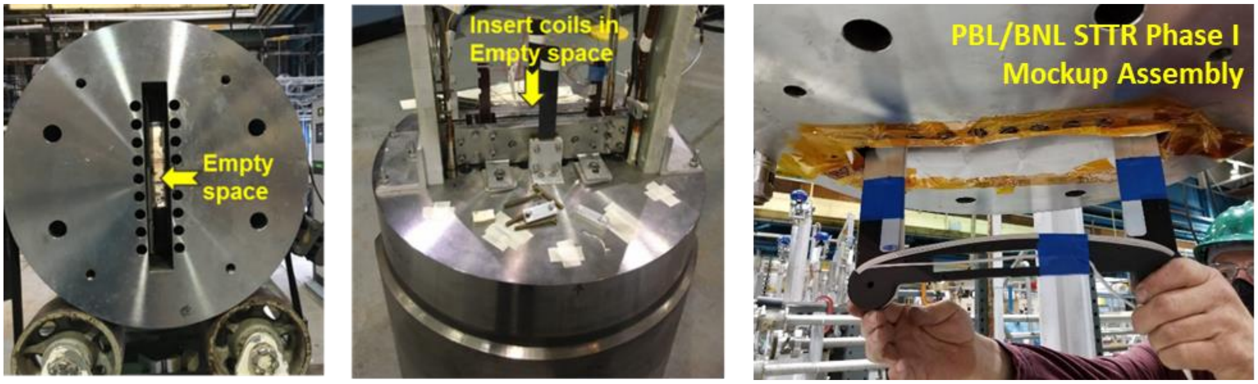


Figure 4.1: BNL common coil dipole DCC017 with a large open space (left), with an insert coil for a previous PBL/BNL STTR (middle), and a view of the mockup insertion test of the overpass/underpass coil wound under this SBIR (right).

Task 8: Test of the overpass/underpass coils in the proof-of-principle dipole. Additional voltage taps and other instrumentation (such as Hall probes and quench detection/localization hardware) will be added. After a series of routine pre-tests, the magnet will be installed in the dewar and tested at 4 K for quench performance. This task will be primarily carried out by BNL, with PBL team member(s) participating in the test.

Task 9. 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. A secondary but strategically important task of the Phase II effort will be to develop a magnetic, mechanical and preliminary engineering design of 16 T, 50 mm aperture block coil and common coil magnets for a future proton collider. In addition, there has been recent interest in building a large-aperture high field background field magnet for High Energy Physics (HEP) and Fusion Energy Sciences (FES) for testing cable and perhaps an insert coil. The final design of either type of magnet will require significant subsequent funding. However, a successful proof-of-principle demonstration of the overpass/underpass coils that clear the bore tube with relatively compact and well performing ends will bring the block coil designs to a more competitive level. This task will be jointly performed by the PBL and BNL teams.

Task 10. Prepare the Phase II final report and plan for follow-on work. The PBL and BNL teams will jointly write the Phase II final report. Follow-on work between PBL and GA or between PBL and BNL or all three together will be planned under Phase IIA, Phase III or some other mechanism. PBL and GA will also examine the potential benefit of this design for other applications.

4.3 Managerial Controls for a Successful Project

To ensure a successful project, PBL will hold regular technical meetings and compare progress made against the performance schedule below. The technical staff will meet to ensure that important milestones are being met in a timely way. PBL PI Dr. Kahn has an office at BNL campus. PBL senior management will also travel to supervise and participate in various activities at BNL. During each meeting, the team will identify any problems as well as ensure ways to solve them.

PBL has extensive experience with the DOE SBIR program, having completed several SBIR research efforts over the years. As such, PBL personnel are well versed in the reporting and administrative needs that will be an important part of the project proposed herein.

5.0 Performance Schedule

The project duration will be 104 weeks (24 months). The following is the schedule of the Tasks corresponding to the Objectives listed in the work plan:

	Months																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1	■	■	■	■	■	■																		
Task 2			■	■	■	■	■	■	■															
Task 3	■	■	■	■	■	■	■	■	■	■	■	■												
Task 4a										■	■	■												
Task 4b													■	■	■									
Task 5						■	■	■	■	■	■	■												
Task 6															■	■								
Task 7																	■	■	■					
Task 8																				■	■			
Task 9													■	■	■	■	■	■	■	■	■	■		
Task 10																							■	■

6.0 Related High Field Magnet R&D Done by the PBL/BNL Team

Over the years, the PBL/BNL team has been involved in various high field magnet SBIR/STTR R&D projects for high energy physics. The R&D proposed herein directly benefits from the technology generated and experience gained in those earlier SBIR/STTRs. This experience also helps in developing high field magnet technology for wider use. This point has been well recognized by professionals in the field as well as in the comments of various SBIR/STTR reviewers on previous submissions.

The PBL/BNL team has established a strong R&D position in high field superconducting magnet technology with several outstanding accomplishments. One HTS solenoid designed and built through a PBL/BNL SBIR produced a field of ~16 T (a record field at that time), exceeding its nominal field by more than 30% [25]. Another major achievement of this team is the demonstration of a significant field HTS/LTS dipole magnet [18]. That STTR demonstrated the value of DCC017 with a large open space as a rapid-turn-around, low-cost R&D facility and now plays a central role at BNL in various HEP and FES programs [19].

