Project Narrative
Cover Page

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Project Title: **Innovative** Design of a High Current Density Nb_3Sn Outer Coil for a Muon Cooling Experiment

Topic No: 66 Advanced Concepts and Technology for High-Energy Accelerators

Subtopic: (b) Technology for Muon Colliders and Muon Beams

Identification and Significance of the Problem or Opportunity and Technical Approach

Introduction

The U.S. Department of Energy is interested in the development of novel devices and instrumentation for use in producing intense muon beams suitable for muon colliders and for other applications. A Muon Collider might allow the study of High Energy Physics at energies higher than practical with more conventional technologies. Such a facility would be much smaller than conventional High Energy Physics facilities such as proton-proton colliders (such as the LHC [1]), or electron positron colliders (such as the ILC [2] or CLIC [3]). Figure 1 illustrates this advantage, showing, on the same scale, the LHC, ILC, CLIC, and a Muon Collider. The energies given are the center-of-mass energies for the electron or muon colliders, where the full particle energies are available. For the proton-proton case the energy given is the approximate energy in the individual parton-parton collisions that are available for high energy physics studies. Muon colliders allow the high energy study of point-like collisions of leptons without some of the difficulties associated with high energy electrons, such as the synchrotron radiation that requires their acceleration to be essentially linear and, for this reason, long. Muons can be accelerated in smaller rings and offer other advantages, but they are produced only diffusely and they decay rapidly, making the detailed design of such machines difficult.

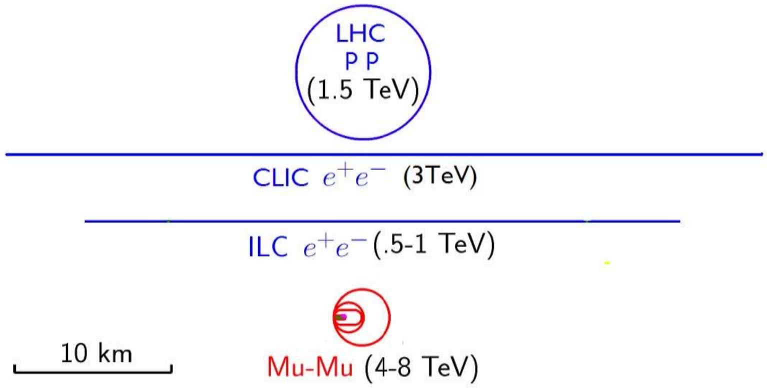


Figure 1: Relative sizes and effective available energies of High Energy Physics facilities.

There are at least two significant technical challenges in the development of the required intense muon beams. The first is the production and collection of the muons, and the second is the reduction of the phase space (cooling) of the muon beam in order to obtain the required beam properties. Such cooling involves the reduction of the beam's extent in 6-D phase space, i.e., in each of the three space and three momentum dimensions. The only technique that is fast enough for muon beam cooling is ionization cooling [4]. In this process, the magnitudes of 3-dimensional momentum vectors of the muon particles are reduced via energy loss in an ionizing media, followed by the subsequent restoration, with rf power, of only the longitudinal momentum component.

The high field solenoid design proposed in this study would be done in the context of the published complete scheme for production and cooling a muon beam for muon colliders [5]. Figure 2 shows a plot of the longitudinal and transverse emittances of the muons as they progress from production to the specified requirements for the colliders. The subsystems used to manipulate and cool the beams to meet these requirements are indicated by the numerals 1-5 on the figure.

The scheme starts (1) with the front end of a proposed neutrino factory [8] that yields bunch trains of both muon signs. Six-dimensional cooling (2), using emittance exchange, in periodic lattices with bending and reacceleration, reduces the longitudinal emittance until it becomes possible to merge (3) the trains into single bunches, one of each sign. Further cooling of all dimensions in periodic lattices with bending and acceleration (4) is applied to the single bunches. Final transverse cooling (5) to the required parameters is achieved in liquid hydrogen absorbers on the axis of 50 T solenoids, alternating with rf acceleration to restore energy lost in the hydrogen. Preliminary simulations of each element have been done at some level. It is the continued design and optimization of the last part (5) of the system that is the focus of this proposed study.

