Project Narrative

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Significance, Background Information, and Technical Approach

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. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs*". This STTR proposes to develop new technologies for high-field superconducting magnets, a key technology for high-energy proton colliders.

Proposed high-energy accelerators such as CERN's Future Circular Collider (FCC) [2] and China's CEPC/SppC [3], envision dipole magnets with central fields approaching 20 T. The maximum field on the conductor will be significantly higher (additional 10% or more) to allow for a safety margin for operation and to account for the fact that the peak field on the coil is higher than the central field. Adequate current density at such fields requires high-temperature superconductor (HTS) such as Bi2212 or ReBCO (rare-earth barium copper oxide—YBCO, if the rare earth is yttrium). Past experience has shown that the needed magnet technology will require at least a decade of R&D before it is mature enough for incorporation into an accelerator.

Because the cost of HTS is high and is likely to remain so, this STTR proposes that HTS be confined to the regions that require it. The work carried out in Phase I showed that a block design is preferable over a cosine(θ) design to partition the coil conveniently into HTS/LTS regions. This STTR will build the HTS coils and test them in the background field of BNL's Nb_3Sn common-coil dipole [4], which will test the basic principles within the budget of an STTR.

ReBCO is superior to Bi2212 in engineering critical current density (J_e), particularly when the field direction is favorable (field parallel to the wide face or plane of the tape, see Fig. 1). It is becoming available in long lengths: ≥100 m now; perhaps ≥1 km soon. Therefore, it is feasible to design and build R&D magnets using it. In fact, BNL recently built a solenoid magnet for energy storage that used over 6 km of 12-mm-wide ReBCO tape [5].

Another advantage of ReBCO (as made by SuperPower, on a Hastelloy substrate) is its tolerance of stresses, such as those found in high-field magnets. However, because of the conductor geometry – tape, rather than multi-filamentary wire – ReBCO is prone to large magnetization effects. We have found a solution that is expected to mitigate this problem to a level low enough so that tape conductor can be used in accelerator magnets. We propose to demonstrate this technique in this Phase II.

This design also reduces the cost of building high-field magnets, as the amount of expensive HTS required is reduced as well.

In summary, a successful outcome of Phase II is expected to have a major impact on the future of high field magnet technology as the design promises to mitigate the conductor magnetization issues, uses high strength HTS, and significantly reduces the amount of HTS required.

Anticipated Public Benefits

In addition to facilitating fundamental research beyond the discovery of Higgs bosons, the development of high-temperature superconductor magnet technology will culminate in magnets of unprecedented field and operating temperature. Commercial spin-offs – in areas not only of research but also medical, energy and national security – are likely to follow the development of this technology, just as the development of MRI magnets followed LTS magnet technology developed for previous generations of HEP accelerator magnets. Because HTS is costly and likely to remain so, the magnets can be commercially viable if a hybrid design, as proposed here, uses HTS only where the field is too high for LTS. The conductor and coil-performance tests of this STTR will encourage conductor manufacturers to improve their conductors to better meet the needs of the magnet community.

Degree to which Technical Feasibility has been Demonstrated

A primary goal of Phase I was to pursue the design of a dipole accelerator magnet capable of fields out of reach of low-temperature superconductors. To achieve this goal, innovative designs were developed that: 1) minimized the amount of expensive HTS conductor needed; and 2) overcame some of the limitations of presently available HTS conductors. Analytical/modelling work optimized the cross section of each conductor block; experimental work wound and tested a coil block and performed bending studies on the clad (bonded) conductor. The specific steps to meet this goal, and the degree to which the accomplishments have met the goal, are listed below.

<u>Analytical tasks</u>

Two primary tasks for Phase I were comparisons of: 1) cos(θ)-shell vs. block-coil cross sections; and 2) YBCO vs. Bi2212 conductor performance. Complete details are presented in the Phase I report included as an attachment. Both shell and block coil designs could reach the 20-T goal, but the block magnet has several advantages. First, it facilitates efficient partition of the windings into low- and high-field regions, where each shell of the cos(θ) design spans a wide range of field. Second, we have conceived of a way to deal with two shortcomings of YBCO tape: 1) orientation-dependent current capacity (see also reference [6]), and 2) conductor magnetization, which can wreak havoc with field quality. Both effects are important. Increasing J_c reduces the amount of expensive HTS conductor necessary to generate the desired field; reducing the conductor magnetization allows the high field quality necessary for a particle accelerator magnet. We have prepared a Record of Invention on this discovery and sent it to the BNL Intellectual Property Group for evaluation [7].

The evaluation of YBCO vs. Bi2212 conductors for hybrid dipole magnets found both to be adequate provided the Bi2212 was overpressure-processed. However, to manufacture Bi2212 coils under the oxygen overpressure conditions needed to achieve high J_c would require a new facility which is unlikely to become available on the timeframe of a Phase II project. A hybrid dipole using currently available Bi2212 conductor can achieve the 20-T design goal, but this option uses too much expensive HTS conductor to be economical.

In summary, the work reported above satisfies the two primary analytical tasks of Phase I project. Other tasks of secondary importance are discussed in the Phase I Final Report (attached).

<u>Experimental tasks</u>

Obtain samples of HTS superconductor and evaluate them with respect to the requirements for use in constructing dipole coils in Phase I and potential use in a follow-on Phase II: The conductor chosen for model coil winding in Phase I was a 4 mm wide tape that has been used extensively at BNL for other projects. This tape is readily available, and its properties are understood, so it was the best choice for the Phase I effort, where time is so limited. However, the relatively small cross section of this tape means that the current is limited, and hence it is not suitable for use in long dipoles such as those required for the target application, a future circular collider. A six-fold increase in current can be achieved by a conductor under development at Superpower. This so-called "clad conductor" consists of two 12-mm wide tapes soldered together.

There are several issues that must be resolved before that conductor can be considered for use in coils. These issues include determining the bending diameter that can be used without conductor degradation, and the current transfer properties of this composite conductor. In addition, there is a long lead-time required to procure long lengths of this conductor, and this precludes its use in a project of only nine months. In order to resolve these issues in preparation of a Phase II proposal, two 18-m long samples were procured. In one sample, procured directly from Superpower, the YBCO layers are on the outside of the clad conductor. The other sample, also made by Superpower but provided to us by Dr. Lucio Rossi of CERN, had the YBCO layers on the inside (closer to the neutral bending axis of the conductor). In summary, the procurement of the 4-mm wide single tape for coil winding tests, and the 12-mm wide clad conductor samples for evaluation for use in Phase II, meet the requirements of the conductor procurement task.

Characterize the YBCO tape: The tests listed in the Phase I proposal were J_c and bending. These tests are sufficient for the 4 mm wide single tape conductors. However, for the clad tape, we determined that it was important to do an additional test in order to verify that current transfer from leads to the tape, and from one tape to the other, wouldbe satisfactory.

Design winding fixtures and tooling, using experimental results of this and earlier Phase I programs: The successful coil winding and coil test experience from the earlier Phase I effort provided the necessary data for the initial coil tooling design for this Phase I effort.

Fabricate coil winding tooling and set up coil winding and tape insulating lines: A 50 mm radius mandrel was constructed to simulate a 50 mm bore coil. A pole piece with a 70 degree angle was used to wind the coil.

Wind coil cross section using the fabricated tooling: A coil with a 300 mm long straight section and consisting of 45 turns was wound, using 4 mm wide tape procured from Superpower, Inc. Turn to turn insulation was provided by co-winding with Kapton tape. Multiple voltage taps were installed so that the total coil, inner turn, and outer turn voltages could be monitored during the coil tests.

Test coil at 77K: The test coil using 4 mm wide tape was tested successfully and the results published in a paper presented at the Applied Superconductivity Conference [8]. In summary, the coil tests showed that the YBCO tape could be wound around the pole in a cos(θ) dipole magnet without any degradation in the tape critical current.

