NATIONAL HIGH MAGNETIC FIELD LABORATORY

NHMFL REPORTS

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New Testing Facilities Available to Users

The Large Magnet Component Test Laboratory (LMCTL) is being established at the NHMFL in Tallahassee, partly to fulfill requirements of the Magnet Science and Technology Group, but primarily to respond to magnet technology development needs outside the laboratory, both from the government and commercial sectors. Presently, the facilities in the LMCTL are being upgraded for better performance as well as for more efficient and safer use. Upgrades include:

- A permanent user platform providing easier and safer access to the various test stations
- Rigid, water-cooled, high-current DC buswork with protected distribution to all test stations
- Simplified connections of the buswork either to one of the building power supply modules or to the Hybrid outsert power supply
- Permanently installed, high-power load resistors that will allow the regulation specifications of the building power supply to be achieved during tests of low-impedance components
- An upgraded rough-vacuum system (500 CFM at 2 mbar)
- LN_2 distribution in vacuum-jacketed lines
- Instrumentation and data acquisition systems optimized for and dedicated to the facilities in the LMCTL.

The LMCTL, in Cell 16 of the Operations and Magnet Development building, has roughly 15 x 15-m^2 floor space covered by a 20-t crane and a 13-m ceiling. Available utilities are 480 V, 300 A, 3-phase electrical service; chilled water; and chilled and deionized water (up to 400 L/s with 3 MPa head). In addition to the regular access ways, the cell has a removable wall for bringing in large equipment.

Magnets and Instrumentation

Several superconducting magnets are available with special capabilities for testing large conductors:

- The Coil Winding and Test eXperiment (CWTX) magnet is a nearly cryostable, NbTi magnet capable of providing 8 T on a conductor sample in its 380 mm cold bore. Sample configuration can be either a loop in the bore or a straight piece fit through the magnet's 67 mm radial-access port.

LMCTL Magnets continued on page 4

Facilities

Electrical

A variety of large, high current electrical equipment is available to support testing in the LMCTL, including:

- Connections to any or all of the four modules of the building power supply, each rated at 500 V, 20 kA with 10 ppm regulation
- Connection to the Hybrid outsert power supply, rated at ±25 V, 11 kA with 100 ppm regulation

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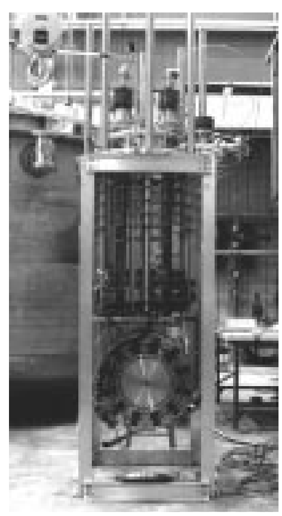
User Activity

Apart from in-house development activities, the following programs are in progress involving external users:

- Tests of Nb_3Sn high-current Rutherford cables (conductors appropriate for high field accelerator dipoles) for sensitivity of the critical current to transverse mechanical loads, with R. Scanlan and D. Diedterich of

LMCTL Users continued on page 4

Test stations on user access platform


14 T, 150 mm bore Oxford split solenoid magnet


"TACL" (Test for AC Loss) 7 T dipole magnet

From the Director's Desk

The change of leadership at the Florida State University System is very important to the ongoing success of the laboratory

In January of this year, Dr. Adam W. Herbert became the sixth chancellor of the Florida State University System (SUS), assuming the vacancy of Charles B. Reed who departed Florida to assume new duties as chancellor of California State University. Chancellor Herbert served as president of the University of North Florida from 1989-1998 following faculty appointments at University of Southern California (School of Public Administration), Virginia Polytechnic Institute and State University, Howard University, USC's Washington Public Affairs Center, and Florida International University in Miami. He earned his bachelor's and master's degrees from the University of Southern California and his Ph.D. in urban affairs and public administration from the University of Pittsburgh. In addition, he has held numerous local and national leadership positions in his field of public administration and is a fellow in the highly prestigious National Academy of Public Administration.

The change of leadership at the Florida SUS is very important to the ongoing success of the laboratory for several reasons. First, the SUS chancellor chairs the NHMFL Inter-Institutional Committee and is the primary advocate for the NHMFL with the Florida legislature and the ten state universities. In addition, he directs the NHMFL External Advisory Committee and appoints its members.

In an effort to get to know more about Chancellor Herbert, and to properly introduce him to our readers, colleagues, and supporters, we posed several questions to him. I am pleased to reprint the Q&As here. As my closing remarks, I would like to publicly welcome Dr. Herbert and his new team at the Office of the Chancellor, and offer them our assistance as we all strive to advance education, research, and economic development.

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

Q. Underpinning the success of the NHMFL is a strong multi-institutional partnership that joins two Florida universities and Los Alamos National Laboratory. Would you share your thoughts on such partnerships with our readers?

A. Multi-institutional partnerships such as the NHMFL bring together the financial and intellectual resources of the partners in the pursuit of knowledge. By providing the laboratory facilities for a diverse range of research, the NHMFL serves as a nexus for intellectual exchange and stimulates creative thinking.

Regardless as to whether they are scientific or philosophical endeavors, multi-institutional partnerships should be encouraged throughout the State University System (SUS). They are crucial to the future of society because they provide the breeding ground for new ideas and encourage interdisciplinary thinking. New discoveries hold the power to change how we perceive the world, and new technologies provide the foundation for economic growth.

Aside from the economic and societal benefits associated with multi-institutional partnerships, they also represent sound public policy. Facilities such as NHMFL are expensive to build and maintain. If that cost had to be born by one institution, it would likely be prohibitive. Partnering allows for the development of superior research facilities and prevents the taxpayer from being saddled with the cost of maintaining underutilized, and perhaps inferior, facilities at each institution.

Q. One of the NSF's charges to the NHMFL is to enhance U.S. competitiveness. To this end the laboratory has developed numerous significant collaborations with private sector partners. Would you please comment on the importance of the laboratory and research universities like FSU and UF teaming with industry?

A. All SUS universities should develop partnerships with private sector organizations, be they involved in business, industry, medicine, or delivery of social services. Those universities that have significant investments in advanced scientific research facilities need to be actively engaged with the industrial community in order to maximize the use of those facilities. The symbiotic relationship achieved through the teaming of academia and industry strengthens both, and enhances U.S. competitiveness in the world marketplace.

Encouragement of such partnerships, especially in high technology fields, is one of the primary goals for the SUS as we enter the 21st century. University research capability provides resources and objectivity that might not otherwise be available to private sector organizations. A certain economy of scale is achieved when multiple partners with similar interests are able to pool their resources, and the process of scientific inquiry reduces the risk associated with new business endeavors. When university research leads to new discoveries or developments in technology, the private sector is better positioned to distribute the associated benefits to society. This takes place through the marketplace, generating economic growth and/or an improved standard of living.

Q. The State of Florida, principally through the public/private partnership Enterprise Florida, is positioning the state to do a better job of attracting high-tech industries. What opportunities do you see for the NHMFL and the SUS in this area?

A. Enterprise Florida is wise to encourage development of high-tech industry in Florida. It will broaden and strengthen the state's economic base without many of the environmental risks normally associated with heavy industry. State universities need to be an active partner in this endeavor for all of the reasons stated in response to the previous question.

A perfect example of this type of partnership is the I-4 (Interstate 4) High-Technology Corridor project that seeks to attract high-tech development along the interstate highway running between Tampa, Orlando, and Daytona Beach. This cooperative effort includes the University of Central Florida in Orlando, the University of South Florida in Tampa, and the Tampa Bay Business Partnership. In conjunction with other efforts by Enterprise Florida, this partnership has been successful in attracting Lucent Technologies to the Orlando area. Lucent plans to locate their Bell Labs Advanced Semiconductor Development and Research Facility with the Cirent Semiconductor operations already in Orlando. This move will bring hundreds of high paying jobs into the area, and create opportunities for advanced research for university faculty and graduate students.

A golden opportunity exists to develop an I-95 Corridor in South Florida, which would be anchored by Florida Atlantic University in Boca Raton and Florida International University in Miami. The combined strengths of these two universities could provide the educated workforce and research capacity that is needed to attract high-tech industry to the area. Similar development strategies will be encouraged for other state universities and established research facilities like the National High Magnetic Field Laboratory. These economic partnerships will become the nucleus around which new high-tech industries can grow, to the mutual benefit of all partners, including Florida's citizens.

Q. The NHMFL serves users from a wide range of science and engineering disciplines and fostering interdisciplinary research is a high priority for the laboratory. What can the SUS do to promote interdisciplinary activities throughout the system?

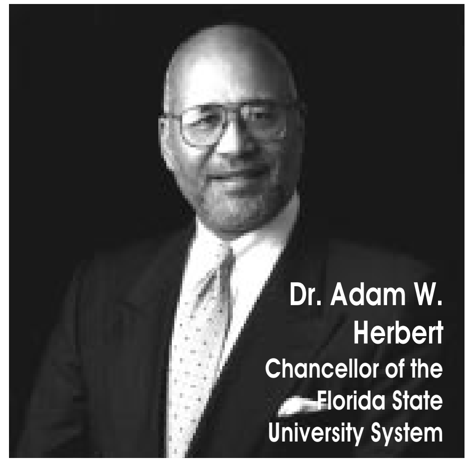
A. The interdisciplinary approach is fast blurring the boundaries between traditional fields of study in higher education. This movement is evidenced by the development of new interdisciplinary degree programs throughout the SUS. Numerous institutions and centers that promote interdisciplinary research have also been established under the umbrella of host universities.

Interdisciplinary thinking should always be encouraged at every level of the university community. Where it makes sense to do so, the SUS should continue to support the development of programs and research facilities dedicated specifically to interdisciplinary research. Care must be taken, however, to ensure that such endeavors do not undermine the theoretical underpinnings of established disciplines. The public good is equally served by depth of knowledge as well as breadth. NHMFL is a perfect example of an institute that promotes interdisciplinary research by bringing together people from distinct disciplines who may have a common need or interest. This type of cooperation serves to invigorate rather than dilute the individual disciplines.

Q. The laboratory has invested heavily in many different K-12 educational programs, including student-oriented programs, teacher training, and curriculum development. What is the SUS role with regard to K-12 education?

