8. Project Narrative

Cover Page

Company Name and Address: Particle Beam Lasers, Inc.
18925 Dearborn Street
Northridge, CA 91324-2807

Principal Investigator: Ronald M. Scanlan

Project Title: Quench Protection for a Neutron Scattering Magnet

Topic No: 18 Instrumentation and Tools for Materials Research using Neutron Scattering

Subtopic: 18(a) Advanced Sample Environments

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

Identification of the Problem

Neutron scattering experiments would benefit from magnets with fields at least 50% more intense than the ~16 T presently available from conventional low-temperature superconductors (LTS) [1-4]. A high temperature superconductor (HTS) such as Rare earth - Barium - Copper Oxide (ReBCO), operating at ~4 K as a high field superconductor, is essential, because commercial LTS has insufficient current capacity at fields this high. Particle Beam Lasers (PBL) and the Magnet Division of Brookhaven National Laboratory (BNL) propose to advance magnet technology for neutron-scattering experiments by capitalizing upon their expertise and equipment developed during many SBIR/STTR collaborations, including ones that designed, built and tested two HTS solenoids capable of nesting to generate a field to reach the desired range [5]. In particular, the PBL/BNL team has significant experience and we also have existing HTS coils to address the quench protection issue, which is one of the most critical issues in developing high field HTS magnets.

For neutron diffraction measurements, the PBL/BNL team have invented a split-solenoid design based on a similar concept for dipoles [6-8] capable of providing viewing access that is simultaneously broad axially, radially and circumferentially. The PBL/BNL team has a Phase I SBIR (Grant Number DE-SC0019722) focused on designing a magnet to meet the requirements for neutron scattering. This effort has resulted in successfully winding a conical shape HTS coil and testing it at 77 K. Construction and testing of a prototype high field solenoid will be carried out in Phase II. That testing will use an extension of quench protection techniques that the team has earlier built [9]. However, the complete development of high field magnet technology, with its multitude of key technical issues, is well beyond the financial constraints of a single SBIR/STTR. PBL has experience addressing these key issues one at a time in separate proposals, to help develop the necessary components of high field magnet technology. As mentioned earlier, one critical issue for developing high field HTS magnet technology is quench protection, and the present Phase I proposal is to develop and test techniques that appear promising.

Goals

Quench protection in high field HTS magnets with large stored energy is a major challenge. The low quench propagation velocity (as small as a few mm/s) means that the normal zone may not spread adequately unless assisted, and the energy deposited in a small section could raise the local temperature high enough to cause permanent damage. The SBIR proposed herein (Phase I followed by Phase II) will specifically focus on the quench protection of a very high field neutron scattering solenoid which involves the protection of HTS/LTS hybrid solenoids and quench initiation of solenoid sections to prevent overstressing these sections during quench. The LTS and HTS coils in a hybrid design have different quench initiation and propagation characteristics, and it is a challenge to design a protection system to guarantee against overheating or overstressing from nonuniform quench currents. The quench velocity in HTS coils tends to be very low, which presents a major challenge in protecting HTS magnets from damage during a quench. We will analyze several approaches to address this issue, including metal-insulation [5] and copper disc inserts [10,12,13] that will accelerate the dispersal of stored energy. Another key component of this effort will be the use of an advanced quench detection system that has been used in prior PBL/BNL SBIR projects [9].

Unique Opportunity

PBL has over 30 HTS coils which were wound under previous programs [5,12,13]. This provides a significant leverage in a limited budget proposal, because the HTS coils are expensive. The PBL/BNL team will use these coils to perform several quench studies at 77K and one at 4K in Phase I. An example of this capability is the two HTS solenoids of Fig. 1, capable of nesting to generate a field to reach the desired range.

Fig. 1a-d.: High field HTS solenoids built and tested by PBL/BNL collaborations. Left: 25-mm bore pancake coils for insert magnet. Left-center: 7-double-pancake solenoid that generated 16 T. Right-center: Solenoid with 12 double pancakes of 100 mm bore. Right: Nested combination.