Technology for the Phase II Project

In this section, we provide a technical basis and summarize the work performed in various programs that support this Phase II proposal. They show significant progress made in HTS magnet technology with much of it directly and indirectly supported by previous PBL/BNL SBIR/STTRs efforts. That, in addition to the work performed in Phase I of this proposal, provides a good platform to launch the program proposed here.

Superconductor

Fig. 1 shows the critical current density of various superconductors at 4.2 K. Generally a minimum critical current density of 500 A/mm^2 at the maximum field on the conductor is desired (1000 A/mm^2 or more preferred) to consider a particular conductor practical for accelerator magnets. It is clear that only HTS (YBCO/ReBCO and Bi2212) are approaching the desired performance at very high fields (~20 T). The proposed work is based on YBCO/ReBCO tape and by keeping field as parallel to the tape plane as possible; it utilizes the higher performance as compared to the case when the field is perpendicular to the tape plane.

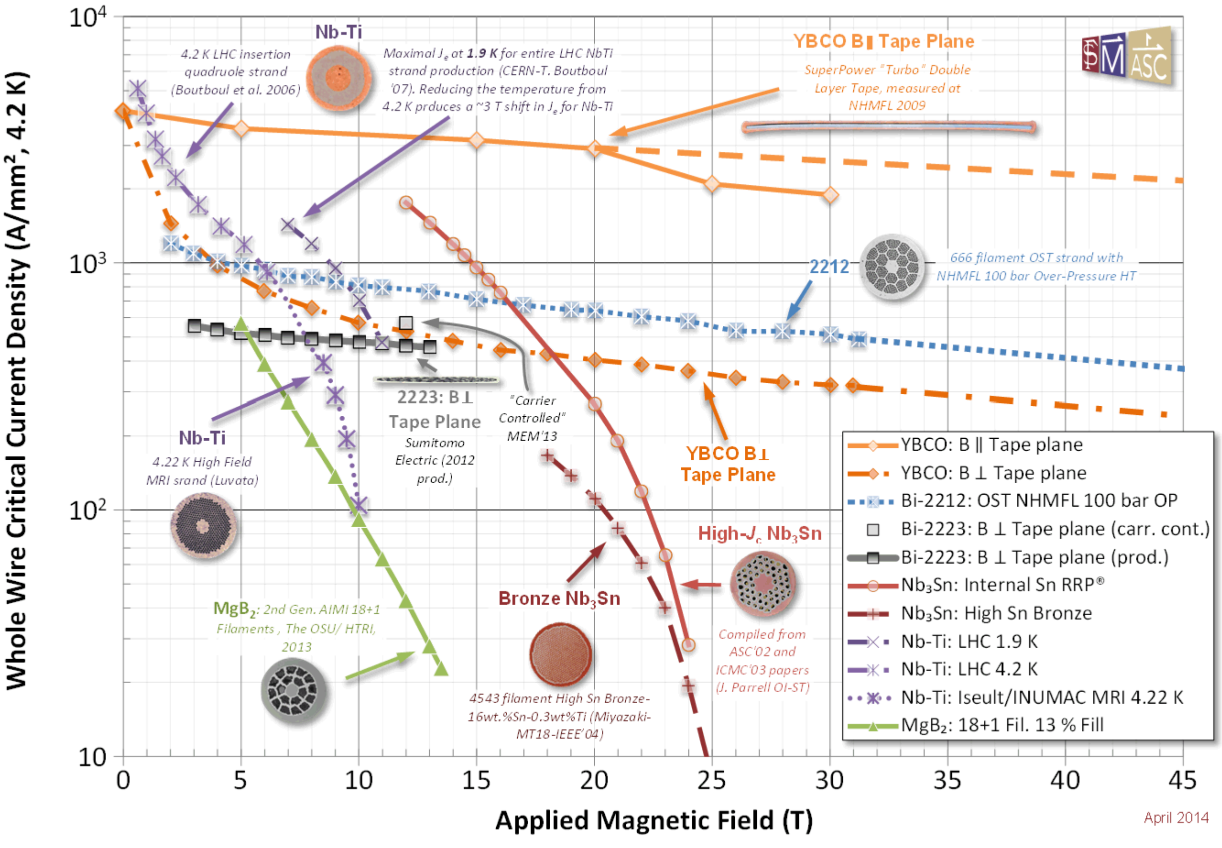


***Fig.1**. Engineering current density for HTS (YBCO tape and Bi2212 wire) compared to other high field superconductors, showing the advantages of HTS at high fields. Data compiled by P. Lee, NHMFL.*

PBL/BNL High Field HTS Coils

The PBL/BNL team has established a strong R&D position in HTS superconducting magnet technology. One of the outstanding accomplishments of this effort is the achievement of several world record fields in HTS solenoids that were designed and built on 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, operated (without quenching) to a central field of > 6 T and an ambient (peak) field of ~9.2 T [9]. For the second SBIR, a 12 T (nominal) solenoid was built to serve as the inner solenoid of an all-HTS coil set when combined with the solenoid built on the first SBIR to reach a field of 22 T. The inner coil reached a field of nearly 16 T (peak field over 16 T), exceeding its nominal field by more than 30%. This is the highest field ever achieved in an all-HTS magnet with overall current density in the coil exceeding500 A/mm^2 [9].

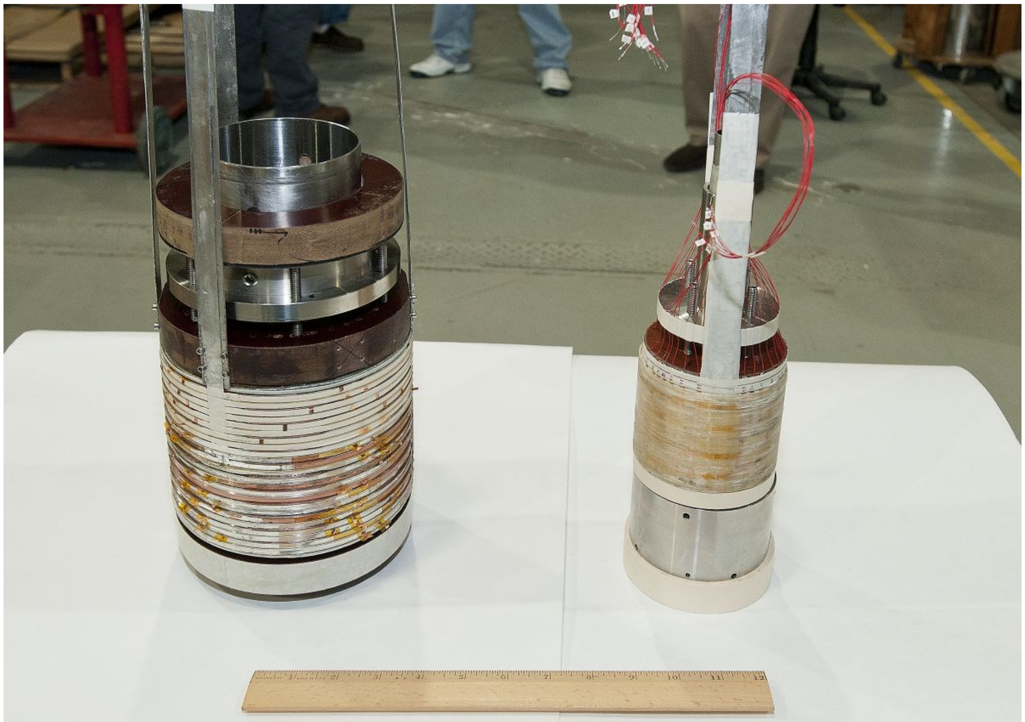


Fig. 2*. Left: 100 mm bore "midsert" solenoid of 24 YBCO pancakes. Right: 25 mm 14-pancake YBCO "insert" magnet. Half-length "midsert" solenoid of 12 YBCO pancakes generated a maximum ambient (peak) field of ~9.2 T at 4 K and full-length 14-pancake YBCO "insert" magnet that generated nearly 16 T on axis (a record for HTS). The two are designed to generate a total field of over 22 T.*