A. One proposed goal of the SUS strategic plan currently under development is establishment of a seamless transition for K-12 students into the state universities and community colleges. Strategies for achieving this goal include closer coordination between the SUS and the Florida Department of Education on issues such as minimum high school graduation standards, teacher education, student advising, and access to technology. Direct outreach programs by the SUS will be emphasized and Education Partnerships between state universities and their local school systems will be encouraged. This is expected to improve graduating seniors' readiness for college and to smooth over some of the psychological hurdles they will face as part of that transition.

Several other special projects in support of this goal are in the planning stages. These projects will attempt to clearly define the educational pathway a K-12 student should follow to ensure that they meet minimum admission standards for a state university. One of these projects is a parent/student guide that will outline required high school curricula, recommend study habits, and identify resources for financing college. It will also include some planning tools for use by parents and students.



Education Partnerships envisioned as part of the new strategic plan will not be limited to the colleges of education. The entire university community will be encouraged to become involved with local elementary and secondary education as part of an investment in the future. Areas of involvement might include direct technical support, research services, or classroom assistance. An excellent model for this type of partnership would be the educational programs and services currently offered by NHMFL.

Q. The NHMFL uses the Internet extensively to enhance our education programs, to facilitate scientific discussions, and to move toward providing users remote access to the laboratory's world-class magnet systems. Distance learning, virtual laboratories, and other uses for the Internet are all hot topics, and new proposals and programs seem to be popping up daily. What are your thoughts on the possibilities…and the pitfalls, if any?

A. The Internet is one of several emerging instructional technologies that provide new opportunities in education. It is used throughout the SUS to provide information and planning services to students, staff and the general public. In addition, it is a powerful tool for conducting research and a facile medium for distance education. During the 1997-1998 school year approximately 58,000 SUS students enrolled in 13 degree programs and 2,500 individual courses delivered using instructional technologies, which included use of the Internet.

Herbert continued on page 4

LMCTL Facilities continued from page 1

- Permanent water-cooled buswork serving each of the 4 test stations rated at 20 kA
- Temporary and flexible water-cooled buswork for up to 80 kA
- High-current cryogenic current leads, presently available with 10 kA and 50 kA ratings (designs with 15 kA and 20 kA capacity are in the works)
- Four individual high-current breakers, each rated at 4 kA, 1 kV
- The high-current breakers of the Hybrid outsert power circuit—two sets rated at 11 kA, 5 kV each
- A variable discharge resistor, designed to absorb up to 750 kJ and adjustable in steps from 0.4 to 90 Ω.
- A variable discharge resistor (part of the Hybrid outsert power circuit) designed to absorb up to 120 MJ and adjustable in steps from 0.25 to 0.6 Ω.

Cryogenics

The LMCTL has ample cryogenics capabilities. Liquid helium is available from three refrigerator/liquefiers: (2) PSI model 1630s capable of 70 L/h or 200 W, and (1) PSI model 1410 capable of 25 L/h or 75 W. In addition, vacuum-jacketed piping is available to transfer LHe from a cryogenic transporter parked outside the building. Vacuum-jacketed piping for LN_2 delivery directly to stations within the laboratory is scheduled for installation in the coming year.

A variety of LHe cryostats are also available with inside diameters of 150 mm, 300 mm, 600 mm, 800 mm, 1 m, and 2 m. The 600 mm cryostat has provisions for He II cooling.

Mechanical

Cryogenic mechanical test apparatus is available for the application of loads up to 500 kN. Of particular value for the characterization of strain-sensitive conductors are specially developed facilities that allow the application of up to 250 kN in tension longitudinal to a test conductor and/or 250 kN of transverse compression while simultaneously applying field and current.

LMCTL Magnets continued from page 1

- The Navy superconducting magnetic energy storage conductor test apparatus (SMES CTA) magnet can apply up to 4 T to a 2 m diameter loop of test conductor and is also designed for operation as part of a 50 MJ SMES system. The sample volume of the SMES-CTA cryostat provides full thermal isolation from the magnet vessel and can be operated over a full range of temperatures from LHe to room temperature.
- The Oxford Split Solenoid is designed to produce 14 T in its 150 mm diameter high field region, which accepts large, straight conductor samples through a 30 mm x 70 mm radial-access port. The inner wall of the Oxford cryostat is structurally designed to be capable of transmitting 250 kN mechanical loads and is equipped with remotely actuated pin-and-clevis at the bottom for attaching samples.
- The "TACL" magnet (Test of AC Loss) is 1 m dipole designed to produce a highly uniform 7 T field over the full length of its 40 mm cold bore. The magnet is primarily used for testing AC losses of large conductor samples in linearly ramped fields with rates up to 1 T/s or exponentially discharged fields with initial rates of up to 45 T/s.

LMCTL Users continued from page 1

Lawrence Berkeley National Laboratory

- Measurements of the critical currents of Al-stabilized NbTi conductors used in the BABAR detector magnet for the Stanford Linear Accelerator Center, with T. O'Connor of Lawrence Livermore National Laboratory
- Measurements of coupling losses in model conductors appropriate for a SMES system for power line stabilization, with V. Karasik and M. Nilles of BWX Technologies (formerly Babcock and Wilcox)
- Demonstration of a SMES magnet and power-conditioning module, with M. Superczynski of the Naval Surface Warfare Center
- Tests of HTS prototype lead systems intended for the FNAL Tevatron and the CERN LHC, with L. Cowey, R. Hodges, and J. Romans of EURUS Technologies.

This article was contributed by John Miller, head of the Large High Field Systems Group of the laboratory and Hybrid project, who may be contacted at 850-644-0929 or miller@magnet.fsu.edu, for further information.

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Expanded use of educational technology for distance education is another goal of the proposed SUS strategic plan, and will be made a part of each university's academic mission. The Internet will play a major role in the delivery of distance education because it allows for both synchronous and asynchronous interaction between students and faculty. Interactive programming can also be easily transmitted via the Internet, which makes it ideal for self-paced education programs and conducting virtual learning experiences.

Although use of the Internet in the SUS is expected to grow tremendously over the next decade, this growth will not come without some challenges. Infrastructure will need to keep pace with technological advancements if they are to be utilized effectively. This will always be problematic because it is difficult to anticipate what future requirements might be, or how much they will cost. Concerns have also been raised regarding the impact that electronic cut and paste features are having on academic rigor and integrity. In addition, the protection of copyrights and intellectual property is made more difficult by the free-for-all nature of the World Wide Web.

As an educational delivery system, the Internet will not likely replace the classroom. Some coursework is simply better suited for the lecture hall or laboratory. And the majority of students enrolled in the SUS continue to choose the campus/classroom experience over distance education alternatives. This is especially true for the younger students of traditional college age, whom we would assume to be more computer literate than older students.

First 10 Millimeter Bore Pulsed Magnet Reaches 77.8 T Without Destruction

Pulsed magnets presently used at the NHMFL Pulsed Field Facility at Los Alamos National Laboratory (LANL) are running at 50 T and 60 T with the bore sizes of 24 mm and 15 mm, respectively. These magnets are made from Glidcop Al-15 conductor wire with S2-glass fiber composite as internal reinforcement. As users gain experience with pulsed magnets, they are becoming increasingly interested in a higher field magnet with a smaller bore. For this purpose, a 10 mm bore test magnet was designed and manufactured by the NHMFL Pulsed Magnet Group at Tallahassee, together with 15 mm and 24 mm bore upgrade magnets as shown in Figure 1.

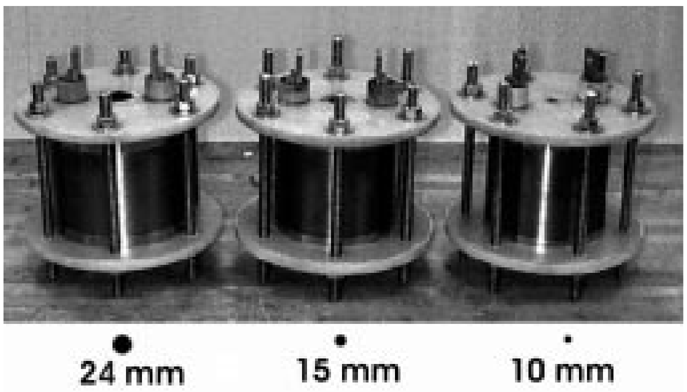

Figure 1. 24, 15, and 10 mm bore pulsed magnets designed by the NHMFL Pulsed Magnet Group. The 10 mm bore magnet produced a record field of 77.8 T without destruction.

Because of the relatively low strength of the Glidcop, the conductor suffers plastic deformation during both the up-sweep and down-sweep of a high field pulse. The requirement for a long life expectancy calls for a design where the strain cycle of the conductor is kept as small as possible compared with its elastic strain range to avoid failures due to material fatigue. It is therefore advantageous to use conductors with a large elastic strain range, i.e. with a high elastic strength. For this purpose, CuNb wire with a cross-section of 3 mm × 4 mm from Supercon Inc. was chosen for the conductor. The wire has an ultimate tensile strength of 1.2 GPa with 5.5% elongation at 77 K. It was insulated with All-Polyimide 32LQI-2 film by Fraivillig Materials Company. The new Zylon fiber is used as the internal and external reinforcement combined with a 10 mm thick stainless steel cylinder. The magnets are designed so that the inner four conductor layers are internally reinforced by the Zylon fiber composite, while the stresses in the outer layers are supported by the conductors themselves and the external reinforcement. Due to the high packing factor, it is difficult to do vacuum impregnation after a dry winding. The magnets were wet wound with epoxy W19.

During the period from June 8 to June 18, 1998, the three pulsed magnets were tested at the NHMFL pulsed magnet facilities at LANL. In order to investigate the behavior and the limits of the magnets using the new combination of CuNb conductor and Zylon fiber, all the magnets were tested to destruction. The 10 mm bore magnet produced a record field of 77.8 T with a non-destructive pulse duration of about 20 ms as shown in Figure 2. The current at the peak field is 41 kA. During an 80.1 T shot, the magnet failed mechanically near the end plates at the transitions. The 15 mm and 24 mm bore magnets suffered the same failure in the inner layers after reaching their peak fields of 74.2 T and 65 T, respectively. The computer simulation of the pulse shape with the capacitor bank data matches the measurement very well. The stress calculation shows that all the magnets failed at the same stress level in the Zylon fiber composite. The failure produced an expansion of the coil in the axial direction at both ends.