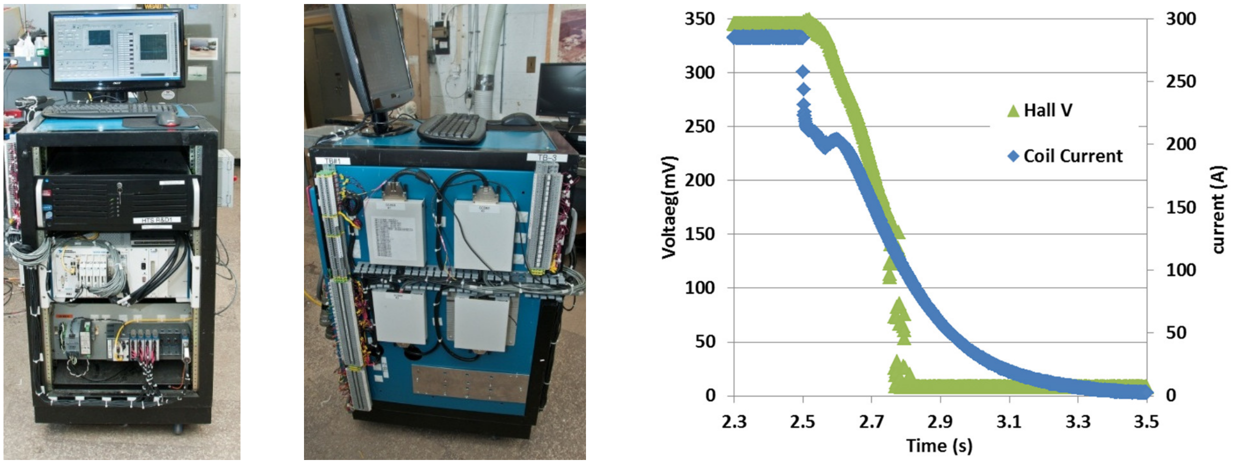

Fig. 2a-c. Quench-detection and magnet-protection system developed during PBL/BNL SBIR/STTR collaborations. Left & center: Hardware (32 channels, 1 kV). Right: Time dependence of magnet's central field, as measured by Hall voltage, and current during rapid shutdown. The very rapid drop in current from 285 A to 230 A is from commutation of current to copper discs between the magnet's double pancakes.

The inner of these two solenoids, of 25-mm i.d. and 91-mm o.d., was successfully operated to a current density greater than 500 A/mm^2 and generated nearly 16 T, at 285 A at 4 K, a world record in 2013 for a magnet exclusively of HTS (see Fig. 3a for the performance of this magnet as a function of temperature). The outer solenoid had respective inner and outer diameters of 100 mm and 163 mm. A half-length version generated more than 6 T (max. ambient field = 9.2 T); full length, its designed contribution is 10 T; the combined field could be 25 T or more. These solenoids employed metallic (stainless steel) insulation [5]; the technology led to further R&D at BNL on HTS magnets and contributed to the general development of HTS magnets worldwide, including the 32 T solenoid at the National High Field Magnet Laboratory [14]. BNL has tested magnets with metallic (stainless steel) insulation and no insulation, and though this SBIR will examine various options initially, stainless steel insulation is the preferred choice for a multi-layer neutron-scattering magnet at this stage.

Quench Protection Strategies

Another valuable legacy of the PBL/BNL collaborations is the development of a multi-prong strategy including an advanced system to detect incipient magnet quenches and shut down the magnet to protect it from burnout. These strategies, developed with an intention to successfully protect and operate such a magnet, are summarized below.

Co-Winding of HTS Tape with Insulating SS Tape

The PBL/BNL team uses stainless steel (SS) tape, rather than Kapton$^{®}$ (or similar organic insulation), to provide turn-to-turn insulation and extra structure to the coils [5]. SS tape, being a metal, distributes energy faster over a larger region of the coil and reduces the local increase in temperature. Finite Element Analysis (FEM) has shown [15] that the reduction in hot spot temperature could be a factor of five or more and in some cases the SS tape could prevent a stagnant normal zone.

Detection of Pre-Quench Phase

To protect the coils from damage, we start extracting energy from the coil during the "*pre-quench*" phase where the coils are safe to operate. The "*pre-quench"* phase, a semi-resistive phase with voltage one to two orders of magnitude below what is considered to be the quench voltage, occurs well before the onset quench or runaway. In LTS magnets, the quench detection threshold is typically well over 10 mV to even 100 mV. In HTS, the critical current is typically defined at 1 μV/cm, which becomes 100 mV for a coil made with 1 km of conductor. We define the "*pre-quench*" phase as the phase that corresponds to ~1 mV. We have developed fast-acting high-performance electronics and filtering software to isolate the onset of a small "*pre-quench"* resistive voltage in the presence of large noise and inductive voltages [14]. Fig. 3 shows the case where this "*pre-quench"* phase was identified at <1 mV by using the difference voltage between two coils even when the ramp rate (and hence inductive voltage) was changing. We have been able to use a pre-quench detection threshold of a few hundred μV in a magnet made with several hundred meters to several kilometers of HTS tape. The goal is to keep this threshold to a regime where HTS coils can safely operate for a short period while energy is extracted.

Fast Energy Extraction Phase

Once the pre-quench threshold is reached at current "*I*", our strategy is to extract energy quickly (on the order of seconds). The extraction time constant is given by "*L/R*" and the voltage across the coil as "*I*R*", where "*L*" is the inductance and "*R"* the external resistance. Such a fast energy extraction requires the quench protection circuitry for a larger magnet system to be able to handle high voltages. We have developed an electronic system that can handle isolation voltages of over a kV. Coils are also divided in sections to ensure that the inductance of a section (and hence the isolation voltage) is not too large.

