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NATIONAL HIGH MAGNETIC FIELD LABORATORY

MAG LAB REPORTS

FLORIDA STATE UNIVERSITY · UNIVERSITY OF FLORIDA · LOS ALAMOS LAB

- **Puzzling features of new fractional quantum hall states**
  Page 9
- **The quest for higher field pulse magnets**
  Page 17

TABLE OF CONTENTS

3 *From the Director's Desk*

5 It's only a phase - a smectic vortex phase

7 Micromechanical devices for magnetometry in pulsed and continous magnetic fields

9 *Fractional quantum Hall effect in the first excited Landau level:* High-field, low-temperature studies

12 Using MR microscopy to build an *in vivo* mouse brain atlas

14 *A life in physics*: Bill Moulton and the birth of the Magnet Lab

17 The quest for better conductor wires to meet demands of ever-increasing pulse fields

20 Success! Conical model coil tests prove promising

22 *DC and NMR*: a hot new couple? Notes on the progress of the Series Connected Hybrid project

24 CIRL gets one-on-one with undergrads

25 *People in the news*

27 *Science starts here:* Madalina Furis

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On the cover:

The Magnet Lab enjoyed record attendance at this year's Open House, held Feb. 23, with over 4,600 guests visiting during the five-hour event. In the cover shot, a girl reacts to static electricity from a Van de Graaff generator.

— Photo by Larry Gordon

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A Perfect Storm

A Perfect Storm is descending on the MagLab budget for 2008… but if you've seen the film, I assure you that the MagLab's boat will fare better than the *Andrea Gail*. But there could be enough rocking and rolling (the bad kind) to make us all a little bit sick.

How is this possible? Didn't the MagLab receive the glowing endorsement of the National Science Board … something about jewels and crowns?

Yes, it did. But that was then. And since then, the federal government passed a 2008 budget that blew up a disastrous storm for scientific research.

What about the "America Competes" initiative? Didn't the President call for and the Congress agree to doubling the budget for scientific research in 10 years?

Yes, again. But the President capped all non-defense spending and Congress opted to meet this demand by (among other cuts) pulling roughly $1 billion from the anticipated level of 2008 funding for physical sciences research.

What about MagLab support from the State of Florida?

You certainly ask a lot of questions. It turns out that times are tough all over. State revenues continue to decline and Florida State University and the University of Florida have already absorbed a budget cut. The next round is much more uncertain and some say it will likely be determined during the regular session of the Florida Legislature, which begins in early March.

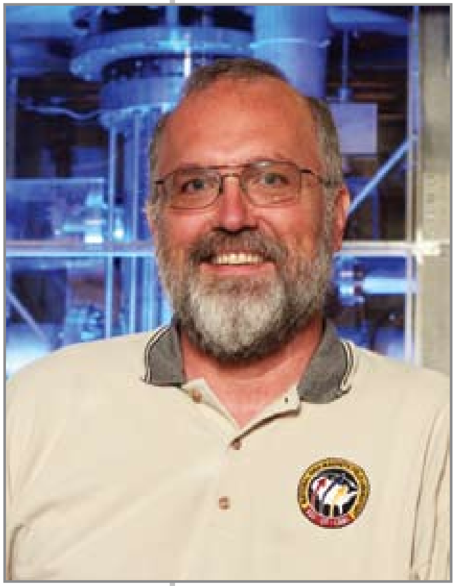
Will the cuts be painful?

The cuts will be painful. To those who are interested, I am willing to provide rationale for the cost-cutting decisions, but in this brief column, let me simply summarize the results:

- We are freezing hiring at the MagLab, even to replace recent departures, with very few exceptions when clear cases can be made based upon cost-cutting or critically important science.
- Each department has been challenged to cut equipment purchases and expenses in half without hindering the future of the Lab. This may not leave enough to replace broken equipment, but we'll address the problems as they arise.
- We are delaying the DC Resistive Split Magnet for a year, and are focusing on the Series Connected Hybrid Magnet projects, which are funded from other grants.
- Finally, we will almost certainly have to shut down the DC magnet user program for an extra month to save $500,000 on our power bill. This is in addition to our annual shutdown for maintenance.

This is depressing.

Yes it is. But we can either wring our hands – and some of us could pull out our hair – or we can man the bilge pumps and bail water from the bottom of the boat.



Our plan is to do what we feel is most important when times are tough:

- Focus on the user programs and meet their immediate needs.
- Delay new initiatives, but prepare them to restart when the funding returns.
- Maintain a sense of community … we're all in this together.

It's still a little depressing.

Short of pharmaceuticals, the best I can offer is the following:

- The cuts above attempt to address the worst case scenario. Things could be better than they look.
- We will be shielding our DC magnet users from the rising cost of liquid helium by providing 200 liters of liquid helium at no cost to each user experiment in the DC magnet user program.
- We will offer DC magnet users more flexibility to tailor the daily operating schedule to maximize the productivity of the limited magnet time available.
- The user programs have the funding needed for world-class science, and the MagLab will be in a great position when the funding improves.

As long as we perform at the highest level of our abilities, I'm confident the user programs will continue at their highest levels of quality. The quantity might be reduced, but the quality will remain.

So it is going to be a rough year. We may get wet, we may go without sleep, we may even get seasick, but years from now, we'll have a heck of a family story to tell.

Gregory S. Boebinger

GREGORY S. BOEBINGER

Smectic vortex phase in optimally doped $YBa_2Cu_3O_7$ at high magnetic fields

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1 Los Alamos National Lab

Deep inside the superconducting state when a magnetic field penetrates a superconductor, vortex matter can exist in solid or liquid phases. The nature of these phases is determined by that of the pinning centers. Pinning centers enable films to carry current without dissipation, which is extremely important for applications of superconductivity. When magnetic field or temperature increases, the vortex lattice crosses the melting line and becomes a liquid with the concomitant increase of the electrical resistance. Although the low density (low field) vortex phases have been well studied, new phases are expected to appear in high fields. By studying the melting of vortices, one can identify these vortex phases.

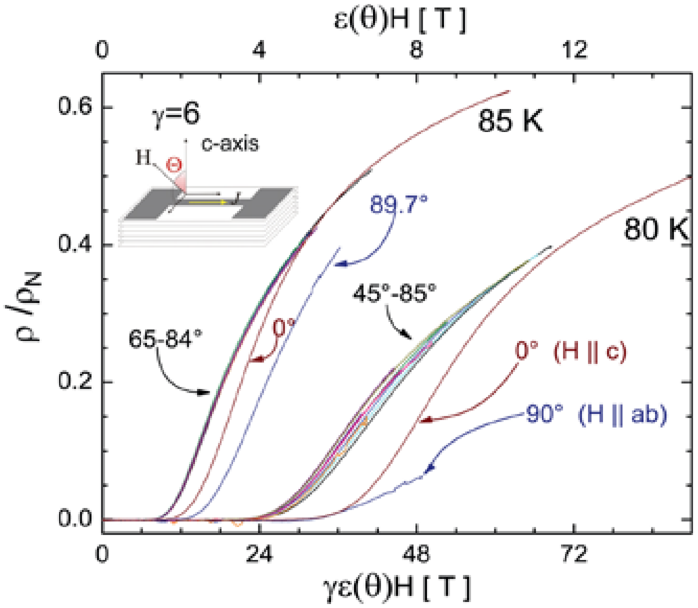
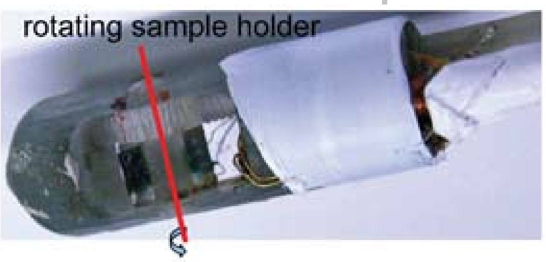


Figure 1.
Normalized resistivity vs. magnetic field scaled with angle using anisotropic scaling at 80 and 85 K. Intermediate angles collapse, but the curves are altered significantly by correlated pinning near the crystalline axes. The effects of intrinsic pinning persist further into the liquid state than those of defect-induced pinning.

The very large magnetic fields only attainable by pulsed magnets, which are available at the Magnet Lab, enable us to investigate these high vortex-density regimes. Also, these magnets have recently allowed us to resolve a long-standing debate[1-4] about the existence of a smectic vortex phase in "low anisotropy" high temperature superconductors with evidence for a smectic vortex phase in optimally doped $YBa_2Cu_3O_7$ at fields higher than 40 tesla.[5] By using angular and field dependent resistivity measurements, we are able to clearly distinguish between correlated pinning along the crystalline axes and point-like random pinning that scales with 3D anisotropy.

Along the crystalline axes, we observe that up to the highest fields measured (50 T) correlated defects decrease the motion of vortices well into the liquid phase. At intermediate angles, 3D anisotropy ($\varepsilon(\theta)H=H[\cos^2(\theta)+\gamma^{-2}\sin^2(\theta)]^{-1/2}$) completely describes the angular dependence of the vortex dynamics. We obtain the same anisotropy parameter ($\gamma=6$) at all temperatures measured, and the entire resistivity curve in the liquid phase scales with the same single parameter at all temperatures measured. However, correlated pinning (from defects or intrinsic pinning) clearly alters the shape of the curve (by reducing dissipation in the liquid state) as well as increasing the vortex melting field.



In layered superconductors, a smectic vortex phase is expected to cause a rapid increase in the vortex melting field H_m at low temperatures.[1] In optimally doped $YBa_2Cu_3O_7$ this upturn was predicted to occur near 80 K at fields near 50 T.[2] For **H** || ab, we find a dramatic increase in $H_m(T)$ and an even greater reduction of the dissipation in the liquid state for $T<80$ K and $H>40$ T. By fitting the rise of the resistivity vs. field curve

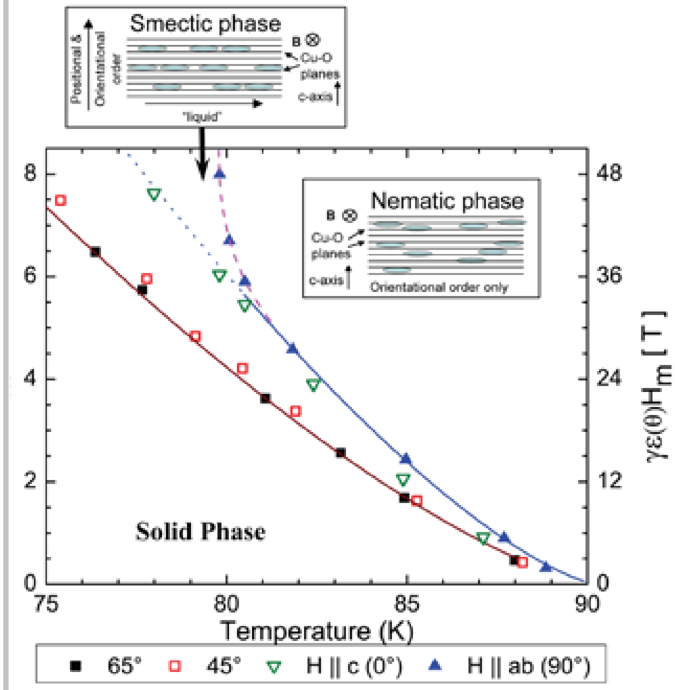


Figure 2.
Temperature dependence of the melting line at various angles. Solid lines: fits to the data using $H_m=C(T_c-T)^{1.4}$ at 65° and **H** || *ab*. Dotted line: extension of the fit for **H** || *ab*. Dashed line: guide to the eye.

we are able to detect a change in critical exponent, as the Bose-glass to liquid melting transition is replaced by a smectic-nematic melting transition.[5] The critical exponents we obtain at the lowest temperatures are consistent with those obtained for smectic-A to nematic melting transitions in liquid crystals,[6] as predicted.[1]

