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, funded primarily by the National Institutes of Health (NIH) and the Department of Energy, currently involves approximately 30 NMR and EPR magnets and spectrometers.

Highlights for the Year

Professor Robert G. Griffin (Department of Chemistry) and professor Gerhard Wagner (Harvard Medical School [HMS]) continue to operate the MIT/Harvard Center for Magnetic Resonance (CMR), a collaborative research effort between MIT and HMS. CMR is supported by an NIH Research Resource grant and has been funded continuously since 1976. This grant was recently renewed and is scheduled to continue until May 2014. The past year saw the installation of a 9 GHz pulsed EPR and significant improvements in the pulsed 140 GHz machine, which has been used by several faculty members from MIT and HMS. In addition, the first of two 800 MHz NMR spectrometers was installed. The instrument, designed for solution NMR, is used primarily by Professor Wagner and his collaborators from HMS. A second 800 MHz magnet for solid-state NMR was delivered in August 2010, following completion of several building renovations. Space renovations for these instruments were jointly financed by MIT and HMS. In addition, FBML brought into operation the 700 MHz/ 460 GHz DNP spectrometer and obtained the initial DNP results with this instrument.

Under the leadership of Dr. Yukikazu Iwasa, the FBML Magnet Technology Division is currently involved in four NIH-funded programs on NMR and MRI magnets, and two Air Force Office of Scientific Research–funded projects on stability and protection issues in yttrium barium copper oxide (YBCO)–coated conductors. These projects are briefly summarized below; one of the most exciting is the design and construction of a 1.3 GHz NMR magnet using high-temperature superconductors (HTS).

Professor Alan Jasanoff (Departments of Nuclear Science and Engineering; Biological Engineering; and 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. Their experiments are being performed in small animals, using prototype imaging agents for "molecular functional MRI."

Senior staff scientist Jagadeesh Moodera continued research efforts in nanoscience condensed matter physics through collaboration with various universities and industries, and funding from the Office of Naval Research (ONR), the National Science Foundation (NSF), and the Korean government (via the Korea Institute of Science and Technology [KIST]). In addition, he has continued mentoring graduate students, undergraduates, and high school students by providing research opportunities in his lab. Dr. Moodera has also successfully carried out a long-term collaborative project on nanospintronics funded by the Korean government; the project, called the KIST-MIT Research Laboratory, has a provision for the exchange of students and scientists. His group's breakthrough work has attracted media attention in publications such as MIT's *Tech Talk* and *Technology Review*; *Electronic Design*; *IEEE Spectrum*; the *Hindustan Times*; and the *Times of India*.

Senior research scientist Richard Temkin (Department of Physics, and Plasma Science and Fusion Center) and his colleagues completed the construction of a tunable 460 GHz gyrotron. Another project involves the design and construction of a 330 GHz tunable oscillator for use in dynamic nuclear polarization (DNP)/NMR experiments. Two amplifiers (140 and 250 GHz) are being designed and constructed. It is anticipated that these developments will ultimately produce a gyroamplifier operating at approximately 600 GHz for use with 900 MHz NMR magnets.

Research Activities

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. These disorders are becoming especially important as the average age of the overall population increases. Approximately 20 different proteins are known to form amyloid-like aggregates involved in several diseases—for example, beta-amyloid (Aβ) in Alzheimer's disease; the prion protein PrPc, which converts to PrPsc, leading to transmissible spongiform encephalopathy; the synuclein protein, which is responsible for Parkinson's disease; and beta-2-microglobulin (β2m), which is responsible for amyloidosis associated with kidney failure and dialysis. Currently, there are about 5.3 million Americans with Alzheimer's disease, and the annual cost of caring for these individuals is $172 billion. Thus, amyloidosis is a major health problem in the US and other countries as well.