Another important improvement made in this coil test was the connection between the terminals of the magnets and the bus bars. A well-insulated and reinforced coaxial assembly was used instead of the two parallel copper bars. This connection avoided the magnetic coupling of the leads and the magnet and thus significantly reduced the vibration and the acoustic noise of the system during the high current pulses.

These test results have shown a promising future in the field of the pulsed magnet development. A 70 T, 10 mm bore pulse magnet will be provided to our users in the near future.

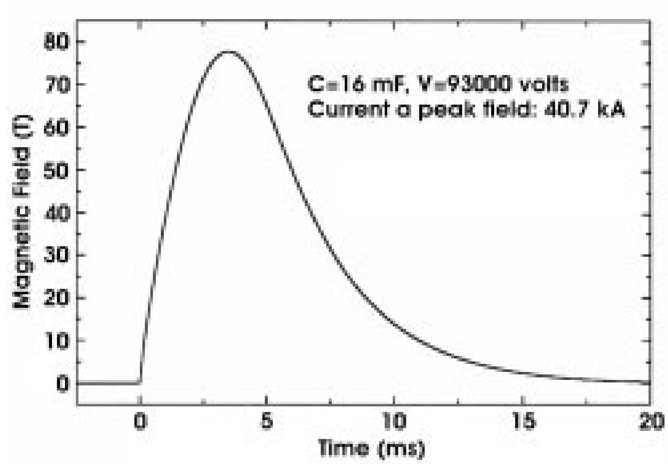

Figure 2. The waveform of the 10 mm bore magnet at the 77.8 T pulse.

For further information on design and construction of pulsed magnets contact Liang Li, Benny Lesch, and Vincent Guy Cochran of the NHMFL Pulsed Magnet Group, 850-644-0854, liang@magnet.fsu.edu. Liang Li contributed this article.

From the Chief Scientist's Desk

Microwave resonances in high magnetic field insulating phases of two-dimensional electron and hole systems

Lloyd W. Engel

In this issue Lloyd Engel describes experiments on two-dimensional electron systems at very high magnetic fields, B.

Since the kinetic energy of the electrons (holes) is essentially quenched by large B, the electrons form a crystal with a triangular structure. With a random array of pinning centers, the crystal breaks into domains, each of which oscillates at the characteristic frequency, ω_o. Dr. Engel describes the anomalous behavior of ω_o as a function of magnetic field strength which deviates strongly from the theoretical predictions.

The experiments are a highly effective method for studying the dynamics of pinned crystalline electron phases. These results require a new theoretical approach to the dynamics of these systems.

Robert Schrieffer

Two-dimensional systems of electrons, realized in semiconductor devices such as GaAs/$Al_xGa_{1-x}As$, are widely studied in high magnetic fields. When such a sheet of electrons is made with sufficiently low disorder, it exhibits a series of integer and fractional quantum Hall states as the magnetic field is changed. The series of fractional quantum Hall states terminates at high magnetic field in an electrical insulator. This insulator is of special interest because it may be a form of an exotic phase of matter called a "Wigner crystal.'' This paper will review recent microwave measurements[1,2] done on such high magnetic field insulators in two-dimensional systems. The measurements reveal spectacularly sharp, well-defined spectral lines (resonances), whose characteristics indicate that some rethinking of the conventional picture of the insulator is required.

A Wigner crystal is a periodic lattice of individual electrons, just as an ordinary crystal is a lattice of atoms. Also like an ordinary crystal, a Wigner crystal is a solid, and its stiffness is due to the electrostatic repulsion between electrons. A disorder-free two-dimensional electron system (2DES) is theoretically predicted[3] to be a Wigner crystal, with a triangular lattice, at low temperature (T) and sufficiently high magnetic field (B). For electrons in GaAs, and a relatively high density sample, the Wigner crystal would form for Landau filling $\nu<1/6.5$. (The filling factor $\nu=nh/eB$, where e is the electronic charge, and h is Planck's constant.) Any real 2DES is subject to disorder, in the form of impurities and imperfections of the semiconductor host. Large enough disorder would prevent crystalline order from manifesting itself, and that case is not considered here. The case we do consider occurs when disorder creates imperfections in the Wigner crystal lattice, and so gives a finite correlation length to the crystalline order, breaking the Wigner crystal into domains of size L. Without disorder the Wigner crystal could slide along freely, but the interaction with the electric potential of the disorder "pins" the crystal, which is why we expect it to behave as an insulator. Within the picture of a pinned Wigner crystal[4], the microwave resonance phenomenon to be discussed is usually interpreted as a "pinning mode," in which the crystal domains oscillate within the impurity potential without breaking free of it.

The high B insulators, though they occur in simple systems, and are of fundamental interest, have certain properties that make them difficult to study experimentally, especially for the most interesting case of low T, and B far greater than that of the transition from a quantum Hall state to the insulator. Determination of structure by scattering methods is difficult since the two-dimensional system has too few electrons. Standard DC electrical measurements are made difficult by the high resistivity (in the linear regime) of the insulator, and by problems with the electrical contacts between the 2DES and the measuring apparatus. Nonlinear I-V measurements have proven, at least so far, to be difficult to interpret.

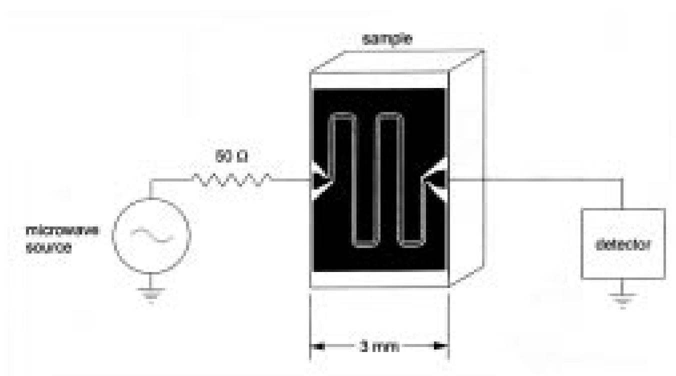

Figure 1. A simplified schematic of the microwave measuring set-up. Metal films (shown in black) on the front surface of the sample define a microwave transmission line. The conductivity ($Re(\sigma_{xx})$) of the 2D system is calculated from the loss of the microwave signal in its transmission from the source to the detector.

The microwave method we used is ideally suited to studying the insulating phases of two-dimensional electron systems in high magnetic fields, since it is contactless, and since large signals can be obtained from these insulators. The idea behind the method is to use a metal structure to create a microwave frequency electric field in the plane of the 2DES, and to measure the power the 2DES dissipates, which, for the small conductivities of 2DES in high B, is proportional to the conductivity ($Re(\sigma_{xx})$) of the 2DES. So a wide range of rf and microwave frequencies can be studied, the metal structure is designed as a "transmission line.'' Figure 1 shows a sketch of a sample, with a transmission line patterned onto it, where metal films are shown in black. The 2DES lies about half a μm below the surface of the sample onto which the line is patterned. The transmission line is most easily understood as a planar analogy to a coaxial cable. The narrow central line of the structure is driven with respect to the outside metal films, which are shorted together outside the device. In the slot between the central conductor and "ground" planes an in-plane electric field is created, which couples to the 2DES. The 2DES has the effect of absorbing some of the microwave power transmitted through the line, and measurement of the absorbed power allows calculation of a reasonably accurate value of Re(σ_{xx}), which will prove useful in interpreting the resonance data. The reason why the transmission line meanders across the face of the sample is that increasing the length of the line increases the measured absorption. The detector used is a coaxial bolometer, operating at high B, and low T<50 mK, only 1 cm away from the sample. The microwave source is put together with a second cold detector, which regulates the microwave power sent into the transmission line.

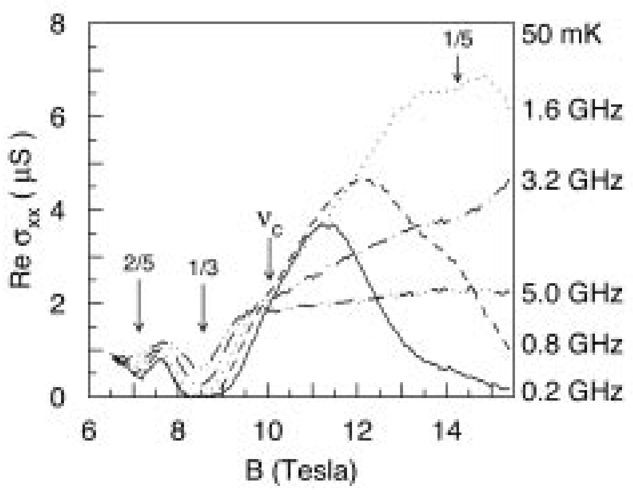

Figure 2. Microwave conductivity (Re(σ_{xx})) of sample 1, vs magnetic field. ν_c marks the transition from the 1/3 fractional quantum Hall effect to the insulating phase. Temperature is 50 mK.

Figure 2 shows Re(σ_{xx}) vs. B at several frequencies (f), for a moderate-quality 2DES in a GaAs/$Al_xGa_{1-x}As$ heterojunction that we will call Sample 1. Data on sample 1 is treated in detail in ref. 2. The dips marked 2/5 and 1/3 show the fractional quantum Hall effect, and are like the dips seen in DC diagonal resistivity traces. The sample is an insulator for magnetic fields above a critical B of about 10 T. At lower B than that, the conductivity increases with f, while at higher B, in the insulator, the conductivity shows the effect of the resonance: it first increases with f, to reach a much larger value than in the lower B regime, and then decreases.

The resonances are more naturally displayed in spectra, Re(σ_{xx}) vs. f, as shown in Figure 3. Data from Sample 1, taken at several magnetic fields within the insulating phase, appear in Figure 3a. At the lowest B of 10.5 T, the conductivity monotonically decreases with frequency. As B is increased further into the insulating phase, the resonance becomes larger and sharper, while f_{pk}, the frequency of the maximum in the curve, increases slightly. The dc conductivity can be seen from the low frequency limit of the curves, and it becomes smaller as B is increased.