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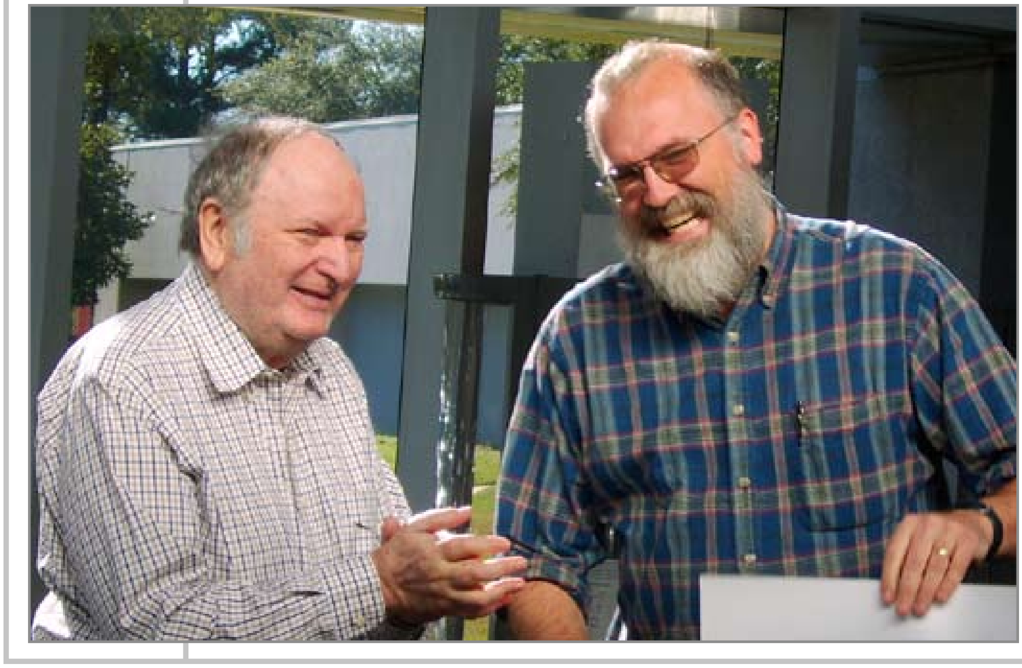

Celebration

Lab Director Gregory Boebinger and retired Chief Scientist and Professor Emeritus Bob Schrieffer share a laugh as Schrieffer accepts a recognition of the 50th anniversary of the Bardeen, Cooper, and Schrieffer (BCS) paper that explained conventional superconductivity and resulted in Schrieffer's shared 1972 Nobel Prize.

Micromechanical devices for magnetometry in pulsed and continuous magnetic fields

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Magnetization is one of the most important physical parameters characterizing a given material. It provides crucial information about the magnetic state, magnetic and electronic phase transitions, their corresponding critical behavior (for a second order phase transition) and the valence of ions in a variety of compounds. A variety of standard instrumentation is available for magnetization measurements at the Magnet Lab. For a certain experiment, the choice of magnetization measurement technique depends on a number of factors, including the sensitivity required, magnetic field strength, measurement speed, temperature range, and the sample size and magnetic moment. Magnetization measurements of small samples at high field and low temperature are of great interest because high-quality, novel materials are often available only in small quantities and many low-dimensional structures are inherently small.

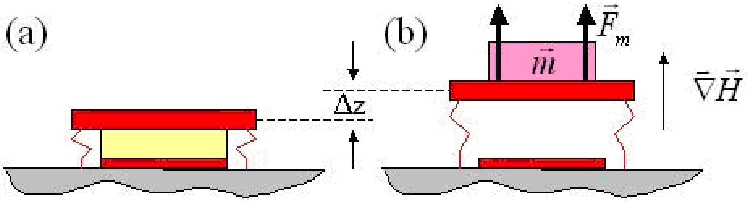

Figure 1.
(a) Schematic of the micromechanical "trampoline" magnetometer before etching of sacrificial oxide. (b) After sacrificial oxide etch, the top plate is suspended by the springs. The sample is attached to the movable top plate. The magnetic force is measured by the change in capacitance between the top plate and the fixed electrode.

So far, cantilever magnetometers[1,2] are used to measure the magnetic response of small samples at the DC field facility. Cantilever magnetometers are particularly useful in measuring relative changes in the magnetization of anisotropic samples, or in revealing sharp changes in magnetization at a phase transition. The major limitation of cantilever magnetometry is that the flexible beam experiences both a force $\vec{F}_m = \vec{m}\cdot\vec{\nabla}\vec{H}(\vec{r})$ and a torque $\vec{\tau}_m = \vec{m}\times\vec{H}$ due to the interaction of the moment $\vec{m}$ with the magnetic field $\vec{H}(\vec{r})$. Since magnetization is the product of the susceptibility tensor by the external field, one usually detects pronounced changes in the magnetic torque as a result of changes in the off-diagonal terms of the susceptibility tensor instead of changes in the magnetization of the sample. As a result, cantilever magnetometry measures the anisotropy of the susceptibility instead of the absolute value of the magnetic moment. In the pulsed field facility, magnetization measurements can be performed up to 65 tesla using sample-extraction magnetometers. Accurate measurements of small samples in pulsed magnetic fields are challenging due to the short duration of the pulses and the considerable electrical and acoustical noise in the pulsed magnet environment.

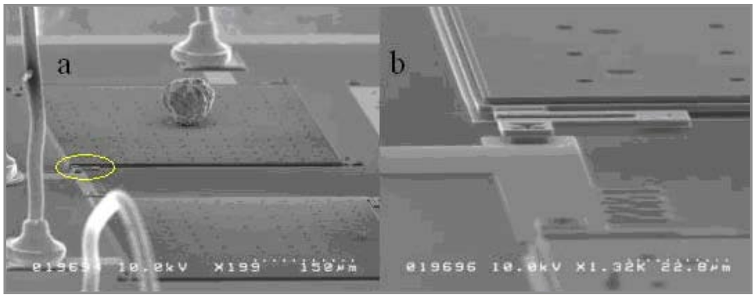

Figure 2.
Scanning electron micrograph of a micromechanical Faraday balance magnetometer. (a) Top view. A nickel particle with mass of ~ 4 μgram is attached to the top plate for calibration. (b) Close-up view on one of the springs (yellow circle in (a)). The mobile plate is suspended by the springs above the fixed electrode.

Using silicon surface micromachining technology[3,4], we fabricated micromechanical Faraday balance magnetometers for measuring the absolute moment of small samples (down to 1 μgram) at high fields and low temperatures. As shown in Figure 1a and 1b, each magnetometer consists of a highly doped silicon plate that is suspended by a spring at each corner (like a trampoline). The space underneath the movable plate is created by selectively etching away a "sacrificial" silicon oxide layer. Each spring is connected to the movable plate at one end and anchored to the substrate at the other end. Figure 2 shows scanning electron micrographs of a typical device with the sample (a nickel particle for calibration) attached to the center of the plate. A spatially inhomogeneous magnetic field generates a magnetic force F_m on the sample. F_m is countered by the restoring force of the springs that is proportional to the displacement Δz of the movable plate through Hooke's law. The displacement of the movable plate is detected capacitively through a fixed silicon electrode located underneath the movable plate. Provided that the magnetic field gradient and the spring constants are known, the magnetization of the sample can be inferred from the measured capacitance. The gap between the top plate and the fixed electrode is 2 um. The area of the top plate is limited to < 600 um square due to concerns of intrinsic stress in the poly-crystalline silicon layer. We have successfully operated the magnetometers at 3He temperatures at both the DC and pulsed field facilities. The maximum DC and pulsed fields were 31 T and 65 T, respectively.

The micromechanical "trampoline" magnetometers were designed to measure the magnetic force. In contrast to cantilever magnetometers where the movable parts are only supported on one side, the movable plates of trampoline magnetometers are supported by springs at all four corners, as seen in Figure 2. The symmetry of this design minimizes the response of the magnetometer to the magnetic torque. Furthermore, calibration can be performed through the electrostatic attraction from the fixed electrode underneath the movable plate by applying a DC voltage between the movable plate and the fixed electrode. Before magnetization measurements are performed, the electrostatic force is used to calibrate the spring constants and the capacitance signal at zero magnetic field. For subsequent measurements in magnetic fields, the electrostatic force is turned off. Measurement of the magnetic force enables the determination of the absolute magnetic moment provided that the magnetic field gradient is known.

Magnetization measurements as a function of field and temperature were performed in the first single crystals of the spin-dimer compound $Ba_3Cr_2O_8$ [5] (mass ~1.3 μgram). At each temperature, two sets of measurements were taken, with the sample located 1 cm above and below the magnet center respectively. The remnant torque signal is eliminated by taking the difference of these two data sets. As shown in Figure 3, the magnetic response is consistent with the existence of a Bose-Einstein condensation of spin-triplet excitations. The sensitivity of the device was $1.5\times10^{-8}\,emu/\sqrt{Hz}$ under the natural field gradient of 38.5 Tm^{-1}, with considerable room for future improvement. In a separate effort, 65 T pulsed field measurements in $BaCuSi_2O_6$ quantum spin system were conducted using the micromachined magnetometers, where the high field data show signature of field-induced spin triplet phase.

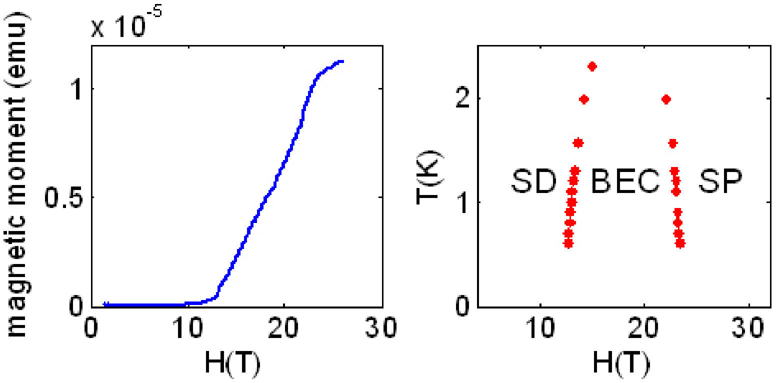

Figure 3.
(a) Magnetic moment of a $Ba_3Cr_2O_8$ single crystal (~1.3 μgram) measured with a micromechanical device as a function of magnetic field at 0.8 K. (b) The partial phase diagram with asymmetry in the phase boundary between the spin-dimerized state (SD), Bose-Einstein condensate (BEC) of spin-triplets excitations and the spin-polarized state (SP). Preliminary results suggest the possible existence of additional structure in the magnetization within the region where the BEC of spin-triplet excitations is observed. As a next step, we plan to determine the overall phase diagram and the respective critical behavior in the vicinity of both quantum critical fields. Of particular relevance will be the comparison between its phase diagram with that of its sister compound $Ba_3Mn_2O_8$, where the greater complexity of its phase diagram suggests a relevant role for the spin-quintuplet degrees of freedom.

The Faraday balance micromechanical magnetometers offer the important capability to measure the absolute magnetization of small samples at high magnetic field and low temperature, with sensitivities rivaling commercial SQUID magnetometers. Further reduction of the temperature by operating in dilution refrigerators appears feasible with construction of new experimental probes. Devices with a new spring design are under development, providing the possibility of further reducing the torque response by a factor of 10 while maintaining comparable force sensitivity.

This work is supported by the Magnet Lab User Collaboration Grants Program.

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Fractional quantum Hall effect in the first excited Landau level: High-field low-temperature studies

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A large number of fractional quantum Hall effect (FQHE)[1] states have been discovered in the lowest Landau level for high mobility two-dimensional electron systems (2DES). These states occur when the filling factor $\nu=n/n_B$ [where n is the 2DES density and n_B is the degeneracy of the Landau level] is the ratio of two integers. The transverse resistance R_{xy} exhibits well-defined plateaus at low temperatures, and the longitudinal resistance R_{xx} well-defined troughs with a vanishingly small value for the resistance. The resistance at the plateau is given by $R_{xy}=h/\nu e^2$ and corresponds to a new quantum state characterized by dissipationless behavior.

Table I lists all odd-denominator FQHE states that have been identified to date in this Landau level. Remarkably, more than 90% of these FQHE states can be mapped onto an integer quantum Hall effect (IQHE) state of composite fermions (CFs)[2]. For example, the state pictured as having three flux quanta associated with each particle (Figure 1a) can be mapped by a gauge transformation to a weakly interacting system of composite fermions each with one particle and two flux quanta (Figure 1b) .

