Project Narrative

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Principal Investigator:	*Ronald M. Scanlan*
Project Title:	*Development of an accelerator quality high field common coil dipole magnet*
Topic No. 27:	*Superconductor Technologies for Particle Accelerators*
Subtopic: (b)	*Superconducting Magnet Technology*
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1.0 Significance, Background Information, and Technical Approach

To search beyond the Higgs boson requires particle accelerators of unprecedented energy, most requiring dipoles of very high field to bend the particle beam to the desired radius. The 2014 Particle Physics Project Prioritization Panel (P5) vision document [1] addressed pressing scientific questions and made dozens of recommendations to the U.S. Department of Energy. #24 was: "*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*". The High Energy Physics Advisory Panel (HEPAP) subpanel further called for "*simplicity in design for cost reduction" and "development of R&D platforms that reduce turn-around-time*". In this SBIR/STTR proposal, the PBL/BNL team proposes to develop new technologies for high-field superconducting magnets, a key for high-energy proton colliders, which satisfies the guiding principles laid out in the reports by P5 and by the HEPAP subpanel.

This proposed Phase II advances a new approach and technology for building high field dipoles based on the common coil design [2] for high energy colliders [3, 4, 5]. Because of the inherent simplicity and conductor friendly nature of the design, the common coil magnets are likely to be less expensive and easier to manufacture than the more conventional cosine theta magnets, particularly for high fields that require the use of brittle conductors such as Nb_3Sn. In Phase I, we developed several designs for 16 T Nb_3Sn dipoles [6], which in addition to other advantages met the field quality requirements as specified for the proposed Future Circular Collider (FCC) [3] with the help of appealing configurations of the pole coils. In Phase II, we will wind the most promising configuration of the pole coil and integrate it with the existing common coil magnet DCC017 at BNL [7] for a proof-of-principle demonstration of the design. Such a task is possible within the budget of an SBIR/STTR, as demonstrated in another PBL/BNL Phase II proposal, due to the unique geometry of the DCC017 magnet, which allows new coils to be inserted and become an integral part of the magnet with the existing Nb_3Sn coils without requiring expensive and time consuming disassembly and reassembly of the magnet.

Most previously tested dipoles based on the common coil design [8, 9, 10] had generally good quench performance, likely due to the simpler racetrack geometry. Designs also tolerated large displacements (reducing the cost of the structure) without causing large strain on the conductor. The common coil geometry also allows easier segmentation between Nb_3Sn and NbTi or HTS and LTS coils, reducing the costs. Another significant advantage of the common coil design based on simple racetrack coils with large bend radii is that it allows winding with pre-reacted conductor. The "React & Wind" approach is compatible with a greater variety of insulation and coil materials (because they don't have to withstand the high reaction temperature) and magnet construction techniques that could not be used with "Wind & React". Furthermore, the modular nature of the common coil design also facilitates a "rapid-turn-around" and "cost-effective" magnet R&D, which allows proposals such as this to make major technology developments and demonstrations within a limited budget and timeframe.

Another significant deliverable of Phase II will be the preliminary engineering design of a 16 T common coil dipole that minimizes cost, provides an adequate support structure to withstand the Lorentz forces associated with these high fields, and can be built industrially in large numbers.

In summary, a successful completion of Phase II is expected to have a major impact on future high field magnet technology, as it will build and test a never-before demonstrated proof-of-principle accelerator grade common coil dipole that allows more options and has the potential to produce reliable and lower cost collider dipoles.

2.0 Anticipated Public Benefits

The common coil design is expected to provide a lower cost and technically attractive solution to the high field dipoles required for a Future Circular Collider (FCC). Lower cost magnets will provide significant savings to the public, and in fact may be essential for building these very expensive machines that will cost tens of billions of dollars. Lower costs are expected because of (a) the simpler geometry and (b) the reduction in the number of coils by a factor of two that accrues from the same coil serving both beam apertures. The common coil design is technically attractive for high field magnets because the coil modules move as a unit against the large Lorentz forces and therefore the relative motion and internal strain on the conductor is minimized by this approach.

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

The public benefit from High Energy Physics 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 presently unforeseen. 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 cease.

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. As discussed more fully in the Commercialization Plan attached as part of this proposal, the MRI, ion therapy and SMES markets together are in the billion-dollar range, which is indicative of a significant public market.

3.0 Technology for the Phase II Project

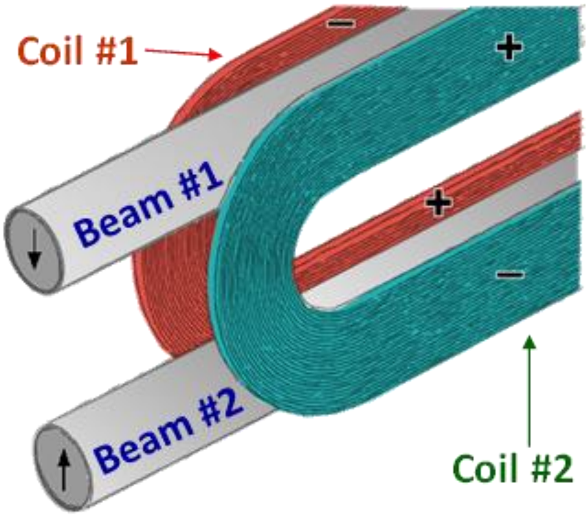
In this section, we summarize the technical basis of the Phase II proposal. That, in addition to the work performed in Phase I of this proposal (see next section), provides a sound basis for the Phase II project proposed here.

3.1 Common Coil Design for High Field Collider Dipoles

In the common coil design, the coils are common between the two apertures, providing a natural 2-in-1 configuration with fields in opposite directions as needed in particle colliders (Fig. 1). It offers a conductor-friendly design based primarily on racetrack coils with large bend radii. The design is particularly suitable for high field magnets made with brittle conductor. The common coil geometry is expected to produce magnets that are lower in cost, easier to manufacture and technically attractive for high field 2-in-1 dipoles. Several anticipated advantages of the common coil design are:

- Simple 2-d coil geometry for colliders
- Fewer coils (about half), because the same coils are common between the two apertures (2-in-1 geometry for both iron and coils)

- Conductor friendly simpler ends with much larger bend radii (determined by the separation between the two apertures rather than the aperture itself)
- Allows both technology options: "React & Wind" in addition to the predominantly used "Wind & React"
- Additional material options for insulation and coil material in the "React & Wind" approach, because the coil doesn't go through a high temperature reaction
- More automated manufacturing possible in large scale production because of simpler geometry
- Lower internal strain on the conductor under Lorentz forces, because coils move as a unit
- Savings from less support structure, because much larger deflections are acceptable
- Potential for producing lower cost, more reliable (less margin necessary) high field magnets
- Offers a flexible and modular design with easier segmentation for hybrid high field dipoles (accrues from the natural decrease in field from inner layers to outer ones) using a variety of conductors (Nb_3Sn, NbTi and also HTS for very high fields)



