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 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. They have nearly completed the construction of a simple quantum information processor based on NMR and will start exploring this approach experimentally in the fall. 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. This grant was renewed this past year and is presently scheduled to continue until May 2014. In the coming year, the facility will expand with the addition of two 800 MHz NMR spectrometers for liquids and solids and a 9 GHz pulsed EPR.

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-coated conductors. These projects are briefly summarized below.

Professor Alan Jasanoff of NSE and the Department of Brain and Cognitive Sciences (BCS) 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 extensive 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. Moodera was nominated for the International Magnetism Award (given triennially by the International Union of Pure and Applied Physics) for outstanding research breakthroughs. He has also been nominated for the Oliver E. Buckley Prize of the American Physical Society for outstanding research in condensed matter physics.

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

David G. Cory

Quantum Information Processing

Quantum mechanics provides a fundamentally new approach enabling us to build devices that exceed the performance of any possible classical device. Quantum mechanics pushes the fundamental physical limits of information processing: by building quantum sensors, actuators, secure communication channels, and computers, we effectively reach the limits in power and accuracy allowed by the laws of physics. The challenge to utilizing quantum mechanics is to control a large enough system so that the efficiency gains offered by quantum mechanics outweigh the technical challenges. Professor Cory and his colleagues have demonstrated control over quantum devices that are so large that they cannot be simulated classically. They are working to turn these quantum systems into practical quantum devices. The program has two stages. The first is directed at laboratory scale devices for characterizing and controlling magnetization, transport, and chemistry. These will enable the advance of nano- and quantum-technology. The second stage aims to construct devices that can operate outside of the laboratory and yet still demonstrate the efficiencies achieved uniquely through quantum mechanics. Professor Cory and his students approach quantum information processing through collaborations with Dr. Chandrasekhar Ramanathan (NSE), professor Seth Lloyd (Department of Mechanical Engineering), Dr. Will Oliver (Lincoln Laboratory), Dr. Mohamed Arif (NIST), professor Mikhail Lukin (Harvard University), Dr. Paola Cappellaro (Harvard University), professor Lorenza Viola (Dartmouth College), and professor Raymond Laflamme, professor X.W. Tang, professor Jonathan Baugh, and Dr. Joseph Emerson (all at the University of Waterloo). A few of the highlights of the last year are described below.

Cecilia Lopez has developed a unifying description of approaches to efficient error finding. A challenge in quantum computing is that achieving fault tolerance requires some knowledge of the error model. Since the number of terms in a generic error model grows exponentially with the number of qubits, directly measuring all possible errors is not an option. The efficient error finding schemes that have been developed through collaborations between MIT and Waterloo parameterize reasonable physically relevant models from a polynomial number of measurements.

Troy Bornamann has taken a different approach to dealing with errors. He has demonstrated a quantum code that protects coherent information even in the presence of large experimental errors in implementing the code. He is now working to demonstrate this experimentally.

Dr. Ramanathan has reported on a series of experiments that use NMR to simulate multibody dynamics. One of his findings showed that even in a dipolar coupled spin chain, information can be efficiently transported. Applications include using spin chains as channels for quantum information and creating highly polarized spin systems as potential transducers.

Dr. Jonathan Hodges has implemented a new series of optically detected magnetic resonance experiments based on the nitrogen/vacancy defect in diamond. He has demonstrated that quantum information can be manipulated between electron and nuclear spins and that the contrast of electron spin readouts can be improved by considering nuclear spins as a quantum resource. This work is in collaboration with Professor Lukin's laboratory at Harvard.

Fei Yan has started a project to use optimal control theory to improve coherent control over persistent current flux qubits patterned from superconductors. In a collaboration with Dr. Will Oliver and professor Terry Orlando, they have used enhanced control to obtain an improved model of noise, which presently limits the applications of superconducting quantum systems.

Clarice Aiello and Mohamed Abutaleb have continued to develop pulsed electron spin resonance as a test bed for coherent control of quantum information. They have developed new instrumentation to enable studies at cryogenic temperatures with optimal control pulses and demonstrated a new approach to control where there is a finite bandwidth on control parameters.

