Francis Bitter Magnet Laboratory

The Francis Bitter Magnet Laboratory (FBML) has continued to make notable advances in several areas of science and engineering involving high magnetic fields. The research program in magnetic resonance (nuclear magnetic resonance [NMR] and electron paramagnetic resonance [EPR]) has continued to grow and remains the largest effort at FBML. The program is funded primarily by the National Institutes of Health (NIH) and the Department of Energy (DOE), and involves 28 NMR and EPR magnets and spectrometers. The lab recently launched a new comprehensive website, found at http://web.mit.edu/fbml/.

A few of this year's highlights:

Professor Robert G. Griffin, and Professor Gerhard Wagner of Harvard University continue to operate the MIT/Harvard Center for Magnetic Resonance, a collaborative research effort between MIT and Harvard Medical School. The center is supported by an NIH Research Resource grant and has been in operation since 1976.

Professor Cory and his colleagues continue to make advances in the theory, practice, and implementation of quantum information processing. They have nearly completed the construction of a simple quantum information processor based on nuclear magnetic resonance and will start exploring this approach experimentally this summer. In collaboration with the National Institute of Standards and Technology (NIST), Professor Cory and his colleagues have implemented a reciprocal space approach to coherent imaging via a three-blade neutron interferometer, which promises improved contrast and resolution.

The Magnet Technology Division (MTD) is currently involved in four NIH-funded programs on NMR and magnetic resonance imaging (MRI) magnets and three Air Force Office of Scientific Research (AFOSR)–funded projects on stability and protection issues for YBCO-coated conductors. One of MDT's most important goals is the design and construction of a ≥ 1 GHz NMR magnet.

Professor Jasanoff recently joined FBML. His research is focused on developing noninvasive functional imaging methods to study systems-level neural plasticity involved in low-level learning and perceptual behavior in small animals by producing prototype imaging agents for "molecular functional MRI."

Dr. Jagadeesh Moodera has continued to strengthen his research efforts in nanoscience and condensed matter-physics through collaboration with various universities and industries, as well as the Office of Naval Research and National Science Foundation. In particular, he has established a new, long-term collaboration focused on spintronics with the Korea Institute of Science and Technology. In addition, he has continued his mentoring of graduate students, undergraduate, and high school students by providing research opportunities within his lab.

Dr. Temkin and his colleagues have completed the construction of a 460 GHz gyrotron, which is undergoing initial tests, and have begun to develop a 140 GHz gyroamplifier.

Research Activities

Professor David G. Cory

Quantum Information Processing

Professor Cory and his students continue to explore NMR approaches to quantum information processing (QIP) through a set of collaborations with Dr. Timothy F. Havel (NSE), Dr. C. Ramanathan (NSE), Professor Seth Lloyd (Mechanical Engineering), Dr. Raymond Laflamme (University of Waterloo), and Dr. J. Emerson (Perimeter Institute for Theoretical Physics).

Their recent accomplishments focus on the precision of coherent control and efficient measures thereof. The challenge to building a quantum computer is to find experimental means of preserving quantum information in the presence of noise. This is best achieved through logical encoding of quantum information into multiple qubits with the mapping into the encoded space determined by the symmetries, correlation times, and amplitudes of the noise. They have extended their work on experimentally accessible random maps to build a metric for bounding the noise and also the characteristics of the noise. This forms the basis of the first efficient measure of scalability. In related work, they have explored the control available over logical qubits and for the first time demonstrated logical operations on multiple logical qubits. Quantum chaos and quantum simulation of physics share many features and they have completed an experimental demonstration of localization in the perturbative area of a cat map.

They have extended a benchmark to a Hilbert space spanned by 14 spins (the computational equivalent of a PDP-11 computer in terms of storing the Hilbert space). An interesting observation is that using their classical simulators, the quantum computation as run on their NMR-based quantum information processor is more efficient.

Last year they described the first potentially scalable approach to building a quantum computer based on nuclear magnetic resonance. The quantum computer is engineered in the solid state and relies on their recent advances in truncating the dipolar Hamiltonian to just nearest neighbors as well using quantum entanglement as a resource for more sensitive metrology. They have nearly completed the construction of a simple quantum information processor based on this idea and will start experimentally exploring this approach this summer.

Coherent Imaging via Neutron Interferometry

In collaboration with NIST they have implemented a reciprocal-space approach to coherent imaging via a three-blade neutron interferometer. This new approach promises improved contrast and a resolution that is independent of the spatial resolution of the detector. This work has been extended to using a three-blade interferometer to create a neutron beam consisting of a coherent superposition of two beams separated by a controllable distance limited by the coherence length of the interferometer (about 300 Å in this case). This spatially separated coherent beam will enable a new class of coherent scattering and holds great promise for future neutron scattering studies in condensed matter.