1/3	1/5	1/7	1/9	2/11	2/13	2/15	2/17	3/19	5/21	6/23	6/25
2/3	2/5	2/7	2/9	3/11	3/13	4/15	3/17	4/19	10/21		
4/3	3/5	3/7	4/9	4/11	4/13	7/15	4/17	5/19			
5/3	4/5	4/7	5/9	5/11	5/13	8/15	5/17	9/19			
7/3	6/5	5/7	7/9	6/11	6/13	11/15	6/17	10/19			
8/3	7/5	9/7	11/9	7/11	7/13	22/15	8/17				
	8/5	10/7	13/9	8/11	10/13	23/15	9/17				
	9/5	11/7	14/9	14/11	19/13						
	11/5	12/7	25/9	16/11	20/13						
	12/5	16/7		17/11							
	13/5(?)	19/7									5/2
	14/5										7/2
	16/5										3/8(?)
	19/5										5/8(?)
	21/5										19/8
	24/5										3/10(?)

Table I: List of FQHE states discovered to date.
States with (?) have been observed as particular features in R_{xx} and/or R_{xy}, but the accuracy of their quantization needs to be established with further experiments.

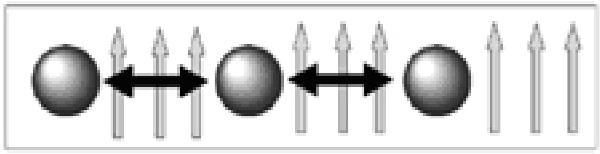

Figure 1a.
At ν =1/3 , there exists 3 flux quanta for each particle, but the particles are strongly interacting. (from A.I. Milstein, http://jilawww.colorado.edu/pubs/thesis/milstein/ch9.)

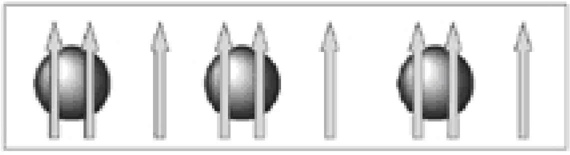

Figure 1b.
By associating two quanta with each particle the state maps to a weakly interacting set of composite particles at ν=1 (each composite having two quanta per particle).

The remaining fractions that cannot be mapped onto IQHE states of CFs are *viewed as FQHE states of CFs*[3], demonstrating the importance of residual interaction between CFs.

In the first excited (N=1) Landau level the FQHE has been observed at *even-denominators ν=5/2, 7/2, and 19/8*, as well as at *several odd-denominator fillings*. Compared to the N=0 Landau level, the FQHE states in the N=1 Landau level are quite unusual. Most of them cannot be viewed as the IQHE states of composite fermions. The most bizarre among them and the most studied is the state at ν=5/2[4]. This state does not follow the odd-denominator rule set by the initial Laughlin wave function[5], and is believed to result from pairing of composite fermions[6]. In analogy to the formation of Cooper pairs in superconductivity, this pairing creates a gapped, BCS-like ground state at ν=5/2, which displays the FQHE.

There is great interest in the ν=5/2 state because its quasi-particle excitations may obey non-Abelian statistics and could therefore be used as topologically protected states for fault tolerant quantum computation[7].

DISORDER AND UNDERLYING PHYSICS OF THE 5/2 STATE

On the experimental side, however, neither CF pairing nor the bizarre statistics of its quasiparticles has been demonstrated. At this stage, we only have comparisons between measured and calculated energy gaps to support the theory based on the paired CF QH state. All previous data[8,9,10,11], however, show an energy gap that is much smaller than the theoretically calculated value[12]. In order to reconcile this difference, an ad hoc disorder broadening of ~2 K must be assumed[8], which, taking up 95% of the gap, is rather unphysical and exceeds a broadening estimated from the mobility by a factor of 300. Thus, the role of disorder in determining the size of the many-body energy gap at 5/2, or in general, the stability of the 5/2 state, remains to be understood.

The energy gap of the 5/2 state is obtained from the temperature dependence of R_{xx}. Figure 2a shows such a plot for a high mobility state ($\mu=31\mathrm{X}10^6$ cm^2/Vs). An energy gap $\Delta= 0.45$ K is deduced. To quantify the role of disorder, we have measured the energy gap at ν=5/2 in a series of high-quality samples. The results for five high-quality samples with different mobilities are shown in Figure 2b (and compared to previous data from Eisenstein et al[9] and Choi et al[10]). The inferred normalized energy gap $\Delta^{norm}=\Delta_{5/2}/e^2/\varepsilon l_B$ [where $e^2/(\varepsilon l_B)$ is the strength of the electron-electron interaction, e is the electron charge, ε is the dielectric constant of GaAs, and $l_B = (\hbar/eB)^{1/2}$ is the magnetic length] clearly scales with 1/μ. Δ^{norm} increases with decreasing disorder, and implies an energy gap for vanishing disorder of $\Delta_{5/2} \sim 0.006 – 0.007\ e^2/(\varepsilon l_B)$. The scale factor (0.006 - 0.007) is a factor 2-3 beyond the theoretical values of close to 0.016[12], indicating that there exists an intricate interplay between disorder and electron-electron interaction that goes beyond a simple level broadening. Further experimental and theoretical studies are needed to fully understand the true nature of the 5/2 state and determine if it is indeed the first example of a non-Abelian state.

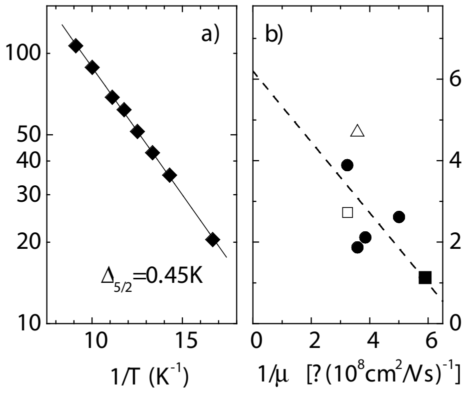

Figure 2.

(a) Arrhenius plot for the R_{xx} minimum at ν=5/2. (b) Normalized energy gap $\Delta^{norm} = \Delta_{5/2}/e^2/\varepsilon/_B$ for five samples of different mobilities. Results from Ref. 9 (open squares) and Ref. 10 (open triangles) are included. The lines are linear fits to the data.

EVEN-DENOMINATOR STATE ν=19/8

The ν=19/8 state occurs only in very high quality samples at very low temperatures and was first observed[13] at the Magnet Lab High B/T Facility. Figure 3a shows R_{xx} and R_{xy} around ν=19/8. Clearly, a new even-denominator FQHE state is developing at this filling factor. Figure 3b shows the value of R_{xx} at the minimum of the ν=19/8 state as a function of 1/T and indicates an activated behavior at low temperatures. The scatter of the data and the limited range of R_{xx} reflect the fragility of the state. A linear fitting at low temperatures yields an energy scale of ~ 5mK. Higher quality specimens and lower temperatures are required to confirm this state a true FQHE state.

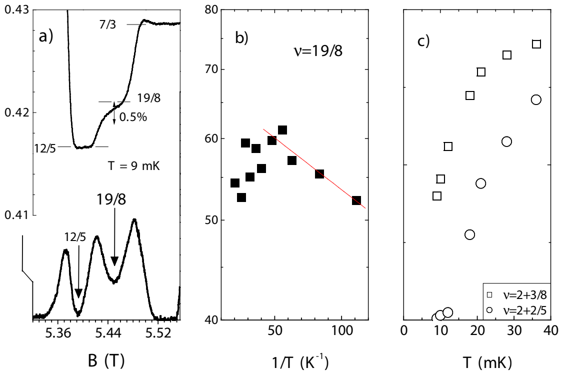

Figure 3.

(a) R_{xx} and R_{xy} around ν=19/8, showing a new, developing even-denominator FQHE state at this filling factor.

(b) Temperature dependence of the R_{xx} minimum at ν=19/8. The line is a linear fit.

(c) Temperature dependence of the derivative of the Hall resistance R_{xy} at ν=19/8 and 12/5.

Figure 3(c) compares the derivative of R_{xy} at ν=19/8 and at ν=12/5 as a function of T. Both fractions show very similar behavior, moving from their classical high temperature dR_{xy}/dB value towards the vanishing slope of a quantum Hall plateau at low temperatures; ~ 10mK for ν=12/5 and ~2-3 mK for ν=19/8. Lower temperatures are needed to determine if a vanishing slope is truly attained for the latter.

THE ORIGIN OF THE ν =19/8 FQHE STATE IS UNKNOWN. The ν=19/8 state may be a paired CF state, similar to the state at ν=5/2. If this were the case, the sequence of creating the ν =19/8 (=2+3/8) state would be to first map the partially filled 3/8 state onto the ν*=3/2 state of CFs with two attached flux quanta (or ^{2}CFs), where ν* is the effective filling factor of ^{2}CFs. Then, two additional flux quanta are attached to the ^{2}CFs in the top, half-filled CF Landau level, transforming the ^{2}CFs to ^{4}CFs. Ultimately, pairing of ^{4}CFs would give rise to the FQHE at ν=19/8.

MISSING QUANTUM STATE ν 13/5 (?) The most surprising result of the studies of the high quality sample is the apparent absence of the =13/5 state, while its particle-hole conjugate state at ν = 12/5 has been shown to be a fully developed FQHE state at low temperatures. This breaking of particle-hole symmetry is contrary to previous trends where both fractions have been observed for conjugate pairs. Recalling the observation in a very different sample with a small electron density (thus lower B) which favors spin flips[8], the absence of the 13/5 state in this high mobility, higher electron density sample may be associated with a transition from a spin unpolarized state at small B to a spin-polarized state at higher B.

FUTURE WORK

The exciting observation of the new even denominator state at ν=19/8 needs to be confirmed, and more exhaustive search needs to be made to understand the nature of 13/5 state. These studies require experiments at even lower electron temperatures, which is a considerable technical challenge. The bottleneck to achieving lower electron temperatures is the thermal barrier between the electrons and the thermal bath (superfluid helium), which is limited by the available surface area for a given geometry. Currently, we use sintered silver powder socks surrounding the wires connected to the 2DES. Even with such elaborate structures, the electron temperatures are typically a few mK while the external bath is at a few tenths of a mK. Major enhancements of the thermal contact to the 2DES are needed to make further progress and understand the puzzling features of the new fractional quantum Hall states.

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Development of an *in vivo* digital mouse brain atlas using MR microscopy

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INTRODUCTION

In a previous study, we developed several Web-based mouse brain atlases, including for the first time a probabilistic atlas, using magnetic resonance microimages of isolated fixed mouse brains (1). This atlas competes with those being developed by several other groups (see references in (1)). Our atlas is online and available to users free of charge at http://www.bnl.gov/CTN/mouse/

The probabilistic atlas essentially averages 10 normal mouse brain atlases, so that when structures are interrogated, meaningful statistics and regional dimensions, volumes and shapes can be extracted for comparison with other data sets in a quantifiable manner. These atlases are used to quantify accurately the volumes and shapes of brain structures, for statistical mapping of functional brain activation in a well-defined stereotaxic anatomical space, and for mapping of gene expression patterns.

Although these atlases are valuable, they are collected on *ex vivo* specimens where the brain has been extracted from the animal skull and placed in a preserving fixative solution. Although this allows high spatial resolution data to be collected (especially since the data acquisition times can be extensive), the image contrast is altered by the fixative solution. There also are structural changes related to changes in intracranial pressure and the collapse of the ventricles, as well as potential morphological changes caused by the brain extraction. Further, *ex vivo* studies preclude time-course exams on the same animal and can be problematic for comparative purposes in functional studies.

However, *in vivo* atlases are challenging because of animal stability considerations and potential motion artifacts. Maintaining animal stability is paramount and can be limited due to anesthesia issues. Consequently *in vivo* studies usually dictate limited data acquisition times, resulting in a lower signal and ultimately a reduced spatial resolution. Nevertheless, *in vivo* atlases are still required for the reasons stated, and may complement *ex vivo* atlases.

In this study we describe the development of the first *in vivo* mouse brain atlas.

