Bitter solenoid of dual-coil type requires 8 MW to achieve 23 T in 3-cm bore. Access to the field is through the hole at top. Purified water flows through the magnet at the rate of 1500 gal/min, entering at the manifold to the right. In the foreground are the four pairs of water-cooled cables that supply current up to 39 kA. Figure 1

High magnetic fields for physics

In its first years the National Magnet Laboratory has become the preeminent center for advanced magnet technology and the "Mecca" of visiting experimentalists eager to use the Laboratory's extensive high-field facilities.

Lawrence G. Rubin and Peter A. Wolff

For many years magnetic fields have served as an essential tool of the experimental physicist. For example, in solid-state physics our current understanding of the Fermi surfaces of metals, the band structures of semiconductors, the phases of magnets and the properties of superconductors is in each instance based on observations that involve magnetic fields. Yet, until 25 years ago, the highest dc field available to most scientiists was that provided by iron-cored electromagnets—about 3 T (30 kG) in air gaps of a few centimeters. In 1960 the Francis Bitter National Magnetic Laboratory was established to develop magnetic field facilities beyond 3 T and use them for solid-state physics research. The Magnet Lab was the first center for research on high magnetic fields in the world and remains the focus for such work in the United States.

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Since 1960, the Magnet Lab's role in high-field research has changed significantly. The development of high-field superconductors made possible modestly priced magnets, wound with NbTi wire and operated at 4.2 K, that routinely provide fields to 8 T. Moreover, during the past decade, superconducting magnet performance has been extended to 15 T—and in at least one instance to 17.5 T—as a result of advances in the technology of superconducting materials such as Nb_3Sn and V_3Ga. Thus, in recent years, the Laboratory has emphasized facilities and science in the field range above 15 T.

There is no *easy* way to generate magnetic fields larger than those provided by superconducting magnets.[1] Brute force is required—a large power supply coupled to sturdy electromagnets. At fields above 10 T, thermal and mechanical limits are approached as the levels of power, power density and stress continue to increase with the square of the field. The heat generated by the very high power densities must be removed, which calls for a porous structure to accommodate an efficient cooling system. This requirement conflicts with the need for a strong, hence solid, structure to handle the stresses. One of the most successful solutions to these design problems has been a disk-type solenoid that uses shallow helical windings cooled by purified water. Several dozen such "Bitter solenoids" (see figure 1), patterned after the elegant design of Francis Bitter, are located at the Magnet Lab, on the west campus of the Massachusetts Institute of Technology in Cambridge, Massachusetts. Included in the Laboratory's magnet inventory are four that produce 19–20 T, and three of smaller bore that achieve 22–23 T. These field limits are determined by the existing power supply (10 MW). However, even if more power were available, there would be severe problems in engineering an all-water-cooled magnet to make use of it. Instead the Laboratory's magnet designers have exploited the hybrid-magnet concept, wherein a 22.5-T Bitter solenoid is operated in the 7.5-T background field provided by a superconducting magnet. The resulting 30-T dc magnetic field is the world's highest.[2]

In our overview of the Magnet Lab we will address the following questions:

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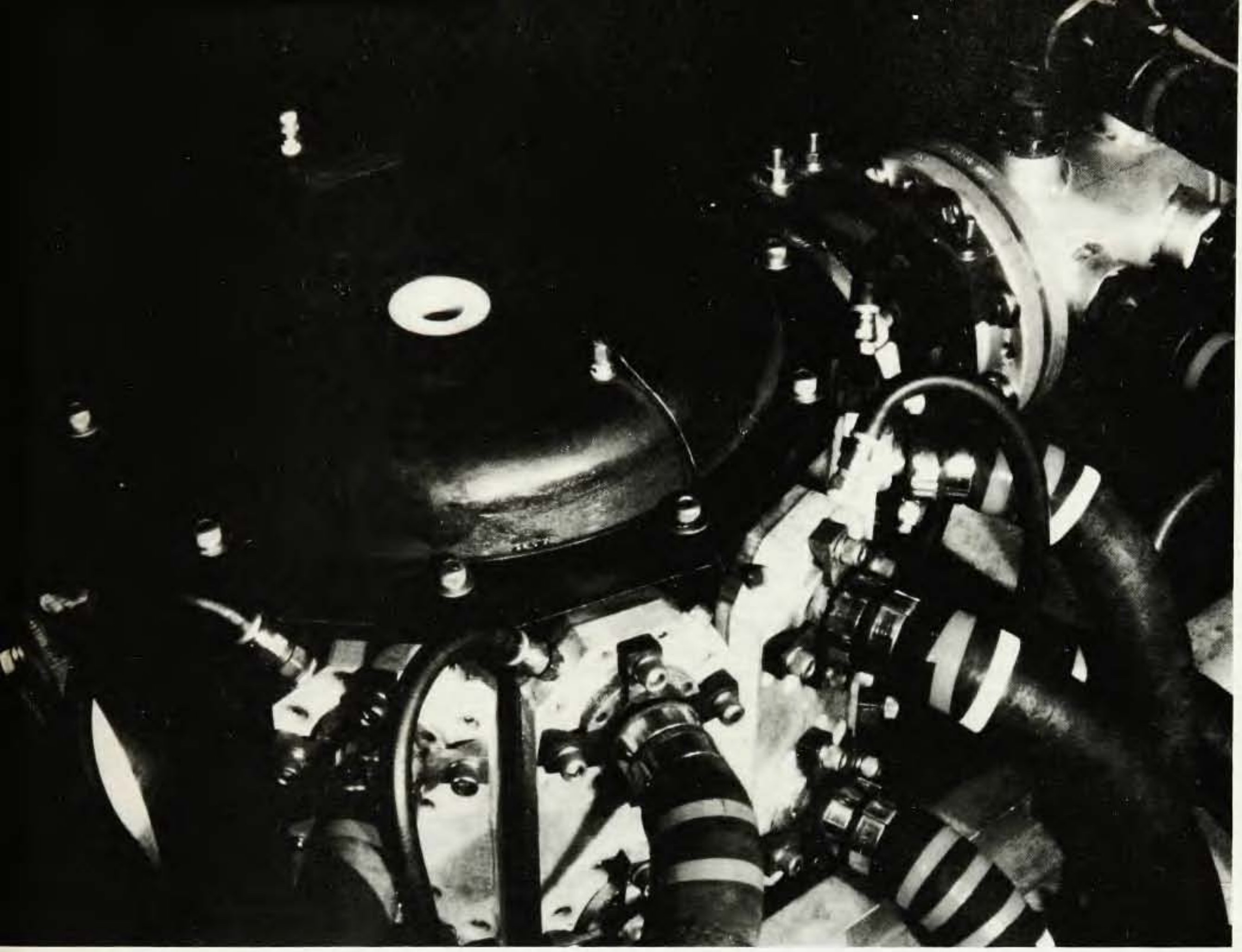