Professor Robert G. Griffin

High-frequency Electron Paramagnetic Resonance

Using the 140 GHz spectrometer and 9 GHz spectra, Professor Griffin's group has determined the mechanism of the interaction of the azido inhibitors of ribonucleotide reductase.

Structural Studies of Amyloid Peptides and Proteins

Amyloidosis is a group of disorders due to peptide or protein misfolding and is characterized by the accumulation of insoluble fibrillar protein material in extracellular spaces. Sixteen different proteins are known to form amyloid-like aggregates involved in several diseases. Among them are ß-amyloid (Ab), invoved in Alzheimer's disease; the prion protein PrPc, which converts to PrPsc, leading to the transmissible spongiform encephalopathies; and the synuclein protein, which is responsible for Parkinson's disease.

During the last two years, this group developed methods to obtain large amounts of fibrillar peptide material and to maintain this material in a state suitable for magic angle spinning (MAS) NMR experiments. They have used these techniques in a collaborative study of the structure of 11 residue fibrillar peptides (TTR105-115) in collaboration with professors Cait MacPhee and Chris Dobson of Cambridge University. The peptides are derived from transthyretin and the group has determined the initial structure of this type of system with solid-state NMR distance and torsion angle measurements. Their success with the TTR system has encouraged them to initiate studies of three other systems—the L111M mutant of TTR, the GNNQQNY peptide from the Sup35 protein, and the peptide NFGSVQFV that is believed to initiate aortic medial amyloid. They anticipate that they will complete these structures and the structure of a fibril itself during the coming year. They have also started to perform structural studies of two amyloid-forming proteins, PI3-SH3 and p53-tet.

Dynamic Nuclear Polarization

The 140 and 250 GHz dynamic nuclear polarization (DNP) spectrometers continue to operate reliably and routinely, allowing the group to pursue new applications of DNP. Significant advances have been made in combining MAS with DNP and in the development of new polarizing agents. Specifically they have improved many aspects of the 250 GHz system so that it is now capable of recording spectra at low temperatures for extended periods. Results of these efforts are just beginning to be realized. The new polarizing agents that they have developed in collaboration with Tim Swager (Chemistry) consist of biradicals—two TEMPO molecules tethered by a polyethylene glycol chain. They are using the 250 GHz system to examine the photocycle intermediates of bacteriorhodopsin and determine structural features of each. The increased signal-to-noise ratio available from DNP is essential for the experiments. They have also performed the first experiments that permit them to observe enhanced signal intensities in liquids. During the past year they successfully operated the 460 GHz gyrotron that will be interfaced to a 700 MHz NMR spectrometer and have also started the construction of a 140 GHz amplifier.

Dipolar Recoupling

Over the last decade they have been heavily involved in the development of techniques to measure distances and torsion angles in solids. The goal is to be able to determine the structure of membrane proteins, amyloid fibrils, etc., with solid-state NMR. This past year they developed a method for simultaneously measuring multiple ^{13}C-^{13}C distances in uniformly labeled materials, and demonstrated the method successfully on a small peptide. This is a complementary approach to measuring ^{13}C-^{15}N distances used in their amyloid experiments. They anticipate that with increased sensitivity available from DNP experiments, these methods will be applicable to a large number of systems not accessible to solution NMR and X-ray crystallographic investigations. This year they have developed a new experiment that permits dipolar recoupling at high MAS frequencies and magnetic fields.

Center for Magnetic Resonance

The Center for Magnetic Resonance has completed its 28th year of operation as a facility providing scientists with access to high-field NMR equipment. During this year, 38 projects were worked on by 69 investigators from the departments of Chemistry, Biology, Physics, and Nuclear Science and Engineering (NSE), as well as users and collaborators from outside institutions such as Harvard University, Brandeis University, and Massachusetts General Hospital. Work resulted in 39 publications in print or in press.

As was the case in previous years, highlights of work conducted at the center include advances in high-frequency dynamic nuclear polarization with magic angle spinning, structure determination of large proteins, and high frequency EPR and electron-nuclear double resonance.

The Center for Magnetic Resonance recently received approved funding from NIH for a 900 MHz spectrometer, to be operated as part of the center. In addition, the center anticipates applying for widebore 800 MHz NMR systems in the next year or two. The renewal of the center grant this past fall will also support the development of 330 GHz tunable gyrotrons and low-temperature MAS probes for use with 500 MHz spectrometers.