EXPERIMENTAL

MR microimages were acquired on a superconducting 9.4 T/210 horizontal bore magnet (Magnex) controlled by an ADVANCE console (Bruker) and equipped with an actively shielded 11.6 cm gradient set capable of providing 20 G/cm (Bruker, Billerica, MA). Inbred C57BL/6J male mice were used and anesthetized and monitored. Additionally a new concentric coil support system was developed to isolate the sample from the gradient coils and reduce vibrationally induced motion artifacts. The hardware essentially is a concentric sample tube running the length of the magnet and supported at the magnet ends so that it does not rest on the gradient coils themselves, as shown in Figure 1.

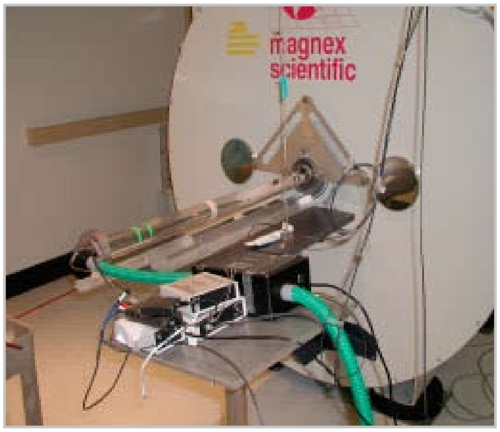

Figure 1.
Illustration of the animal setup on the 9.4T magnet. The animal support cradle is isolated from the gradients in the magnet by external supports (the triangular metal section on the magnet face – the same support is on the back of the magnet).

Three-dimensional acquisitions with isotropic resolutions of 100 microns were achieved in 2.8 hours. The animal respiration was monitored and found to be stable over a two-hour period, after which it tended toward being faster and more fluctuating. Studies were thus limited to two hours (which is the major factor limiting the resolution to 100 microns).

RESULTS AND DISCUSSION

Figure 2 shows example images comparing *in vivo* and *ex vivo* images. Although the *in vivo* image is blurrier due to a reduced resolution (100 vs. 47 microns isotropic), differences in contrast and particularly the full ventricle can be observed compared to the *ex vivo* data. We are in the process of determining exactly what the consequences of these differences will be to the atlas user, and their significance when compared to abnormal tissues.

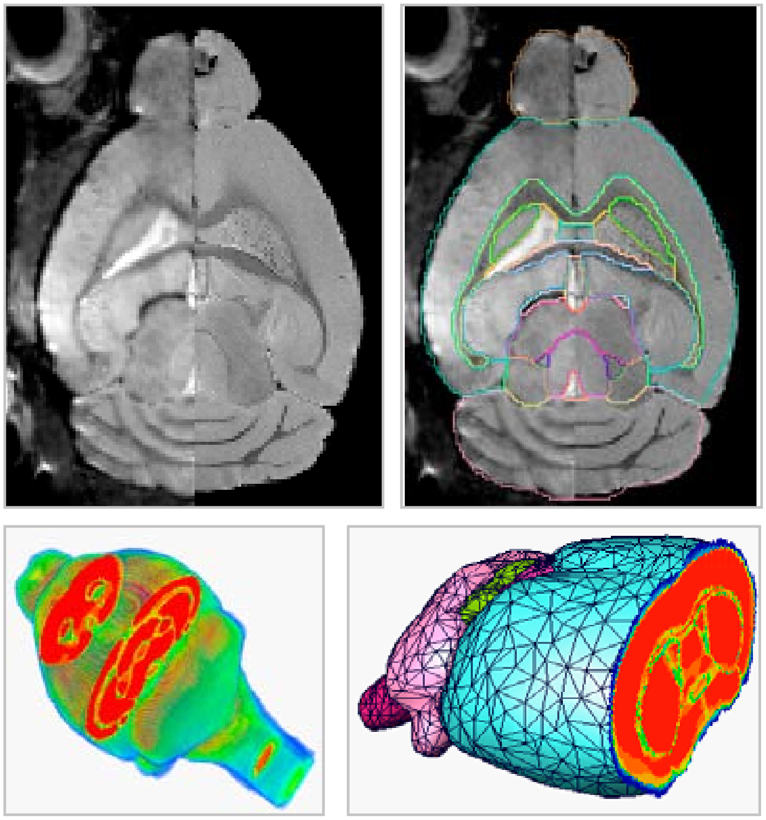

Figure 2.
Top: composite images of a mouse brain where the left half is *in vivo*, and the right half *ex vivo* for comparison, accompanied by a segmented version of the same data. Note the ventricles are hyperintense and clearly visible *in vivo* (red arrow) but absent (collapsed) *ex vivo*. Bottom: example views of the 3D *in vivo* probabilistic atlas.

Several atlases were constructed including 12 individual brain atlases, an average atlas, a probabilistic atlas (shown in Figure 2) and average geometrical deformation maps. Our analyses revealed significant volumetric as well as unexpected geometrical differences between the *in vivo* and *in vitro* brain groups.

CONCLUSIONS

The new *in vivo* mouse brain atlas dataset presented here is a valuable complement to the current mouse brain atlas collection and will soon be accessible to the neuroscience community on our public domain mouse brain atlas Web site, and has been submitted for publication. Our *ex vivo* atlas presently has more than 1,300 registered users and we are polling them on what new developments they require to make the atlas more useful to them. At this point, paramount improvements requested include an improved Web interface for ease of use, and atlases of rat and macaque money brains. This work is a good example of cooperative research studies between national labs (the National High Magnetic Field Laboratory and Brookhaven National Laboratory) and university-based research groups.

ACKNOWLEDGEMENTS

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Tidying up can wait- Moulton in his office.

Bill Moulton : A life in physics

Interview by Lloyd Lumata and Amy Mast

Bill Moulton has been in science longer than our lab director has been alive. An instrumental figure in the drive to move the Magnet Lab to Tallahassee and a working scientist and Professor Emeritus of physics at 83, he's seen three generations of new scientists join his professional ranks.

Here, Moulton talks about the genesis of the Magnet Lab, the evolution of his field, and the challenges that lie ahead.

HOW DID YOU BECOME INVOLVED IN PHYSICS?

I can remember from back in my early grammar school days, my toys were a microscope and chemistry sets and a telescope. I had an interest in science from way back in my grammar school days. In high school, I got very interested in mathematics and I had a superb math teacher who mentored me. When I went to college, I changed to physics.

WHERE'D YOU GO TO COLLEGE?

Western Illinois University, and from there to University of Illinois for my Ph.D.

WHERE DID YOU MEET YOUR WIFE?

I met her when we were first-year graduate students. We met in thermodynamics class.

WERE THERE A LOT OF WOMEN TAKING THERMODYNAMICS?

Actually at the University of Illinois at that time, out of about 200 graduate students in physics, there were about 12 or 14 women. Very few of them finished Ph.D.s because they got married, and they'd have to move with their husbands. A lot of them were excellent students. Some went on to careers in physics. I think there were at least as many then as now, percentagewise.

I WONDER WHY, WITH ALL THE EFFORTS TO ENCOURAGE WOMEN IN SCIENCE SINCE THEN?

Well, I think it's just a male-female thing and there's also some residual resistance still encountered in some places. It's a lot better now than it was, but a few feel women in physics are not being fully capable or dedicated. I know a lot of women physicists and they all had to overcome this, even Millie Dresselhaus. It was a common thing some time ago. It's a lot better now; I don't see any of it in this physics department or the NHMFL, but I do know in some places it's still occurring.

TELL US SOMETHING ABOUT YOUR CAREER BEFORE COMING TO THE MAGNET LAB.

I went from graduate school to the University of Illinois in Chicago. They wanted to get a research program started and they hired me and another person who got his Ph.D. at the same time. We got funding and set up a Condensed Matter/ NMR (what we called solid state physics then) lab and published several papers but it became pretty clear that there was not going to be the kind of support for it that you really need. They've come a long way since then but at that time, it was pretty limited. I started looking around for what to do. Jobs were wide open back then. I chose the University of Alabama because it was connected to the space program and at that time they were just converting the old ballistic missile command to NASA. This was just at the time of the formation of NASA and they were rolling in money, and so there was a lot of opportunity there for research connected with NASA. Over the next five or six years, the state support didn't correspond to what we needed. I turned around and came here.

ERIC PALM DESCRIBED YOU AS THE GRANDFATHER OF THE MAGNET LAB. TELL ME A LITTLE BIT ABOUT THE GENESIS OF THAT PROJECT.

It's not that simple. When I was brought here, the physics department was almost exclusively nuclear physics with a small component of particle physics. The department chair at that time wanted a token condensed matter person, and I was hired to be that person. I'm not complaining – I got a good program going and I bought the first He liquifier in the state; I was able to get in the low-temperature game early on. I was pretty well-funded during that time by the AFOSR and the NSF, so I could keep about five graduate students going.

By the time I was 59, CM physics had changed such that it was difficult for a very small group to survive, so I decided I needed to either retire or do something to invigorate what we had. Chuck Hooper at the University of Florida was going after a bigger program, and I thought maybe we could join their effort and get three or four more positions. We ended up with 14 positions at FSU and an earmarked budget of about three million a year for five years when it became a part of FSU's base budget. By that time it had been built up, and I just felt like I wanted somebody better than I was to run the program. I managed to find Lou Testardi, who had been director of the metallurgy division at NIST.

The state of Florida had put a lot of money into trying to compete for semi-tech, which was a huge DARPA semiconductor research facility. But they put it in Texas.

As a token, they gave $50 million to the state of Florida. Lou asked me to help him both distribute the money within the SUS and oversee the program. This required running all over the state all the time; there were constant meetings and so forth, which we had to go to. Then Lou quit, and I had to run the whole thing. Anyway, this provided the infrastructure to get the Magnet Lab. Without this infrastructure, we wouldn't have had a chance. We had to have a base of condensed matter physics, engineering, and chemistry in order to have any chance of getting the Magnet Lab.

Lou retired, and we were looking for somebody to direct Martech, and Jack Crow's name kept coming up in my calls around the country. I had met Jack, but I didn't really know him. I met him at the airport for his first visit down here to interview and it was on a Sunday evening. We went out to dinner and within 30 minutes he said, "What would you think about going after the National High Magnetic Field Lab?" I said, "Why not?"

I had gotten to know the Vice Chancellor of the University system very well, so I called him and I said, "What do you think about going after the National Magnet Lab? We've got a real hotshot here that really wants to go after it." I made an appointment for meeting with Jack, and after Jack's selling job he made an appointment with the chancellor for Jack and others.

Charlie Reid gave $50K to FSU and $50K to UF to write the proposal, so we set about frantically writing it. By that time we had all kinds of people coming through from both UF and Los Alamos. There was a lot of resistance to it outside the state up until the site visit, which lasted several days.

Some of the site visit people were slightly negative, but not all of them. When they got through they were rather wishy-washy about it. Then it went to the National Science Board, and they were also kind of wishy-washy. Sanchez at the NSF was the person who would make the final choice and he finally said "Do we get more of what we had before, or do we take a chance with a totally new opportunity?" What really sold it, among other things, was the commitment of the state of Florida. They put a lot of money into it – they agreed to build the building and do the infrastructure for the cooling towers and the power supplies as well as several faculty level positions. Sanchez put his foot down and said, "it's going there – it's a great opportunity. They decided it would be here and all hell broke loose in the newspapers. The reaction went from one end of the country to the other. MIT of course just raised hell about it, as did Ted Kennedy.

IT MUST HAVE REQUIRED AN ENORMOUS AMOUNT OF SALESMANSHIP TO MAKE THE MOVE HAPPEN.

Jack was just fantastic. He was absolutely fantastic. And once we got the money, then it really got wild, because it had to be done in a hurry. Otherwise, it would have failed, because MIT was in place and there was a user community that wanted to do experiments as soon as possible. Jack and I started immediately. He was very good at attracting excellent people, and that's where the success came from.

Does your parking space have your name on it? We didn't think so.

WHY DO YOU THINK THE LAB'S BEEN ABLE TO MAINTAIN THIS LEVEL OF SUCCESS?

Because of the people Jack hired and the early leadership, now Greg's. It's that simple. It's excellent people that are very highly motivated and have strong feelings about the laboratory. Usually, by this time, there's a lot of fussing around and internal politics and so forth, in any scientific department. There's a lot less of that here. There seems to be much more of a cooperative feeling.

