STTR Phase II Proposal

Project Narrative

Magnet Coil Designs Using YBCO High Temperature Superconductor

Erich Willen, PI

Particle Beam Lasers, Inc

December 11, 2012

Project Narrative--Cover Page

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Project Title: Magnet Coil Designs Using YBCO High Temperature Superconductor

Topic No: **30:** High-Field Superconductor and Superconducting Magnet Technologies for High Energy Particle Colliders

Subtopic: **b:** Superconducting Magnet Technology

Grant Award Number: DE-SC0007738

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2.b. Project Narrative

Significance, Background Information, and Technical Approach:

Magnet coils built with the superconducting "cos θ" technology have proven extraordinarily popular, cost effective and reliable in modern particle accelerators. The term "cos θ" describes a coil design in which current conductors are placed on the surface of a cylindrical tube with more turns near the mid-plane and less near the pole proportional to the cosine of the angle as measured from the mid-plane. Once this challenging technology is mastered, the design offers many options regarding cost, field intensity and quality, size of aperture, and multi-pole fields that are important to accelerator designers and builders for bending and controlling beam particles. The workhorse conductor used to date has been NbTi, with some magnets built with the more challenging but higher field-producing Nb_3Sn, both operating at the very low temperature of liquid helium. However, the current carrying capacity of Low Temperature Superconductor (LTS) drops rapidly with increasing field. This makes it unattractive for magnets above 15-18 T. Now, High Temperature Superconductor (HTS), which is able to carry significant current above 15 T, has reached a level of development where it is commercially available for some applications. "High Temperature" in this context refers to temperatures between that of liquid helium (4.5 K) and that of liquid nitrogen (77 K). Its use as a replacement for LTS material for particle accelerators would probably be limited for now because of its cost. However it could prove very useful in places where limited numbers of high field, elevated temperature and/or good radiation resistant magnets are needed---for instance in focusing of beams near collision points, or in places where space is limited but strong bends are still required. Such applications are to be found for instance in upgrade goals for the LHC at CERN. This work addresses primarily the issues involved in using the YBCO HTS superconductor to build cos θ dipole magnets for accelerators. This is the first time that this design of HTS cos θ coils with constant diameter through the ends are being proposed.

The focus of the work is to investigate coils made with YBCO tape. Other alternate choices of HTS are Bi2212 in the form of wires, which allows Rutherford cable, and Bi2223 tape, but YBCO tape seems the most promising for our approach. An advantage of YBCO is that it is the most widely available HTS superconductor. Moreover, coils made with YBCO tape from SuperPower, Inc. can operate at high stress levels as the tape can tolerate stresses over 500 MPa and strains over 0.5%. These limits are not possible with other HTS materials. A challenge for magnets made with tape is possibly large field errors generated by higher magnetization than would be the case with smaller wires.

Anticipated Public Benefits:

The continued development of High Temperature Superconductor is beneficial to most areas of science and technology that require the use of strong magnetic fields---pure research, medical applications, defense, and homeland security applications. Their ability to remain superconducting at elevated temperature up to that of liquid nitrogen enhances performance, reduces cost and eases construction requirements. They are clearly the foundation stone for significant future technologies. This proposal aids in the development of an industry that can furnish these existing and even newer such materials now and into the future.

Degree To Which Phase I Has Demonstrated Technical Feasibility:

The major goal in Phase I was to investigate coils made with YBCO. We made a winding with this conductor that would simulate a cos θ coil and determined 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.

The coil winding made in 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 cos θ coil of 50 mm diameter with 12 mm wide YBCO tape is feasible using the techniques employed here. We learned the following: 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 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. We found that after all these steps the resulting assembly can perform at an impressively high level.

We were not able to accomplish our secondary goals of a mid-plane winding or a flat winding in this Phase I because of an insufficient length of the expensive YBCO conductor. But since the winding we built worked well, the loss of these additional results was disappointing but less significant. The central and most important goal, learning how a cos θ magnet might be made with HTS conductor, was accomplished with good success.

We investigated possible magnetization effects via calculation and found that they may be manageable in their effect on field quality [1]. More work is required in this area using the actual coil designs to be made in Phase II. However, these effects are of sufficient complexity that calculation alone will not answer the questions. Measurements have to be made in an actual magnet.

The magnetization arises from persistent eddy current that circulate in the conductor as the magnet current is ramped up. They worsen with conductor width. They can crowd out the transport current and reduce the achievable field in the magnet. They can also distort the desired field in the aperture and thereby negatively affect beam transport. Rapid magnet ramping will worsen both effects.

The reduced current capacity of tape HTS conductor caused by field components perpendicular to the wide face of the conductor is also a concern. The reduction is caused by the disruption of the necessary pinning of magnetic flux in the YBCO crystal structure.

In cos θ magnets, the reduced current capacity may not be a major problem because there tends to be access conductor capacity in the regions where the perpendicular components are significant. This can be seen in field plots for particular designs, but only further calculation and measurements of a completed coil can give definite answers. However, the field distortion is real and must be studied and understood through field measurements on actual magnets. At Brookhaven, the Isabelle magnets in 1980 were being made with 20 mm wide, soldered-braid superconductor and exhibited serious magnetization distortions in the field caused by this wide conductor. However, the accelerator physics calculations at the time indicated that the machine could function if ramp rates were held to approximately 10 A/s or less.