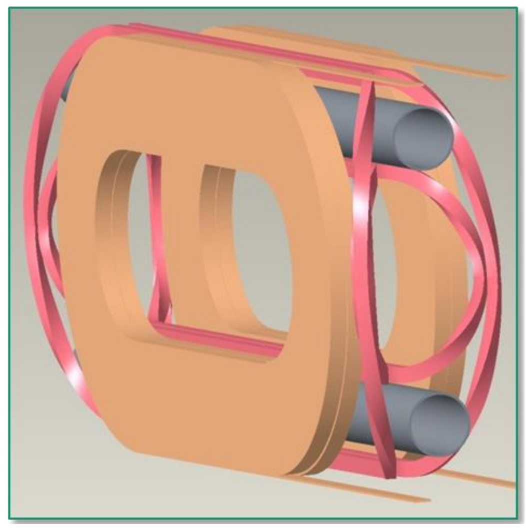
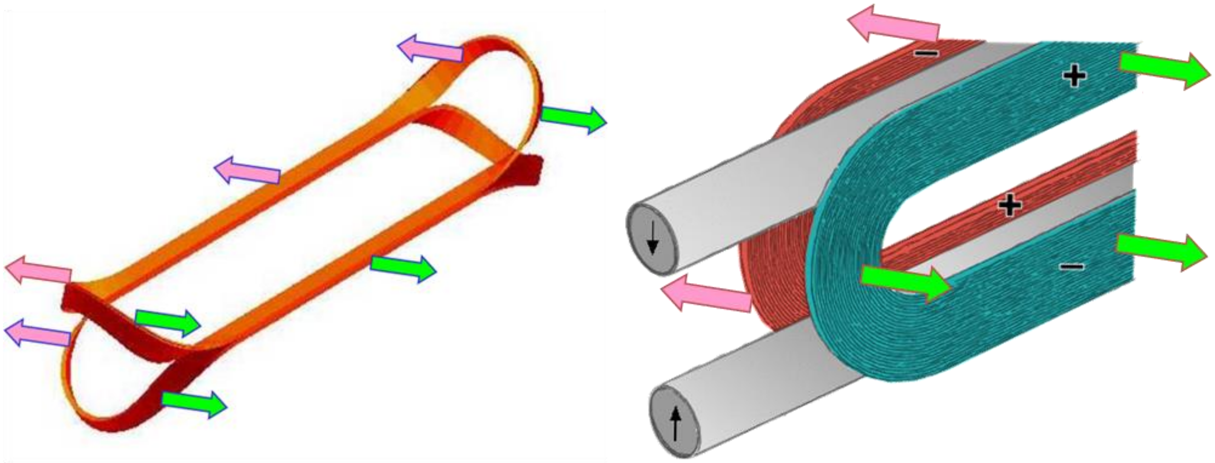


Figure 1: Illustrative common-coil dipole magnets. Left: A rudimentary design, with two racetrack coils energized oppositely. Plus and minus signs indicate the polarity of current flow; arrows, the field direction in the beam pipes—downward in #1 and upwards in #2. Right: With "pole" coils (pink), necessary for accelerator-quality field homogeneity.

A great virtue of the common-coil design is that it allows each coil block to move as a separate unit, which reduces stresses and strains on the conductor at the ends. As suggested by Fig. 2a, cosine-theta (and also conventional block-design) magnets tend to be plagued by large stresses and strains on the conductor in the end region. In contrast, the common-coil design (Fig. 2b) allows each coil to move as a separate unit, thus incurring much smaller stresses and strains, despite what might be a large displacement of each coil as a whole. Less support structure may suffice, so long as field quality remains adequate. Lowered conductor strain despite reduced structural material may imply better performance as well as lowered cost—both issues in high-field accelerator magnets, where reliability is absolutely essential and magnet structure a major contributor to cost.

In various laboratories where R&D magnets based on this design were built and tested [7, 8, 9, 10], with the initial test results were obtained relatively quickly. The very first common coil test magnet at LBNL was designed and built [8, 9] while the P.I. was Program Head and Dr. Gupta was the chief designer. It reached the short sample limit with no training quench.

However, none of the successful magnets had the field quality that is required in accelerator magnets. To produce the good field quality needed, pole blocks must be added to the simple coil geometry (Fig. 1). The addition of pole blocks brings some complexity to the design, but it remains simpler and attractive as compared to the other conventional designs such as cosine theta and single aperture block coil design. Whereas the conductors in the simple flat racetrack coils automatically clear the bore in going from one aperture to another aperture, conductors in the ends of the pole blocks (particularly the pole away from the center) do not. In the design optimized for pole blocks during Phase I, the conductors must be shifted sideways, which is different from the simple racetrack coil geometry.



Figures 2a&b: Lorentz forces in dipole magnets. Left: Cosine-theta (or conventional block-design) magnets typically suffer large internal stresses and strains in the conductor in their end regions. Right: Common-coil magnets may incur lower internal stresses and strains, because each coil moves as a separate unit.

3.2 BNL Common Coil Nb_3Sn Dipole DCC017 with Main Coils

BNL designed and built a unique Nb_3Sn common coil dipole DCC017 (Fig. 3, left) which has a large opening (~30 mm by ~220 mm). It reached a bore field of over 10 T [7] and plays a key role in this proposal. Mechanical structure analysis with ANSYS showed that such a design with a large open space can be built while keeping stress on the collar and end plates comparable to those in other accelerator magnets. There was no excessive internal deflection and strain within the coil, despite a displacement of the coil module as a whole by as much as 200 microns.

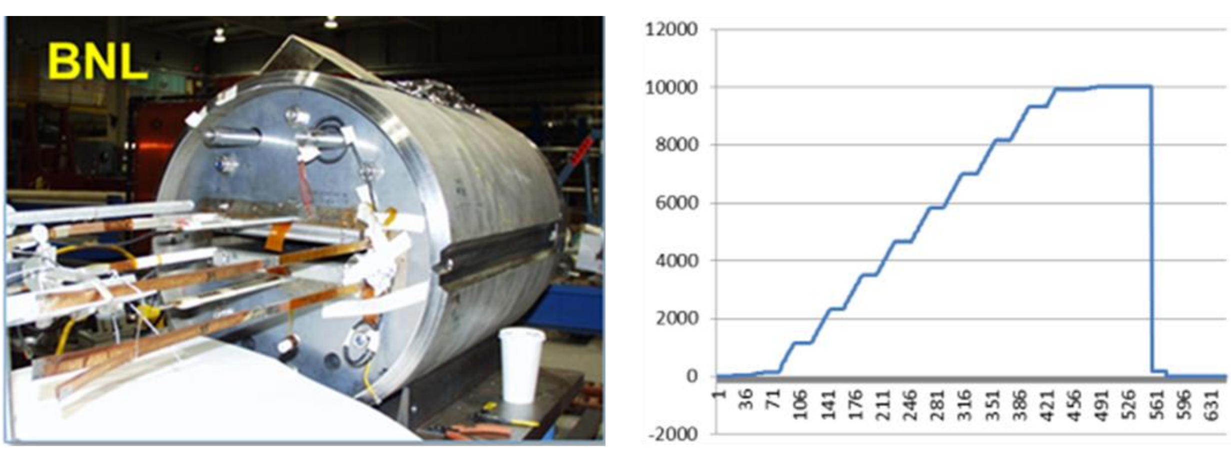


Figure 3: BNL common coil dipole DCC017 (left) and its performance during the recent tests (right) showing current vs. time plot with stepwise increase in current to 10 kA without any quenches. This is 92 % of the short sample field.

In this proposed Phase II, the new Nb_3Sn pole coils will be integrated with the existing Nb_3Sn main coils with no disassembly or re-assembly of the magnet DCC017. The new pole coils will be of the type that produces accelerator grade field quality. The common coil dipole was initially tested in 2006, when it reached the designed short sample field of 10.2 T at 10.8 kA. Recently, after a 10-year hiatus, DCC017 was recommissioned in February 2017 [11] to test an HTS insert coil as part of another PBL/BNL Phase II STTR program [12]. The magnet performed flawlessly, reaching 92 % of short sample field without quenching (Fig. 3, right). Limitation of leads, not the magnet itself, prohibited powering it to higher current. This test proved that the existing magnet DCC017 and its main Nb_3Sn coil can be used in this Phase II, a critical part of this proposal.

3.3 Quench Protection of Proof-of-Principle Common Coil Dipole with Pole Coils

In terms of quench protection, the above mentioned test shows that the magnet DCC017 remained fully protected while being tested in the PBL/BNL HTS/LTS hybrid dipole Phase II STTR; the Nb_3Sn coils were quenched together with the HTS coils many times. In addition, the Nb_3Sn coils survived many quenches during their earlier tests in 2006 [7]. Small pole coils running in series with the main coils in the proposed Phase II will not change the situation significantly. Therefore, it is expected that a similar system with only some minor modifications would be able to provide adequate quench protection.

