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 Laboratory's research program in magnetic resonance, which includes nuclear magnetic resonance (NMR), electron paramagnetic resonance (EPR), and magnetic resonance imaging (MRI), 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 presently involves approximately 30 NMR and EPR magnets and spectrometers.

Highlights for the Year

Professor David G. Cory of the Department of Nuclear Science and Engineering (NSE) and his colleagues continue to make advances in the theory, practice, and implementation of quantum information processing (QIP). They have nearly completed the construction of a simple quantum information processor based on NMR 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.

Professor Robert G. Griffin of the Department of Chemistry and Professor Gerhard Wagner of Harvard University continue to operate the MIT/Harvard Center for Magnetic Resonance (CMR), a collaborative research effort between MIT and Harvard Medical School. CMR is supported by an NIH Research Resource grant and has been funded continuously since 1976. In September 2005 we took delivery of a 900 MHz spectrometer (which became operational this past summer) for experiments in liquids and solids. It is one of about a dozen such instruments in North America. Professor Wagner is using this instrument in his research program devoted to structural biology and signaling, and Professor Griffin is employing it to develop new methods for solid-state structural investigations, which he is applying to structural studies of membrane and amyloid proteins.

Under the leadership of Dr. Yukikazu Iwasa, the FBML Magnet Technology Division (MTD) is currently involved in four NIH-funded programs focusing on NMR and MRI magnets and three Air Force Office of Scientific Research (AOFSR)-funded projects on stability and protection issues for yttrium barium copper oxide (YBCO)-coated conductors. One of MTD's most important goals is the design and construction of the next generation ≥ 1.3 GHz NMR magnet.

Professor Alan Jasanoff of NSE, the Department of Brain and Cognitive Sciences, and his colleagues are pursuing functional imaging methods aimed at studies of systems-level neural plasticity involved in low-level learning and perceptual behavior. The experiments are being performed in small animals using prototype imaging agents for "molecular functional MRI."

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

Dr. Richard Temkin of the Department of Physics and the Plasma Science and Fusion Center and his colleagues are completing the construction of a 460 GHz gyrotron, and they have initiated the development of a 140 GHz gyroamplifier. Another project involves the design and construction of a 330 GHz tunable gyrotron oscillator for use in dynamic nuclear polarization (DNP)/NMR experiments. We anticipate that these developments will ultimately produce a gyroamplifier operating at approximately 600 GHz for use with 900 MHz NMR magnets.

Research Activities

Professor David G. Cory

Quantum Information Processing

Professor Cory and his students continue to explore magnetic resonance approaches to QIP through collaborations with Dr. Timothy F. Havel (NSE), Dr. Chandrasekhar Ramanathan (NSE), Professor Seth Lloyd (Mechanical Engineering), Dr. Raymond Laflamme (University of Waterloo), and Dr. Joseph Emerson (University of Waterloo).

Their recent accomplishments focus on developments leading to fault-tolerant computation. In particular they have developed efficient means of bounding errors based on the return of quantum states under brief periods of time-reversed dynamics. By averaging the quantum paths during these brief intervals over random states in the Hilbert space, they force the probability of return to be an accurate and efficiently measurable estimate of the error strength. They have shown that they can tailor such measurements to report on the strengths of different types of errors. Knowledge of the error types and strengths permits the design of logical encodings that may eventually reach the fault-tolerant threshold necessary for quantum computation. In related work, they have explored the resources necessary to control logically encoded quantum information and they have experimentally demonstrated high fidelity control over multiple logical qubits.

They have just initiated a new set of experiments on coherent spintronics where the electron spin plays an essential role in control of the nuclear spin-based qubits. These are solid-state experiments with eventual implementations imagined in Si or in quantum dots. The nuclear/electron spin system is quantized such that the electron Zeeman interaction dominates, with the second leading term being the electron/nuclear hyperfine coupling. When we orient the sample such that the asymmetric part of the hyperfine interaction is stronger than the nuclear Zeeman term, then we can achieve universal control over the full Hilbert space while only applying microwave radiation at any one electron spin transition. This permits QIP where the nuclear spins are the qubits and the electron spin is a quantum channel used to control the qubits. The benefits are an increase in the clock speed and long decoherence times for the qubits.

