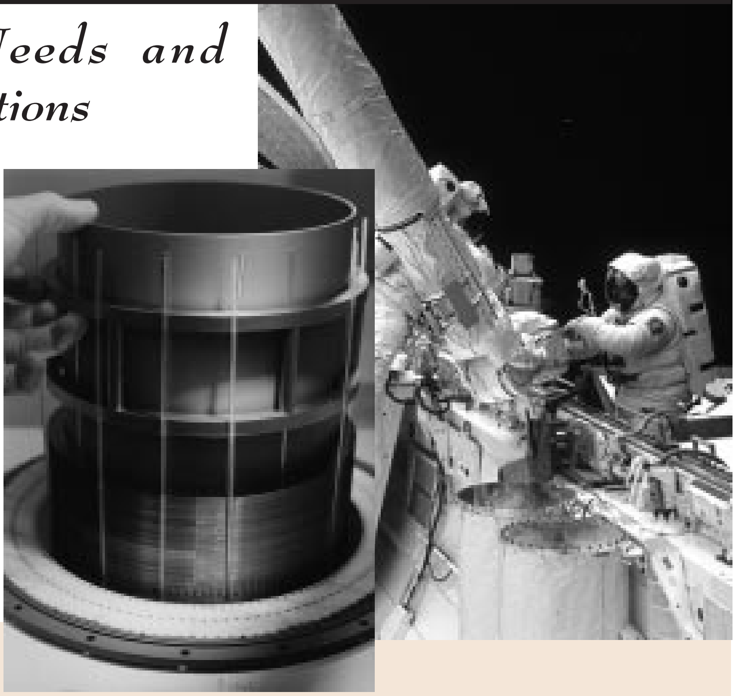
NHMFL REPORTS
NATIONAL HIGH MAGNETIC FIELD LABORATORY
SPRING 1997
Florida State University • University of Florida • Los Alamos National Laboratory

NHMFL Magnets

Engineered for Unique Needs and Sometimes Unworldly Destinations



In the first years of the laboratory, NHMFL magnet engineers, designers, and technicians focused their efforts on building state-of-the-art, high field magnet systems for NHMFL on-site users. Their success is well-documented: world record resistive magnets at 27, 30, and 33 tesla, important new pulsed magnet systems for users at the NHMFL facilities at LANL, and probably the widest assortment of user magnet systems and instrumentation in the world. Lately, these same resistive and pulsed magnet teams have been doing some very interesting work for others. A few highlights and updates:

> *The Resistive Magnet Group at the NHMFL recently completed a 0.14 T, 184 mm bore, 3 kW resistive magnet for growing crystals on the International Space Station.*

This new magnet was funded by NASA on a cost reimbursement contract and has been tested, accepted, and delivered. It is just the latest in a series of magnets engineered to the specific needs of customers.

Typically when crystals are grown, the presence of a temperature gradient and gravitational field lead to mixing of the melt. Diffusion-controlled growth (in which the diffusive transport is larger than the convective transport) can be achieved (in principle) by eliminating the gravitational field. Unfortunately, growing crystals on the space shuttle does not necessarily lead to diffusion-controlled growth due the fact that the experiment is typically not at the center of mass of the orbiter (micro-gravity) and vibrations are essentially unavoidable (g-jitter).

NHMFL Magnets *cont. on page 6*

Motion of Grain Boundaries in Bi-Bicrystals under a Magnetic Driving Force

D.A. Molodov,[1] G. Gottstein,[1] F. Heringhaus,[2] L.S. Shvindlerman[3]

Recently, using the DC high magnetic field facilities of the NHMFL in Tallahassee, Florida, for the first time a plane grain boundary in a specially grown bicrystal was moved by means of a magnetic driving force.

Macroscopically, a grain boundary is an interface between two differently oriented crystals in a single-phase material. At high temperatures, a grain boundary is able to move under the action of some

Magnetic Driving Force *cont. on page 6*

From the Director's Desk

Top NHMFL Structure Gets Fine-Tuning

The laboratory is very rapidly moving to forge new international and private sector collaborations that will drive magnet-related research and technology to new frontiers. To help us keep up with the frenzied pace of these activities, we are pleased to announce that NHMFL Deputy Director Hans Schneider-Muntau, who has served the laboratory in a dual capacity as the Director of Magnet Science and Technology (MS&T), has passed the MS&T management duties to Acting Director Steven Van Sciver. This will afford Hans the opportunity to focus more extensively on the collaborative activities of the laboratory.

On behalf of the laboratory and the partner institutions, we would like to thank Hans publicly for his dual service and extraordinary leadership. Under his direction, the NHMFL has structured one of the finest magnet science and technology programs in the world. The Resistive Magnet Group—with its track record of engineering design excellence, innovation, and three world records—continues to set and achieve new goals and to attract worldwide attention. The state-of-the-art pulsed magnet development activities of the laboratory were largely initiated by Hans, and he will continue to be a critical member of the 100 T magnet project for the NHMFL–Los Alamos facilities. He will also continue to provide guidance for materials and other development programs.

In all, eight groups comprise MS&T—a huge job. For the last year, members of the NHMFL Executive Committee have been asking Hans to focus a greater share of his time and attention "outward," that is, toward developing important new international and industrial collaborations. Hans, as he is held in high esteem by the international science and engineering communities and frequently invited to speak and make presentations, is the most appropriate person for this leadership role. Already Hans has been a significant force in exploring the laboratory's participation in the large Hadron Collider Detector Program at CERN, and he is building extremely valuable new bridges to the international science and engineering communities.

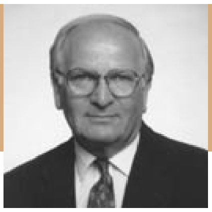
Steven Van Sciver (left) and Hans Schneider-Muntau

This spring, after six years as Director of MS&T *and* NHMFL Deputy Director, Hans will now focus his many talents on helping to define the future of the NHMFL. Dr. Steven Van Sciver—who is a leading expert in cryogenics, an outstanding engineering and professor, and an excellent program manager—has been tapped as the interim director. Steven came to the laboratory in 1991 to head the cryogenics program, and his leadership has been essential to progress on the 45 T Hybrid project, the ΔB program, and other initiatives. Before coming to the NHMFL, Steven was the associate director of the Applied Superconductivity Center at the University of Wisconsin-Madison and a professor in the departments of Nuclear Engineering and Engineering Physics, and Mechanical Engineering. Steven was recently designated "Distinguished Research Professor" by Florida State University (see *People*, page 14).

In closing, we cannot impress just how critical Hans' leadership has been—and will continue to be—to the laboratory. During the establishment phase of the facility, his engineering expertise and very effective management were absolutely essential. They laid the solid foundation upon which we may now build important new partnerships for the future. Our most sincere personal thanks to Hans for his outstanding ongoing efforts on behalf of the NHMFL.

