8. Project Narrative

Cover Page

Company Name & Address:	Particle Beam Lasers, Inc. 18925 Dearborn Street Northridge, CA 91324-2807
Principal Investigator:	Ronald M. Scanlan
Project Title:	A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets
Topic No: 33	High Field Superconductors and Superconducting Magnet Technology for High Energy Physics Colliders
Subtopic: (b)	Superconducting Magnet Technology

Table of Contents

Proprietary Data: None

Identification and Significance of the Problem or Opportunity, and Technical Approach

Cost considerations drive accelerator magnet technology toward small apertures and high fields. The proposed LHC energy upgrade (HE-LHC) will require dipole magnets with fields approaching 20 T (Ref. 1). Such high fields are not possible with conventional low-temperature superconductor (LTS) technology, so innovative technology with new conductor must be developed. Only high-temperature superconductors (HTS) such as Bi-2212 and YBCO (yttrium barium copper oxide), or more generally REBCO (rare-earth barium copper oxide) are capable of adequate current density at such fields (Fig. 1). Past experience has shown that the technology-demonstration R&D such as proposed in this SBIR/STTR must be started at least a decade before the technology is mature enough for incorporation into an accelerator.

We propose a hybrid cosine theta accelerator magnet based on the combination of inner windings of HTS and outer windings of a conventional LTS material such as NbTi and/or Nb_3Sn. This proposal will develop the technology for a magnet that would have the desirable features of meeting the high field and field quality requirements while minimizing the cost impact resulting from the use of the much more expensive HTS materials such as YBCO or Bi-2212 alone.

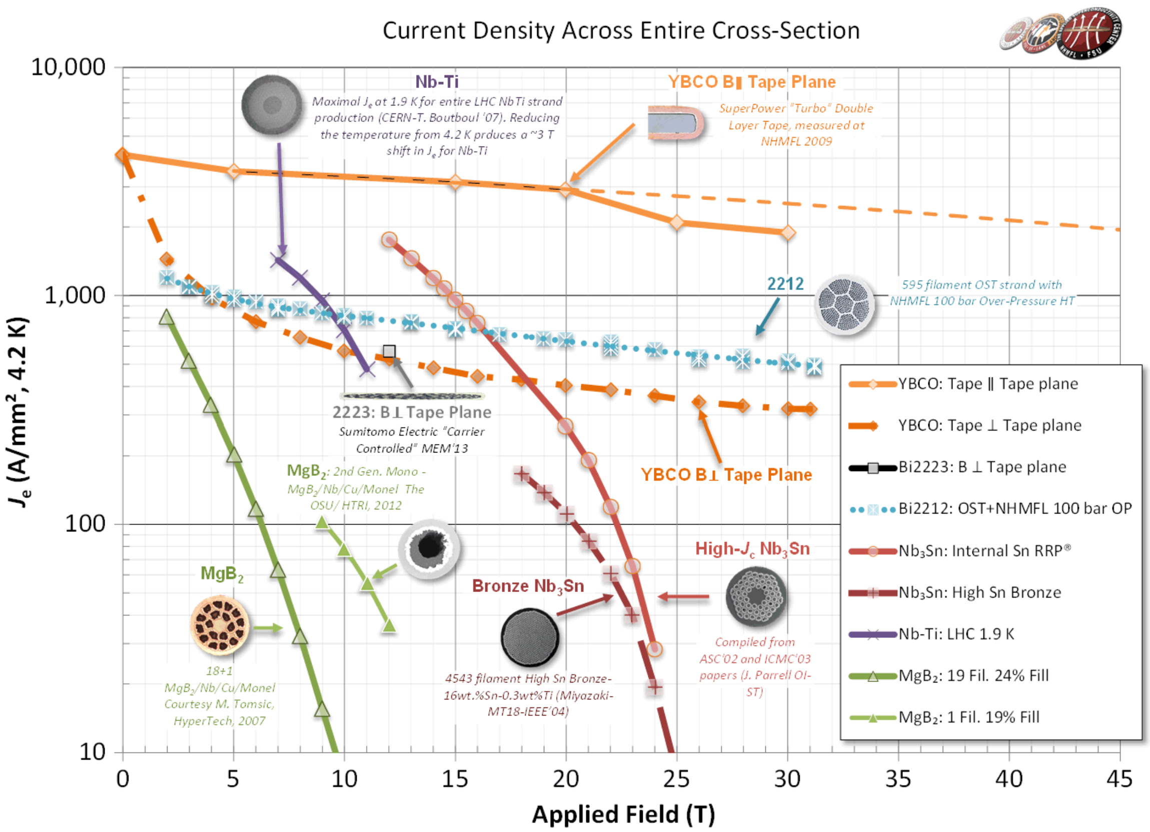

Fig.1. Engineering current density for YBCO tape and Bi-2212 wire compared to other high field superconductors, showing the advantages of YBCO and Bi-2212 at high fields. Data compiled by P. Lee, NHMFL.