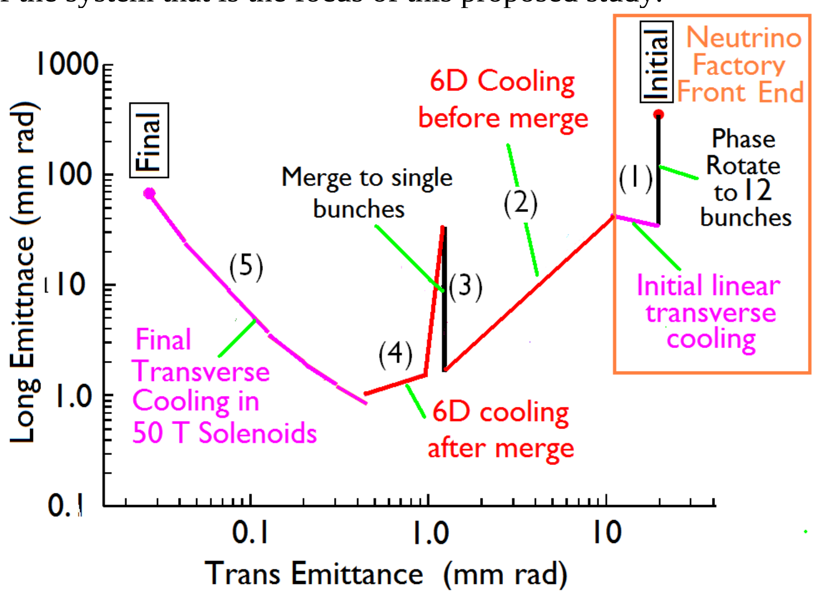


Figure 2: Proposed complete Scheme for a Muon Collider: Plot of longitudinal emittance vs. transverse emittance for each step.

At the end of stage #4 the transverse emittance is about one order of magnitude greater than required, but the longitudinal emittance is about two orders of magnitude less than required. This low longitudinal emittance allows us to do the final cooling in a channel without dispersion or wedges: a channel that cools only in the transverse direction and allows the longitudinal emittance to rise.

To attain the required final transverse emittance, the cooling needs stronger focusing than is practical with 6D cooling lattices. The higher the field, the lower the equilibrium emittance; and since the lowest possible emittance is desirable, we propose the use of the highest feasible DC magnet fields. Preliminary studies, including those in an earlier Phase I study and a current phase II study, both by PBL, suggest that fields of 50 T should be possible in all-super-conducting solenoids, but much R&D is needed before such magnets can be assured. This SBIR study, by designing the outer coils of a potentially 37 T test solenoid, will represent a necessary and useful step towards designing and building the required 50 T magnets.

A previous SBIR by the PBL team demonstrated that a hybrid magnet based on the system at the National High Magnetic Field Laboratory (NHMFL) could meet the requirements for the high field muon collider cooling channel magnets. Further work on this SBIR explored the possibility of replacing one or more of the water cooled copper insert coils with superconducting coils. The result of this study was an all-superconducting magnet system using Nb_3Sn to replace the outermost copper coil and HTS (high temperature superconductors Bi-2212 or YBCO) to replace the inner higher-field copper coils. This new design was shown to produce the desired field strength in the appropriate configuration with a greatly reduced power requirement and overall cost. However, from the standpoint of being useful for a muon cooling experiment and eventually being used in a muon collider, it has several drawbacks. The innovative features in the previous SBIR were the inner high-field coils, but the outer coils used the same design and technology employed in the NHMFL hybrid system. Due to the operational requirements of fast discharge and heat input, the NHMFL coils used a cable-in-conduit design that provided for helium flow through the coils and thus very good cooling. However, this is accomplished at the expense of overall current density, and the result is a large and expensive coil system. The PBL team believes that this large and expensive coil system can be replaced with a less expensive system utilizing a much higher overall current density by adopting a new technology developed for high field dipole magnets.