What are the characteristics and capabilities of the magnets at the Magnet Lab? How can researchers gain access to them conveniently and with a minimum of delay? What are the unique features of the Magnet Lab as an operating facility that make it possible to perform unparalleled experiments there? Finally, what are some examples of research programs?

History and background

The National Magnet Laboratory officially came into existence on 1 July 1960, under a contract between MIT and the US Air Force through its Office of Scientific Research. Renovation of a 5-story, 150 000-square-foot building to house the facility was completed in 1963. The location was chosen for its convenient access to electrical power (10 MW continuously available) and cooling water (the Charles River) and for its proximity to the academic–scientific community in the greater Boston area. The formal dedication ceremony, held on 30 April, culminated years of advocacy and planning by the Laboratory's founder and first director, Benjamin Lax. Four years later, the Laboratory was rededicated in honor of the late Francis Bitter. The Laboratory is now directed by Peter A. Wolff, who succeeded Lax on 30 June 1981. Donald T. Stevenson has been the assistant director of the laboratory since its inception.

In 1971, the National Science Foundation assumed sponsorship of the Magnet Lab and continues to provide the primary support for the Laboratory through its Division of Materials Research. NSF support is used to accomplish three specific goals:

▶ the operation and maintenance of the high-magnetic-field facility for the benefit of the broadest possible user community and at no cost to the users (see box, page 27)

▶ the advancement of magnet technology and the development of new high-field magnets for users' research programs

▶ the support of basic research in those scientific areas vital to the generation and use of high magnetic fields.

High-field facility

The principal part of the power supply consists of two identical shafts of rotating machinery. Each includes a 4.6-MW synchronous motor fed from a 4160-V substation, a pair of 240-V dc generators and an 80-ton flywheel to smooth field ripple and store energy to provide pulses for special purposes. Each generator can supply ± 10 kA continuously, ± 11 kA for 2 hours and ± 12 kA for 15 minutes; the overload ratings add significantly to the field range of magnets operated by linearly sweeping the current to its maximum value. The generators may be connected to magnets singly or in parallel. Until 1970, many experiments were profitably run in 2.7-MW Bitter solenoids producing 10-T fields in a 5.4-cm bore; four of them could be run simultaneously, each connected to a single, independently-controlled generator. However, with the increasing use of NbTi superconducting magnets outside the Laboratory, the 10-T Bitters were no longer in demand and so were gradually phased out. The present magnet inventory includes only 5- and 10-MW models; thus fewer experiments are performed, but the average field is higher. Experiments using 5-MW magnets (about half the total) continue to be run in simultaneous pairs.

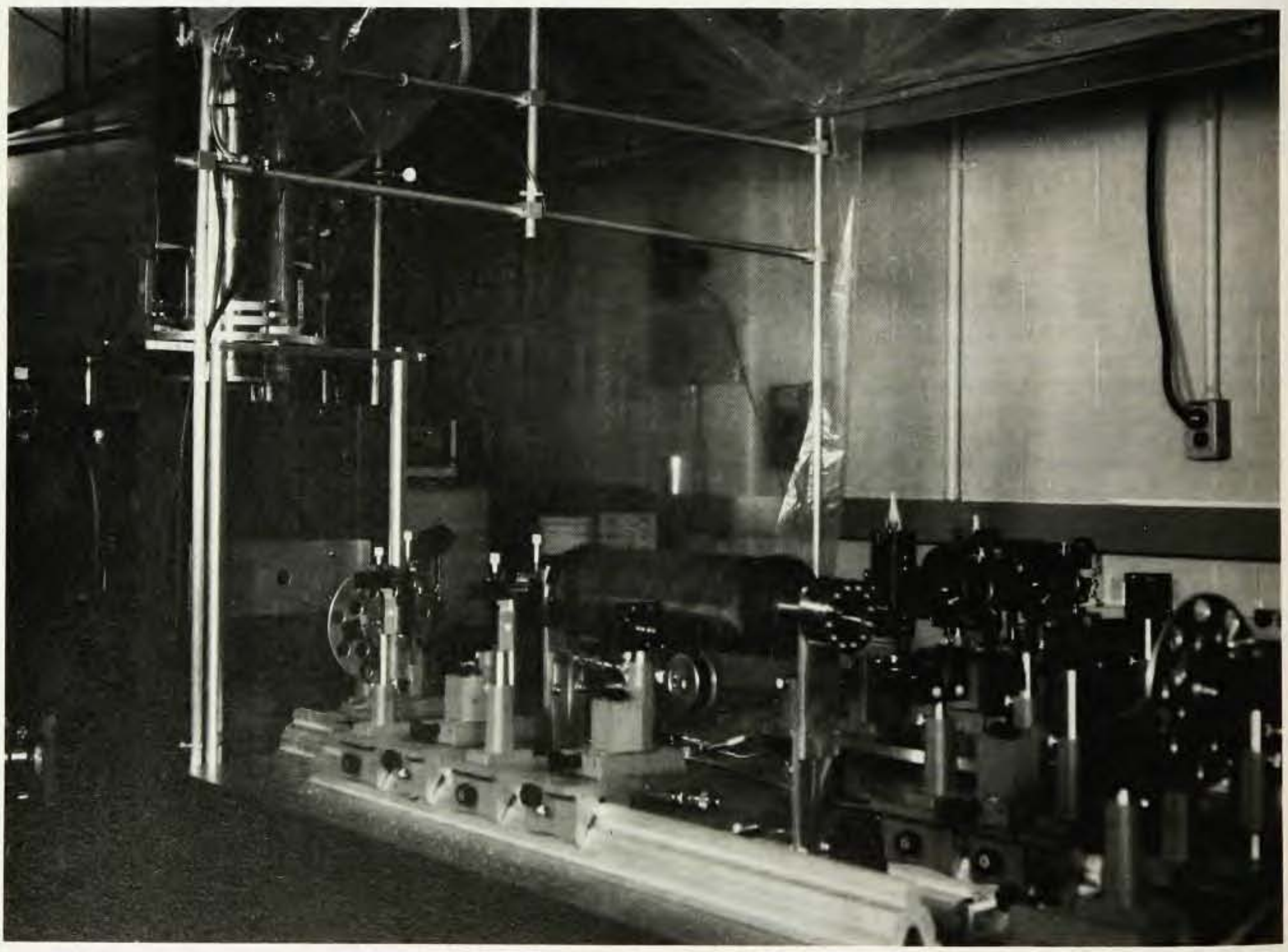
Associated with the motor-generator sets is a complex control system. It provides a current stability of approximately 0.1% peak-to-peak, with a 6-Hz ripple the major noise component. Stability can be increased to a few parts in 10^5 with a localized feedback system that employs a 1.5-kW power amplifier feeding a compensating coil wound directly on the magnet bore tube. The magnet current can be precisely set, or swept smoothly or discontinuously from zero to maximum in as little as one minute or as much as two hours. Narrow-range sweeps superimposed on a dc baseline are also possible, as is sweeping in a positive-zero-negative mode. Field setting and sweep operations are under local control by the user if so desired.