Kevin Kruslich has initiated a study to directly observe spin injection into superconductors via magnetic resonance. He has implemented NMR studies at controlled cryogenic temperatures and demonstrated that he can develop control methods that work in metallic samples. Note that this is an extreme situation since the skin depth of metals dictates that the necessary radio-frequency fields drop off exponentially as they move into the sample.

Sarah Sheldon has developed the theory, numerical simulations, and experiments to extend the liquid state NMR test bed to decoherent processes. She has demonstrated the loss of information associated with the Overhuaser enhancement and has developed means of controlling it.

Dr. Dimitri Pushin is building the new neutron interferometer geometry that he described last year. This novel approach employs quantum error correction to suppress noise from vibrations (which is the greatest experimental challenge to using neutron interferometry). We anticipate that this improvement will permit broader applications of neutron interferometry and enable communities of condensed matter scientists and biochemists to access the instrument.

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. 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.

During the last few years, Professor Griffin and his group 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 $TTR_{105\text{-}115}$ 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. Just completed cryo-electron microscopy experiments will yield a complete structural model for the fibril. Finally, they have made significant progress toward assigning the spectrum of the SH-3 domain of the proteins phophatidylinostol-3-kinase (PI3-SH3) and β2m, the protein associated with dialysis-related amyloidosis.

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, called temperature jump DNP, that yields approximately 150–400% increased sensitivity for solution NMR experiments and has recorded the initial 2D ^{13}C-^{13}C spectrum with an enhancement of approximately 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.

High-Frequency Electron Paramagnetic Resonance

Using the 140 GHz spectrometer and 9 GHz spectra, Professor Griffin's group is studying the inhibition mechanism of ribonucleotide reductase. For the latest version of these experiments, they have constructed a rapid freeze-quench apparatus that will trap intermediates on a microsecond-to-millisecond timescale. They are also performing extensive EPR studies of biradicals that will serve as polarizing agents for DNP experiments. In addition, they have used the 140 GHz spectrometer in experiments to determine the structure of biradicals. They will also take delivery of a 9 GHz pulse spectrometer that will become part of CMR in late August 2009.

Center for Magnetic Resonance

The Center for Magnetic Resonance has completed its 34th 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. In addition, CMR has purchased two 800 MHz instruments to meet the growing demand for NMR spectrometer time.

Yukikazu Iwasa

During the period July 1, 2007, through June 30, 2009, the Magnet Technology Division was involved in four NIH-funded programs on NMR and MRI magnets and one project on design and operational issues in 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. These projects are briefly summarized below.

NIH-Supported Programs

HTS Insert Coil for 1.3 GHz NMR Magnet

Our three-phase NMR magnet project, comprising a low-temperature superconducting (LTS) background magnet and an HTS insert, was initiated in 2000; its ultimate frequency goal, to be achieved at the end of Phase 3, was 1 GHz. In 2007 this ultimate goal was upgraded to 1.3 GHz, and Phase 3 was split into Phase 3A and Phase 3B. In Phase 3A, which began in August 1, 2008, the goal was to complete a 600 MHz HTS insert to be operated in the bore of a 500 MHz LTS magnet available in the Magnet Technology Division. Thus, at the conclusion of Phase 3A (2012), we expect to achieve a combined total field of 1.1 GHz, corresponding to a central field of 25.84 T. In Phase 3B, this 600 MHz HTS insert will be combined with a 700 MHz LTS-based magnet (to be purchased during Phase 3B) to achieve the ultimate goal. Because of the large sum of funds required to complete both Phases 3A and 3B, beginning in Phase 3A the National

Institute of Biomedical Imaging and Bioengineering (NIBIB) and the National Institute of General Medical Sciences joined the National Center for Research Resources, the original sponsor that has been supporting this program since 2000.

Digital Flux Injector (Flux Pump) for NMR Superconducting Magnets

The goal of this program is completion of a digital flux injector to be coupled with the HTS insert of our 1.3 GHz LTS/HTS NMR magnet. The program is expected to end in August 2009.