Jack Crow, Director and Co-Principal Investigator, FSU
Don Parkin, Co-Principal Investigator, LANL
Neil Sullivan, Co-Principal Investigator, UF

From the Chief Scientist's Desk



Dear Colleagues,

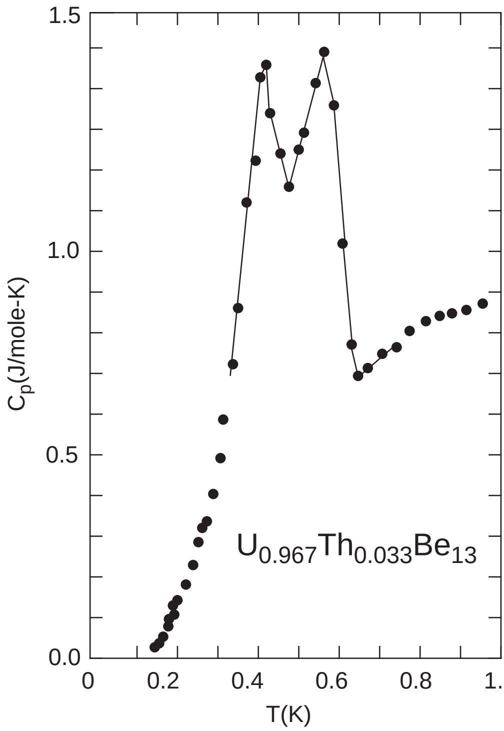
As I have mentioned before, the NHMFL has very successfully completed its building and "build-up" phase: We have an outstanding, multidisciplinary faculty and offer world-class magnet-related user facilities. Now, however, we are well into the second phase, the emphasis of which is research, engineering, and technology at the frontiers of science. In keeping with this evolution, it is appropriate for this column to move away from the general science and organizational topics of the past and on to the science of the present and future. This month, I am pleased to defer to Zachary Fisk, who will discuss interesting developments in correlated electron materials research. Dr. Fisk is an experimentalist with the Condensed Matter/Theory group of the laboratory, an FSU professor of physics, and a new member of the National Academy of Sciences.

R. Schrieffer

Correlated Electron Materials

Zachary Fisk

The study of the electronic and other properties of materials containing transition metal and rare earth elements is the field of correlated electron physics. The d- and f-electrons of these atoms are often "inner" electrons in the sense that they do not directly overlap spatially with electrons on neighboring atoms in the solids. Loosely speaking, spatially overlapping electrons are involved in bonding the solid, and the generic chemical bond is the electron pair bond which is essentially inert magnetically. Magnetic effects come from unpaired electrons, and the correlation between such unpaired electrons is the important feature underlying the physics of magnetism in solids, a primary concern of the study of correlated electron materials.



Double specific heat peaks corresponding to two different bulk superconducting phases in Th-doped UBe_{13}.

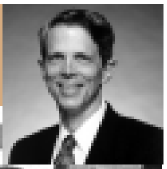
Particularly interesting fundamentally is the study of properties near the magnetic-non-magnetic boundary. As intimated above, this is also a boundary between bonding and non-bonding behavior of particular electrons, as well as in many cases the boundary between localized and itinerant character of certain electronic states in a material. Atoms of rare earth elements that can possess more than one chemical valence state are especially suited for such studies: 4f-electrons tend to be deeply "inner" and their interaction with other electrons in the materials are often easy to observe and can be varied through compositional or external means, such as pressure and applied magnetic field. The variation of properties so induced can be particularly marked in metallic materials and easily monitored through what the conduction electrons are doing, using resistance or specific heat, for example.

A small variation of electrons in the conduction and localized pools in correlated electron metals often leads to large changes in properties, as reflected in large response functions or susceptibilities. Large susceptibilities are of technological importance, and they also can lead to new electronic ground states. The way to think about this is as a large susceptibility, meaning that the material is potentially unstable to the

Electrons *cont. on page 4*

Attention Users

Bruce Brandt
Director, DC Field User Programs



The annual NHMFL Users' Group Meeting was held as part of the American Physical Society March Meeting and was again sponsored by Oxford Instruments. For those of you who are not familiar with this meeting, it is an opportunity for users and potential users to meet and find out what has been going on at the various NHMFL facilities, what capabilities exist, and what is planned for the near and far future. It is also a chance for users to discuss their needs for new magnet systems or instrumentation. Similar meetings are planned before major conferences attended by users of the magnetic resonance facilities.

Some of the discussion topics included the research opportunities in DC fields, opportunities for electron magnetic resonance studies of condensed matter systems, the Ultra-High B/T facility, the Pulsed Field Facility, and a 30 T pulsed magnet for neutron scattering experiments.

Nominations were also taken for the Users' Committee, which represents you and is the driving force behind the decisions as to what magnets, instrumentation, etc., are needed at the NHMFL. The floor is still open so if you have any nominations please send them to the new committee chair, Gil Clark.

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For the first time the NHMFL had a booth at the APS trade show. Our displays, which attracted a *lot* of visitors, presented abstracts from users who are conducting cutting-edge research at the NHMFL. We also had large-scale mock-ups of the 60 T quasi-continuous magnet at LANL and the world-record 33 T resistive magnet. Participation in the trade show offered us the opportunity "to get the word out" about our magnet systems, instrumentation, and user support programs and allowed us to get re-acquainted with old friends, make many new ones, and increase our list of potential users.

NHMFL Director Jack Crow (right) talks with NSF Division Director Tom Weber, Division of Materials Research (center), and APS March Meeting participant in front of the laboratory's trade show display.

Users—both present and potential—might be interested in the accompanying article, "More Energy, More Power, More Comfort," by Thomas Schmiedel, who reports on the visible optics facilities for users.

***Electron** cont. from page 3*

spontaneous establishment of an internal, bootstrapped field coupling to this susceptibility, such as a magnetic field that couples to the magnetic susceptibility. In strongly correlated electron materials, the interplay between the localized and itinerant electrons can lead to electronic ground states that have not been seen before. We now know this to be the case in the heavy electron superconductors, which support multiple types of superconducting order in the same material (see figure).

It is possible that the high Tc cuprates are related in a fundamental way to the physics of the heavy electron superconductors: the cuprate superconductors derive from an insulating magnetic state. The d-electrons of Cu are intrinsically more delocalized than f-electrons, but what we know from the latter provides hints for understanding the former. We have little ability to predict the behavior of solids near the magnetic–non-magnetic boundary as cuprate superconductivity resoundingly shows us. But this very fact shows that we have only begun to learn the capability of highly correlated electron materials.

More Energy, More Power, More Comfort

This is not intended to be a write-up about how to improve your physical condition; it is actually about the visible optics facility in Tallahassee and its newest laser.

Optical experiments depend very much on the use of lasers, spectrometers, and detectors. The visible optical facility in Tallahassee has a number of lasers covering a wavelength range between 325 and 1100 nm with laser powers of up to 4W. Our most recent addition has expanded this range to higher energies at 275 nm. At the same time the average output powers at different wavelengths were increased by a factor of greater than three. With all this, what did we gain for our users?

