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 20 NMR and two EPR magnets and spectrometers. FBML is leading the US effort in the production of the next generation of high-field NMR spectrometers, in particular a 1.3 GHz spectrometer assembled from a combination of low- and high-temperature superconductors. We are also pioneering the application of high-frequency microwave sources via gyrotron oscillators and amplifiers to magnetic resonance. Finally, we are hosting an outstanding program in spintronics.

Highlights of 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 P41 grant and has been funded continuously since 1976; a grant renewal application was submitted to continue operations until May 2019. The past year saw significant improvements in the pulsed 140 GHz machine which has been used by several faculty members from MIT and HMS. In addition, the second of two 800 MHz NMR spectrometers was installed. The instrument, designed for solid state NMR, is supervised by Professor Griffin and used by his group and collaborators. Space renovations for these instruments were jointly financed by MIT and HMS. In addition, FBML published the initial results for the 700 MHz/460 GHz dynamic nuclear polarization (DNP) spectrometer.

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. 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.

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 mentoring graduate students, undergraduates, and high school students by providing research opportunities in his lab.

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 DNP/NMR experiments. Two amplifiers (140 and 250 GHz) are being designed and constructed, and the NIH grant supporting this work was renewed for four years.

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 30 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.

During the last few years Professor Griffin and his group, working with professor Susan Lindquist of the Whitehead Institute for Biomedical Research, have developed methods to prepare large amounts of Aβ and 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 $TTR_{105\text{-}115}$ derived from transthyretin. Recently completed cryo-electron microscopy experiments will yield a complete structural model for the fibril. In addition, 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 and the ΔN6 variant 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, a highlight of the year was the initial operation of the 700 MHz/ 460 GHz spectrometer during which we obtained an enhancement of –55. With continued improvements, it is anticipated that enhancements will grow to approximately +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).

High-Frequency Electron Paramagnetic Resonance

An NMR console has been added to the 140 GHz 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

The Center for Magnetic Resonance has completed its 37th year of operation as a facility providing scientists with access to high-field NMR equipment, including two 600s, a 700, two 750s, two 800s, 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 the period July 1, 2012, through June 30, 2013, the Magnet Technology Division, under Dr. Iwasa's leadership, was involved in four NIH-supported programs on NMR and MRI magnets. These projects are briefly summarized below.

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

Work on Phase 3A of this two-phase (3A and 3B) program is proceeding, as follows. To replace the stolen 600 MHz high-temperature superconducting (HTS) insert (H600), we first designed a 700 MHz HTS insert (H700), which will be combined with a to-be-purchased 600 MHz/254-mm cold bore low-temperature superconducting (LTS) NMR magnet (L600). The newly designed H700 consists of a coil wound with gadolinium barium copper oxide (GdBCO) tape and a second coil wound with Bi2223 tape. In December 2012, to further reduce the overall cost of the 1.3 GHz LTS/HTS NMR magnet, we designed a new HTS insert that would operate at 800 MHz and require a 500 MHz LTS magnet (L500). Given that we already own an L500, this combination results in a considerable cost savings. The new H800 comprises three coils, each wound with GdBCO tape, and applies the no-insulation winding technology we are developing. This project is now supported by the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and the National Institute of General Medical Sciences.

Compact, Neon/Cryocooled NMR Magnets 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 yttrium barium copper oxide (YBCO) annuli and thereby demonstrate the feasibility of manufacturing, in the continuation program that follows, 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 a stack of YBCO annuli. The project, which was supported by NIBIB, was successfully completed on June 30, 2013.

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. 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: 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, the MgB_2 MRI magnet operates in persistent mode and is fully protected. Because the technique we use to make superconducting joints has proven quite unreliable with unreacted multifilamentary MgB_2 wires but very reliable with monofilament wires, and because our MgB_2 wire supplier, Hyper Tech Research (Columbus, OH), manufactures 3-km-long wire that is reliable only up to 300 m, we have decided to complete a scaled-down MRI magnet (still comprising eight coils) of 240-mm room-temperature bore with a monofilament MgB_2 wire and each coil requiring a MgB_2 wire length of 300 m. Our small-scale measurements of MgB_2 (0.4-mm filament size) have demonstrated that the monofilament wire is free of flux jumping, which was in the past the major cause of premature quenches in monofilament NbTi wire. This project is supported by NIBIB.

