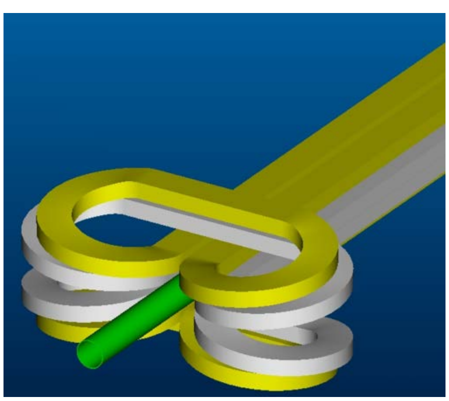
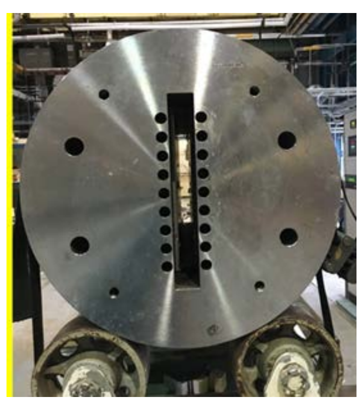
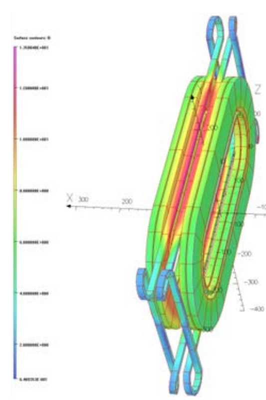
8. Project Narrative

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







Proprietary Data Legend

This narrative contains no proprietary data.

Identification and Significance of the Problem

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".

This proposal is for developing an innovative overpass/underpass coil design for the ends of high field block coil dipoles made with Nb_3Sn Rutherford cable. The block coil dipole design is an alternative to conventional cosine theta dipoles for future circular colliders with a goal of increasing performance and reducing costs. Block coil geometries have the virtue of simplicity of the 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 [2], 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 lose the simplicity of the flat racetrack coil design. The cable in the ends of those blocks needs to be lifted in the hard direction (edgewise) and/or have a reverse bend, as in dog-bone ends, which is difficult to support during the coil winding and during the assembly and also has difficulty in maintaining the winding tension or applying pre-stress without the risk of damaging. The complications in the end geometry may have contributed to the degraded performance of some block coil magnets, particularly those built with Nb_3Sn, which is a brittle superconductor. The overpass/underpass design addresses this issue for high field magnet coils. Another significant disadvantage in the ends of many earlier block coil magnets has been their much longer ends as compared to those of conventional cosine theta designs. The overpass/underpass design (also called cloverleaf end design) overcomes that disadvantage.

Block Coil Nb_3Sn Dipoles with Lifted Ends

Photos of an early block coil design by Sampson at BNL are given in Fig. 1, with the coil cross-section shown on the left, and the magnet ends, with Rutherford cable gently lifted, shown on the right [2].

Figure 1: Nb_3Sn block coil dipole with cross-section (left) and lifted ends (right).

Several more Nb_3Sn block coil designs with lifted ends have been designed and/or built since then. These include (a) a 13.8 T, 36 mm aperture dipole (named HD2) at Lawrence Berkeley National Laboratory (LBNL) [3], (b) a 13 T, 100 mm aperture dipole (named FRESCA2) at CERN [4], and (c) a high field block coil magnet at Texas A&M [5]. The ends of these magnets are shown in Fig. 2, showing how the cable is lifted to clear the bore tube.

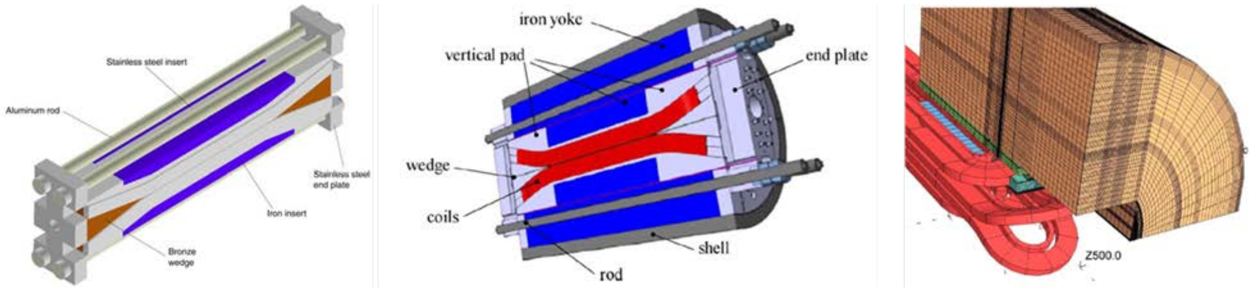


Figure 2: Models of block coil dipoles with lifted ends to clear the bore tube: (a) HD2 at LBNL on the left, (b) FRESCA2 dipole at CERN in the middle, and (c) Block coil dipole at Texas A&M on the right.

Lifted Hard-way Bends to Clear the Bore Tube at the Ends of 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. 2). This is a particularly sensitive issue for brittle conductors such as Nb_3Sn, which are prone to damage due to *excessive strain* from the bending in *hard* direction, and even filament breakage can occur in extreme cases. As mentioned earlier this issue has often been attributed to poor performance of the magnet, particularly in the transition region from the straight section to the end. To minimize the impact of this sensitive issue (or to avoid *excessive strain*), the ends are typically made 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.

Ends of Pole Blocks of Common Coil Designs

Some of the issues that are 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 [6].