The Bitter magnets are cooled by distilled, deionized water of high resistivity (10^6 Ωcm) circulating in a closed loop, which transfers the heat to water pumped in from the Charles River. Flow is typically 1500 gal/min at a pressure of 14 atm, of which 5 atm is the drop across the magnet. Four 5-cm-diameter flexible fire hoses connect the magnet to its inlet and exit hydrants.

The electrical turns in an axially-cooled Bitter magnet are flat Bitter plates interleaved with insulators to form a shallow helix (see cover). The plates are punched from copper or one of its high strength alloys; the insulators are punched from materials such as fiberglass, Teflon, Kapton and so on. A stack of up to 200 turns is assembled in the Laboratory's magnet shop and mounted in an aluminum housing, typically 60 cm in diameter and 40 cm long, which encloses the stack and provides the connection to the power and the cooling system. There are two important variations in this basic design: one is a magnet in which the cooling water flows radially through channels etched in the Bitter plates; another employs two concentric stacks in series electrically and in parallel hydraulically, in an arrangement that optimizes the distribution of current and stress.

The Laboratory's Bitter magnets include models with 5 bore diameters (3.3, 5.4, 10.5, 14.7 and 24.8 cm), providing a wide range of tradeoffs between bore size and maximum field. Most are designed to maximize the on-axis central field, which decreases quadratically with distance from the center. However, there are several magnets with uniform fields homogeneous to about one part in 10^5; this performance is achieved at a sacrifice of about 7% in central field. There is also a group of magnets with radial (perpendicular to the axis) access—a broad midplane gap through which to view the magnetic center. Because they have been built in 5-MW versions only, their maximum fields are limited to 11 T. For many experiments, this field is more than adequate. The convenience of this configuration, particularly for certain magneto-optical studies, is often an overriding factor (see figure 2). However, a wide variety of optical systems has also been designed for experiments in solenoidal magnets to take advantage of their higher fields.

The Magnet Lab's hybrid magnet system, in operation since early 1981,[3] offers two combinations of field and bore: 30 T in a 3.3 cm bore and 25 T in a 5.4 cm bore with a homogeneity of about one part in 10^5 over a 5-mm sphere. This complex system—consist-



Magneto-optical experiment showing a cryostat sitting in vertical 5-cm bore of Bitter magnet. Beam from light source system at right has perpendicular access to cryostat through hole in aluminum plate. A spectrometer is visible at right rear of magnet.
Figure 2

ing of a 9-MW Bitter insert in a 35-cm bore, 7.5-T superconducting magnet (with 3.5 MJ stored energy), quench protection and liquid helium delivery and recovery apparatus—was developed to meet the need for dc fields higher than those produced by all-water-cooled magnets.

All of the facility's magnets, including the hybrid, can be used in experiments requiring field modulation. Low-frequency (<15 Hz) fields of as much as 0.4 T peak-to-peak are generated by injecting ac control signals into the main current-control system. It is also possible to produce up to 0.1-T ac fields at *any* audio frequency by local modulation in most of the magnets.

Magnetic-field calibrations are performed on a regular basis to assure high accuracy. Errors are maintained below $\pm 0.25\%$ and can be reduced to $\pm 0.1\%$ by calibration at the time of the experiment. Magnetometers used for this purpose include a coil-integrator system and a Hall probe instrument, both of which are checked against an nmr standard.

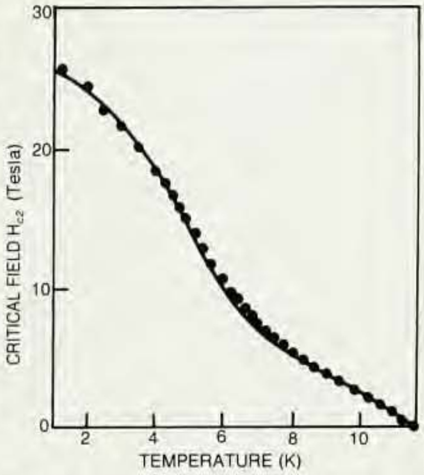
Beginning in September 1983, a new magnet was made available to our user community, namely, a compound $NbTi/Nb_3Sn$ superconducting magnet manufactured by the Intermagnetics General Corporation. The decision to incorporate this magnet in the facility was made for several reasons:

▶ Some experiments require longer continuous running times (24 to 48 hours in some cases) than can be provided in our Bitter magnet.

▶ Other experiments, operating at barely tolerable signal-to-noise ratios, would benefit from the higher field stability and lower vibrational noise associated with a superconducting magnet.