4.0 Degree to which Technical Feasibility has been Demonstrated

In this section, we summarize the work performed in Phase I. There were two primary goals to justify pursuing the common coil design in Phase II. The first goal was to demonstrate that a high field (16 T with 50 mm aperture) accelerator quality common coil dipole could be designed. The second goal was to show (including test winding of pole coils) that a proof-of-principle accelerator type Nb_3Sn magnet could be designed, built and tested within the limited budget of Phase II. This was done by leveraging the investment in magnet DCC017, which allows integration of new pole coils with the existing main coils. Both goals were achieved.

Several common coil designs were developed in the early part of Phase I with special pole coils for the 16 T, 50 mm dipole for a FCC. These designs were reported at the 2016 Applied Superconductivity Conference [6] and had a major impact in the field, influencing common coil design elsewhere, including at CERN [13].

The technical feasibility of Phase II was demonstrated with the design and winding of similar practice pole coils. These new coils, when inserted in the existing common coil dipole at BNL, will demonstrate a proof-of-principle common coil dipole with the type of field quality needed in accelerator magnets. This could be done within the limited budget of SBIR/STTR Phase II (as demonstrated in another PBL/BNL STTR on a hybrid magnet [11, 12]), due to the unique structure of the BNL common coil dipole, with its large open space. Therefore, Phase I was very successful not only in meeting its objectives and tasks but also in creating a strong platform for the successful completion of Phase II.

Following is the list of tasks that were proposed and completed successfully in Phase I:

Task 1: Prepare a magnetic design of pole blocks to improve field quality of the DCC017 common coil magnet.

Task 2: Selection of conductor and cable for common coil magnet.

Task 3: Prepare a mechanical design of pole blocks to withstand large Lorentz forces and to reduce conductor movement.

Task 4: Develop a conceptual design for the assembly and operation of the pole block coils in a common coil dipole.

Task 5: Model coil winding tests.

Task 6: Plan the basic steps required for proof-of-principle tests.

Task 7: Plan for the design of a 16 T, 50 mm aperture common coil for a future proton collider.

Task 8: Prepare the Phase I Final Report and identify the key components for a Phase II proposal.

A very brief summary and highlights of the progress made on these tasks are discussed below. (A more comprehensive summary of the progress is presented in a separate file attached to this proposal entitled "PhaseIFinalReport,pdf".)

4.1 Common Coil Field Quality Dipole Designs for the FCC

Prior to this Phase I work, there were several concerns when the common coil design was compared to other magnet designs for collider magnets such as cosine theta, canted cosine theta and other block coil designs. These included (a) Can the common coil design produce good field quality? (b) Is the common coil design competitive in conductor usage, magnet size, inductance and stored energy? (c) Will its mechanical structure be similar in size/cost to the other designs, and can it meet the structural requirements for stress/strain in the conductor?

Field quality in accelerator magnets is quantified by normal and skew harmonics b_n and a_n:

$$B_y + iB_x = 10^{-4} \times B_{R0} \sum_{n=1}^{\infty} (b_n + ia_n)[(x+iy)/R]^{n-1}, \qquad [1]$$

where B_x and B_y are the components of the field at [x, y], and B_{R0} is the magnitude of the field from the dominant harmonic at a "reference radius" R, typically 2/3 of the coil inner radius.

The magnetic design, shown in Figure 4, not only met the field quality requirements (both in geometric harmonics and in saturation-induced harmonics), but exceeded other designs for the FCC developed under the EuroCirCol study. As shown in table I, the optimized geometric harmonics were much smaller than the specification of 3 units. The key to these results was orienting pole turns in a plane perpendicular to the turns in the main coil which gave much better leeway in optimizing field quality. In addition, with the bend in the easy direction, it also helps in clearing the bore tube easily in the ends. This design technique now has been implemented in the EuroCirCol and other common coil designs. The design was able to achieve lower saturation-induced harmonics (see Fig. 4) than specified even with a similar or smaller yoke outer diameter.

Table I: Calculated skew (a_n) and normal (b_n) harmonics for a 17 mm radius at 16 T for the common coil design of Figure 4.

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

The Nb_3Sn strand chosen for the 16 T design is the same strand used in the EuroCirCol Common Coil [14]. This will allow easy comparison of our design with those being studied by CERN and others. Our design utilizes a wider cable than the EuroCirCol [14]. The magnet built with this cable reaches the design field of 16 T at 16 kA. The wider cable is desired over narrower cable as it reduces the inductance and hence makes quench protection easier. It also reduces the number of coils to be built, thus reducing the magnet cost. The wider cable can be used here, because the common coil configuration is more conductor-friendly in bending than the alternative designs.

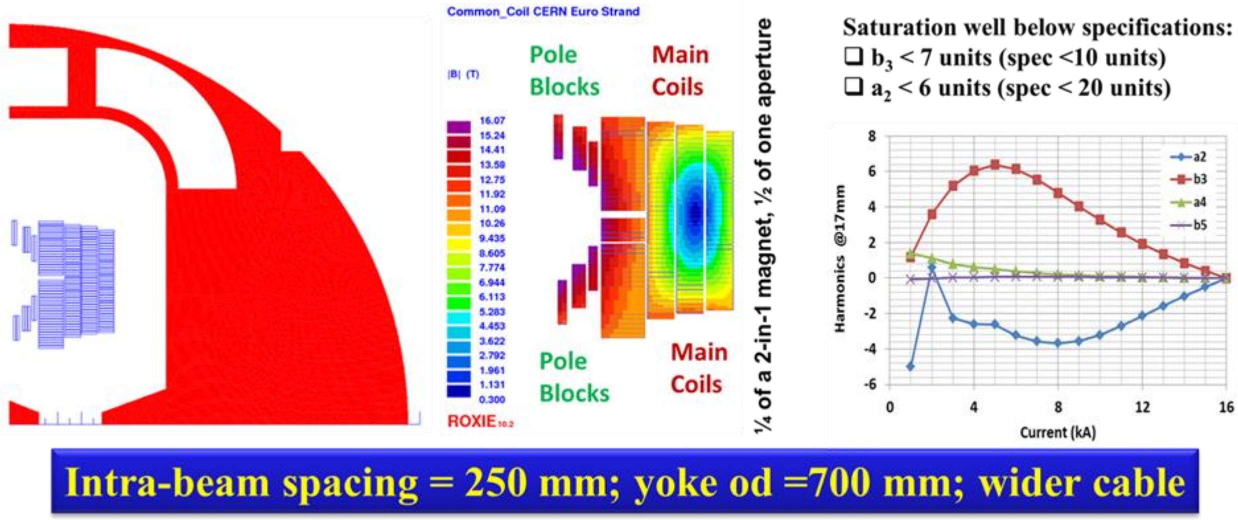


Figure 4: A first-quadrant model of the 2-in-1 common coil design (½ of the upper aperture, left) and the magnitude of the field superimposed on the conductors (middle) when the field at the center of aperture is 16.034 T. Conductors in the main coils are stacked vertically. Conductors in the pole blocks are stacked horizontally and lifted sideways to allow a bend in the easy direction to clear the bore. Saturation induced harmonics were also optimized well within specifications (right).