Coherent Imaging via Neutron Interferometry

In collaboration with NIST, Professor Cory's group has demonstrated a reciprocal-space approach to coherent imaging via a three-blade neutron interferometer. The 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 that is a coherent superposition of two beams separated by a controllable distance limited by the coherence length of the interferometer (about 500 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. We are working to transition this research into the first demonstration of coherent neutron-scattering via neutron interferometry.

Professor Robert G. Griffin

Structural Studies of Amyloid Peptides and Proteins

Amyloidosis is a group of disorders created by peptide or protein misfolding and 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 β-amyloid (Aβ) 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 few years, Professor Griffin and his group have developed methods to prepare large amounts of fibrillar peptide and to maintain this material in a state suitable for magic angle spinning (MAS) NMR experiments. Most recently, they have used these techniques in a collaborative study of the structure of 11 residue fibrillar peptides of the L111M mutant derived from transthyretin. They have determined the structure of these peptides with solid-state NMR distance and torsion angle measurements. Their success with the target tracking (TTR) system has encouraged them to initiate experiments with other systems—the GNNQQNY peptide from the Sup35 protein, the peptide NFGSVQFV that is believed to initiate aortic medial amyloid, and the SH-3 domain of the protein phophatidylinostol-3-kinase (PI3-SH3). They anticipate that they will complete these structures and the structure of a fibril itself during the coming year.

Dynamic Nuclear Polarization

The 140 and 250 GHz DNP spectrometers continue to operate reliably and routinely, allowing the group to pursue new methods and 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 (approximately three weeks). Results of these efforts are just beginning to be realized with excellent spectra of the membrane protein bacteriorhodopsin (bR) and its photointermediates that are produced via in situ laser irradiation. The increased signal to noise ratio (S/N) available from DNP is essential for the experiments. The new polarizing agents that they have developed in collaboration with Professor Tim Swager of the MIT Department of Chemistry consist of biradicals—two TEMPO molecules tethered by a polyethylene glycol or a three carbon chain. They have also performed the first experiments that permit them to observe enhanced signal intensities in liquids, achieving an enhancement factor of 400.

Dipolar Recoupling

Since Professor Griffin's group initiated ^{13}C-^{13}C dipolar recoupling experiments in the late 1980s, the field has grown enormously, and many advances in technique have been made by multiple laboratories. Over the last decade the Griffin group has been heavily involved in these developments, particularly with regard to techniques to measure distances and torsion angles in solids. Their goal is to be able to determine the structure of membrane proteins, amyloid fibrils, etc., with solid-state NMR. During the past year they have concentrated on approaches that are applicable to experiments performed at high spinning frequency and at high magnetic fields. In particular, they have developed:

- Methods that permit dipolar 13C-13C recoupling at high MAS frequencies and magnetic fields without application of proton decoupling
- Methods for simultaneously measuring multiple 13C-13C distances in uniformly labeled peptides and proteins
- An improved method for cross polarization that was necessitated by experiments at high spinning frequencies and fields

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. It is also possible that they will be able to measure distances and torsion angles with higher accuracy and precision than is possible with diffraction experiments.

High Frequency Electron Paramagnetic Resonance

Using the 140 GHz spectrometer and 9 GHz spectra, we are studying the inhinition mechanism of ribonucleotide reductase. For the latest version of these experiments we have constructed a rapid freeze-quench apparatus that will trap intermediates on a microsecond to millisecond timescale. We are also performing extensive EPR studies of biradicals that will serve as polarizing agents for dynamic nuclear polarization experiments.

Center for Magnetic Resonance

The Center for Magnetic Resonance, of which Dr. Griffin is the director, has completed its 31st year of operation as a facility providing scientists with access to high-field NMR equipment. In September 2005 CMR took delivery of a 900 MHz spectrometer for performing experiments on liquids and solids. The system will become fully operational in July of 2006 with the delivery of the cryprobe. The 900 will be operated as part of CMR and will be available to investigators at MIT, Harvard, and other universities and companies. In addition, CMR anticipates applying for the funding to purchase an 800 MHz widebore NMR system in the next year or two.

