Cover Page

Magnet Coil Designs Using YBCO High Temperature Superconductor

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Principal Investigator: Erich H. Willen

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

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2) Proprietary Data: none

3) Identification and Significance of the Problem or Opportunity and Technical Approach

High magnetic fields approaching 25 T are needed for significant advances in the physics reach of colliders for high energy physics. The new Large Hadron Collider (LHC)[1] at CERN needs high field magnets for planned energy and luminosity upgrades. The envisioned Muon Collider[2] needs such magnets in several areas of the machine. Dipole magnets, quadrupole magnets and even solenoid magnets are all needed. High Temperature Superconductors (HTS) currently are the only superconductors that could produce magnets for these applications because they have a significantly higher critical current density than any other superconductor at high fields. Thus, HTS coils can be incorporated in hybrid designs where they add several Tesla of central field to the field produced by more conventional coils. They also offer higher temperature margins before losing their ability to carry current (quenching), important for magnets subjected to high energy deposition, especially interaction region (IR) magnets. Technology involving HTS opens a unique and important opportunity for progress towards these important goals.

Many applications for both accelerators and other devices have already been successfully demonstrated with first generation (1G) HTS wire or tape (in the HTS industry tape is referred to as wire; the term “tape” is used only when this aspect needs emphasis). These were based on Bi2212 or Bi2223 superconductor. For example, the Brookhaven National Laboratory (BNL) Superconducting Magnet Division has developed medium field R&D HTS quadrupole magnets for the Facility for Rare Isotope Beams (FRIB)[3] in Michigan. A round wire that allows the use of Rutherford cable, a possibility with Bi2212, would facilitate conventional design. In fact, BNL has earlier built and tested several racetrack coils with Bi2212 Rutherford cable. However, this cable suffers significant degradation under high stresses (above ~100 MPa) and thus poses a significant technical challenge in high field magnets. Moreover, despite being in existence for over two decades, the current availability and future market of these materials appears limited.

This proposal addresses magnet coil designs and technology that would enable high field magnets using second generation (2G) YBCO coated conductor as an alternate to Bi2212. This material is available from multiple US and several worldwide manufacturers, for example SuperPower Corporation. Their material shows no degradation below 700 MPa and hence is suitable for high field magnets which must deal with high stresses.

YBCO is primarily available in tape form. This poses a new set of challenges in winding coils and with large magnetization and anisotropy in the magnetic and mechanical properties of the superconductor. A major goal of this proposal is to demonstrate the viability of hybrid (HTS+LTS) high field dipoles by building small coils using designs that could be scaled up for use in such hybrid magnets. Another goal is to (a) quantify magnetization effects (for example to measure the persistent currents) and to determine if they can be managed in applications where magnets will ramp slowly and (b) to find ways to mitigate these problems. Figure 1 shows a preliminary calculation for an HTS insert in an existing common coil Nb_3Sn dipole magnet using presently available current densities for the HTS. This design approaches 15 T in the center of the aperture.

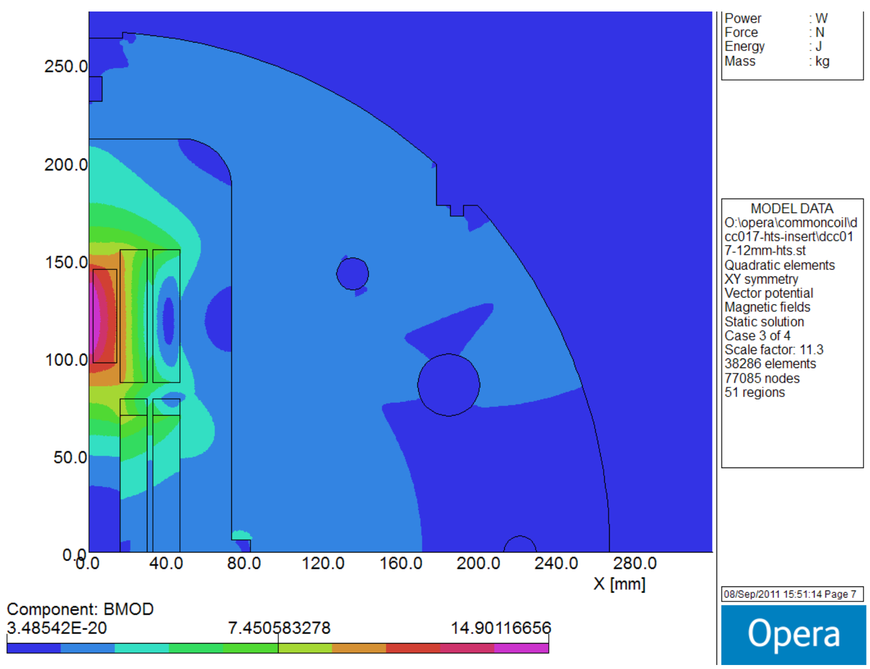

Figure 1. HTS insert in a common coil magnet approaches 15 T in field strength.

