8. Project Narrative

Cover Page

Company Name and Address:	Particle Beam Lasers, Inc. 18925 Dearborn Street Northridge, CA 91324-2807
Principal Investigator:	Robert J. Weggel
Project Title:	HTS Solenoid for Neutron Scattering
Topic No: 17	Instrumentation and Tools for Materials Research using Neutron Scattering
Subtopic: (a)	Advanced Sample Environments

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

Neutron scattering experiments would benefit from magnets with fields at least 50% more intense than the ~17 T presently available from conventional low-temperature superconductors (LTS). A high temperature superconductor (HTS) such as ReBCO, operating at ~4 K as a **high field** superconductor, is essential, because LTS falls far short of the needed combination of critical field and critical current density.

Particle Beam Lasers, Inc. (PBL) and the Superconducting Magnet Division (SMD) of Brookhaven National Laboratory (BNL) propose to advance magnet technology for neutron-scattering experiments by capitalizing upon their expertise and equipment, some of which was developed during several SBIR/STTR collaborations, including ones that designed, built and tested 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 set.

The inner of these two solenoids, of 25-mm i.d. and 91-mm o.d., operated perfectly at a current density greater than 500 A/mm^2 and generated nearly 16 T, a world record in 2013 for a magnet exclusively of HTS. 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 might be 25 T or more. These solenoids employed metallic (stainless steel) insulation; the technology led to further R&D at BNL on HTS magnets. BNL has tested magnets with conventional insulation and no insulation, and will consider these options, too, for neutron-scattering use.

Another valuable legacy of previous PBL/BNL collaborations is the advanced system of Fig. 2 to detect incipient magnet quenches and shut down the magnet to protect it from burnout. Such a system is essential to successful magnet operation.

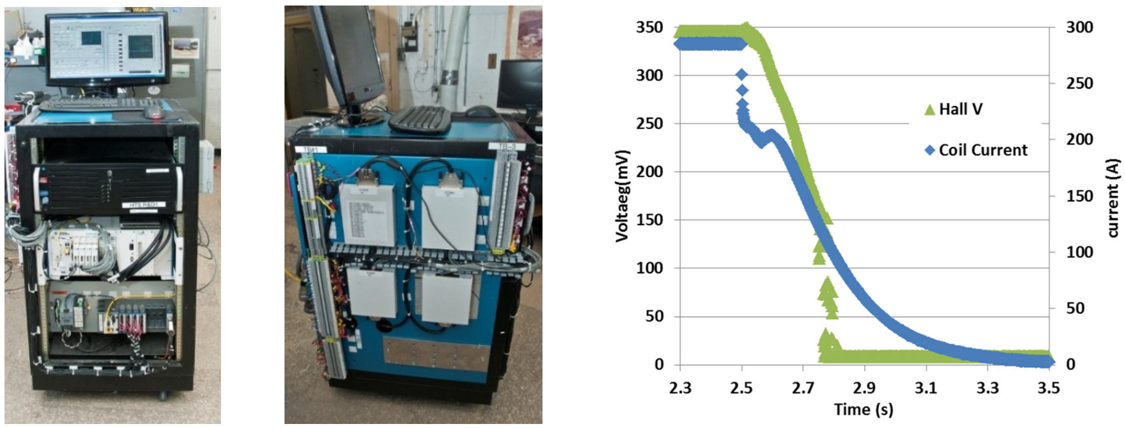

Fig. 2a-c. Quench-detection and magnet-protection system developed during PBL/BNL SBIR/STTR collaborations. Left & center: Hardware (32 channels, 1 kV). Right: Time dependence of magnet's central field, as measured by Hall voltage, and current during rapid shutdown. The very rapid drop in current from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

The PBL/BNL team proposes in Phase I to use conductor on hand to wind coils and to test them. Phase I proposes also, with input from Dr. John Tranquada, Dr. Igor Zaliznyak and other scientists familiar with neutron-scattering experiments, to generate a preliminary design of a magnet of several nested solenoids, of which those in high field use HTS, with a goal of ~25 T.

Proposed is a magnet design of a revolutionary geometry that provides generous viewing access radially, axially, and circumferentially for the detection of scattered neutrons. To illustrate the concept, this Proposal presents 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%, providing cone angles of 22° and 54°, respectively. The major computational task of Phase I is to optimize these magnet designs to reduce their cost in materials and fabrication and to limit the strain on their conductors.