Although they both are HTS superconductors, YBCO and Bi-2212 have very different properties as magnet materials. At the present stage of development, YBCO has a superior engineering critical current density (J_e) and better strength, due to its Hastelloy substrate, which is half the conductor cross section. Until recently, YBCO was available only in relatively short lengths, whereas Bi-2212 was available in lengths greater than 1000 m. However, YBCO now is available in lengths of several hundred meters, and so it now is feasible to make practical magnets from these tapes. A limitation of YBCO is that it is highly anisotropic, its critical current density being an order of magnitude poorer in the field-perpendicular vs. the field-parallel direction (Fig. 1). Another limitation is that YBCO is available only in tape form, a geometry susceptible to large magnetization currents that can degrade field quality. The degradation may not be excessive, however. Preliminary analysis suggests that a dipole magnet with a field homogeneity of $1x10^{-4}$ could maintain adequate field quality despite a magnetization that averaged ½ T (1 T at its outer faces, ramping linearly downward to zero at its midplane). Furthermore, one may be able to restore most of the theoretical field quality by trim coils or iron shims.

The big advantage of Bi-2212 at present is that it is available as round wire, which is easier than tape to make into multiple strand cables (such as Rutherford cable) and to wind into magnets. The primary limitation of Bi-2212 at this time is in overall current density, due to a combination of lower intrinsic current density (J_c) and the need for a high percentage of silver matrix material. During the past several years, DOE has funded a Bi-2212 R&D program, with the acronym VHFSMC, aimed at understanding and improving the J_c properties of this conductor. The program, involving several DOE laboratories, the NHMFL (National High Magnetic Field Laboratory), and several conductor manufacturers, has provided insight and a significant improvement in J_c (see Fig.1). However, Bi-2212 appears to be more strain sensitive than YBCO, and this needs to be remedied if Bi-2212 is to be used in high field, highly stressed magnets.

In Phase I, we will examine the trade-offs between Bi-2212 and YBCO for the specific application of a high field dipole magnet (although most of the results will be relevant to high gradient quadrupoles as well). For Bi-2212, we will design a hybrid dipole that will provide a quantitative value for the improvements in engineering current density, J_e, necessary to make Bi-2212 an attractive conductor choice. For YBCO, we propose to develop ways of dealing with the challenges of fabricating a cosine theta magnet from tape conductor, in order to reap the benefits of YBCO's high current density and good mechanical properties and thereby achieve the high fields and high field gradients required for the next generation accelerator magnets. We will use the present HE-LHC dipole magnet parameters as design targets for both YBCO and Bi-2212 coil designs, in order to be able to make a quantitative comparison with the more-conventional all-LTS design. If a clear choice cannot be made between YBCO and Bi-2212 coils based on modeling and bending studies in Phase I, we may build and test one or more coil blocks using both technologies in Phase II, based on state-of-the-art conductor and cable available at that time. The conductor showing the better performance can then be used to build a model coil later in Phase II. A possible YBCO coil configuration that could be built under a Phase II program is shown in Fig. 2. The combined experience of Principle Investigator, his PBL collaborators and BNL personnel (see Related Research and Key

Personnel sections below) places the team in a strong position to pursue both conductor options.