Research in visible optics is mainly concentrated on investigations of electronic states in semiconductors. Techniques include photoluminescence and excitation spectroscopy. In the former, the laser excites a sample with light that has a fixed energy that is higher than that of the detection range. Excitation spectroscopy, on the other hand, uses the laser as a tunable light source to scan an energy range higher than a fixed detection energy. The energies of interest are close to the bandgaps of the materials with most energy scales twenty years ago at 1 to 1.5 eV in Si and GaAs. Ten years ago the demand to investigate materials with larger bandgap grew and moved the energy scale up to 2.8 eV (ZnSe). Research is now moving into areas of blue lasers and even ultraviolet-capable materials, like GaN, which add another eV to this scale. We realized very soon that future research will require higher energy laser beams for excitation, which prompted us to upgrade our laser system.

The new laser is a milestone in technology. For the first time it is possible to circumvent cumbersome laser alignment procedures by pressing a button and letting the laser align itself automatically. The technology is very reliable while providing high flexibility. Users can concentrate on their experiment and the laser automatically monitors its current state and keeps its output constant. While such an instrument costs about $100,000, it lasts more than twice as long as a similar powered laser from five years ago. For us, it paid off in many ways to upgrade the laser system to higher power, more energy, and greater user comfort.

The chart below lists the various visible optics equipment and probes available at the NHMFL facilities in Tallahassee and Los Alamos. For more information on optical experiments, contact Bruce Brandt (904-644-4068) or Thomas Schmiedel (904-644-1060) in Tallahassee or Larry Campbell (505-667-1482) or Yongmin Kim (505-665-8972) in Los Alamos.

Visible Optics Equipment and Probes Available at the NHMFL

Spectrometers and Detectors

- 0.25 m, f/4 Jarrel-Ash monochromator *
- 0.28 m, f/4 Acton monochromator w/ CCD detector *
- 0.6 m, f/10 SPEX “Triple-Mate” spectrometer with CCD detector
- 0.75 m, f/6.8 McPherson monochromator with CCD detector †
- 0.65 m, f/6 SPEX double monochromator
- GaAs TE cooled photomultiplier tube
- Liquid nitrogen cooled ultra low noise Ge detector

Sources

- Tungsten-halogen and Xe lamp † for reflection and transmission
- Coherent Sabre 25 W Ar laser with deep UV (275.4 nm) option †
- ACI HeCd laser with 40 mW at 325 nm
- Coherent Innova 10 W Ar laser *
- Coherent Innova 7 W Ar laser with UV (351.1 nm) option †
- Electro-optical light modulator (75 MHz) *
- Coherent MIRA DUAL modelocked Ti:S laser with 3 optics sets
- Second harmonic generation for use with Ti:S laser *
- Fs/ps rapid scan autocorrelator *
- Electronics for time resolved spectroscopy *

Sample Holders (probes)

- Multiple sample holders (reflectivity, PL) for 5x5 mm samples up to 33 T †
- Sample holders for Voigt geometry
- Transmission sample holder
- Diamond anvil cells for optical studies at pressures up to 25 GPa.
- Optically detected resonance sample holder †
- Optically excited NMR sample holder †
- Magneto-Optical Kerr-Effect (MOKE) probe, 632.8 nm†

† available in the Tallahassee facility only
* available in the Los Alamos facility only

This article was contributed by Thomas Schmiedel, a post-doctoral fellow who put together the facilities for magneto-optical research in the DC High Field Facility in Tallahassee.

Magnetic Driving Force *cont. from page 1*

driving force by consuming one grain and expanding the other one. There is substantial interest in this subject, since the motion of grain boundaries constitutes the fundamental process of recrystallization and grain growth. While grain boundary migration rates can be obtained from recrystallization and grain growth data, experiments on polycrystals can provide information on average grain boundary behavior, but not on the relationship between grain boundary structure and mobility. The structural dependence of boundary mobility can only be retrieved from investigations of the motion of boundaries with known crystallography under the action of a defined driving force.

A driving force for grain boundary migration occurs if the boundary displacement leads to a decrease of the total free energy of the system. There are two ways by which this may be accomplished. The first uses the free energy of the grain boundary itself, the second utilizes a free energy difference of the adjacent grains. The most frequently used method for the study of grain boundary motion in bicrystals is the displacement of a curved grain boundary. The driving force in this case is provided by a reduction of grain boundary area. A curved grain boundary, however, implies that its structure changes along the boundary line, since it is composed of different grain boundary planes. The obtained mobilities can therefore not be related to a specific grain boundary structure. By using the second category of driving forces, a plane boundary can be forced to move. A bicrystal with grains, which have an orientation-dependent property like elastic constant or magnetic susceptibility, can be utilized in this case. Under the impact of a respective, directed, external field, the property anisotropy will generate a free energy difference between adjacent grains that causes a driving force for boundary displacement. This driving force does not depend on the boundary properties and moves a boundary from the grain with lower free energy toward the one with higher free energy. Such conditions were established in our experiment by the action of a magnetic field on a bicrystal of Bismuth, which is strongly magnetically anisotropic. The driving force, p, for boundary migration in the current experiment is given by

$$p = \mu_0 \frac{\Delta\chi}{2} H^2 (\cos^2\theta_1 - \cos^2\theta_2) \quad , \qquad (1)$$

Magnetic Drving Force *cont. on page 7*

NHMFL Magnets *cont. from page 1*

By applying a magnetic field to an electrically-conductive melt, Lorentz forces are established that retard the development of convection currents (artificial viscosity). Unfortunately, the magnetic field strength required to achieve diffusion-controlled growth on Earth can easily exceed the approximately 10 T typically available in large bore magnets.

By combining the microgravity of space flight and a moderate magnetic field (approximately 0.1 T), however, it is believed that diffusion-controlled growth can be accomplished for many crystal systems (Volz *et al*., “Magnetic Damping of Convective Flows During Semiconductor Crystal Growth,” *International Workshop on High Magnetic Fields: Industry, Materials and Technology*, NHMFL, 1996).

In addition to providing greater than 0.1 T, the magnet needed to have a field inhomogeneity less than 10% over a 150 mm distance on axis. Furthermore, the power available on the space station will be only 3 kW; the magnet must not contaminate the cooling water; the fringe field 200 mm from the magnet must be less than 3 gauss; and the overall length must be less than 238.1 mm. NASA requested a resistive magnet for this application because they wanted to be able to sweep the field and were concerned about the safety of cryogens in a manned space flight compartment.

The final magnet design consists of four split coils electrically in series. The splits were provided to meet the homogeneity requirement. Each coil has 268 turns and each turn consists of two nickel-plated copper disks (or rings) 0.2 mm thick. There was no space for tierods so the coils are clamped by the housing and 200 small compression springs. The housing is made of nickel-plated and Teflon-coated steel to provide magnetic shielding and a slight field enhancement without reducing the water purity.

The magnet was successfully tested on March 25 at the NHMFL and shipped to the Marshall Space Flight Center shortly thereafter.

On April 23, the NHMFL Resistive Magnet Group successfully tested the 30 T magnet under contract for the Tsukuba Magnet Laboratory operated by NRIM (*NHMFL Reports*, Fall 1996). The magnet is very similar to the NHMFL’s own 30 T magnets but uses Cu-Ag sheet in the innermost coil instead of the Cu-Be, in order to be compatible with NRIM’s pumps and power supplies. Yukihiro Sumiyoshi

Magnetic Driving Force *cont. from page 6*

where θ_1 and θ_2 are the angles between the direction of the magnetic field and the trigonal (or *c* or <111>) axes in both grains of the Bi-bicrystal, $\Delta\chi$ is the difference of susceptibilities parallel and perpendicular to the trigonal axis and *H* is the strength of the field. The force, *p*, is directed toward the grain with a larger value of θ and does not depend on the sign of the magnetic field.