The magnet coil to be designed in this SBIR, and hopefully built in the phase II, would allow the testing of a 37 T all-superconducting magnet that would be an important step toward the construction of 50 T all-superconducting solenoids for Muon Colliders. It could also be used in a low emittance ionization cooling experiment.

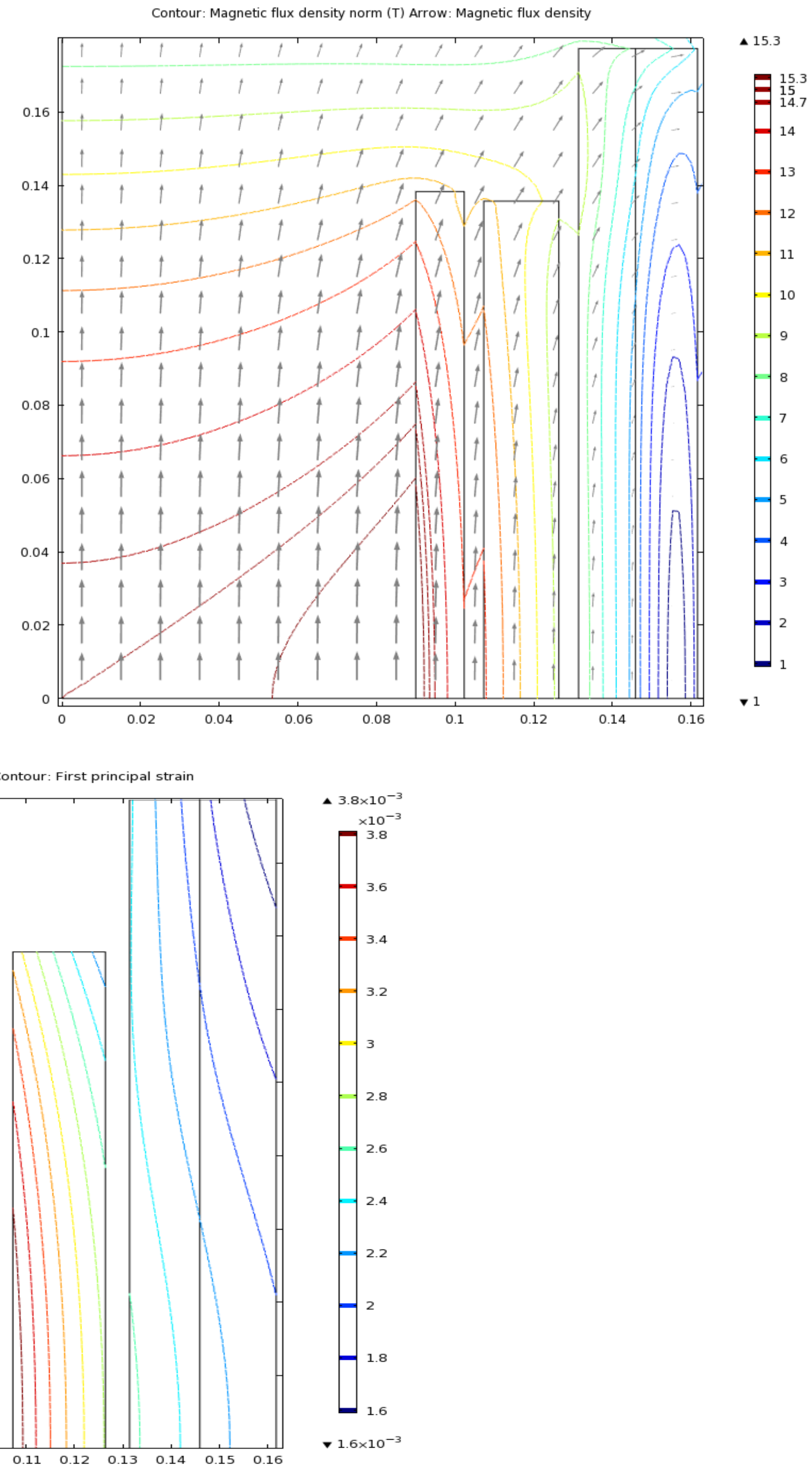
The demonstration of a large bore 15T Nb_3Sn based solenoid would represent an important step toward establishing a stand-alone 40-T, all superconducting solenoid system. Such a high-field (40T) magnet has been shown to be a possible solution for a final cooling scheme capable of producing a muon beam with the required specifications for the storage ring of muon collider [9]. The role of such a system was noted recently by the reviewers of the national Muon Acceleration Program (MAP) who commented on the importance of this high-field solenoid system to the eventual success of the Muon Collider [http://indico.fnal.gov/getFile.py/access?resId=0&materialId=16&confId=3474]. In addition, a 40-T all superconducting magnet would find other important uses for advanced studies in solid-state physics, chemistry programs and biological studies.