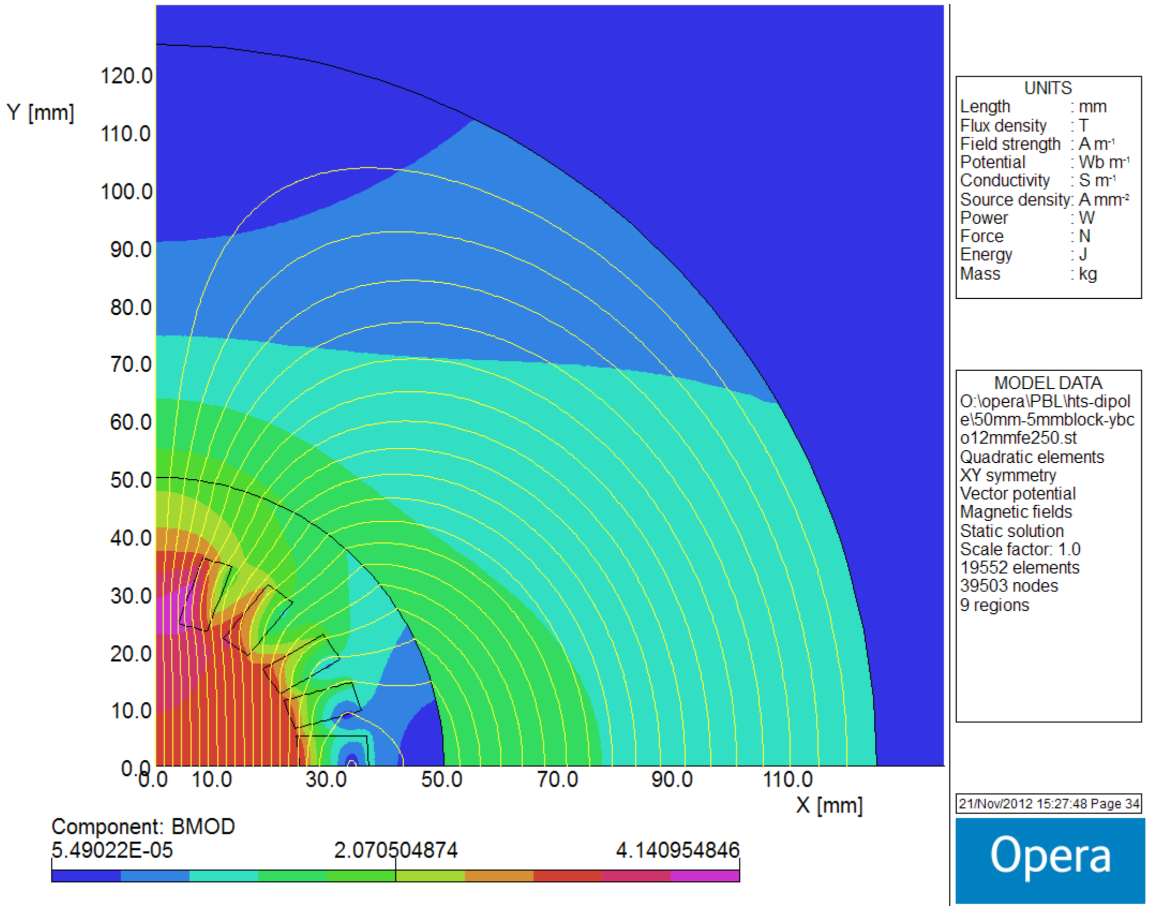

Fig. 2. Example of a YBCO coil design that could be built in a Phase II program. This design has about 125 turns of conductor in five rectangular blocks of 25 turns each. For a current density of 400 A/mm^2, about 960 A, the central field is about 4 T. An iron yoke surrounds the coil.

In the earlier Phase I SBIR, the PBL/BNL team made a preliminary investigation of the feasibility of winding a cosine theta coil using YBCO tape (Ref. 2 and Fig. 3). The major goal of this earlier Phase I was to investigate coils made with YBCO. Tooling was designed, and several pole turn windings were made with this conductor to simulate a cosine θ coil. The results showed that this could be done in such a way that its ability to carry current would not be degraded. The figure below is a picture of the winding that was made and tested.

Fig. 3. The coil winding made in the previous Phase 1. An actual magnet would be made of a series of such windings filling the circumference of the tooling mandrel, separated by wedges to control field shape.

This is a significant result as it gives promise that making a full cosine θ coil of 50 mm diameter with 12 mm wide YBCO tape is feasible using the techniques employed here. 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 in the ends; the wound coil can be heated to the required 225 °C for curing the epoxy 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.