Dr. Yukikazu Iwasa

NIH-supported Programs

High-temperature Superconducting Insert Coil for 1-GHz NMR Magnet

In Phase 2, the goal is to complete a 700 MHz NMR magnet comprised of a 600 MHz all low-temperature superconducting (LTS) NMR magnet and a 100 MHz high-temperature superconducting insert (HTS) coil. Phase 2 is expected to be completed in 2006.

Digital Flux Injector (Flux Pump) for NMR Superconducting Magnets

The ultimate goal of this five-year continuation program on the development of the digital flux injector (DFI) is the completion of a DFI to be coupled to the HTS insert of the 1-GHz LTS/HTS NMR magnet. The program is currently in its second year.

Development of Low-cost MgB_2/Solid N2 MRI Magnets

This program aims to demonstrate the feasibility and practicality of a low-cost (i.e., commercially viable) superconducting MRI magnet incorporating MgB_2 composite conductor and an innovative cryogenic design/operation concept specifically targeted for use in small hospitals, rural communities, and underdeveloped nations. They achieve this by building and operating a 0.5 T/80 cm bore demonstration magnet that, except for its lack of an MRI-grade spatial homogeneity, satisfies key operational requirements of 0.5 T/80 cm MRI magnet systems. This prototype system introduces two important firsts to MRI superconducting magnet technology, both benefiting the operation of their type of MRI systems: 1) a trendsetting MgB_2 magnet for the next generation of MRI magnets, and 2) an entirely new design/operation concept for the system cryogenics. The presence of solid nitrogen in the magnet housing greatly enhances the magnet's heat capacity and enables the magnet to maintain its operating field over a limited period of time, even with its cryocooler shut off, as would be in case of a power outage, an event not rare in rural communities and underdeveloped nations. During this shut-off period, the magnet will warm up from a nominal operating temperature of 10 K to a design limit of 15 K over a period of 29 hours. The program is currently in its second year.

A Cryocooler/Solid Ne–Cooled 500 MHz/20 cm MRI Magnet

This project seeks to apply a new design/operation concept for MRI superconducting magnets that enable these magnets to achieve operational features that in some respect resemble those of low-field permanent-magnet–based counterparts, and demonstrate applicability of this concept to high-field MRI (500 MHz and above) magnets by completing a 500 MHz/20 cm superconducting MRI magnet. The completed system will be installed in FBML for a group of MRI and brain science researchers. They strongly believe that the commercial magnet manufacturers for the next generation MRI magnets will in time adopt this new design/operational concept. These features include a liquid-free system; a quiet, noise/vibration-free system operation over a specific time period (12 h in this system), if required by the user; and the ability to maintain a constant operating field over this time period, even in the event of a power outage or while the cryocooler undergoes scheduled maintenance. That is, the proposed MRI magnet will be almost as easy to operate as a low-field permanent magnet-based system. The program is currently in its second year.

AFOSR-supported Programs

In early 2005, MTD was awarded three programs on stability and protection issues of YBCO-coated conductors:

- Phase 1 Small Business Technology Transfer (STTR) Program, as a principal subcontractor of Hyper Tech Research of Troy, OH;
- Phase 1 Small Business Innovation Research (SBIR) Program as a principal subcontractor of Tai-Yang of Oak Ridge, TN;
- Phase 1 SBIR program as the sole subcontractor of American Superconductor Corp. of Westborough, MA.

In June, Hyper Tech Research was awarded the Phase 2 STTR program, with MTD as its principal subcontractor.

Professor Alan Jasanoff

Professor Alan Jasanoff recently joined FBML, moving from a position as a Whitehead fellow to an assistant professor position in the departments of Nuclear Science and Engineering and Brain and Cognitive Science. His research is focused on developing noninvasive functional imaging methods to study systems-level neural plasticity involved in low-level learning and perceptual behavior in small animals by producing prototype imaging agents for "molecular functional MRI." Functional MRI (fMRI) studies in awake animals will be an increasingly important tool for studying mechanisms of brain plasticity as a function of behavior. MRI could achieve cellular-level detection of neural activity if used in conjunction with contrast-enhancing chemicals (contrast agents) that are sensitive to aspects of microscopic physiology. Professor Jasanoff's laboratory is also developing calcium-sensitive contrast agents that could be used for fMRI studies in vivo. Such experimental tools will find broad applicability in brain research; Professor Jasanoff's specific goal is to apply them to several problems in the context of rodent behavior and instrumental learning in particular. He has collaborative research efforts with faculty in the departments of Biology and Chemistry, and the Biological Engineering Division. He continues to collaborate with colleagues at the Whitehead Institute and will be collaborating with faculty in Harvard University's Department of Molecular and Cellular Biology.