HOW HAS YOUR APPROACH TO PHYSICS RESEARCH CHANGED WITH TECHNOLOGY?

We used to sit there and draw graphs and things like that by hand – there were draftsman and so forth for final publication copy. It's evolved over the years. Nowadays, we have most things under computer control, type our papers, and do our own graphics, whereas before, you had to sit there and twiddle knobs.

WAS IT HARDER TO ACCESS THE WORK OF YOUR CONTEMPORARIES?

You had to go to the library, which you don't have to do anymore. Doing a literature search at the library could be a lot harder and a lot more time consuming. It took a little while, but as the technology changed, we all adapted – at least everybody I know. I started out mostly having my graduate students do the computer work as I gradually learned.

DO TODAY'S STUDENTS HAVE THE SAME GRASP OF THE FUNDAMENTALS AS YOUR PEERS DID AS STUDENTS?

Yeah, I don't think that's a problem. It's different, but it doesn't change the physics or your approach. A theory is a theory. It doesn't make any difference what tools you use – they're just tools.

DO YOU THINK GLOBAL ACCESS TO INFORMATION HAS CHANGED THINKING IN PHYSICS?

I don't think it's changed thinking, just the access is a much broader range and more rapid than before, it gets a little more inundating, but other than that I don't think it's really changed that much.

DO YOU THINK PHYSICS STUDENTS NOW ARE DIFFERENT THAN YOU WERE?

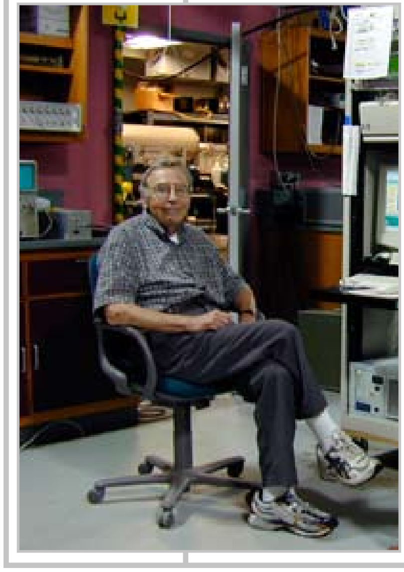
Yeah. When we were in graduate school, and after graduate school, and even the early days here, the graduate students were a much more cohesive group then I see now. They used to party a lot more on weekends than I see now. Maybe that's just a perception and I'm not seeing the parties anymore. In the early days of the lab, there were always parties going on with Jack. We had this enormous flux of people from all over the world coming through; almost every two weeks there'd be something. I don't know how Joan put up with it. Sometimes we would all pick up and go down to the coast for dinner with candidates, etc.

WHAT QUALITIES DO YOU THINK YOUNG SCIENTISTS MUST POSSESS TO BE SUCCESSFUL?

Two things. He or she has to have a talent and be dedicated. You can't get easily discouraged, but you have to know when to quit. It's a fine line. A lot of people think that science is not something that's creative, but the opposite is true. It's a really an art form. It's art, and it can be beautiful.

WHERE WOULD YOU LIKE TO SEE THE MAGNET LAB 10 YEARS FROM NOW?

I'd like to see us at the forefront just like we are now. That means we are going to have to keep up and even start getting ahead in the instrumentation field, and the magnets must continue to evolve. There will be some major jumps when the high temperature superconductors become more easily accessible, but other than that, I think the increase in fields is going to be incremental. It's going to depend on materials development and all kinds of things and that's going to continue. We need to keep improving the instrumentation. We need to keep constant contact with the outside world – the users groups and the collaborations and so forth. You have to have a satisfied user-collaborator community from all over the world. We have that now, but we need to keep the momentum going.



HOW HAS THE LAB'S USER COMMUNITY CHANGED OVER TIME?

The user community at MIT was an excellent community and fairly good sized, but kind of a closed one and static. Here, it hasn't been. That's one of the reasons I stay here; I have a continuous stream of people to talk and collaborate with on work. I'm 83 and I'd rather do this than anything else because it's fun.

AT 83, WHAT KEEPS YOU COMING INTO THE LAB EACH DAY?

There's always the next mountain to climb. There's always an interesting problem showing up, and we have the best facilities in the world and excellent people to collaborate with – why would I want to do anything else?

Thermal stability of the microstructure of OFHC Cu processed by ECAE

D. R. Waryoba[1], P. N. Kalu[1], and R. Crooks[2]

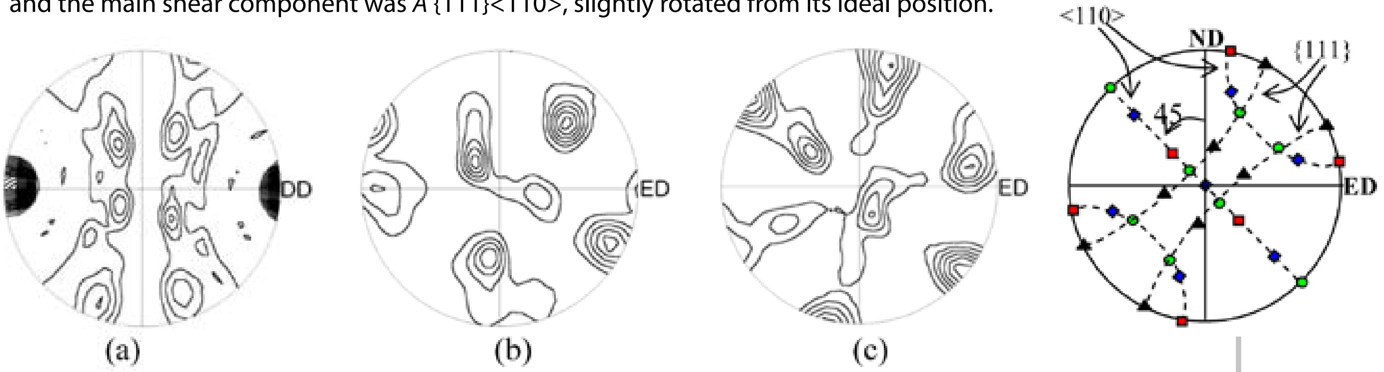
1 FAMU-FSU College of Engineering and National High Magnetic Field Laboratory
2 Black Laboratories

The quest to achieve higher field strength (≥ 100 T) in pulse magnets has led to the need to find alternative methods for fabricating conductor wires. The key requirements for such conductors are: (1) high mechanical strength to counter the effect of the *Lorentz* force and (2) high electrical conductivity to limit the *Joule* heating[1]. In addition to using fiber-reinforced metal-matrix composites, the fabrication method employed at the National High Magnetic Field Laboratory incorporates some form of severe plastic deformation to produce ultra-fine microstructure, which is needed for high strength[2]. It is important to note that some researchers[3] have used flux-melting and melt-solidification in conjunction with wire drawing to produce nanostructured Ag-Cu wires with high strengths. Although wire drawing has been extensively used to impart large strain deformation, there are efforts to explore other methods such as equal channel angular extrusion (ECAE). As in most conductor fabrication technology study, the primary goal of this research is to explore the production of high strength material through grain refinement by ECAE, with particular emphasis on the thermal stability of the microstructure produced by this method, as opposed to that produced by wire drawing.

EXPERIMENTAL SETUP, RESULTS AND DISCUSSION

OFHC Cu was deformed by drawing (to a true strain, $\varepsilon \sim 4$) or by ECAE (to equivalent Von Mises strains of ~4 and 8) via route B_C (where the billet is rotated by 90° in the same direction between consecutive passes), and characterized using orientation imaging microscopy (OIM) technique in a high resolution, field emission gun scanning electron microscope (FEGSEM). In contrast to wire drawing, one of the advantages of ECAE is its ability to produce intense and uniform deformation by simple shear while retaining the same cross-sectional area[4]. It was therefore possible to achieve a strain of 8 by ECAE, a strain that is unattainable by conventional wire-drawing on a laboratory drawing bench.

Due to the axisymmetric nature of the deformation of the wire drawing, the microtexture of the drawn wire can be described as a duplex <111>+<100> fiber texture, with the <111> as the major component (see Figure 1a). This is typical of most drawn fcc materials[5]. Unlike wire drawing, ECAE did not produce a stable orientation, possibly due to the repeated changes in the strain path. Rather, it produced two major fibers (see Figure 1b and 1c): the {111}<uvw> or simply {111} partial fiber, and the {hkl}<110> or simply <110> partial fiber. These fibers comprise of shear components (shown in Figure 1d): $A/\bar{A}$, $B/\bar{B}$, C, and A_1^*/A_2^*. In the ideal case of the 90°-die pressing, the two partial fibers will be rotated by 45° such that <110> is parallel to shear direction (SD). However, after 4 or 8 passes, the fibers were rotated by 30° to extrusion direction (ED) and the main shear component was *A* {111}<110>, slightly rotated from its ideal position.



Component	Symbol
A $\{1\bar{1}1\}\langle110\rangle$ / $\bar{A}$ $\{\bar{1}1\bar{1}\}\langle\bar{1}\bar{1}0\rangle$	●
B $\{1\bar{1}2\}\langle110\rangle$ / $\bar{B}$ $\{\bar{1}1\bar{2}\}\langle\bar{1}\bar{1}0\rangle$	◆
A_1^* $\{\bar{1}\bar{1}1\}\langle112\rangle$ / A_2^* $\{11\bar{1}\}\langle112\rangle$	▲
C $\{001\}\langle110\rangle$	■

Figure 1.
OIM (111) pole figures showing partial fibers (a) in the drawn wire ($\varepsilon \sim 4$), and ECAE processing to (b) 4 passes, and (c) 8 passes (contours at 1, 2, 3, …times random). The key in (d) shows ideal components in simple shear.

Wire drawing (strain, ε ~ 4) produced elongated grains, with an average grain and sub-grain thickness of 3μm and 1 μm, respectively – both aligned in the drawing direction (DD). On the other hand, the microstructure of the ECAE (4 passes) processed material was finer than that of the drawn wire. It was essentially lamellar structure with grain boundary waviness and multidirectional cell bands of low angle boundaries with average misorientation angle of 2°. The bands were of two types: narrow and wide bands with average width of 0.5μm and 1.5μm, respectively. While some cell bands were aligned in the ED, the majority of the bands were aligned at 30° to ED. This direction is slightly off the principal SD. For a 90°-die, the SD is along the die-angle bisector, which is at ~45° to ED. This complex structure can be attributed to the directional changes in the strain path. Although the microstructure after 8 passes consisted of lamellar structure which were roughly aligned in ED, it was more refined and contained virtually no shear bands. The average width and aspect ratio of these elongated grains was about 0.4 μm and 0.15, respectively. The grains contained clearly defined cellular structure of average sub-grain width of about 0.1μm.

Despite the differences in the two deformation modes, the fraction of the high angle grain boundaries (HAGBs), with misorientation angle ≥ 15°, in all processed materials was less than 50%: it was 50%, 30% and 25% for the 8-pass, wire drawn and 4-pass processed materials, respectively. This was lower than the critical fraction (~70%) required for the microstructure to be considered as a true submicron grained structure[6]. Similar observations have been previously reported in ECAE processed copper[7] and aluminum alloys[8].

Assessment of the stability of the microstructure was carried out by annealing the processed materials at 250°C, 500°C and 750°C. Despite having finer as-processed grain size, the annealed grain size of the 4-pass material was comparable to that of the drawn material upon annealing at 250°C and 500°C. Contrary to conventional wisdom, the grain size (~88μm) of the 4-pass ECAE material was larger than that of the drawn material (~55μm) when the materials were annealed at 750°C. However, the grain size (~32μm) of the 8-pass ECAE material annealed at 750°C was significantly smaller than that of the annealed 4-pass and annealed drawn materials. Figure 2 shows the OIM maps of the microstructure of the materials annealed at 750°C, and the summary of the variation of the grain size as a function of annealing temperature is presented in Figure 3. The observed difference in the processed materials response to annealing, especially, the annealed grain sizes, can be attributed to the differences in the as-deformed grain boundary structure of the materials. Recent studies[9, 10] have shown that the presence of mobile or pinning boundaries in a material can enhance or retard grain growth, respectively. A detailed investigation of the grain boundary structure is being carried out with the view to assess the role of the pinning boundaries in the stability of the microstructure [11].