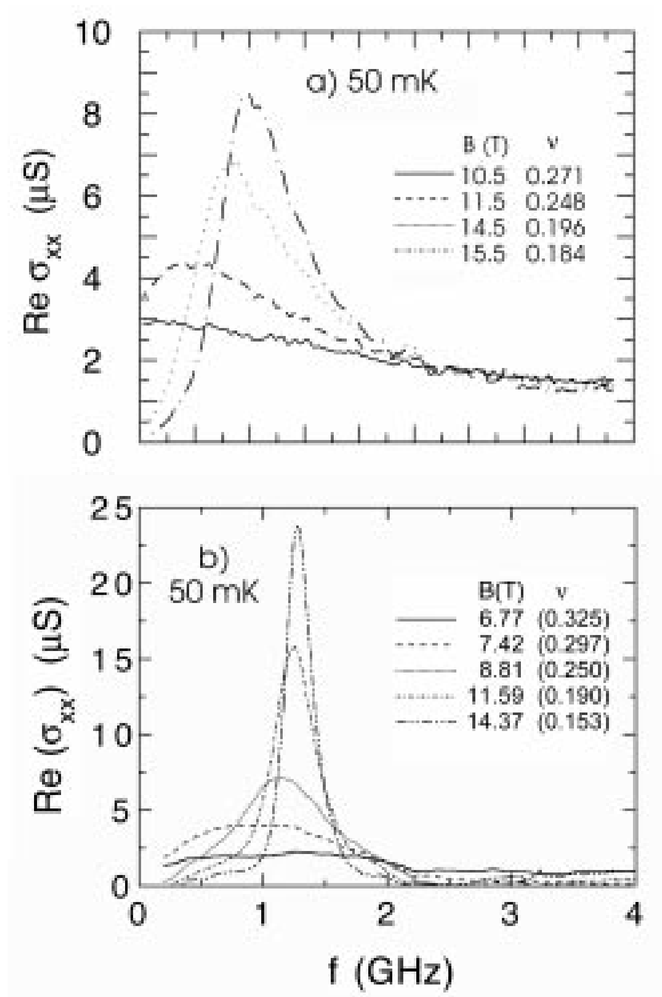

Figure 3. Microwave spectra, conductivity (Re(σ_{xx})) vs frequency (f), taken at several different magnetic fields in the insulating phase. The resonance peaks become more pronounced as the magnetic field is increased. a) shows data from sample 1, b) shows data from sample 2.

Figure 3b shows spectra taken on a different sample, sample 2, of which a detailed account in given in ref. 1. Sample 2 is a two-dimensional hole system (2DHS), which for our purposes can be thought of just like a 2DES, except with positive charge carriers of different effective mass. As in sample 1, the resonance gets larger and sharper, and at least at lower B, shifts to higher f_{pk} as B increases in the insulating phase. The resonance in sample 2, though, develops a much larger peak conductivity and gets much sharper than in sample 1. These effects are probably due to sample 2 being a somewhat cleaner and lower density system than that in sample 1, not to sample 2 being a hole system, since resonances nearly as strong and sharp have been observed in preliminary data on an electron system.

Figure 4 summarizes the features of the spectra for sample 2. f_{pk} increases with B, but this increase saturates for B>10 T, where the resonance is better developed. S is the numerical integral of Re(σ_{xx})

MICROWAVE continued on page 8

MICROWAVE continued from page 7

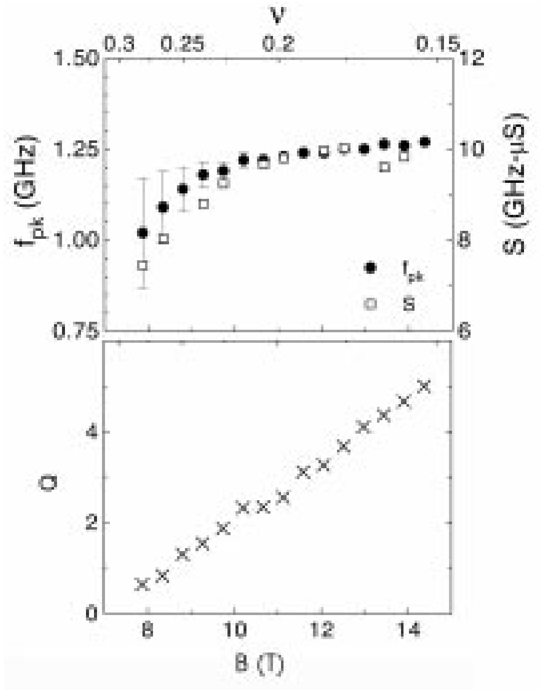

Figure 4. Measured parameters of the resonance in sample 2, vs magnetic field, at temperature of 50 mK. f_{pk} is the frequency of the maximal conductivity $Re(\sigma_{xx})$. S is a measure of the oscillator strength obtained by integrating spectra like those in Figure 3. Q is a measure of the sharpness of the resonance, f_{pk} divided by the full width at half maximum. While f_{pk} and S level off with increasing B, Q continues to increase.

vs. f (area under a curve like those in Figure 3b) over the entire experimental frequency range (0.2 to 9 GHz). For sample 2, where the resonance is much narrower than this measured frequency range, S is a good measure of the oscillator strength of a resonance. The curves for S and f_{pk}, each plotted on an axis that varies over a factor of two, follow each other well, suggesting f_{pk} and S are directly proportional. We will see that the sharpness of the peak is its most surprising feature. The sharpness is measured by Q, defined as the peak frequency divided by the full width of the peak at half its maximum value. Though f_{pk} and S vs. B level off at large B, Q does not. Instead, Q vs. B increases linearly to a maximum value of 5, indicating that the data shown do not reach a true high B limit of the resonance. Therefore, it would be interesting to study this system at higher magnetic field, and this will be done at NHMFL in the near future.

Theory[5] of the spectrum of a pinned Wigner crystal typically obtains results equivalent to an ensemble of harmonic oscillators in the magnetic field. An oscillator of the ensemble is formed by a domain of Wigner crystal bound by the impurity potential. Each oscillator has a mass M, contained in a parabolic "bowl," whose potential is proportional to $M\omega_0^2$, where ω_0 is a parameter of the potential called the pinning frequency. In the magnetic field such an oscillator has two resonant frequencies. The upper mode frequency, ω_+ , is shifted above the cyclotron frequency, $\omega_c=eB/m^*$, (m^* is the effective mass) and is too high to be of interest here. When ω_0 is much less than ω_c, the lower mode frequency is $\omega_-= \omega_0^2/\omega_c$, which can be comparable to the observed values of $2\pi f_{pk}$. The oscillator model also lets us calculate an oscillator strength. The calculated oscillator strength, S_0, is given by $S_0=n_s e^2\omega_0^2/2m^*\omega_c^2=(n_s e/B)\pi f_{pk}$, where n_s is the density of carriers participating in the resonance, f_{pk} is taken as $\omega_-/2\pi\$$, and S_0 is in units of an integral of $Re(\sigma_{xx})$ with respect to f.

Many features of the data cannot be explained by this simple theory. The observed increasing or nearly constant f_{pk} vs. B means that the pinning frequency ω_0 would have to be changing with B, which is difficult to explain, especially far from the transition to the insulator from the quantum Hall effect. Also, for the observed peak frequencies a model[6] of the pinned crystal results in a calculated domain size that would imply there are only a few carriers per domain. The value of S is in order-of-magnitude agreement with the oscillator model if all the carriers participate in the resonance. For sample 2 with all holes participating, the predicted S_0 is 24 μS-GHz, for f_{pk} of 1.25 GHz and B=14.4 T, while the observed S at that B is about 10 μS-GHz. Likewise for sample 1, at B=15.5 T, S_0 from f_{pk} is 45 μS-GHz, and the observed S is 24 μS-GHz. On the other hand, the oscillator model predicts the ratio f_{pk} /S should be proportional to B. The B dependence of f_{pk} /S in Figure 4 is clearly nearly constant rather than increasing with B. The resonance in sample 2 appears to be in conflict with the oscillator model, unless an unlikely combination of trends occurs: (1) the amount of resonating Wigner crystal in the sample increases as $n_s \propto 1/B$, and (2) ω_0 increases with B as well, roughly as $B^{1/2}$.

For a mode arising from random disorder, the oscillators would be expected to have a broad distribution of parameters, so by itself, the sharpness of the resonance in sample 2 is surprising. An intriguing possibility[7] is that the motion of the Wigner crystal is coherent over quite long length scales, much larger than a static correlation length.

In summary, the microwave methods described here are an ideal probe of the fundamentally simple high magnetic field insulating phases of two-dimensional electron or hole systems. The results require a new picture at least of the dynamics of a pinned Wigner crystal.

The work described here is the result of an ongoing collaboration of the author and the group of D. C. Tsui, at Princeton University. The study of the 2DHS is part of the dissertation research of C.-C. Li, and the samples were provided by M. Shayegan, also at Princeton.

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Magnet Lab Showcases Integrated Education & Research Activities

Throughout the summer of 1998, students at the NHMFL have been building their own computers, exploring conductors and superconductors in high magnetic fields, learning how to use a scanning electron microscope to study materials, and taking advantage of the laboratory's cutting-edge research and facilities to gain valuable workplace experiences. In addition, teachers have been developing new education resources to help them integrate what they have learned in the laboratory this summer into their classrooms this fall.

On July 31st, the laboratory recognized the students and teachers and showcased their outstanding accomplishments for the media, parents, and the general public. Forty students and five area teachers participated in this summer's NHMFL educational activities in one of six different, yet frequently complementary, programs:

- 6th Annual NHMFL Minority/Women Research Internship Program
- Computer Science Internships
- Governor's Integrating A.R.T.S. (Art, Research, Technology & Science) Program
- Summer Youth Job & Training Partnership Act
- Teacher Quest
- Young Scholars Program

The 6th Annual NHMFL Minority/Women Research Internship Program attracted 14 undergraduates from 12 universities in 9 states. Several students worked at the laboratory's partner institutions, the University of Florida and Los Alamos National Laboratory. These interns, who are pursuing degrees in science or engineering, worked with senior researchers investigating topics as wide ranging as studies of trace elements in soil from the Everglades and solid state at extremely low temperatures. In a similar way, the other five programs integrated middle and high school students and teachers from Leon, Wakulla, and Gadsden counties (Florida) into the computer science, mathematics, general science, and curriculum development activities of the laboratory.

The NHMFL's Center for Integrating Research and Learning, under the direction of Dr. Sam Spiegel, is an enormously important educational resource for the community, the state, and the nation. It continues to expand the laboratory's education programs and engage an ever-increasing number of students and teachers. All of these programs are developed through close consultation with the scientists, engineers, and technicians who conduct and support the research at the laboratory.