Phase II would extend the theoretical and experimental studies of Phase I, with still-greater emphasis on geometries that can meet all of the challenging requirements of a system for neutron-scattering experiments.

Design requirements for high field magnet for neutron scattering

High magnetic field is an important tool for tuning the state of matter, creating new states and quantum phases, and changing the fundamental properties of materials. Magnetic fields can modify transport properties of conductors, correlations in magnetic insulators, and the way conduction electrons interact with atomic moments in magnetic metals. Neutron-scattering techniques provide a powerful tool for studying these atomic, molecular and microscopic properties and correlations in condensed matter systems. The importance of developing high magnetic field environments for such studies has therefore been widely appreciated, e.g., in the National Research Council of the National Academy of Sciences report "High Magnetic Field Science and Its Application in the United States: Status and Future Directions".[1] Workshops by the ORNL Neutron Science Directorate[2-4] discussed advances in high magnetic field science and practical routes for building high-field magnets for neutron scattering to enable the new science that neutron-scattering measurements in high magnetic fields can provide. The most recent Workshop[4] focused on the new opportunities provided by the progress in the commercial development of high-temperature superconductor technology.

Low-temperature superconductor (LTS) magnets for neutron-scattering measurements can reach only 15 T to 17 T. To reach 25 T, the dedicated beam line EXED at the Helmholtz Zentrum, Berlin (HZB)[5,6] required a field boost of 11 T from resistive coils consuming 4.4 MW. The magnetic field is horizontal, with a viewing angle of only 30°. The geometry severely limits neutron spectroscopic studies, which require rotation of the sample with respect to the detector array and the incident beam in order to explore its reciprocal space. HTS coils may be able to deliver magnetic fields as intense as 25 T.[4] A 25 T split-coil, vertical-field magnet could be similar in usability and versatility to the LTS systems that are currently the mainstay of neutron scattering studies in magnetic fields below ~15 T. Ideally, the magnet would be experiment-friendly, with large viewing ports (~90°-180° horizontally and 5°-15° vertically) and compact and portable between different neutron spectrometers, rather than requiring a dedicated beam line.

Magnet design and requirements

The main requirement for a neutron- or X-ray-scattering magnet is a large solid angle for the passage of incident and scattered beams, unobscured by the magnet coils and their bulky support structures. Especially for time-of-flight (TOF) neutron spectroscopy, the viewing ports should be as free as possible of material, to avoid spurious TOF background features from neutrons scattering in, for example, thin aluminum cylinders separating the members of a split-coil pair.[7-9]

Two basic magnet geometries are used to position the coils out of incident and scattered beam paths in neutron-scattering magnets: (i) vertical-field (VF), split-coil, and (ii) horizontal-field, conical-bore. The latter optionally may split the coil to accommodate the incident beam and/or the top-loading sample environments. The former is used in most high field LTS magnets for neutron scattering; the HZB uses the latter. The horizontal field geometry also is used in some scattering experiments that require the field direction to be paraxial with the incident beam, or to rotate in the horizontal scattering plane. These include some experiments using reflectometry or small-angle neutron scattering (SANS), or that require the field to be quasi-parallel with the momentum transfer vector, which usually is in the horizontal scattering plane. The LTS magnets used for such measurements typically have horizontal-field, conical-bore geometry with an opening up to 90° (±45°) that can be positioned either along, or perpendicular to, the incident beam. For the latter, the coil usually is split to accommodate the incident beam as well as the top-loading sample environments. Horizontal-field magnets typically have fields lower than vertical-field systems, usually no more than 9 T; the recent 17 T SANS magnet[10] has only limited acceptance.

Preferred is the vertical-field, split-coil geometry, which is compatible with the sample rotation techniques for broad surveys of reciprocal space. Furthermore, stray fields at the side of magnets are lower than near the axis and easier to shield or to mitigate using compensation coils. Additionally, the geometry more easily accommodates ^{3}He and dilution-refrigeration inserts, pressure cells, and high-temperature inserts, providing opportunities for neutron studies under multiple extreme thermodynamic conditions. For these reasons, the recommendation of the Ultra-High Field Magnets for X-Ray and Neutron Scattering Using High Temperature Superconductors Workshop was to concentrate on developing magnets with the vertical-field, split-coil geometry.[4]

Table 1 presents a tentative summary of the design parameters for the next generation HTS magnet for neutron scattering.