In the past, efforts were made by Mullins *et al.* to apply the magnetic method to the study of grain boundary kinetics in Bi. It was found on Bi polycrystals (*Acta Metall.* **4** (1956) 421) that a magnetic force favors preferred orientations of grains during their growth. It was also shown (*Acta Metall.* **9** (1961) 960) that a grain, which was generated by recrystallization after a local deformation of a Bi single-crystal, grew and consumed the initial single-crystal under the action of a magnetic force. No specific boundary motion was investigated, however.

For our experiment, bicrystals of high purity Bi (99.999%) containing either a 90°<112>{111} or 90°<110>{111} boundary were prepared (Figure 1). The used field strengths were $1.63\cdot10^7$ and $2.39\cdot10^7$A/m using 20 and 33 T Bitter magnets. To ensure sufficient boundary mobility, the specimens were kept at a temperature of 255 °C.

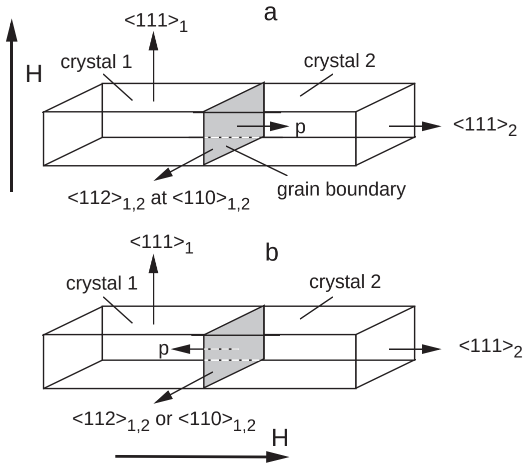

Figure 1. *Bicrystal with moving grain boundary in two positions with regard to the magnetic field.*

The experiments reveal that the grain boundaries in Bi-bicrystals actually move in a magnetic field with rather high velocity (30-50 µm/s at a field strength $H=1.63\cdot10^7$A/m, B=20.45 T) (Figure 2). To prove that boundary motion is caused exclusively by the magnetic driving force, the experiment was carried

Magnetic Driving Force *cont. on page 10*

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and Masura Tezuka of Toshiba Corporation were on hand for the testing and follow-on celebration the next day. The magnet was tested to 30.0 +/- 0.1 T and met all specifications.

In late March, the magnet built by the NHMFL Pulse Magnet Group for the X-ray Radiography Group at Sandia National Laboratories (*NHMFL Reports*, Winter 1997) was successfully utilized in an experiment in their $20 million Hermes III X-ray Diode. The 50 T magnet (one of four) was designed to focus a high intensity electron beam in the final target stage of the experiment.

The Pulse Magnet Group also delivered the largest coil they have produced to date to the PHAEDRUS Laboratory for Plasma Science of the University of Wisconsin. The 1.5 m long winding has a bore of 58 mm and will generate 18 T. It is to be utilized as the central resistive core of PEGASUS, a small Tokamak device for nuclear fusion studies. Initial testing of the coil will begin in June.

The Pulse Magnet Group also recently completed a fiber winding project for the Physics Department of Harvard University. The task was to precision wet-wind a thick kevlar composite shell to provide outer reinforcement for a quadrupole magnet. The magnet will be used to form a magnetic containment trap for ultracold neutrons formed by the scattering of phonons from superfluid helium. Once trapped the beta decay of the neutrons will be studied to calculate the neutron lifetime, beta-decay asymmetry coefficient, and eventually, the weak force coupling constants.

In May, the Pulse Magnet Group completed the commissioning of two 50 T coils at the Australian National Pulsed Magnet Laboratory in Sydney. The tests were remarkably successful. By replacing the carbon composite outer reinforcement shell of the magnets with a custom machined steel shell, the time taken for a magnet to cool down between shots was cut by 50%, thus allowing twice as many high field experiments per day. It is likely that in future, all user coils for the LANL facility will be similarly reinforced.

Information for this article was contributed by Mark Bird, Resistive Magnets, 904-644-7789, bird@magnet.fsu.edu, and Paul Pernambuco-Wise, Pulse Magnets, 904-644-0854, wise@magnet.fsu.edu.

Conference & Workshop Activity

First North American FT-ICR Mass Spectrometry Conference Follow-Up

The First North American Fourier Transform Ion Cyclotron Resonance (FT-ICR) Mass Spectrometry Conference was convened at the National High Magnetic Field Laboratory in Tallahassee, Florida, on March 13-15, 1997. The meeting drew 110 registrants from leading FT-ICR research groups from the United States, United Kingdom, Germany, France, The Netherlands, and Japan, and consisted of an intensive two days of twenty-four oral and fifty-two presentations. All sessions were plenary—i.e., no parallel sessions—and well attended. The meeting was sponsored by the NSF National High-Field FT-ICR MS Facility, with additional support from Finnigan and Bruker. Travel grants helped to attract participation by approximately forty graduate students. The conference was staged by Alan Marshall (Florida State University), Christopher Hendrickson (NHMFL), and John Eyler (University of Florida), with critical assistance by Jo Ann Palmer, Janet Cox, and numerous NHMFL colleagues. The scientific program was planned by Jonathan Amster (University of Georgia), Michelle Buchanan (Oak Ridge National Laboratory), David Dearden (Brigham Young University), David Laude (University of Texas)), and David Weil (Minnesota Mining and Manufacturing).

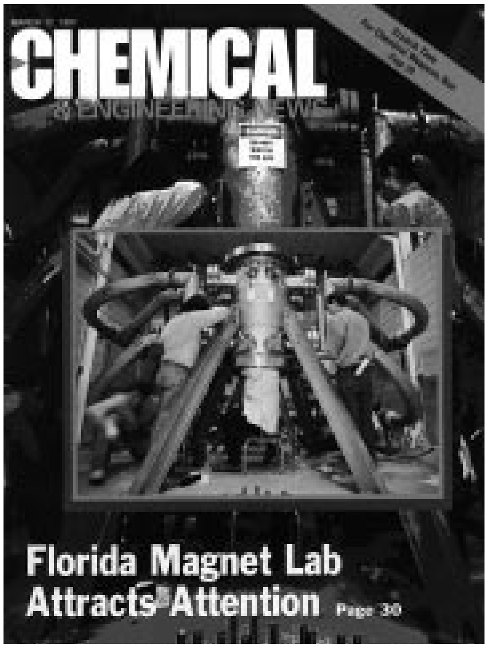
Attendees spent the first conference day at the NHMFL, ending with a southern-style barbecue, a tour of the laboratory and the local FT-ICR MS facilities *(Rapid Commun. Mass Spectrom.* **10** (14), 1814-1818 (1997); *Chem. & Eng. News* **75** (11), 30-40 (1997)), and poster session. The scientific program featured four symposia—Instrumentation; Polymers/Electrospray; Laser Applications (MALDI, Photodissociation, Ion Spectroscopy); and Ion Chemistry and Ion-Molecule Reactions—plus several invited posters on industrial applications, and a closing guest lecture on ion mobility mass spectrometry by Michael Bowers (University of California, Santa Barbara).