Figure 2 shows the current density possible in background magnetic fields for various superconducting materials.

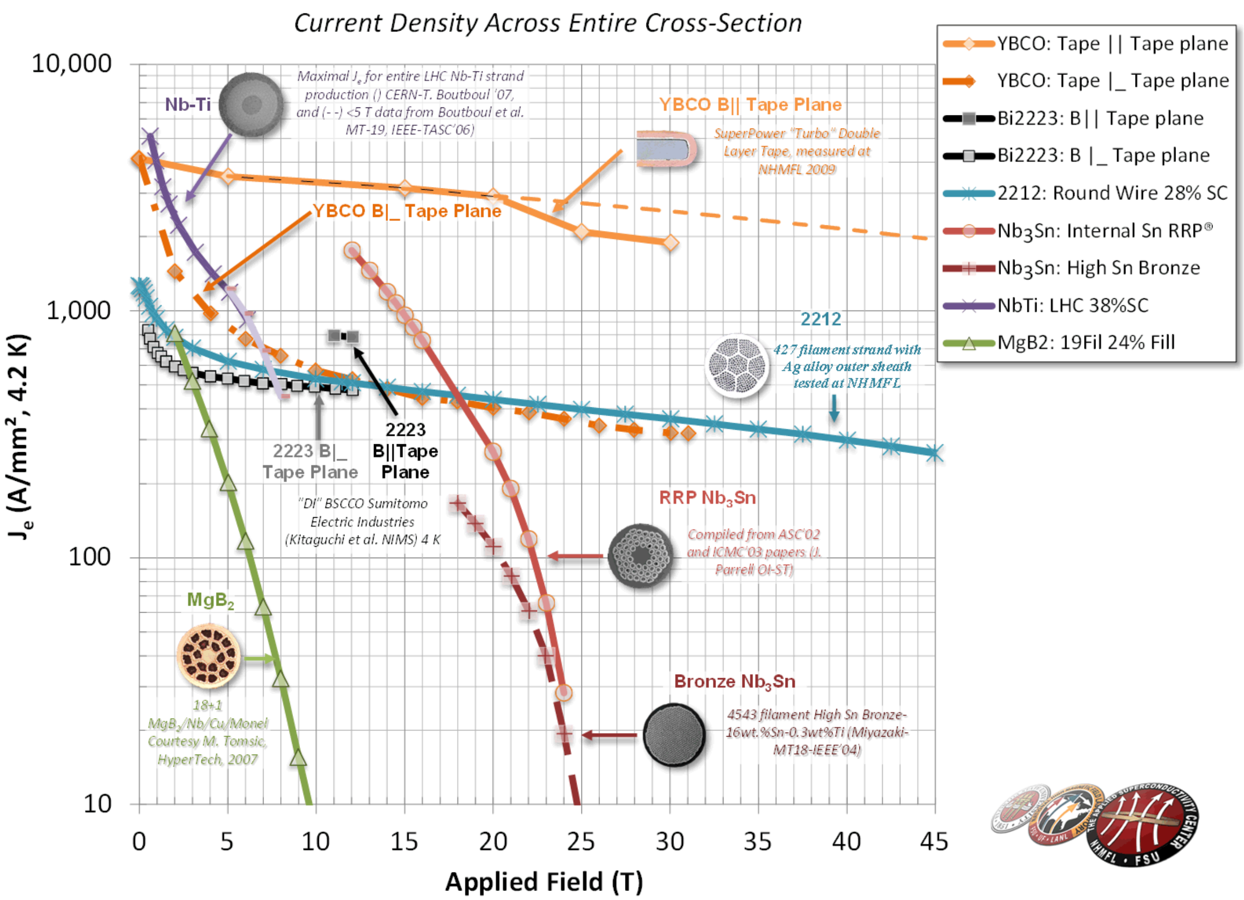

Figure 2. Current densities available in various superconducting materials.