2.c. The Phase II Project

2.c.1. Technical Objectives: The primary objective is to build several single layer cos θ magnet coils using 10 to 12 mm wide YBCO HTS conductor and to test them at 77 K in liquid nitrogen and at 4.5 K in liquid helium. The coils will be designed to have adequate field quality and to reach a field in the range of about 4 Tesla. They would have a coil inner diameter of 50 mm and the coil package would be approximately 300 mm long. Their mechanical structure would contain the magnetic forces and would allow them to be incorporated into an iron yoke for a stand-alone magnet or to be part of a multi-coil magnet designed for higher field. These would be secondary objectives pending positive results with the primary objective. Several such single layer coils are planned in order to allow for recovery from possible weaknesses in the initial efforts and to hopefully confirm that success with a “one-of” magnet can be reproduced. These stand-alone coils are the core element in any cos θ magnet and here they are magnets in their own right. The parameters listed here are preliminary and are subject to possible modification for technical reasons as the work progresses.

We are not planning flat coils in this Phase II. They had been part of Phase I but were not built because of a shortage of HTS tape conductor. They had been included there to compare to the cos θ winding that was being built. Since that winding worked so well, the need for a flat coil comparison is mitigated and we will now focus our efforts on cos θ coils.

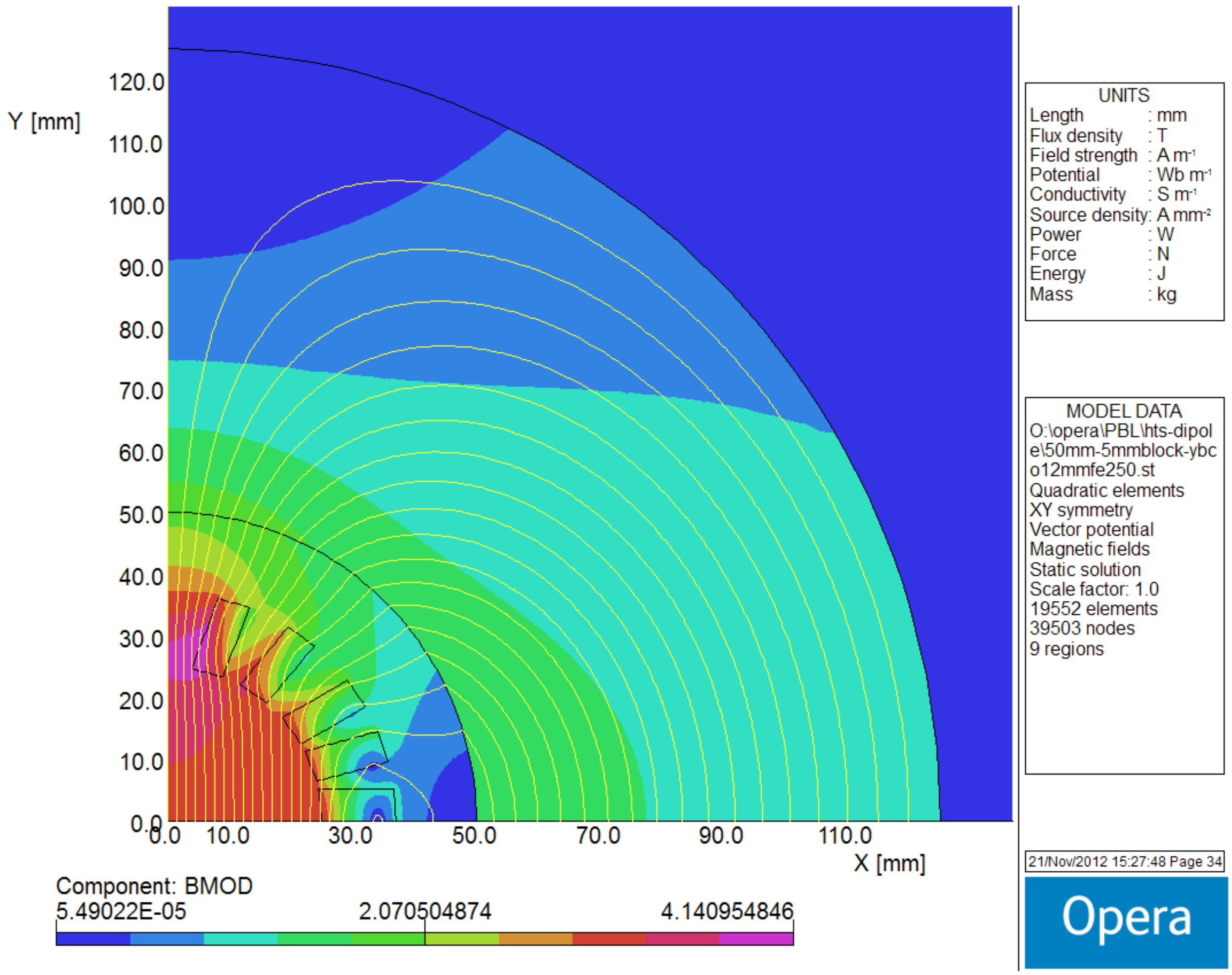
2.c.2. Work Plan: As mentioned in Section 2.b above, we have confirmation from the building and testing of a coil winding in Phase I that the planned conductor can be used to fabricate a cos θ winding. In Phase II, we will build on that effort by building a complete coil suitable for a dipole magnet. It is anticipated that building such coils will offer many challenges and that significant effort will be required to find suitable solutions for these challenges. Adequate time, dedicated effort, and much patience will be required. A particular challenge with cos θ magnets is the need for precision tooling for making coils. This tooling is expensive and time consuming to build. The tooling used in Phase I [2] was simple and did not require tightly controlled dimensions. That approach changes for Phase II where we wish to build coils with sufficient precision that actual magnets can be built. We expect to achieve good but not accelerator-level field quality in the magnets because field design iterations involving conductor packing factor and turn spacing are required for that. However, the goal of a working magnet should not be compromised.