It was decided not to publish the proceedings, so as to encourage presentation of new and controversial results. In response to strong encouragement from the ICR community, the organizers propose to repeat the meeting in Tallahassee in March, 1999.

FT-ICR Program in the News

It was a coincidence, but great timing nonetheless. Just as the FT-ICR Conference was welcoming an unexpectedly large number of participants, the NHMFL landed on the cover of *Chemical and Engineering News* (March, 1997, pages 30-40). In an interview with Stephen K. Ritter, NHMFL Director Jack Crow discussed the unique role of all science and engineering disciplines to the success of the laboratory:

> *Laboratories such as this one traditionally around the world have centered on standard condensed-matter physics research...When we proposed this lab [in 1989], however, we looked at chemistry and biology with the greatest potential for growth. I think condensed-matter science will continue to be very stable, but there is real opportunity in chemistry and related fields. The impact of advanced magnetic resonance on drug development is one area, for example, that will greatly benefit from magnet research in the next few years.*



In the last two years of the laboratory, magnetic resonance technologies—nuclear magnetic resonance, magnetic resonance imaging, electron magnetic resonance, and ion cyclotron resonance mass spectrometry—have become well integrated in the NHMFL's Center for Interdisciplinary Magnetic Resonance (CIMAR).

The ICR program, under the direction of Dr. Alan Marshall, and FT-ICR MS have been featured in other publications as well:

- *Analytical Chemistry* **69**, 157A (1997) included a brief highlight on the paper: Marshall, A.G.; Senko, M.W.; Li, W., Li, M.; Dillon, S.; Guan, S.; Logan, T.M., "Protein Molecular Mass to 1 Da by ^{13}C, ^{15}N Double-Depletion and FT-ICR Mass Spectrometry," in *J. Am. Chem. Soc*. **119**, 433-434 (1997). The paper introduced a technique for extending by an order of magnitude the upper mass limit for protein mass spectrometry.

- The March issue (page 19) of *Chemistry and Industry* (a British chemical journal) featured a summary of the paper: Guan, S.; Marshall, A.G., "Two-Way Conversation with a Mass Spectrometer: Non-Destructive Interactive Mass Spectrometry," *Anal. Chem*. **69**, 1-4 (1997). This paper showed for the first time how to control mass spectrometry experiments in "real-time," i.e. by adjusting the instrumental parameters as the experiment is in progress.

Gulf Coast Alliance for Technology Transfer (GCATT)

July 29, 1997
NHMFL
Tallahassee, Florida

The GCATT Quarterly Meeting will be held at FSU in July. GCATT is a voluntary cooperative organization of nine federal laboratories and six colleges and universities. Founded in 1992, GCATT fosters technology transfer and enhances industrial and economic development by transferring member technologies to the private sector. GCATT is affiliated with the Southern Technologies Application Center funded by NASA and operated by the University of Florida.

The newest member of GCATT is the University of South Alabama (USA). The university brings a wealth of expertise in marine science, chemical, mechanical, civil, electrical and computer engineering. The new National Center for High Speed Sealift is located at USA, as well as the largest medical complex on the Gulf Coast.

GCATT has been actively pursuing, among other things, commercialization of a unique acoustic material and a skull-mounted microphone. It is working with the NHMFL in many areas, but its primary effort presently focuses on bringing "GAMMA" (a magnetic resonance simulation package) to market in support of magnetic resonance educational and training needs at the undergraduate and graduate levels (see *NHMFL Reports*, Summer 1996). For further information on GCATT, see *NHMFL Reports*, Spring 1996, or contact GCATT directly at 904-833-9360, *gcatt@eglin.af.mil*.

29th Annual Southeastern Magnetic Resonance Conference (SEMRC)

October 30 - November 1, 1997
University of Florida
Gainesville, Florida

SEMRC will feature invited and contributed papers and posters in NMR, MRI, EPR, and ICR, including time-resolved and multidimensional spectroscopies; high magnetic fields; and applications in material sciences, physics, chemistry, biology, and the medical fields. Invited keynote speakers are Michael Mehring (University of Stuttgart, Germany), Hans Thomann (Exxon Corp.), and Warren Warren (Princeton University).

Conferences *cont. on page 10*

Conferences *cont. from page 9*

Abstracts, which are requested for all presentations and posters, are due by September 15; they will be reproduced and bound for distribution to conference participants. The advance registration deadline is also September 15, but on-site registration, at increased fees, will be available.

For further information on registration, accommodations, transportation, and the Companion Program, contact SEMRC, Lori Clark, University of Florida, Department of Chemistry, Box 117200, Gainesville, FL 32611-7200; Tel: 352-392-4654; Fax: 352-392-0872; e-mail: *lori@chem.ufl.edu*.

Alexander Angerhofer (*alex@chem.ufl.edu*) and C. Russell Bowers (*russ@physical27.chem.ufl.edu*) are serving as the organizing committee chairs.

Magnetic Driving Force *cont. from page 7*

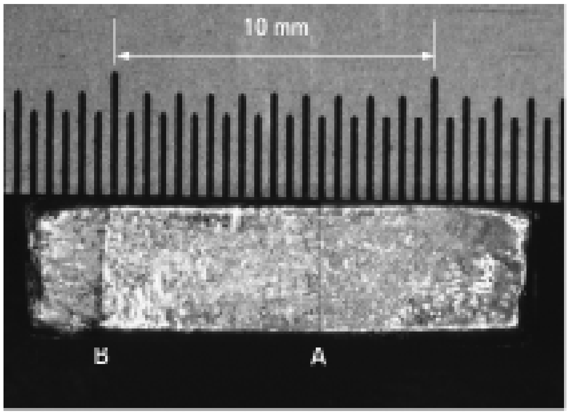


Figure 2. *Grain boundary displacement (from A to B) in Bi-bicrystal under a magnetic driving force after 180 seconds at B=20.45 T and T=255 °C.*

out in two different ways. Firstly, a specimen was mounted in a holder such that the *c* axis (<111>) of crystal 1 was directed parallel to the field. The <111> axis in crystal 2 in this case was perpendicular to the field, and the grain boundary moved in the direction of the latter crystal due to its higher magnetic free energy (Figure 1a). Secondly, a specimen was tested in a position where the axis <111> in crystal 2 was close to the field direction and the corresponding axis in crystal 1 was perpendicular to the field. The direction of boundary motion in this case was opposite, from crystal 2 to crystal 1 (Figure 1b). This result provides unambiguous evidence that the grain boundaries in our bicrystals were forced to move by the magnetic driving force only. In addition, some bicrystals were annealed in a magnetic field in both positions, and boundary motion in opposite directions was observed in the same specimen dependent on its position with regard to the magnetic field.