Table 1 Main technical specs of 20-25 T magnet for diffraction measurements

Maximum field	25T
Field homogeneity:	< ½% over 10 mm DSV; < 2% over 10 mm x 20 mm
Persistent mode stability	< 0.01%/hr
Stray field (at max field)	≤ 0.1T @ 2m; ≤ 0.01T @ 4m
Open bore diameter	25-30 mm
Coil split height	20-30 mm
Vertical opening	Minimum −2.5° to +2.5°, design goal −7.5° to +7.5° (to the back of the 20 mm cylindrical sample height)
Horizontal opening	120° (±60°), or 180° total (excluding support wedges)
VTI temperature range	1.5 K – 300 K (to 50 mK with a dilution fridge insert)
VTI temperature stability	±0.1 K
Magnet bath temperature	4.2 K

Anticipated Public Benefits

A publication[11] 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 the technology to design, fabricate and test proof-of principle and prototype magnets, has the potential to broaden and deepen 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.

PBL/BNL experience in high field HTS solenoid development

PBL and BNL have acquired extensive experience in high field HTS solenoid technology by collaborating on several Phase I and Phase II SBIRs supported by the Office of High Energy Physics. The solenoid of Fig. 3a&b, consisting of seven double pancakes of 25 mm i.d., generated 16 T, a record field at that time for an all-HTS solenoid. The solenoid of Fig. 3c, with twelve double pancakes of 100 mm bore, designed as an outsert for the inner HTS solenoid, generated, at only half length, 6.4 T on axis and 9.2 T maximum. Both solenoids used insulation of stainless steel, providing valuable experience for the SBIR Phase I proposed here.

In addition, as described in the Related Research section below, Dr. Gupta and his BNL team have designed, constructed, and tested many other large high-field HTS magnets, including a solenoid for a superconducting magnetic energy storage (SMES) project. Currently, the team is leading a project to fabricate a 25 T solenoid of 100 mm bore for the Institute for Basic Science (IBS).

PBL will be working with distinguished members of the user community as part of the proposed effort. PBL has already established a relationship with scientists at BNL and ORNL who are providing valuable input on the requirements for the proposed high field magnet we aim to build in Phase II.

Technical Objectives: Concept of Revolutionary, Open-Midplane Design of Magnet

The revolutionary designs proposed for the magnet-technology development of this SBIR/STTR employ 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. Support for the outboard coils straddles the midplane, but at a radius so large as to block little of the circumference of the midplane viewing port. The design is an axisymmetric version of the open-midplane dipole design[11,12] proposed fifteen years ago by Ramesh Gupta and pioneered by a collaboration of PBL and BNL.[13]

Figure 3 illustrates two candidate winding-pack magnet geometries; the magnet axis is vertical. To maximize viewing port angles and magnet efficiency, the designs portray every coil to have a cross section that is not rectangular but is either a parallelogram or shaved on one corner to avoid intruding on the viewing port. Wherever the field is greater than ~14 T, the conductor is YBCO tape, assumed 12 mm wide, wound into pancakes that are dished slightly into a very blunt cone, like a nearly flat cone spring (See Fig. 3c). The winding of such coils and testing them (at 77 K in Phase I) are candidate tasks for this proposal.

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In Fig. 3, the current density magnitude [A/mm^2] grades rainbow-like from blue to red; selected contours of magnetic flux density magnitude suggest where Nb_3Sn or NbTi suffices instead of HTS. In magnet 3a, HTS is red or orange; Nb_3Sn is sky blue or cyan; and NbTi is greenish yellow. The maximum ambient field is 29.6 T in the HTS, 14.0 T in the Nb_3Sn, and 7.4 T in the NbTi; the magnetic energy, U_m, is 1.0 MJ. The coil volumes aggregate to 1.6 liters of YBCO, 5.6 liters of Nb_3Sn, and 1.6 liters of NbTi. The midplane cone angle is 15° (±7.5°); the axial cone angle is 30° (±15°). The field inhomogeneity $\delta_B \equiv [B_z(r,z)/B(0,0) - 1]$ at a distance 10 mm from the magnet center is –1.15% along the magnet midplane and +2.0% along its axis. In magnet 3b, HTS is orange, green or cyan, and Nb_3Sn is navy. The ambient field reaches 28.7 T in the HTS and 13.5 T in the Nb_3Sn; U_m = 3.6 MJ. The conductor volumes are 9 liters of YBCO and 24 liters of Nb_3Sn. The field inhomogeneity δ_B is 37% better than magnet 1a: –0.7% radially and +1.3% axially.