This earlier Phase I was not able to accomplish the goals of a mid-plane cosine theta winding or a flat winding because of an insufficient length of the expensive YBCO conductor. The PBL/BNL team planned to continue this promising work under a Phase II SBIR, and a proposal was submitted. However, this Phase II was not funded, and the work was halted. The main experimental goal of the present SBIR will be to continue these promising initial results by winding the midplane turns of the cosine theta coil in order to show that these turns can be wound successfully and placed in correct position without damaging the YBCO tape conductor. This result, combined with the results of the first Phase I, will demonstrate that a YBCO tape conductor can be used successfully to wind a cosine theta magnet.

A preliminary OPERA2d design of the cross section with Bi-2212 Rutherford cable has been made. The performance using currently available long length J_e values was inferior to that with YBCO. However, these calculations did serve to reveal the value of J_e necessary for an attractive hybrid design with Bi-2212: ~400 A/mm^2 (averaged over the coil cross section, including insulation and epoxy), implying a $J_e \approx 500$ A/mm^2 for the Bi-2212 cable itself. Recently, Oxford Superconducting Technology (Fig. 1) has achieved J_e

values approaching 650 A/mm^2 in short wire lengths as a result of a densification step added to the processing. We will continue to monitor Bi-2212 wire improvements during Phase I, in case high-performance wire becomes available in long lengths by the time we are ready to finalize a conductor choice for Phase II.

Anticipated Public Benefits

The recent announcement by CERN of the discovery of the Higgs boson has generated worldwide excitement. It provides the opportunity for the High Energy Physics community to move forward with the next step. One attractive possibility is a "Higgs factory", which could be based on an LHC upgrade or a muon collider. Both options would require high field dipoles (e.g., 20 T) and large-aperture, high-gradient quadrupoles for the interaction regions. This Phase I project will explore the feasibility of using HTS superconductor to meet the field and aperture requirements of these interaction region magnets.

In addition, commercial spin-offs in the areas of medical accelerators and security screening can follow the development of this technology, just as the development of MRI magnets followed LTS magnet technology developed for earlier HEP accelerator magnets. Because HTS likely will remain costly, it is important to develop hybrid HTS/LTS designs, such as the ones explored in this Phase I, in order to make these magnets commercially attractive. The knowledge gained from the conductor bend tests and coil performance tests will provide valuable feedback to the conductor manufacturers in their efforts to improve these conductors to better meet the needs of the magnet community.

Technical Objectives

The standard approach for building superconducting accelerator magnets has been to use a conductor made by cabling together wires of either NbTi or Nb_3Sn superconductor. However, the superconductor with the highest J_c at high fields, YBCO, is available only in the form of a tape in widths of 4 mm to 12 mm and 0.1 to 0.3 mm in thickness. Conductor manufacturers eventually may be able to develop a wire form, but at present it is the challenge of the magnet designers to develop coil fabrication methods that will allow them to exploit the excellent critical current density available in YBCO. This challenge is more severe for accelerator magnets, since they require both a tight bend radius at the magnet ends combined with out-of-plane bending in order to dodge the bore tube. Some earlier work has been done using tape-geometry superconductors to fabricate accelerator magnets. When Nb_3Sn was available only in tape form, before the conductor became available in multifilamentary form, Sampson and colleagues at Brookhaven National Laboratory (BNL) demonstrated a quadrupole made from Nb_3Sn tape (Fig. 4 and Ref. 2).

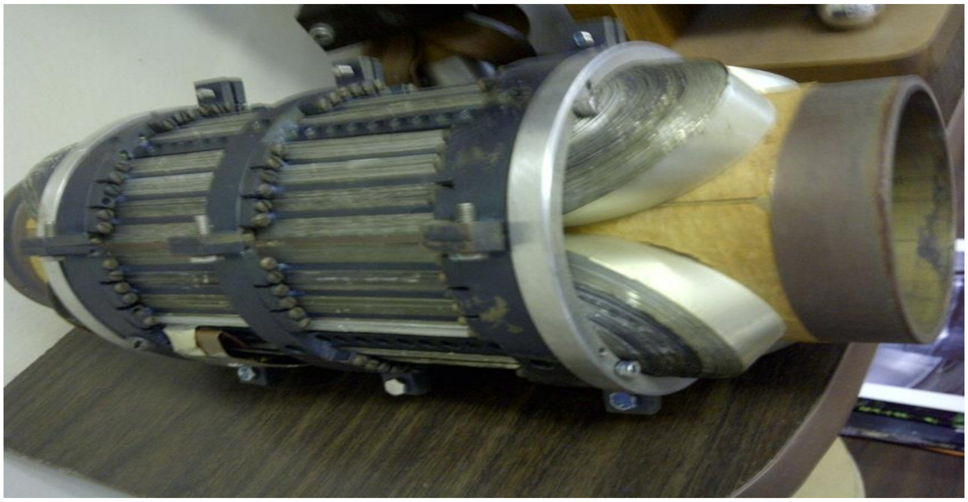

Fig. 4. Nb_3Sn tape quadrupole made by W. Sampson at BNL.