Technical Objectives

The primary objective of this Phase I proposal is to develop a baseline design for high current density solenoid coils that can replace the large, expensive outer solenoids in our previous design (which used the conventional approach with low current density cable-in-conduit conductors). We propose here to use an innovative technical approach for the construction of these coils—the high current density Rutherford cable technology developed for high-field dipole magnets. We believe that, using this approach, the effective current density at 12 T can be increased from around 100 A/mm^2 in the cable-in-conduit coils to over 200 A/mm^2 in the Rutherford cable design. The cost of the Nb_3Sn coil decreases with increasing current density, so this innovative design will greatly reduce the size and cost of the 50 T magnet system and thus make the next step, a muon cooling experiment, more feasible. The Rutherford cable technology has been successful in high field dipole magnets. The P.I., while working at LBNL, led the R&D program that produced a world-record 13 T cosine-theta type dipole [10], and was a member ofhe team that subsequently developed a world-record 16 T racetrack-type dipole [11]. These dipoles operate at significantly higher coil current densities than coils using a cable-in-conduit approach; 300 A/mm^2 for the 13 T cosine theta magnet and 760 A/mm^2 for the 16 T racetrack magnet. However, the Rutherford cable technology has not yet been applied to high field solenoids, for several reasons. If this high-current-density design is used in a large-bore, high-field solenoid, the coil protection issues are more formidable. Also, these high-current-density coils rely on dynamic stability and are sensitive to heat inputs due to external or internal sources (epoxy cracking, coil motion, etc.). Until this new technology is demonstrated successfully in high-field solenoids, commercial magnet manufacturers are likely to be reluctant to adopt this approach.

The PBL team will use the Rutherford cable and the wind-and-react technology as the baseline design for a new set of outer solenoid coils. The approach used for high-field Nb_3Sn dipoles will be modified to suit the unique requirements for solenoid coils. In particular, the stress environment is different, and the high tensile stresses associated with solenoids will be addressed. In addition, a key component of this Phase I effort will be to look at alternative approaches that may be better solutions for the unique issues involved with the high-field, high-current-density solenoids.

Another key feature of this proposal is its integration into the overall effort by PBL to develop a high field muon cooling solenoid. Figures 3a and 3b shows the fields and forces on a 15 T example coil. A 12 T design (not shown) will also be studied. Either would have an inner diameter chosen so that these coils will be compatible with HTS insert coils designed and built by PBL on earlier SBIR programs. [14,15]. If this Phase I and the subsequent Phase II are funded, PBL will be able to combine the HTS insert coils with a new outer Nb_3Sn solenoid to attempt a combined field of 34 T for the 12 T design or 37 T for the 15 T design.



Figs. 3a&b: Field & strain in four-coil 15-T magnet. Inner Nb_3Sn coil: I.R. ≡ a_{11} = 90 mm; O.R. ≡ a_{21} =102 mm; half length ≡ b_1 = 138 mm; coil current density ≡ j_1 = 188 A/mm^2; central field contribution ΔB_1 = 2.4 T; maximum ambient field B_{a1} = 15.8 T. Outer Nb_3Sn coil: a_{12} = 107 mm; a_{22} = 126 mm; b_2 = 136 mm; j_2 = 198 A/mm^2; ΔB_2 = 3.6 T; B_{a2} = 13.2 T. Inner NbTi coil: a_{13} = 131 mm; a_{23} = 146 mm; b_3 = 177 mm; j_3 = 250 A/mm^2; ΔB_3 = 3.6 T; B_{a3} = 9.6 T. Outer NbTi coil: a_{14} = a_{23}; a_{24} =162 mm; b_4 = b_3; j_4 = 361 A/mm^2; ΔB_4 = 5.4 T; B_{a4} = 8.0 T. Left: First-quadrant cross section and field magnitude (contours) &