▶ The demand for experimental time in our standard 15-T, 5-cm-bore Bitters has been maintained at a remarkably steady level. Some fraction of this demand could be satisfied by a superconducting magnet with suitable magnetic and physical characteristics.

The new magnet was designed to match as closely as possible its "role model"—a 5-MW, 15-T Bitter solenoid. Thus, it provides a 15-T reversible field with 20 minute sweep capability, in a dual cryostat configuration of only 70 cm length and with a 5-cm-diameter room-temperature bore. Compatibility with the facility's dewars, variable temperature sample holders, magnetometers and so on (see the box below) is thus assured. This magnet is available



Upper critical field H_{c2} of $EuMn_6S_8$ pressurized at 16 kbar. The solid line is a fit to the theory postulating negative exchange coupling between Eu^{2+} moments and the external field. Figure 3

Information for Magnet Lab users

The high-field facility operates on a 5-day week, each day incorporating four 3¼-hour shifts within a 15-hour framework. Two experiments can be run simultaneoulsy when two-generator magnets are scheduled; during the past five years, this has been about half the time. Users often request two consecutive shifts, and occasionally three, but always within a limitation set by that user's total allotment.

Magnet scheduling is done on a biweekly basis, with time being assigned to two categories of users. Those from the Boston area typically request from 4 to 16 generator-shifts (defined as the product of shifts and the two or four generators assigned to the shift) but recognize that they could be scheduled for as little as half that many. Another group of users, mostly non local, prefer to take their place in a queue that entitles them to reserve in advance a guaranteed block of up to 20 generator-shifts in a single week. Since 1982, two separate queues have developed: one for the hybrid magnet and one for all other magnets. The length of each queue has varied from 10 to 14 weeks. However, special cases, such as first-time users, or those trying to meet a specific deadline, have usually been accommodated within a month.

A necessary condition for such a quick reaction time is the Laboratory's relatively informal application procedure, with its emphasis on personal communication and the minimizing of red tape. Prospective users are invited to the Laboratory to discuss the nature of the experiment and to ascertain its needs with respect to field intensity, field volume, field configuration and associated apparatus. A mutually satisfactory interview leads to a request for a brief two-page application form, which is sent to three referees outside the Laboratory whose rating determines the success of the proposal. For the unique hybrid-magnet facility, a user must demonstrate a need for 25–30 T fields on the basis of data taken in the 18–23 T range.

Facility users can take advantage of the assistance available from an experienced support staff, who are familiar with the often-unexpected problems associated with high-field experiments. They can also provide expert advice on the capabilities and limitations of the facility's pool of electronic, mechanical, and cryogenic equipment and instrumentation. The pool includes:

▶ General purpose equipment, such as recorders, oscilloscopes, digital voltmeters, dc and ac amplifiers, ac sources, dc power supplies, filters and lock-in amplifiers.

▶ Complete 1.5–300 K low-temperature systems that include metal cryostats, pumping equipment, pressure regulators and readouts and specially designed variable-temperature sample holders with thermometry suitable for use in high fields.[22]

▶ Helium-3 and dilution refrigeration systems for use at temperatures to as low as 30 mK.

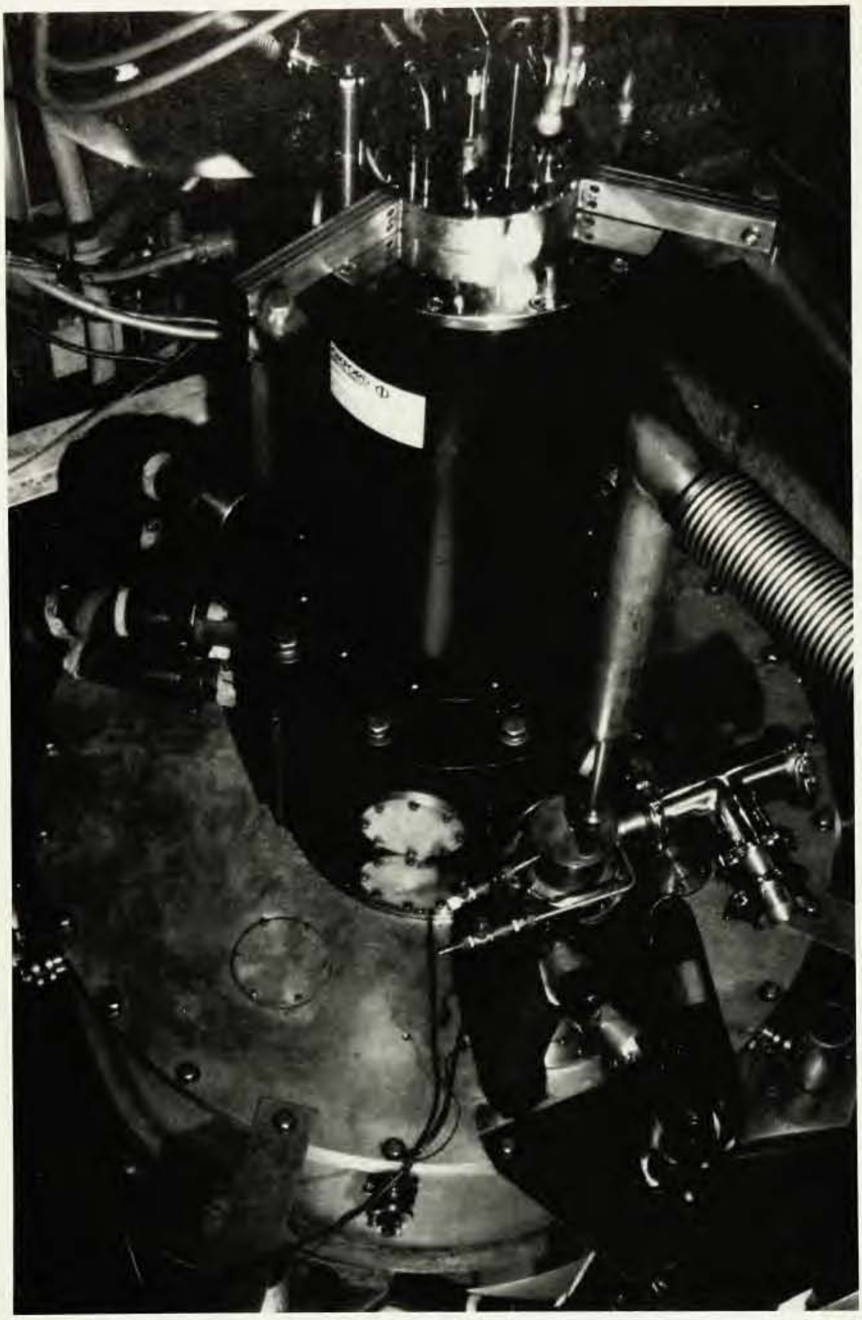
▶ Digital Equipment Corporation MINC microcomputers for on-line use. Data from one to three analog channels can be stored with 16-bit resolution directly on dual-density floppy disks for processing at a later time or processed immediately by using existing FORTRAN or BASIC programs.