More recently, a quadrupole magnet with the acronym FRIB (Ref. 5) was made at BNL using 2G (second generation) YBCO tape. This magnet uses a special 4-ply tape (two superconductor and two copper tapes soldered together) in order to increase the operating current, and this demonstrates the type of development work we propose here in order to adapt the YBCO tape to this new application. Another recent effort to use YBCO tapes (Ref. 6) to build a quadrupole magnet illustrates the importance of understanding the details of conductor bending during the magnet fabrication process. Our approach will be to begin with experimental winding tests, first with stainless steel and then actual YBCO tape, to determine the natural contour of the tapes around the ends of the coil. End pieces will be machined to allow the tape to follow this natural contour. This will be followed by coil winding tests and measurements of the current capacity to quantify any degradation. Finally, good fit and support of the ends will be achieved by adding a thermally conducting filler material and impregnating with epoxy (similar to a technique used in Ref. 6). In Phase II, these empirical results will be incorporated into computer programs such as ROXIE and/or BEND to develop codes that can be used to calculate conductor and end piece configurations for the various coil blocks in a magnet.

The field distortion due to magnetization effects in YBCO tape will be an issue. Measurement and field-error correction is beyond the scope of Phase I and will be deferred to Phase II. However, in Phase I we plan to use recent magnetization test results (Ref. 7), together with the OPERA2d finite-element code and COMSOL, to predict the approximate magnitude of the magnetization effects. More-refined calculations will be made in Phase II, and correction schemes such as the passive iron strips (Ref. 8) will be explored.

The issues for Bi-2212 conductor are different from those for YBCO, and our technical approach reflects those differences. Because the limitation on Bi-2212 is J_e, we will design a hybrid dipole magnet, using the same design parameters as used for YBCO, but with a J_e value extrapolated from the presently available value to a value that produces a magnet with a field comparable to that obtained with YBCO. This will provide valuable feedback to the conductor manufacturers on the J_e improvements necessary to make Bi-2212 competitive with YBCO. It will also provide us with a reference J_e that we can use in evaluating any improvements that are reported for Bi-2212 during the period of this Phase I effort.

Phase I Work Plan

A. YBCO

As noted above, the two primary challenges limiting the use of YBCO tape in accelerator magnets are (1) winding the tape conductor around the ends of the magnet, and (2) analyzing and mitigating the large magnetization effects. These challenges will be addressed in the following tasks:

1) Obtain samples of candidate YBCO tape superconductors. These will include a single tape of 4-mm width, two 4-mm tapes laminated together, and tape of 12-mm-width (Scanlan, Gupta).
2) Use test windings, together with data from the earlier Phase I SBIR, to optimize end configurations for these candidate tape conductors (Gupta, Willen, BNL engineers).
3) Design and fabricate bending fixtures based on a 40 mm bore and the results of (2) above (Gupta, BNL engineers).
4) Using these fixtures, perform bending studies on the candidate YBCO tapes in complex shapes that simulate the 3-D ends of coils of cosine-theta geometry. Measure the I_c at 77 K before and after bending; analyze results to quantify degradation, if any (BNL engineers, Gupta, Scanlan).
5) Develop an optimized coil cross section based on these bending studies and fabricate one or more midplane coil blocks. Measure I_c to check for any degradation due to coil winding (Weggel, BNL engineers).
6) Using this cross section and magnetization data for YBCO tapes, estimate the field distortion using OPERA 2d and/or COMSOL (Weggel, Gupta).

B. Bi-2212

1) Design a hybrid dipole using Bi-2212 Rutherford cable, using the LHC-HE parameters (40 mm aperture, 20 T field). This design will provide a target J_e necessary to make a Bi-2212 hybrid option feasible (Scanlan, Weggel, Gupta).
2) Monitor the J_e improvement program being funded by DOE and update our design to take into account any Bi-2212 conductor improvements (Scanlan, Gupta).