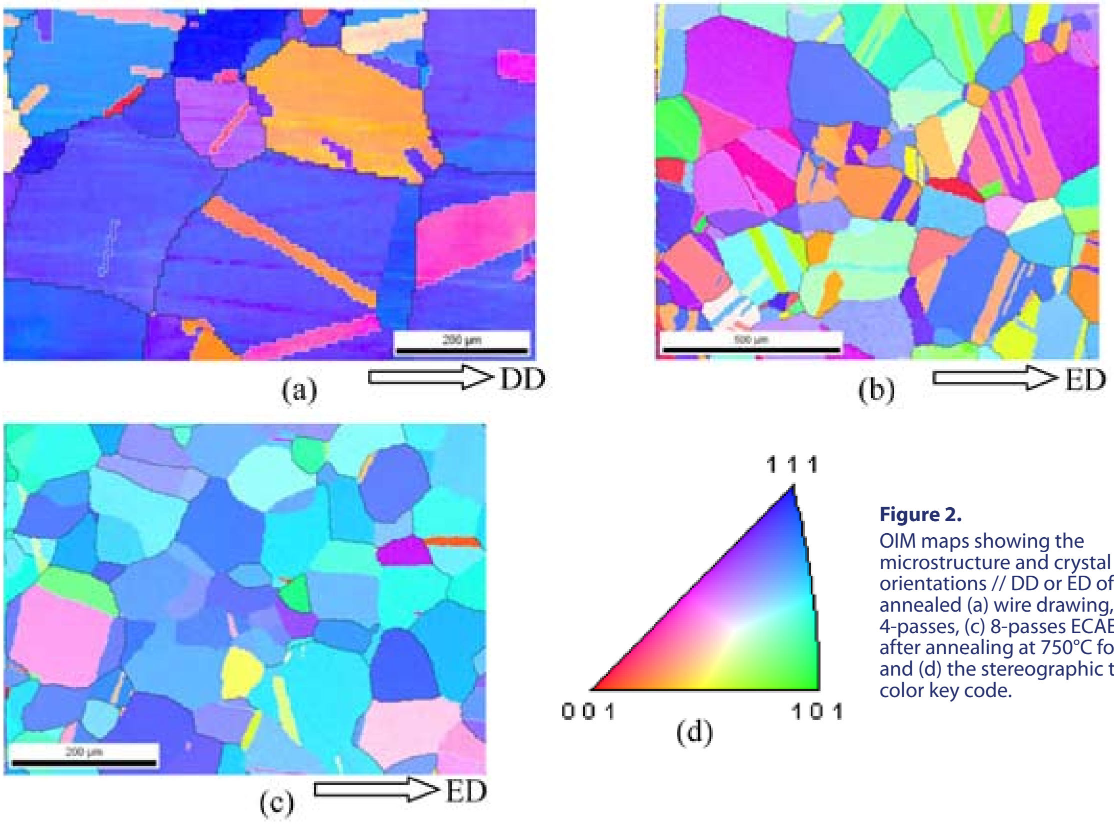


Figure 2.
OIM maps showing the microstructure and crystal orientations // DD or ED of the annealed (a) wire drawing, (b) 4-passes, (c) 8-passes ECAE billets after annealing at 750°C for 1 hr, and (d) the stereographic triangular color key code.

CONCLUSION

The processing of OFHC Copper via wire drawing or ECAE route B_C resulted in microstructure that can not be classified as submicron grain structure due to the low fraction of the HAGBs (< 70%). The grain size of the annealed 4-pass ECAE material was either comparable (when $T = 250$°C and 500°C) or larger than (when $T = 750$°C) that of the drawn wire, in spite of having finer as-deformed grain size. A comparison of the fraction of the HAGBs for the three processing conditions showed that the 8-pass ECAE had the highest percentage, while the 4-pass ECAE had the least. It is important to note that increasing the number of ECAE processing passes (8-pass) resulted in smaller annealed grain size. While additional work is needed to analyze the grain boundary character of the materials, it is reasonable to tackle the issue of stability through increasing the number of processing passes.

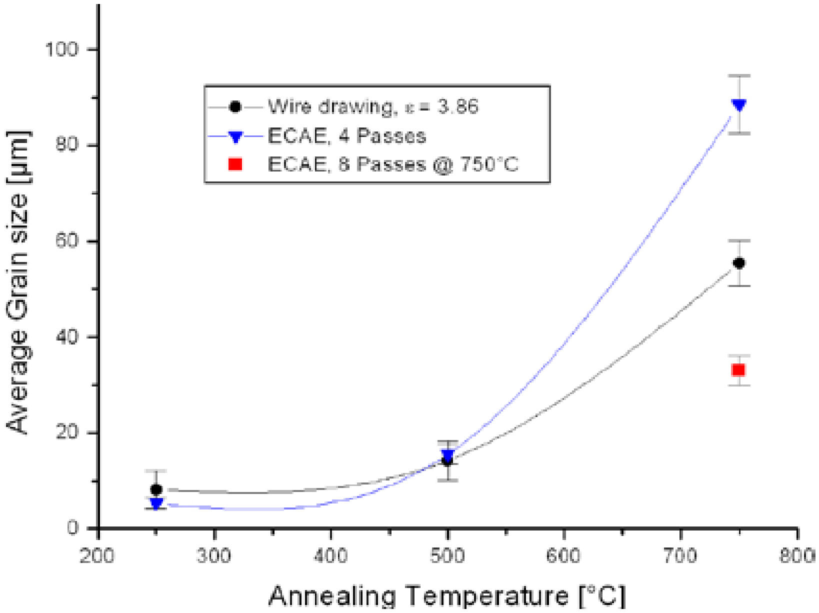


Figure 3.
Average grain size in the ECAE processed billets and drawn wires after annealing at different temperatures.

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Successful test of the conical model coil

By Jingping Chen and Mark D. Bird

The Magnet Lab is developing a high field conical bore hybrid magnet suitable for neutron scattering experiments for both the Hahn-Meitner Institute in Berlin and the Spallation Neutron Source (SNS) in Oak Ridge, TN. The new conical hybrid magnets will provide much larger scattering angle and much higher field than all existing conical-bore magnets, as shown in Figure 1, where the new magnet for SNS is shown by the red star. In contrast to the cylindrical bore of regular magnets, the conical shape bore in both magnet systems significantly reduces the space available for the resistive insert coils. To make the most of the limited space, the conical Florida-Bitter (CFB) magnet technology (patent pending) will be applied. The sketch of the CFB is shown in Figure 2a, where the red part is the space for the coil generating magnetic field, and the green part is the space required for mechanical and electrical connections. Figure, 2b and c show the other two potential methods, i.e. conical bitter technique and conical polyhelix. Obviously, the CFB technology outperforms the other two by reducing the connection spaces and maximizing the space factor in a conical configuration significantly. Figure 3a shows the relation between field and opening angle. The red curve represents 12MW Series Connected Hybrid (SCH) using CFB technique, while the other two curves stand for 40 MW regular resistive magnets. To get similar field, SCH with CFB technique consumes much less power than the resistive magnets. More importantly, CFB technique makes the magnet system relatively insensitive to the opening angle (scattering angle), which users want to be as large as possible. With opening angle increasing from 10º to 30º, the field capability of the hybrid drops from 36 T to 34 T, while the capability of the resistive magnet drops from 38 T to 24 T. Therefore, CFB is much more suitable for large opening angles than traditional technology.

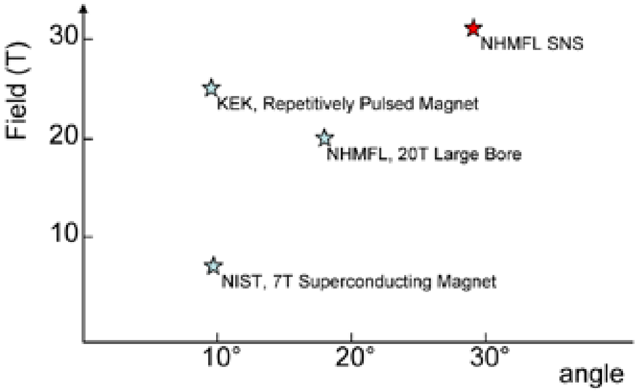

Figure 1.
The performance of existing conical bore magnets and the one that we going to build for SNS.

The user magnet for HMI will consume either 4 or 8 MW to generate 25 to 30 T field, while the one for SNS will consume 12 MW power for the field higher than 30 T. To demonstrate the new technology, we have designed and built a model coil. The picture of the model coil is shown in Figure 4. The working model consists of one coil with 10 different zones. The inner radii of each zone are different, while the outer radii are the same. Because of the different inner radii, the distribution of the current density, temperature and stresses are different for each zone, so these design values need to be calculated and optimized zone by zone. The main design parameters and the detailed zone stacking feature are listed in the first reference[1].

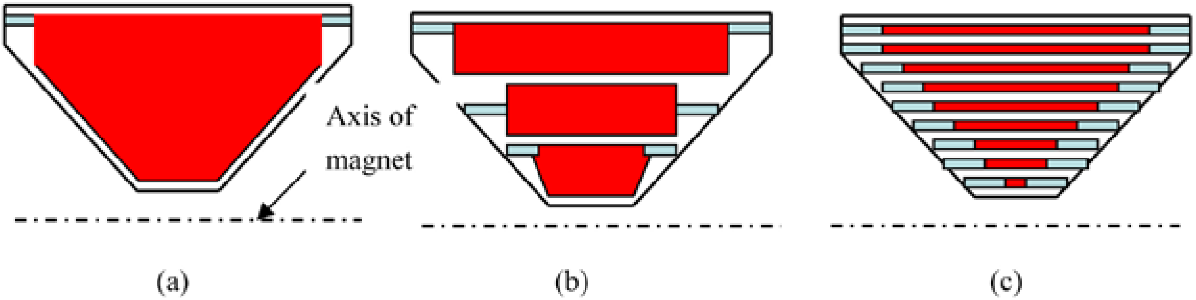

Figure 2.
(a) Conical Florida Bitter; (b) Conical Bitter ; (c) Conical Polyhelix; The red part represents the space for the coil and the blue parts is for mechanical and electrical connection.

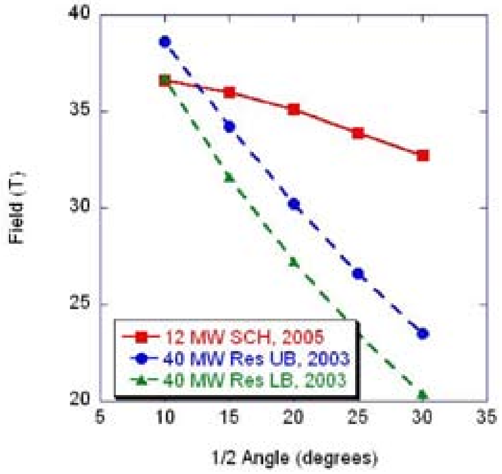

Figure 3.
Field vs. opening angle, the red curve represent 12 MW series connected hybrid. The other two are 40 MW resistive magnets.

The model coil was tested in the existing 20 T 200-mm bore resistive magnet at the Magnet Lab. It successfully operated at a current-density of 672 A/mm^2 and a power density of 13.2 W/mm^2, both of which are higher than those of the 45 T hybrid. The mechanical stress in the coil due to Lorenz forces was beyond the yield strength of the material.

The model coil generated 12.1 T with the background field of 19.4 T for total 31.5 T, which meets the design objective. To further test the coil, we pushed the insert current from 15kA (design value) to 18 kA. In this case, the model coil sustained stresses high enough to deform the bitter disks plastically. The model coil still worked in this severe condition and generated field of total 33.5 T. In addition, the cyclic testing indicates that the coil structure of the present design is stable.