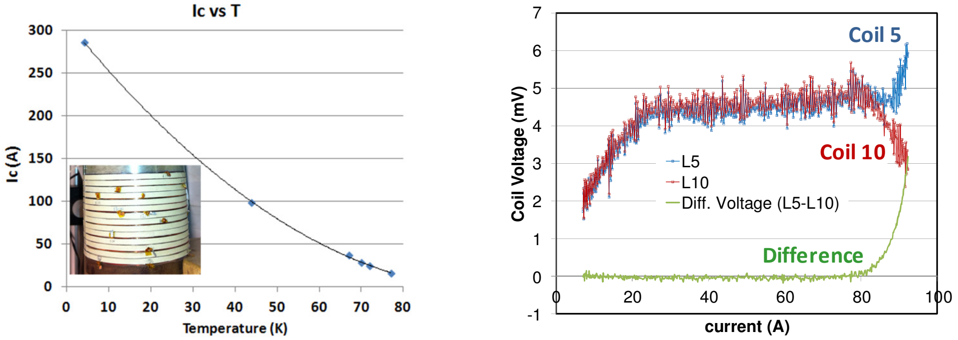

Fig. 3 (a) Measured critical current as a function of temperature in 25 mm HTS insert consisting of 14 pancakes. A current of 285 A (achieved at 4 K) corresponds to 16.2 T peak field in the coil. The coil is shown in the inset, (b) Measured voltage in two pancake coils along with the difference between the two to detect the pre-quench phase during a current ramp at 77 K.

Copper Discs for Rapid Energy Extraction

Copper discs are used between the pairs of double-pancakes to provide more uniform cooling across each coil. It has been found that a significant fraction of the current is inductively transferred from the HTS coils to the copper discs [10] in the beginning of the energy extraction process. Fig. 2(c) shows the Hall voltage (roughly proportional to the field) and current in the coil when the energy was extracted at a field of 15.8 T. This reduction in current occurs almost instantaneously and provides a crucial margin at a critical time.

Other Strategies

The use of quench protection heaters, as used in the NHMFL 32 T [14, 17] should further help in protection and will be examined for protecting the proposed solenoid for neutron scattering. Overall there is a need for continuing an extensive R&D program, which includes making coils for this study.

Quench Detection, Protection and Energy Extraction System

Quench detection and protection (QDP) in high-temperature superconducting (HTS) magnets is critical because of its slow normal zone propagation. BNL has designed and fabricated (patent awarded) a quench-detection and protection system [9].

The system quickly detects very small resistive voltages (~100 μV) in the presence of large noise and inductive voltages. The system safely transfers energy into a dump resistor (of proper size), greatly decreasing the hot spot temperature that could damage the coil.

The advanced quench-detection and protection system at BNL consists of state-of-the-art hardware and software. The hardware consists of two real-time controller platforms from National Instruments (NI), an energy-extraction Insulated Gate Bipolar Transistor (IGBT) switch from Infineon, Inc., a dump resistor, and an industrial PC. The main functions performed are 1) Quench detection, 2) Long-term data logging, 3) Transient data logging during the interval just before and after the quench, 4) Coil-current ramp-profile control, and 5) Energy extraction.

The quench-detection platform consists of a NI CRIO backplane powered by reconfigurable Field Programmable Gate Array (FPGA) technology, a real-time controller, a data-acquisition (DAQ) module with 4-channel, 50-KS/s simultaneous sampling, a 16-bit A/D converter, and a 16-channel fast-digital I/O module. The transient and slow data logger platforms consist of 1) a NI PXI chassis, a real-time controller, four PXI DAQ modules each with 8-channel, 16-bit, 50 KS/s simultaneous sampling, and an A/D converter; and 2) two PXI DAQ modules, each with 16-channel, 250 KS/s, multiplexed, and a 16-bit A/D converter. The PXI chassis also houses four NI SCXI-1125 isolation modules. These modules provide 300-V channel-to-channel isolation and 300-V channel-to-ground isolation. Both of the above targets are monitored and interfaced via a local network connection to an industrial PC.

Energy extraction during quench is achieved by simultaneously turning off the IGBT switch and power supply, to divert the freewheeling current through a dump resistor, thus diverting energy from the magnet into the dump resistor. The value of the dump resistor R is selected based upon the total circuit inductance and rate at which the energy needs to be extracted. Part of the hardware developed at BNL for QDP is shown in Figures 2 and 4.

Software for the quench detection system is developed using Graphical Design Language LabView from National Instruments. It consists of three separate LabView VIs (Virtual Instrument) modules: 1) FPGA code for quench-detection running on the CRIO target, 2) Real-time data logging and monitoring code running on PXI target, and 3) Host code running on the industrial PC to provide HMI (Human-Machine Interface).

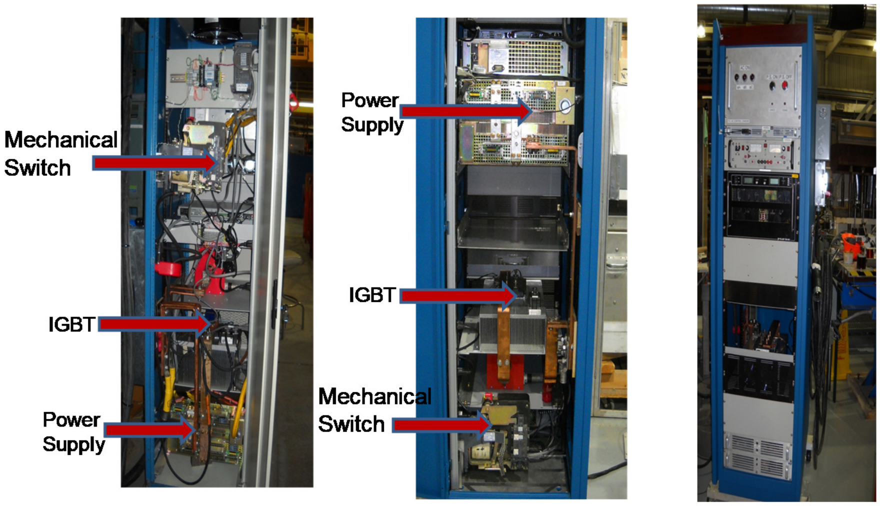

Fig. 4. Part of the quench detection, protection and energy extraction hardware at BNL.