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 an MgB2 composite conductor and an innovative cryogenic design/operation concept specifically targeted for use in small hospitals, rural communities, and underdeveloped nations. We achieved the original goal, and the program ended on August 31, 2008. The notable achievement was our successful development of a technique to construct superconducting splices with unreacted, multifilamentary MgB2 wires, making it possible to build persistent-mode MgB2 magnets. As a continuation of this program, we submitted to NIH in March 2009 a proposal to build a liquid-helium-free, persistent-mode, fully protected 0.5 T/800-mm whole-body MRI magnet; the result of the NIH panel review in June 2009 was excellent, and we expect NIBIB to fund this MgB2 whole-body MRI magnet project in early 2010.

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

The specific aims of this project were to apply a new design/operation concept for MRI superconducting magnets that enables these magnets to achieve operational features that in some respect resemble those of low-field permanent-magnet 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 program ended in March 2009. In Phase 3A of the magnet project, this 500 MHz NMR magnet will be used to achieve the goal of 1.1 GHz.

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).

Alan Jasanoff

In 2008, Professor Jasanoff gave the Issekutz Memorial Lecture at Dalhousie University and organized a session on molecular imaging at the American Chemical Society annual meeting, among other professional activities. He codeveloped a new course, 9.472J Neuroimaging Cells and Circuits, which had a successful debut in the fall 2008 semester.

Research highlights included publication of an article on a new genetically encoded MRI sensor for kinase activity and demonstration of in vivo sensing by a novel engineered protein sensor for neurotransmitter release in intact animals.

Jagadeesh S. Moodera

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; the Centre national de la recherche scientifique (CNRS), the Commissariat à l'énergie atomique, and the University of Paris in France; Tohoku University in Japan; KIST and Ewha University in South Korea; 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 structures 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.

The group's research resulted in several articles (published in journals such as *Physical Review Letters*, *Nature Materials*, and *Nature Nanotechnology*), reviews, book chapters, and invited talks at various national and international conferences and universities. Four patent applications have been filed.

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.

Research Highlights

Dr. Moodera is involved in 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). His group has acquired a scanning electron microscope (through an ONR grant) with full capability and begun producing nanostructures for spin injection studies. He has also continued his mentoring of graduate students, undergraduates, and high school students by providing research opportunities within his lab. His most recent PhD student (Tiffany Santos, 2007), now at Argonne National Lab, was awarded the prestigious L'Oreal Women in Science Fellowship in May 2009. His postdoctoral fellow (Marius Costache) has joined a nanoscience center in Barcelona as a scientist. Dr. Moodera has also successfully carried out the earlier-mentioned long-term collaborative project on nanospintronics with Korea and the second three-year phase was secured.

Dr. Moodera won the 2009 Oliver E. Buckley Award for outstanding research in the field of spintronics, the highest award of the American Physical Society in condensed matter physics. He also was selected as American Competitiveness and Innovation Fellow by NSF (2008–2010) and was cited "for his achievements and world-leading role in the field of spintronics and his dedication to diversity while educating the next generation of scientific and technological leaders of the world." He won the Indian Institute of Technology's highly prestigious Distinguished Alumnus Award in April 2009.

Richard J. Temkin

Dr. Temkin's research on millimeter wave and terahertz gyrotrons for EPR and DNP/NMR is continuing with support from NIH/NIBIB. 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. The 250 GHz gyrotron was rebuilt in 2008–2009 to improve its efficiency and reliability. It is being used for DNP research and has been operated under computer control for periods of weeks at a time. A 140 GHz gyrotron amplifier has achieved a power level of 820 watts and 34 dB of gain with a bandwidth of 1.5 GHz in microsecond pulsed operation. The amplifier will be improved later in 2009 with a new mode converter and interaction structure. A novel 330 GHz gyrotron oscillator with up to 2 GHz of frequency tunability has been designed. A prototype of the gyrotron worked well and the final gyrotron has been built and will be tested in the summer and fall of 2009. A 250 GHz gyroamplifier project was initiated in 2009 and the gyrotron will operate at the second harmonic. The magnet for this gyrotron has been designed and is under procurement, with delivery scheduled for 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/.