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 used these techniques in a collaborative study of the complete structure of 11 residue fibrillar peptides of the $TTR_{105-115}$ derived from transthyretin. Specifically, using these peptides they determined the structure of solid-state NMR distance and torsion angle measurements and developed additional methods to determine the interstrand and intersheet alignments of the peptides, finding them to be parallel and antiparallel, respectively. Recently completed cryo-electron microscopy experiments will yield a complete structural model for the fibril. Finally, during the past year the group completed assigning the spectrum of the SH-3 domain of the protein phophatidylinostol-3-kinase (PI3-SH3) and a large fraction of β2m, the protein associated with dialysis-related amyloidosis. Other experiments have been developed to determine the alignment of the fibrils, and for both PI3-SH3 and β2m they are parallel in register. DNP has also been used successfully to establish other interstrand and intersheet contacts in PI3-SH3.

Dynamic Nuclear Polarization

As mentioned above, the highlight of the year was the initial operation of the 700 MHz/460 GHz spectrometer, where FBML obtained an enhancement of -20. With continued improvements, it is anticipated enhancements will grow to ~+70. 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, many aspects of the 250 GHz system have been improved so that it is now capable of recording spectra at low temperatures for extended periods (approximately three weeks). FBML also has a collaborative program with professor Timothy Swager (Department of Chemistry) to develop new biradical polarizing agents: two TEMPO molecules tethered by a three carbon chain, or BDPA and TEMPO tethered together, and a water-soluble version of BDPA. Metal ions have also begun to be used as polarizing agents.

High-frequency Electron Paramagnetic Resonance

The 140 GHz spectrometer was rebuilt over the past year to increase its power output to 120 mW so that it can drive the 140 GHz gyroamplifier. In addition, an NMR console has been added to the spectrometer so that pulsed DNP experiments can be performed. These experiments will require several years of development but will likely replace continuous wave experiments as the preferred approach to performing DNP.

Center for Magnetic Resonance

CMR has completed its 36th year of operation as a facility providing scientists with access to high-field NMR equipment, including two 600s, a 700, two 750s, an 800, and a 900 MHz instrument. The collection of instruments operates as part of CMR and will be available to investigators at MIT, Harvard University, and other universities and companies. The arrival of two 800 MHz instruments partially addresses the growing demand for high-field NMR spectrometer time.

Yukikazu Iwasa

During July 1, 2010 through June 30, 2011, the Magnet Technology Division, under Dr. Iwasa's leadership, was involved in three NIH-supported programs on NMR and MRI magnets. These projects are briefly summarized below.

NIH-supported Programs

HTS insert coil for 1.3-GHz NMR magnet—Phase 3A of a two-phase (3A and 3B) program

The main goals of Phase 3A of a two-phase (3A and 3B) program are to:

- Complete a 600 MHz (14.09 T) insert magnet (H600) consisting of two nested HTS coils—one a stack of 56 double-pancake coils, each wound with YBCO

(HTS) tape; and the other a stack of 56 double-pancake coils, each wound with Bi2223 (HTS) tape

- Operate H600 at 4.2 K in a background magnetic field of 11.74 T, generated by a low-temperature superconducting (LTS) 500 MHz (11.74 T) NMR magnet, and thereby achieve a 1.1 GHz (25.84 T) field
- Characterize the screening-current field (SCF), generated by H600, which degrades the spatial field homogeneity of the 1.1-GHz HTS/LTS magnet and that of a 1.3-GHz NMR magnet, to be completed in Phase 3B, that will use the same H600
- Design, to minimize this SCF field, a special set of superconducting shim coils to be installed in an all-LTS 700 MHz NMR magnet to be purchased in Phase 3B

In 2010–2011, FBML completed winding both HTS coils. The project is supported jointly by the National Center for Research Resources, the National Institute of Biomedical Imaging and Bioengineering (NIBIB), and the National Institute of General Medical Sciences.

Compact, neon/cryocooled NMR magnet assembled from superconducting YBCO annuli

The main goal of this project is to complete a "miniature" 100-200 MHz NMR magnet assembled from a stack of YBCO annuli and thereby demonstrate the feasibility of manufacturing, in the continuation program that follows, a 500 MHz NMR magnet that is compact (a ~ 1 ft^2 footprint vs. >10 ft^2 footprint for "conventional" units) and assembled entirely from a stack of YBCO annuli. Results thus far are promising, and FBML expects to meet its goal when this project ends on June 30, 2012. The project is supported by NIBIB.