direction (arrows). Right: Hoop strain ε_φ with orthotropic windings. Young's moduli $\{E_r, E_\varphi, E_z\} = \{16, 80, 40\}$ GPa in Nb_3Sn coils and {16, 80, 32} GPa in NbTi coils. E_φ of Nb_3Sn coil derived from 30% Rutherford Nb_3Sn cable of ~38 GPa + 25% steel of ~230 GPa + 15% copper of ~80 GPa+ 30% coolant & insulation (~0 GPa). E_φ of NbTi coil derived from 30% cable of ~38 GPa + 15% steel + 25% copper of ~135 GPa+ 30% residual. Maximum percent ε_φ = {0.393, 0.396, 0.266, 0.232}.

As this example shows, the current densities required and the resulting stresses are well within the capabilities of the present generation Nb_3Sn conductors. With these promising initial results, we propose the following work plan, which will complete a design for these high-current-density, high-field solenoids.

The Phase II of this proposal will be to construct a 12-15 T outer solenoid and operate it with the YBCO 10 T and 12 T inner coils to provide the approximately 12 + 10 + 15 = 37 T all-superconducting solenoid magnet. Figure 4 shows field directions and axial fields for the combined magnet.

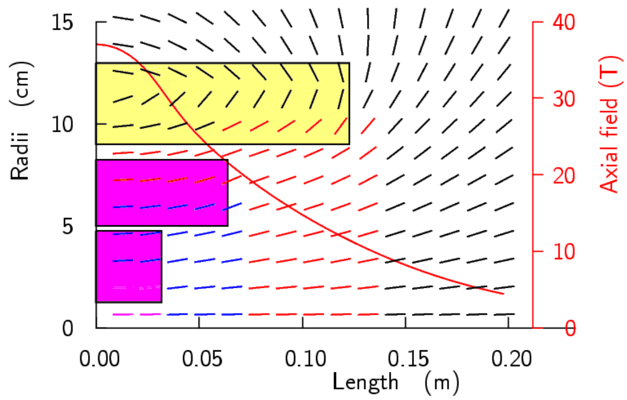


Fig. 4. Field directions and axial fields for the combined magnet using the Nb3Sn coil (yellow) and the two YBCO coils (magenta) being constructed under other SBIRs.

The completed 34-37 T magnet would enable:

a) Studies of operation and quench protection of a magnet with many of the features of the 50 T solenoids envisaged for the final cooling stage for a Muon Collider.
b) Would provide a test facility for HTS materials and small coils being developed for their later use in the 50 T all superconducting coils needed for the Collider.
c) Provide the magnet needed for a low emittance ionization cooling demonstration experiment. The emittance down to which such cooling can be achieved is inversely proportional to the solenoid field, so such a cooling experiment would demonstrate cooling to 34 pi mm mrad, compared with the 25 pi mm mrad using 50 T solenoids, as in the proposed Collider. Such a demonstration would represent an important step beyond the cooling to around 1000 pi mm mrad that the Muon Ionization Cooling Experiemnt (MICE) should demonstrate when that experiment is completed. It is envisaged that the experiment using the 37 T solenoid would be mounted at the same facility (Rutherford Appleton Lab in the UK) as MICE, where a muon beam and emittance measuring equipment will be available.

d) It would represent a step towards higher-field all-superconducting solenoids that could be used for material studies, avoiding the high power costs of hybrid magnets now operating at the NHMFL (e.g. 30 MW for 45 T) and other institutions around the world.