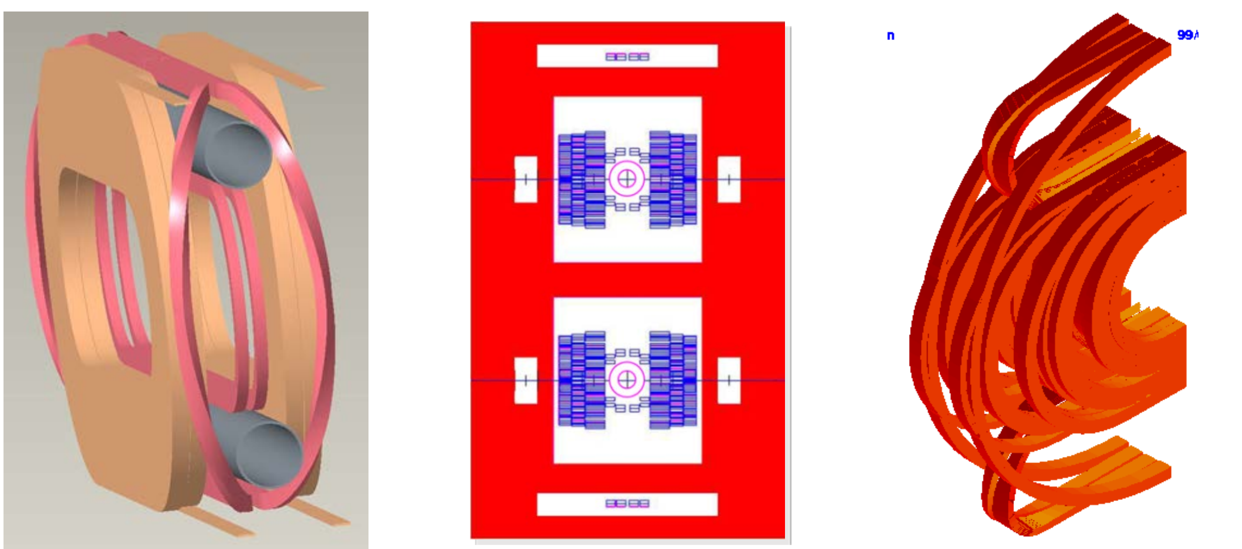


Figure 3: Common coil design with the turns of pole blocks lifted sideways to clear the bore tube (left), common coil cross-section for allowing all coils to be simple racetrack coils (middle), and ends of the simple racetrack coils showing certain turns returning away from the aperture, and thus subtracting from, rather than contributing to, the field in the bore.

Although the majority of turns of the common coil have simple racetrack coil ends (referred to as the main coils, as shown by the golden-brown color in Fig. 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. 3, left). Another design option is to have turns of certain pole blocks return away from the aperture as shown in Fig. 3 (center) for the cross-section and Fig. 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.

Technical Approach

<u>Overpass/Underpass Design</u>

To overcome the excessive strain and associated concerns on magnet performance, an alternative end geometry, called the overpass/underpass (or cloverleaf), has been proposed [7, 8]. The overpass/underpass design, as explained below, practically replaces the *hard-way* bend by a *gentle twist.* This significantly reduces the strain on the cable. Another major benefit of this design, as discussed more in the next section, is a significant reduction in the length of the ends of the block coil designs.

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 factor of five 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 0.2 mm and the length/radius of the overpass/underpass ends being 50 mm while the length of conventional lifted ends would be 250 mm. A more detailed and complete modelling of these strains will be carried out as a part of this proposal.

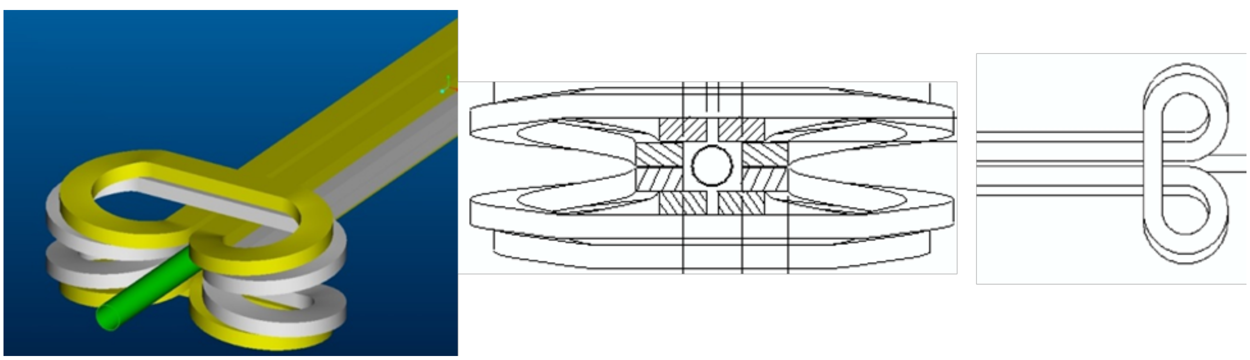


Figure 4: Overpass/Underpass design concept [7] for clearing the bore tube (left) in racetrack coil dipoles. A view from the side (middle) and top (right) showing the cross-section and coils (including ends) of the overpass/underpass design.

Fig. 4 illustrates the conceptual design concept of a block-coil dipole in a paper by Gupta, et. al, [7] based on the overpass/underpass design for the magnet ends. An easy way to understand this concept (or path of the cable) is to imagine that the cable is traveling as an automobile on a highway and then it reverses direction using a highway overpass/underpass bridge (see Fig. 4, right). The cable (or automobile) clears the beam (traffic) via the overpass/underpass, comes back to the same plane and changes the direction of travel, as desired. The coil ends clear the beam tube without a hard-way bend. Moreover, unlike as in dog-bone ends [2], no reverse curvature is involved. The cable traverse involves a twist or tilt, as also seen sometimes on an overpass/underpass of high-speed expressway. This twist is much smaller than that in a "Twisted Stacked-Tape Cable [9]" made with HTS tape, and is unlikely to degrade a Nb_3Sn cable

For winding the coil, the turns are wound outside-in (i.e., the turn furthest away from the center is wound first), and one turn naturally goes over another. 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 along the width of the tape will remain the same through the end).

The primary purpose of this proposal is to develop and demonstrate the overpass/underpass design for a high field Nb_3Sn racetrack coil block made with the current Rutherford cable to clear the beam tube. 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 needs 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 make the ends much shorter.