The PBL/BNL team has unique and significant experience and on-going programs for developing magnets, for example a high field HTS solenoid magnet with 2G tape[4], dipole magnets with various conductors, and other projects (please see Section 8 labeled ***Related Research or R&D***). Utilizing this experience, both a flat coil and a cosine theta (cos θ) coil will be designed, built and tested to liquid nitrogen (LN2) temperatures in Phase I. Flat coils using HTS tape have been built before but the parameters envisioned here differ sufficiently that additional modest development effort is required. Previous cos θ coils have used Rutherford-style cables made with twisted and transposed NbTi superconducting wire, a technique that is not possible for this HTS conductor. We propose to build at least one current block of cos θ geometry and to test it at 77 K in LN2 in order to determine conductor degradation in the complex end geometry of a cos θ magnet. Testing of both coils in background field geometries is not planned for Phase I but will be reserved for Phase II.

In summary, HTS offers two major potential advantages for very high field accelerator magnets that can have a large impact on the design of future high luminosity high-energy accelerator or future high energy storage rings. These are:

- At 4.2 K, 2G HTS offers much higher critical currents than LTS at fields exceeding 20 T, due to its high critical field.
- Available 2G HTS has robust mechanical characteristics.
- HTS in general can tolerate large heat loads due to its high critical temperature. This advantage was successfully demonstrated through a large energy deposition experiment with an R&D quadrupole that was designed and built for RIA (now called FBIR).

In addition, a larger scale application in arc magnets may become viable if there is a significant reduction in conductor price, an anticipated and important aspect for 2G HTS.

Summarizing further, second generation HTS poses significant challenges that need to be addressed when designing dipole and/or quadrupole magnets for particle accelerators. Some of these challenges are:

- 2G HTS is available in tape form rather than conventional Rutherford cable form.
- 2G HTS, unlike NbTi, but like Nb_3Sn, is brittle. However, because of its relatively good strain tolerance it can be used in a “react and wind” technology.
- The conductor must have a minimum bend radius of 6 to 15 mm (present technology and dependent on the conductor vendor) in the “easy” direction (bend perpendicular to wide face) and bending in the “hard” direction (bend perpendicular to narrow face) should preferably be minimized.
- 2G HTS in the entire magnet must stay within its stress and strain limits.

Many of these challenges can be accommodated in “conductor friendly” magnet designs based on racetrack or cos θ coils having a bend radius equal to or larger than 6 mm.

4) Anticipated Public Benefits

This R&D program will advance the understanding and use of High Temperature Superconductors. By seeking to build magnet coils with this material, the practical challenges of using the materials in actual devices will be confronted and hopefully overcome. This would be immediately useful for magnets to be used in accelerators and related devices, but would also be beneficial in many technological systems that require magnetic fields to be produced economically and reliably. Such systems include the production and distribution of electrical energy, the rapidly growing communications industry, and the accelerating demands for medical and security-related devices. It would also advance the technology for producing newer and better types of HTS material as the vendors of these products respond to and are supported by the developing demand for their efforts.

5) Technical Objectives

Available 2G YBCO HTS tapes have excellent mechanical properties and allow a convenient react-and-wind technique for coil construction. These tapes are typically 4 or 12 mm wide and 0.1 to 0.3 mm thick, though widths ranging from 2 to 12 mm are available. Larger widths are expected to be available soon. In addition, 4-ply tape (two HTS and two copper) has been used in the FRIB quadrupole to increase the current with apparently adequate current sharing between the conductors. Issues related to using tapes to build coils will be one of the critical areas of this investigation. One goal will be to identify electrical and mechanical issues for conductor development.

Magnet coils are expected to operate at a few KA of current. To avoid quenching, the coil current would be increased slowly, reaching full field in several tens of minutes to about an hour. The proposed R&D is expected to demonstrate that the superconductor and coil package can tolerate the stress and strain that are expected in specific high field magnet designs and to demonstrate that the conductor does not suffer significant degradation (fatigue) after a number of current cycles.

Flat coils:

The design will be developed in such a way that the same flat (racetrack) coil could be used in two different dipole magnet configurations: either (1) for an open mid-plane dipole for use in a collider interaction region or for a Muon Collider bending magnet, or (2) for a 2-in-1 common coil dipole. These two different orientations are expected to provide essential data because the magnetic and mechanical properties of HTS tape are rather different in the two configurations. Another goal will be to develop a magnetic and mechanical design of the racetrack coil module to allow it to be tested in the BNL Nb_3Sn common coil dipole magnet in Phase II. These are incremental steps that will allow the development of specific practical techniques in the construction and use of such coils.