Phase I Work Plan

The specific tasks are:

1. Perform conductor design trade-off studies (J_c, copper content, cable design).
2. Perform detailed field and stress analyses
3. Compare react-and-wind vs. wind-and-react approaches and select the best approach for this application.
4. Complete the coil design and incorporate any structural elements required to keep the stresses and strains within acceptable bounds.
5. Determine the features of the coil protection system required to protect the coils
6. Develop the final design and cost estimate for a coil that can be built and tested in Phase II as a demonstration of this new technical approach.
7. Study the use of this Nb_3Sn coil as an outsert for a 34-37 T magnet using the YBCO solenoids built on earlier SBIR's.
8. Prepare a final report and a Phase II SBIR proposal.

A more explicit and detailed description of these tasks is presented below.

1. Conductor design trade-off studies(Scanlan). The optimized conductor must combine a high overall current density with the other key features necessary for reliable operation, e.g., copper for stability and protection, insulation, and strengthening elements to prevent the conductor from mechanical damage. Current densities for Nb_3Sn wires (at 12 T and 4 K) presently in production range from 500 A/mm^2 for ITER-type bronze-based wires to over 3,500 A/mm^2 for internal- tin-process wires used for accelerator dipole magnets. The highest current density compatible with the other design requirements will be chosen for this project. The copper content will be chosen in an iterative process with the coil protection design task. Likewise, the cable design will be chosen with coil protection and stress management issues in mind. The cable chosen will have the number of strands required to provide a high operating current and thus provide for a fast coil discharge. The strand diameter will be chosen in order to accommodate the required bending strains. Placement of strengthening elements (e.g., stainless steel strips) will be provided either as part of the cable or as overbanding. Finally, insulation will be chosen depending on the coil construction approach (wind-and-react will require a high-temperature insulation to withstand the coil reaction temperature of 700 C).

2. Field and stress analysis(Weggel). ANSYS, COMSOL and perhaps other finite-element programs will be used to model the coils and to determine the detailed stress and strain properties. Adequate strengthening elements will be added in order to keep the stresses and strains within acceptable limits.

3. Coil fabrication(Scanlan, BNL). A wind-and-react approach has been used for most high-current-density dipole magnets, due to the large bending strains experienced at the poles of the dipole magnets (the Nb_3Sn, with a maximum strain limit of around 0.8 %, would be damaged if wound around the poles in the reacted state). However, the relatively large bore of the present solenoid will allow both wind-and-react and react-and-wind approaches to be examined.

4. Final coil design, including structural elements(Weggel, Palmer, Scanlan). Several options are available for coil winding; the solenoid can be wound as a single coil (depending on conductor lengths available, protection, etc.) or as stacked double pancakes or as nested solenoids. Structural elements can be added either as banding on the outer diameter of the coil or incorporated within individual turns. If stainless steel tape is incorporated within turns, for example, it may also be used as a current shunt and thus help in coil protection. The PBL team are experienced with these coil design options, and will choose the one that best fits this particular application.

5. Magnet protection(Palmer, Weggel, BNL). As the size and stored energy of the coils increase, protection in the event of a coil quench become a more important issue. A coil protection code such as QUENCH will be used in order to determine what types of protection (internal coil shunts, external dumps, etc.) are required for this application.

6. Final design and cost estimate(Weggel, Scanlan, BNL). A coil design that can be built within the funding constraints of a Phase II SBIR will be presented. We will aim for a coil that provides the highest field possible, consistent with the time and cost constraints of the SBIR program. As in the earlier PBL SBIR projects, we anticipate conductor fabrication will be subcontracted to an experienced manufacturer and that some of the coil fabrication work will take place at BNL.

7. The coil design will be modified as needed to enable it to be used as an outsert for the two YBCO coils being constructed on the other SBIR projects(Weggel, BNL). In particular the spacing of the Nb_3Sn pancakes will be adjusted so as to reduce the radial field components on the ends of the YBCO coils. The Superconducting Magnet Division at BNL will lend its support in the development of the conceptual and magnetic design of the proposed Nb_3Sn outsert solenoid. This will include development of the parameters of the solenoid so that the three nested solenoids (one constructed under this project and two constructed under two prior SBIR Phase II projects at BNL) can be assembled together. Geometry and other parameters for the demonstration of Nb_3Sn solenoid to be built in Phase 2 will be optimized so that the use of existing tooling can be maximized to minimize cost. In addition Superconducting Magnet Division will help in developing cost and schedule for the construction of Nb_3Sn solenoid and integration of that with HTS solenoids in Phase 2.