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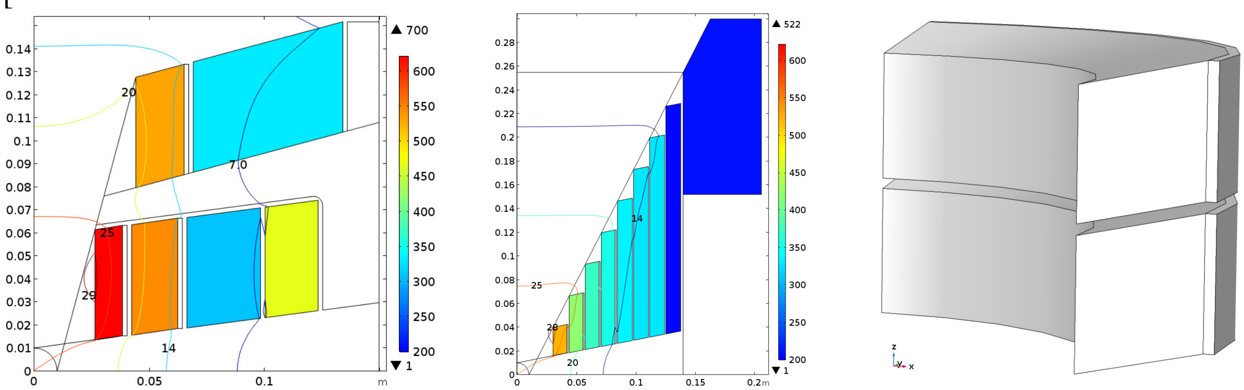
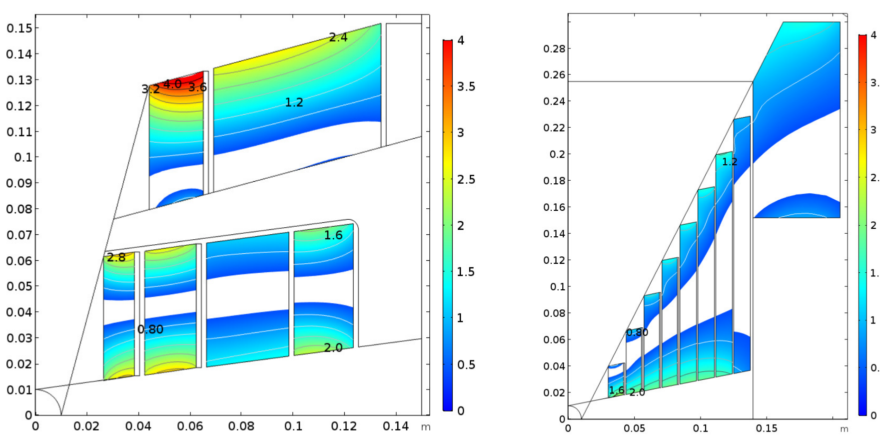


Proprietary Fig. 3a-c. Coil cross sections, current densities (color) and contours of field magnitude of 25-tesla magnets with large-angle access both radially (*x* axis) and axially. Left: Access = 15° (±7.5°) radially and 30° axially. Center: Access = 22° (±11°) radially and 54° axially. Right: 3-D view of quadrant of innermost coil of magnet 3b. Stainless steel (right-hand rectangles) bears against the outermost layer of YBCO tape.



Proprietary Fig. 4a&b: Absolute value of density of Lorentz force component parallel to magnet axis in magnets of Fig. 3. Magnetic attraction from outboard coils attracts inboard coils upward, overpowering the downward attraction from coils on the opposite side of the midplane. Left. Magnet 3a. Right: Magnet 3b.]