Cosine theta coils:

Here the conductor is placed around a beam aperture with a cos θ turn distribution from mid-plane to pole. Such coils are attractive because of their efficient use of superconductor to generate a magnetic field; all current hadron colliders use this design. Efficient use of superconductor becomes an important consideration because of the high cost of HTS materials. The usual problem of conductor end configuration in this type of coil design will be addressed. As the tape rounds the end, it must be kept free of stress as it loops up and over the aperture of the magnet. Initial windings will be made with only a few turns per block before a spacer is introduced to provide support between blocks. Filler impregnation with a loaded epoxy will be used to stabilize the turns. The conductor will be Kapton-wrapped if necessary to avoid degradation from contact with epoxy. Calculation with the design program ROXIE or a suitable CAD program will more accurately define the zero-stress path that each turn must follow.

Common issues:

In the testing phase, the critical issue will be whether the coil magnetic and mechanical design will allow the coil current to reach the level expected for the conductor being used. In addition, in either coil design, eddy currents induced in the conductor when the magnet is ramped, also referred to as conductor magnetization, must be addressed. The eventual magnets envisioned are destined for use where rapid current ramps are not required, so this is a manageable issue at this time. A similar issue arose in the helical magnets that control the proton spin polarization in RHIC[5]. There, a 7-strand superconducting cable was used with a center conductor that is not transposed and is therefore vulnerable to serious eddy current losses if ramped too fast. However, the magnets have worked well when ramped with the ten minute RHIC ramp rate. In the future, a Roebel cable[6] design for the conductor could be considered if ramp rate becomes an issue. We will observe and measure this conductor magnetization in the testing phase of our coils.

Longer term goals:

The long-term goal in future accelerator designs is to utilize hybrid, accelerator quality magnets that are capable of producing a field of over 20 T. Hybrid magnets use not just HTS but also low-temperature superconductor (LTS) to generate the field. This work is planned to address just the inner-most portion of a hybrid design, where HTS can play a unique role, and does not envision building a complete such magnet. Phase I will be planned to allow a smooth transition to a more robust development program in Phase II. In Phase I, a single coil of each of two designs will be built and tested in liquid nitrogen. In Phase II, at least two coils of each design, if that design is promising, would be built and assembled into actual dipole magnets. Such magnets would be tested in larger magnets that provided a background field: 10 T from the BNL Nb_3Sn common coil dipole magnet[7] for the racetrack magnet and 5 T from a RHIC dipole[8] for the cos θ magnet. Thus, Phase II is expected to produce two proof-of-principle dipole magnets:

(a) a flat coil magnet that will experience a peak field in the range of 12 to 14 T when tested in the BNL common coil magnet, and (b) a cos θ magnet that will experience a field of 8 T when tested in a RHIC dipole. The funding level in Phase II is not sufficient to make a 20 T or more hybrid dipole. However, these HTS dipoles tested inside LTS magnets should address major technical issues related to using 2G HTS in a 20 T or more magnet.

Related issues:

Issues that will be addressed primarily by PBL include HTS tape procurement, mechanical design issues of the end configuration, and specification of magnet design features that derive from accelerator requirements.

6) Phase I Work Plan

As noted in Section 3, both a flat coil and a cos θ coil will be designed, built and tested to liquid nitrogen (LN2) temperatures in Phase I according to the following plan:

- Design flat coil and cos θ coil with dimensions to be established in initial design effort
  - Flat coil: expected dimensions in range: 15 cm wide, 25 cm long
  - Cos θ coil: expected dimensions in range: dipole half coil, 40 mm ø, 25 cm long
- Order conductor
- Ongoing design and engineering work to parameterize end configuration in cos θ coils
- Design necessary coil containment structures
- Build prototype coils, containment structure: mostly technician labor, some shop work
- Test at LN2 temperature

7) Phase I Performance Schedule

Following are the major performance milestone accomplishments:

Three months after the start of funding:

1. Place order for YBCO superconductor for test coil.
2. Develop conceptual design of the cos θ and racetrack coil magnet.

Six months after the start of funding:

1. Finalize design parameters of Phase II magnet and outline coil construction techniques.
2. Wind coil block(s) in $\cos\theta$ configuration with stainless steel tape having the same size as YBCO tape ordered for the test coil.

Nine months after the start of funding:

1. Wind coil block(s) in $\cos\theta$ configuration with YBCO tape.
2. Perform 77 K testing of YBCO coil at nitrogen temperature.
3. Finish analysis studies and prepare conceptual design report.
4. Prepare and submit Phase II proposal.