Coil and Tooling Design: The initial effort following a Phase II grant will be detailed design work on the magnet proper, the design of the necessary tooling, and the procurement of superconductor. With satisfactory designs in hand, we will order the parts needed for the magnet and for the tooling to build it. Fabrication of tooling will begin as soon as possible. Recognizing that we are building only a few magnets, every effort will be made to control cost by designing only tooling for a limited program and by building the tooling with a minimum of costly Central Shops effort. The BNL Magnet Division has many years of experience in designing and building magnets using Low Temperature Superconductors in a variety of configurations. This experience will be brought to bear as appropriate in the current program while recognizing that there are substantive differences in the conductor and in how it performs.

Procuring the superconductor will be a collaborative effort with SuperPower, Inc. This company has a direct interest in promoting the use of tape YBCO conductors, which they have learned to make such that the conductor has excellent performance. They also have an interest in wrapping the conductor with Kapton CI tape, but in this Phase II program, Brookhaven may choose to wrap the conductor in-house on a modified wrapping machine in order to expedite the availability of the conductor.

Kapton CI is a premium material that was developed jointly by DuPont and Brookhaven in the SSC program in 1990. It is one mil thick Kapton film with a polyimide adhesive coating on one surface that activates at elevated temperature. It was used for both SSC and RHIC magnets and provides superior protection against shorts, good radiation resistance, and good adhesive properties. Brookhaven has adequate supplies of this material on hand as surplus from the RHIC magnet program.

Coil Fabrication: The magnet design will determine the conductor layout required to achieve good field quality. A possible layout is depicted in the figure below.



Example of a coil design for the proposed magnet. 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.

The magnet construction begins with the coils. Conductor turns are wound progressively onto an accurately sized mandrel. Wedges are inserted between blocks to control the field quality and to adjust the conductor block angles, which will become progressively more non-radial because of the flat (un-keystoned) conductor. Block spacers in the ends will serve a similar function---to adjust the block angles as required for each conductor block. As the cable turns traverse the ends, care will be taken to avoid straining the conductor: the goal is no strain on the conductor in either the easy or the hard bend directions. This means that each conductor turn will assume a slightly different vertical angle and that gaps will appear between turns on the inner diameter. These gaps will later be removed with filler epoxy in a post-winding operation.

A single coil will be one of two needed for a magnet (unfortunately the commonly used nomenclature refers to a "coil" both as a winding covering half the magnet bore and the two windings covering the entire bore.) Upon completion of the winding of the turns, the coil will have some fluff and will require a sizing operation to bring it to the required dimensions. This will be done with a compression fixture designed to apply modest azimuthal pressure while the coil rests in a sized cavity (formblock). With azimuthal pressure applied to the turns until compressed to a stop, the entire fixture including the coil will be placed into an oven and heated to 225 °C to activate the polyimide adhesive. Following this curing/sizing step, the coil will be released from its tooling and be ready for the necessary filling of end gaps with epoxy, and for application of current leads and of voltage taps, if any. At this stage the coil will be able to withstand modest handling because the adhesive on the Kapton wrap will secure all the turns to one another and make a semi-rigid package.

Before the actual HTS conductor is used, we will debug the apparatus and make windings with inexpensive stainless steel tape. This will help to reveal flaws in the winding plan and the tooling, and better establish the actual coil dimensions that will be realized.

Some testing of the HTS coil will be done at this point. Certainly coil size and coil electrical measurements will be made. In addition, a simple current test in liquid nitrogen will be done to confirm that the conductor has survived its construction in good shape.

Coil Assembly: Two coils made in this way will be secured onto a thin-walled, Kapton-wrapped stainless steel tube, which will become the inner surface of the coil package. This structure will then be placed into a wrapping machine and overwrapped with layers of Kevlar and painted with epoxy. A Kapton layer will separate the turns of the coil from the Kevlar/epoxy on the outside. Tension in the Kevlar wrap will result in the desired compressive stress on the coil. The amount of this tension must be determined through engineering calculations and practical experience. Multiple layers of Kevlar/epoxy will result in an oversized cylindrical package that, when the epoxy cures, can be machined to a precise diameter for nesting into another coil or into an iron yoke. This fabrication approach is similar to that used to build helical magnets for RHIC and it proved robust and reliable in that program. It supplies both the strength required to contain magnetic forces in this application and the precision required for good field quality.