Shorter Ends of Overpass/Underpass Coils

A significant disadvantage of lifted ends in block coil designs is that they are excessively long, as required to keep the strain low when the cable is bent in the hard direction. Fig. 5 shows a conceptual comparison to illustrate the significant reduction in the length of the coil (for the same length of the magnet straight section) when overpass/underpass ends are used (see the lower coil in Fig. 5) as compared to that of a convention block coil with lifted ends to clear the bore tube (see the upper coil in Fig. 5).

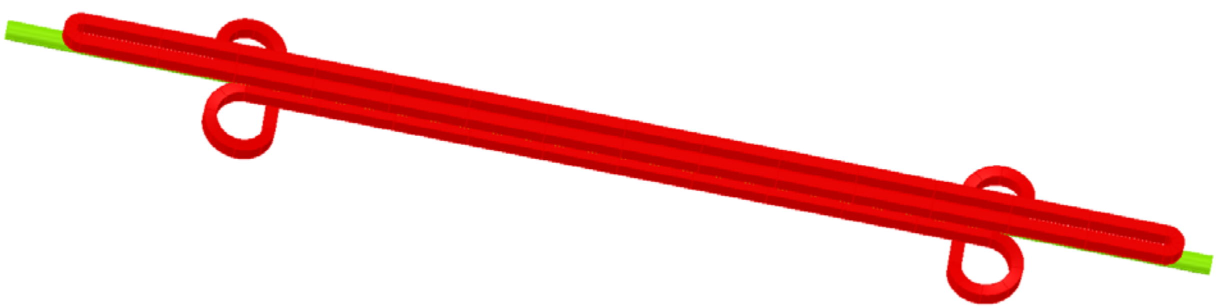


Figure 5: A comparison of the length of the ends in a coil with overpass/underpass ends (see the lower coil) and a coil with lifted ends (see the upper coil) needed to clear the bore tube (shown in green).

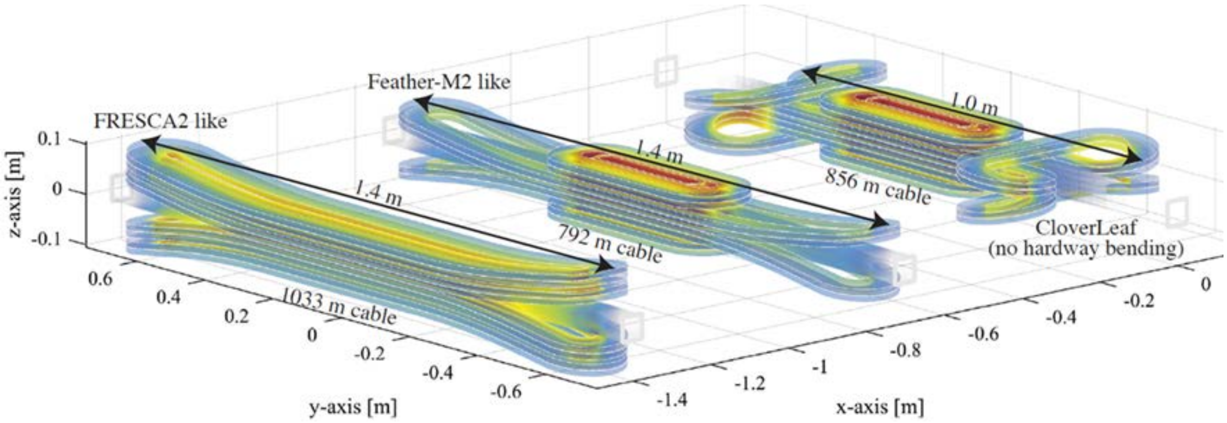


Figure 6: A comparison of the length of the ends in a coil with lifted ends (see left) and a coil made with overpass/underpass ends (right) needed to clear the bore tube [10].

This feature was also noted by J. van Nugteren, et al., in a recent paper at the European Conference on Applied Superconductivity, EUCAS 2017 [10] with updates on the program provided on this site [10]. An illustration from the EUCAS paper [10] is shown in Fig. 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 a more careful calculation. A 3-D mechanical analysis of the design will also need to be performed.

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 in conventional lifted-end designs, particularly at and near the end region. The primary purpose of this proposal is to demonstrate this technology for Nb_3Sn coils.

Anticipated Public Benefits

The block coil designs (two single aperture coils for 2-in-1 or the 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) [11]. 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 to clear the beam tube which 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.

Because the proposed project aims to benefit the science of building colliding beam accelerators, the most immediate beneficiaries are researchers working in High Energy Physics (HEP) around the world. The market for colliding beam accelerators is small when measured in the number of units, with typically only one or two such devices constructed every 10 to 20 years. However, the market as measured in dollars can be huge, with project costs in the range of tens of billions of dollars. The high field magnets used in such colliders are a major portion of this cost.

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 unforeseen at present. 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 proposed project can also contribute to more immediate practical advances in an indirect way. Compact, high field superconducting magnet technology may find use in the fields of Magnetic Resonance Imaging (MRI), Superconducting Magnetic Energy Storage (SMES), proton and ion therapy accelerators, and wind power generation. Although these fields are unlikely to need the common coil geometry of a colliding beam accelerator, the advances in superconducting technology gained during the project may prove very important for superconducting magnet technology in general. (For instance, advances in stabilizing coils against the Lorentz Forces can be important for many applications.) These issues are discussed more fully in the Commercialization Plan (attached as part of this proposal).

Global Interest in Overpass/Underpass Coils

The overpass/underpass or cloverleaf design for high field dipoles is being currently advocated at BNL by Gupta (PI of this proposal) and at CERN by Nugteren, et. al. [12-14] 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 an 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 only at low field level and force level at 77 K due to the budget constraints of a Phase I SBIR. Those test results, as partially presented at the 2016 Low Temperature Superconductor Workshop (LTSW16), showed no measurable degradation in the overpass/underpass geometry [15].

The BNL-built HTS coil which was part of the SBIR on overpass/underpass design with e2P is shown in Fig. 7 (left). A practice winding of the overpass/underpass coils at CERN is shown in Fig. 7 (right).

