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High-Magnetic-Field Research Collaborations

Jeff Goettee*

Abstract

This is the final report of a two-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The purpose of this project was to develop collaborations with the academic community to exploit scientific research potential of the pulsed magnetic fields that might be possible with electrically pulsed devices, as well as magneto-cumulative generators. We started with a campaign of experiments using high-explosive-driven flux compression generators. The campaign's objective was to explore completely novel ideas in condensed-matter physics and chemistry. The initiative was very successful in pulling together top researchers from around the world.

Background and Research Objectives

Los Alamos National Laboratory (LANL) and Florida State University (FSU) are the principal locations of the National High Magnetic Field Laboratory (NHMFL). Los Alamos has a 60-tesla pulsed magnet currently under construction and has recently received approval for construction of a 100-tesla pulsed magnet. These facilities will use the same large motor-generator that may be used for part of the energy compression process in Atlas, which may be able to create fields perhaps in excess of 1000 tesla. At present, however, we can produce such fields with flux-compression generators thereby providing a jump on the research opportunities we expect to be offered by electrical pulsed power facilities. Thus we have the potential for a unique and unparalleled program of basic and applied research using high magnetic fields.

The objective of this LDRD project was to develop collaborations with the academic community for the purpose of exploiting scientific research potential of the pulsed magnetic fields. Some of the possible research areas include high-temperature superconductor (HTSC) critical-field measurements; exploration of Fermi surface topology with the de Haas-van Alphen (dHvA) effect; magnetoresistivity; the chaotic behavior of electronic wavefunctions at low principal quantum number; and the physics of white dwarf stars.

Our initial focus was to investigate quantum-limit phenomena in anisotropic metals. The collaborations involve James S. Brooks of FSU and Robert G. Clark of the University of New South Wales (UNSW). The 1000-tesla fields provided by the Russian-built MC-1

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flux-compression generator can drive materials with anisotropic electronic structure to their quantum limit, where the magnetic energy is comparable to the Fermi energy. We expect to see new electronic configurations in low-dimensional materials when they are subjected to such intense fields. If the materials retain their metallic (Fermi-liquid) character, then we should observe something like the fractional quantum Hall effect. In the 1000-tesla regime, however, the magnetic energy is comparable to the electronic bandwidth, so the field may localize the conduction mechanism causing a nonmetallic behavior to appear. Although accessible in semiconductors, the quantum limit has not been observed in conventional metals.

In parallel to the explosively driven, flux-compression generator approach, a programmatic effort is developing the techniques and apparatus for producing high magnetic fields with electrical pulsed power. Several different approaches are visualized but the one most suitable to the pulse characteristics and geometry of Pegasus and Atlas is the z-pinch flux-compression technique, which uses an imploding cylindrical liner to compress a "seed" magnetic field inside the liner and parallel to the liner's axis. The operation is analogous to a flux-compression generator, but with the compression supplied by a θ -field on the outside of the liner, rather than by a high explosive assembly. The compressed field should be relatively homogeneous and tend to mitigate "bead" instabilities. The liner-driven device might employ several "cascades"—cylindrical shells composed of insulator with imbedded wires parallel to the axis. The cascades become conductors in the θ direction when compressed and thereby trap the axial magnetic field. Being of progressively smaller mass, they also amplify the implosion velocity.

Importance to LANL's Science and Technology Base and National R&D Needs

Development of a unique high-magnetic-field facility will lead to collaborations with industry and academe in the areas of materials science, condensed-matter physics, and atomic physics. The research effort is directly aligned with the Laboratory's and DOE's vision of building support for science-based stockpile stewardship within the academic and industrial communities by involving those communities in our research programs.

First observation of the quantum limit in a bulk metal would excite the materials science community and draw attention to the Los Alamos program of academic collaborations in pulsed power. We expect this to grow into other collaborations, perhaps in high temperature and high pressure as well as high magnetic fields. It may even attract more basic research funding to the Laboratory. It will certainly gain support of the broader scientific community for the stockpile stewardship activities at Los Alamos.

Scientific Approach and Accomplishments

The experimental campaign named Dirac, a collaboration among this LDRD project, the NHFML at Los Alamos, and the nuclear weapons program office, set out to explore the applicability of current kilotesla technology to basic science. The series of experiments done in 1996 and in 1997 built on initial work done in 1993 within a collaboration between Los Alamos National Laboratory and the All-Russian Institute of Experimental Physics (Arzamas-16) that brought the reproducible production of fields in excess of 1000 tesla to the United States. Work within this experimental campaign has focused on developing the tools needed to use this technology for modern, fundamental research in chemistry and physics.

In FY 1997 we completed four shots in the Russian-built MC-1 generator (Figure 1) and four shots in the single-stage strip generator. We also performed countless experiments using more traditional capacitor-driven magnets in preparations for the final series of kilotesla shots. Each explosive shot contained nine to ten individual experiments and each investigator repeated his experiment on a second shot. Collaborators from Russia, Australia, Japan, Belgium, Germany, England, Brazil, Yugoslavia and the United States contributed to the technology advancement and were able to collect data on their experiments in these ultra-high magnetic fields. What follows are brief highlights of several of the experiments done in FY 1997. Analysis of all of these experiments is ongoing at the time of this report and therefore statements of final results would be premature.

Robert Clark, UNSW, led a team that explored the high-field behavior of quantum-confined electrons. Quantum wells defined in gallium arsenide/aluminium-gallium arsenide were placed at low temperature (1.5K) and the high-frequency electron transport was studied. The team was searching for magnetic-field-induced superconductivity. The large magnetic field could cause the cooperative behavior between electrons that is a requirement for superconductivity. Andrew Dzurak, also from UNSW, led an effort to map the behavior of the high-temperature superconductor, yttrium barium copper oxide, at high fields and low temperatures. The team from UNSW was instrumental in developing and perfecting a radio frequency technique to measure sample resistance. This new tool is not only useful in the extremes of low temperatures (<4K) and high fields that these experiments required but in any electrically noisy environment. This technique could be useful for measurements within the violent implosions done on machines like Pegasus and Atlas.

Andrew Maverick and Leslie Butler of LSU led an effort to determine the magnetic field required to Zeeman split molecular energy levels within two different systems. Each system had a quadruple metal-metal bond that a large enough field should break by causing the bond energy to Zeeman shift and no longer be the lowest energy state.

James Brooks of FSU and the NHMFL at FSU fielded several experiments that examined the high-field behavior of lower-dimensional metals and two-dimensional (2-D) electron gases. Several different organic conductors were measured using the radio frequency transport techniques of the Australian team. He also looked at a 2-D electron gas using optical reflectivity. It is this second experiment that has produced the most reproducible results. The analysis of the results is ongoing at the time of this report (Figure 2).

Publications

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Figure 1. A schematic of shots MC1-D and MC1-F, courtesy of the Australian team. Experiments in the upper half of the MC-1 generator share space within the specially developed plastic cryostat that supplied a base temperature of 1.5K. These experiments also utilized the radio frequency transmission lines developed by the Australian team to measure electron transport within several different condensed matter systems. The lower half of the generator contained the quadruple metal-metal bond experiments from LSU as well as the field diagnostics.

Figure 2. Data from MC1-D courtesy of the Brooks-led team superimposed with a Faraday rotation signal. The solid trace shows the optical reflectivity of the two-dimensional electron gas confined by a quantum well. This signal can be related to the conductivity of the electron gas. The dashed trace is the Faraday rotation signal and is related directly to the intensity of the magnetic field.