Fast discharge creates high voltages that must be addressed in the design. We (the PBL/BNL team) are working on techniques to reduce the maximum value of these voltages. First, we are dividing the coil into sections. This partitions the inductance and hence the maximum voltage generated, but requires the use of multiple power supplies. We are upgrading our existing power supplies and control systems so that they can accommodate the high voltages that are generated when energy quickly is extracted into an external dump resistor. Also, we are using the IGBT switches as shown in Fig. 4.

Proposed Magnet Design for the Neutron Scattering

The neutron scattering magnet being proposed in the ongoing Phase I is a design with a revolutionary geometry that provides generous viewing access radially, axially, and circumferentially for the detection of scattered neutrons. PBL has prepared two conceptual designs of magnets with central field of 25 T, a midplane gap that is unobstructed circumferentially over nearly the full 360°, and has midplane and axial viewing ports that flare uncommonly broadly. One magnet has flare angles of 15° (±7.5°) along the midplane and 30° (±15°) along the axis, both upstream and downstream. The other magnet—at a severalfold increase in conductor usage and magnetic energy—greatly improves the midplane access by 50% and the axial access by 80%, delivering cone angles of 22° and 54°, respectively. The major computational task of the ongoing Phase I is to optimize these magnet designs to reduce their cost in materials and fabrication and to limit the strain on their conductors. The follow-on Phase II would extend the theoretical and experimental studies of Phase I, with still-greater emphasis on geometries that can meet all the challenging requirements of a system for neutron scattering experiments.

The revolutionary design proposed in the ongoing Phase I SBIR employs magnetic attraction instead of mechanical support for the inner solenoids of a magnet with multiple nested split-solenoids—i.e., solenoids with a midplane gap, as in a Helmholtz pair. Coils that are outboard (i.e., relatively far from the magnet midplane) magnetically attract inboard coils so strongly as to overpower the attractive force from coils on the opposite side of the magnet midplane. These inner coils therefore need no midplane-straddling structure for mechanical support, which would preempt for support the volume most efficient in generating field. The outboard coils need midplane-straddling mechanical support, but at a radius so large as to block little of the circumference of the midplane viewing port. While this design is attractive for this application where open midplane space is highly desirable, it does pose some challenges in quench protection.

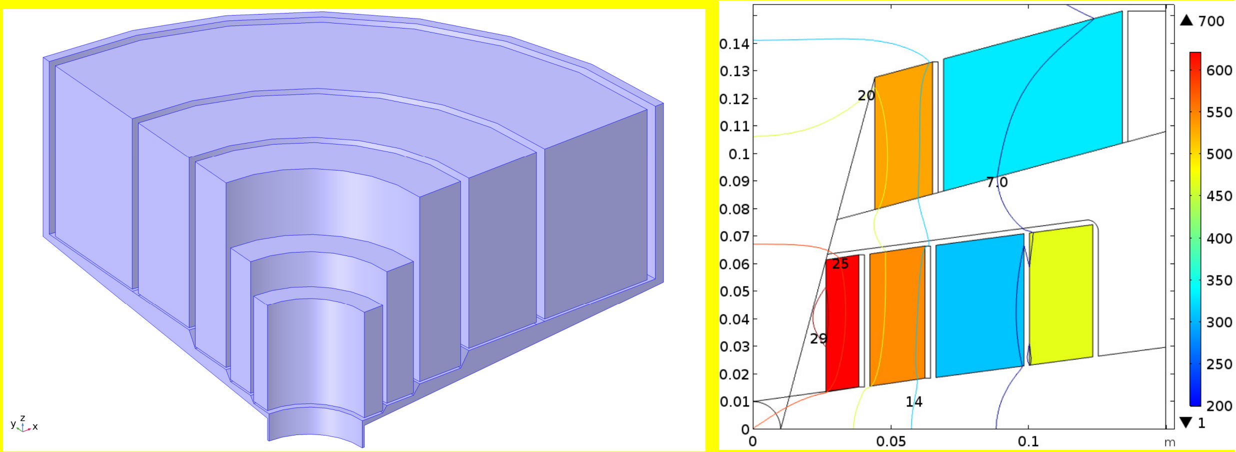

Fig. 5a: A quadrant of the top half of a magnet for neutron scattering experiments. The three inner coils are of ReBCO HTS (high temperature superconductor); the outer two coils are of Nb_3Sn. Fig. 5b: Coil cross section with current densities (color) and contours of field magnitude of 25-tesla magnet with large-angle access 15° (±7.5°) radially and 30° axially.