Unexpectedly, the determined boundary mobilities for the boundary motion in two opposite directions were found to be distinctly different. The boundary is less mobile, if the *c* (<111>) axis in the growing grain is perpendicular to the direction of the motion ($m=v/p=1.0\cdot10^{-6}$ m^4/J·s at $p=30.3$ J/m^3 and $\Delta\chi^{255°\mathrm{C}}=1.82\cdot10^{-7}$) and moves faster, if the trigonal c axis in the growing grain is close to the direction of motion ($m=1.7\cdot10^{-6}$ m^4/J·s at $p=28.3$ J/m^3). In other words, the growth rate is higher, if the <111> axis in the growing grain is close to the direction of growth (action of driving force) and, conversely, the growth rate is less, if <111> is perpendicular to the growth direction. This result provides clear evidence that Bi possesses an anisotropy of grain growth perpendicular and parallel to the trigonal axis *c*. This result may have a serious impact on our understanding of grain boundary motion, since the mobility of a grain boundary is commonly assumed not to depend on the direction of its motion.

In summary, the described experiments have proven that a magnetic field provides a unique means to force a planar grain boundary to move under the action of a constant driving force. This opens up new ways for the investigation of grain boundary mobility. Next, we plan to study by this method the driving force and temperature dependence of boundary mobility for boundaries with specific structures.

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8th U.S.-Japan Workshop on High-T_c Superconductors

December 8-10, 1997
NHMFL
Tallahassee, Florida

For updated information, contact conference co-chair Justin Schwartz at *schwartz@magnet.fsu.edu*.

VIIIth International Conference on Megagauss Magnetic Field Generation and Related Topics (Megagauss VIII)

October 18-23, 1998
NHMFL
Tallahassee, Florida

Megagauss VIII is the next meeting in a series that began in 1965 in Frascati, Italy. The scope of the conference is to provide the latest results on the generation of very high magnetic fields at the megagauss level and higher, and to present up-to-date highlights of state-of-the-art research in extremely high magnetic fields. Principal topics will be the generation of multi-megagauss fields, the production of non-destructive fields up to a megagauss, the handling of extremely high power in the terawatt range at high energy density, and the application of ultra-high fields in technology and science.

The meeting is intended to combine technological and scientific aspects of generation and use of megagauss fields. Researchers actively involved in ultra-high field studies, engineers building these advanced devices, and young engineers, scientists and students who want to get acquainted with this new and promising area of ultra-high magnetic fields should attend. They will find a stimulating and motivating cross-fertilization among these mutually complementing areas of research, applications, and technology.

The First Announcement for Megagauss VIII was released in April 1997; the Second Announcement, calling for papers, will be released in September 1997. For details and deadlines, and to get on the mailing list for further information, contact Ysonde Jensen, NHMFL, 1800 E. Paul Dirac Dr., Tallahassee, FL 32310; Tel: 904-644-0566;
e-mail *megagauss@magnet.fsu.edu*.

Focus on Science

High Sensitivity NMR and MRI Without High B/T

Part Two: Applications of Optical Pumping to Magnetic Resonance Imaging

C. Russell Bowers, Chemistry Department, University of Florida
Bastiaan Driehuys, Magnetic Imaging Technologies, Inc., Durham NC

> Part One of this article, *Applications of Optical Pumping in NMR Spectroscopy*, appeared in the Winter 1997 Issue of *NHMFL Reports*.

One of the more exciting recent developments in optical pumping science is its application to *in-vivo* MRI. The first ^{129}Xe and ^{3}He MRI images of the human chest, one example of which is shown in Fig. 4b, have only very recently been published.[15,16] This method is clearly superior to γ-ray photography, the established method of functional imaging of the lung. NMR signals from optically pumped ^{129}Xe in the brain have also been detected, raising the possibility for chemical shift selective imaging of the brain tissue.

In spite of this rapid progress in applying optically pumped ^{129}Xe and ^{3}He to *in-vivo* MRI, optimization of the experimental conditions and pulse sequences presents some new difficulties. One complication is the diminished image intensity and resolution that arises from the greater diffusion coefficient in a gas. A second fundamental difference is that in the case of optically pumped imaging, it is advantageous to acquire the entire image from the same initial polarization. Using an imaging pulse sequence such as 2D or 3D FLASH (fast low-angle shot),[17] small tip angle pulses can be used to ensure that the magnetization remains constant during the acquisition.[17] It would appear that echo planar imaging (EPI) would be better suited to this situation. The optimization of EPI sequences for both clinical and materials imaging applications requires further attention.

MRI *cont. on page 12*

MRI *cont. from page 11*

The Bowers research group plans to develop exemplary optically pumped microimaging applications in materials science and biological systems. A Rb-^{129}Xe optical pumping system has been operational since in Gainesville since March 1996. This system can routinely provide approximately 0.1 L atm quantities of ≈10% spin polarized ^{129}Xe with pumping times of 1800 s. The optical pumping system is based on a Ar-ion pumped Ti:sapphire laser which has the ability to pump lower pressures (c.a. 10-200 Torr) of xenon gas to ≈10% polarizations. In collaboration with B.A. Inglis at UF's Center for Structural Biology, a preliminary image of a phantom containing optically pumped xenon has been obtained[18] (see Fig. 4a). The envisioned applications range from *in-vivo* to materials imaging. For example, it is proposed that optically pumped ^{3}He MRI be applied to the study of the fracturing process in the cryogenic epoxies being developed by A. Brennan of the UF Materials Science Department. These epoxies are being used to construct a 900 MHz superconducting magnet at NHMFL.

Continued growth in the use of hyperpolarized gases for fundamental research and clinical imaging studies will require development of a relatively inexpensive robust system capable of delivering as much as tens of liters per day of hyperpolarized gas. To this end, the Princeton research groups of Drs. Happer and Cates have continued to focus on studying the fundamental physics that will lead to higher polarizations as well as faster polarized gas production rates. For the case of ^{129}Xe it can be shown that the theoretically attainable gas polarization rate is 40 cm^3 hr^{-1} per watt of light absorbed by the Rb vapor . Thus, to produce one 1 STP liter polarized ^{129}Xe in 1 hr requires that the Rb continuously absorb 25W of laser light. Such calculations make it clear that large-scale polarization of these noble gases require high CW laser power. The most promising new laser sources for optical pumping are AlGaAs diode laser arrays, due in large part to their high power, small size, and relatively low cost. Present arrays are already able to produce 100-150 W of laser power at the 795 nm Rb D1 transition. In order to make use of a large part of the broad spectral width (≈ 2 nm) of these lasers it is necessary to use very high buffer gas pressures to collisionally broaden the Rb absorption spectrum. The Princeton group has recently published a technique for using AlGaAs diode laser arrays for polarization of ^{129}Xe in a flowing gas stream with subsequent cryogenic accumulation and storage of the polarized ^{129}Xe for later use.[23] This technique should achieve gas production rates close to the theoretical optimum, opening the door to a wide range of applications.

These refinements and others, along with full automation, storage and transport capability, are currently being incorporated into a product that will be commercially available in the near future from a new company called MITI (Magnetic Imaging Technologies, Durham, NC). According to Robert D. Black, President of MITI, the MITI hyperpolarizer is primarily targeted for clinical and medical research imaging, but can also be employed in materials, physics, chemistry and biological applications. A beautiful example of a human lung image obtained with helium is shown in Fig. 4b.