The final task is the preparation of a final report describing the results for Phase I and the plan for Phase II. The results for YBCO and Bi-2212 will be compared, and the best configuration will be used in Phase II to design and build a model magnet. In addition, field correction schemes, such as iron shims, will be investigated in Phase II (Scanlan, Weggel, Gupta).

Phase I Performance Schedule

The following are major tasks for Phase I:

Analytical tasks:

1. Initial hybrid coil cross section design studies for YBCO option (months 1-3).
2. Initial hybrid coil cross section design studies for Bi-2212 option (months 1-3).
3. Use BEND/ROXIE to help optimize the end cross sections (months 2-7).
4. Complete design studies for YBCO hybrid option, including an estimate of magnetization effects (months 6-8).
5. Complete design studies for Bi-2212 hybrid option, including a determination of minimum practical J_e needed for this option (months 6-8).
6. Select best option for more detailed design work in Phase II (month 8).
7. Prepare Phase II proposal (month 9).

Experimental tasks:

1. Procure YBCO tape for model coil winding (months 1-3).
2. Characterize YBCO tape (bending, Jc); (months 2-4).
3. Design winding fixtures and tooling, using experimental results of this and earlier Phase I programs (months 2-4).
4. Fabricate coil winding tooling and set up coil winding and tape insulating lines (months 3-5).
5. Wind midplane turn block using tooling from step 4 (months 5,6)
6. Test midplane turn block at 77K (month 7,8).
7. Prepare Phase II proposal (month 9).

Related Research or R&D

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. These include the recently completed Phase II SBIR titled "Development of a 6-Dimensional Muon Cooling System Using Achromat Bends, and Design, Fabrication and Test of a Prototype High Temperature Superconducting (HTS) Solenoid for the System," Al Garren and Robert Weggel, P.I.s., and another Phase II titled "Study of a Final Cooling Scheme for a Muon Collider Utilizing High-Field Solenoids," Robert Weggel, P.I. In the first SBIR, 24 pancake coils destined for the magnet have been wound and tested at 77 K. A half-length set of 12 of these coils (see Fig 5.) has been tested at 4 K, operating (without quenching) to a central field of >6 T and an ambient field of ~9.2 T. For the second Phase II, a 12 T (nominal) solenoid has been completed and will serve as the inner solenoid of an all-HTS coil set when combined with the solenoid built on the first SBIR. This inner coil has operated flawlessly, generating—without quenching—nearly 16 T, exceeding its nominal field by more than 30%.

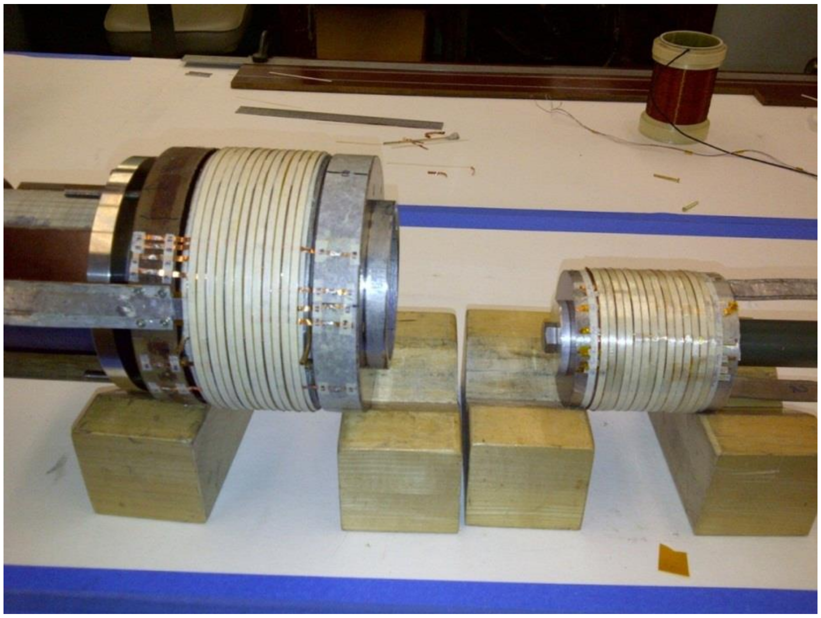

Fig. 5a. Left side—half-length “midsert” solenoid of 12 YBCO pancakes that generated a maximum ambient field of ~9.2 T at 4 K. Right side—14-pancake YBCO “insert” magnet that generated nearly 16 T on axis. Neither magnet quenched.

