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 University) continue to operate the MIT/Harvard Center for Magnetic Resonance (CMR), a collaborative research effort between MIT and Harvard Medical School (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. This past year saw the installation of a 9 GHz pulsed EPR that has been used by several faculty members and the addition of the first of two 800 MHz NMR spectrometers. The spectrometer, designed for solution NMR, is used primarily by Professor Wagner and his collaborators from HMS. A second 800 MHz magnet for solid state NMR will be installed in January, pending completion of several building renovations. Space renovations for these instruments were jointly financed by MIT and HMS.

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.

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

Senior staff scientist Dr. 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 his mentoring of graduate students, undergraduates, and high school students by providing research opportunities within 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 recent breakthrough work has attracted media attention in publications such as MIT's *Tech Talk*, *Technology Review*, *Electronic Design*, *IEEE Spectrum*, the *Hindustan Times*, and *The Times of India*.

Dr. 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. We anticipate 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, and the annual cost of caring for these individuals is $172 billion. Thus, amyloidosis is a major health problem in this 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 $\mathrm{TTR}_{105\text{-}115}$ 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

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, 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 (approximately three weeks). The results of these efforts appeared in a recent article in the *Proceedings of the National Academy of Sciences*. Specifically, we obtained excellent spectra of bacteriorhodopsin (bR) and were able to differentiate functional from shunt states. The increased signal-to-noise ratio available from DNP is essential for the experiments. In addition, we have developed a laser melting experiment, temperature jump DNP, that yields approximately 150 percent to 400 percent increased sensitivity for solution NMR experiments and has recorded the initial 2D ^{13}C-^{13}C spectrum with an enhancement of roughly 150. We also have a collaborative program with professor Tim Swager of the 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. We have also begun to use metal ions 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, we have added an NMR console to the spectrometer so that we can perform pulsed DNP experiments. 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

The Center for Magnetic Resonance has completed its 35th year of operation as a facility providing scientists with access to high-field NMR equipment including a 700, two 750s, and a 900 MHz instrument. The collection of instruments operates as part of CMR and will be available to investigators at MIT, Harvard, and other universities and companies. The arrival of two 800 MHz instruments meets the growing demand for high-field NMR spectrometer time.

Yukikazu Iwasa

During the period July 1, 2009, through June 30, 2010, the Magnet Technology Division was involved in three NIH-supported programs on NMR and MRI magnets; one project on design and operational issues for high-temperature superconducting (HTS) power devices under DAPAS, a Korean government research program whose goal is to develop HTS-based electric power devices such as transformers, motors, and fault-current limiters; and one project, supported by the General Electric Global Research Center (Niskayuna, NY), to develop a technique to make superconducting joints with reacted multifilamentary MgB_2 wires. These projects are briefly summarized below.

NIH-Supported Programs

HTS Insert Coil for 1.3 GHz NMR Magnet: Phase 3A

The main goals of Phase 3A of this 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 the 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 the 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, as a means of minimizing the 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

During this reporting period, we completed the winding of both HTS coils. The project is supported jointly by the National Center for Research Resources, the National Institute of Biomedical Imaging and Bioengineering, and the National Institute of General Medical Sciences.

Compact, Neon/Cryocooled NMR Magnets Assembled from Superconducting YBCO Annuli

Although the official title of this project is the one listed above, it is a misnomer; the project should really be called “Compact NMR Magnets Assembled from Superconducting YBCO Annuli,” because a prototype to be completed by June 30, 2011, will be cooled by a combination of solid nitrogen and liquid helium and operate in the range from 4.2 K to 10 K. The main goal of the project is to assemble a “miniature” 100–200 MHz NMR magnet from a stack of YBCO annuli and thereby demonstrate the feasibility of manufacturing, in the subsequent continuation program, a 500 MHz NMR magnet that is compact (a footprint of approximately 1 square foot vs. more than 10 square feet for “conventional” units) and assembled entirely from YBCO annuli. Results thus far are promising, and we expect to have met our goal when this project ends on June 30, 2011. The project is supported by the National Institute of Biomedical Imaging and Bioengineering.

MgB_2 0.5 T/800-mm Whole-Body MRI Magnet: Phase 1

The specific aim of this two-phase project, initiated on September 30, 2009, is to complete, at the conclusion of Phase 2, a whole-body MRI magnet. Using the MgB_2, a high-temperature superconductor, we will demonstrate the feasibility of low-cost, liquid-helium-free magnets suitable for small hospitals, rural communities, and underdeveloped nations. Our 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: MgB_2 versus NbTi wires, 10 K versus 4.2 K operation, and solid nitrogen versus LHe. As a result of this combination of features, MgB_2 magnets operated at 10 K are (even in the absence of liquid helium) at least an order of magnitude more stable than their NbTi counterparts against the disturbances that still afflict most of these magnets (at least when NbTi MRI magnets are energized for the first time). As with the conventional NbTi MRI magnets, our MgB_2 MRI magnet operates in persistent mode and is fully protected. The project is supported by the National Institute of Biomedical Imaging and Bioengineering.

DAPAS Program

In September 2008, under the sponsorship of Korea Polytechnic University, we began a three-year project to study design and operational issues for HTS power devices as part of the DAPAS program; the start date in Korea was April 2008. The project focuses on AC losses, conductor design, and stability and protection for HTS power devices. SuNAM, a private company in Korea, became the program's sponsor in April 2009 (year 2).