ATTENTION USERS

Alex H. Lacerda
Pulsed Field Facility User Programs

60 T Q-C Magnet Ready for Commissioning

The NHMFL–Los Alamos team is very pleased to announce the completed construction and initial use of the strongest magnet of its class: the 60 T Quasi-Continuous (Q-C) magnet. This significant accomplishment earned the team, which comprised members from three LANL divisions, the Distinguished Performance Award (see People in the News, page 14). The Q-C magnet, which will be officially commissioned at a ceremony at LANL on August 28, 1998, will offer experimentalists the opportunity to make fixed-field measurements at 60 T for as long as 100 ms. It will also allow them to tailor the magnetic field pulse profile to accommodate the particular requirements of any given experiment. Figure 1 presents an actual magnetic field pulse profile from the 60 T Q-C magnet.

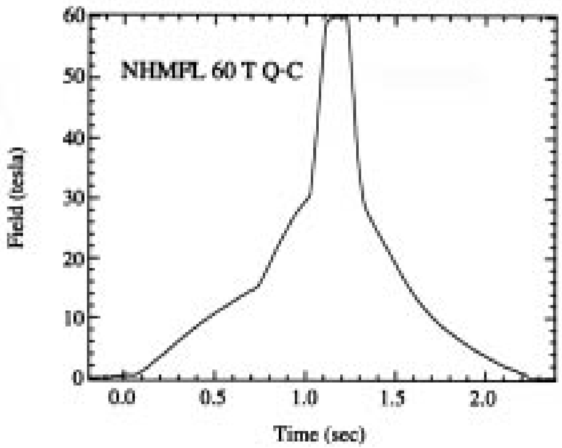


Figure 1. A magnetic field versus time profile of the 60 T Q-C magnet.

In-house researchers are currently performing experiments on this magnet in order to develop the experimental techniques and infrastructure necessary to support the users program for this magnet. During the commissioning period, the laboratory will gain experience with operating the magnet, develop a library of approved magnet pulse profiles, and establish the safety envelope and operational procedures for the users program.

To date, in-house researchers have tested a variety of experimental techniques, including the transport measurement (Figure 2) performed by Mielke, *et al.* on a two-dimensional organic conductor [α-(BEDT-TTF)$_2$TlHg(SCN)$_4$]. Clear Shubnikov-de Haas oscillations can be seen and the noise level is only 20µV, even though this is a DC-transport measurement. Substantially lower noise levels should be readily achievable from AC-transport measurements using phase-sensitive detection.

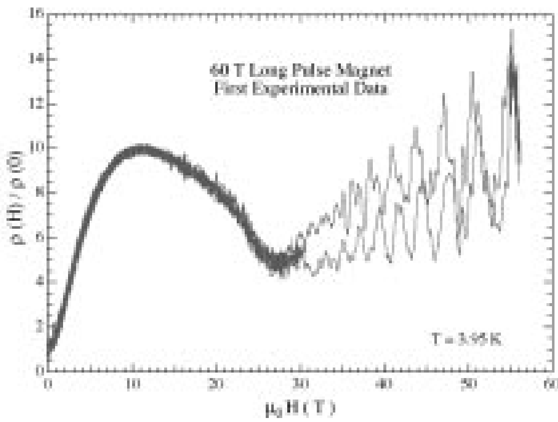


Figure 2. Magnetoresistance of α-(BEDT-TTF)$_2$TlHg(SCN)$_4$ at 3.95K by C. H. Mielke, D. G. Rickel, J. Shillig, H. Boenig, J. Sims, J. Betts, N. Harrison, L. K. Montgomery, and A. H. Lacerda

A high resolution optical spectroscopy system was tested recently by Crooker *et al.* for use with the 60 T Q-C magnet. With this system, optical spectra can be acquired at rates up to 1 kHz, which enables the continuous monitoring of the optical response through the entire two second duration of a 0 to 60 T magnet pulse. With this system, up to 200 spectra above 30 T can be acquired during a single magnet pulse. Present instrumentation includes the optics components and fibers required for experiments using wavelengths from 350 nm to 1000 nm. A cryostat allows the experiment to reach temperatures down to 350 mK. An example of the data recently taken is shown in Figure 3.

Figure 4 shows the pressure effect at high magnetic fields on type I-type II transition field in a two-dimensional diluted magnetic semiconductor by Yokoi *et al.*

Once online as a user facility in fall, 1998, the 60 T Q-C magnet is likely to be operated during evening hours with the magnet being available for alternating 4- to 6-week periods. (Some uncertainties regarding initiation of the users program on this magnet result from the radically different magnet and power supply; others are imposed by planned utilities shutdowns associated with the NHMFL move to a new building in 1999.)

Research proposals for 60 T Q-C experiments are welcome anytime, and will be actively solicited beginning September, 1998. For further information, contact me at 505-665-6504, (fax) 505-665-4311, or lacerda@lanl.gov.

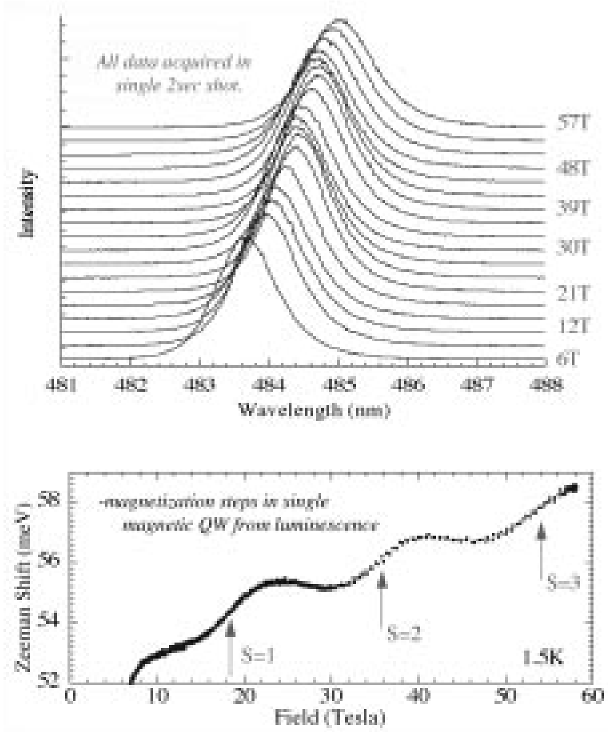


Figure 3. Top figure shows 18 of the over 2000 photoluminescence (at T = 1.5 K) spectra acquired during a single 2-second shot. The sample is a single ZnSe/Zn (CdMn)Se quantum well. Analysis of the data (bottom figure) shows clear evidence of magnetization steps (as measured via the Zeeman shift of the luminescence peak–each point is derived from a complete optical spectra). By: S. Crooker, D. Awschalom et al.

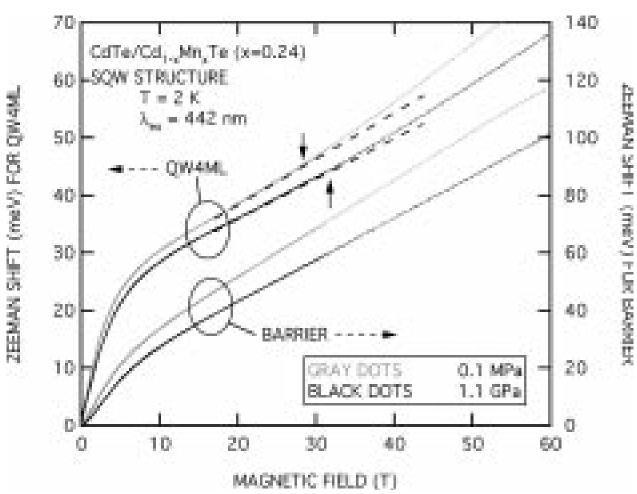


Figure 4. Zeeman shifts for a barrier layer and a quantum well of 4ML(1ML=3.2Å) width (QW4ML) in a CdTe/$Cd_{1-x}Mn_xTe$ (x=0.24) single quantum well (SQW) structure at the ambient pressure (black dots) and 1.1GPa (gray dots) as a function of magnetic field. The kinks observed in the Zeeman shifts for QW4ML, as indicated with an arrow, suggest that a type I-type II transition is induced. The valence band of magnetic barriers is supposed to shift to higher energy than that of a semiconductor well. It is observed that the transition field increases with increasing pressure. By: H. Yokoi, Y. Kim, S. Tozer, S. Crooker, J. Shillig, J. Sims, H. Boenig, D. G. Rickel

Progress Report on the 45 T Hybrid

Systems for the 45 T Hybrid are coming together at a vigorous pace, as this major NHMFL project heads toward completion in early 1999. This system has been designed to be a versatile, reliable, user-friendly magnet system capable of providing researchers at least 45 T steady field in a 32 mm clear bore. The name Hybrid derives from the fact that both resistive and superconducting magnet technologies are combined in this system to achieve the world-record level of field. The system also has been designed with capability for upgrade to produce 50 T in the future, using higher-power resistive inserts to be developed. For background information on the Hybrid, see NHMFL Reports, Fall 1996, and Summer 1995.

Significant progress on the Hybrid has occurred principally on two fronts: the recent, very successful testing of the outsert cryostat and the progress on assembly of the outsert itself.

In its most recent test in April, 1998, the outsert cryostat met or exceeded several critical performance milestones:

- The measured heat load at 1.8 K was < 8 W (8.8 W budgeted)
- A minimum temperature of < 1.5 K was attained
- Operation at 1.75 K was achieved with only one of the PSI Model 1630 refrigerator/liquefiers dedicated to the outsert cryostat (the other was operated simultaneously making liquid for users).

These achievements were made possible primarily by minor modifications to correct a thermal short between a 20-K shield and the 1.8-K piping—and a lot of hard work and long hours put in by Scott Welton, John Pucci, and Kevin Bryant of the NHMFL. The cryostat has now been opened and is being prepared to accept the outsert magnet, which is being assembled.

The outsert assembly is in its final stages. All parts have been fabricated, fixtures for handling the nearly 14 metric ton magnet have been prepared and tested, and assembly tolerances and compliances have been checked by stacking all the subcoils on the magnet-vessel base and loading with a 500-kN press. At present, a crew (Jerry Kenney, Steve Kenney, Robert Stanton, and Lee Windham) is immersed in the tedious and critical tasks of precision alignment, electrical connection, electrical insulation, instrumentation, and vessel closure.