A preliminary mechanical design was performed using a 2-D ANSYS Workbench [6]. Fig. 5 (left) shows a simplified two-dimensional model. Lorentz forces are applied to the edges of the coil blocks. The collar is monolithic stainless steel, with no joints. The coil windings, Nb_3Sn plus fiberglass impregnated with epoxy, have a Young's modulus of 20 GPa. Frictionless "roller" symmetry is assumed at the horizontal and vertical split lines, and at the outboard edge of the collar, whose thickness is 37 mm. Fig. 5 (center) shows the main-coil windings cross sections and stresses, which reach 144 MPa near the midplane of the outermost coil, a value that held even without the roller constraint on the collar. Stresses on the pole coils, as shown in Fig. 5 (right) are below 150 MPa except near the "X" on the right-most pole coil blocks. Future iterations should reduce this value. The maximum horizontal displacement was found to be ~0.77 mm (in the main coils), which should be acceptable, because each coil moves as a whole (a major benefit of the common coil design), so long as the internal deformations are sufficiently small to keep the strain within the acceptable limit. The horizontal displacement of the pole coil blocks will be limited by the main coils and the support structure. The goal of future iterations will be to make displacements more uniform. The vertical displacements are less than 0.1 mm, which indicates that the support for the pole coils should be able to hold them against the vertical Lorentz forces.

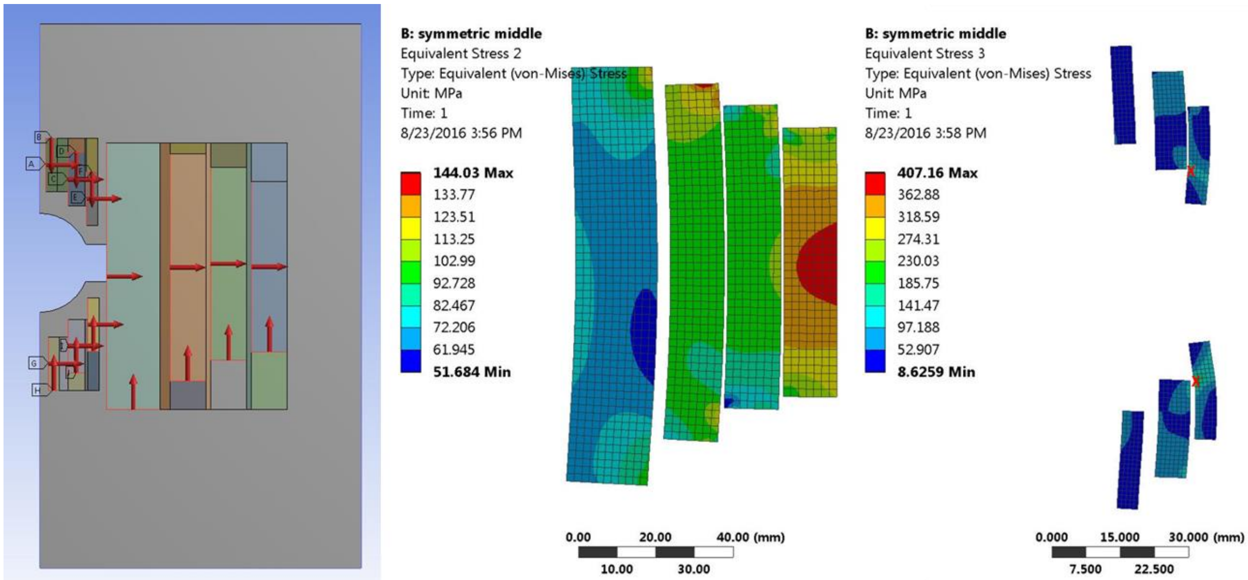


Figure 5: Simple ANSYS model showing the structure considered and Lorentz forces applied (left), stresses in the main coil (middle) and pole coils (right).

Displacements due to Lorentz forces have an impact on field harmonics as well, and the change may be significant when the displacements are as large as here. However, changes in field harmonics in the block designs tend to be smaller when displacements are horizontal than when they are vertical, which is the case as per the ANSYS model [6]. We performed a number of calculations to quantify these impacts. If all blocks are allowed to move horizontally, then a displacement of 1 mm causes a change primarily in the sextupole (b_3) with a magnitude ~9 units/mm [6]. The field harmonics also change due to iron saturation. A proper yoke optimization would accommodate both the combined changes in harmonics due to non-linear iron saturation and conductor displacement due to Lorentz forces. This can be accommodated in the iron optimization so that the net values of harmonics remain within the specifications of 10 units. We don't expect deflections over 1 mm.

4.2 Accelerator Quality Proof-of-Principle Common Coil Design with Pole Coils

A magnet design was developed for the proposed proof-of-principle common coil dipole to optimize pole coils similar to those proposed for the FCC design. These pole coils can be installed in the existing DCC017 magnet (Fig.6, left) and produce field quality as generally required in accelerator magnets. The as-built multipoles of the original DCC017 were far from the requirements of an accelerator quality dipole, because the magnet was built with no field quality consideration. It is remarkable that we could optimize the position and spacing between the turns of the pole block to obtain field quality adequate for typical accelerator magnets. These pole coils are designed so that they can be assembled within the common coil structure (Fig. 6, right) and may run in series with the main coils. The calculated multipoles in the as-built 31 mm bore dipole DCC017 and in the optimized design are given in Table II at a reference radius of 10 mm.

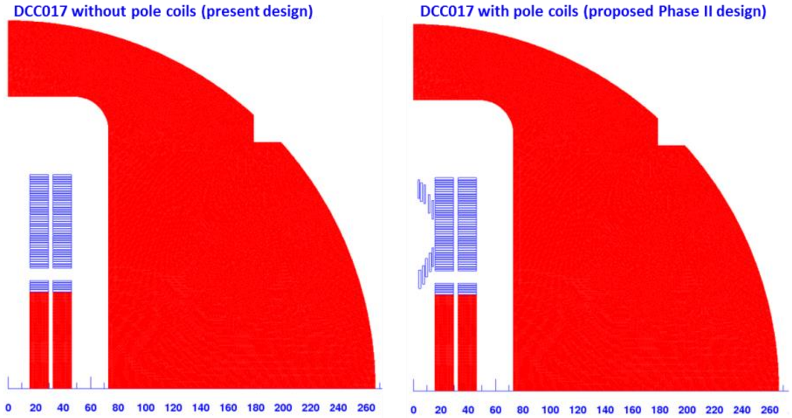


Figure 6: DCC017 as-built, without pole coils (left), and with pole coils to improve field quality (right).

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

DCC017 without pole coils (present design)

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

NORMAL RELATIVE MULTIPOLES (1.D-4):

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

SKEW RELATIVE MULTIPOLES (1.D-4):

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

DCC017 with pole coils (proposed Phase II design)

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

NORMAL RELATIVE MULTIPOLES (1.D-4):

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

SKEW RELATIVE MULTIPOLES (1.D-4):

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

These pole coils will be inserted in DCC017 following an assembly procedure similar to that developed for the HTS insert coil for our earlier STTR program (see Fig.7).

