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 the FBML. Funded primarily by the National Institutes of Health (NIH) and the Department of Energy, the program involves 28 NMR and EPR magnets and spectrometers.

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 of MIT and Harvard Medical School. The center is supported by an NIH Research Resource grant and has been in operation since 1976.

—Professor David G. Cory, Drs. Timothy F. Havel and C. Ramanathan, and their colleagues continue to make advances in the theory, practice, and implementation of quantum information processing. Over the last year we have 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 our recent advances in truncating the dipolar Hamiltonian to just nearest neighbors as well as using quantum entanglement as a resource for more sensitive metrology. In liquid-state NMR test beds of quantum computers we have implemented the first 10 + qubit quantum processor, and have shown the first quantum logic with qubits encoded against noise.

—The journal *Quantum Information Processing*, published by Kluwer Academic with Professor Cory, editor in chief, and Dr. Havel, managing editor, has completed its second year of publication, and is publishing a special issue devoted to "Progress Towards Quantum Computation" with Dr. Henry Everitt as the guest editor. *QIP* is an international forum for the publication of peer-reviewed papers on all aspects—theory and experimental—of quantum information processing.

—The Magnet Technology Division (MTD) successfully completed the first phase of a three-phase 1-GHz NMR magnet project. A 350 MHz/55 mm NMR magnet completed in Phase 1 is the world *first* NMR magnet comprised of a low-temperature superconducting (LTS) magnet and a high-temperature superconducting (HTS) insert. In June 2003, the MTD received funding from the NIH Center for Research Resources to proceed with Phase 2 of this project. Also successfully completed by the MTD is the world *first* digital flux injector (DFI), a full-scale version of which may be coupled to a "slightly" dissipative NMR magnet and used to periodically inject a precisely metered amount of flux into the magnet, thus enabling the magnet to operate effectively in persistent mode and maintain its required temporal stability requirements. The MTD was awarded a five-year project grant by the NIH Center for Research Resources to continue developing DFI for "slightly" dissipative NMR magnets, including a 1-GHz NMR magnet comprised of an LTS-background field magnet and an HTS insert, in which the HTS insert is expected to be slightly dissipative.

—Dr. Jagadeesh Moodera has continued to strengthen his research efforts, specializing in nanoscience, in condensed matter physics through collaboration with various universities and industries, as well as the ONR and NSF. In addition, he has continued his mentoring of graduate students, undergraduates, and high school students by providing research opportunities within his lab. Dr. Moodera is cochairman of the August 2004 Gordon Research Conference on Magnetic Nanostructures and chairman of the following one.

Research Activities

Professor David G. Cory

Quantum Information Processing

Professor Cory and his students continue to explore NMR approaches to quantum information processing through collaborations with Dr. Havel (Nuclear Engineering), Dr. Ramanathan (Nuclear Engineering), Professor Seth Lloyd (Mechanical Engineering), Dr. Raymond Laflamme (University of Waterloo), and Dr. J. Yepez (AFRL). Over the last year, this group has 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 recent advances in truncating the dipolar Hamiltonian to just nearest neighbors, as well as using quantum entanglement as a resource for more sensitive metrology.

In liquid state NMR test beds of quantum computers, the group has implemented the first 10 + qubit quantum processor, and has shown the first quantum logic with qubits encoded against noise.

NMR of Hydrogen Storage

In collaboration with Professor Yip (Nuclear Engineering), we have initiated NMR studies of hydrogen chemistry and dynamics in confined spaces (such as carbon nanotubes). These are prototype systems for hydrogen storage.

Coherent Imaging via Neutron Interferometry

In collaboration with NIST we have implemented 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.

Professor Robert G. Griffin

High Frequency Electron Paramagnetic Resonance

Using the 140 GHz spectrometer and 9 GHz spectra as well, we have 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 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: ß-amyloid (Aß) in Alzheimer's disease; the prion protein PrPc converts to PrPsc, leading to the transmissible spongiform encephalopathie; and the synuclein protein is responsible for Parkinson's disease.

During the last two years, we developed methods to obtain large amounts of fibrillar peptide material and to maintain this material in a state suitable for MAS NMR experiments. We have used these techniques in a collaborative study of the structure of 11 residue fibrillar peptides (TTR105-115) in collaboration with Professor Cait MacPhee and Professor Chris Dobson of Cambridge University. The peptides are derived from transthyretin, and we have determined the initial structure of this type of system with solid state NMR distance and torsion angle measurements. Our success with the TTR system has encouraged us 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 arotic medial amyloid. We anticipate that we will complete these structures and the structure of a fibril itself during the coming year. We have also started to perform structural studies of two amyloid-forming proteins.

Dynamic Nuclear Polarization

The 140 and 250 GHz DNP spectrometers continue to operate reliably and routinely, allowing us 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 we 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 we have developed in collaboration with Tim Swager of the MIT Chemistry Department consist of biradicals—two TEMPO molecules tethered by a polyethylene glycol chain. We are using the 250 GHz system to examine the photocycle intermediates of bR and determine structural features of each. The increased S/N available from DNP is essential for the experiments. We have also performed the first experiments that permit us to observe enhanced signal intensities in liquids.