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Figure 4 plots $|F_z|$, the absolute value of the density of the component of Lorentz force parallel to the axis of the magnet, facilitating comparison of the upward and downward forces by showing equal magnitudes as equal colors. Throughout the white band within each coil $|F_z|$ is less than 0.4 N/mm^3. Above the band, forces are downwards, toward the magnet midplane; below the band, they are upwards. In magnet 3a the net upward force, in kN, on each of the four successive inboard coils is 613, 53, 90 and 37. In magnet 3b, the forces are 50, 73, 80, 70, 54, 28, 6 and 1.

Figure 5 plots the hoop strain in the magnets of Fig. 3. Figures 5a&b plot the strain $\varepsilon_{hoop} \equiv j\, r\, B_z(r) \div E_p$, where E_p is the circumferential Young's modulus, that would occur if each turn were self-supporting, not subject to any radial tension or compression from its neighbors. This stress estimate is appropriate for turns in an unbonded coil in a high background field, whose radial expansion of turns increases with increasing radius, opening up radial gaps between successive layers. The maximum strain in magnet 3a is 0.40 in HTS, 0.22% in Nb_3Sn, and 0.25% in NbTi. In magnet 3b the maximum strains is 0.42% in HTS and 0.25% in Nb_3Sn.

Figure 5c plots the hoop strain were turns bonded so strongly that radial gaps could not open to relieve stress. Bonding greatly increases the strain in the inner turns of coils in a high background field. Despite steel banding on the outer radius of all three of the HTS coils of magnet 3a, and of the four inner ones of magnet 3b, peak strains remain high near the inner radius of each coil: up to 0.50% in magnet 3a and 0.58% in magnet 3b.

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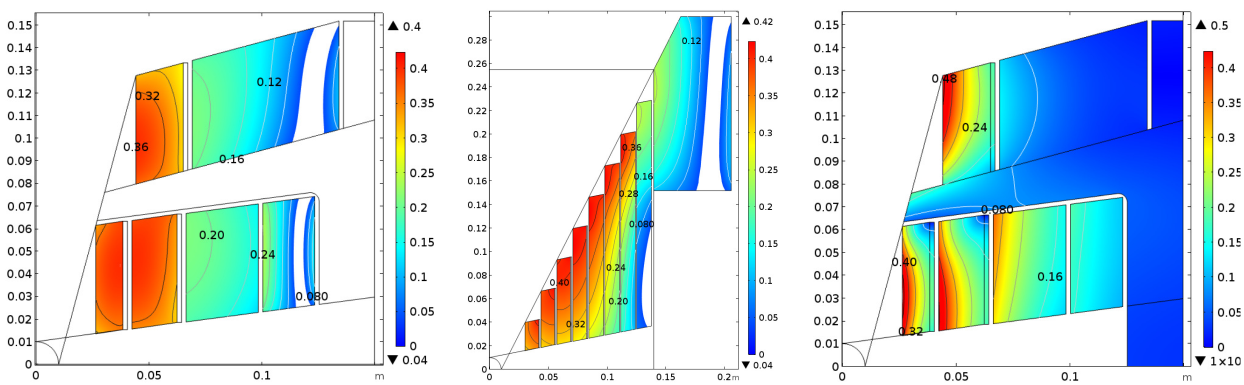

Proprietary Fig. 5a-c. Hoop strain of magnets of Fig. 3. Left and center: $\varepsilon_{hoop} \equiv j\, r\, B_z(r) / E$, in magnets of, respectively, magnet 3a and magnet 3b in the absence of radial tension or compression; turns are self-supporting and therefore neither aggravate nor diminish the strain in their neighbors. Right: Hoops strain in magnet bonded so strongly as to prevent sliding or gap opening anywhere.]

Figure 6 predicts the deformation in magnets 3a&b, acknowledging that the windings are orthotropic, not isotropic, but not allowing relative motion at boundaries nor radial gaps to open within windings to redistribute stresses. Where the thick-walled ring that supports the outermost coil would block neutrons, it reduces to radial ribs that obstruct very little of the circumference to carry the axial load: ~<15% at 700 MPa to carry the 2.5 MN axial load of magnet 3a, ~12% to carry the 4.0 MN load of magnet 3b.