In the Phase I program, we found that it is not possible to have the tape conductor in the ends conform completely to the surface of the mandrel onto which it is being wound without straining the conductor. We will avoid such strain by allowing the conductor to follow a path that lifts slightly off the surface, a path it naturally wants to follow. The diameter of the coil package is not expected to increase, however, because the turns traversing the ends do not stand fully upright but rather lie at an angle. Should the diameter nevertheless increase even a small amount outside the allotted dimension as defined by the sizing cavity, a challenge will be to accommodate this small oversized diameter in the coil sizing operation described above. Failing to do so will stress the conductor and possibly result in strain beyond an acceptable limit. Any added height resulting from an enlarged cavity can later be accommodated, if that is required, in the buildup of material in the Kevlar-wrap operation and subsequent machining of the coil's outer diameter.

Coil Testing: With the sizing of the coil, its construction will be complete and it can be prepared for testing at 77 K. Leads and voltage taps will be attached and it will be connected to the sophisticated instrumentation cluster developed at BNL for HTS magnet testing. This instrumentation features many channels of sensitive, low noise, high sensitivity electronics that can detect developing voltage at low levels (typically 5 mV), turn off power to the coil, and maintain a digital log of the many channels of information. This all ensures the safety of the magnet and provides a wealth of data for understanding magnet performance [3]. The testing at 77 K is only a first step; if successful, the coil will be tested at 4.5 K, a much more costly operation because of the price of liquid helium. A suitable dewar for testing coils at either temperature will be purchased because one of the correct size is not available at Brookhaven.

If the test in liquid helium is successful, the coil would be tested in a background field provided a suitable magnet can be found. Surprisingly there is a paucity of such magnets at Brookhaven or elsewhere and it is not clear at this time that one is available.

We do not plan to measure the field quality at cryogenic temperature unless the available funding is adequate in the later stages of the program. The funding will probably not be sufficient to acquire the equipment nor to operate the available cryogenic system required to carry out this task. Brookhaven has the capability of measuring field quality on a warm magnet using low current, and this will be part of the testing program. That however will give no information on magnetization effects.

Secondary Objectives: The secondary objective of adding an iron yoke around the coil would be pursued at this time, time and budget permitting. Since the coil package at this stage is accurately sized, at can be fitted into a yoke made of stacked laminations with an aperture sized to receive the coil. This test is definitely worth pursuing and every effort will be made to accomplish it. Adding the yoke increases and reorients the field on the conductor turns and adds valuable information on the HTS performance under these altered conditions. Building a second coil that will nest with the planned coil will probably not be possible because of the additional tooling required for such a (larger) coil.

Challenges: We recognize that there are many practical challenges in building the coils and their containment. The placement and hold-down of the numerous turns, the correct placement of various wedges and end parts that may not all fit correctly at first, the sizing of the coil package, the need to avoid shorts or near-shorts between turns or to metal surfaces, the placement of voltage taps and leads, to name just a few. A particular concern is the sizing of the coil after winding. The fixture required for doing this, in the case of LTS magnets, is costly and complex. In this project, we will seek to design and build a device that can do the job at minimum cost, possibly by reusing existing tooling. Fortunately Brookhaven still has on staff a number of the engineers and technicians who have met and overcome many such challenges before and we expect to involve them in critical parts of this work. They are and will remain a priceless asset in this program. In addition, Brookhaven has built a number of successful HTS magnets over the last five years and the experience gained in those programs will prove helpful in this program as well.

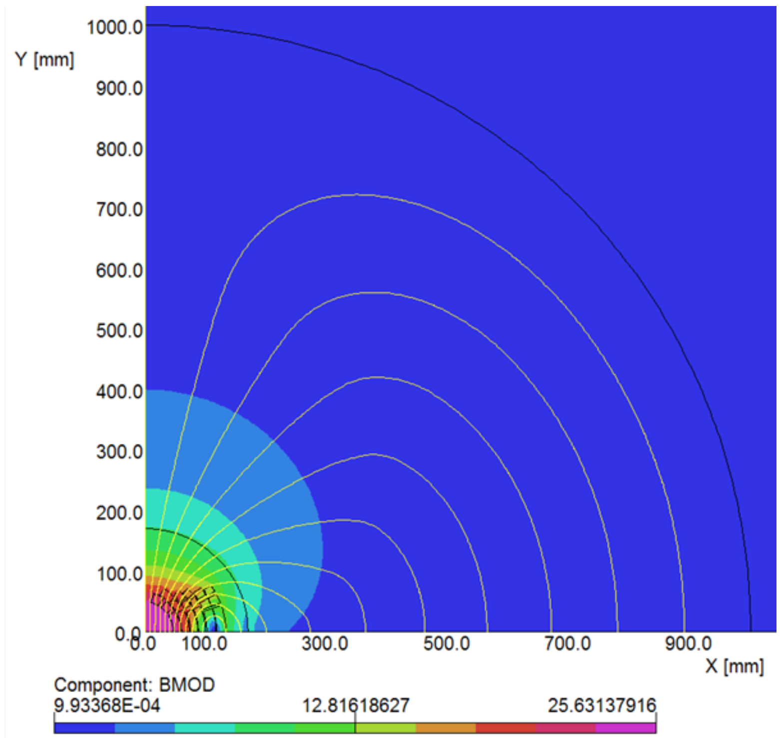
Particularly important will be the electrical integrity of the proposed coils. The history of magnet and even whole accelerator failure is replete with cases stemming from this source---in fact, the history is dominated by electrical causes. Superconducting magnets normally run with low voltages in the system but under upset conditions develop extraordinarily high voltages and failure because of the large stored energy. High temperature superconductors are more benign in this regard then their low temperature predecessors because quenches spread more slowly, allowing time for protective actions. Still, there are numerous failure modes that can generate high voltage and subsequent component breakdown caused by the still large stored energy. Our designs and our construction approach will remain cognizant of this dangerous potential throughout the program.