Dr. Yukikazu Iwasa

Under the direction of Dr. Iwasa, MTD is currently involved in four NIH-funded programs on NMR and MRI magnets and three AFOSR-funded projects on stability and protection issues for YBCO-coated conductors. The AFOSR-funded projects are being conducted in collaboration with Hyper Tech Research of Troy, OH, and American Superconductor Corporation in Westborough, MA. Progress on each of the NIH projects is summarized briefly below

High-Temperature Superconducting Insert Coil for ≥1.3 GHz NMR Magnet

In Phase 2, MTD's goal was 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 (HTS) insert coil. We achieved a field of 700 MHz in the spring of 2006, but there still remains the important task of shimming the field to improve the field homogeneity. As of this writing the shimming is underway.

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 our ≥1.3 GHz LTS/HTS NMR magnet. By coupling to a persistent-mode LTS NMR magnet a DFI can also shift the frequency of an NMR magnet by pumping in or pumping out a quantified amount of flux from the magnet.

Development of Low-cost MgB2/solid N2 MRI Magnets

The specific aim of this program is to demonstrate the feasibility and practicality of a low-cost, commercially viable superconducting MRI magnet incorporating an MgB_2 composite conductor and an innovative cryogenic design/operation concept specifically targeted for use in small hospitals, rural communities, and underdeveloped nations. MTD is achieving this specific aim 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 of which benefit the operation of MTD's type of MRI systems—a trend-setting MgB_2 magnet for the next generation of MRI magnets, and an entirely new design/operation concept for the system cryogenics. The presence of solid N_2 in the housing that enhances the magnet's heat capacity enormously enables the magnet to maintain its operating field over a limited time period even with its cryocooler shut off, as it would be in the case of a power outage, an event not rare in rural communities and underdeveloped nations. Only during this shutoff 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 project is moving forward.

Cryocooler/Solid Ne-cooled 500 MHz/20 cm MRI Magnet

The specific aims of this project are to apply a new design/operation concept for MRI superconducting magnets that enables them to achieve operational features that resemble those of low-field permanentmagnet-based counterparts and to demonstrate the 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 the FBML for a group of MRI and brain science researchers. We strongly believe that 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; 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 is under scheduled maintenance. 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 third year.

Professor Alan Jasanoff

Professor Alan Jasanoff has been a faculty member in NSE and part of the FBML since the autumn of 2004. In the past year, he accepted a joint appointment in the Biological Engineering Division, along with his previous appointments in NSE and the Department of Brain and Cognitive Sciences. Jasanoff's work and recent publications continue to focus on the development of MRI contrast agents for next-generation functional brain imaging. He was recently awarded a Technological Innovations grant from the McKnight Endowment Fund for Neuroscience to support this research.

Dr. Jagadeesh S. Moodera

Dr. Jagadeesh Moodera has continued his research efforts in condensed matter nanoscience physics through collaboration with various universities and industries, with funding from ONR, NSF, and the Korean government (via KIST). In addition, he has continued his mentoring of graduate, undergraduate, and high school students by providing research opportunities within his lab. Recently he acquired an electron beam lithography system and built a state-of-the-art ion milling system for creating nanostructures down to less than 50nm length scale. Dr. Moodera has also successfully initiated a new long-term collaborative project on nanospintronics, the KIST-MIT research program, which has a provision for the exchange of students and scientists. His group's recent breakthrough work published in *Nature Materials* has attracted extensive media attention (e.g., in MIT *Tech Talk, Technology Review*, *Electronic Design*, *Hindustan Times,* and *The Times of India*).

Research in Nanoscience Condensed Matter Physics

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

The basic investigations emphasize spin transport in thin film nanostructures, specifically semiconductor spintronics. Using our molecular beam epitaxy (MBE) system, our research seeks to contribute to the understanding of the spin properties of conventional materials and to unravel the spin properties of certain novel magnetic compounds that have a high potential for technological application. Our research into the structure of these materials is being further developed by various companies such as IBM, Motorola, Seagate, TDK, and Fujitsu for application in digital storage. In fact, these companies have introduced to the market mini- and microdisc drives with unprecedented capacity that have read head sensors based on magnetic tunnel junctions. Another important area of application includes nonvolatile magnetic random access memory (MRAM) elements as well as reprogrammable logic circuits that will potentially have a significant and highly profitable impact on memory technology. Freescale (an offshoot of Motorola) has introduced the MRAM chips to the market. In this context, we are continuing national and international collaborative research efforts with scientists and faculty from industry and from national laboratories and universities including the Eindhoven University of Technology, the University of Twente, the University of Gottingen, Ewha Woman's University, Tohoku University, KIST, Boise State University, UCLA, and the Institute of Physics (Bhubaneswar, India). Exchange of scientists and graduate students is a part of this program.