Technical Approach for quench protection

High field magnets with HTS coils have very high energy density that must be either extracted or distributed uniformly to prevent the magnet from exceeding localized allowable temperatures (hot spots), which can damage the superconductor. The low quench propagation velocity means that the normal zone grows so slowly that only a small fraction of the magnet can absorb the stored energy, leading to damaging hot spots. Attempts have been made to adapt the techniques used to protect LTS magnets to HTS magnets. To address the issue of slow quench propagation, new and faster methods of quench detection have been developed by BNL [9] and others [16,17,18] so that energy extraction can be initiated sooner. Extensive use of quench heaters has been employed [17], and they will be considered as a part of the overall integral approach, however, in order for heaters to be effective, large amounts of energy must be used and applied over large portions of the magnet.

Previous SBIR work by a collaboration of PBL with BNL discovered a simple and effective technique to improve quench protection [10]. In constructing a high field solenoid with a series of HTS double pancakes, copper plates were placed between the double pancakes to provide uniform heating and cooling of the coils. During a quench it was observed that the coil current decayed faster than usual (Fig.2c). The explanation is that the copper plates formed an inductively coupled secondary circuit. The idea of using an inductively coupled secondary circuit for LTS coils has been explored previously [18]. However, we are investigating its application to HTS coils. This technique of employing inductively coupled copper disks to extract the stored energy will be referred to as “Energy Dispersion Plates” (EDP). The purpose of this proposal is to investigate this technique, together with ultra-fast quench detection and conductor insulation choices, into a well-developed technology that will enable operation of a high field (25 T or more) magnet for use in neutron and x-ray scattering facilities. As part of developing this technology, PBL will design in Phase I and execute in Phase II an experimental program aimed at improving the quench protection of high field hybrid LTS/HTS magnets. Our approach will be to identify the key parameters that need to be addressed in quench protection and apply innovative solutions based on this technology to optimize these key parameters.

The technique employs highly conductive copper sheets placed at key locations throughout coupled to the HTS coils as the primary circuit. The copper sheets almost instantaneously inductively respond to changes in magnet current (e.g., upon quench detection inserting an external dump resistor), in effect diverting some magnet current to themselves, thereby reducing the heating rate in the hot spot. Global Joule heating in the copper raises its temperature. If the temperature rise is sufficient, it may trigger global quenching of the magnet before the hot-spot temperature has become excessive. Because of the large gap between the transition temperature and the operating temperature, it is not clear that the heat generated helps to significantly trigger transition neighboring conductor to normal (as the quench-back mechanism would do for LTS coils [19]).

Instrumentation of the coils and copper plates can indicate to what extent quench-back heating occurs. Since the decay time for the magnetic flux is long compared to the coil current decay, the transient voltages of the magnet coil are reduced [10]. Reducing the current in the main coils prevents hot-spots from overheating. Initial promising results using this technique were obtained from the high field solenoid experiment with an earlier SBIR and are shown in Fig. 2. For this method to be effective it requires that the copper plate be closely coupled to the primary coils.

In Phase I, the effectiveness of EDP will be optimized by varying the sheet properties—thickness and composition. Thicker sheets with higher conductivity should absorb more energy; however, the mechanical properties of the sheets must be selected to ensure that the sheets do not experience excessive deformation. MIDPC (metal insulated double pancake coils) will be assembled with EDP and tested. Data will include quench propagation velocities, coil temperature, and plate temperature as a function of time. These data will be used as input to analytical codes (COMSOL and LTspice) to develop a model for coil quench behavior. In Phase II, additional testing will be performed on coils in order to obtain a more complete database and the codes will be optimized. These optimized codes will then be used to test various quench scenarios to ensure that all coils are protected from damage during quench.

This new method of energy extraction and heat distribution throughout the coil requires rapid quench detection. It will be used in conjunction with the BNL fast quench detection system [9], and has the potential to provide a passive option to supplement the active heater protection system for HTS magnets. The detection system is sensitive to a *prequench* phase, which corresponds to seeing ~1 mV across the coil with several kilometers of HTS tape. Fig. 3 shows a case where this *prequench* is identified by using the difference voltage between two coils of the magnet when the ramp rate was changing [9]. This allows the magnet to operate safely for a short period while energy can be extracted. The electronics system that was developed can handle isolation voltages of the order of a kilovolt. Coils can be divided into sections to ensure that the induction of the section is not too large.

Another important consideration of the neutron scattering solenoid will be the coupling between the HTS and LTS coils due to the hybrid nature of the magnet. The PBL/BNL team has partially dealt with this issue in a previous STTR where an HTS/LTS hybrid dipole was tested. The quench protection system was designed to protect both the main magnet Nb_3Sn coils and the insert HTS coils. The two coils were powered separately with independent power supplies. A common quench platform was used with fast energy extraction from both coils. The BNL advanced quench protection system consisting of fast response and high power IGBT switches was used. The impact of inter-coil coupling (especially in the event of a quench) is an important consideration in protecting both coils. Fig. 6 (left) shows the measurements [13] showing the impact of a part of energy from the quenching HTS coil getting inductively transferred to the LTS coil and Fig. 6 (right) shows the results of computer models with LTspice [Ref H. Song, et. al, private communications] simulating this energy transfer to a LTS coil with some variations in parameters.