MgB2 0.5-T/800-mm whole-body MRI magnet: Phase I

The specific aim of this two-phase project, begun on September 30, 2009, is to complete, at the conclusion of Phase II, a whole-body MRI magnet. Using the MgB_2, an HTS, the feasibility of *low-cost*, *liquid-helium-free* magnets, suitable for small hospitals, rural communities, and underdeveloped nations, will be demonstrated. The 0.5-T/800-mm whole-body MRI magnet has the following features that are distinct from "conventional" MRI magnets now widely available in the marketplace: (1) MgB_2 vs. NbTi wire; (2) 10-K vs. 4.2-K operation; and (3) solid nitrogen vs. LHe. A combination of these features makes 10-K operated MgB_2 magnets, even in the absence of liquid helium, at least an order of magnitude more stable than NbTi counterparts against disturbances that still afflict most NbTi MRI magnets, at least when the NbTi MRI magnets are energized for the first time. As with the conventional NbTi MRI magnets, the MgB_2 MRI magnet operates in persistent mode and is fully protected. The project is supported by NIBIB.

During 2010–2011, Dr. Iwasa oversaw one graduate student, who is a master's degree candidate in the Department of Mechanical Engineering, and three undergraduate students as part of the Undergraduate Research Opportunities Program (UROP).

Alan Jasanoff

In 2010–2011, professor Alan Jasanoff was promoted to associate professor with tenure.

The laboratory published several significant studies, including a paper on boosting efficiency of MRI contrast agents. Additional research highlights included development of a novel MRI serotonin sensor and completion of a study on reward processing in rodent brains.

Jagadeesh Moodera

Dr. Jagadeesh Moodera was appointed senior research scientist by the Department of Physics; his research effort is in nanoscience condensed matter physics, through collaborations with various universities and industries and with funding from ONR, NSF, and the Korean government (via KIST). Recently, he has focused on two-dimensional and interface-induced effects at the molecular level, emphasizing graphene, topological insulators, and organic semiconductors—currently three of the most significant topics in his field. His group investigates nanostructures for spin injection studies in these novel systems. He has also continued mentoring graduate students, undergraduates, and high school students by providing research opportunities in his lab. Karthik Raman, one of his graduate students, successfully defended his PhD thesis in materials science and engineering and will be joining the IBM Research Division in Bangalore, India, as a visiting research scientist. Guoxing Miao, a research staff member, joined the University of Waterloo (Canada) as a research professor. Seven visiting diploma and graduate students from Europe, along with two visiting scientists, took part in research during the past year, and a large group of physics majors from Nijmegen University in the Netherlands visited and spent a half-day with Dr. Moodera's group to learn about the state-of-the-art research activities conducted at MIT. (FBML was one of only three research sites in the country chosen for this activity.) Dr. Moodera also completed the final phase of the long-term collaborative project on nanospintronics with Korea (the KIST-MIT Research Laboratory). The highly competitive and prestigious Partner University Fund grant from the French Embassy is in its second year of collaboration with CEA Saclay (France), with a provision for exchange of students and scientists. Dr. Moodera's group published several articles in journals such as *Nature Materials*, as well as reviews and book chapters; received many invited talks, seminars, and colloquium invitations; and filed a patent application. The University of Waterloo/Institute of Quantum Computation, in Canada, appointed Dr. Moodera as a distinguished visiting scientist/professor, and he was appointed as a distinguished visiting professor by the physics department in the Indian Institute of Technology.

In nanoscience condensed matter physics, and in particular in magnetism and superconductivity, the research of Dr. Moodera's group continues to make significant contributions to both fundamental science and industrial applications. The group's basic investigations emphasize spin transport in two-dimensional nanostructures (spintronics), including graphene, topological insulators, and organic semiconductors. Using its molecular beam epitaxy system, the group 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. The group's past research in the structure of these materials has been further developed by various companies such as IBM, Motorola, Seagate, TDK, and Fujitsu for application in digital storage. These companies have introduced into the market mini- and micro-disc drives with unprecedented capacity and read head sensors based on magnetic tunnel junctions. Another important area of application involves 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 has introduced the MRAM chips into the market. In this context, Dr. Moodera's group is continuing national and international collaborative research efforts with scientists and faculty from national laboratories and universities, including the University of Eindhoven and the University of Twente in the Netherlands; the University of Göttingen in Germany; Centre national de la recherche scientifique (CNRS), CEA Saclay, and the University of Paris, all in France; KIST and Ewha University in South Korea; Tohoku University in Japan; the University of California, Los Angeles; and the Institute of Physics in India. Exchange of scientists and graduate students is part of this program.