A Phase I SBIR titled "Magnet Coil Designs Using YBCO High Temperature Superconductor", Erich Willen, P.I., was awarded to the PBL/BNL team in 2012. That SBIR successfully demonstrated [8] the construction and test of an HTS coil block made for an accelerator main ring dipole (small bore, high field). Specifically, the following promising results were obtained: the tape can be wrapped with Kapton for protection of the conductor without degradation; the tape can be wound into a coil without damaging the conductor in the process (especially the ends); the wound coil can be heated to the required 225 °C for reacting the polyimide adhesive and thereby form a structure that can be handled for further fabrication steps; leads and voltage taps can be attached; the assembled structure can be compressed into a compacted dimension as required in an actual magnet. After all these steps, the resulting coil assembly can perform at an impressively high level. Further progress in the HTS coil technology was made in Phase I of this proposal and can be seen in the report attached with this proposal.

Fig.3*. Left: Coil with Kapton-insulated HTS tape being wound on the fixture. Right: Wound and fully cured HTS coil (top-right shows stand-alone block and bottom-right shows with pole spacer).*

Large Bore High Field HTS Magnet

Following the success and using the basic design principles of the above work, BNL took part in high-risk, high-reward R&D Superconducting Magnetic Energy Storage (SMES) project funded by ARPA-E with ABB, Inc. and SuperPower, Inc. [5]. The responsibility of BNL was to develop a large aperture (100 mm) HTS SMES coil with a target field of 25 T at 4 K which would be higher than anything ever obtained in a superconducting magnet. This required the superconductors to be subjected to stress levels (over 400 MPa) not previously attained. It also used a large amount of superconductor (over 6 km of 12 mm wide tape). Fig. 4 shows the inner coil (top-left), outer coil (bottom-left) and fully the assembled SMES magnet (right).

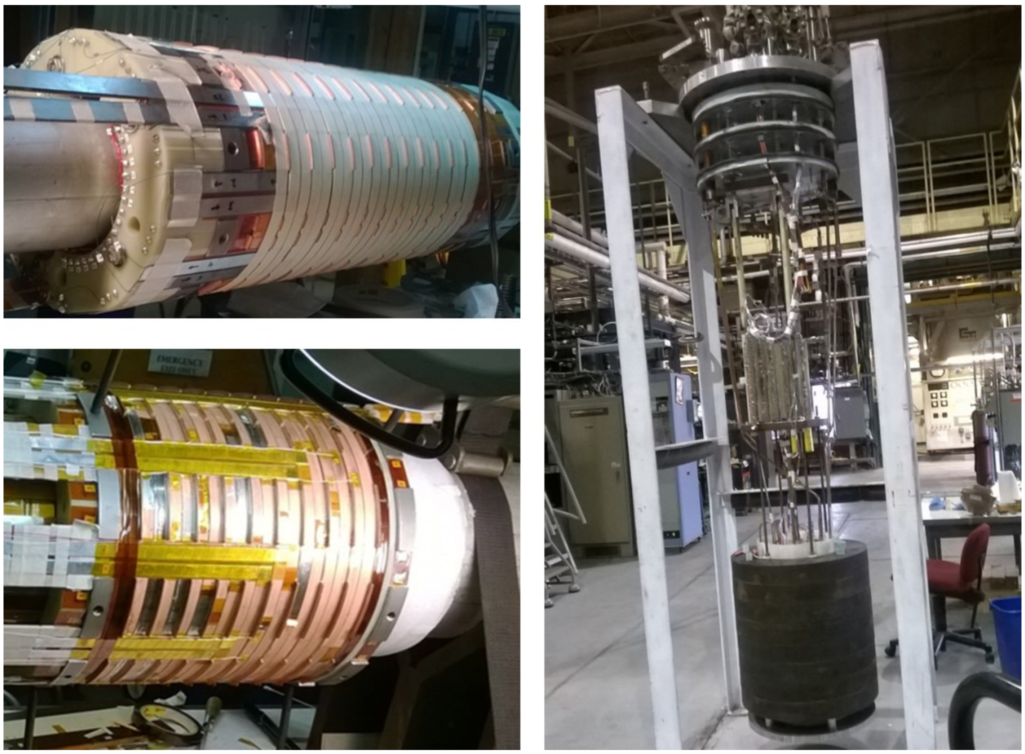


Fig. 4. *High Field HTS SMES magnet with inner coil at top-left, outer coil at bottom-left and fully assembled magnet on test stand at right.*

HTS allows a wide range of operating temperature (higher field at lower temperature). Therefore, as a part of the test the performance of the magnet was measured as a function of temperature. The magnet reached 12.5 T at 27 K, which is the highest ever achieved or planned for a superconducting magnet. Although the magnet developed a short at a much lower field (due to a data entry error) and therefore the test at 4 K could not be carried out, the program allowed the team to continue high field magnet R&D based on an HTS magnet.

Quench Protection

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 [10] and has applied this technology to various HTS programs including the SMES described above. One key feature of the multi-pronged approach was using copper discs [11] to quickly (on the order of a milli-second) extract significant energy and drop the current in the coil – a method under review for a possible patent application. In addition, we plan to use fast acting quench heaters in this program such as those developed at NHMFL [12].

Fig. 5 shows the advanced quench protection system that can isolate the pre-quench voltage to below 1 mV and can tolerate isolation voltages above 1 kV and for which a patent has been awarded.

Fig. 5*. Advanced quench protection system (patent awarded) that can isolate pre-quench voltage below 1 mV and can tolerate isolation voltage. This is a key component of the HTS technology program.*

Common Coil Background Field Nb_3Sn Dipole

In a 2-in-1 common coil magnet design [13], the coil is common between two apertures [Fig 6, left] and naturally creates fields in opposite directions, as is required for the counter-rotating beams of proton colliders. BNL has a unique, fully tested, Nb_3Sn common coil dipole DCC017 (Fig 6, middle) with a large opening (~30 mm horizontal and ~220 mm vertical) that reached a bore field of over 10 T [4]. This magnet can be used to provide a background field for testing an HTS insert coil, such as the Bi2212 Rutherford cable coil that reached 4.3 kA. This provides an opportunity to simulate an HTS/LTS hybrid magnet in a fast and low-cost turn-around manner, because it does not require the magnet to be disassembled and reassembled. A similar Nb_3Sn common coil magnet was used earlier to provide a varying background field on a Bi2212 coil, and thus there is existing experience [14], [15]. 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 (Fig. 7). There was no excessive internal deflection and strain within the coil despite the coil module as a whole deflecting by as much as 200 microns.