The power consumed in all the tests is very close to the design value, implying that the cooling system performed as intended. Moreover, we measured the cooling water temperature in eight different positions in the cooling channels. These temperature data are critical for the assessment of thermal and hydraulic design parameters, such as water velocity, disk temperature distribution, friction and heat transfer coefficient. The calculation results show that most of data locate well in the range of design value, but some parameters, such as water velocity, do show the discrepancy between design and real values. These are the things that we will improve in the real user magnet design.

In general, the model coil tests are successful. This test demonstrates the Conical Florida Bitter technology. It provides lot of data very important for the future design of the user magnet.

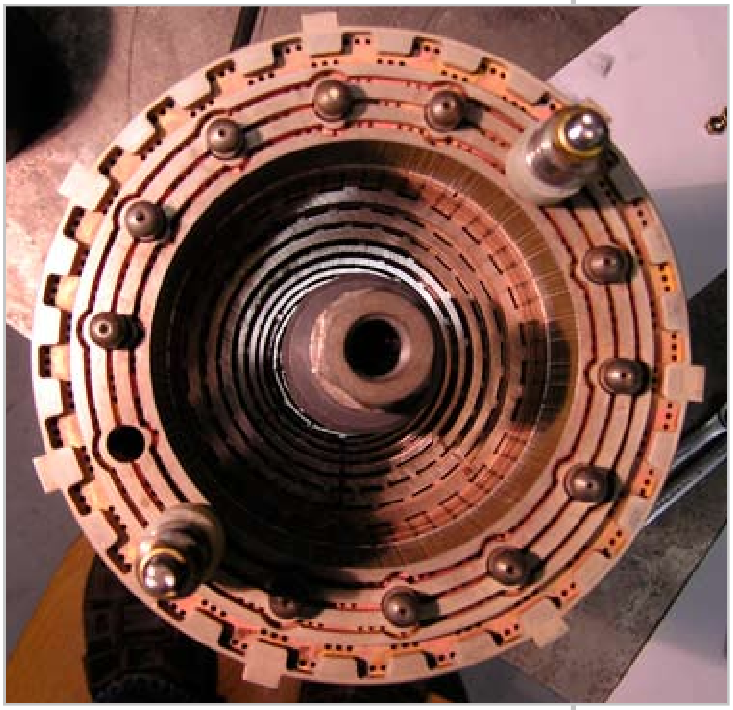

Figure 4.
Photo of the conical model coil.

ACKNOWLEDGEMENTS

This work was supported by the SNS Series Connected Hybrid DMR-0603126. The authors greatly appreciate the efforts of Scott Bole, Youri Viouchkov and Jim O'Reilly developing and testing this magnet.

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Progress toward NMR in DC magnets

By Kiran K. Shetty

With the 36 T Series Connected Hybrid (SCH) project the Magnet Lab has embarked on a journey toward building more efficient high field hybrid magnet systems [1]. But the SCH will also have a larger bore (40 mm), higher homogeneity, and fewer magnetic fluctuations than today's highest field DC magnets. These features will bring the very high fields of DC magnets to demanding resonance experiments, such as EMR and NMR, that are now limited to the lower field of supercons. As the construction of the SCH magnet proceeds, many of the improvements needed for the SCH will be demonstrated and refined on the high homogeneity Keck magnet with a ^{1}H resonance frequency of up to 1065 MHz. These enhancements include resistive shims, a flux regulation system, and better control of cooling water temperature. Once in place, these capabilities will be available to Magnet Lab users even before the SCH is completed.

A constant magnetic field is perhaps the most fundamental requirement for NMR. The continuous efforts of the Operations Group to reduce power supply noise have already paid large dividends in the very lower level of AC ripple present in our magnets. To further reduce temporal field fluctuations, a flux regulation system that uses a digital feedback control system is being developed in collaboration with Jeff Schiano of Penn State University. It relies on an inductive sensor and integrating preamplifier to detect fluctuations in the 0.1-1 kHz range. At its heart is a powerful digital signal processor from dSPACE Gmbh on which control algorithms can be quickly implemented and tested using the Simulink environment of Matlab. Using an internal model principle (IMP) approach, field noise at 60 Hz and its first few harmonics has been virtually eliminated. Random fluctuations have also been greatly suppressed. The dramatic improvement in resolution is shown in Figure 1. Using a Mag Lab-developed magic angle spinning (MAS) probe to reduce the effect of inhomogeneity, field fluctuations (even with our excellent power supply) completely distort the resonance of a reference sample of H_2O. But with the field regulation system, we have resolved the water line down to just 66 ppb, representing a fluctuation level of 1.7 µT.

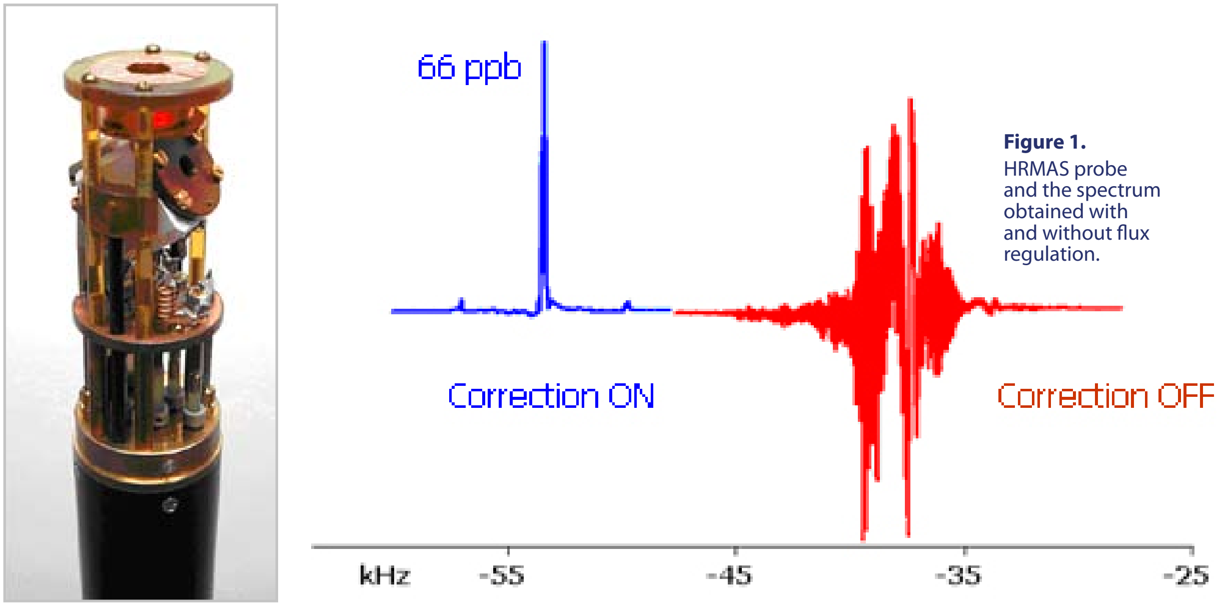

Figure 1. HRMAS probe and the spectrum obtained with and without flux regulation.

An important test of field quality is the phase fluctuation of an NMR "spin echo," the signal following a 90°-TE/2-180°-TE/2-acquire pulse sequence. And the ability to measure the phase of a spin echo unlocks the power of NMR for almost any type of "2D" experiment, including measurements of inter-spin couplings that reveal the structure and dynamics of molecules and materials, as well as measurements of diffusion and even imaging experiments. Without the flux regulation system, standard deviation of the echo phase for TE = 1 ms is about 40°. Figure 2 shows that, with the IMP-based flux regulation system, we reach that same 40° fluctuation at TE ~ 30 ms, a factor of 30 improvement. Although this is already sufficient for many applications, even lower phase fluctuations may be achieved with the NMR field-frequency lock system now in development.

Longer-term temporal field fluctuations are due to the thermal expansion of the solenoid in response to changes in cooling water temperature, resulting in a ~16 ppm/°C field dependence. To provide faster response and better regulation, a 6 in. butterfly valve was plumbed across the main 12 in. plug valve that regulates flow to the heat exchanger—and hence regulates water temperature in the magnet. Thermal fluctuations in a test run were reduced from 4 ° C to <1° C.

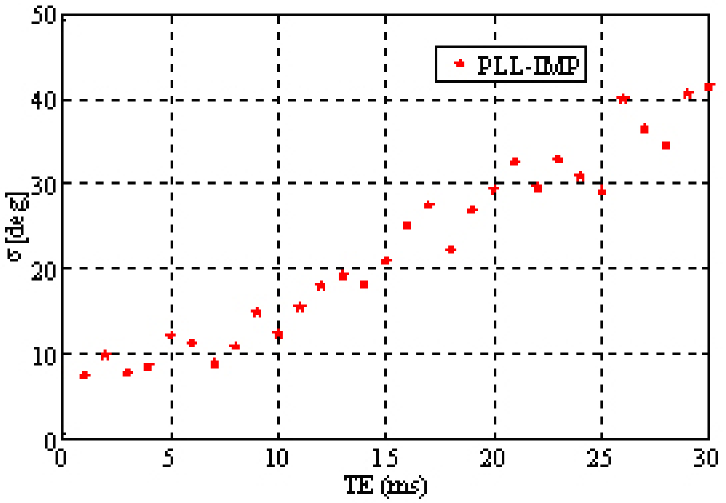

Figure 2.
The standard deviation of spin echo phase achieved with the IMP flux regulation system.

Although fast sample spinning, such as MAS, can sometimes be used to obtain high resolution spectra in inhomogeneous magnets, there are many experiments for which it is not appropriate. For those, a homogenous magnetic field is still important. With the help of an innovative water-cooled shim set, homogeneity of the SCH magnet will be adjustable at any field. The concept will be tested later this year on the Keck. Figure 3 shows the shim coil prototype that was designed by Magnet Science and Technology at the Magnet Lab and constructed by Advanced Magnet Lab Inc. The prototype recently passed its first test, for its shim strength and purity, in a NMR magnet. It will be installed in the Keck magnet later this year where it will allow users to achieve homogeneous field at any desired field by adjusting currents through the coils with the help of computer controlled power supplies.

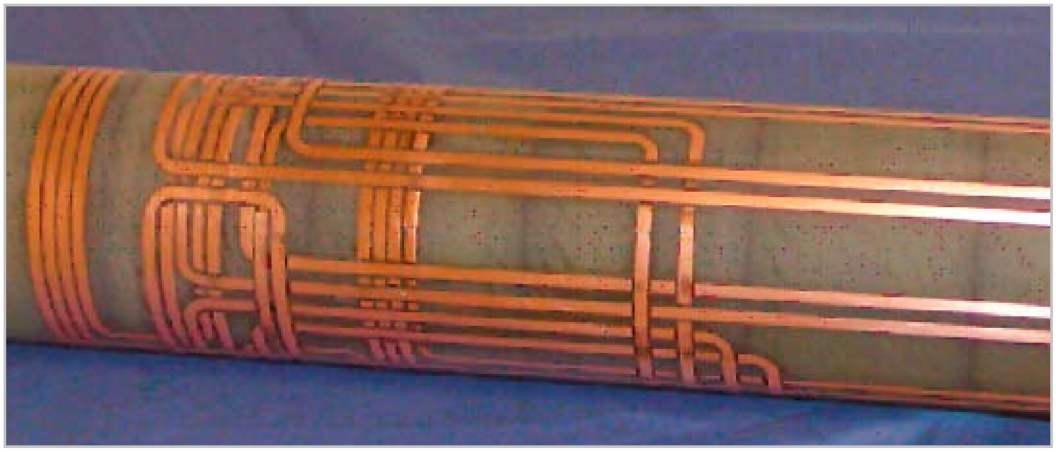

Figure 3.
The water-cooled resistive shim set built for the Keck resistive magnet.

With these innovative technologies, the DC facility will soon not only have efficient high field magnets but will also be able to boast of high spatial field uniformity and very low temporal field fluctuations. The ability to produce field uniformity in the range of 1 ppm over a 10 mm DSV at any desired field strength and NMR echo phase stability for long TE's that are comparable to a superconducting magnet presents unique opportunities for the NMR user community. NMR researchers interested in using the facility should e-mail William Brey (wbrey@magnet.fsu.edu).