1.5 T Superconducting Solenoid Dipole for Slow Magic Angle NMR: Phase 1

Phase 1 of this project has two specific aims. The first is to build a superconducting magnet system comprising an axial-field solenoid and an x-y plane dipole whose combined magic angle field (MAF) is of NMR quality and 1.5 T points at an angle of 54.74^o (magic angle) from its spinning (z) axis. The second is to demonstrate an innovative cryogenic system for a rotating low-temperature cryostat that houses this superconducting MAF magnet. The first phase of the program began on September 1, 2011, and is scheduled to end on August 31, 2014. The project is supported by NIBIB.

During 2012–2013, Dr. Iwasa oversaw one graduate student, who is a PhD degree candidate in the Department of Mechanical Engineering, and three undergraduate students as part of the Undergraduate Research Opportunities Program.

Jagadeesh Moodera

Dr. Moodera is a senior research scientist in the Department of Physics; his research efforts focus on nanoscience condensed matter physics, with funding from ONR and NSF. Recently, he and professor Patrick Lee were awarded a prestigious John Templeton Foundation research grant. He is part of the large NSF-funded Center for Integrated Quantum Materials program, a collaboration involving MIT, Harvard, Howard University, and the Boston Museum of Science. In addition, Dr. Moodera has collaborations with various universities in the United States, Canada, Europe, India, and Korea.

Currently he focuses on two-dimensional quantum coherent materials and interface-induced effects at the molecular level, emphasizing graphene, topological insulators, and organic semiconductors—some of the most significant topics in his field. His group investigates nanostructures for spin transport studies in these novel systems as well as searching for Majorana fermions.

As noted, Dr. Moodera continues to mentor graduate students, undergraduates, and high school students. In addition, as one of the highlights of the past year, he hosted 20 kindergarten students from a local school for half a day of hands-on science, showing them some exciting science experiments. Karthik Raman, one of his recent graduate students, has been hired as a faculty member at the prestigious Indian Institute of Science after a two-year stay at the IBM Research Division in Bangalore, India. Two visiting diploma and graduate students from Europe, along with two visiting scientists, took part in research during the past year. The highly competitive Partner University Fund grant from the French Embassy—part of a collaboration with CEA Saclay (France)—is in its third year, with a provision for exchange of students and scientists.

Dr. Moodera's group published several articles in journals such as *Nature*, as well as reviews and book chapters, and received many seminar and colloquium invitations. The group's *Nature* publication titled "Towards Molecular Spintronics" garnered huge national and international press coverage, including coverage on the MIT website's front page. Dr. Moodera continues his appointment as a distinguished visiting scientist/professor at Canada's University of Waterloo/Institute of Quantum Computation, and he was appointed as a distinguished institute professor by the Physics Department at the Indian Institute of Technology. He was also appointed as a distinguished foreign scientist at the National Physical Laboratory in New Delhi.

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. 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 (MBE) 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. Dr. Moodera will be building an extremely versatile conglomerate MBE system for studying combinations of quantum materials, which should lead to new discoveries and open up many technological possibilities. The group's past research on 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 elements as well as reprogrammable logic circuits that will potentially have a significant and highly profitable impact on memory technology.

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 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. Collaborations are also in place with two faculty members in the Department of Physics to explore topological insulators.

Eight postdoctoral scholars, graduate students, and undergraduates, as well as four 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.

Dr. Moodera continues as a visiting professor at Eindhoven Technical University. In addition, 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 and serves on the scientific boards of international meetings. He is a review panel member of 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 10–50 watts of continuous power at 527 GHz or up to 1 kW of pulsed power at frequencies of 140 to more than 600 GHz. The MIT 460 GHz gyrotron oscillator was moved from the gyrotron test lab to the 700 MHz NMR laboratory and installed. Up to 20 watts of power have been generated in a high-quality beam at 460 GHz with low transmission loss to the 700 MHz NMR probe. The gyrotron was successfully employed in DNP/NMR experiments at 700 MHz. This is the highest frequency operational DNP/NMR system in the world. Work is continuing on the development of the next phase of the DNP/NMR research program, namely its extension to 527 GHz/800 MHz. The final design of a 20 watt 527 GHz gyrotron oscillator has been completed, and the cryogen-free 9.7 T gyrotron magnet has been delivered. The gyrotron will be built and tested during the coming year.

Research continued 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 now undergoing high-power microwave testing; the goal is to produce higher gain and bandwidth than previously available. A 250 GHz gyrotron amplifier has been fabricated and tested. Output power of up to 45 watts has been achieved with over 50 decibels of gain. This is the highest frequency gyrotron amplifier in the world.

Robert G. Griffin
Director
Professor of Chemistry