Fig. 6*. Left: Basic design of 2-in-1 common coil dipole, Middle: Nb_3Sn common coil dipole DCC017 with large open space, Right: An HTS coil, such as a Bi2212 coil that reached 4.3 kA, in a background field.*

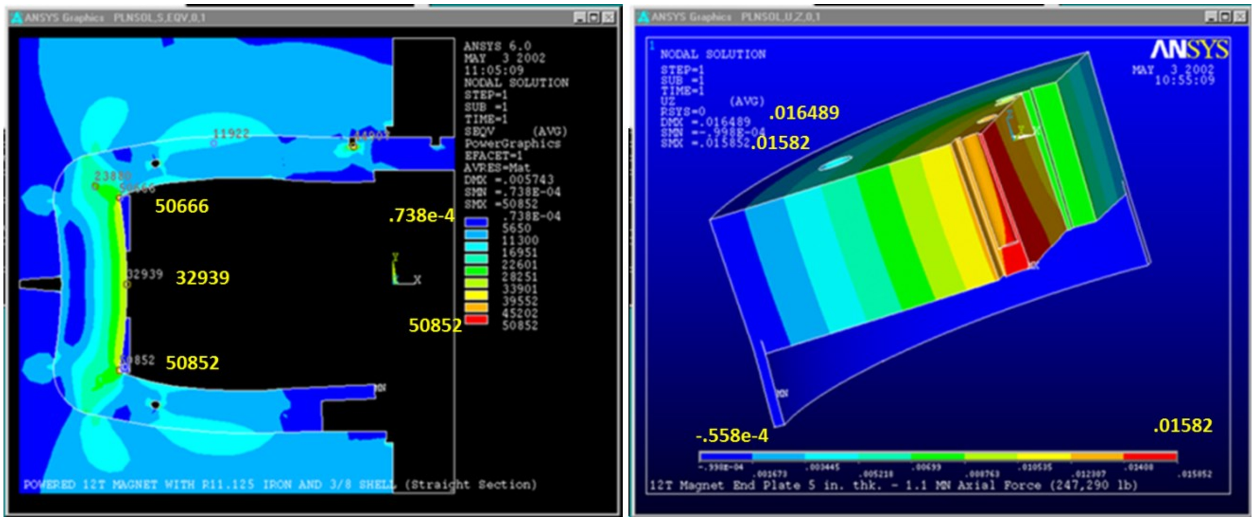


Fig. 7. ANSYS simulation showing stresses in the collar (left) and on the end plates (right) in the common coil dipole DCC017.

Field Quality in Common Coil and/or Block Design

The common coil and/or block coil design that we propose for our hybrid magnet can be optimized to produce good field quality. The design work performed on an earlier 15 T common coil Nb_3Sn magnet [16] showed that it is possible to obtain low geometric- and saturation-induced harmonics in the cross-section, as well as small harmonics in the ends of a common coil magnet (Fig. 8).

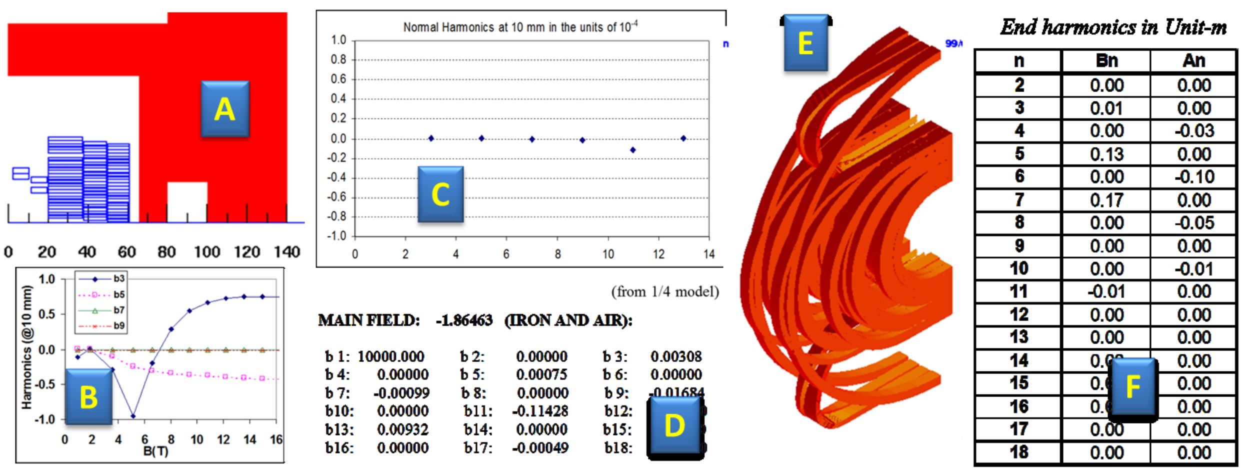


Fig. 8: Example of the optimization for good field quality in a common coil design (coil aperture 40 mm, reference radius 10 mm).(a)1/4 of magnet cross section in one aperture, (b) normal saturation induced-harmonics, (c) plot of geometric harmonics, (d) values of geometric harmonics, (e)optimized end geometry, and (f) end harmonics.

Accelerator Magnet Coils Made with Tape Conductors

BNL has built and tested a number of racetrack coils with tape conductor for various applications. For example eight flat coils, each using over 300 meters of YBCO tape (Fig. 9), were made and successfully used in a FRIB magnet [17]. Moreover in the 1960's, when Nb_3Sn was available only in tape form, before the conductor became available in multi-filamentary wire form, Sampson and colleagues at Brookhaven National Laboratory (BNL) demonstrated a quadrupole [18] made from Nb_3Sn tape (Fig. 9). In addition we have made blocks of coils in PBL/BNL Phase I proposals, as mentioned earlier [8].

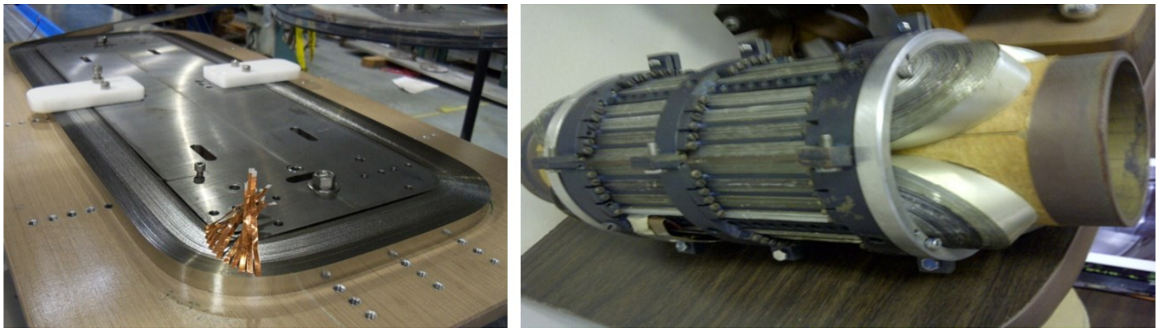


***Fig. 9**. Magnets made with tape conductors. On the left is a recently made FRIB coil using ReBCO tape, and on the right are four coils made using Nb3Sn tape and assembled in a quadrupole configuration in the 1960's.*

Cosine Theta and Block Designs

During Phase I, both the cosine theta and block designs were evaluated (see Fig. 10). We concluded that it is easier to separate the HTS and the LTS coils in a block design. This is consistent with work reported elsewhere [19], [20].

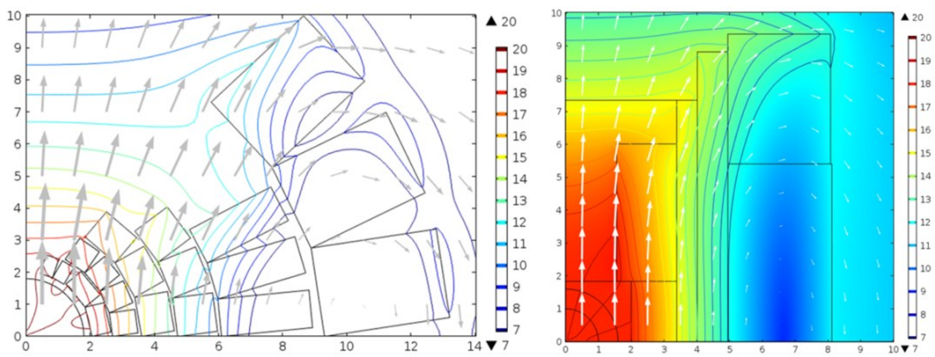


***Fig. 10**: Cosine theta hybrid design (left) and block coil hybrid design (right) evaluated during Phase I. The block coil is preferred for separating HTS/LTS coil layers and for better optimization.*

The Phase II Technical Objectives

("Objective 1 through Objective 6 contains proprietary information, trade secrets or commercial information that is privileged or confidential and exempt from public disclosure.")