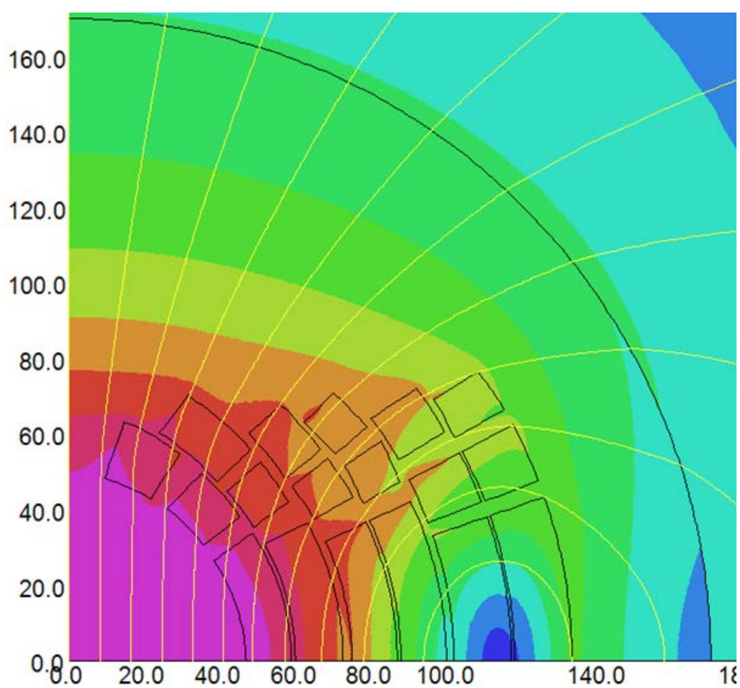
Another challenge to consider is the cooling of the conductors. We have learned from experience with LTS magnets that liquid helium will adequately permeate a coil structure for cooling to occur without special flow provisions. This is true provided that there is no source of heat in the coil or inside the diameter of the coil. If this is not the case with HTS designs, possibly running at a temperature above that of liquid helium, then various channels can be incorporated into the structure proposed here that carry cooling directly into the coil.

The inability to measure the magnet thoroughly in liquid helium will be extremely disappointing. The funding is simply insufficient. The Laboratory has legacy cryogenic systems built for major programs such as SSC, RHIC and LHC. They are large and capable, but extremely expensive to operate. Missing in the Magnet Division is a small helium refrigerator that could be used for this modest program at a tolerable cost. The Division infrastructure has not been updated for such a reduced scope capability in recent years because of funding limitations.

Further R&D: We will focus our efforts in this Phase II program on learning to build HTS coils that perform to spec. We will adopt a coil containment that is at once robust, economical, and adequate for the job at hand. The Kevlar wrap will give the required strength to contain the expected magnetic forces from a single layer coil. We expect that as the program progresses, and with successful magnet performance, there will be an opportunity to examine more robust structures that would be needed for higher field magnets. The standard high strength stainless steel collar designs backed up by a stainless steel shell may be incorporated as fields approach 20 T. The advanced structures needed for such magnets are beyond the scope of this program, but it will not be too early to contemplate their actual design requirements and how those requirements might be achieved.

The successful demonstration of a HTS cos θ magnet would open the door to many opportunities. Certainly hybrid magnets reaching 20 T or so can be contemplated, in which the inner layers are made of HTS windings and the outer layers the less expensive LTS windings. A paper study is shown in the figures below. A Phase III effort could be proposed as a natural continuation of this work, to further develop the designs and structures for much higher fields than have been obtained to date for accelerator magnets. The same principles of coil construction could be used for quadrupole magnets that reach high field gradients or that could operate at elevated temperature caused by beam heating. The technology can be transferred to industry, which has in the past successfully adapted lab designs for industrial production. As the use of HTS conductor increases, it might be expected to become less expensive, opening the door to wide-spread, advantageous use where ever accelerators are found. The figures below show a conceptual high field design.





These figures show a hybrid design of nested cos θ coils that together reach a field of 25 T on paper, using realizable conductor parameters. The coil inner diameter is 100 mm in this example.

Forces in the magnet depicted would be large and no work has been done to determine how they would be contained. This exercise shows only that such a field could in principle be attained in a hybrid design including HTS and other conductor.

Management and Control: Management and control of the project will be ensured by PBL through its several employees including the PI, working on site at Brookhaven in collaboration with Laboratory staff. As with other PBL SBIR/STTR, the activities in the Magnet Division at BNL will be coordinated by Dr. Gupta, the sub-grant PI of this proposal. Throughout the construction effort, we will incorporate a plan for thorough testing in order to detect problems early and allow corrective actions with a minimum of wasted time and material. There is every reason to believe that this program will succeed in building good magnets. If they cannot be built, we will understand why and we will know what must be done to make further progress in the use of these materials. Since the specific technology being developed here is unique and possibly significant, we will investigate whether patents on the ideas and designs are indicated.