▶ A variety of optical equipment, specialized magnetometers, vibration-free mountings and so on.

The responsibility for operating and maintaining the high-field facility is shared by the personnel of the Instrumentation and Operations Division, including staff members Bruce Brandt, James Coffin and Jean Morrison. Design of the facility's magnets originates in the Magnet Technology Division, headed by John E. C. Williams, with the key contributions coming from Robert Weggel, Mathias Leupold and Yukikazu Iwasa. Staff members from the Research Division (see box, page 32) are an important source of expertise in their respective areas of high-field research. While it is obvious that they work quite closely with users who are involved with them in collaborative programs, they are also available for consultation in all user programs. The staff includes semiconductor theorist David Larsen.

There is no charge to visitors for the use of the magnets, or of the associated equipment, or for liquid nitrogen and inexpensive bottled gases. However, users are expected to reimburse the Laboratory for the cost of liquid helium. Prospective users of any of the Laboratory's high-field magnets should write to or telephone:

Larry Rubin, Head, Instrumentation and Operations Division
Francis Bitter National Magnet Laboratory
MIT, Building NW14-1108B
Cambridge, MA 02139
(617) 253-5517.



He^3-He^4 dilution refrigerator sitting in the 3-cm bore Bitter insert of the hybrid magnet. This apparatus produced 85 mK in a 28.5 T field. Figure 4

to users on the same no-charge basis as all other magnets in the facility.

Barring a major breakthrough in high-field superconductivity, dc fields would appear to be limited to the 30–40-T range (the laboratory's future hybrid will probably operate at 33 T). To provide higher fields, the Laboratory is gradually developing pulsed-magnet capabilities. A 45-T facility was made available to users last summer. This system was built by Simon Foner, chief scientist of the Laboratory, who has done pioneering work in the development of pulsed magnets and in their application to problems in magnetism, superconductivity and semiconductor physics. Fields are generated in 200-turn, copper-wound, helical coils of 2-cm bore driven by a 5-kV, 30-kJ capacitor bank; the system gives several pulses, 10 ms in length, per hour. Dedicated instrumentation (two-channel data acquisition, tunable mid- and far-infrared) is being developed. Several interesting experiments have already been performed with this system; potential users should contact Foner.

Because copper coils of reasonable diameter fail mechanically at fields of 45–50 T, steel coils are required beyond 50 T. The Laboratory recently purchased a fast condenser bank (20 kV, 250 kJ) to energize such coils. After engineering studies, it will become part of a power supply for a 70–75 T pulsed-field facility.

Regardless of the type of magnet involved, experimenters need unencumbered access to them prior to their actual run. While this preliminary setting-up is often done in a few hours or less, it can also be a long and complicated process. The high-field facility has 24 magnet stations. This large number of sites and magnets enables us to accommodate an extensive program, involving both simple, as well as complex, experimental arrangements.

High-field experiments

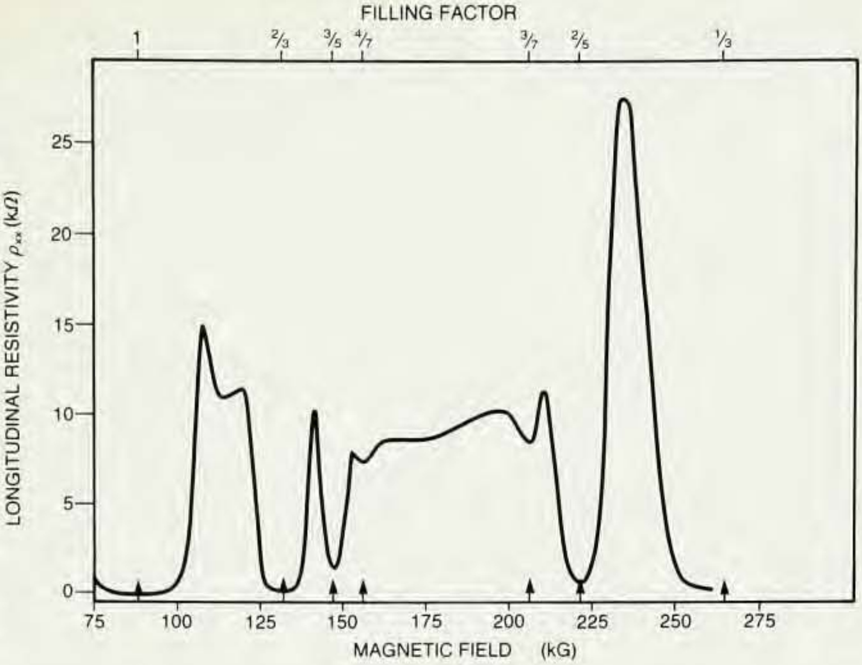
The largest fraction (65%) of high-field magnet use is accounted for by visitors from outside the Laboratory, who run their own experiments with assistance from the support staff, as needed. Another 15% of the experiments are performed by visitors who collaborate with members of the Laboratory research staff. Some of these programs are long-term projects wherein the users spend substantial time at the Laboratory. Others involve less frequent visits, and there are instances in which only a sample is delivered, mounted and measured. Programs conducted by the Laboratory staff account for the remaining 20% of the time (see box, page 32).

Our visitors represent a diverse community, geographically and technically. They have traveled to Cambridge from 30 of the states in the US and from 25 other countries on 5 continents. They have performed experiments in superconductivity, semiconductor physics, magnetism, optics and spectroscopy, electronic and thermal transport, low-temperature, atomic and plasma physics, Mössbauer spectroscopy, liquid crystals, biology and chemistry.