GE Program

We have initiated a one-year program, sponsored by the GE Global Research Center in Niskayuna, NY, in an effort to develop superconducting joints between unreacted multifilamentary MgB_2 wires and reacted multifilamentary MgB_2 wires. Partly because the manufacturer of multifilamentary MgB_2 wires, Hyper Tech Research (Columbus, OH), changed the wire configuration late last year from the design that worked well with our splicing technique, we have yet to develop the technique required by GE.

Alan Jasanoff

During 2009–2010, Alan Jasanoff's laboratory was awarded substantial new funding from NIH and other sources. Professor Jasanoff became an associate editor of the journal *ACS Chemical Neuroscience*. Research highlights included publication of a paper demonstrating in vivo detection of neurotransmitter release using an engineered MRI dopamine sensor. This work, the first example of molecular-level neural activity monitoring using an MRI probe, was widely reported in secondary sources. The laboratory also published significant studies relating to detection of gene expression and application of cell-permeable probes for noninvasive molecular imaging in the brain.

Jagadeesh S. Moodera

Dr. Jagadeesh Moodera has continued research efforts in nanoscience condensed matter physics through collaborations with various universities and industries and with funding from ONR, NSF, the Defense Advanced Research Projects Agency, and the Korean government (via KIST). A newly acquired (through an ONR grant) scanning electron microscope with full capability has allowed his group to produce nanostructures for spin injection studies in novel systems. He has also continued his mentoring of graduate students, undergraduates, and high school students by providing research opportunities within his lab. One of his graduate students (Marc van Veen Huizen) successfully defended his PhD thesis in physics and has joined Intel Corporation as a research engineer. Another PhD student (Karthik Venkataraman) was invited to give a talk at the March meeting of the American Physical Society for a special symposium. Seven visiting diploma and graduate students from Europe, along with two visiting scientists, took part in research during the past year. Dr. Moodera also successfully continued the long-term collaborative project on nanospintronics with Korea (the KIST-MIT Research Laboratory, funded by the Korean government), and the second three-year phase was secured. A highly competitive and prestigious Partner University Fund grant from the French Embassy was obtained for a new three-year 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 *Physical Review Letters*, *Nature Materials*, and *Nature Nanotechnology*, as well as four reviews and book chapters. In addition, the group received more than 20 invited talk, seminar, and colloquium invitations over the past year. A patent was issued, and two patent applications are in the process.

Research Activities

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

Their basic investigations emphasize spin transport in thin film nanostructures (spintronics), specifically in semiconductors, including organic semiconductors. Using their molecular beam epitaxy system, their 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. Their 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. In fact, 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 Twente University in the Netherlands; the University of Göttingen in Germany; CNRS, CEA, and the University of Paris 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 collaborating with another company to develop terahertz radiation sources and detectors.

He and his group have successfully developed a research program in the new superconductor (MgB_2) science and technology for Josephson junctions that have a potential for hybrid superconducting electronics in areas such as computers, logic elements, mixers, switches, and sensors. They intend to start a new collaboration with the Department of Electrical Engineering and Computer Science (EECS) to develop

Josephson junction-based ultrafast circuitry that is useful for the Navy. There is an ongoing collaboration with scientists from Lincoln Laboratory as well.

The 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, they are investigating injecting spins into 2D electron gas semiconductors to create spin field effect transistors. They are 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. They are involved in an ongoing collaboration with another group in EECS after their initial success in this area.

Seven postdoctoral scholars, three visiting scientists, three graduate students, three undergraduates, 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. Four 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 in the Netherlands as a visiting professor. He is an expert advisor for a spin-related national nanotechnology program in the Netherlands and at KIST. He has taken part in national-level magnetism committee policies and meeting initiatives, as well as serving on the scientific boards of international meetings. For example, 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 J. Temkin

Dr. Temkin's research on millimeter wave and terahertz gyrotrons for EPR and DNP/NMR is continuing with support from the National Institute of Biomedical Imaging and Bioengineering. The goal is the development of stable sources that produce 10 to 50 watts of continuous power or up to 1 kW of pulsed power at frequencies of 140 to more than 600 GHz. In 2009–2010, the 330 GHz tunable gyrotron was completed and tested. Initial results were obtained with an available cryomagnetics magnet; results were improved with the new Bruker magnet. In continuous wave operation, an output power of 18 watts was obtained with a 10 kV, 200 mA electron beam. More than 5 watts of power could be obtained over a tuning range exceeding 700 MHz and more than 1 watt over a 1.2 GHz tuning range. With higher beam power, at 7 to 13 kV and up to 600 mA, in pulsed mode, more than 1.2 GHz of tuning could be achieved with a minimum of 21 watts of output power.

A 140 GHz gyrotron amplifier was tested with input pulses as short as 400 picoseconds. To our knowledge, this is the first observation of picosecond pulse amplification in a vacuum electron device. The pulses show measurable broadening due to two distinct phenomena: group velocity dispersion and spectral narrowing resulting from the finite gain bandwidth of 1.2 GHz. Experimental results over a wide range of parameters showed good agreement with a theoretical model in the small signal gain regime. These results indicate that, in order to limit the pulse-broadening effect in gyrotron amplifiers, it is crucial to both choose an operating frequency at least several percent above the cutoff of the waveguide circuit and operate at the center of the gain spectrum with sufficient gain bandwidth. In 2009–2010, initial work began on rebuilding both the 250 and 460 GHz gyrotron oscillators. This work should be completed late in 2010.

Robert G. Griffin
Director
Professor of Chemistry

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