The ultimate technical objective of this proposal is to develop technology for a 20 T HTS/LTS hybrid dipole. Because of the budget limitations of an STTR program, we will demonstrate the key features of the technology in a proof-of-principle magnet. A successful outcome of this additional program is expected to attract funding to carry out further R&D, to build a prototype magnet, and eventually to commercialize full length magnets.

In particular, we have found a way to design accelerator magnets such that the magnetization errors induced by the tape conductor are significantly reduced. The Phase II design utilizes this technique together with the superior magnetic and mechanical properties of ReBCO to produce a hybrid magnet design that makes efficient use of conductor while managing the field quality.

The specific objectives of this Phase II proposal are outlined below.

Objective 1: Technique to Reduce Field Errors Due to Magnetization in HTS Tape

One of the most serious issues in using HTS in tape geometry is the distortion in field uniformity caused by magnetization (due to persistent currents induced by the changing field as the current is changed).

Persistent-current magnetization that produces the unwanted distortion of the magnetic field is proportional to the width of the superconductor that is perpendicular to the magnetic field. We propose to greatly reduce these magnetization effects by designing magnets wherein the wide face of the tape is aligned with the field lines. Tape conductors have one wide dimension (tape face, typically 2 mm to 12 mm) and one narrow dimension (tape thickness, conductor typically a few microns). Thus, if the tape width can be oriented parallel to the field, the persistent current effect can be reduced by orders of magnitude compared with that found in conventional magnet designs.

Of course, it is impossible to align the conductor at all points in a magnet. However, in hybrid magnet designs where HTS is used in the higher field regions and conventional Low Temperature Superconductor (LTS) is used in the lower field regions, it is possible to align the tape conductor within a few degrees of the field lines where it matters most. LTS (such as Nb_3Sn and/or NbTi), which is usually composed of fine filaments, have relatively smaller magnetization than the tape conductors and therefore do not create similarly large field distortions. This technique is illustrated in Fig. 11 for an earlier hybrid HTS/LTS design [19] that was presented at the 2008 Low Temperature High Superconductivity Workshop (LTSW'08). This particular design had two double-pancake coils with a support structure between the pancakes. It used a 12 mm wide conductor for both HTS and LTS coils. The conductor blocks are tilted to align them parallel to the field lines as much as possible, especially in the higher field regions.

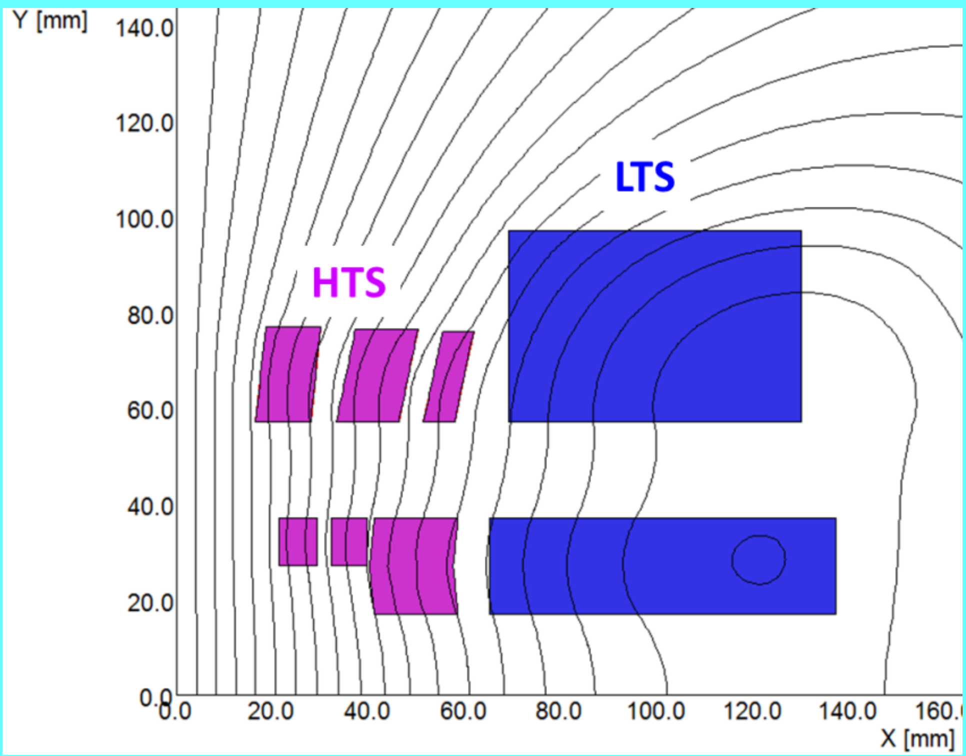


Fig. 11: Optimized design to significantly reduce magnetization-induced errors. The 12 mm wide conductor makes six LTS and four HTS layers with the wide side of the HTS tape generally aligned to the field lines.

Computational techniques (a combination of finite element modeling and analytical tools) will be developed to examine in detail field errors due to persistent current magnetization in various configurations. The results of these calculations will be compared with the measurements in a proof-of-principle magnet. These techniques will be applied in developing the design of a 20 T hybrid dipole.

This task will be carried out jointly by BNL and PBL.

Objective 2: Proof-of-Principle Demonstration Magnet

We propose to experimentally evaluate the validity of the proposed technique by building and testing an HTS tape coil with wide face of the tape reasonably aligned parallel to the field lines. The testing will be performed in the background field of dipole DCC017 (see Fig. 6 middle). The magnetic model of the preliminary design is shown in Fig. 12 where small HTS coils are placed inside DCC017. The complete coil will consist of four windings, each made with the 12 mm wide HTS tape from SuperPower. It will use Kapton insulation as in Phase I. Furthermore, because of the small pole angles (see Fig. 3), the winding technology developed and demonstrated in previous Phase I grants [8] will be directly applicable here. The minimum bend diameter will be kept at 12 mm, which is within the range recommended for this tape. A 12 mm thick coil together with the Nb_3Sn coils of DCC017 create a combined field of ~15 T with at least 10% margin in both the LTS and HTS coils. The margin in the LTS is based on the previous test of the magnet [4]. The margin in the HTS is based on the in-field measurements of previous SuperPower tapes and the fact that the assumed current density of 1000 A/mm^2 is less than double what was already achieved at 16 T when the field was not parallel to the tape surface in the ends of solenoid. A proper structure/filler will be placed inside the HTS coil and between the HTS and LTS coils to contain the Lorentz forces. Hall probes will be placed inside the assembly to make measurements. The HTS coil structure will be made such that it can be rotated by 90^o (worst case with the field perpendicular) in the future for comparison of performance (not part of the present work scope due to budget limitation).