8) Related Research or R&D

Projects recently completed or currently underway by the PBL/BNL team and at BNL include the following:

- Building a 20-22 T HTS solenoid with two Phase II SBIRs.
- Building an “outsert” Nb_3Sn Rutherford cable solenoid using a Phase I SBIR.
- Just completed a Phase I SBIR to build an open mid-plane dipole magnet.
- BNL has successfully built and tested many HTS coils and a number of HTS magnets.
- BNL has made coils with a variety of HTS round wires (Bi2212, MgB_2), Bi2223 tape both 4 mm and 12 mm wide, 2G tapes from both SuperPower, Inc. and American Superconductor, Inc.
- Currently underway is a ~24 T HTS Superconducting Magnetic Energy Storage (SMES) coil to be built with ~10 km of 12 mm wide HTS tape.
- BNL has used about 20 km of HTS wire (4 mm tape equivalent) in the last decade and plans to use about another 35 km in the next two years based on programs that are already funded.

Among the completed projects are the following:

High Field Open Mid-plane Dipole Design

In the open mid-plane dipole design, there is no structure at the mid-plane between upper and lower coils. This offers a significant advantage when removing large amounts of energy deposited by spray particles originating from the interaction point. The design consists of flat racetrack coils. 2G HTS is ideally suited here in a hybrid design. The design uses an intermediate structure to minimize accumulation of Lorentz forces and hence stress and stress on the conductor. HTS can be placed in a high field and/or in a high energy deposition region of the coil. Moreover, the field in the HTS is parallel to the surface of conductor. This is helpful as the current density in 2G HTS is higher in the field-parallel direction as compared to the field-perpendicular direction.

The design shown in Figure 3 was developed for a Nb_3Sn magnet with a central field of over 16 T and peak field of over 17 T[9]. The design is optimized for field quality that is acceptable for the "Dipole First" optics for an LHC luminosity upgrade. Hybrid designs for a central field above 20 T could be developed. The expected overall current density of the 2G HTS coil pack (J_o) in the field direction is expected to be about 1000 A/mm^2 at 20 T with current technology (this assumes a reasonable turn-to-turn insulation and the fact that the current carrying capacity of HTS is significantly higher in field parallel direction). The magnet aperture would be reduced for making more affordable R&D coils.

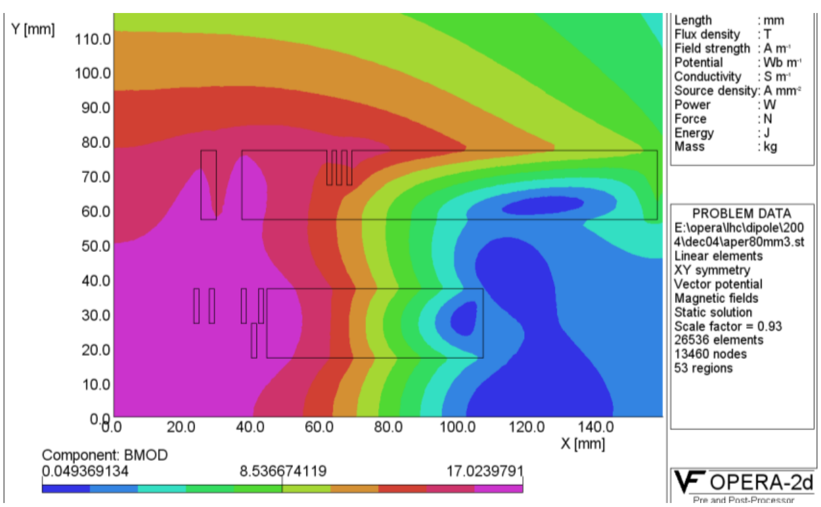

Figure 3. A quadrant of an open mid-plane dipole design.

Common Coil Design for High Field Common Coil Dipole

A common coil design[10] has been developed for the arc dipoles that account for most of the cost in high-energy circular particle accelerators and must be produced in large numbers. Similar to the designs described in previous section, the common coil design is also based on racetrack coils. The basic concept is shown in Figure 4 (a). The common coil magnet design is a 2-in-1 block design where the racetrack coils are shared between two apertures. The bend radius in the ends is much larger than that in a conventional design as it is determined by the separation between the two apertures rather than the size of the aperture itself. The design offers a "conductor friendly" geometry that is suitable for brittle materials and for containing large Lorentz forces. The common coil concept for a hybrid design is shown in Figure 4(b) where the inner coil (where the field is high) is made of 2G HTS and the outer coils (where the field is relatively lower) are made of Nb_3Sn (LTS). In a fully developed design, HTS coil modules would be placed in an adequate support structure to keep maximum stress and strain below the acceptable limits in all directions.