Dr. Jagadeesh S. Moodera

In nanoscience condensed-matter physics, in particular magnetism and superconductivity, the Moodera group's research continues to make significant contributions to both fundamental science and industrial applications.

Their basic investigation emphasizes spin transport in thin-film nanostructures, specifically semiconductor spintronics. Using their molecular beam epitaxy system, their research seeks to contribute to the understanding of the spin properties of conventional materials and to unraveling the spin properties of certain novel magnetic compounds that have a high potential for technological application. Their research in these materials is utilized and further developed by companies such as IBM, HP, Motorola, Seagate, TDK, and Fujitsu for application in digital storage. These industrial research groups have developed prototype devices: readhead sensors for over 140 Gbits/sq storage, nonvolatile magnetic random access memory elements, and reprogrammable logic circuits that will potentially have a large impact on memory technology, which generates hundreds of billions of dollars. In this context, they are continuing national and international collaborative research efforts with scientists and faculty from national laboratories, US universities, industry, the University of Eindhoven, the University of Gottingen (Germany), Tohoku University (Japan), the Korea Institute of Science and Technology, the Institute of Physics (India), as well as the Ukrainian Academy of Sciences. Exchange of scientists and graduate students is a part of this program.

They have successfully developed a research program in the new superconductor (MgB_2) science and technology for Josephson junctions that have the potential for hybrid superconducting electronics in areas such as computers, logic elements, mixers, switches, and sensors. There is ongoing collaboration with other companies, such as NVE Inc., in the field of magnetic sensors and nonvolatile memory.

They have also started research programs in the fields of nanoscience for single-spin transistors as well as the materials aspect for quantum computing. In parallel, they are also investigating injecting spins into semiconductors. Another program they just embarked on is a new approach to read qubit information using a quantum dot structure and spin filter approach.

Seven postdoctoral scholars, two graduate students, two undergraduates, and 10 high school students (including MIT Research Science Institute students) have taken part in Dr. Moodera's research. The high school students have won several science competitions—one was a regional finalist in the Intel/Westinghouse Science Competition—as well as other regional and top state-level awards. Several of the high school students have joined the MIT undergraduate program. Research resulted in several publications (including an article in the News and Views section of *Nature*) and invited talks at various national and international conferences and universities.

Dr. Moodera continues his collaboration with Eindhoven Technical University (Holland) as a visiting professor. He is the expert advisor for a spin-related nanotechnology program in Korea Institute of Science and Technology. He has taken part at the national-level magnetism committee policies and meeting initiatives, and has served on the scientific board of international meetings. He is the cochairman for the upcoming Gordon Research Conference on Magnetic Nanostructures.

Richard Temkin

Dr. Temkin's research on 140, 250, and 460 GHz gyrotrons for EPR and DNP is continuing with support from NIH. The 140 GHz and 250 GHz gyrotrons are operational and are being used for DNP research. The 460 GHz gyrotron has been constructed and is undergoing initial tests; it should be operational this fiscal year. In early 2003, Dr. Temkin received an NIH grant to initiate development of a gyroamplifier at 140 GHz. Another proposal is pending for the development of a new class of tunable gyrotron oscillators and will begin with work on a 330 GHz tunable device. There is considerable interest at Bruker in commercializing these developments. They anticipate that this program will continue with the extension of amplifier technology to 600 GHz.

Facilities

Renovations are complete for the magnet cell accommodating the 700/89 system. Renovations have also been completed for the 900 MHz instrument in NW15. We expect to receive the instrument in early fall 2005.

Education and Personnel

The laboratory contributes to undergraduate education by participating in the Undergraduate Research Opportunities Program, which encourages and supports research-based intellectual collaborations of MIT undergraduates with Institute faculty and research staff. In addition, the laboratory has 31 full-time graduate and 12 postdoctoral associates and fellows performing research.

Future Plans

In the longer term, we also plan to complete construction of the second floor magnet hall, and instruments currently housed on the fourth and fifth floors will be relocated in order to create a comprehensive Center for Magnetic Resonance. This will involve the acquisition of an 800/89 magnet and a widebore 600 magnet currently being used in tests of HTS material by Dr. Iwasa and his colleagues.

We are also participating in national efforts to start the development of a 30 T magnet (1.3 GHz for ^{1}H) and to plan the installation of such systems at MIT.

Robert G. Griffin
Director
Professor of Chemistry

More information about the Francis Bitter Magnet Laboratory is available online at http://web.mit.edu/fbml/.