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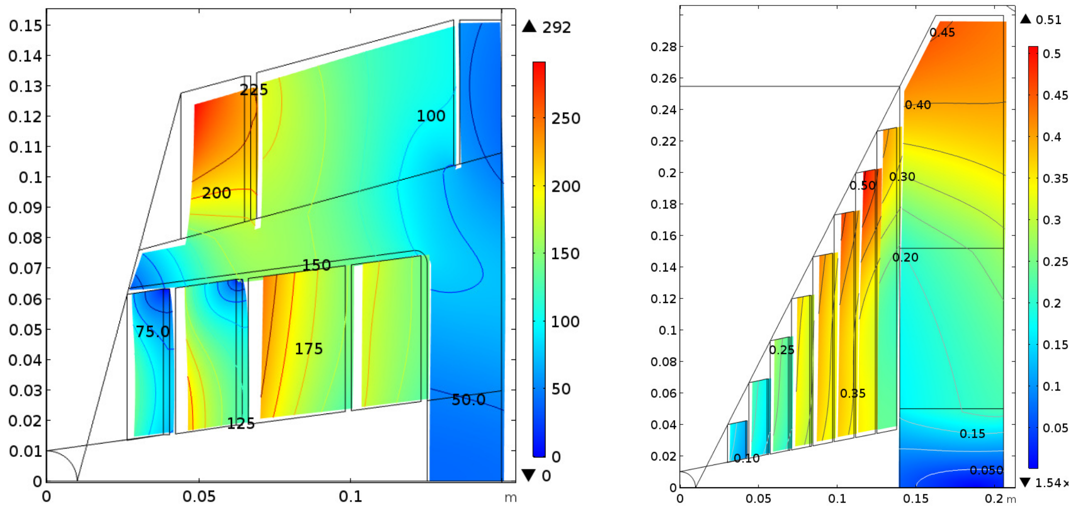

Proprietary Fig. 6a&b. Deformation in magnets 3a&b. Left: Magnet 3a. Right: Magnet 3b.]

Work Plan

The specific Phase I tasks are:

1. Perform detailed analyses of fields, stresses, strains, deformations and energy storage.
2. Determine and satisfy the requirements of the magnet protection system.
3. Wind and test conical-shaped HTS coils.
4. Prepare a Final Report and a Phase II SBIR proposal.

Elaborating on the above:

1. Analyses of field, stress, strain, deformation and energy storage (Weggel, BNL): COMSOL, ANSYS and perhaps other finite-element programs will be used to model the solenoids and to determine the detailed stress and strain distributions. Strengthening elements will be added if necessary to keep the stresses and strains within acceptable limits.
2. Final report and Phase II proposal (Weggel & Gupta, assisted by PBL & BNL teams).

Phase I Performance Schedule

1. Perform analysis – Weeks 1-28
2. Determine and satisfy requirements of quench protection for Phase II – Weeks 10-30
3. Procure HTS tape (at no cost, from inventory) for HTS coil – Weeks 1-12
4. Wind and test conical-shaped pancake coils– Weeks 13-33
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 work described above will be carried out in office space in Los Angeles, CA, the home office of the principal investigator in Reading, MA, 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 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, and Pro/ENGINEER and AutoCAD for engineering design.

The SMD has a staff of about 30, including scientists, engineers, technicians and administrative staff. Construction and test of coils will be 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 endeavor 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

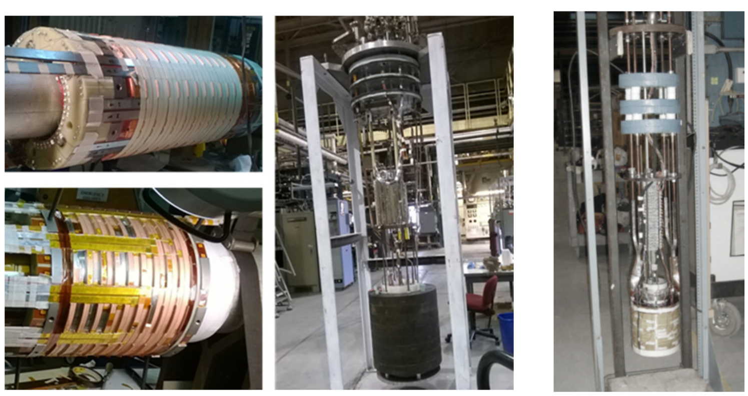

Fig. 8a-d. SMES magnet. Upper left: Inner solenoid. Lower left: outer solenoid. Center: Magnet, with iron laminations, prepared for testing. Right: 12-pancake magnet tested at 4 K to 760 A, 11.4 T central field. Rapid discharge upon quenching extracted ~125 kJ into the external resistor; a post-quench test at 77 K confirmed coil health.