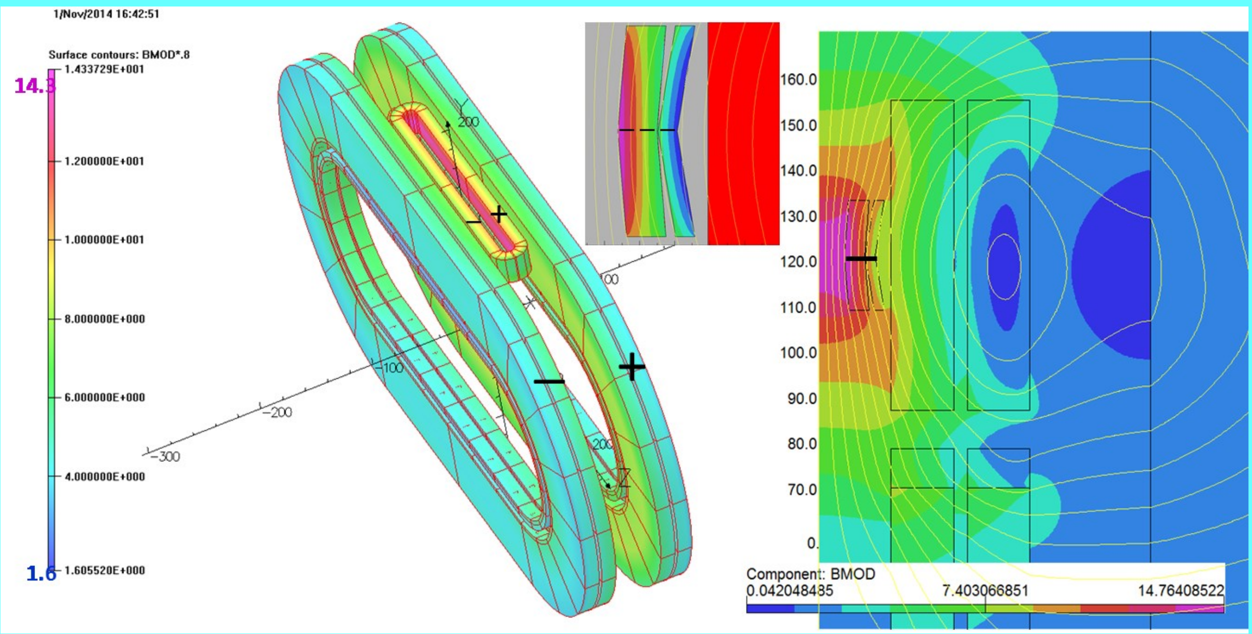


Fig. 12: Magnetic model of the Proof-of-Principle configuration to experimentally test the applicability of the proposed technique. A small HTS coil is placed inside the large Nb3Sn coil of DCC017. A 2-d model shows that the field lines (yellow) are reasonably aligned parallel to the wide face of the HTS tape. This alignment can be seen more clearly in the inset where field contour is superimposed only on the HTS coils.

This proof-of-principle dipole will be a partial demonstration of the HTS/LTS hybrid magnet technology to the extent possible in the Phase II budget. This will also be a test of quench protection in a high field HTS/LTS hybrid magnet. We will use the advanced quench protection system developed at BNL [10] in addition to heaters. Inductive coupling between the HTS and LTS coil will be considered. Initially the background field LTS coil will be operated well below its established short sample limit so as to minimize the chances of a quench. As done in earlier hybrid magnet tests at BNL, the current in the HTS coils will be increased gradually while the current in the background field coil is kept constant.

In the eventual 20 T hybrid design, both HTS and LTS coils are expected to run in series. That possibility appears within range in the future, as we are only a factor of two or three away with a bonded double tape (as examined in Phase I) or other multi-tape technique. Moreover, manufacturers have already been developing techniques to increase the thickness of the superconductor (currently only about one micron).

This task will require significant electrical and mechanical work (including structure/filler pieces for the HTS coils). It will be primarily carried out at BNL with help and guidance from PBL. One of the four HTS coils in this proof-of-principle magnet will be made at Energy to Power Solutions (E2P), as part of the tech transfer portion of this project.

Objective 3: Optimization of the High Field Accelerator Magnet Design

Our present baseline is to have a common coil design for the outer, lower-field, LTS coils and an HTS block design for the inner, high-field, coils (Fig. 13). However, alternate designs for both will be examined. The magnetic design will be carried out with the programs OPERA, ROXIE and COMSOL. Magnetic designs will be optimized to reduce 2-d and 3-d field errors and to reduce the amount of conductor needed (particularly HTS) by making the field lines parallel to the wide face of the tape conductor. In the body of the magnet, the goal will be to make the HTS tape maximum deviation from the field direction no more than five degrees. This, however, will not be possible in the ends. The magnetic design of the end region is likely to use reverse field coils to reduce the field on the winding without necessarily making the field parallel to the wide face of the tape. This will make field errors due to magnetization larger in the end section, but since the ends are a small part of a long magnet, the net influence on the integrated error should be small.

As was the case in DCC017, finite element codes such as ANSYS and COMSOL will be used for optimizing the mechanical structure so that the maximum stress and strain on all material (superconductor, stainless steel support structure, etc.) remain within desired limits. The net Lorentz forces in the design shown in Fig. 13 are 11.5 MN/m per quadrant horizontally and 3.8 MN/m per quadrant vertically. The structure may be segmented with an intermediate support structure and possibly employ a stress management technique [21]. The mechanical structure will include stainless steel collars and a shell, somewhat similar to that in DCC017 [4].

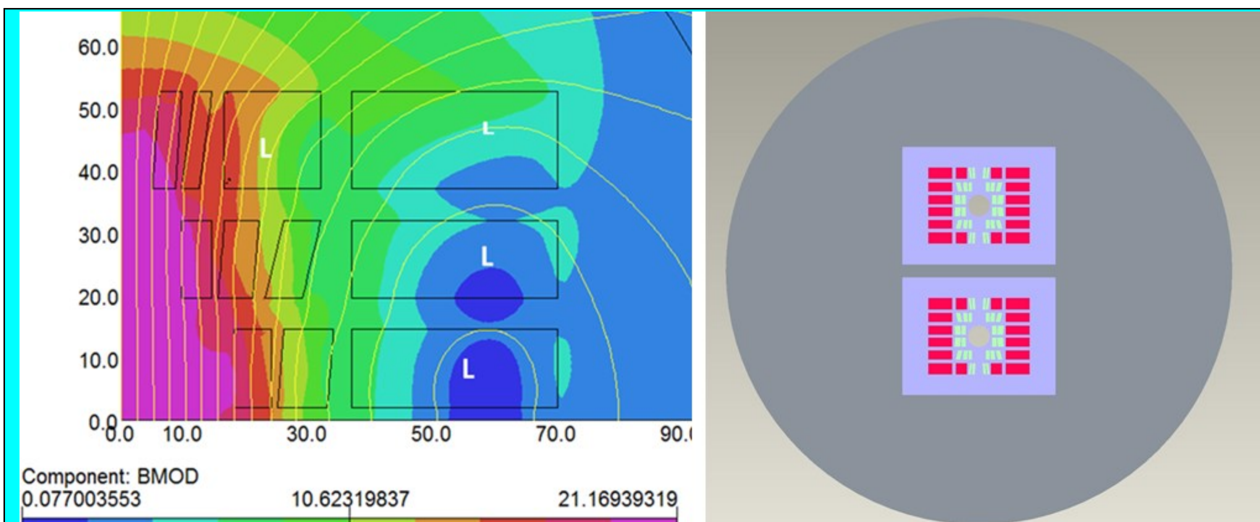


Fig. 13: Initial magnetic design of a 20 T HTS/LTS hybrid dipole shown on left with superimposed field contours and field lines (L indicates LTS coils in a quadrant of one aperture). There will be an intermediate structure between and around the coil blocks (see right for full cross section of 2-in-1 dipole). The design will be optimized to reduce cost and improve performance (align coil blocks to field lines).

A preliminary engineering design will be carried out by BNL engineers to develop a mechanical structure to contain large Lorentz forces so as to keep all components within allowable stress and strain limits as well as for easy manufacturability and cost reduction.

This is a significant task and will be jointly carried out by BNL and PBL with input from E2P.