Conclusion

The mushrooming interest in gas phase optical pumping in recent years has resulted primarily from a few key experimental breakthroughs. The ability to separate the polarized gas from the alkali metal and subsequently transport it to high magnetic field for NMR or MRI has opened the door to a diverse range of applications in chemistry, physics, materials science, and medicine. MRI has especially benefited from the recent leaps in laser technology that allow enormous quantities of the highly polarized gases to be produced.

The usefulness of optical pumping in spectroscopy can be extended by cross-polarization techniques. However, achieving efficient cross polarization has remained an elusive goal. Though definite progress has been made, there are still some formidable

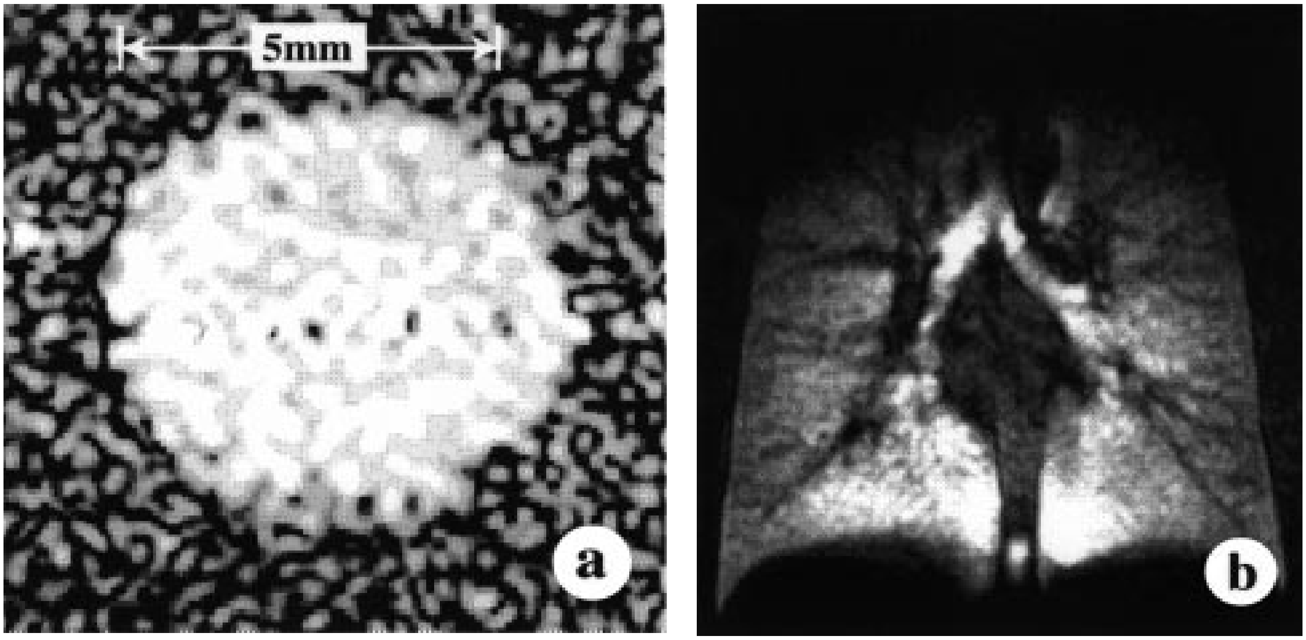

Figure 4. *Optically pumped nuclear magnetic resonance images. (a) A preliminary ^{129}Xe image of a cylindrical tube at 4.2 T obtained by C.R. Bowers, E. Hughes, and B. Inglis using the small animal MRI system located in the Center for Structural Biology at the UF. (b) Optically pumped ^{3}He image of the human lung, obtained by the Duke-Princeton collaboration (courtesy of MITI).*

challenges to be faced before the technique will obtain any measure of generality.

Perhaps the most exciting recent development in optical pumping science has been its application to *in-vivo* MRI. The optimization and commercialization of the optical pumping process is permitting large quantities of highly polarized xenon or helium gas to be prepared in an automated fashion by technical personnel in a clinical environment. Although the human being is perhaps the most interesting subject for optically pumped MRI, a plethora of materials science and biological microimaging applications can also be envisioned.

In conclusion, optical pumping is a technique that yields dramatically enhanced NMR signals without resorting to ultra-high *B/T*, since the optically pumped nuclear polarization is independent of *B/T*. The development of optical pumping and other NMR signal enhancement methods should be pursued at NHMFL in parallel with the efforts in the magnet development program.

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People in the News

Welcome

Betty Gaffney joined the FSU Department of Biological Science and the NHMFL in September, 1996. Dr. Gaffney served for 22 years on the faculty at Johns Hopkins University in Baltimore, and she was professor of chemistry with adjunct appointments in Biophysics and Biology. She is on the editorial board of Annual Reviews of Biophysics and Biomolecular Structure and the publications committee for FASEB and is serving a second term on the NIH BBCB (biophysics) study section. She has been chair of the Gordon Conference on Magnetic Resonance in Biological Systems (1992) and was a member of the organizing committee for the XVIIth International Conference on Magnetic Resonance in Biology and Medicine held last summer. Her research emphasizes developing new applications of EMR spectroscopy to biology, and the cell biology of lipid mediators, particularly with regard to inflammatory diseases. Postdoctoral associates currently working with Dr. Gaffney are Brendan Maguire, Viktoria Kofman, and Tom Morgan.

Universities Recognize NHMFL Faculty & Associates

James Brooks (FSU Prof., Physics) received a university planning grant to develop a research proposal on “Molecular Materials and Their Applications.” The university sponsors these awards to encourage development of proposals that attract outside funding for research activities. Dr. Brooks has been a member of the international team of experimentalists conducting the Dirac Series experiments at Los Alamos. As noted in the March 22, 1997 issue of *The Economist* (page 101), the Dirac experiments are performed under “extreme conditions—so extreme that the materials, and most of the experimental apparatus will be utterly destroyed in the process.” For further information on the Dirac Series, see the 1996 Summer Issue of *NHMFL Reports*.

Peter Fajer (FSU Assoc. Prof., Biological Science) and **Adriana Moreo** (FSU Assoc. Prof., Physics) earned Developing Scholar Awards, which are given to faculty who have shown exceptional promise as scholars early in their careers. Dr. Fajer’s research focuses on a novel application of the technique of electron paramagnetic resonance spectroscopy to understanding the molecular interactions and structural changes that occur within muscle proteins during force generation. Dr. Moreo, according to Dr. Susan Allen, the FSU vice president for research, “has been a major player in computational physics and, in particular, to the application of these techniques to strongly correlated systems. Her quantum Monte Carlo studies of complex materials, including HiT$_C$, have received international recognition.”

Gary Ihas (UF Prof., Physics) won a College of Liberal Arts & Sciences Teacher of the Year award. He was nominated by undergraduate students in his classes for this highly selective award, and was cited for his innovative teaching methods and the special lengths to which he went to meet student needs. Dr. Ihas teaches the Modern Physics Course taken by physical sciences majors and advanced engineering students.