The overpass/underpass (cloverleaf) ends are now being used in 8 an T HTS dipole for the high field (https://www.researchgate.net/project/EuCARD2-HTS-Magnet) EuCARD2/EuCARD3 dipole [10]. The basic design [10] of integrating overpass/underpass block coils required clearing the bore tube with the other flat racetrack block coils is shown in Fig. 7 (right).

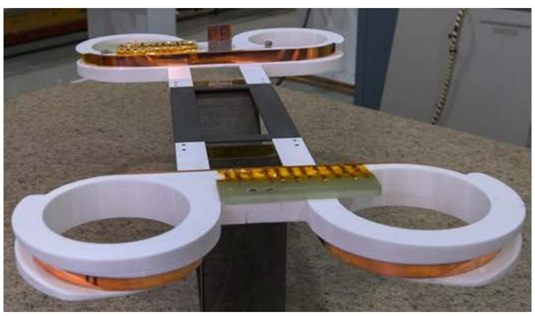
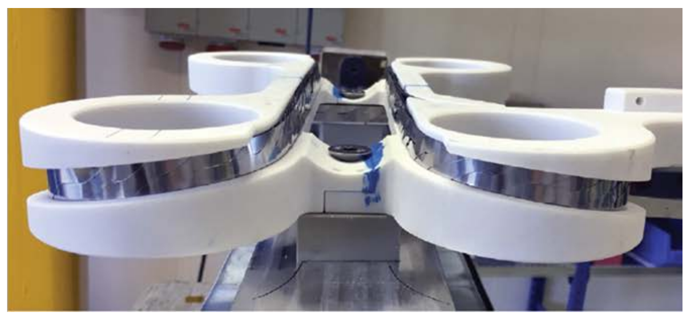



Figure 7: (left) Winding of an HTS coil at BNL under an SBIR with Energy to Power Solutions, e2P [15], and (rjght) winding of the practice coils at CERN [9] under EuCARD program.

The overpass/underpass or cloverleaf geometry was also considered for use in the EuCARD2 program, but the construction of the magnet was already underway which made its use impractical at that time. As written by Jeroen van Nugteren [12] of CERN:

> *"To achieve an optimized conductor alignment with the magnetic field direction in three dimensions is challenging. Due to the alignment requirement only few coil-end options are available. The first is the Freeway Overpass/Underpass End designed at Brookhaven National Laboratory [.., ..]. This is a very promising coil-end because it needs almost no hard-way bending, can achieve field alignment and results in very short coil ends. However, for this project, these coil-ends would prevent the placement of the insert into an existing outsert as for example Fresca2. In the future this can be avoided by assembling the outsert on top of the insert, implying that the insert coil must be longer than the outsert."*

Design studies for a 20 T dipole based on the overpass/underpass (cloverleaf) ends are also being performed at CERN [13-14]. The cross section of such a model magnet is shown in Fig. 8 (left) and mechanical analysis of the ends in Fig. 8 (right). The mechanical analysis performed at CERN shows that strains on the conductor remain low in this design [14].

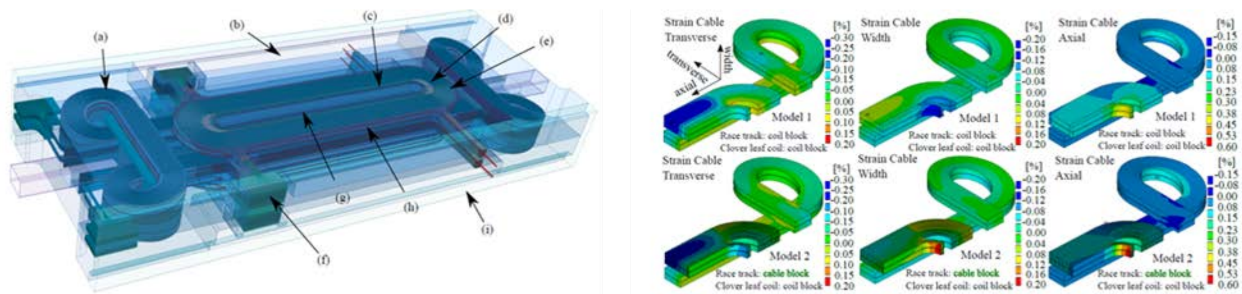


Figure 8: The basic design of the proposed 20 T HTS R&D dipole [13] at CERN (left) and 3-d mechanical analysis showing lower strains on the conductor in this new design [14].

Technical Objectives

The PBL/BNL team will use its expertise and working relationship to develop this design and technology. The primary technical objective of this proposal is to apply the overpass/underpass design to the "Wind & React" Nb_3Sn technology. The basic design itself, however, offers the potential for it to be applicable to HTS (ReBCO tape and Bi2212 Rutherford cable) magnets as well [7]. Due to budget constraints, the Phase I will be limited to the design and practice winding; however, Phase II will involve an actual demonstration of this design at a field over 10 T with a pair of coils wound with Nb_3Sn. This ambitious 10 T demonstration within the budget of Phase II is possible due to the unique design of the BNL common coil dipole magnet DCC017 [16] which allows insert coils to be inserted and become part of the magnet, as first demonstrated in an earlier PBL/BNL Phase II SBIR [17]. 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 [18].

In Phase I, 2-d and 3-d magnetic and mechanical design studies will be performed for a "proof-of-principle" dipole. In addition, the practice overpass/underpass coils will be wound with the Rutherford cable. These practice windings may also be used to simulate the coils to be integrated with the BNL common coil magnet DCC017 [16] in a "mockup assembly". The team of PBL and BNL will utilize its 3-D printer to make parts, which will allow the parts for practice coils and mockup structure to be manufactured within the Phase I budget. Magnetic and preliminary mechanical designs of a 16 T Nb_3Sn dipole will be carried out. The PBL/BNL team will use analytical tools such as ROXIE, OPERA, ANSYS, COMSOL and other CAD/CAM programs.