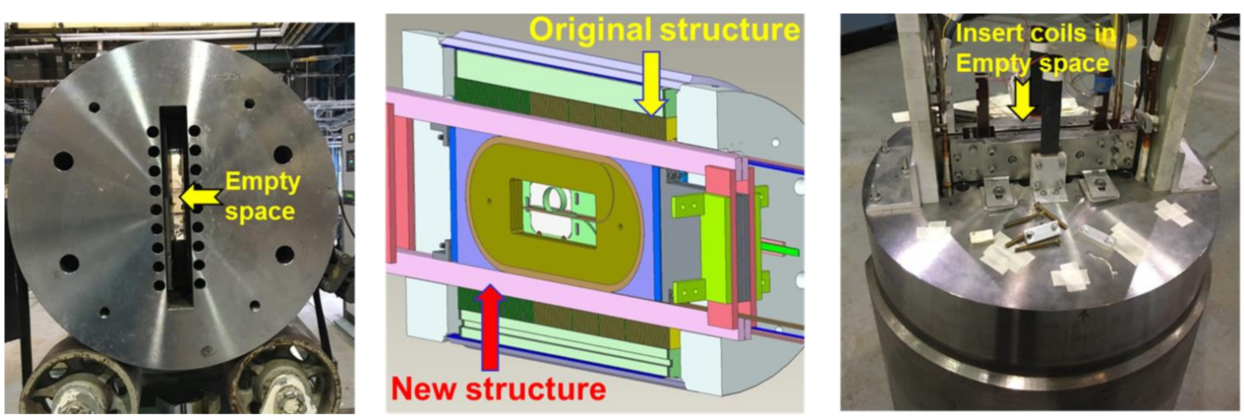
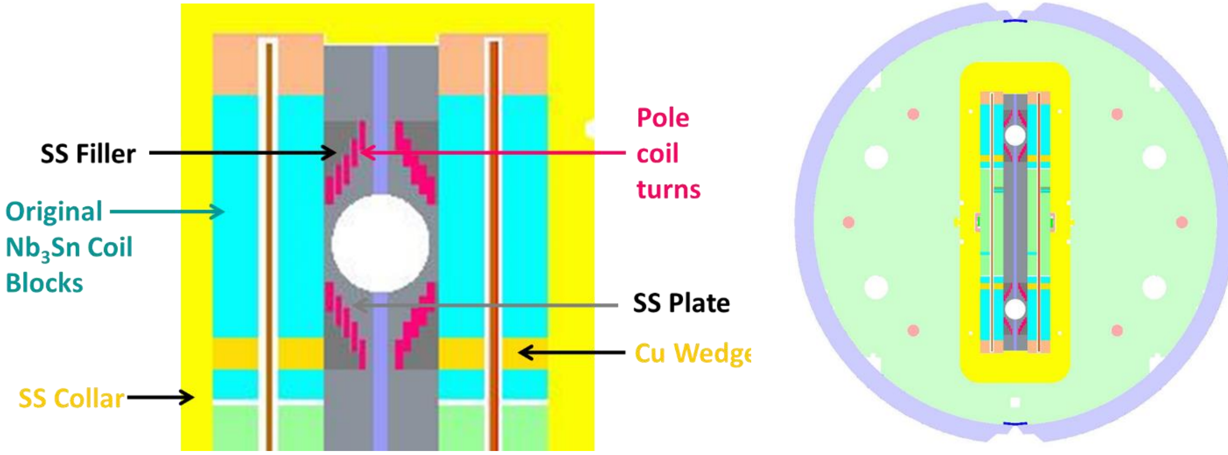


Figure 7: BNL common coil dipole with a large open space (left) where additional coils can be inserted without disassembling the magnet (see schematic in the middle), and after they are successfully inserted (right) as a part of another PBL/BNL STTR program.

A conceptual mechanical design of a possible structure for the pole coils with DCC017 is shown in Fig. 8. A detailed design was beyond the scope of Phase I and will be carried out in the intial stages of Phase II.



Figures 8 a&b: CAD cross section of support-structure concept, with structure (gray), pole coils (pink), main coils (cyan), wedges & SS collars (yellow), and magnetic iron (pale chartreuse). Left: Detail of support structure for the upper aperture. Right: Cross section through both apertures.

For the pole coils to be built in Phase II, the LHC Accelerator Research Program (LARP) strand and the strand for the upcoming LHC HiLumi upgrade are being considered [15]. Both are readily available and will produce a cable (around 23 strands) that can be operated in series with the DCC017 main coils with a good critical current margin.

4.3 Practice Pole Coil Winding Clearing the Bore Tube

To verify that the coils designed above can indeed be wound and supported, an existing Nb_3Sn cable was obtained from LBNL [16] and used to simulate the coil ends. This cable has 23 strands of 0.8-mm diameter ITER Nb_3Sn; the cable cross section is 10 mm by 1.44 mm. In addition, PBL/BNL has used a modern 3-D printer that PBL purchased under another STTR program to print parts to make practice windings. One of several printed parts and the practice coil wound using the cable placed in these printed parts are shown in Fig 9.

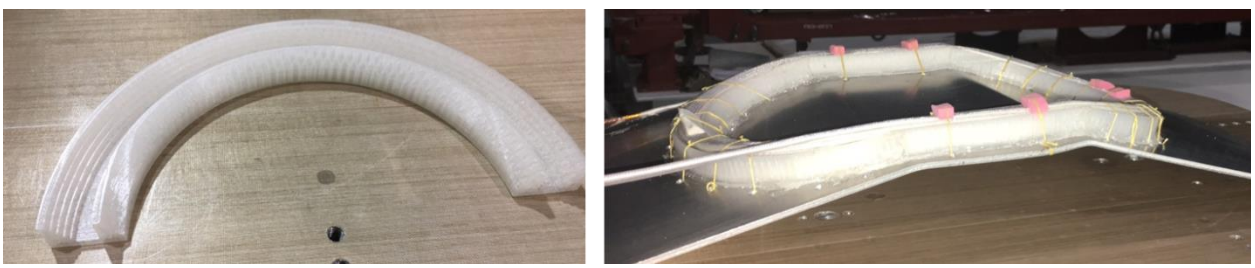


Figure 9: Printed coil part made with the PBL 3-d printer (left) and the coil wound (right) using these printed parts and Nb_3Sn cable obtained from LBNL.

5.0 The Phase II Technical Objectives

The ultimate technical objective of this proposal is to develop technology for a 16 T common coil dipole with accelerator field quality. *This will be an alternate technology to the conventional cosine theta magnet design with a goal of producing collider dipoles with lower cost and higher reliability.* Because of the budget limitations of an SBIR/STTR program, we will demonstrate the key features of the technology in a proof-of-principle magnet using the existing DCC017 magnet and adding pole coils intended to obtain accelerator magnet type field quality. A successful outcome of this program is expected to attract funding to carry out further R&D, to build a prototype magnet, and eventually to commercialize full length magnets. To achieve this goal within the framework and budget of an SBIR/STTR program, the specific key objectives are listed below:

- Develop the engineering design for the proof-of-principle field quality common coil dipole
- Wind, react and impregnate pole coils that can be accommodated in DCC017
- Construct a proof-of-principle dipole by integrating pole coils with the existing Nb_3Sn coils
- Perform a 4K test of the proof-of-principle dipole, which includes the measurements of field harmonics
- Develop a preliminary engineering design of the 16 T, 50 mm bore dipole
- Outline cost reduction strategies for large scale, reliable production of collider dipoles in industry

6.0 Work Plan (list of tasks)

We plan to achieve the technical objectives described above through the following tasks:

Task 1. Iterate the baseline pole coil design that was developed in Phase I. The design developed in Phase I will, in principle, meet the accelerator magnet field quality required for this Phase II. However, before the fabrication of the pole coils is initiated, alternative pole coil designs will be explored to see if any improvement in ease of pole coil winding and/or pole coil support can be discovered. One promising case that was briefly examined in Phase I, is with the pole coils near the center of the magnets wound essentially flat even while the cable is bent in the hard direction. This keeps the coil pack and magnet assembly simple. The design is shown in Fig. 10 (left). We laid the cable bent at the radius needed in the magnet and found it to be promising (see Fig. 10, right). This is primarily possible because the bend radius in the common coil design (determined by the separation between the two apertures) is much larger than that in conventional cosine theta or block designs (where it is determined by the aperture itself).

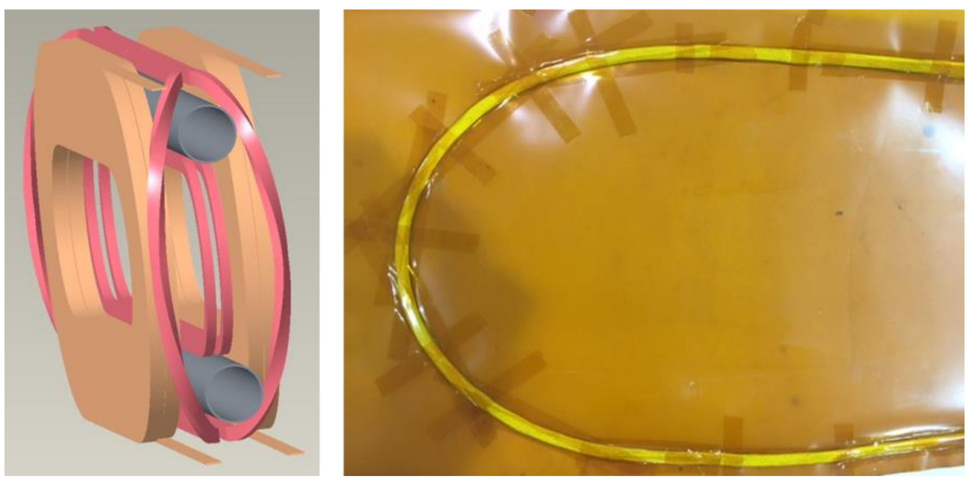


Figure 10: Alternate proof-of-principle design (left) with the pole coils (pink) near the center for two apertures being flat. Cable laid/bent at the radius needed in the magnet (right).