The distribution among these fields is far from even, the emphasis being on the first six listed. This distribution is also reflected in the publications by Laboratory users. Over the past decade, approximately 150 papers have appeared annually in refereed archival journals, divided about evenly between visitors and Laboratory staff. In the same period, about 40% of the experiments performed at the Magnet Lab have been in superconductivity. A dozen US superconductivity groups regularly use the Laboratory's facilities; the critical fields of many high-field superconductors were first measured here. Despite the maturity of the subject, superconductivity continues to generate exciting scientific and technological problems for Laboratory users, as the following examples indicate:

▶ Pressure-induced superconductivity.[4] High-field/high-pressure experi-

Longitudinal resistivity ρ_{xx} of a GaAs/(GaAl)As epitaxial layer versus magnetic field. Filling factors of the quantum Hall effect are indicated. Figure 5



ments have been used to determine the upper critical field H_{c2} as a function of temperature in the Chevrel salt $EuMo_6S_8$. The remarkable phase diagram, strongly distorted by exchange interactions with Eu^{2+} moments, is illustrated in figure 3; the fit to theory is excellent. This work demonstrates that $EuMo_6S_8$ undergoes a bulk superconducting phase transition at 13 kbar.

▶ Specific heat of A-15 Nb_3Sn.[5] The low-temperature specific heat of Nb_3Sn was measured in a magnetic field (18 T) high enough to suppress T_c significantly. The Deybe temperature θ_D changes abruptly as T is reduced; the data imply an electronic specific heat coefficient $\gamma = 35$ mJ/mole-K^2.

▶ J-B-T-ϵ interactions and strain limits in A-15, B1, and C15 crystal structure superconductors.[6] Critical current (J_c) as a function of uniaxial strain (ϵ) and field (B) was measured in several important superconductors (Nb_3Sn, Nb_3Ge, Nb_3Al, V_3Ga, NbN, V_2HfZr). Strain severely degrades J_c in A15 superconductors, but has little effect on those in B1 or C15 structures. These data are used to determine strain limits in the mechanical design of superconducting devices.

▶ Improved high-field performance of Nb-Al wire.[7] Powder metallurgy techniques have been used to produce small segments of Nb_3Al wire with critical current densities exceeding 10^4 A/cm^2 at 20 T and 2 K. If this process can be scaled up, such wire might serve as the basis for high-field nmr spectroscopy magnets, fusion-machine magnets and research magnets. This is one of several areas of high-field research in which Foner and his group are engaged. They were also responsible for performing the first experiments[8] in the hybrid magnet, during which the upper critical fields of cubic and tetragonal single-crystal and polycrystalline Nb_3Sn were measured in dc fields to 30 T.

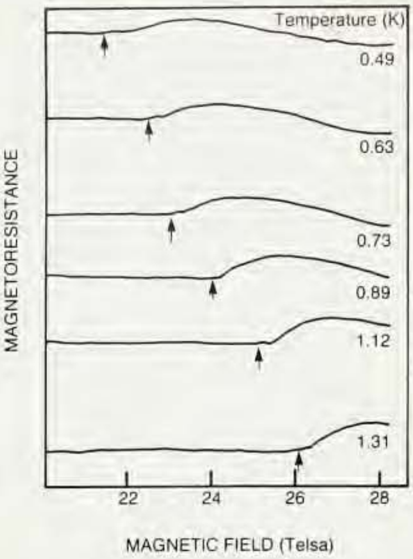
Semiconductor physics is another major research area at the Magnet Lab, accounting for about 25% of the work there. Recently, the most spectacular discoveries in this field have involved electron dynamics in two-dimensional semiconductor systems; the Laboratory's facilities have proven crucial to the understanding of these phenomena. The work was stimulated by the discovery of the quantized Hall effect, an effect unique to two-dimensional systems that manifests itself as a series of plateaus in the Hall resistivity plotted against the field. At the plateaus, the resistivity has values $e^2/n\hbar$ (where n is an integer to better than 1 part in 10^7, of obvious interest to metrologists). Hall steps result from the complete quantization of two-dimensional electron motion in a strong magnetic field. They occur at those fields that cause the first n magnetic quantum states (or Landau levels) to be exactly filled.

This abbreviated explanation of the quantized Hall effect suggests that *no* plateaus should be observed at fields beyond what is required to achieve the $n = 1$ condition (all electrons in the lowest Landau level). Instead, theorists predicted crystallization of the two-dimensional electron gas, into a triangular lattice, in the high-field limit. To search for this elusive "electron crystal," Horst Störmer of Bell Labs and Dan Tsui of Princeton University brought to the Magnet Lab high-mobility GaAs/(GaAl)As layers grown by Arthur Gossard of Bell Labs, and performed high-field, low-temperature transport measurements on them. Not surprisingly, they observed all the standard Hall steps ($n = 1, 2, 3$ and so on); however, in addition, they found evidence for an extra plateau at $n = 1/3$ where the lowest Landau level is $1/3$ filled.[9] Subsequent work[10] confirmed this observation, and revealed further structure at $n = 4/3, 5/3, 2/5, 3/5, 4/5$, and $2/7$. These totally unexpected results were, at first, attributed to electron crystallization. However, none of the electron-crystal theories could account for the plateau at $n = 1/3$ or other fractional quantum numbers. The puzzle of the fractional quantum numbers has since been partially resolved by a remarkable theory of Robert Laughlin,[11] who constructed two-dimensional electron-liquid states, for the special cases $n = 1/3, 1/5, 1/7, \ldots$, with energies substantially lower than those of the corresponding electron crystal. (See PHYSICS TODAY, July 1983, page 19.)