References:

[1] R. Weggel, private communication. In an email dated June 19, 2012, Weggel reports that for a plausible magnetization that is proportional to the distance from the magnet mid-plane in a cos θ dipole operating at 20 T, the field-homogeneity contour shrinks negligibly at the 10^{-4} level, and shrinks only ~40%, from ~32 mm to ~20 mm at the 10-ppm level, compared to the case with no magnetization. Such effects are tolerable in an accelerator magnet.

[2] C. Kolz et al., Structural Design of a High Temperature Superconductor Cosine Theta Coil, Report submitted at conclusion of the Summer Intern Program, Brookhaven, 2012, unpublished.

[3] The testing and results for the Phase I winding has been comprehensively reported by: L. S. Lakshmi et al., “Construction and Test Results of Kapton Insulated 2G HTS cos θ Coil”, Presentation at the 2012 IEEE Low Temperature High Field Superconductivity Workshop (LTHFSW), Napa, CA, November 6, 2012. Please see also the Phase I Final Technical Report, attachment to this Phase II application.

Letter of Support: The following letter of support from Dr. Luccio Rossi of CERN expresses support for this R&D effort and its relevance to the LHC program at CERN.

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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6 December 2012

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 proposal by PBL*

Dear Mr. Kolonko,

I am pleased to learn that Particle Beam Lasers, Inc. (PBL) has been very successful in accomplishing the Phase I of the SBIR/STTR program, on "Magnet Coil Designs Using YBCO High Temperature Superconductor" with Dr. Erich Willen as Principle Investigator (PI) and Dr. Ramesh Gupta as sub-grant PI for Brookhaven National Lab. I understand that the collaboration is now submitting application for Phase II of such a program, engaging in a more detailed engineering and prototyping activity.

This study and prototyping is important and timely for the future upgrade of Large Hadron Collider (LHC) that CERN has engaged in. Very high field (20-25 T) dipole and quadrupole magnets are essential for the energy upgrade of LHC by a factor of 2 and more from the present design energy of 7 Tev on 7 TeV. This program is now officially part of the main studies of our long term planning and is getting high in the score of the European Strategy for Particle Physics that is presently under update.
In addition, this high field magnet technology will also have some synergy with help in the luminosity upgrade of LHC, for which we intend to use HTS cable for d.c. power transport. Both of these will significantly increase the physics reach of LHC.

Use of High Temperature Superconductor (HTS), together with conventional Low Temperature Superconductor (LTS), is mandatory for achieving 20-25 T field. One option is to use Rutherford cable made with Bi2212 round wire. However, Bi2212 is available in limited quantities and only a few conductor manufacturers have any significant R&D program. Other option is to use second generation (2G) YBCO HTS which is being produced by several conductor manufacturers around the world and has several order of magnitude more production. In addition YBCO is the choice of preference of the Energy Industry, so synergy with other field of activity are more important than for Bi-2212.

Despite its higher current density and robust mechanical performance, the coated YBCO conductor poses new challenges. Your proposal is significant as this will develop 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. This information will help accelerator physicists determine if these harmonics can be corrected and accommodated in a machine that will ramp-up slowly (which makes it easier).

Dr. Willen and Dr. Gupta are fully qualified to lead this project. Both have long experience in superconducting magnet technology. Dr. Willen has a great experience in leading large projects based on accelerator superconducting magnets and Dr. Gupta has been actively involved in the development of HTS magnet technology over the last decade and he has a great experience in HTS-oriented magnet design with innovative features.

For the above reasons, I strongly support this proposal. The results produced by this R&D will be helpful to our European program EUCARD2, that will focus on HTS for very high field HF accelerator magnets) magnet program. The program Eucard2 has been now approved and funded and will start in May 2013: we certainly keep a close link with your program, which could be an important component of the scientific movement opening the gate way to the 20 T domain and can significantly increase the applications of the new superconductors.

Sincerely,

Prof. Lucio Rossi
CERN Technology Department Deputy Head
High Luminosity LHC Project Coordinator
(formerly leader of Superconductor and Magnets for the LHC project)

2.c.3. Performance Schedule:

Start: program funding arrives, design magnet

1 month: design tooling, prepare HTS purchase order, order materials as designs solidify

3 months: begin tooling fabrication within MD, @PBL w/ outside vendors, in-house at BNL if so indicated