The outsert magnet is in its final stages of assembly, which should be complete by the end of October. Testing of the outsert magnet will begin later this fall.

This article was contributed by John Miller, head of the Large High Field Systems Group of the laboratory and Hybrid project, who may be contacted at 850-644-0929 or miller@magnet.fsu.edu, for further information.

Conference and Workshop Activity

High Frequency Electron Magnetic Resonance: Scientific Opportunity & Challenges

September 17-18, 1998
DoubleTree Hotel Park Terrace
Washington, D.C.

The NHMFL, Albert Einstein College of Medicine, Pacific Northwest National Laboratory, Northeastern University, Argonne National Laboratory, and the University of Illinois are co-sponsoring this meeting that will facilitate an important dialogue on scientific opportunities of EMR and serve as a planning and advisory tool for the sponsoring institutions. Forty to 50 participants are expected to attend, by invitation only. Attendees will represent academia, national laboratories, the private sector, and several federal agencies.

For further information contact Jo Ann Palmer (850-644-1933, palmerj@magnet.fsu.edu, (fax) 850-644-9462).

VIII[th] International Conference on Megagauss Magnetic Field Generation and Related Topics (Megagauss VIII)

October 18–23, 1998
Main Campus FSU & NHMFL
Tallahassee, Florida

Complete Information & Registration:
http://www.magnet.fsu.edu/whatsnew

Megagauss VIII focuses on the latest results on the generation of very high magnetic fields at the megagauss level and higher. Over 150 abstracts have been received, principally from Russian and American scientists affiliated with national laboratories and academia. The plenary speakers for the conference include C.M. Fowler of Los Alamos National Laboratory; Victor D. Selemir, of VNIIEF, Russia; and Nobel Laureate J. Robert Schrieffer, NHMFL Chief Scientist. The banquet dinner speaker will be Fritz Herlach of Katholike University, Leuven, Belgium, who will present "A View on Megagauss Fields from 40 Years Ago Into the Next Century."

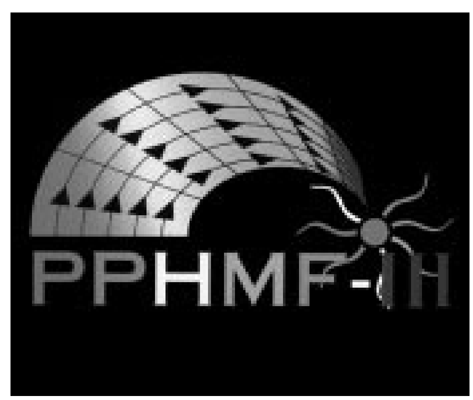
This conference was first held in 1965. Megagauss II was held in 1979 and has been held every two to three years since then. The last meeting was in 1996 in Sarov (Arzamas-16), Russia.

Late registrations are still being accepted. For further information, see the website or contact Ysonde Jensen (850-644-0807, Megagauss@magnet.fsu.edu, (fax) 850-644-0867).

Physical Phenomena at High Magnetic Fields (PPHMF-III)

October 24–27, 1998
Main Campus FSU & NHMFL
Tallahassee, Florida

Complete Information & Registration:
http://www.magnet.fsu.edu/whatsnew



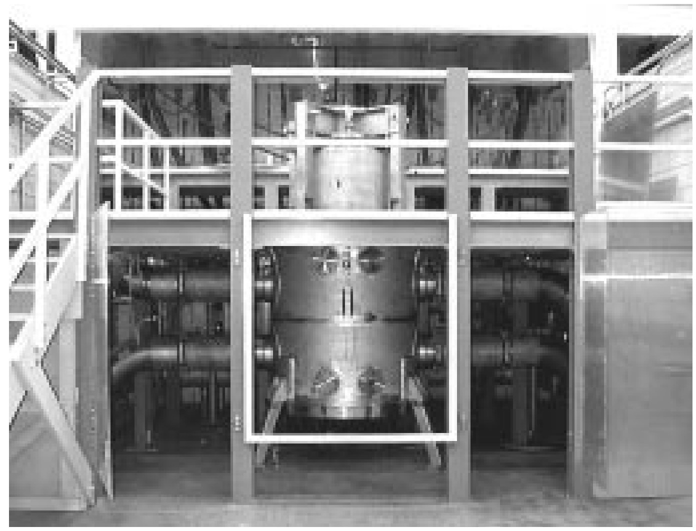
Megagauss VIII and PPHMF-III are planned back-to-back intentionally, because many of the interesting science and research developments in these areas overlap. PPHMF-III is anticipating up to 200 participants and forty speakers; over 150 abstracts had been received by mid-June. The program will cover a broad range of materials and phenomena, including semiconductors, magnetic materials, superconductivity, organic solids, quantum Hall effect, chemical and biological systems, and the technological use of high magnetic fields.

Registration can be accomplished over the Internet, by phone or fax. For further information, check out the website or contact Mary Layne (850-644-3203, layne@magnet.fsu.edu, (fax) 850-644-5038).

Conference and Workshop Activity continued on page 13

20 T Large Bore Magnet Completed

On June 3, 1998, the 20 T large bore resistive magnet at the NHMFL was operated to high field for the first time and attained a peak on-axis field of 19.8 +/- 0.1 T. The maximum field in the 195 mm room temperature bore is approximately 20.5 T. Since commissioning, the magnet has been heavily used for acceptance testing (I_c measurements) of the wire for the 900 MHz superconducting magnet as well as curing high strength epoxies in high magnetic field. Magnet time has been scheduled for summer 1998 for testing high T_c coils in field, specific heat measurements, and sonoluminescence. Other experiments being discussed include ICR, double axis rotation, and optics with a light path perpendicular to the field direction. For a full report on 20 T large bore magnet, refer to NHMFL Reports, Winter 1998.



Conference and Workshop Activity from on page 13

Biomagnetics Metabolism Research

NHMFL
November 6-7, 1998

The NHMFL is sponsoring a workshop to define the scientific challenges presented by using magnetic spectra to assess in vivo chemical structure and function. Thirty-five scientists and researchers from various disciplines have been invited to attend.

Second North American FT-ICR Mass Spectrometry Conference

March 18-20, 1999
San Diego, California

The NHMFL initiated and hosted the first meeting of this two-day conference at the laboratory in Tallahassee in March 1997. Over 110 participants attended, representing leading FT-ICR research groups from the United States, United Kingdom, Germany, France, The Netherlands, and Japan. It was so successful that organizers were immediately encouraged to hold similar conferences in the future.

Consequently, planning for the Second North American FT-ICR Mass Spectrometry, which will be held in San Diego, is well underway, and the first announcement has been released. Look for more information on the Internet,http://www.magnet.fsu.edu/whatsnew, or contact Jo Ann Palmer (850-644-1933, palmerj@magnet.fsu.edu, (fax) 850-644-9462).

16th International Conference on Magnet Technology (MT-16)

September 26–October 1, 1999
Leon County Civic Center & NHMFL
Tallahassee, Florida

For the first time in 10 years, this international conference will be held in the United States. It will bring together experts from around the world to present recent developments in the fields of technology, operation, and application of superconducting and conventional magnet systems. Industrial applications, such as magnets for NMR and MRI, energy storage, levitation, and separation, will be featured, and several sessions will be devoted to new developments in the field of low and high temperature superconductors and other materials.

Over 500 participants are expected for this major conference, including significant representation by industry. An industrial exhibition of new products and developments in magnet technology will be held in conjunction with the conference.

MT-16 Proceedings, including both oral and poster papers, will be published as an issue of the IEEE Transactions on Magnetics.

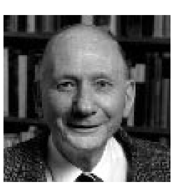
A website for information about this conference is being developed and will appear at http://www.magnet.fsu.edu/whatsnew. Further information may also be obtained by contacting Jo Ann Palmer (850-644-1933, palmerj@magnet.fsu.edu, (fax) 850-644-9462).

People in the News

60 T Magnet Development Team, which comprises professionals from three LANL divisions, recently received the Distinguished Performance Award from LANL for their outstanding achievements in developing and commissioning the world-class 60 T quasi-continuous magnet system. This magnet represents a huge increase in capability— nearly a 50 percent increase in field capacity—over existing magnets of its class, and provides the NHMFL's Pulsed Field Facility with a unique user capacity. The official commissioning of the 60 T Q-C magnet is scheduled for August 28, and will be featured extensively in the next issue of NHMFL Reports.

Congratulations and thanks to the members of the 60 T Magnet Team:

Dwight Rickel, DX-6
Heinrich Boenig, DX-6
Joe Schillig, DX-6
Mike Pacheco, DX-6
Woody Bowman, DX-6
Mike Gordon, DX-6
John Rogers, DX-6
Serafin Roybal, DX-6
Tom Dominguez, DX-6
Chuck Mielke, DX-6
Jim Sims, ESA-DE
Kurt Eberi, ESA-DE (now at Savannah River)
Cathleen Grastataro, ESA-DE
John Ledford, LANSCE-1
Larry Campbell, MST/CMS
Mary Ann Hill, MST-6
John Vananne, APT-TPO/contractor
Glenn Zimmermann, DX-6/contractor
Jeff Martin, BN/EXT, contractor
Robert Williams, CST-4, contractor



Raymond Andrew, a distinguished faculty member at UF and a major participant in the proposal to establish the NHMFL in Florida in 1990, was awarded the honorary degree of Doctor of Science by the University of Wales on April 18, 1998, in Cardiff. The citation stated "in recognition of his distinction as a physicist and his contribution to the study of nuclear magnetic resonance."

Peter Fajer, associate professor of biology with the FSU Institute of Molecular Biophysics, the Department of Biological Sciences, and the NHMFL, received a five-year, $410,000 grant from NSF to investigate the molecular mechanisms of muscle contraction. Dr. Fajer's former postdoc, Hui-Chun Li, has returned to FSU from a position at Northwestern University to assist in their efforts to determine how the protein molecules generate force in muscle.