This task will use the magnet design tools ROXIE, OPERA, COMSOL and ANSYS and will be performed jointly by PBL (Weggel) and BNL (Gupta, BNL engineers).

Task 2. Design and procure the Nb_3Sn cable that will be used to construct the pole coils. The baseline cable design from Phase I will be reviewed to ensure that it will meet the requirements for Phase II. These requirements are: capability to operate in series with the main coils, windability, and timely, cost-effective procurement. Existing strand designs will be used so that time-consuming and expensive strand development will not be required. The LARP and HiLumi strands will be considered. R. Scanlan (PBL) and R. Gupta (BNL) will perform this task.

Task 3. Perform the detailed ANSYS calculations of the magnet structure with the pole coils. Preliminary calculations were done in Phase I. Structure analysis with the code ANSYS of the stresses has also been carried out for DCC017 without pole coils (see Fig. 11). However, before pole coil construction can commence, these 2-d calculations will be carried out in more detail with a range of options for internal structure examined. The calculations will be extended to 3-D for the option chosen. These calculations will include more realistic conditions such as friction, shear planes, and component moduli. This task will be performed jointly by R. Weggel (PBL) and BNL engineers.

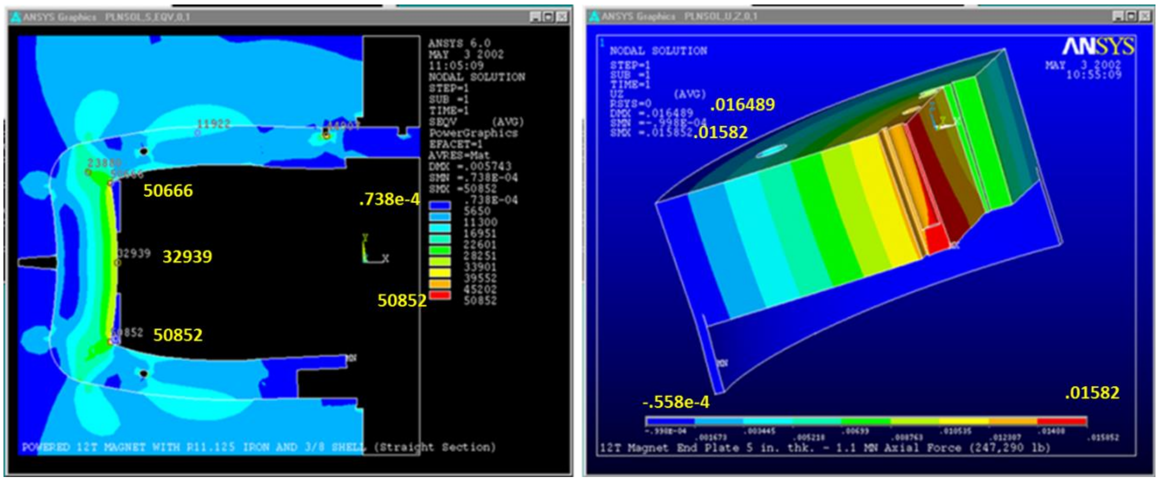


Figure 11: ANSYS simulation showing stresses in the collar (left) and on the end plates (right) in the common coil dipole DCC017.

Task 4. Design the pole coil support structure, splice joints, and end spacer parts. This task will rely heavily on the techniques developed in the earlier STTR that resulted in the very successful HTS insert coil that was tested in DCC017. We are likely to follow a “wind & react” approach for the pole coils. It is also likely that only one side of the coil ends will be flared to allow easy insertion of the coils into the magnet aperture. The field measuring coil will obviously be inserted from the flared end side. The alternative approach of “react & wind” will be explored for the 16 T design study. This task will be performed by BNL engineers directed by R. Gupta; the design will be reviewed by PBL staff (Scanlan and Weggel) before fabrication begins.

Task 5. Fabricate the coil parts based on the Task 4 design. Coil parts will be designed at BNL, where the experience and the DCC017 magnet reside. However, wherever practical, the part fabrication will be done at an outside shop under PBL supervision. This approach was used successfully on the earlier STTR [11, 12], and saved both time and money over in-house fabrication at BNL. The end spacer parts for the practice coils will be fabricated where it is practical with the 3-D printer purchased by PBL for an earlier SBIR project. Parts for the actual coil will be metallic and can’t be printed with the printer in-house. This will be a joint task between PBL (Larson) and BNL engineers.

Task 6. Wind, react and impregnate the pole coils using the conductor procured in Task 2 and the parts procured in Task 5. The pole coils will be wound and instrumentation will be installed at BNL. The coil will be wound on a metallic bobbin with appropriate wedges or spacers for field quality and then the entire winding will be enclosed in a structure that will be reacted. Appropriate consideration will be given for the thermal expansion during the high temperature reaction. Subsequently, the entire structure will be epoxy impregnated. The details of the above steps may be modified after a more detailed engineering design during the initial part of Phase II. These tasks will be performed by BNL Magnet Division engineers and technical staff, using existing equipment and expertise.

Task 7. Assemble the pole coils in the background field magnet DCC017. The two halves of the pole turn coils will be inserted into the bore of DCC017. The coil halves will be pressed firmly against the main coils and fastened in place. Finally, the field measurement coil will be inserted into the bore and the coil package will be attached to the header/support structure. After room temperature testing of instrumentation and coil electrical integrity, the magnet will be inserted into the cryostat. This task will be done by BNL engineers and technical staff.

Task 8. Test the magnet at 4 K and measure the field quality. After verifying that the quench protection system is functioning correctly, the magnetic field measurements will be made, starting at low field and going to progressively higher fields. Any hysteresis effects due to motion of pole or main coils will be measured. Finally, if all operations are normal, the magnet will be taken to the short sample limit. These tests will be performed at BNL and witnessed by PBL staff (Willen, Larson, Scanlan, Weggel).

Task 9. Analysis of the test results and iteration of the design, if required. The field harmonics will be analyzed and any discrepancy, if any, between the calculations and measurements will be studied in detail to see if the cause can be determined and corrected. The design will be iterated, if required, to ensure that accelerator field quality can be obtained in the common coil magnet design. This will be a joint task involving Weggel (PBL) and the BNL team.

Task 10. Preliminary engineering design of a 16 T accelerator dipole magnet. A secondary but strategically important task of the Phase II effort will be to develop the magnetic, mechanical and preliminary engineering design of a 16 T, 50 mm aperture common coil dipole for a future proton collider. The final design will, of course, be developed as a part of subsequent funding (which is expected to be much larger). However, the further development of the common coil R&D design to a more advanced level is essential to place this design in a technically competitive position with cosine theta and canted cosine theta designs, which have benefited from significant funding over a period of years to increase their maturity. Taking the design developed in Phase I as a baseline, the design will be further developed using ROXIE, OPERA, COMSOL, and ANSYS. This will include optimization of the 3-D magnetic and preliminary 3-D mechanical designs. We will perform a 3-D coil end optimization with the CERN code ROXIE [17], following the strategy we successfully used earlier in our 40 mm aperture common coil design [18]. This will be a joint task involving Weggel (PBL) and the BNL team.