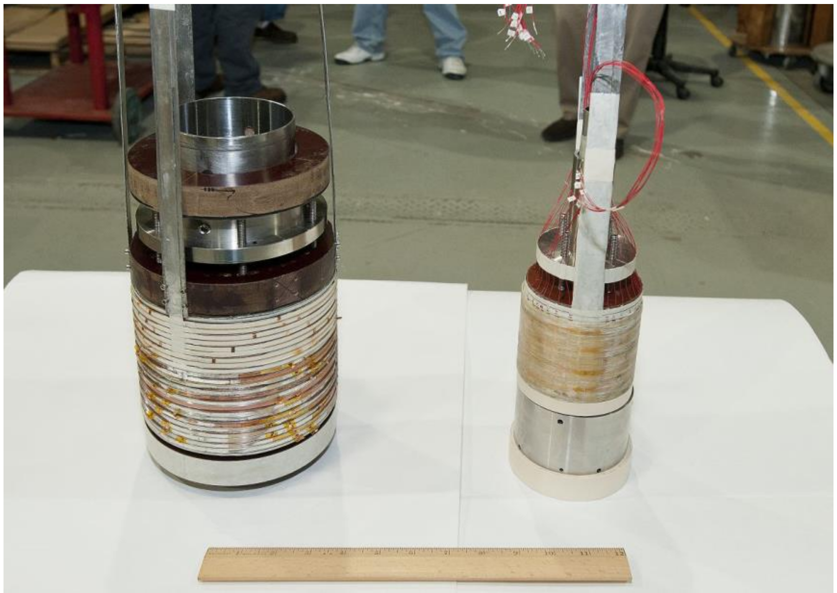

Fig. 5b. Left—Full-length “midsert” solenoid of 24 YBCO pancakes. Right—14-pancake YBCO “insert” magnet. The combined magnet is to be tested soon.

A new 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. This SBIR, which is complementary to the present proposal, is aimed at developing a design for an accelerator main ring dipole (small bore, high field).

Principal Investigator and Other Key Personnel

Ronald M. Scanlan has had 35 years of experience in the field of superconducting magnets and materials at 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 had nearly 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 had 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. Currently, he is PI on a related SBIR entitled "Magnet Coil Designs Using YBCO High Temperature Superconductor." His experience on this previous SBIR will be useful in selecting the best approach for the high-gradient quadrupole design options being explored in this new SBIR.

Dr. Ramesh Gupta will be sub-grant Principle Investigator (PI) for the work performed in the Superconducting Magnet Division (SMD) at the Brookhaven National Laboratory (BNL). The R&D at BNL will focus on the design, construction and the test of the HTS 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 is also PI for the development of HTS magnets for RIA, FRIB and sub-grant PI of a HTS Superconducting Magnetic Energy Storage (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.

Facilities/Equipment

The Superconducting Magnet Division (SMD) at BNL working in collaboration with the PBL Principle Investigator will have responsibility for the detailed mechanical design and for the construction and test of the HTS coils. The Division has extensive facilities for winding demonstration coils and for testing these coils. It also has access to simulation and engineering software tools that will aid in the design of coils and magnets. The design software available includes ROXIE, OPERA2d, OPERA3d and in-house software for magnetic design, ANSYS for mechanical design, and Pro/ENGINEER and AutoCAD for engineering design. The BNL Magnet Division has been a major player in the development conventional superconducting magnets over the last four decades and of HTS magnets for over a decade. It has dedicated HTS coil winding machines and cryo-coolers and other equipment. The Division has a staff of about 40 scientists, engineers, technicians, administrative staff and others. Construction and testing of HTS coils will be carried out in a 55,000 ft^2 multipurpose complex at the Division. The facility allows testing of a variety of superconductors, coils and magnets from 2 K to 80 K. The infrastructure (space, tools, test equipment, etc.) that are part of the Division will be made available for the Phase I and Phase II work. The value of the infrastructure at BNL is well over $1 million, an "in-kind" contribution crucial to the project.

Consultants and Subcontractors

No consultants will be involved with this SBIR. BNL will be a subcontractor.

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