Alan Marshall, professor of chemistry and director of the National High Field Fourier Transform Ion Cyclotron Resonance (FT-ICR) Mass Spectrometry Facility at the NHMFL, has been selected to receive the 1998 New York Society for Applied Spectroscopy Gold Medal. This award recognizes outstanding contributions to the field and includes an honorarium, plaque, and a special symposium at the 37th Eastern Analytical Symposium in Somerset, New Jersey, in November, 1998. Dr. Marshall also holds the 1997 Maurice F. Hasler Award in Spectroscopy and was a co-winner of the 1995 Field-Franklin Award in Mass Spectrometry.

Ryan P. Rodgers, a graduate student in the ICR group headed by Dr. Marshall, received Honorable Mention in the recently completed national competition for ACS Analytical Division Fellowships. His research activities center on complex mixture analysis by use of FT-ICR mass spectroscopy. Recently they have been concentrating on petroleum mixtures and looking at important environmental impact issues such as risk assessment and bioremediation. Ryan expects to receive his Ph.D. in chemistry in 1999.

Electron Magnetic Resonance En Route to 1 Terahertz

Louis-Claude Brunel, EMR Program Director

This report features the research and development activities of Dr Brunel's electron magnetic resonance (EMR) group at the NHMFL. The group has developed a strong in-house program and state-of-the-art instrumentation and methodologies to support the needs of external users. The motivations to perform EMR spectroscopy at high field/high frequency is well understood by the scientific community: one expects an increase in resolution and sensitivity, and some systems are spectroscopically active only at high frequency.

NHMFL High Field EMR Spectrometers

Two high field EMR spectrometers have been developed since the laboratory's Magnet Science and Technology (MS&T) group got the "Keck" magnet online in February, 1998. (The Keck magnet was funded by the W. M. Keck Foundation and the NHMFL. For further information see NHMFL Reports, Spring 1998.) The first spectrometer operates with the 15/17 T superconducting magnet; the second machine uses the 25 T resistive Keck magnet. It should be noted that the Keck magnet is perfectly suited for EMR: fast ramping to the magnetic field of interest, very convenient sweepability, homogeneity in the 10 ppm range, good thermal stability of the cooling system, and "the best resistive magnet" this author has ever used.

The 15/17 T Spectrometer

Frequency range: 95 GHz up to 550 GHz for a g = 2, optimized at 220 and 330 GHz
Sensitivity (spin/gauss): with a Fabry-Perot: room temperature: 10^{10}; 4 K: 10^{8}
Averaging: up to 100 spectra
Field calibration: g determination accuracy: +/- 3.10^{5}
Resolution: 1-10 ppm
Sample temperature: 1.4-300 K

The 25 T Keck Magnet Spectrometer

Background: Built around a 25 T, high homogeneity resistive magnet; it uses a far infrared laser for its source
Frequency range: up to 700 GHz for a g=2 system
Sensitivity (spin/gauss): 10^{12} room temperature (a Fabry-Perot is under development)
Field calibration: g determination accuracy: +/- 3.10^{5}
Resolution: 10 ppm
Sample temperature: 1.6-400 K

Current Developments

One of our goals is to increase the sensitivity of the spectrometers and to obtain information regarding the phase of the signal. For these purposes we are implementing quasi-optical techniques that will decrease the losses between the source and the detector and allow for the detection of both the in-phase and in-quadrature components of the signal.

With a grant from the NSF and matching funds from the NHMFL and two external institutions (University of Chicago and University of North Carolina), we are developing a transient EPR spectrometer that will operate at 360 GHz and in the subnano second time scale. This effort is being accomplished by a consortium of ten scientists from five different universities: FSU, UF, UNC, University of Chicago, and Northeastern University.

Challenges for Next-Generation Machines

Commercial instruments are available at 9, 35, and 95 GHz, so the next-generation machines will be in the 300 GHz range (roughly following the 1-3-10 dynamical scale of most instruments). There are two challenges to be tackled: the development of continuous wave (CW) and pulsed sources, and the application of the quasi-optical techniques developed by astrophysicists to electron paramagnetic resonance (EPR) instrumentation. Regarding new spectroscopic sources, gyrotrons are good candidates, and the NHMFL is perfectly poised to embark on the elaboration of these CW and pulsed sources. Concerning the development of quasi-optical techniques, the NHMFL EMR group is already

EMR continued on page 16

addressing this issue via collaborations with outside institutions.

In-House Research Activities

Study of spin gapped low dimensional compounds. With E. Dagotto (NHMFL Condensed Matter/Theory Group), A. Hassan, G. Martins, L.A. Pardi, and L.C. Brunel are studying Zn doped $CuGeO_3$, a spin-Peierls system. This was the body of Dr. Alia Hassan's thesis. The focus is on the influence of non magnetic impurities upon phase transition, and a publication resulted from the work: High-Field Electron Spin Resonance of $Cu_{1-x}Zn_xGeO_3$, A.K. Hassan, L.A. Pardi, G.B. Martins, G. Cao, L.-C. Brunel, Phys. Rev. Lett. **80**, 1984 (1998).

EPR in diluted magnetic semiconductors (DMSs). In collaboration with J. Furdyna (University of Notre Dame), A. McCarty, G. Martins, and L.C Brunel are studying diluted magnetic semiconductors. EPR in DMSs contains important information on anisotropic superexchange in strongly-coupled random magnetic alloys. Naturally it is especially desirable to probe the limit where the systems of interest are coupled the most strongly, i.e., high magnetic contents, low-T region. This is precisely where measurement of EPR using "standard" frequency proves impossible because the linewidth is comparable to the resonance field. Recent advances at the NHMFL in establishing a high-field EPR facility allow us to circumvent this bottleneck. Furthermore, since the facility offers a series of wavelengths, it also offers the ability to study EPR (and thus the information it provides on magnetic coupling) as a function of field.

High Field EMR studies of photosynthesis. A. Angerhofer (UF) is interested in photosynthesis and conducted numerous projects with the EMR group, which includes J. Krzystek, A. Hassan, and A.-L. Maniero, a visitor from the University of Padua (see "Keck Magnet Milestone" and photo, next page).

EMR External Users and Visitors Program

External Users Program. Thirty projects from 12 different principal investigators have been completed. These projects involved 32 institutions (3 from Florida, 15 from the U.S. outside Florida, 11 from Europe, 1 from Japan, 1 from Taiwan, and 1 from Brazil). Among the 15 U.S. institutions, 13 were universities and 2 were government labs.

Visitor Program. The EMR Visitor Program has been increasingly active. During the last eleven months we had four visitors: Dr. Bruce Robinson (University of Washington) stayed three months (see NHMFL Reports, Fall 1997); Dr. Anna Lisa Maniero (University of Padua) is with us for a year. Both Dr. Jack Freed (Cornell University) and Dr. Jack Furdyna (University of Notre Dame) stayed with us for two months.

Keck Magnet Milestone

The very successful operation of the spectrometer using the Keck magnet projected the EMR

Dr. Jack Freed visited the NHMFL during January and April, 1998. At Cornell University, where he is a Professor of Chemistry, Dr. Freed has developed experimental and theoretical methods for electron spin resonance (ESR) studies of nitroxide spin labels at far infrared (FIR) frequencies in the range of 170 to 250 GHz. This requires magnetic fields of 6 to 10 T. The objective of this work is to study the dynamic structure of complex fluids. One area of particular interest has been his studies of the approach to the glass transition in the hydrocarbon fluid, ortho-terphenyl. At the NHMFL, Dr. Freed worked with L.C. Brunel's EMR group to extend these studies to the 500 to 700 GHz regime by utilizing the new 25 T Keck resistive magnet, illustrating for the first time the potential of the magnet developed with the support of the Keck Foundation. The initial temperature-dependent results obtained at 525 GHz (19 T) and 670 GHz (24 T) are supplying useful ESR spectra, which will complement the results at lower fields and frequencies in providing insights specifically into the molecular basis of the glass transition, and more generally into molecular dynamics in a wide range of complex fluids.

Conclusion

The NHMFL EMR Facility offers users from all around the world, unique opportunities to perform EMR spectroscopy at the frontiers of what is currently technologically available. The program well beyond the boundaries of other laboratories. This unique 25 T system is a milestone in the development of high field/high frequency EMR as it opens up the route to 1 THz. Any lab with sufficient funding can buy a superconducting 17 T machine, but only the NHMFL with the MS&T department can boost a high homogeneity spectrometer in the 700 GHz range and no longer **dream of but makes plans for a 1 THz machine**. The series-connected hybrid, which is at the very earliest stage of infancy, will be perfectly positioned to fulfill this goal.

The activity with the Keck magnet dealt with photosynthesis and motional dynamics.

Outstanding results have been obtained for photosynthesis-related projects. For instance, in a collaboration with Drs. Evans and Smith (Queen Mary and Westfield College, University of London), A. Angerhofer (UF) used the Keck magnet to perform very high frequency EPR spectroscopy (670 GHz, 24 T). They investigated a number of photosynthetic reaction centers: *Rb. sphaeroides, heliobacter*, and others. The possibility to operate at very high field was instrumental in these studies and, for the first time, allowed for the complete resolution of the g-Lande tensor components. This opens up new opportunities to determine the electronic structure of the reaction centers—structures of paramount importance to the understanding of the processes involved in photosynthesis.

At Cornell, the group headed by Dr. Freed is interested in motional dynamics of complex fluids that he had studied at 250 GHz. With the Keck magnet, Dr. Freed made measurements at frequencies of up to 670 GHz, opening new avenues for the study of nitroxide spin-labels (see photo page 16).

Dr. Anna Lisa Maniero, from the Chemical Physics Department of the University of Padua, is on sabbatical for one year with Dr. Brunel. Dr. Maniero's scientific interests are in material science. She is interested in probing the structure and dynamics of molecular systems via the magnetic properties of γ-irradiation induced radicals. She is also interested in C60 based derivatives. She studies the electron transfer processes between the fullerene systems and poly and oligothiophene donors, and the more fundamental and unusual properties of TDAE doped C60 which behaves like a "soft" molecular ferromagnet at low temperature. Dr. Maniero has expertise in CW, pulsed and transient electron paramagnetic resonance (EPR), and in electron nuclear double resonance (ENDOR), which combines the high sensitivity of EPR and the high resolution of NMR. Dr. Maniero came to the NHMFL to take advantage of the potential of the newly developed machines: multifrequency EPR in the 15/17 T superconducting magnet and very high frequency EPR in the Keck magnet. She also has a strong interest in the machines currently under development: transient EPR spectrometer at 360 GHz in the subnanosecond time scale, and ENDOR at high magnetic field.