Task 11. Cost reduction strategies for reliable, lower cost, large scale magnet production in industry. Having built the last superconducting collider in the US (the Relativistic Heavy Ion Collider or RHIC), BNL has a team of engineers, scientists, designers and technicians who have firsthand experience in working with industry to design magnets that can be successfully built in industry at a low cost. The BNL/PBL team will utilize this unique experience and the simplicity of our design to develop and present strategies for a large scale reliable production of magnets that can be successfully built in industry. This is a very important task which will be jointly carried out by both the BNL and PBL teams.

Task 12. Prepare the final report and proposals for continued funding. We anticipate that the successful proof-of-principle tests and the optimized design of a 16 T common coil dipole with accelerator field quality will generate renewed interest in the common coil dipole approach. We will prepare a proposal for continued work on the common coil dipole and present this to the U.S. Magnet Development Program. This will be a joint task involving both the PBL and BNL teams.

7.0 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. Four times during the course of the project the technical staff will meet to ensure that important milestones are being met in a timely way. In two of the meetings, PBL senior management will also travel to participate. 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.

8.0 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																								
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Task 9																								
Task 10																								
Task 11																								
Task 12																								

9.0 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. This section will now highlight some of the important contributions made by the PBL/BNL team.

9.1 Construction and Test of a HTS/LTS Hybrid Dipole

The PBL/BNL team was awarded a Phase II STTR in 2015 to demonstrate a HTS/LTS hybrid dipole and to measure the magnetization of the coils made with ReBCO tape. That STTR required inserting new HTS coils inside the dipole DCC017 and then integrating them with the existing Nb_3Sn coils without disassembling the magnet.

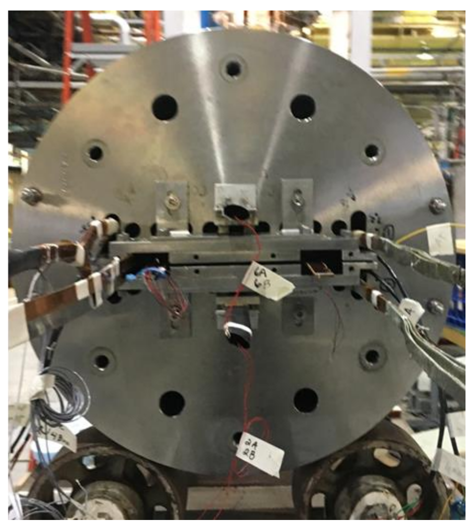

Figure 12: Dry run for inserting additional coil without disassembling common coil magnet (left) and after the insertion of actual coils (right).

The success of our earlier STTR gives us confidence that we can demonstrate the first proof-of-principle accelerator type common coil dipole as proposed in this Phase II SBIR/STTR, just as we did for the first significant HTS/LTS hybrid dipole demonstration [11] in our previous Phase II STTR. Fig. 12 shows the dry run of inserting the structure (left) before the actual HTS coils are inserted within the structure (right).

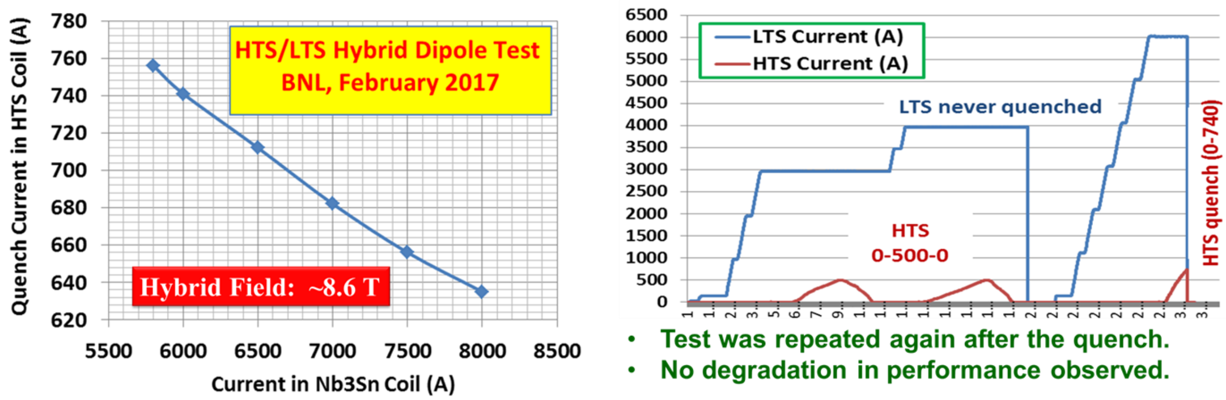

Figure 13: Quench performance of HTS coils in the background field of LTS (Nb_3Sn) coils (left) and currents in HTS and LTS coils during the magnetization measurements.

Fig. 13 shows the measured quench current of HTS coils as a function of Nb_3Sn coil current (left) in a hybrid dipole magnet. The HTS coil quenched (when it reached its short sample limit) at 4 K several times at significant fields and survived every time, including at the maximum field of 8.6 T in a HTS/LTS hybrid dipole configuration. In one series of tests (shown in Fig. 13, right), the HTS coil was ramped up from 0 to 500 A and then down from 500 A to 0 A to measure the magnetization induced dipole field errors at different background fields provided by the Nb_3Sn dipole coils. The HTS coil was quenched a couple of times at 800 A. No degradation of in the performance of the HTS coil was observed. This result not only presents one of several highlights of the joint technology developed by PBL/BNL, but also points to the capability of the group. For example, development of HTS quench protection technology (discussed in the next section) and the high field HTS solenoid technology played a key role in developing this technology.

9.2 Advanced Quench Protection System

It has been recognized that due to slow quench propagation in HTS, quench protection in high field HTS magnets with large stored energy is a major challenge. The PBL/BNL team has responded to this challenge and has developed technology for detection of pre-quench voltage and fast energy extraction and we have applied this technology to various HTS programs including a SMES system. One key feature of the multi-pronged approach was using copper discs [19] to quickly (on the order of a milli-second) extract significant energy and drop the current in the coil. The advanced quench protection system which we developed can isolate the pre-quench voltage to below 1 mV and can also tolerate isolation voltages above 1 kV.

9.3 Hybrid HTS/LTS solenoids for very high fields

Another outstanding accomplishment of the PBL/BNL SBIR collaboration is the achievement of several world record fields in HTS solenoids [20] that were designed and built during SBIR programs. In the first SBIR, 24 pancake coils destined for the magnet were wound and tested at 77 K. A half-length set of 12 of these coils was tested at 4 K and operated (without quenching) up to a central field of > 6 T and with an ambient (peak) field of ~9.2 T. For the second SBIR, a 12 T (nominal) solenoid was built to serve as the inner solenoid of an all-HTS coil set. When the second solenoid was combined with the solenoid built during the first SBIR the two solenoid set reached a field of 22 T. The inner coil reached a field of nearly 16 T (with peak field over 16 T), exceeding its nominal field by more than 30%.

10.0 Facilities/Equipment

The Superconducting Magnet Division (SMD) at BNL has been a major force in the development of accelerator magnets for many decades. The Superconducting Magnet 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 superconducting magnet division has a staff of about 30, including scientists, engineers, technicians and administrative staff. Construction and test of the pole coils will be carried out in a 55,000 ft^2 multipurpose R&D complex at the SMD. A prominent asset of the complex is an active cryogenic test facility, complete with high-current, high-resolution and high-stability power supplies.

The facility allows testing of a variety of superconductors, coils and magnets from ~2 K to ~80 K. Among the elements of the dedicated equipment in the facility are several computer-controlled, automated coil-winding machines, automated-cycle curing and soldering stations, centralized exhaust-vent systems, and hydraulic presses, all of which are available for use in the construction of superconducting magnetic devices. The building has several large-capacity (>15 ton) overhead cranes. Within the building complex are two machine shops with capacity to manufacture the majority of components needed for the R&D task. BNL also has a central machine shop and a procurement group to handle orders with private companies.