The Hall steps at fractional quantum numbers become sharper, and the corresponding minima in the longitudinal resistivity, ρ_{xx}, become deeper as temperature is lowered and field increased. To understand better the new state of matter described by Laughlin and to seek the fractionally charged excitations he predicts, one must extend the measurements to higher fields and the lowest temperature possible. To this end, Bell Labs, Princeton and the Magnet Lab have established a collaboration whose goal is the study of the quantized Hall effect at 50 mK in a 30-T field. The project requires a unique dilution refrigerator with a long, slender mixing chamber to fit into the 3-cm bore of the Laboratory's hybrid magnet (figure 4). Peter Berglund, an experienced low-temperature scientist from the Technical Institute of Helsinki, spent a year on sabbatical at MIT designing and setting up this refrigerator and helping to make possible several successful runs during which 85 mK at 28.5 T was achieved. Those experiments combine three of the more sophisticated technologies in condensed-matter science:

▶ The Bitter solenoid at the heart of the hybrid magnet (the black cylinder in figure 4) dissipates 8 MW in a two-cubic-foot, radially-cooled, compound copper-alloy helix operating at the stress and thermal limits of such a material.

▶ Within the solenoid, and separated from it by only a millimeter, is the dilution refrigerator which must contend with the vibrations and current ripple of the magnet.



High-field magnetoresistance of Kish graphite in the field range from 20 to 28.5 T at several temperatures. Onsets of the magnetoresistance anomalies are indicated by arrows at each temperature. Figure 6

▶ Finally, inside the refrigerator, there are GaAs/(GaAl)As epitaxial layers—developed through many staff-years of effort by Bell Laboratories—with carrier mobilities 50 times those achievable a decade ago.

All of these components, as well as the superconducting coils surrounding the Bitter solenoid and the measuring instrumentation, must work properly for the experiment to succeed. Turning on such a system is something of an adventure that can end in flashes of flame and geysers of water if the Bitter magnet fails, clouds of helium vapor condensation as the result of a false trip of the superconducting magnet's quench-detection system or a spurious signal if the sample or its leads misbehave. Minor catastrophes are not infrequent, yet the ever-present possibility of failure only heightens the excitement when data such as those shown in figure 5 are obtained.

Störmer, Tsui, and Gossard were recently awarded the Oliver E. Buckley Prize for discovery of the fractional quantized Hall effect. Pioneering experiments, of the sort they performed at the Magnet Lab, are a primary justification for the funding needed to build and operate such a national facility. Yet they were far from alone; many other groups have used the Laboratory's facilities during that period to investigate electron dynamics in systems of lower dimensionality. Other 2D systems studied at the Laboratory include: graphite,[12] InAs/GaSb,[13] a variety of Si MOSFETS,[14,15] HgTe/CdTe,[16] TaS_2,[17] and thin Pd films.[18] The subject is now among the most active in solid-state physics, and a wide variety of phenomena have been studied. In graphite, for example, the electron system appears to prefer a charge-density-wave ground state in high fields. Magnetoresistance experiments to 28 T were performed on high-quality graphite crystals,[12] and a striking anomaly observed in the magnetoresistance near 25 T as illustrated in figure 6. Yoshioka and Fukuyama have developed a charge-density-wave theory of this transition that quantitatively explains its temperature and field variation. Though less well publicized than the GaAs/(GaAl)As work, these studies of graphite are a second, quite different, experimental indication that two-dimensional (or nearly two-dimensional) electron systems have unusual properties in high magnetic fields.

Studies of the optical properties of the quantum wells in GaAs/(GaAl)As epilayers have complemented the electronic transport work. Lax, still active since his retirement as director, and Han Le have shown that photoluminescence and excitation spectroscopy at low intensities reveal a marked enhancement of features associated with free excitons.[19] The finite size of quantum wells splits the 4-fold degeneracy of the excitons into two doubly degenerate light-hole and heavy-hole exciton bands. In the plane of the quantum wells, however, the light hole behaves as the heavy hole and vice versa. Zeeman studies of free excitons sensitively probe this two-dimensional band structure and demonstrate this role-reversal effect.

Lax and Le have also studied the high-density effects associated with exciton gas and the electron–hole plasma at densities close to the metal–insulator transition. They observed a new quantum state that can not be attributed to single-particle states, that is, excitons, biexcitons or molecular excitons. The conspicuous absence of any semblance of the quantum Hall effect in bulk GaAs indicates the crucial nature of the two-dimensional character.

There is another exciting area of semiconductor physics—the study of crystals containing magnetic ions—wherein magneto-optics plays a key role. These materials are interesting and important because the internal fields of the magnetic ions greatly enhance carrier Zeeman splittings. Roshan Aggarwal and coworkers[20] have recently studied such effects via magneto reflection in the semimagnetic semiconductor, CdMnSe. They observe huge splittings of the A- and B-exciton peaks, reflecting the large internal field (of order 1 MG) experienced by carriers in this material. When combined with susceptibility data, these experiments measure the exchange couplings for electrons and holes. The exchange interactions are crucial parameters in semimagnetic semiconductors that determine the enhancement of Zeeman splittings and, in some instances, are responsible for bound magnetic polaron formation.

The exciton splittings are still increasing at the highest field (15 T) attainable in the magneto reflection set-up; this result was unexpected because 15 T is enough to fully align the spin of an isolated Mn^{2+} ion. The high-field variations are now attributed to partial break-up of anti-ferromagnetically-coupled Mn^{2+} spin clusters—doublets, triplets and so on. Experiments at higher fields will be needed to resolve this question fully.

Another group of materials, the $(TMTSF)_2X$ family of organic conductors, possess phase diagrams whose boundaries are apparently crucially dependent on high fields and low temperatures. Hall-effect and magnetoresistance measurements were made on $(TMTSF)_2ClO_4$ crystals at fields up to 22 T and temperature down to 80 mK.[21] To explain the appearance of approximately stepwise increases in Hall resistance as the field was increased past a low-temperature threshold, it was suggested that the phenomenon was the result of a series of transitions induced by the orbital motion of the carriers in the applied field. This experiment was the result of a collaborative effort by scientists from four institutions.