5 months: assemble tooling, begin practice windings

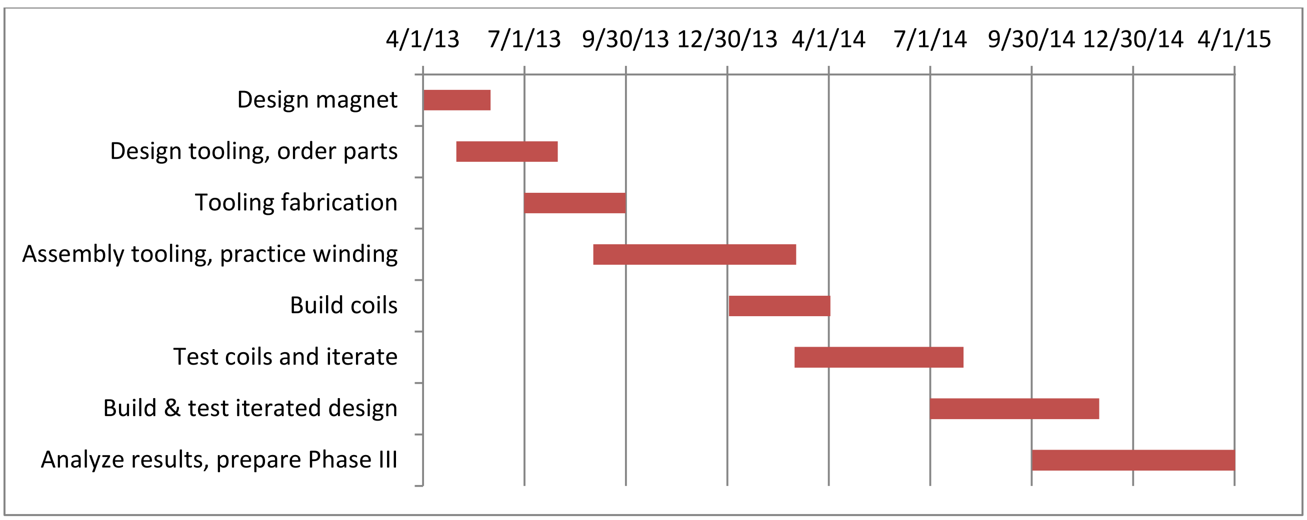
9 months: build actual coils, include robust testing regime during construction

11 months: test coils at 77 K, then at 4.5 K, iterate designs as needed

15 months: test iterated designs, iterate further if needed

18 months: finish measurements, report and discuss results, begin report writing, proceed with secondary objectives if so indicated, prepare Phase III application if results permit

24 months: conclude Phase II



A Gantt Chart showing the schedule for the proposed tasks assuming a start on April 1, 2013.

2.c.4. Facilities/Equipment: The work of designing, building and testing the proposed magnets and required tooling will be done largely at Brookhaven. The Superconducting Magnet Division (SMD) at BNL working in collaboration with the PBL Principle Investigator will have direct responsibility for the 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 but is not limited to ROXIE, OPERA2d and OPERA3d (in addition to several software that are developed in-house) 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 of HTS magnets for over a decade and conventional superconducting magnets over the last four decades. It has dedicated HTS coil winding machines, cryo-coolers and other equipment for the HTS program. The Division has a staff of about 40, including scientists, engineers, technicians and administrative staff. 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 is part of the Division will be made available for the Phase II work. The value of the infrastructure at BNL is well over $1 million, an "in-kind" contribution to the project.

<u>2.c.5. Other Topics:</u> Only American-made equipment and products are foreseen for this work.

2.c.5.a. Consultants and Subcontractors: Brookhaven National Laboratory will be a subcontractor to PBL, Inc. for this work. A BNL Statement of Work, budget, and budget justification is included in this proposal. Also included is a letter from Michael Furey, BNL Manager for Research Partnerships, authorizing the BNL Superconducting Magnet Division to participate in the project and a letter from the BNL DOE Contracting Officer allowing BNL to participate in the project. Dr. David Cline will be a consultant on the project. Dr. Cline is a distinguished elementary particle physicist known internationally for his research in experimental high energy physics and accelerator physics. Dr. Cline will provide technical input on physics issues connected with the use of such magnets connected with the upgrade of the LHC and explore commercial opportunities in the industry selling medical particle accelerators.

2.c.5.b. Research Institution: Brookhaven National Laboratory
Office of Technology Commercialization and Partnerships
Building 490C
P.O. Box 5000
Upton, NY 11973-5000

Michael J. Furey, Manager, Research Partnerships
Ph: 631-344-2103
e-mail: mfurey@bnl.gov

Subcontract Dollar Value: $494,245

2.c.5.c. Consultants and Other Subcontractors: See 2.c.5.a above. No other subcontractors

2.c.5.d. Phase II Funding Commitment (Commercial Contribution): None

2.c.5.e. Phase III Follow-On: None

2.c.5.f. Bibliography and References Cited: Information included in the Project Narrative.

2.c.5.g. Facilities and Other Resources: Information included in the Project Narrative.

2.c.5.h. Equipment: Information included in the Project Narrative.

2.c.5.i. Other Attachments: Included in the Grants.gov file and include Phase I Final Technical Report, letters of commitment, etc.