Objective 4: Coil Ends (practice windings)

Since the baseline design assumes a flat racetrack coil for the LTS, in keeping with the common coil design (see Fig. 6, Fig. 13 and Fig. 14), the magnet ends will be simple for LTS (red color blocks in Fig. 14). However, the ends of the HTS coils must dodge the bore, and that will be more challenging. The baseline design for the HTS assumes either (a) vertically lifted ends with a small bend radius for a single aperture dipole (see Fig. 14 left) as has been used in a previous R&D magnets at BNL and at several other places, or (b) horizontally lifted ends (sideways) with a large bend radius as permitted in the common coil design (see Fig. 14, middle, for one block and Fig. 14, right, for a possible combination). It should be emphasized that only some HTS coil blocks will need to be lifted up or sideways to clear the bore tube. The common coil sideways end design may put less strain on the conductor and may produce shorter ends.

Short coils of the two types of lifted ends will be built (one at BNL and another at E2P) and tested at 77 K.

This task will be carried out jointly by BNL and E2P with the guidance from PBL.

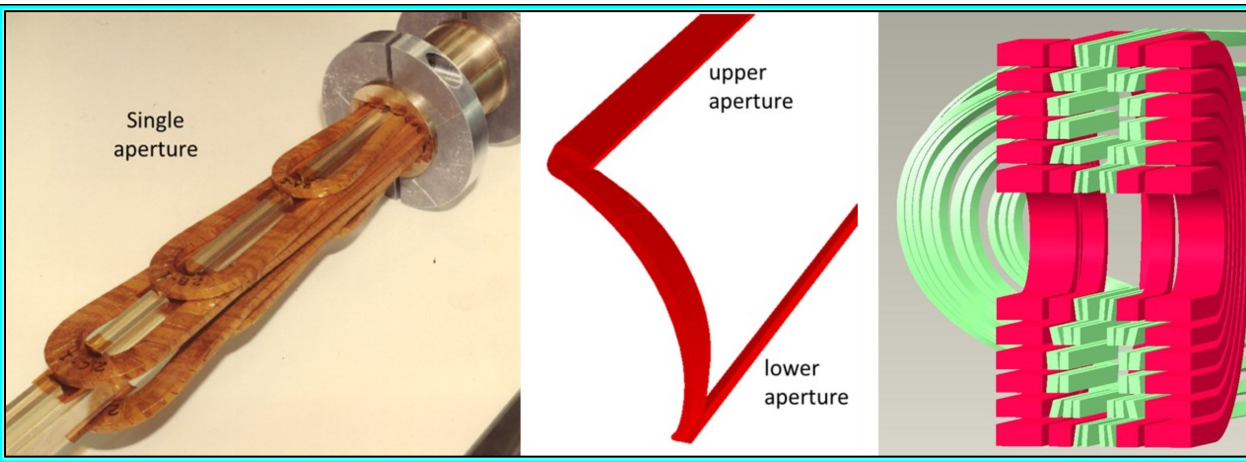


***Fig. 14**: Vertically lifted coil ends for a single aperture dipole (see left) and a horizontally lifted ends for a 2-in-1 common coil design (see right). Only the blocks needed to clear the aperture would be lifted vertically or sideways. One sideway lifted block is shown more clearly in the figure on the middle.*

Objective 5: Cost Reduction

Apart from the technical goal of developing technology for high field HTS/LTS hybrid magnets, another major goal of this program is to find ways to reduce the cost of manufacturing high field magnets. Orienting tape parallel to the field significantly reduces the amount of expensive HTS needed (by about a factor of three) for a given field as its current carrying capacity is much higher. For LTS, the cost of making the coil should be lower in a common coil design because of (a) a simpler racetrack coil geometry for most coils and (b) a reduction in the number of coils required by a factor of two since the same coils serve both apertures. The common coil concept accommodates both conventional “wind and react” and alternate “react & wind” technology (as used in DCC017) for making coils. This opens up another window for using a different insulating material and coil manufacturing process and thus offers possible cost reductions.

This task will be jointly carried out by PBL, BNL and E2P.

Objective 6: Commercialization and Technology Transfer to E2P

PBL has teamed up with Energy to Power Solutions (E2P) to focus on bringing the HTS technology developed during this proposal to the marketplace. PBL has developed significant IP and has a team of technology, managerial and legal experts who in various capacities have played a major role in working with industries in building superconducting magnets. Please see the commercialization plan submitted as a part of this proposal. PBL, however, does not have its own cryo-testing and manufacturing facilities. E2P is a small private company with its own infrastructure, facilities and revenues and has a significant program of its own on HTS magnets. Apart from manufacturing and testing of HTS coils, E2P collaboration with PBL and BNL will be a vital part of the planned tech transfer. In addition to accelerator magnets (see the letter from Dr. Rossi of CERN), HTS technology is of significant interest in high field NMR (see the letter from Dr. Melham of Oxford Instruments), medical gantries (see the letter from Derenchuck of ProNova) and wind turbines (see the commercialization plan from E2P).

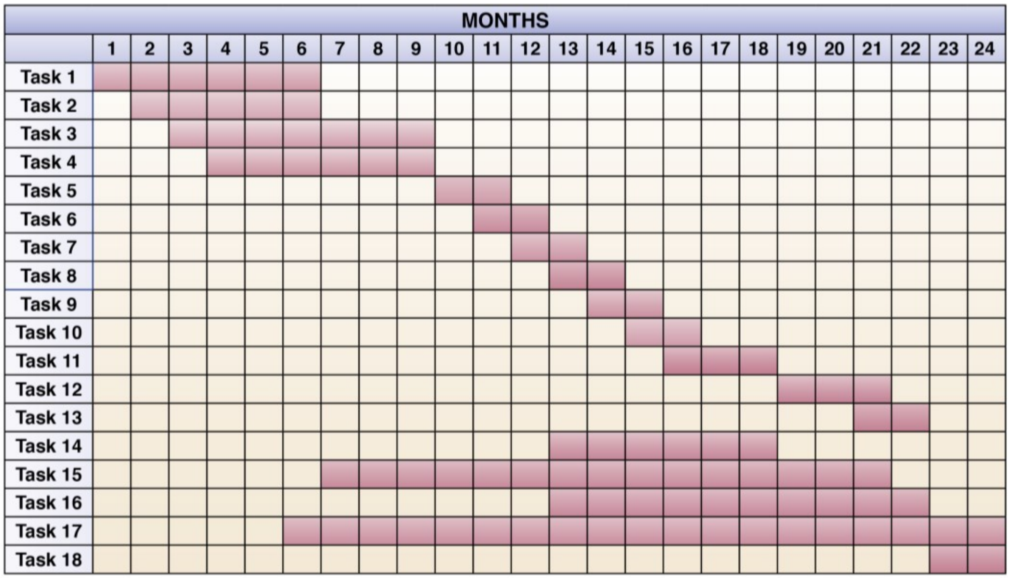
Work Plan (task list)

The two primary challenges limiting the use of YBCO tape in accelerator magnets, as mentioned earlier, are (1) mitigating the magnetization effects and (2) winding the coil with the tape conductor as required for the accelerator magnets. The tasks listed below are meant to (a) demonstrate the proposed solution in a proof-of-principle HTS/LTS hybrid dipole and (b) develop an optimized design of a high field (>20 T) HTS/LTS hybrid dipole. The primary persons (see attached list of key personnel) with major responsibilities for tasks are indicated in parenthesis. PBL, BNL and E2P will work jointly throughout to develop the technology, reduce costs and commercialize all or parts of the technology.