NHMFL is now the world premier center for high frequency EMR. This is possible thanks to a very dedicated group of scientists and engineers, to the support of the laboratory's leadership, and with the help of the "Magnet Lab's" extended family.

Dr. Jack Furdyna's research interests involve the preparation of new semiconducting compounds and the investigation of their physical properties. Most recently this activity has focused on diluted semiconductors in which semiconducting as well as magnetic properties can be tailored to produce new physical phenomena that are of interest from both fundamental and applied points of view. These novel materials are prepared in the form of bulk crystals as well as quasi-two-dimensional layered structures. After preparation, the semiconductors are investigated spectroscopically in the visible and infrared ranges of the spectrum, as well as by electron paramagnetic resonance (EPR) spectroscopy. Optical "magnetospectroscopy" provides unique insights into the electronic structure of these new semiconducting materials and supplies the basic knowledge necessary for constructing magneto-optical devices to be used in integrated optical circuits. EPR spectroscopy provides information on exchange interactions between magnetic ions, which is of fundamental importance to the understanding of the magnetic behavior of these alloys. In addition to the spectroscopic studies carried out at the University of Notre Dame, Dr. Furdyna , a Professor of Physics, is involved in an extensive program of collaborations with other institutions in the area of EPR measurements, structural studies, magneto-optical studies, and neutron scattering in diluted magnetic semiconductors.

An Accurate Code for the Simulation of Turbulent, Incompressible Fluid Flow in Complex Geometry

Soren Prestemon and Hans Schneider-Muntau, NHMFL
Anjaneyulu Krothapalli, Eminent Scholar, Mechanical Engineering, FSU

High field resistive magnets dissipate large quantities of energy in the form of heat, which must be extracted by forced convection cooling with deionized water. In polyhelix magnets the flow passage is an annulus between consecutive helices; in the case of Florida-Bitter magnets, it is a highly elongated hole. The size, shape, and distribution of wall roughness elements are known to affect the transfer of momentum and heat. This can be seen through empirical global parameters such as the friction factor and heat transfer coefficient, obtained by experiment. The size and dynamics of fluid structures (vortices), which play a pivotal role in the energy transfer process in turbulence theory, are expected to account for the variations.

In order to investigate in detail the effect of wall geometry on flow structures and their dynamics, we have developed a highly accurate numerical simulation code capable of integrating the system of conservation laws governing the motion of an incompressible fluid. Some unique features of the code are that it:

- solves the dynamic equations of motion for an incompressible fluid;
- allows for variable (e.g. temperature dependant) viscosity and thermal conductivity, critical for high heat-flux scenarios;
- handles complex geometry via a locally structured/ globally unstructured domain decomposition approach;
- is highly accurate, particularly for smooth problems;
- is based on a stress tensor formulation, which allows for direct implementation of sub-grid scale turbulence models.

The last feature is critical for variable viscosity fluids, as well as for the simulation of high Reynolds number, turbulent flows. In such flows, the smallest eddies have a characteristic length scale of $l \sim LR^{-3/4}$, where L is the hydraulic diameter and R is the Reynolds number. For large values of R, the range of scales of motion is so vast that simulation of all flow phenomena becomes impossible. The dissipative effect of small scale, unresolved motion is modeled as an additional viscous "sub-grid scale" stress tensor, while the essential, energy-carrying structures are dynamically resolved.

The code is based on the recently developed spectral element method.[1] The method shares some features of the p-refinement (high order polynomial) finite element method. First, the underlying set of partial differential equations are written in variational form by multiplying through by appropriate test functions and integrating. The physical domain is then decomposed into simple quadrilateral elements and the solution approximated

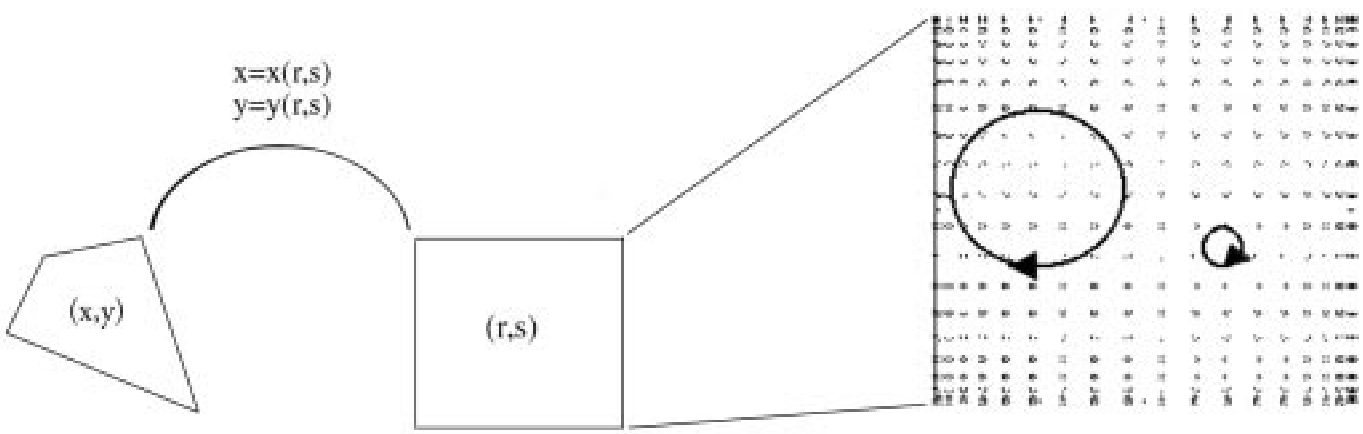


Figure 1. An arbitrary quadrilateral element is mapped onto the $[-1,1]^2$ square. The solution is then represented by the tensor product of high-order polynomials defined on the Gauss-Lobatto-Legendre quadrature points. Resolved and unresolved eddies are sketched on the right.

by multi-dimensional polynomials in each element. Continuity is imposed on element interfaces, and the required resolution is achieved by adapting the order of the approximating polynomials.

Each element is mapped via an affine transformation onto the domain $[-1,1]^d$. High-accuracy Gauss-Lobatto-Legendre integration is used to evaluate the resulting integrals (see Figure 1).

The choice of test functions is somewhat arbitrary; for optimal computational efficiency, however, we choose a tensor product of the 1D Nth order Lagrange interpolating polynomials defined at each of the N+1 integration points. Convergence results typically show a factor of 10 reduction in error when the polynomial order is increased by 1. The extraordinary (exponential) convergence rate is typical of spectral methods, and is particularly advantageous for problems requiring high spatial accuracy, as is the case in the simulation of turbulent flow.

We have applied the method to the full Navier-Stokes equations in three spatial dimensions. The third dimension is assumed to be homogeneous, which allows the use of Fourier transform methods in that direction. For incompressible fluid flow there is no equation of state relating pressure to energy; the pressure acts as a formal variable whose sole purpose is to enforce the conservation of mass. By taking the divergence of the momentum equation and using mass conservation, an elliptic Poisson equation can be obtained relating the velocity field to the pressure. The existence of one homogeneous direction simplifies the calculation of the pressure, since the 3D Poisson equation is transformed into a set of independent 2D Helmholtz equations for each Fourier mode.

The code has been successfully tested on numerous benchmark problems. Runs are currently in progress for diverse roughness geometries at high Reynolds numbers ($R \geq 4000$). Examples are given in Figure 2.

The flows are forced by a superimposed pressure gradient, resulting in flow from top to bottom. For these runs, variables at the inlet and outlet are set equal at each time step, resulting in a flow that evolves in time. Such temporal simulations avoid the ambiguity of imposing inlet flow profiles and exit boundary conditions. The flow pattern is initially symmetric (as shown here) and will result in a statistically stable solution around a chaotic, turbulent flow regime. By locally refining the grid along the walls, we are able to resolve the critical momentum and thermal boundary layers while inhibiting the spread of numerical errors, emanating from pressure singularities which occur at sharp geometric edges, into the rest of the flow domain. At present, we investigate different geometries for their efficiency in heat and momentum transfer for optimal performance. Insight gained from this research will benefit the design of resistive magnets, and more importantly of heat exchangers in general. The computations are being performed on the IBM SP2 nodes at the Supercomputing Computations Research Institute (SCRI) at Florida State University, as well as on a Cray C90 at NASA Ames.

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[1] Patera, A.T., JCP, **V54**, 468-488 (1984).

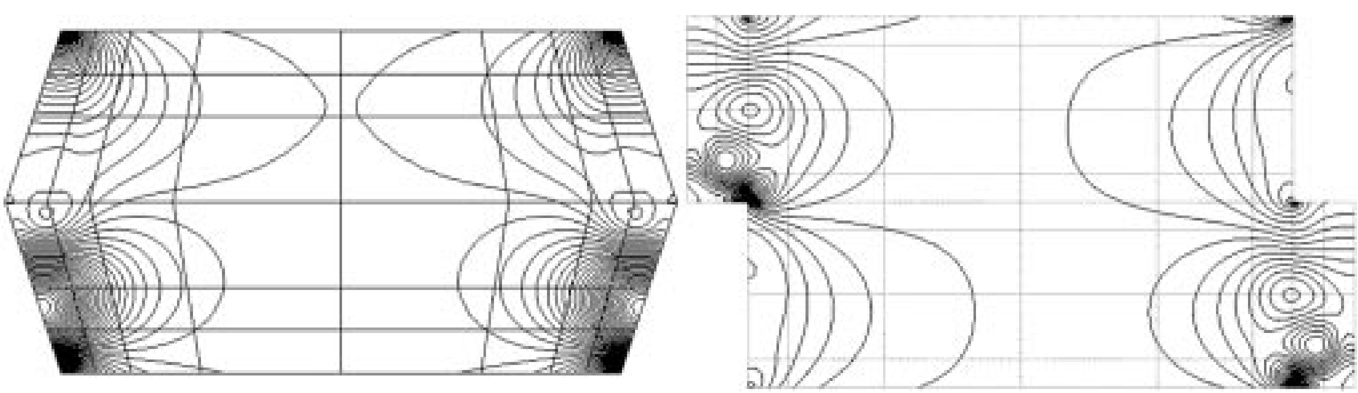

Figure 2. Two roughness scenarios for cooling channels of 1 mm in width. In each case instantaneous isobars are shown along with the elements. Note the high spatial resolution (on the order of 1μm) in the boundary layers.

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