In Phase II, a Nb_3Sn coil will be wound, reacted and impregnated. The coil will be integrated with other Nb_3Sn coils, reaching a bore field of about 12 T in the "proof-of-principle" dipole magnet. Such a high field demonstration is possible within the budget of Phase II, thanks to the unique geometry of the BNL common coil dipole DCC017. An earlier PBL/BNL Phase II demonstrated that R&D test coils can be inserted and tested as an integral part of the magnet without any need to disassemble and reassemble this magnet [17]. To allow insertion of an overpass/underpass coil without disassembling, one end may have the overpass/underpass end geometry with the other end having a conventional flat racetrack coil geometry, depending on the cable parameters and on the assembly technique developed. In addition, at the end of Phase II preliminary engineering 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, and into the Phase III effort of the model magnet production.

Work Plan

The detailed work plan will involve the following series of tasks:

Task 1: Perform 2-d and 3-d magnetic design for the proof-of-principle Nb_3Sn dipole. The concept of the Overpass/Underpass designs for the pole blocks of a 2-in-1 common coil dipole is shown in Fig 9. Previously built and tested BNL common coil dipole DCC017 [16], which was built without the field shaping coils, will be used to facilitate proof-of-principle magnet. The initial design studies show that the proof-of-principle overpass/underpass coils if used with the additional racetrack coils (not part of this proposal) will significantly improve the field quality (see model and improvement in field uniformity plotted along vertical axis of one aperture in Fig. 10). The expected increase in the field at the center of the aperture is modest, from 10.2 T to about 10.6 T. As a part of Phase I, a few magnetic designs involving both 2-D and 3-D models will be developed where new Nb_3Sn pole coils will run in series with the existing Nb_3Sn coils of DCC017. The computer codes ROXIE and OPERA will be used to perform this task. BNL will have primary responsibility for this task, with support from PBL.

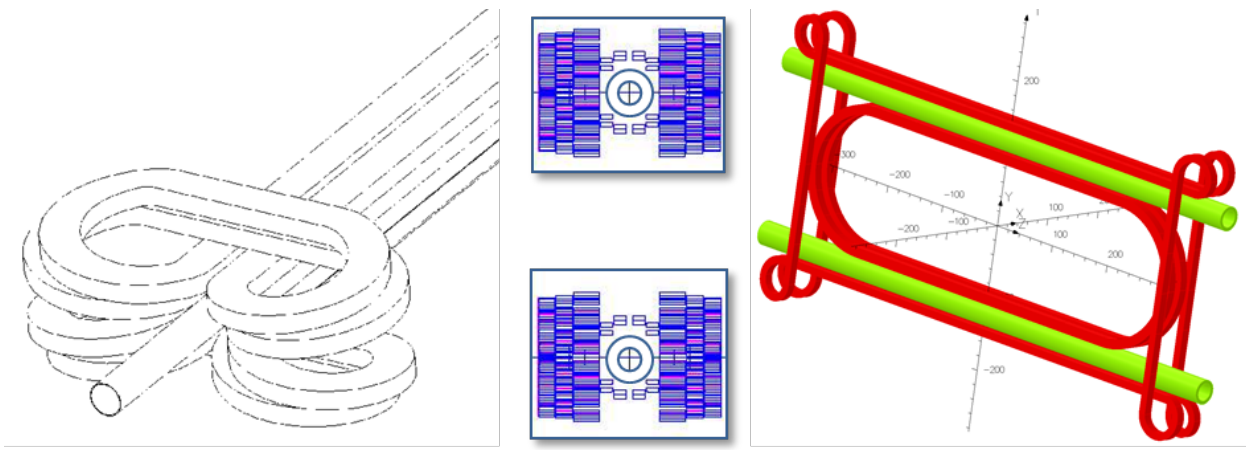


Figure 9: Conceptual design of the block coil single-aperture dipole based on the overpass/underpass design clearing the bore tube (left), common coil design with narrower cable used for pole coils over and under the beam tube (middle), and pole coils of a common coil (right) with a pair of overpass/underpass coils and a pair of racetrack coils (right). The conductor is shown in red, and the beam tube in green.

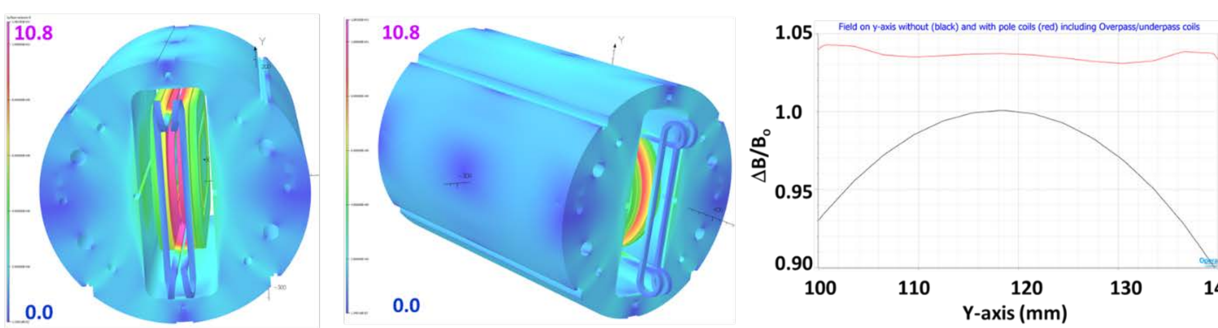


Figure 10: Initial magnetic model (left and middle) with magnetic field superimposed over the coils and the yoke of the BNL common coil dipole DCC017 with field shaping coil which include overpass/underpass coils (proposed to be built in Phase II). Improvement in field uniformity is clear from the picture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

Task 2: Perform 2-d and 3-d mechanical design for the proof-of-principle Nb_3Sn dipole. We will perform 2-D and 3-D mechanical analysis of the selected magnetic design for the proof-of-principle overpass/underpass dipole, where the new structure will get integrated with the existing structure of DCC017 providing the background field. The task will involve the use of sophisticated design and analysis tools such as ANSYS and COMSOL. We will also perform a more complete calculations of the strain on the conductor in the ends. This will be a joint task between the PBL and BNL teams, with PBL taking the lead.