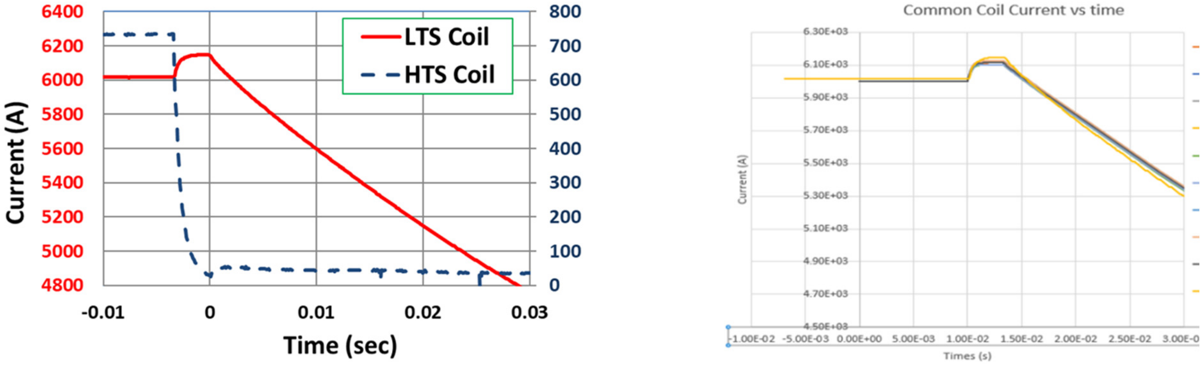

Fig. 6(left): Measurements of current as a function of time in an HTS/LTS hybrid magnet when the HTS coil quenched and part of its energy was inductively transferred to the HTS coil. (right): Computer simulations showing energy from the HTS coil getting transferred to the LTS coil.

Anticipated Public Benefits

A publication by the Institute of Physics states, “Neutron scattering is routinely used in modern science to understand material properties on the atomic scale. Originally developed as a tool for physics, the method has led to advances in many areas of science, from clean energy and the environment, pharmaceuticals and healthcare, through to nanotechnology, materials engineering, fundamental physics and IT. …

“Neutron scattering is used in many different scientific fields. Neutrons can be used to study the dynamics of chemical reactions at interfaces for chemical and biochemical engineering, in food science, drug synthesis and healthcare. Neutrons can probe deep into solid objects such as turbine blades, gas pipelines and welds to give microscopic insight into the strains and stresses that affect the operational lifetimes of crucial engineering components. Neutron studies of nano-particles low-dimensional systems and magnetism are used for the development of next-generation computer and IT technology, data storage, sensors and superconducting materials. Neutron scattering is a delicate and non-destructive measurement technique, making it ideal for use in heritage science. …

“Neutron scattering can be used to address the global challenges facing society, and to make developments that have immediate or long-term economic impact.”

Many consider neutron scattering to be the most valuable of all tools for investigating matter of all sorts, employing many thousands of researchers, as evidenced by organizations such as the Neutron Scattering Society of America and the European Neutron Scattering Association. Their research is of extreme commercial as well as intellectual value, justifying the expenditure of billions of dollars on neutron sources and detectors, including magnets such as those from HTS-110, a division of the SCOTT Group.

As with nuclear magnetic resonance, sensitivity and resolution improve **very** greatly with increased magnetic field intensity. The R&D proposed by this SBIR/STTR to develop a quench protection system for a hybrid HTS/LTS high field magnet has the potential to increase greatly the value of neutron scattering, carrying it into a new regime of utility. Developing the technology for such magnets is vital for their success, and therefore amply justifies the investment.

Work Plan

The specific Phase I tasks are:

1. Select a few HTS coils (four to six) from the existing large inventory of HTS coils to perform several (three to four) measurements at 77 K and one at 4 K. Some instrumentation, such as the voltage taps, are already installed on the existing double pancake coils. Additional instrumentation (voltage taps, temperature sensors and Hall probes) will be installed to help quantify the quench parameters. Energy dispersion plates with different thicknesses and compositions will be added. Quench heaters will be installed on the surface of the coils to initiate a quench.
2. Acquire quench data (minimum quench energy, quench propagation velocity, field decay time constant, energy transfer to energy dispersion plates) for the metal insulated double pancake coils from 77 K and 4 K.
3. Analyze the results from the tests in Task 2 and incorporate the data into analytical codes to develop a model for quench behavior. Additional data may be available in published results

and will be used where possible. Development of a complete quench code is beyond the scope of this Phase I; however, work on the code in Phase I will identify where more data are needed so that the codes can be optimized in Phase II.

4. Determine the requirements for a code that can analyze different quench scenarios to ensure that the coil temperature and the stresses are maintained within acceptable limits for all sections of the neutron scattering magnet. Optimize overall design for protecting the high field solenoid that PBL/BNL is developing and examine possible solutions for similar systems. Phase II work will further optimize and experimentally demonstrate the design in a high field neutron scattering solenoid.
5. Prepare a Final Report and a Phase II SBIR proposal.