8. Final report and Phase II proposal(PBLteam and BNL team).

Phase I Performance Schedule

1. Perform conductor design trade-off studies—Months 1-3
2. Perform field and stress analyses—Months 1-4
3. Compare react-and-wind vs. wind-and-react approaches for this application—Months 2-4
4. Complete the coil design and incorporate the structural elements required—Months 3-6
5. Conceptually design a coil protection system—Months 6-8
6. Develop a design for a model coil that can be built and tested in Phase II as a demonstration of this new technical approach—Months 6-8
7. Verify that Nb_3Sn coil is compatible with HTS coils built on earlier SBIR programs—Months 6-8
8. Prepare final report and Phase II Proposal—Months 8-9

Related Research or R&D

The proposed Phase I SBIR is part of the overall strategic plan by PBL to develop a high-field solenoid for a muon collider cooling channel. Earlier SBIR proposals have been aimed at developing the HTS inner coils necessary to reach 40-50 T. Two Phase I proposals were granted, and they were followed by two Phase II grants that are now in progress[14,15]:

1. "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." This 10 T solenoid will serve as the outer solenoid for the 12 T insert solenoid being built on the SBIR listed below, thereby leveraging other SBIR funding to achieve even higher field solenoids for muon beam cooling.

2. "Study of a Final Cooling Scheme for a Muon Collider Utilizing High-Field Solenoids". The 12 T solenoid being built on this SBIR will serve as the inner solenoid of the coil set.

The present phase I SBIR will design an outer solenoid coil using Nb_3Sn. In Phase II, this solenoid will be constructed. At the completion of the Phase II effort, the three solenoids will be combined with a goal of 34-37 T. This solenoid can be used as the basis for a muon collider cooling experiment and will provide key design information for the next step toward a 50 T solenoid. A complementary effort, funded by DOE and focused on development of HTS coils based on Bi-2212, is underway at a consortium of National Laboratories. This effort, combined with the SBIR work by PBL, will provide the information necessary to design the final 50 T muon collider cooling channel solenoids.

This research is carried out in collaboration with the Neutrino Factory and Muon Collider Collaboration (NFMCC) [12] and the Muon Collider Task Force (MCTF) [13].

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. 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 (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. Larbalestier "for the development of NbTi superconducting material for high current density application in high field superconducting magnets".

Robert J. Weggel will be the magnet designer for this Phase I project. 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 co-authored with D.B. Montgomery the book "Solenoid Magnet Design".

Robert B. Palmer is an internationally recognized accelerator physicist. He is a world's expert on stochastic cooling and the cooling of muon beams. He has a deep understanding of magnet technology and the physics and magnet requirements for muon cooling. Dr. Palmer will help coordinate the design of the coil the muon cooling experiment requires.

Ramesh Gupta will coordinate activities of Superconducting Magnet Division at BNL. He is currently overseeing the construction and test of Phase 2 HTS solenoids mentioned earlier.

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Facilities and Equipment

The applicant has been successful in prior years obtaining SBIR grants and has experience complying with federal government grant guidelines and regulations and working with federal grant officers. The Phase I work described above will be carried out in leased office space in Los Angeles, the home office of the principal investigator in

Ramona, CA, and the home offices of the other PBL, Inc. employees. Company-furnished computer hardware and public-domain software will be used as appropriate. The facilities and personnel of the BNL Magnet group will be involved in the Phase II effort to construct and test the proposed Nb3Sn magnet.

Consultants and Subcontractors

There are no consultants proposed for this SBIR Phase I project. Brookhaven National Laboratory (BNL) is the proposed subcontractor. BNL is partner with PBL, Inc. in two SBIR Phase II projects [14,15] where it is constructing (a) an approximately 10 T, 100 mm aperture solenoid and (b) another approximately 12 T, 25 mm aperture insert solenoid. The ultimate goal of this Phase I effort and the other Phase II efforts is to build a solenoid such that when the three are assembled together they will generate a field in the 35-40 T range.

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