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. 8) for superconducting magnet energy storage (SMES) that developed technology that will be applied to this Phase I—e.g., 12 mm wide HTS tape and metallic insulation. Another HTS project is a 25 T solenoid (See Fig. 9) for IBS, which is now being fabricated 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.

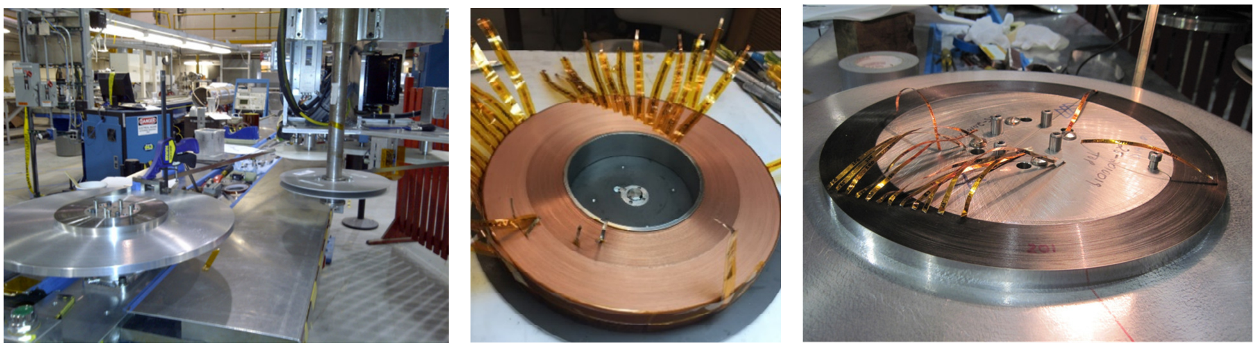

Fig. 9a-c. Left: Winding machine. Center: 971-turn pancake of 100 mm I.D., 220 mm O.D. with 550 m of 12-mm tape. Right: 258-turn pancake with 210 m of 12 mm tape wound on a 220 mm mandrel.

Team Qualifications; Where and How Tasks Will Be Done.

Robert J. Weggel will be the Principle Investigator (PI) of the project and the magnet designer for this Phase I SBIR/STTR. Mr. Weggel has had 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.

Ronald M. Scanlan has had 35 years of experience with superconducting magnets and materials at General Electric R&D Laboratory and Lawrence Livermore (LLNL) and Lawrence Berkeley National Laboratories (LBNL). 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 was the industrial development of economical high field superconductors 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 on 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."

Dr. Erich Willen, a PBL employee, will contribute his expertise in the areas of magnet design and magnetic field quality. He previously served as PI on a related SBIR entitled "Magnet Coil Designs Using YBCO High Temperature Superconductor." His experience on this previous SBIR will be useful in evaluating the design options being explored in this new SBIR. Dr. Willen has over 30 years of experience with high field magnets and served as the BNL magnet division head, Project Head for the RHIC Helical Magnet System and Project Head for the BNL-built magnets for the US LHC project.

Ramesh Gupta will supervise the work performed at the BNL Superconducting Magnet Division, which will focus on the winding and testing of coils, including the manufacturing of the parts needed. Dr. Gupta is the inventor of the overpass/underpass dipole design and has also 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 is 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". He is also sub-grant PI of several previous Particle Beam Lasers, Inc. SBIRs. Among major other projects, Dr. Gupta is PI for developing and building a 25 T, 100 mm bore solenoid for the Institute for Basic Science (Korea), as a critical part of the Axion search experiment. Dr. Gupta was also PI for the development of HTS magnets for RIA, FRIB and sub-grant PI of an HTS magnet for superconducting magnetic energy storage (SMES). Dr. Gupta has worked on conventional LTS 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.