Phase I Performance Schedule

1. Identify coils in inventory for quench studies. Install additional instrumentation and energy dispersion plates as required—Weeks 1-12.
2. Acquire quench and other data – Weeks 12-28
3. Analyze test results – Weeks 14-30
4. Determine requirements for quench protection and optimize design for Phase II– Weeks 10-34
5. Prepare Final Report and Phase II Proposal — Weeks 34-39

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 design work in Phase I described above will be carried out in office space in Waxahachie, TX, 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 lead the Phase I and Phase II effort to construct and test coils. BNL’s Superconducting Magnet Division (SMD) has been a major contributor to the development of magnets for many decades. The SMD has extensive facilities for winding coils and testing them. It also has simulation and engineering software tools that will aid in the design of coils and magnets—ROXIE, OPERA2d, OPERA3d and in-house software for magnetic design, ANSYS for mechanical design, Pro/ENGINEER and AutoCAD for engineering design, and LTspice for electrical circuit analysis.

The SMD has a staff of about 30, including scientists, engineers, technicians and administrative staff. Construction and test of the coils will be carried out in the SMD’s 55,000 ft^2 multipurpose R&D complex. A prominent asset of the complex is an active cryogenic test facility, complete with high-current, high-resolution and high-stability power supplies.

The facility allows testing of a variety of superconductors, coils and magnets from ~2 K to ~80 K. Dedicated equipment includes several computer-controlled, automated coil-winding machines, automated-cycle curing and soldering stations, centralized exhaust-vent systems, hydraulic presses and two machine shops adequate for most of the components needed for the R&D task. BNL also has a central machine shop and a procurement group to handle orders with private companies.

American-Made

To the extent possible in keeping with the overall purposes of the program, PBL will work to ensure that only American-made equipment and products will be purchased with the funds provided by the financial assistance under DOE Phase I grants.

Related Research or R&D

The BNL SMD has world-class experience in superconducting magnets of practically all kinds. Recently it completed a project for a 25 T proof-of-principle HTS magnet (See Fig. 7) for superconducting magnet energy storage (SMES) that developed significant technology that will be applied to this Phase I. This solenoid used 12 mm wide HTS tape and metallic (stainless steel) insulation. Another relevant project is a 25 T HTS solenoid (See Fig. 8) for the Institute for Basic Science (Korea) (IBS), which is now in the construction phase at BNL. It will use the latest HTS conductor and a no-insulation approach that will complement the Kapton insulation and metallic insulation techniques developed for HTS magnets on other PBL/BNL projects.

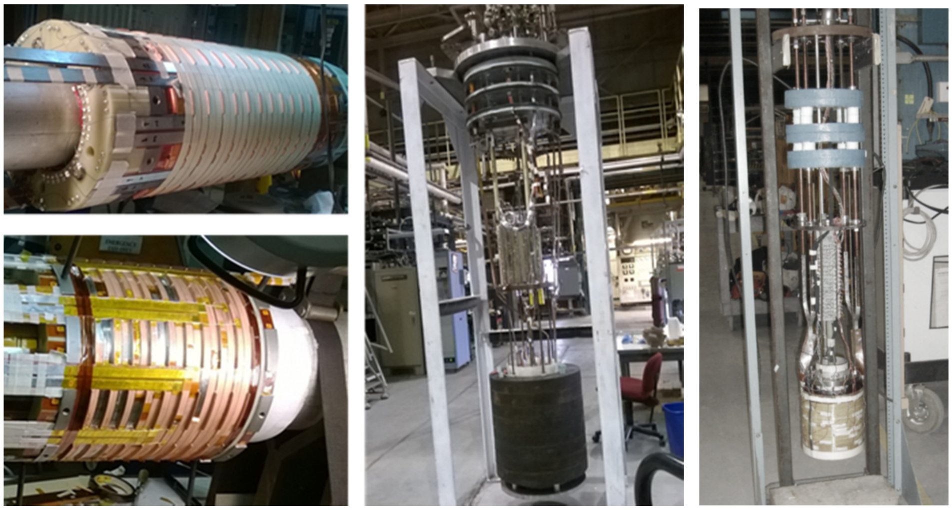

Fig. 7a-d. SMES magnet. Upper left: Inner solenoid. Lower left: outer solenoid. Center: Magnet, with iron laminations, prepared for testing. Right: 12-pancake magnet tested at 4 K to 760 A, 11.4 T central field. Rapid discharge upon quenching extracted ~125 kJ into the external resistor; a post-quench test at 77 K confirmed coil health.

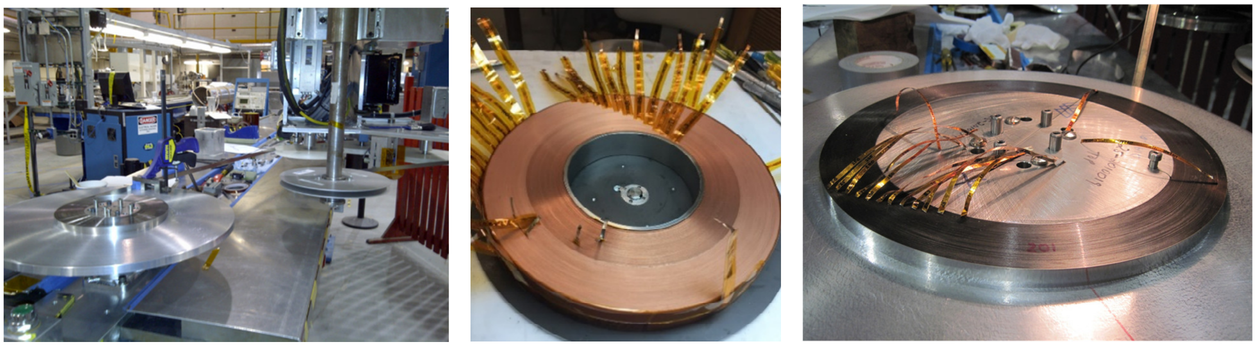

Fig. 8a-c. Left: Winding machine. Center: 971-turn pancake of 100 mm I.D., 220 mm O.D. with 550 m of 12-mm tape. Right: 258-turn pancake with 210 m of 12 mm tape wound on a 220 mm mandrel.