Task 3. Perform coil winding tests. We will wind the practice coil for the underpass/overpass design using the Rutherford cable by designing and using a proper former. Winding of a freestanding one turn with Rutherford cable is shown in Fig. 11.

Figure 11: Two views of the winding of a freestanding turn of the overpass/underpass end design with the Rutherford cable.

As a first step and in preparation for the demonstration of the proof-of-principle high field coil design during Phase II, two small scale model coils with the overpass/underpass ends will be wound with Rutherford cable. These coils will be made for the pole blocks of the common coil (see Fig. 11). Parts will be made using the PBL 3-D printer purchased for an earlier proposal. The BNL technical staff, with input from the PBL team, will take the primary responsibility for this task.

Task 4. Perform mockup assembly tests. Coils wound in the previous tasks and parts made by using the PBL 3-D printer purchased for an earlier proposal will be used to practice a mockup assembly (such as one shown in Fig. 12) of the "proof-of-principle" dipole to be built and tested in Phase II. The BNL technical staff, with input from the PBL team, will take the primary responsibility for this task.

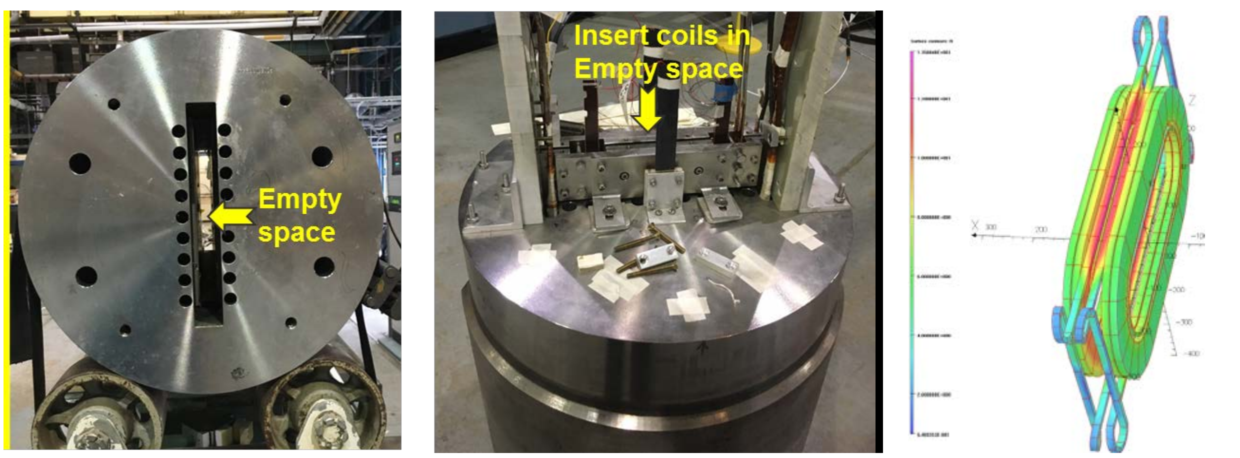


Figure 12: BNL common coil dipole with a large open space (left), with insert coil for another PBL/BNL STTR (middle), and the magnetic model of the proof-of-principle test (right). Similar to the design of the pole blocks of a high field common coil dipole, the overpass/underpass ends of the proof-of-principle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

Task 5: Selection of conductor and cable for the proof-of-principle magnet. This task will involve choosing the proper strand and cable for various magnetic designs for Task 1 above, as well as for the coils proposed to be built in Phase II. The cable to be used in Phase II will use Nb_3Sn strands developed for the LARP (Large Hadron Collider Accelerator Research Program) project. The choice of the Nb_3Sn cable for Phase II will be made such that the overpass/underpass insert coil runs in series with the existing Nb_3Sn coils in DCC017 with a single power supply. This task will be led by PBL.

Task 6. Plan for proof-of-principle tests in Phase II. Construction and testing of a field approaching 16 T is beyond the budget and scope of the STTR program. However, two proof-of-principle tests with Nb_3Sn coils will be performed in Phase II. BNL built its Nb_3Sn common coil dipole DCC017 [16] with a large open space (see Fig. 11, left) between the coils (~30 mm horizontal and ~220 mm vertical). This large open space allows coils to be inserted and tested. This was successfully demonstrated [17] in an earlier PBL/BNL STTR (see Fig. 11, middle). The envisioned Phase II effort is expected to be a low-cost, fast-turnaround proof-of-principle demonstration, primarily because DCC017 was designed and built such that it requires no major disassembly and reassembly for insert coil testing. New Nb_3Sn pole coils will be built and integrated (see Fig. 11, right) with the existing coils of DCC017 in Phase II, to reach a bore field of over 12 T. A special support structure for the ends will be required for the new coils. In the proof-of-principle magnet, the coils will have a conventional flat racetrack coil end geometry on the end that will be inserted and the overpass/underpass geometry on the ends that will protrude. This also brings the overpass/underpass ends into a region of low field. Phase I will develop the basic plans based on which detailed engineering design will be carried out and the support structure will be designed for Phase II. This task will be led by BNL with input from PBL.

Task 7: Develop a conceptual design for the assembly and test of the overpass/underpass coils in the proof-of-principle dipole. Using the results of the mechanical analysis performed in the previous tasks, the support structure design concepts will be developed to withstand the Lorentz forces within the limits of space available in the BNL background field common coil magnet. A similar program was successfully carried out in a previous Phase II PBL/BNL STTR, where the HTS coils were inserted in the background field of the magnet DCC017 and became an integral part of the magnet during the test [17]. That experience will be useful for performing this task. This will be a joint task between the PBL and BNL teams and will involve the use of sophisticated design and analysis tools such as ANSYS, COMSOL and other CAD/CAM programs. Both teams will provide input into the technical approaches for coil support. The BNL team will take the lead on adapting the coil support plan to the specific interface with the common coil background field magnet at BNL.

Task 8. 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 which clear the bore tube with relatively compact and well performing ends, will bring the block coil designs to a more competitive level. The cable design for an optimized 16 T design is likely to be different from the one that will be used in the proof-of-principle test, where the insert overpass/underpass coils will run in series with the main coils. This task will be jointly performed by the PBL and BNL teams.