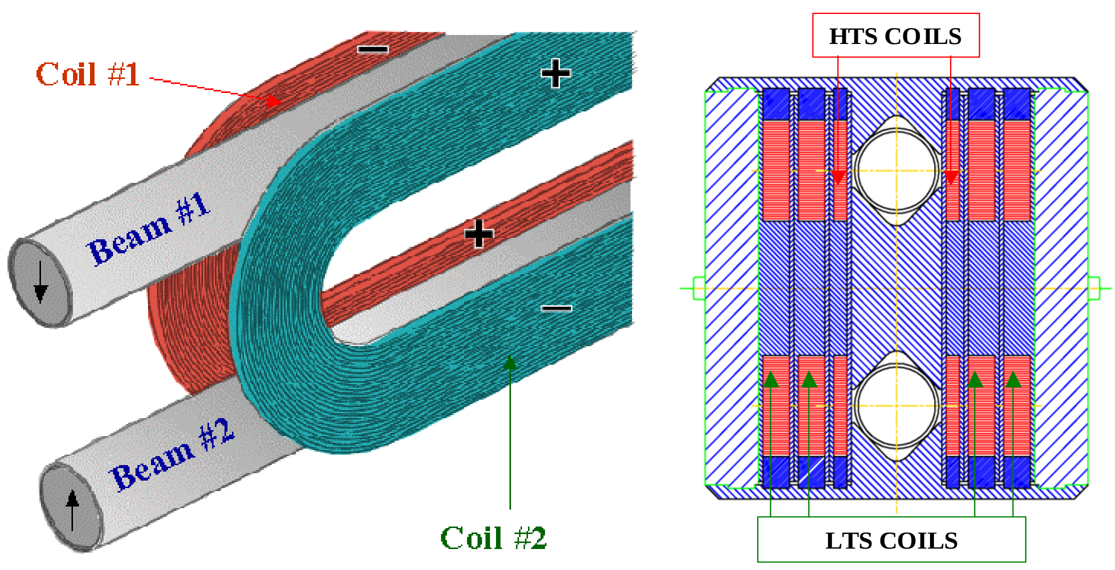

Figure 4. (a) Common coil design concept on left and (b) Common coil design for a HTS/LTS hybrid test magnet on right.

Cosine theta coils with tape superconductor

Before Rutherford cable became the favored conductor configuration for cos θ coils in superconducting accelerator magnets, the manufacturers of superconductor made it as a flat ribbon tape. Such tape was used to build R&D coils by William Sampson and colleagues at Brookhaven in the 1960's. A photograph of such a coil is shown in Figure 5. The coils shown are made of Nb_3Sn and worked modestly well and within the limited parameters of this early material.

Figure 5. An early cos θ coil made with Nb_3Sn tape.

9) Principal Investigator and Other Key Personnel

Erich Willen 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.

Ramesh Gupta 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. 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. 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 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 two 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. Dr. Gupta has given several courses at the US Particle Accelerator Schools on superconducting magnets.

Robert J. Weggel will develop the magnetic and mechanical design of the coils and support structures in collaboration with Ramesh Gupta of BNL. 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*".

Dr. Ronald Scanlan will assist Ramesh Gupta in the selection of the conductor and evaluate the impact of energy deposition on 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, serving as group leader and program head.

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

10) Facilities/Equipment

The Superconducting Magnet Division (SMD) at BNL working in collaboration with the PBL Principle Investigator will have 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 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 to the project.

Appendix – Letter of Support

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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11 September, 2011

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) is submitting a SBIR/STTR proposal 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.

This R&D is important and timely for the future upgrade of Large Hadron Collider (LHC) that CERN has now started planning. 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. 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.

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 qualified to lead this project. Both have long experience in superconducting magnet technology. Dr. Gupta has been actively involved in the development of HTS magnet technology over the last decade.

For the above reasons, I strongly support this proposal. The results produced by this R&D will be helpful to our own future European Coordination for Accelerator Research & Development (the present EuCARD and its successor EUCARD2, that will focus on HTS for very high field HF accelerator magnets) magnet program. If funded, we certainly keep a close link with this 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
(Leader of Superconductor and Magnets for the LHC project)

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