7.0 Facilities/Equipment

The Superconducting Magnet Division (SMD) at BNL, working in collaboration with PBL, will have responsibility for the detailed magnetic and mechanical design tasks. In addition, the SMD will be responsible for winding the block pole test coils. The Division has extensive facilities for winding demonstration coils and for testing these coils. It also has access to simulation and engineering software tools that will aid in the design of coils and magnets. The design software available includes ROXIE, OPERA2d, OPERA3d, COMSOL and in-house software for magnetic design, ANSYS for mechanical design, and Pro/ENGINEER and AutoCAD for engineering design. The BNL SMD has been a major player in the development of conventional superconducting magnets over the last four decades and of HTS magnets for over a decade. It has dedicated coil winding machines, cryo-coolers and other equipment. The SMD has a staff of about 35 scientists, engineers, technicians, administrative staff and others. Construction and testing of the coils will be carried out in a 55,000 ft^2 multipurpose complex at the SMD. The facility allows testing of a variety of superconductors, coils and magnets from 2 K to 80 K. The infrastructure (space, tools, test equipment, etc.) that are part of the Division will be made available for the Phase I and Phase II work. The value of the infrastructure at BNL is well over $40 million, use of which is an "in-kind" contribution crucial to the project.

8.0 Principal Investigator and Other Key Personnel

Dr. Dr. Ramesh Gupta will be the Principal Investigator (PI) of the project. Dr. Gupta will be joined by M. Anerella (chief mechanical engineer), P. Joshi (chief electrical engineer), A. Yahia (Postdoc), Dr. J. Avronsart (Postdoc), Mr. P. Kovach (senior design engineer) and other technical staff at BNL.

Dr. Stephan Kahn (senior scientist) will be the principal investigator for PBL. Other key members of PBL team are Dr. Ronald M. Scanlan (senior scientist), Mr. Robert J. Weggel (senior engineer), Dr. Erich Willen (senior scientist), Dr. Al Zeller (senior scientist and consultant), Mr. Richard deHaas (engineer and senior designer), Mr. Roger London (Commercialization Assistance Provider and consultant), Dr. Delbert Larson (senior scientist and Vice President), and Mr. James Kolonko (President).

More information about our team members, including their brief bios, can be found in the form "Research and Related Senior/Key Person Profile" which is uploaded as a part of this proposal.

9.0 Consultants and Subcontractors

9.1 Brookhaven National Laboratory (Research Institution)

This grant application involves a formal collaboration between Particle Beam Lasers, Inc. and a research institution, Brookhaven National Laboratory (BNL). As can be found in more detail in the attachments found in block 12, what follows is the requested identifying information for this collaboration:

Name and address of the institution:

Brookhaven National Laboratory, Building 460, P.O. Box 5000, Upton, NY 11973-5000

Name, phone number, and email address of the certifying official from the RI:

Ivar Strand, Manager of Research Partnership, (631) 344-7549, istrand@bnl.gov

Total dollar amount of the subcontract: $590,000

9.2 Consultants

Dr. Al Zeller will serve as senior physicist consultant for the Phase II work. Dr. Zeller will assist the project by providing his technical services on superconducting magnets, PBL has a budget of in $9,600 of consultant payments for each year during this Phase II. PBL will also be using Roger London as our CAP provider. Mr. London will assist PBL in all phases of business development and marketing during the Phase II. PBL has a total budget of $25,000 for his services in each year.

10.0 Letters of Support

10.1 Letter of support and Participation from General Atomics (GA)

A letter of support from GA is attached to this proposal in field 12 "Other Attachments" where it states: "***GA will support PBL with at least one full-time-equivalent-month of engineering and technical effort to investigate the large-scale production and start up issues associated with the overpass/underpass coil technology as part of PBL's Phase II project.***" Furthermore, "***GA views the SBIR/STTR program as a critical effort to develop next-generation accelerator technology, and a keyway to facilitate partnerships between technology innovators, such as PBL, national laboratories, such as BNL, and industrial leaders, such as GA, to commercialize the results of SBIR/STTR research and development.***"

10.2 Letter of Support from Dr. Soren Prestemon (Director of USMDP)

The proof-of-principle demonstration of the overpass/underpass design as proposed in Phase II is complementary to and has a good synergy with the high field magnet program that is being carried out under the US Magnet Development Program (USMDP). The PBL/BNL team has presented this work in several working group meetings and at the annual collaboration meeting. A letter of support from Dr. Soren Prestemon, Director of USMDP, is attached to this proposal in field 12 "Other Attachments" where it states: ***"The project you propose would complement the MDP well, as it is aligned with our general goals of developing high field accelerator magnet concepts that explore the limits of Nb_3Sn magnet technology."***

10.3 Letter of Support from Dr. Glyn Kirby (CERN)

A letter of support from CERN, which is pursuing this design for 20 T HTS dipole, attached to this proposal in field 12 "Other Attachments", mentions that, ***"… team at CERN realised that it incorporated many great features (conductor hard-way bending is strain free, short coil ends, low integrated field errors through the ends, lower max field, and more).***", and further recommends, "***It is only in following the process of imagination, trying to design a coil, then studying that design, and finally building and testing coils, that we can finally understand the deep details that will give the answers.***"

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