Dipolar Recoupling

Over the last decade we 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, and the like with solid state NMR. This past year we 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 distances ^{13}C–^{15}N distances used in our amyloid experiments. We 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.

Center for Magnetic Resonance

The Center for Magnetic Resonance (CMR) 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 departments within MIT including Chemistry, Biology, Physics, and Nuclear Engineering, as well as users and collaborators from institutions outside MIT 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 (MASDNP), structure determination of large proteins, and high-frequency EPR and ENDOR.

The Center for Magnetic Resonance recently received approved funding from NIH for a 900 MHz spectrometer. The 900 will be operated as part of CMR. In addition, we anticipate applying for widebore 800 MHz NMR systems in the next year or two. The renewal of the CMR 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

In addition to the two NMR-related projects described earlier, in FY2004 the Magnet Technology Division was awarded two MRI magnet projects by the National Institute of Biomedical Imaging and Bioengineering: (1) "Development of low-cost MgB2/solid N2 MRI magnets" (a three-year project with a start date of September 1, 2003); and (2) "A cryocooler/solid Ne cooled 500 MHz/20 cm MRI magnet" (a three-year project with a start date of March 1, 2004). These projects are briefly summarized below.

HTS Insert Coil for 1-GHz NMR Magnet

In Phase 2, our goal is to complete a 675 MHz NMR magnet comprised of a 600 MHz all-LTS NMR magnet and a 75 MHz HTS insert coil. We expect to complete Phase 2 in March 2006.

Digital Flux Injector (Flux Pump) for NMR Superconducting Magnets

The ultimate goal of this five-year continuation program on the development of DFI is completion of a DFI to be coupled to the HTS insert of our 1-GHz LTS/HTS NMR magnet.

Stability/Protection of HTS Magnets

The large heat capacity of solid nitrogen impregnating the winding of an HTS magnet in an electric power device limits the temperature rise in the HTS winding subjected to fault-mode overcurrent pulses. We are investigating quench/recovery processes of YBCO-coated tape, bare and copper-laminated.

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, i.e., commercially viable, superconducting MRI magnet incorporating MgB2 composite conductor and an innovative cryogenic design/operation concept specifically targeted for use in small hospitals, rural communities, and underdeveloped nations. We achieve 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 benefiting operation of our type of MRI systems: (1) a trend-setting MgB2 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 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 would be in case of a power outage, an event not rare in rural communities and underdeveloped nations. Only 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.

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

The specific aims of this project are to: (1) 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 (2) 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 the FBML for a group of MRI and brain science researchers. We strongly believe that commercial manufacturers of the next generation of MRI magnets will in time adopt this new design/operational concept.

The features include: (1) liquid-free system; 2) if required by the user, a quiet, noise/vibration-free system operation over a specific time period (12 h in this system); (3) 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. That is, the proposed MRI magnet will be almost as easy to operate as a low-field permanent-magnet based system.

Total number of graduate students: 2
Total number of undergraduate students: 0
Total number of UROP students: 2

Dr. Jagadeesh S. Moodera

In the nanoscience part of condensed matter physics—in particular, magnetism, as well as superconductivity—our research continues to make significant contributions to both fundamental science and industrial applications.

Our basic investigation emphasizes spin transport in thin-film nano structures, 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 unraveling the spin properties of certain novel magnetic compounds that have a high potential for technological application. Our research findings are being applied by companies such as IBM, Hewlett-Packard, Motorola, Seagate, TDK, and Fujitsu to applications in digital storage. They have reached prototype devices: readhead sensors for over 140Gbits/sq. storage, nonvolatile magnetic random access memory (MRAM) elements, as well as reprogrammable logic circuits that could have a large impact on memory technology running into the hundreds of billions of dollars. In this program, we are continuing to pursue collaborative research with scientists from industry, national laboratories, US universities, the University of Eindhoven, the University of Gottingen, Tohoku University, Korea Institute of Science and Technology, Institute of Physics (India), and the Ukrainian Academy of Sciences. The exchange of scientists and graduate students is a part of this program.

We 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.

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

Seven postdoctoral scholars, two graduate students, two undergraduates and ten high school students (including RSI students) have taken part in Dr. Moodera's research. The high school students have won several science competitions, including a regional finalist in Intel-Westinghouse Science Competition, as well as other regional and top state level awards. Several of the high school students subsequently enrolled in MIT's undergraduate program. Research resulted in several publications (including an article in News and Views 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 the Korea Institute of Science and Technology. He has taken part in national-level magnetism committee meetings, and serves on the scientific board of international meetings. He is the cochairman of the upcoming Gordon Research Conference on Magnetic Nanostructures.

Facilities

Renovations are complete for the magnet cell accommodating the 700/89 system. Renovations have begun for the 900 MHz instrument in NW15.

Education and Personnel

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

Future Plans

In the longer term we plan to complete construction of the second-floor magnet hall, and the instruments currently housed on the fourth and fifth floors will be relocated in order to create a comprehensive Center for Magnetic Resonance.

Robert G. Griffin
Director
Professor of Chemistry

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