3. Senior/Key Persons

Erich Willen, PhD will be the Principle Investigator (PI) for this proposal. He holds a PhD in Nuclear Physics from the Johns Hopkins University in Baltimore, MD. Before retiring in 2006, he was a Senior Physicist at Brookhaven National Laboratory. Here he spent many years following graduate school doing experimental high energy particle research using electronic detectors. He was instrumental in the development and construction of several major detector systems at the AGS. In 1980, he joined the Magnet Division and, with John Herrera, developed the widely-used equipment and protocols for accurately and reliably measuring magnetic fields in accelerator magnets. He became the Division Head in 1984 and led the development of the SSC and RHIC superconducting magnets in the 1980's and 1990's. He later led the development of the helical magnet system for RHIC and the BNL magnet contribution to the LHC machine in CERN. Since 2006, he has maintained his office in the Magnet Division and has contributed informally to its work in various ways. Over the years, he has served on a variety of review and advisory committees including the technical review panel for the LHC magnet system in 1993. He has published numerous papers on all aspects of his work. Several magnet publications include:

E. Willen, E. Kelly, M. Anerella, J. Escallier, G. Ganetis, A. Ghosh, R. Gupta, A. Jain, A. Marone, G. Morgan, J. Muratore, A. Prodell, P. Wanderer, M. Okamura, Brookhaven National Laboratory, Construction of Helical Magnets for RHIC, PAC99, (April, 1999)

M Anerella, J Cottingham, J Cozzolino, P Dahl, Y Elisman, J Escallier, H Foelsche, G Ganetis, M Garber, A Ghosh, C Goodzeit, A Greene, R Gupta, M Harrison, J Herrera, A Jain, S Kahn, E Kelly, E Killian, M Lindner, W Louie, A Marone, G Morgan, A Morgillo, S Mulhall, J Muratore, S Plate, A Prodell, M Rehak, E Rohrer, W Sampson, J Schmalzle, W Schneider, R Shutt, G Sintchak, J Skaritka, R Thomas, P Thompson, P Wanderer, E Willen, Brookhaven National Laboratory, The RHIC Magnet System, NIM, Volume 499, Issues 2-3, Pages 280-315, (March 1, 2003)

Ramesh Gupta, PhD will be sub-grant Principle Investigator (PI) for the work performed at 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. His current interest includes developing and demonstrating HTS magnet designs and technology for particle accelerators and beam lines (website: http://www.bnl.gov/magnets/staff/gupta/). Over the last decade, he has developed several new innovative designs such as the common coil dipole, the HTS quadrupole for the RIA and FRIB, and the low cost medium field HTS dipole. He has developed a cost-effective, rapid turn-around and systematic magnet R&D approach that is now being used at LBNL and Fermilab in addition to his home institution at BNL. This approach will also be used in the HTS coil development work for this proposal. Dr. Gupta is the PI or sub-grant PI of several HTS R&D grants. He is sub-grant PI of several previous Particle Beam Lasers, Inc. SBIRs on a HTS solenoid for a muon collider and the open mid-plane dipole. He is also PI for the development of HTS magnets for RIA, FRIB and sub-grant PI of a HTS Superconducting Magnetic Storage (SMES). Dr. Gupta has also worked on the conventional Low Temperature Superconductor cosine theta magnet designs (an area that he still continues to pursue) for the RHIC and SSC projects. With Dr. Gupta playing the key role, BNL 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. Dr. Gupta has given several courses at the US Particle Accelerator Schools on superconducting magnets. Several magnet publications include:

R. Gupta, M. Anerella, J. Cozzolino, A. Ghosh, H. Hocker, W. Sampson, J. Schmalzle, Y. Shiroyanagi, P. Wanderer, Brookhaven National Laboratory, A. Zeller, National Superconducting Cyclotron Laboratory, Second Generation HTS Quadrupole for FRIB, 2010 Applied Superconductivity Conference, Washington, DC, (August 2010)

R. Gupta, M. Anerella, A. Ghosh, H. Kirk, R. Palmer, S. Plate, W. Sampson, Y. Shiroyanagi, P. Wanderer, B. Brandt, D. Cline, A. Garren, J. Kolonko, R. Scanlan, R. Weggel, Particle Beam Lasers, Inc., High field HTS R&D solenoid for muon collider, 2010 Applied Superconductivity Conference, Washington, DC, (August 2010)

R. Gupta, M. Anerella, J. Cozzolino, J. Escallier, G. Ganetis, A. Ghosh, M. Harrison, J. Muratore, W. Sampson and P. Wanderer, React & Wind Nb3Sn Common Coil Dipole, ASC 2006, in Seattle, WA, (August 27 - September 1, 2006)

M Anerella, J Cottingham, J Cozzolino, P Dahl, Y Elisman, J Escallier, H Foelsche, G Ganetis, M Garber, A Ghosh, C Goodzeit, A Greene, R Gupta, M Harrison, J Herrera, A Jain, S Kahn, E Kelly, E Killian, M Lindner, W Louie, A Marone, G Morgan, A Morgillo, S Mulhall, J Muratore, S Plate, A Prodell, M Rehak, E Rohrer, W Sampson, J Schmalzle, W Schneider, R Shutt, G Sintchak, J Skaritka, R Thomas, P Thompson, P Wanderer, E Willen, Brookhaven National Laboratory, The RHIC Magnet System, NIM, Volume 499, Issues 2-3, Pages 280-315, (March 1, 2003)

Robert J. Weggel will study the magnetization effects in the proposed magnet designs. He 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*".

Ronald Scanlan, PhD will assist Ramesh Gupta in the selection and evaluation of the conductor. He has had 35 years experience in the field of superconducting magnets and materials at the General Electric R&D Laboratory, LLNL (Lawrence Livermore National Laboratory), and LBNL Lawrence Berkeley National Laboratory), serving as group leader and program head.

The work at BNL will be supported by M. Anerella, Head of the Mechanical Engineering Group in the Brookhaven Magnet Division, and various members of that Group.