The preceding examples give some feeling for the physics now being uncovered with the highest dc fields and, in one or two instances, suggest directions for future, even higher, pulsed-field research. Though it is difficult to predict the new phenomena that will be discovered in the 30–40 T range, one can be confident that they exist. Both Japanese experience (in the Tokyo and Osaka pulsed-field laboratories) and the Magnet Lab experience, with its highest dc fields, have shown that

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In-house research at the Magnet Lab

About one-fifth of the Magnet Lab NSF budget is devoted to research programs conducted by the Laboratory staff. Following is a sampling of these programs:

Biomolecular nmr. The Laboratory houses the National NMR Facility for Biomolecular Research. This facility, under the direction of Leo Neuringer, is supported primarily by the National Institutes of Health. It carries out a broad spectrum of biochemical and biomedical nmr research, making use of four high-field spectrometers based on high-homogeneity persistent-mode superconducting magnets. The facility is used 7 days per week, 24 hours per day by the resident staff and outside users. Under development are a unique 14.1 T (600 MHz) Nb_3Sn/NbTi duplex superconducting magnet and an advanced whole body nmr imaging system, the latter sponsored jointly by MIT and IBM.

Spin-polarized tunneling. Robert Meservey and Paul Tedrow have developed the technique of spin-polarized tunneling, showing for the first time that the quasiparticle states of superconductors can be split in energy in a magnetic field because of the electron spin. This technique can be used to measure simultaneously spin–orbit scattering, orbital depairing and the energy gap, three parameters that mainly determine the critical magnetic field of superconductors. Spin-polarized tunneling can also be used to measure the conduction electron spin polarization of itinerant ferromagnetic metals and the magnetism of metal surfaces. It was also recently employed, in a collaboration with T. Orlando, to measure the anti-symmetric Fermi liquid parameter of aluminum.

Magnetic separation. David Kelland and his group work on magnetic separation—a method of separating micron- or submicron-size particles based on high magnetic-field gradients and the magnetic properties of materials. Continuous separation methods selecting either paramagnetic or diamagnetic particulate species have been developed. They are expected to have applications in mineral separation and beneficiation and in biotechnology, medical research and chemistry. Energy-related research by this group includes the application of high-gradient separation to coal-derived liquids and the enhancement of the magnetic properties of undissolved solids remaining in them.

Biomagnetism. David Cohen has pioneered in the measurement of the low magnetic fields generated by the human body. In this new discipline of biomagnetism, areas of interest have been the field over the chest due to ferrimagnetic particles in the lungs, and fields due to steady currents in the body, not measurable with electrodes. By exploiting the low noise of the most advanced SQUID magnetometers used in a magnetically-shielded room, very accurate maps over the head are being produced of currents in the brain. Such maps are being used, in conjunction with EEG measurements, by B. Neil Cuffin to solve inversely for the electrical sources in the brain with much greater accuracy than was previously allowed by EEG measurements alone.

Critical phenomena. Yaacov Shapira and coworkers study critical phenomena in magnetic materials. Measurements of the phase diagrams near the bicritical points of several easy-axis, isotropic and easy-plane antiferromagnets confirm new predictions of the modern theory of critical phenomena. Experiments on MnP gave the strongest evidence to data for the existence of a Lifshitz point—a novel type of multicritical point—in a real material. MnAs provided an opportunity to study the phase competition between a magnetic and a structural order parameter in a field which is conjugate to one of them. Recent studies focused on random fields in zinc-doped MnF_2.

Magnetotactic bacteria. There are various species of aquatic bacteria that orient in the Earth's magnetic fields and swim along magnetic field lines. Richard Frankel and his biologically-oriented research group are studying these magnetotactic bacteria, which are known to contain particles of magnetite, Fe_3O_4, in the size range of single magnetic domains. In most species, the particles are arranged in chains and function as a biomagnetic compass. North-seeking and South-seeking bacteria have been discovered to predominate in the Northern and Southern hemispheres, respectively. Research is now focusing on the process by which bacteria synthesize the Fe_3O_4 particles. The chief tools are Mössbauer spectroscopy, SQUID susceptometry and the magnetically induced birefringence of bacteria in culture.

Submillimeter waves. Kenneth Button and Mohammed Afsar are using Michelson interferometers to perform several types of fundamental millimeter and submillimeter wave measurements. Cyclotron resonance of electrons and holes in semiconductors and ferromagnetic resonance in ferrites are examples. Another is photoionization of shallow donors and acceptors, which requires submillimeter photons in such materials as GaAs, InP and the ternary compounds of these. In the last case, high magnetic fields are used to remove a degeneracy, thus permitting one to identify different residual donors by means of high-resolution spectroscopy.

Solid-state nmr. New nmr methods for high-resolution solid-state nmr experiments at high fields are being investigated by Robert Griffin and his group. For example, they have developed a new class of two-dimensional magic-angle sample-spinning techniques that permit high-resolution measurements of dipolar couplings and hence of intramolecular distance in solids. Another such sample-spinning technique involves chemical shift scaling sequences that reduce the number and intensity of rotational sidebands in high-field sample-spinning spectra. Echo techniques are employed to examine the dynamic properties of amino acid sidechains in peptides and proteins and of lipids in bilayer membranes.

Liquid crystals. Charles Rosenblatt and coworkers are using birefringence and field-dependent light-scattering techniques to study liquid crystals, microemulsions and biologically relevant macromolecules. By perturbing the molecular orientation with high fields in a variety of configurations, information is obtained about elasticity, dynamics, critical behavior and molecular structure. Examples include measurements of critical properties near an unusual second-order nematic-isotropic phase transition in a micellar liquid crystal. In another area, structural information has been obtained about the bacteriorhodopsin molecule in purple membranes of *H. halobium* by means of birefringence measurements of aqueous suspensions of membrane fragments.

Magneto-optical experiments. Giant-spin effects in semimagnetic semiconductors, arising from the exchange interaction between carriers and magnetic ions, are investigated using magneto-optical experiments which include Raman scattering, photo-luminescence, polarization spectroscopy and stimulated emission. Measurements on $Cd_{1-x}Mn_xSe$ by Donald Heiman and co-workers have demonstrated effective g-values greater than 100, and give evidence for "bound magnetic polarons." Here, ferromagnetic bubbles containing 10 to 20 magnetic ion spins are produced by the exchange interaction between holes localized at acceptor impurities and nearby Mn^{2+} ions.

higher fields produce new physics. The Laboratory is committed to the development of more advanced magnet facilities, especially higher-field facilities, for its users. It looks forward, with enthusiasm, to the challenge of building, instrumenting and learning to use magnet systems with fields approaching 100 T.

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