Dr. Moodera is technical advisor to a company developing MRAM chips and is currently collaborating with another company to develop directional sensors and detectors. He is engaged in an ongoing collaboration with scientists from Lincoln Laboratory, in the field of topological insulators. Collaborations are also in place with two faculty members in the physics department; together, they have obtained the Initiative Research Grant from the MIT Center for Materials Science and Engineering to explore topological insulators.

Dr. Moodera's group has research programs in the fields of nanoscience for single-spin transistors as well as the materials aspect of quantum computing. In a parallel approach, it is investigating injecting spins into 2D electron gas semiconductors to create spin field effect transistors. It is also focusing on a new approach to read Q-bit information using quantum dot structure and the spin filter method.

Another recent area of research in which the group is leading is spin transport studies in organic semiconductors, with the future goal of producing mechanically flexible, cheap, and highly efficient spin-based multifunctional devices for bottom-up electronics. Very unique interfacial phenomenon has been observed between an organic compound and a ferromagnet, and this appears to open up an entirely newer field of creating tailored molecular-level devices.

Seven postdoctoral scholars, visiting scientists, graduate students, undergraduates (UROP), and several high school students have taken part in Dr. Moodera's research. The high school students have won several science competitions, and some of these students have joined the MIT undergraduate program. Seven diploma students from Europe carried out research under Dr. Moodera's supervision for several months, resulting in stronger European collaborations.

Dr. Moodera continues his collaboration with Eindhoven Technical University as a visiting professor; is an expert advisor for a spin-related national nanotechnology program in the Netherlands and at KIST; has taken part in national-level magnetism committee policies and meeting initiatives; and serves on the scientific boards of international meetings. He is a review panel member for NSF's Partnership for Research and Education in Materials, a multidisciplinary educational activity of the W. M. Keck Computational Materials Theory Center at California State University, Northridge, and the Princeton Center for Complex Materials at Princeton University. Dr. Moodera was invited to be part of an international review board to set scientific orientations and objectives on nanosciences at the frontiers of nanoelectronics by CNRS, in France.

Richard Temkin

Dr. Temkin's research on millimeter wave and terahertz gyrotrons for EPR and DNP/NMR is continuing with support from NIBIB. The goal is the development of stable sources that produce 10–50W of continuous power, or up to 1 kW of pulsed power at frequencies of 140 to more than 600 GHz. In 2010–2011, the testing and installation of the MIT 330 GHz tunable gyrotron was completed. A four-meter transmission line was constructed to bring the power from the gyrotron to the 500 MHz NMR magnet. The loss on the transmission line was measured to be very low, about 1% per meter. The MIT 460 GHz gyrotron oscillator was moved from the gyrotron test lab to the 700 MHz NMR laboratory and installed. Up to 20W of power has been generated in a high quality beam at 460 GHz with low transmission loss to the 700 MHz NMR probe. Work has begun on the next phase of the research program on CW gyrotrons, namely design and fabrication of a 20W 527 GHz gyrotron oscillator.

Research continued in 2010–2011 on pulsed, 1 kW power level gyrotron amplifiers at 140 and 250 GHz. At 140 GHz, a new gain structure has been built and is undergoing low-power microwave testing; the goal is to produce higher gain and bandwidth than was available in an earlier design. A 250 GHz gyrotron amplifier has been designed and is being fabricated. The 9.6T magnet for this gyrotron was delivered to MIT and successfully tested to full field without quenching. The electron gun has been designed and is being fabricated by CPI, Inc. of Palo Alto, CA. When successfully constructed, this will be the highest frequency gyrotron amplifier in the world.

Robert G. Griffin
Director
Professor of Chemistry