Dr. Igor Zaliznyak is an expert in applying neutron scattering methods to studying quantum condensed matter, especially quantum magnets and superconductors. Dr. Zaliznyak has extensive experience in using superconducting magnets for his neutron-scattering studies. Throughout his career Dr. Zaliznyak used neutron-scattering magnets at many facilities around the world and thus has first-hand knowledge of the requirements and limitations of superconducting magnets for neutron scattering. Dr. Zaliznyak has made important contributions to neutron-scattering instrumentation. He led a team that developed the conceptual design and obtained the funding for a $15 million hybrid spectrometer that was built and commissioned at the Spallation Neutron Source, a DOE Office of Science user facility at Oak Ridge National Laboratory. That instrument is now capable of uniquely distinguishing magnetic excitations from lattice vibrations, a capability that Zaliznyak is currently applying in his studies of quantum matter. Dr. Zaliznyak will provide expertise and guidance for developing HTS magnet systems with specifications consistent with the requirements of neutron-scattering experiments.

All work will be done at BNL or at 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 team 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 success, 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 considerable 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,[9,10] 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.

PBL is very pleased to once again partner in this proposal with Brookhaven National Laboratory's Superconducting Magnet Division, one of the best in the world when it comes to HTS and LTS magnet design and construction. For the proposed project, BNL will perform the following tasks:

1. **Design study participation.** BNL scientific and engineering staff will work closely with the PBL team during all phases of the design study. BNL will employ OPERA and ANSYS to analyze field strength and homogeneity, Lorentz forces, stresses, strains and deformations. During this analysis effort, the BNL team will rely on their prior success with similar magnets, using the experience gained to effectively contribute to the present effort.
2. **Wind and test at 77 K an HTS conical coil.** The BNL team will wind from HTS tape a coil of conical shape and test it at 77 K. This coil will be a scaled down from what is expected to be produced in Phase II, but should demonstrate the capabilities of the staff and equipment and develop techniques later to be applied to the larger scale, Phase II effort.
3. **Interface with the user community to refine requirements of the magnets needed for neutron scattering experiments.** Members of the neutron-scattering user community are employed as staff scientists at BNL, enabling close cooperation of those scientists with the PBL/BNL team. The BNL scientists are leaders in the field, and they have frequent interactions and conversations with other leading scientists. This intimate knowledge of the subject matter will refine detailed requirements for the later magnet development. These requirements will then feed back into the PBL/BNL design effort.
4. **Participate in the design of the scaled-down version for construction in Phase II.** BNL will participate in all phases of the design of the scaled-down version of the magnet planned for construction in Phase II. This is a critical step in the Phase I work, because the eventual construction will be at BNL. The BNL staff will provide PBL with valuable commentary and advice, so that the magnet planned for Phase II will fit its budget and timeline and also fit seamlessly into BNL's ongoing scientific program.

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October 5, 2018

Dr. Ramesh Gupta
Building 902A
Superconducting Magnet Division
Brookhaven National Laboratory
Upton, NY 11973

Dear Ramesh:

I am writing to express my enthusiastic support for the SBIR proposal "HTS Solenoid for Neutron Scattering," from Particle Beam Lasers, Inc., and you.

As Leader of the Neutron Scattering Group at Brookhaven, I am a frequent user of the Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL). In the last 10 years, I have published 35 papers involving neutron scattering experiments, with 14 of those involving work at the SNS. I have worked closely with Dr. Barry Winn, who is the lead instrument scientist for the HYbrid SPECtrometer (HYSPEC) and who led a 2016 ORNL study on needs and requirements for ultra-high field magnets for x-ray and neutron scattering.

In my own research, I am particularly interested in the study of copper-oxide superconductors, where interesting charge order can develop that interacts with the superconductivity. An applied magnetic field can be used to depress the superconductivity and enhance the charge order. The fields necessary for this work are > 20 T, which is well beyond current capabilities of magnets made from conventional superconductors. We need a steady-state field, so that we can measure weak diffraction peaks and low-energy antiferromagnetic spin fluctuations.

I am well aware of your considerable experience in designing magnet systems with first and second generation high-temperature-superconductor wires. I am also aware of your productive history with Particle Beam Lasers. We have discussed the issues relevant to practical magnets for neutron scattering experiments at instruments such as HYSPEC, at SNS's first target station, and also at the proposed second target station. You have some innovative ideas on how to deal with several practical challenges with high-field split coil and single-coil magnets.

Again, I strongly support your project. If you are successful, I will be happy to continue to interact on this project and to communicate with instrument scientists at the SNS.

Sincerely yours,

John M Tranquada

John M. Tranquada
Senior Physicist
Neutron Scattering Group Leader