1) Obtain ReBCO tape superconductor (Scanlan, Gupta).
2) Optimize the detailed design of the ReBCO coil with aligned blocks and support structure that can be integrated with the background field Nb_3Sn dipole DCC017 at BNL (Gupta, Anerella, Willen, Scanlan, Weggel).
3) Using this cross section for ReBCO tapes, estimate the field distortion due to conductor magnetization (Scanlan, Weggel, Gupta).
4) Design and fabricate winding fixtures based on the experience of the previous Phase I and the results of (2) above (Gupta, Anerella, E2P, Scanlan).
5) Perform winding of four coil blocks. One block is to be made by E2P and three by BNL (Willen, Gupta, Sampson, Anerella, E2P, Scanlan).
6) Measure the performance of the coil blocks wound by BNL at 77 K to check for any damage or degradation due to coil winding (Gupta, Sampson, Scanlan).
7) Measure the performance of the coil block wound by E2P at 77 K before sending it to BNL to be integrated with the other coil blocks (E2P, Scanlan).
8) Assemble the four coils into a mechanical structure which will be later inserted into the common coil magnet and to secure retention during test (Gupta, Anerella).
9) Test the assembled structure at ~4 K in liquid helium to assess its performance (Gupta, Sampson).
10) Based on performance and testing results, make indicated revisions to the assembly and its components (Gupta, Anerella).
11) Integrate the HTS coil structure with the background field Nb3Sn dipole DCC017 (Gupta, Anerella, Willen, E2P).
12) Perform the test of HTS/LTS hybrid structure at 4 K. Testing protocols will be decided based on lessons learned. This test will include magnetization measurements (Gupta, Sampson).
13) Continue the testing program to guide the path forward and to maximize future success (Gupta, Sampson).
14) Wind and perform 77 K tests on the alternate coil end design to check for any damage of significant degradation due to coil winding (Willen, Gupta, Sampson, E2P, Scanlan).
15) Optimize magnetic and mechanical design of high field (>20 T) HTS/LTS dipole (Gupta, Anerella, Scanlan, Weggel).
16) Develop preliminary structure and mechanical assembly design of the high field hybrid dipole (Willen, Gupta, Anerella).
17) Commercialization and technology transfer to E2P (Larson, Kolonko, Scanlan, Willen, Gupta).
18) Complete analysis, write report and make recommendations for a future program (all).

Performance Schedule

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



Consultants and Subcontractors (Including Research Institution)

No consultants will be involved with this STTR. BNL and E2P will be subcontractors. Brookhaven National Laboratory, 30 Bell Ave., Bldg. 460, Upton, NY 11973 is the research institution on this proposed work. 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.

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

Facilities/Equipment

The Superconducting Magnet Division at BNL has been a major force in the development of HTS magnets for over a decade and conventional superconducting magnets over the last three decades. BNL has designed, built and tested over 100 HTS coils and over 10 HTS magnets using the BNL resources available. 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 35, including scientists, engineers, technicians and administrative staff. Construction and test of HTS solenoids 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.

The Superconducting Magnet Division also has a conductor test facility which has been used for testing a variety of conventional and HTS wire, tape and cable samples in the background field magnet of up to 15 T. These facilities have been extensively used for measuring a large number of HTS samples at various temperatures and applied fields. These facilities will continue to be utilized during this program.

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

Summary and Impact

Successful demonstration of high field magnets using our proposed technique will have a major impact in the field of accelerator magnets. High strength ReBCO conductors with a Hastelloy substrate were always preferred in high field magnets due to their high strength and their ability to deal with large stresses, but they were not seen as practical primarily because of the large field errors due to conductor magnetization in tape geometry. The technique developed during our Phase I project overcomes that shortcoming. As a result, very high field magnets made with ReBCO HTS tape will now become viable for future circular colliders (FCC). The strength of Phase II is the real demonstration of the technique in an actual high field hybrid magnet. It maximizes the use of existing hardware to allow this ambitious task to be carried out in the limited budget of STTR. The proposed design techniques are also likely to reduce the quantity and hence the cost of expensive HTS by a factor of two or more. Moreover, Phase II will use the experienced team of scientists and engineers at PBL, BNL and E2P to develop a preliminary engineering design for a 20 T magnet with a goal of easy manufacturability and reduced cost in a large volume industrial production. The design and technology developed is likely to be useful in other areas as well, and PBL has already made significant progress in creating interest with other technology companies as indicated by letters of interest. Our Phase II project is expected to produce a transformational design and technology for HTS magnets.

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Attachment: Letter of support from Prof. Lucio Rossi, CERN

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28 October 2014

To: James J. Kolonko
President
Particle Beam Lasers, Inc.
18925 Dearborn Street
Northridge, CA 91324-2807

Subject: *Letter of support for SBIR/STTR application of HTS/LTS hybrid magnet*

Mr. James Kolonko
Particle Beam Lasers, Inc.
1825 Dearborn St.
Northridge, CA. 91324

Dear Mr. Kolonko,
I am pleased to learn that the PBL/BNL team is submitting a SBIR/STTR – phase II proposal on "A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets" with Dr. Ramesh Gupta as Principle Investigator (PI) with the involvement of Dr. Erich Willen and Dr. Ron Scanlan. This R&D on HTS superconductors is important and timely for future upgrades of the Large Hadron Collider (LHC) that CERN has now started.

A possible use of a hybrid magnet, composed by LTS and HTS coils could be a future replacement of the high gradient/large aperture (140 T/m – 150 mm) quadrupole for the LHC luminosity upgrade. A first upgrade is already under study based on Nb3Sn technology. While HTS will not have the possibility to be ready by 2016 when we need the final prototype before engaging in a series production, it could be a viable solution for a possible replacement of these quads that are planned as the first generation of the upgrade, since this first upgrade may have problem to withstand the heat deposition and to survive for the necessary time in the strong radiation environment caused by the debris of proton collisions. In such a case a hybrid quadrupole ready as prototype on the horizon 2022/2023 it would be eligible to be installed in LHC after 2030, even anticipating the energy upgrade. The momentum in favor of HTS study for high field accelerator magnets continue in the frame of the CERN-led study program for a new energy frontier Hadron Collider, according to the recommendation

of the Document of Update of the European Strategy for the High Energy Physics. For the moment we keep open the two solutions: either an energy upgrade of the LHC, the so called HE-LHC, or a brand new machine in a new 80-100 km tunnel, which in this phase is becoming the main goal, under the name of FCC (Future Circular collider). In any case the HTS, either in the form of YBCO tape or Bi-2212 round wire will be a key and necessary ingredients to break the barrier of the ~15-16 T that is the intrinsic limitation of Nb3Sn. On May 2013 we have officially started the program FP7-EuCARD2, with a partial support of the EU commission and the collaboration of ten European laboratories with CERN. EuCARD2 is aimed at design and manufacture an acceleration quality dipole in HTS rated for 5 T to be inserted in a 13-15 T dipole facility to increase its field up to 18-20 T. The scope is to have this high field available for 2018-19. At minimum we foresee to use these technology in some key magnets and superconducting links of the FCC (or HE-LHC). However, a technical breakthrough in HTS magnet design and construction, with a necessary important decrease of the conductor cost, would make HTS the choice of preference also for the main magnet iof the whole ring (better stability and much easier cryogenics).
Despite the fact that these dates seem far away, it is necessary to start a long term R&D program now. The coated YBCO conductor poses new challenges, and this proposal is significant as it will aid in the development of high field magnet technology with "multi-kilo Amp" 2G HTS tape conductor and will measure and quantify the issues related to the persistent current induced harmonics and the suitability of such cable for the mechanical structure of accelerator magnets. Bi-2212 shows promise as well, and this proposal will allow compare the performance of both HTS superconductors.

Dr. Gupta, Dr. Scanlan and Dr. Willen and are qualified to lead this project. They have long experience in superconducting cable and magnet technology, with a long record of success, and have a great reputation inside the community.
For the above reasons, I warmly recommend this proposal, with which we will be pleased to collaborate. The results produced by this R&D will be helpful to be compared with the ones of Eucard2, and in general to our design parameters for the High Energy LHC, whose study program is scheduled to start officially next January 2014 at CERN.

Prof. Lucio Rossi
CERN
High Luminosity LHC Project Leader
"Future Magnets" WP10 coordinator inside the FP7-Eucard2 Program