Task 9. Prepare the Phase I Final Report and identify the key components for a Phase II proposal. Both the PBL and BNL teams will participate in identifying the key components for a Phase II proposal and for the writing of the Phase I final report.

Performance Schedule

Task 1: Perform 2-d and 3-d magnetic design for the proof-of-principle Nb_3Sn dipole: Weeks 1-20.

Task 2: Perform 2-d and 3-d mechanical design for the proof-of-principle Nb_3Sn dipole: Weeks 4-22.

Task 3. Perform coil winding tests: Weeks 13-26.

Task 4. Perform mockup assembly tests: Weeks 21-34.

Task 5: Selection of conductor and cable for the proof-of-principle magnet: Weeks 1-36.

Task 6. Plan for proof-of-principle tests in Phase II: Weeks 15-36.

Task 7: Develop a conceptual design for the assembly and test of the overpass/underpass coils in the proof-of-principle dipole: Weeks 13-36.

Task 8. 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: Weeks 31-36.

Task 9. Prepare the Phase I Final Report and identify the key components for a Phase II proposal: Weeks 35-39.

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 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.

American-Made

To the extent possible in keeping with the overall purposes of the program, PBL and BNL will work to ensure that only American-made equipment and products will be purchased with the funds provided by the financial assistance under DOE Phase I grants.

Research Institution (RI)

This grant application involves a formal collaboration between Particle Beam Lasers, Inc. and a research institution, Brookhaven National Laboratory. More detail can be found in the attachments in field 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
Phone: (631) 344-2103

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

Erick Hunt
Manager, Research Partnership
(631) 344-2103
ehunt@bnl.gov

Total dollar amount of the subcontract: $114,000

Other Consultants and Subcontractors

BNL will be a subcontractor for the Phase I effort. There will be no other consultants or subcontractors on the Phase I effort.

Team Qualifications; Where and How Tasks Will Be Done

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), Anis Ben Yahia (Postdoc) and other magnet division staff at BNL. Dr. Gupta will also supervise the work performed at the BNL, which will focus on the overall magnet design and winding of the practice coils (including the manufacturing of the parts needed) during the proposed Phase I. Dr. Gupta presented [7] the overpass/underpass design at the Applied Superconductivity Conference in 2002 (ASC2002) and more recently at the collaboration meeting of the US Magnet Development Program [7] and has led the development of the common-coil 2-in-1 dipole design for hadron colliders. Dr. Gupta presented the common coil design at the 1997 Particle Accelerator Conference in Vancouver, Canada. Dr. Gupta has more than three decades of experience in the design of superconducting accelerator magnets for various applications. His current interest includes developing and demonstrating high field and HTS magnet designs and technology for particle accelerators and beam lines. Dr. Gupta has developed a cost-effective, rapid-turnaround and systematic magnet R&D approach which will be employed in this proposal. Dr. Gupta is the PI or sub-grant PI of several other grants. He is also sub-grant PI of several previous Particle Beam Lasers, Inc. SBIRs. Among other major projects, Dr. Gupta leads the BNL activities for the US Magnet Development Program (MDP) for developing high field magnets. Dr. Gupta was also PI for the development of HTS magnets for RIA, FRIB and sub-grant PI for the BNL magnet division of a program concerning HTS SMES. Dr. Gupta has also worked on conventional Low Temperature Superconductor cosine-theta magnet designs for RHIC and the SSC. Dr. Gupta has taught several courses on superconducting magnets at U.S. Particle Accelerator Schools.

Dr. Stephan Kahn will be the principle investigator and magnet designer for PBL. Dr. Kahn has 35 years of experience with superconducting accelerator magnets. He has worked as a PI on four previous SBIR grants. He has worked at the Advanced Accelerator Group at BNL on neutrino factory and muon collider R&D. His previous experience at Brookhaven has been broad, including work on high energy physics experiments (neutrino bubble chamber experiments and the D0 experiment) and superconducting accelerator magnets (for ISABELLE, RHIC, the SSC and the APT). Work to design superconducting magnets included 2D and 3D finite-element field calculations using the Opera2d and Tosca electro-magnetic design programs along with structural finite-element calculations with ANSYS.

Dr. Ronald M. Scanlan will lead the conductor specifications and procurement on this project. Dr. Scanlan has had 35 years of experience in the field of superconducting magnets and materials at the General Electric R&D Laboratory, Lawrence Livermore National Laboratory, and Lawrence Berkeley National Laboratory (LBNL). From 1999 until his retirement from LBNL in 2003, he was the Group Leader for Superconducting Wire and Cable Development. He was responsible for the U. S. Department of Energy, Division of High Energy Physics, Conductor Development Program. From 1995 to 1999, he was Program Head for Superconducting Magnet Development at LBNL, during which time a world-record 13 T Nb_3Sn dipole magnet was built and tested. Earlier in his career, he was responsible for the development of Nb_3Sn conductor for the MFTF fusion magnet (a 14 T solenoid) at the Lawrence Livermore National Laboratory. He is the author or co-author of over 100 publications in the field of superconducting magnets and materials. In 1991, he shared the IEEE Particle Accelerator Conference Award with Dr. David Larbalestier for "the development of NbTi superconducting material for high current density application in high field superconducting magnets", and in 2011 he received the IEEE Council on Superconductivity award for "Continuing and Significant Contributions in the Field of Applied Superconductivity".

Robert J. Weggel will support the PBL magnet design work for this Phase I project. He has been PI for PBL on several recent SBIR/STTR projects. Mr. Weggel has over 50 years of experience as a magnet engineer and designer at the Francis Bitter National Magnet Laboratory at MIT and BNL and as a consultant in magnet design. In the course of his career he has authored over 100 peer-reviewed articles concerning resistive and superconducting magnets as well as hybrid high-field versions. He has extensive experience optimizing magnets for various uses including solid-state research, accelerator and medical applications. He has contributed extensively to the book *Solenoid Magnet Design* by Dr. D. B. Montgomery and was principal proofreader and equation-checker for the 682-page textbook *Case Studies in Superconducting Magnets*, 2nd edition, by M.I.T. Prof. Y. Iwasa.