Team Qualifications; Where and How Tasks Will Be Done.

Ronald M. Scanlan will be the PBL Principal Investigator on this Phase I. Dr Scanlan has 35 years of experience in the field of superconducting magnets and materials at General Electric R&D Laboratory and Lawrence Livermore and Lawrence Berkeley National Laboratories. 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, supervising the building and testing of a world-record 13 T Nb_3Sn dipole magnet. Earlier in his career, he was responsible for development of Nb_3Sn conductor for the MFTF fusion magnet (14-T solenoid) at the LLNL. 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."

Steve Kahn has 30 years of experience with superconducting accelerator magnets and will be responsible for the analytical work on this SBIR. He has worked as a PI on four previous SBIR grants. He has worked at the Advanced Accelerator Group at BNL on neutrino factory and muon collider R&D. His previous experience at Brookhaven has been broad, including work on high energy physics experiments (neutrino bubble chamber experiments and the D0 experiment) and superconducting accelerator magnets (for ISABELLE, RHIC, the SSC and the APT). Work to design superconducting magnets included 2D and 3D finite-element field calculations using the Opera2d and Tosca electro-magnetic design programs along with structural finite-element calculations with ANSYS.

Robert J. Weggel is PI on the Phase I SBIR effort (Grant Number DE-SC0019722) on design of the neutron scattering magnet, and will collaborate on the present Phase I. Mr. Weggel has over 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. He has authored over 100 peer-reviewed articles concerning resistive and superconducting magnets as well as hybrid high-field versions. He has had extensive experience optimizing magnets for various uses including solid-state research, accelerator and medical applications. He has contributed extensively to "*Solenoid Magnet Design,*" by Dr. D.B. Montgomery, and was principal proofreader, editor and equation-corroborator for the 682-page textbook "*Case Studies in Superconducting Magnets*," by M.I.T. professor Y. Iwasa.

Ramesh Gupta will supervise the work performed at the BNL Superconducting Magnet Division (SMD). Dr. Gupta has led the development of the common-coil 2-in-1 dipole design for hadron colliders. 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 high field and HTS magnet designs and technology for particle accelerators and beam lines. Dr. Gupta has developed a cost-effective, rapid-turnaround and systematic magnet R&D approach which will be employed in this proposal. Dr. Gupta was the PI or sub-grant PI of several HTS R&D grants. He was PI for the Phase II STTR with PBL on "A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets". Among major other projects, Dr. Gupta is PI for developing and building a 25 T, 100 mm bore HTS solenoid for Institute for Basic Science (Korea). Dr. Gupta was also PI for the development of HTS magnets for RIA, FRIB and sub-grant PI of a HTS Superconducting Magnetic Energy Storage (SMES) system. Dr. Gupta has also worked on conventional Low Temperature Superconductor cosine-theta magnet designs (an area that he still continues to pursue) for RHIC and SSC. Dr. Gupta has taught several courses on superconducting magnets at U.S. Particle Accelerator Schools.

William Sampson, senior scientist at BNL magnet division, will play a key role in assembling and testing the HTS coils.

Piyush Joshi, head of electrical system group, will play a key role in designing and optimizing the quench protection system.

All work will be done in the existing PBL offices, often located in our employee's homes. Frequent meetings will be held both over phone conferences and face to face. The tasks will be done in a manner consistent with similar efforts done by our highly qualified employees on previous projects.

How the Research Effort Could Lead to a Product if Funded Beyond Phase I.

If funded beyond Phase I and II, the research effort will lead to the demonstration of a very high field solenoid to extend greatly the power of neutron scattering experiments. For a more complete description of the excellent commercialization potential that this project has, please consult the commercialization plan associated with this proposal.

Managerial controls for a successful project.

To ensure a successful project, PBL will hold regular technical meetings and compare progress made against the performance schedule. The technical staff will meet to ensure that important milestones are being met in a timely way. In the final meeting, approximately six weeks prior to project completion, PBL senior management will participate. The team will identify any problems and find ways to solve them, and will plan for the Phase I Final Report and Phase II proposal.

PBL has much experience with the DOE SBIR program, having completed several SBIR research efforts over the years. As such, PBL personnel are well versed in the reporting and administrative needs that will be an important part of the project proposed herein.

Consultants and Subcontractors

Brookhaven National Laboratory (BNL) is the proposed subcontractor. BNL partnered with PBL, Inc. in two SBIR Phase II projects [12-14], constructing two YBCO solenoids, one of 100-mm bore and the other of 25-mm bore; the latter tested without quenching to nearly 16 T, a world record for an all-HTS magnet at that time.

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