REFERENCE

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Magnet 101: undergraduates get ahead with customized Mag Lab internships

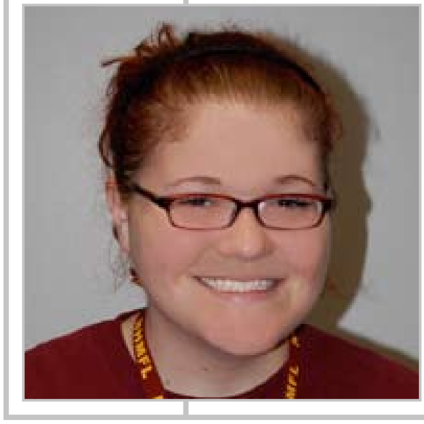
Participating in research is a rare and awesome opportunity for students at any age and at any stage in their career development. The Magnet Lab is continually seeking opportunities to creatively place Florida State University freshmen as well as middle and high school students in research environments in addition to the more structured Research Experiences for Undergraduates and Research Experience for Teachers programs that continue to be well-supported by all departments.

For the spring semester, we have three freshmen women participating in the Women in Math, Science, and Engineering (WIMSE) program working at the lab. They also worked at the lab in fall semester and it is to their credit that their work continues for a second semester. All three of the WIMSE participants are applying to the lab's REU program for summer 2008.

The Women in Math, Science and Engineering Living-Learning Community seeks to increase the retention of women in these fields by promoting a supportive environment, encouraging participation beyond the classroom, providing increased exposure to these fields, and developing skills necessary to be successful.

Kristen Collar is a participant in FSU's WIMSE program and a self-described Army brat having lived in Germany and Italy as well as Kansas, Washington and California. Most recently she attended high school in St. Petersburg, Florida and describes herself as an Exploratory Science Tech in Engineering. Kristen found her science focus in high school. Stan Tozer, Ryan Stillwell and Tesfaye Gebre are providing guidance and instruction for her new project, which is to find an effective way to anneal CeCoIn5. Kristen says she is still "learning the basics, cutting leads and making coils." She is hoping to learn how to apply her new skills to a research-oriented project. She will continue her work at LANL this summer with Chuck Mielke. Kristen says that her 12 hours a week at the Magnet Lab is an outstanding and unusual opportunity for a freshman.

Julia Bourg from Orlando says she has always been interested in science beginning in kindergarten when her class went to a local science center in New Jersey. She is majoring in chemical engineering with an interest in biomedical engineering. Julia is working under the tutelage of Stan Tozer, Tesfaye Gebre, Ryan Stillwell, and Ju-Hyun Park. Having just started, she is learning the basics of crystal growth and the annealing process. She particularly likes the living-learning community because of the level of support it provides just by housing all of the science, math and engineering freshmen in one dorm. Some student join WIMSE just for the opportunity to do research and she feels fortunate that the Magnet Lab has reached out to freshmen and sophomores.



Cassaundra Meyers, also a participant in the WIMSE program, is currently working in geochemistry with Vincent Salters, Roy Odom, and Michael Bizimis and hopes to pursue her research through the summer. Although she is in her first year at FSU, she is a senior transfer from the University of Miami and so as she says is "a bit of an anomaly for a first-year WIMSE student." She developed her love of science while experiencing "oceans to national parks to museums" with her parents. Cassaundra became interested in geology in college, when she took two introductory geology classes and she made her career choice. Cassaundra says, "My experience working in the department [geochemistry] gave me an invaluable look into how laboratory research is carried out, and a great deal of experience that will benefit me greatly in my own research in the future."

People


Alan Dorsey

Alan Dorsey, chair of the Department of Physics at the University of Florida and Magnet Lab affiliate, will play an integral role in a new initiative designed to give a major boost to math and science education in the state's schools. Dorsey, together with Tom Dana, director of the School of Teaching and Learning at UF, will lead FloridaTeach, an ambitious program to recruit more math and science majors into the teaching profession.

The initiative was launched by both UF and FSU. Each university will receive up to $2.4 million over five years from the National Math and Science Initiative (NMSI), an innovative not-for-profit organization launched by ExxonMobil in early 2007 to address one of the nation's greatest economic and intellectual threats — the declining number of teachers qualified to effectively teach science, mathematics and computer sciences to K-12 students.

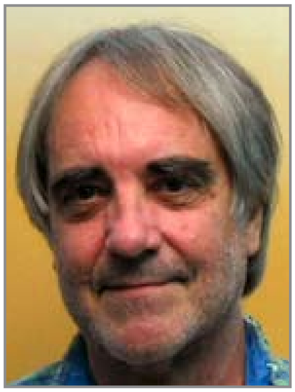

Dr. Kristina Hakansson

In addition, FSU and UF each will receive support in the amount of $1 million from the Helios Education Foundation, another nonprofit, to fund their respective initiatives. With matching funds provided by the Florida Legislature, each university will have a total of approximately $5 million to launch its program.

Former Magnet Lab ICR Program Postdoctoral Fellow, **Dr. Kristina Hakansson**, now Dow Corning Assistant Professor of Chemistry at the University of Michigan, has been appointed to the News and Features Advisory Panel of Analytical Chemistry, the premier journal in its field.

On Nov. 16, 2007, The FSU Office of Research held its Third Annual Innovator Awards Reception at the University Center Club. The purpose of the evening was to recognize members from the FSU community who have contributed during the past year to the intellectual property portfolio of the University.

The following Mag Lab affiliated scientists were honored:


James Brooks

James Brooks – *Electromagnetic Resonant Analysis of Sealed Metal Shipping Containers.* Brooks is developing a method of analyzing shipping container contents as they are moved from ship to shore. This technology is based on the natural electromagnetic resonance of enclosed metal containers, and therefore does not use harmful X-rays or gamma ray beams. This method of securing container cargo could make a significant impact on the multi-billion dollar container shipping industry.


Michael Davidson

Michael Davidson – *Website Design.* Davidson and his team was asked to build a new Web site for the Optical Society of America that will serve as a new educational resource tool in the science of optics and photonics. The underlying site which is the basis for the new Web page, is one of the top science sites and won a Webby award in 2001.

People cont.

2007 Innovators cont.

Timothy Cross

Timothy Cross – *Structure Function Studies of Membrane Proteins by Solid State NMR.* Cross was recognized with a GAP Grant Award for his work on the development of a system that uses NMR spectroscopy to screen libraries of proteins to identify those that bind to insoluble membrane proteins, that cannot be analyzed using conventional SAR techniques.The FSU Research Foundation GAP program is designed to support enhancements of inventions or other original works that have been disclosed to FSU. It funds projects that FSU researchers and other interested parties agree will quickly improve the odds that current research results will lead to public availability of a new product or service. Starting in 2005 the FSU Research Foundation has allocated up to $250,000 per year for at least four years to provide grants under this program.

Dr. Alex P. Malozemoff

American Superconductor Corp. Executive Vice President and Chief Technical Officer **Dr. Alex P. Malozemoff**, a member of the Magnet Lab's External Advisory Committee, has been elevated to the rank of Institute of Electronic and Electronics Engineers (IEEE) Fellow, the highest grade of institute membership.

The University of Florida's 2007 Colonel Allen R. and Margaret G. Crow award was given to graduating senior **Jessica Pfeilsticker**, who finished her BS with a straight 4.0 average and graduated Summa Cum Laude with a superb thesis on resistively detected NMR with Professor Russ Bowers. Jessica has since moved to Pasadena to work on her Ph.D. at California Institute of Technology.

Jessica Pfeilsticker

Justin Schwartz

Justin Schwartz has received a 2007 Special Award for Exceptional Service from the FAMU-FSU College of Engineering.

David Waint

Magnet Lab DC Field user **David Waint** of Kent State is the first American recipient of the prestigious Otto Lehman Award. The prize, which is awarded by the Universitat Karlsruhe and the Otto Lehmann Foundation, is named after Otto Lehmann, the famous German physicist and "father" of liquid crystal technology. Award submissions for the Otto Lehman prize are evaluated by an independent scientific jury, which consists of experts from universities and industry. The final decision for the award(s) is made by the Otto Lehmann Foundation.

Science Starts Here

Madalina Furis

POSITION

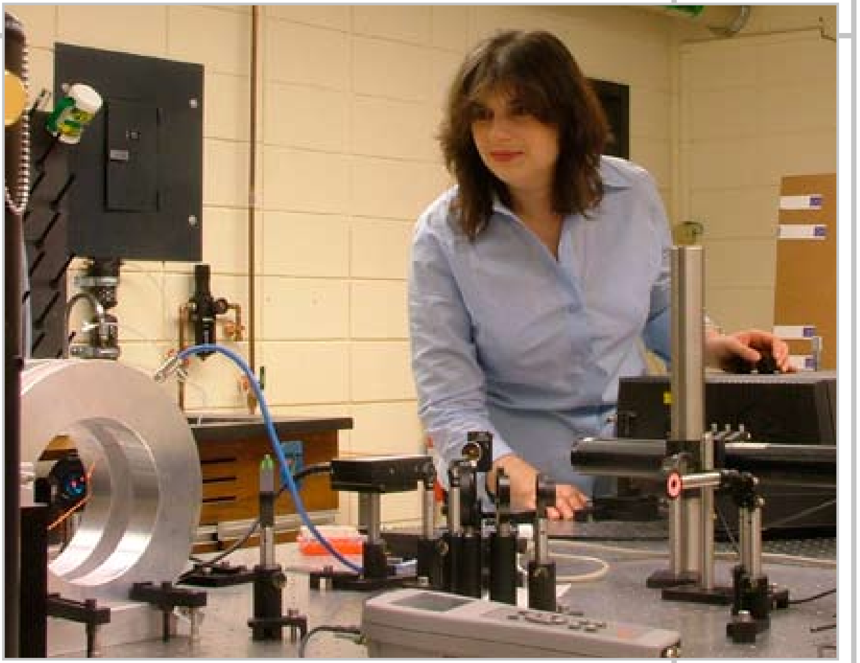
Assistant Professor
University of Vermont, Physics Department

TIME AND ROLE AT THE MAGNET LAB

March 2004- August 2006, postdoc, Pulsed Field Facility

CURRENT WORK:

"At the University of Vermont my research is focused on spin-dependent properties of nitride semiconductors. Widely known as bright blue and white light emitters (everyone has a "blue" keychain or a very bright and "cold" flashlight) nitrides materials hold great promise for the emerging field of spintronics (a radically new way to store and transport information through electron spin rather than charge.)"



"I had the opportunity to interact with many researchers from U.S. and abroad I would have otherwise never met."

"Unlike other semiconductors nitride materials are highly piezoelectric, meaning one can create a very large electric field inside them (~1MegaVolt/cm) simply by mechanically straining the crystal. I am planning on investigating the effects of the strain-induced built-in electrical polarization present in these materials on the spin of free electrons since it is predicted that a fundamental quantum mechanical property of semiconductors, the spin-orbit coupling, is dramatically affected by the presence of these piezoelectric fields."

"My group will probe these effects using state-of the art spin-dependent optical spectroscopy techniques I learned and perfected during the years spent as a grad student at SUNY Buffalo and later on, as a postdoc at the Magnet Lab."

IN HER WORDS:

"The research environment at the Magnet Lab helped me become a better and much more productive scientist. Here I had the opportunity of learning unique high magnetic field experimental techniques from the top researchers in the field, in a friendly and most welcoming atmosphere. Thanks to the open character of the Magnet Lab, I had the opportunity of interacting with many researchers from US and abroad I would have otherwise never met. Most importantly the excellence in scientific research, constantly promoted at NHMFL, helped me achieve my professional goals. The most important lessons I've taken with me are how to be pragmatic and get the most out of six hours of magnet time."

HOW MENTORS MAKE A DIFFERENCE:

"I owe a lot to Scott Crooker, whom I shall always consider my mentor. He taught me that I should never stop when I thought I've done my best, because I could always do better."

"He is an excellent experimentalist with an in-depth knowledge of physics and I will always be grateful to him for teaching me about spin-dependent phenomena."

"I was very impressed by his true passion for discovery and the way he always knew how to channel this passion into exciting new research. As a mentor, he always expected me to rise up to all the scientific challenges raising the bar higher and higher every time."

"Science Starts Here" showcases young Scientists whose career paths have been greatly shaped by their experiences at the Magnet Lab.

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