Dr. Erich Willen, a PBL employee, will contribute his expertise in the areas of magnet design and magnetic field quality. Previously, he served as PI on a related SBIR entitled "Magnet Coil Designs Using YBCO High Temperature Superconductor." Dr. Willen became the head of the Magnet Division at BNL in 1984 and led the development of the SSC and RHIC superconducting magnets.

Work by PBL employees will largely be done in the existing PBL offices, often located in our employee's homes. Work by the PI will be predominantly done at BNL. Frequent meetings will be held both over phone conferences and face to face. The tasks will be done in manner consistent with similar efforts done by our highly qualified employees on previous projects.

How the Research Effort Could Lead to a Product if Funded Beyond Phase I

If funded beyond Phase I, the research effort will lead to the demonstration of this novel design and the technology in Phase II. The Phase II demonstration, if successful, is expected to play a role in high field magnet applications for accelerators, which itself is expected to be a multi-billion-dollar industry. The design and technology have applications beyond magnets for accelerators, such as magnets for testing cables for High Energy Physics (HEP) and Fusion Energy Sciences (FES), etc. in future test facilities in Europe (CERN) and in the US. In fact, the test facility that is currently being developed at CERN is based on the block coil design and the one that is being proposed in US is also considering the block coil design. Both magnets are relatively short and in both the overall magnet length and stored energy has become significantly higher because the ends are made significantly longer than the conventional cosine theta magnets to keep strain low and to avoid the problem of the end region limiting the magnet performance. The overpass/underpass design significantly reduces the magnet length, stored energy and strain. However, such a new design can't be considered in a high cost one-off magnet without a prior proof-of-principle demonstration. Therefore, the success of research in Phase I and then a proof-of-principle demonstration in Phase II has a potential for making significant advances in magnet technology and hence in the applications those magnets are intended for. For a more complete description of the excellent commercialization potential that this project has, please consult the commercialization plan that is attached to this proposal.

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 above. The technical staff will meet whenever needed to ensure that important milestones are being met in a timely way. In the final meeting, PBL senior management will also travel to participate. At the final meeting, held approximately six weeks prior to project completion, the team will identify any problems as well as ensure ways to solve them. We will also plan for the Phase I final report and Phase II proposal at that final face to face meeting.

PBL has much 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.

Bibliography & References Cited

1. The Particle Physics Project Prioritization Panel (P5) and its subpanel on Accelerator R&D, http://science.energy.gov/hep/hepap/.
2. W. Sampson, unpublished (1980).
3. P. Ferracin, et al., "Recent Test Results of the High Field Nb_3Sn Dipole Magnet HD2," IEEE Transactions on Applied Superconductivity, Vol. 20, No. 3, June 2010.
4. A. Milanese, et al., "Design of the EuCARD High Field Model Dipole Magnet FRESCA2," IEEE Transactions on Applied Superconductivity, Vol. 22, No. 3, June 2012.
5. A. McInturff, et al., "Current Status of the Texas A&M Magnet R&D Program," IEEE Transactions on Applied Superconductivity, Vol. 21, No. 3, June 2011.
6. R.C. Gupta, "A Common Coil Design for High Field 2-in-1 Accelerator Magnets," 1997 Particle Accelerator Conference in Vancouver, Canada (1997).
7. R. Gupta, et al., "Next Generation IR Magnets for Hadron Colliders," Presented at the Applied Superconductivity Conference at Houston, TX, USA (2002).
8. A. Koski and S.L. Wipf, "Computational Design Study for an Accelerator Dipole in the range of 15-20 T," IEEE Transaction of Magnetics, Vol. 32, No. 4, July 1996.
9. M. Takayasu, L. Chiesa, P.D. Noyes, and J.V. Minervini, "Investigation of HTS Twisted Stacked-Tape Cable (TSTC) Conductor for High-Field, High-Current Fusion Magnets," IEEE Transactions on Applied Superconductivity, Vol. 27, No. 4, June 2017.
10. 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 and https://www.researchgate.net/project/EuCARD2-HTS-Magnet
11. https://home.cern/science/accelerators/future-circular-collider.
12. J. van Nugteren, "High Temperature Superconductor Accelerator Magnet", Page 46-47, https://cds.cern.ch/record/2228249/files/CERN-THESIS-2016-142.pdf .
13. J. van Nugteren, J. Murtomäki, G. Kirby, T. Nes, G. de Rijk, L. Bottura and L. Rossi, "Design and Optimization of a Full HTS Accelerator Dipole for Achieving Magnetic Fields Beyond 20 T," poster presented at the 2018 Applied Superconductivity Conference, Seattle, USA.
14. J. Murtomaki, J. van Nugteren, A. Stenvall, G. Kirby and L. Rossi, "3-D Mechanical Modelling of 20 T Clover Leaf Ends Coils - Good Practices and Lessons Learned," Presented at the 2018 Applied Superconductivity Conference, Seattle, USA; Early access available at https://ieeexplore.ieee.org/document/8642381/authors.
15. R. Gupta, C. Rey, et al., Presentation and Posters at 2016 Low Temperature Superconductor Workshop," Santa Fe, NM, February 8-10, 2016; one presentation available at https://www.bnl.gov/magnets/staff/gupta/Talks/ltsw16/gupta-ltsw16-poster.pdf https://www.bnl.gov/magnets/Staff/Gupta/Talks/ltsw16/gupta-ltsw16-presentation.pdf.
16. R. Gupta, et al., "React & Wind Nb_3Sn Common Coil Dipole," 2006 Applied Superconductivity Conference, Seattle, WA, USA, August 27-September 1, 2006.
17. R. Gupta, et al., "Design, Construction and Test of HTS/LTS Hybrid Dipole," International Conference on Magnet Technology (MT-25), Amsterdam (2017).
18. R. Gupta, et al., Common Coil Dipoles for Future High Energy Colliders, 2016 Applied Superconductivity Conference, Denver, September 4-9, 2016 .