11.0 Principal Investigator and Other Key Personnel

Dr. Ronald M. Scanlan will serve as Principal Investigator for the proposed project. Dr. Scanlan has over 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. 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. The goal of this program is the industrial development aimed at developing a cost-effective, high field superconductor for accelerator magnet applications. During this time, his team at LBNL developed the technology for cabling the new HTS wire, Bi-2212, and made many thousands of meters of this cable in collaboration with the wire manufacturers (Oxford Superconducting Technology and Showa). 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 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 be the PBL magnet designer for this Phase I project. He has been P.I. for PBL on several recent SBIR/STTR projects (see related research section). Mr. Weggel has over 50 years of experience as a magnet engineer and designer at the Francis Bitter National Magnet Laboratory at MIT and Brookhaven National Laboratory 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 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. Recently, he served as PI on a related SBIR entitled "Magnet Coil Designs Using YBCO High Temperature Superconductor." His experience on this previous SBIR will be useful in evaluating the design options being explored in this new SBIR. Dr. Willen has over 30 years of experience with high field magnets and served as the BNL magnet division head, Project Head for the RHIC Helical Magnet System and Project Head for the BNL-build magnets for the US LHC project.

Dr. Ramesh Gupta will be the sub-grant Principle Investigator (PI) for the work to be performed in the Superconducting Magnet Division at the Brookhaven National Laboratory. The R&D at BNL will focus on the design, construction and the test of the superconducting coils. Dr. Gupta, aided by his BNL colleagues, has led the development of the common-coil 2-in-1 dipole design for hadron colliders as well as the open mid-plane dipole design when it was considered for the luminosity upgrade for the Large Hadron Collider (LHC) in the "dipole first optics". In addition, Dr. Gupta has more than two decades of experience in the design of superconducting accelerator magnets for various applications. His current interest includes developing and demonstrating HTS magnet designs and technology for particle accelerators and beam lines. Over the last decade he has developed several new innovative designs such as the common-coil dipole, the HTS quadrupole for RIA and FRIB, and a low-cost medium-field HTS dipole. He has developed a cost-effective, rapid-turnaround and systematic magnet R&D approach that is now being adopted by BNL, LBNL and Fermilab and will be employed in this proposal. Dr. Gupta is the PI or sub-grant PI of several HTS R&D grants. He is sub-grant PI of two previous Particle Beam Lasers, Inc. SBIRs on a HTS solenoid for a muon collider and the open-midplane dipole. He was also PI for the development of HTS magnets for RIA, FRIB and the sub-grant PI of a HTS Superconducting Magnetic Energy Storage system (SMES). Dr. Gupta has also worked on conventional Low Temperature Superconductor cosine-theta magnet designs (an area that he still continues to pursue) for RHIC and SSC. Dr. Gupta has taught several courses on superconducting magnets at U.S. Particle Accelerator Schools.

12.0 Consultants and Subcontractors (Including Research Institution)

Brookhaven National Laboratory, 30 Bell Ave., Bldg. 460, Upton, NY 11973 is the research institution on this proposed work. BNL will be a subcontractor. The certifying official from BNL is Michael J. Furey, Manager Research Partnerships (Phone: 631-344-2103; Email: mfurey@bnl.gov), BNL will play a substantial role in the Phase II effort, as is described throughout this proposal and indicated in the budget. The dollar amount of the subcontract with BNL will be $440,000.

PBL is pleased to partner with BNL and use the considerable BNL facilities in the Phase II work.

No additional outside consultants or subcontractors will be involved with this SBIR.

13.0 How the Research Effort Could Lead to a Product in Phase III

In Phase III, the research effort will lead to the demonstration of pole coils that can improve the field quality of superconducting common coil dipoles. This demonstration will show that common coil dipoles can be made on an industrial scale in a cost-effective manner. 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.

14.0 Summary and Impact

Successful demonstration of high field magnets using our proposed common coil technique will have a major impact in the field of accelerator magnets. The design and technology developed is likely to be useful in other areas as well. As indicated by letters of interest, PBL has already made significant progress in creating links with other technology companies and laboratories.

15.0 References

1. The Particle Physics Project Prioritization Panel (P5) and its subpanel on Accelerator R&D, http://science.energy.gov/hep/hepap/;
   "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context," P5 Report, http://science.energy.gov/~/media/hep/hepap/pdf/May%202014/FINAL_P5_Report_053014.pdf
2. R.C. Gupta, "A Common Coil Design for High Field 2-in-1 Accelerator Magnets," Presented at the 1997 Particle Accelerator Conference in Vancouver, Canada (1997).
3. Future Circular Collider Study Kickoff Meeting, Geneva, Feb. 12-14, 2014, http://indico.cern.ch/event/282344/timetable/#20140212
4. CEPC/SppC study in China, http://indico.cern.ch/event/282344/session/1/contribution/65/material/slides/1.pdf
5. "Design Study for a Staged VLHC" Fermilab TM-2149 (June 4, 2001) http://tdserver1.fnal.gov/TDlibry/TD-Notes/VLHC/fermilab-tm-2149.pdf
6. R. Gupta, M. Anerella, J. Cozzolino, W. Sampson, J. Schmalzle, P. Wanderer, J. Kolonko, D. Larson, R. Scanlan, R. Weggel, E. Willen and N. Maineri, "Common Coil Dipoles for Future High Energy Colliders," 2016 Applied Superconductivity Conference.
7. R. Gupta, et. al, "React & Wind Nb_3Sn Common Coil Dipole," Presented at ASC 2006, in Seattle, WA, USA August 27- September 1, 2006.
8. S. A. Gourlay, et al., "Fabrication and Test Results of a Prototype, Nb3Sn Superconducting Racetrack Dipole Magnet," 1999 Particle Accelerator Conference, New York, NY, March 1999
9. B. Benjegerdes, et al., "Fabrication and Test of Nb3Sn Racetrack Coils at High Field," IEEE Trans. On Applied Superconductivity, 11, March 2001.
10. G. Ambrosio, et al., "Development of a React & Wind Common Coil Dipole for VLHC, Applied Superconductivity Conference at Virginia Beach, USA (2000).
11. R. Gupta, "ReBCO at BNL", at 4th Workshop on Accelerator Magnets in HTS, Barcelona, Spain, February 15-17, 2017. https://indico.cern.ch/event/588810/contributions/2410720/attachments/1414343/2164680/wamhts4-gupta.pdf
12. "A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets", Grant number DE-SC0011348.
13. F. Toral, et al., "Common coil configuration: electromagnetic calculations", https://indico.cern.ch/event/572501/contributions/2317291/attachments/1367636/2072498/Common_coil_update_20161108.pdf
14. FCC Week 2016, Rome, Italy, April 11-15, 2016 http://fccw2016.web.cern.ch/fccw2016/
    EuroCirCol – The European Circular Energy-Frontier Collider Study, https://fcc.web.cern.ch/eurocircol/Pages/default.aspx
15. I. Pong, et al., "Cable and Its Insulation for the LARP MQXF Magnet Coils", 2016 Applied Superconductivity Conference.
16. We are grateful to the LBNL Magnet Group, and Dr. Ian Pong, in particular, for supplying this cable.
17. https://espace.cern.ch/roxie/default.aspx
18. R. Gupta, et al., "Field Quality Optimization in a Common Coil Magnet Design," International Conference on Magnet Technology (MT-16) at Ponte Vedra Beach, Florida, USA (1999).
19. H. Witte, et al., "Reduction of the Hot Spot Temperature in HTS Coils," International Conference on Magnet Technology, MT23, Boston, USA, July 2013.
20. R. Gupta, et al., "High Field HTS Solenoid for a Muon Collider – Demonstrations, Challenges and Strategies," International Conference on Magnet Technology, MT23, Boston, USA, July 2013.