Benny Lesch (Senior Design Technician, NHMFL Pulse Magnet Group) received an Exemplary Service Award from FSU. This monetary award is the highest university honor available to employees in technical support positions, and his classification faced the greatest level of competition. Benny has been responsible for the fabrication of NHMFL pulsed magnet coils and for many of the innovative and critical engineering modifications. The recognition of his work by the university—alongside the awards to senior and aspiring faculty members—speaks directly to the depth of the expertise resident at the NHMFL.

David Reitze (UF Asst. Prof., Physics), **Fred Sharifi** (UF Asst. Prof., Physics) **Chris Stanton** (UF Prof., Physics) recently won teaching improvement program (TIP) awards. These awards recognize outstanding qualities in teaching following peer review evaluations by faculty and an examination of the teaching record over several years. Dr. Reitze was also a 1996 Cottrell Scholar, one of only 15 in the United States awarded to distinguished young faculty members in the physical sciences. David has developed an optical coherence tomography (OCT) using femtosecond laser pulses to image turbid structures such as the back of the eye.

Steven Van Sciver (FSU Prof., Mechanical Engineering and Acting Director of NHMFL Magnet Science and Technology) was named FSU Distinguished Research Professor. This award recognizes scholarly productivity, national and international visibility, and evidence of recognition and honors related to research. Only three such awards were given university-wide. At the ceremony, Dr. Susan Allen, university vice president for research, said of Dr. Van Sciver, “His research is applicable to real world, state-of-the-art technology. His success in integrating research and development activities, before the national trend toward such partnerships, validates that academic research, when of high quality, leads to significant technological and commercial breakthroughs.”

More Accolades

Jack Crow, NHMFL director and FSU professor of physics, was invited by U.S. Secretary of Energy Federico Peña to serve as a member of the DoE Basic Energy Sciences Advisory Committee. This committee provides advice and recommendations to the Director of Energy Research on policy issues relating to the department’s basic energy sciences program.

Pierre Ramond was recently elected President of the Aspen Center for Physics, a summer institute for theoretical physicists located in Aspen, Colorado. As reported in the Summer Issue of *NHMFL Reports*, Dr. Ramond received the 1996 Scholar/Teacher of the Year award—the university’s highest internal award. It was the first time a physicist had ever won this distinguished award.

Pierre Sikivies won the Jesse Beams Medal from the Southeastern Section of the American Physical Society for his invention of a method to detect axions. This prestigious award is given in recognition of outstanding achievements in research carried out in the southeastern United States.

60 Tesla Magnet Moves to Completion

The first pulses moved closer when the 60 T quasi-continuous (q-c) magnet was set in its thousand-liter dewar in April. The final power converter rectifiers also were received in April, bringing the installed DC power to 560 MVA or 450 MW at maximum voltage. Both magnet and power supply are undergoing final testing and calibration, fueling optimism that the first 60 T pulses will occur in June, if Murphy's Law can be suspended.

The NHMFL 60 T q-c represents a huge increase in capability over existing magnets of its class. The bore area is approximately twice as large and the maximum field is 50% larger than the (only) existing q-c magnet that was pioneered by the University of Amsterdam over 25 years ago. In spite of their versatility and capability q-c magnets are not commonplace in magnet laboratories because of their large sustained power demand. The most practical power source for fields above 40 T seems to be inertial storage, as evidenced by the NHMFL magnet and two new q-c magnets that are either being constructed or designed, all of which will use inertial energy storage. The next q-c magnets are expected at the University of Amsterdam and, possibly, the Institute of Plasma Physics, Hefei, China.

Like the NHMFL capacitor-driven magnets, the 60 T q-c will be pre-cooled to the temperature of liquid nitrogen and then allowed to heat during the pulse with no attempt at active cooling. The resistive heating, in fact, determines the maximum pulse length, and the necessity of re-cooling the magnet determines the repetition rate of the pulses. A 60 T flat-top field can be maintained for 100 ms, and lower fields maintained for considerably longer (about 2 s at 20 T). To speed the re-cooling process the magnet's surface area is increased by spacing the nine mechanically-independent concentric coils a few mm apart. Even so, re-cooling will take about one hour. A monolithic magnet of this size would take about a day to cool, besides being an unwise mechanical design and quite risky to manufacture.

The electrical power from the NHMFL inertial generator is AC, which affords myriad opportunities to shape the pulses (ramps, steps, flat-tops, etc.) at the cost, however, of ripple in the field stemming from the process of rectification to DC. The field ripple will be greatest at 720 Hz and is estimated to be about 1 part in 10,000. Plans are already afoot to reduce it even further. Power from DC generators may lack ripple but it is not so easily controlled to give the variety and precision of pulse shapes using AC generators. The power from DC generators also may be contaminated with brush noise.

Experiments of a wide variety already have been proposed for the 60 T q-c. These initially will use the flow cryostat that just arrived, and later a dilution refrigerator and He-3 cryostat. There will be more reports as we become familiar with this marvelous new research tool—the first ever of its kind in the United States.

This article was contributed by Larry Campbell (505) 667-1482 (ljc@lanl.gov), the Director of the NHMFL Pulsed Field Facility at LANL.

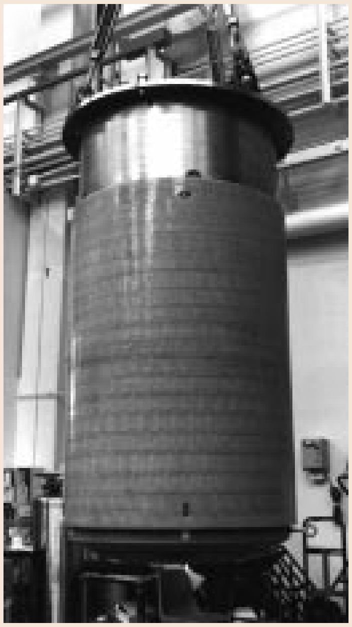

Figure 1. *Five tons of assembled magnet swing free on their way to placement inside the liquid nitrogen dewar. Cool-down and electrical tests are next, followed by test pulses up to 60 T in early summer.*

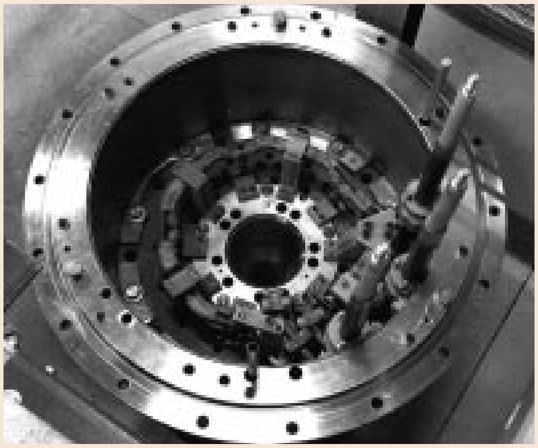

Figure 2. *Looking into the maw of the 60 T quasi-continuous magnet. The bore tapers to 34 mm in the experimental area, approximately a meter down from the top. Three electrical circuits that will carry about 20 kA each emerge on the right.*

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