The Moodera group has successfully developed a research program in the new superconductor (MgB_2) science and technology for Josephson junctions that has a potential for application in hybrid superconducting electronics in areas such as computers, logic elements, mixers switches, and sensors. We intend to start a new collaboration with Department of Electrical Engineering at MIT to develop Josephson junction-based ultra-fast circuitry that is useful for the navy. There is ongoing collaboration with other companies, such as CMI, in the field of magnetic storage and nonvolatile memory.

We have also started research programs in the field of nanoscience for single-spin transistors as well as in the materials aspect for quantum computing. In a parallel approach, we are also investigating injecting spins into two-dimensional electron gas (2DEG) semiconductors to create spin-field effect transistors. Another program we recently embarked on takes a new approach to reading the qubit information using quantum dot structure and the spin filter method.

Seven postdoctoral scholars, two visiting scientists, two graduate students, and several high school students have taken part in Dr. Moodera's research. The high school students have won several science competitions. Several of these students have been admitted to MIT as undergraduates. The group's research has resulted in several publications and invitations to speak at various national and international conferences and universities.

Dr. Moodera continues his collaboration with Eindhoven University of Technology as a visiting professor. He is the expert advisor for a spin-related nanotechnology national program in the Netherlands and at KIST. He has taken part in national-level magnetism committee policies and meeting initiatives, and has served on the scientific board of international meetings. He is a review panel member for the NSF Partnership for Research and Education in Materials (PREM), a multidisciplinary educational activity of the W. M. Keck Computational Materials Theory Center (CMTC) at California State University Northridge (CSUN) and the Princeton Center for Complex Materials (PCCM) at Princeton University. He is the chairman for the upcoming Gordon Research Conference on Magnetic Nanostructures at Oxford in 2006.

Dr. Richard J. Temkin

The Temkin group is performing research on 140, 250, 330, and 460 GHz gyrotrons for EPR and DNP with support from the NIH National Institue of Biomedical Imaging and Bioengineering. The 140 GHz and 250 GHz gyrotrons are operational and are being used for DNP research. The 250 GHz gyrotron has operated continuously for nine months, a major technological accomplishment. This has permitted unique experimental DNP/NMR measurements. The 460 GHz gyrotron has operated for a 24-hour trial run. It is now being upgraded to permit very long run times with high reliability. In early 2003 Dr. Temkin received an NIH grant to initiate the development of a gyroamplifier operating at 140 GHz. It is planned that this amplifier will begin operation in late calendar year 2006. Another proposal for the development of a new class of tunable gyrotron oscillators has recently been funded for research on a 330 GHz tunable device. There is considerable interest from industry in commercializing these developments. They anticipate that this program will continue with the extension of amplifier technology to 600 GHz.

Facilities

Renovations for the 900 MHz instrument in NW15 were completed in January 2005 and the instrument was delivered in September 2005. Installation and initial operation of the equipment will be completed in July 2006 when the solution state cryoprobe is installed and becomes operational.

Education And Personnel

FBML contributes to undergraduate education by participation in the Undergraduate Research Opportunities Program (UROP), a program that encourages and supports research-based intellectual collaborations of MIT undergraduates with Institute faculty and research staff. In addition, the laboratory has 25–30 full-time graduate students and approximately the same number of postdoctoral associates and fellows performing research.

Future Plans

In the longer term we plan to complete renovations of the second floor magnet hall and to relocate new high field magnets and instruments currently housed on the fourth and fifth floors to this space to create a comprehensive CMR. This will involve the acquisition of an 800/89 magnet and the widebore 600 MHz 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 a system at MIT. At present these systems are proliferating in Europe.

The health of the Research Programs in QIP, imaging, magnet design, spintronics, and high field magnetic resonance at the FBML is excellent, and we anticipate that FBML will continue to grow in the next few years.

Robert G. Griffin
Director
Professor of Chemistry

More information about the Francis Bitter Magnet Laboratory can be found at http://web.mit.edu/fbml/.