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October 20, 2005

Dear Carl,

I have attached the report of our panel on the National High Magnetic Field Laboratory. The panel members have unanimously endorsed the document. I look forward to presenting the report to the MPSAC in early November.

Robert C. Richardson

Robert C. Richardson
Chair
National High Magnetic Field Laboratory Review Panel

CC: Dr. Thomas Weber, Division Director, Division of Materials Research
Dr. Lance Haworth, Division of Materials Research

Report of the Advisory Panel on Future Support for High Magnetic Fields

1. Introduction

To address the charge to the NSF Advisory Panel on the Future Support for High Magnetic Fields, the panelists met at the NSF headquarters in Arlington on March 16 to 18, 2005. In addition, all of the panel members paid visits in April to either of the sites of the National High Magnetic Field Laboratory (NHMFL) in Florida or the pulsed field facility in Los Alamos, or had done so in the past. The Report of the National Research Council (NRC) on "Opportunities in High Magnetic Field Science", the COHMAG report, was also a valuable resource for the panel. All members of the panel were very favorably impressed with the technical and scientific achievements of the NHFML. The fundamental science remaining to be investigated in physics, chemistry, materials, and biology remains quite fertile. The potential new applications of high magnetic fields to technology can be critical to future economic strength of the United States. In the following, we provide a brief summary of some important specific observations that led us to the principal unanimous conclusion that there should be no re-competition for management or locations of the NHFML.

2. Charge to the panel

"NSF Advisory Panel on Future Support for High Magnetic Fields

I. Background

The National High Magnetic Field Laboratory (NHMFL) was established in 1991. In October, 2000, the National Science Board approved a five-year award for the operation of the NHMFL. This award, extending through December 31, 2005, authorized up to $117,500,000 over 60 months for NHMFL operations. On 29 March, 2004, the NSB approved a two-year extension of the current Cooperative Agreement *"to allow time for a National Academy of Sciences panel to complete a report on high magnetic field science and technology and for the National Science Foundation (NSF) to convene a 'blue-ribbon' panel to recommend the best course of action concerning re-competition of the NHMFL."* The NSB authorized funding during this period in an amount not to exceed $52,500,000, bringing the award to a total of $170,000,000 over 84 months. The current Cooperative Agreement terminates on December 31, 2007.

The National Science Board (NSB) has adopted the position that "…*expiring awards are to be re-competed unless it is judged to be in the best interest of U.S. science and engineering not to do so*" (Appendix D to NSB 97-241). To address this issue, the NSF Division of Materials Research is convening the Advisory Panel on Future Support for High Magnetic Fields. The members of the panel are distinguished scientists from a wide range of scientific disciplines.

Prior to convening the panel, NSF asked the National Research Council to assess the current state of and future prospects for high-field science and technology in the United States. The resulting report of the NRC Committee on Opportunities in High Magnetic Field Science (COHMAG, appended) states:

"The United States should maintain a national laboratory that provides its scientific community access to magnets operating at the highest possible fields. The National High Magnetic Field Laboratory has successfully met this need for about a decade."

COHMAG went on to identify a number of opportunities for consideration as the U.S. explores future investment in high magnetic field science, namely,: enabling the study of neutron and x-ray scattering properties of materials in high magnetic fields; drawing all relevant communities into the development of new approaches to building the magnets and ancillary technologies needed for research; and developing novel technology and methodology for magnetic resonance and magnetic resonance imaging.

II. Charge to the panel

The panel will determine whether the Laboratory has the potential to fulfill the vision presented in the COHMAG report, and will advise NSF as to a course of action that is in the best interests of U.S. science and engineering. Specifically, the panel is asked to consider the following options available to NSF:

(1) Renewal review of the NHMFL award, rather than re-competition,

(2) Holding an open competition for a magnet laboratory, which would include the possibility of building an entirely new magnet laboratory and phasing out support for the NHMFL,

(3) Holding an open competition for a distributed magnet laboratory, or

(4) Holding a competition for additional sites to be added to the existing NHMFL.

The panel will conduct site visits to NHMFL sites, as needed. The panel is also asked to suggest and prioritize other options that may be appropriate, and to make its recommendations in the context of high magnetic field facilities available internationally or elsewhere in the U.S."

3. Recommendations

In direct response to the charge set before the Panel, we recommend that NSF choose the first option: Renewal review of the award rather than re-competition. The Panel is opposed to the creation of a "distributed laboratory" that is different from, or does not include, the NHMFL.

Throughout its existence, the NHFML has served the national interest very well. It has developed magnificent infrastructure for conducting research in an extremely difficult environment – extremely large magnetic fields. The laboratory has led the world in technology development in essentially every area of significance – high sustained fields, pulsed magnetic fields, and extension of high field technology to important new applications, such as cyclotron resonance.

The infrastructure and funding supplied by the State of Florida have played an important part in the success of the NHFML. It is improbable that any other state or local government would be interested in investing several hundred million dollars in similar facilities to reproduce the space, electrical power, and magnet cooling resources available in Florida. Florida has been an enthusiastic partner in the enterprise.

The Laboratory has provided outstanding user services to a widely based scientific community. Scheduling of time in the facilities has been reliable and the staff has apparently been unfailingly user-friendly. However, we do make some suggestions for improvements in scheduling practices and user housing in this report. The research facilities are the best in the world for high magnetic field science and the forward looking design group can continue to lead in extending the strength and volume of available magnetic fields if given the necessary financial resources.

One possible change in the organizational structure that was considered was the establishment of ‘branches’ of the NHMFL in X-ray and neutron facilities. The Laboratory has developed an innovative split magnet, which will permit beams of photons or neutrons to enter an experimental large field volume. These new magnets can add a very important new capability to the pulsed neutron facility in Oak Ridge and any of the large X-ray facilities. The work is still developmental, and it would be premature to consider any major change in the basic management structure of the NHFML. More specifically, the split magnets should be built, installed, and tested by NHFML personnel traveling to the new facilities. Decisions about longer-term questions related to management of user access to the new capabilities should be postponed until use becomes more of a “turn-key” operation.

Finally, it is important to note that Greg Boebinger is a very effective new director of the Laboratory. He is a highly respected and active research scientist who is also a capable manager. The morale of the staff seemed very high and relations between the NHMFL and its principal partners at Florida State University, the University of Florida, and Los Alamos National Laboratory appear to be working smoothly.

4. Advances in magnet design and development

The NHMFL is the premier high magnetic field laboratory in the world. The Laboratory provides unparalleled opportunities for science and technology involving high magnetic fields. It has the most versatile collection of DC and pulsed field magnets – superconducting, resistive, and hybrid magnets – for different applications. The NHMFL is the world leader in providing high magnetic fields for users, both in number of available magnets and in the supporting equipment to perform a wide range of experiments. The NHMFL has clearly established itself as "the place to go" if you want to use high fields to do experiments on condensed phase systems, and it attracts an international clientele.

The NHMFL has been at the forefront of magnet design and development and is a world leader in this area. Magnets with much higher power density and Lorentz forces than conventional Bitter magnets (round cooling-holes) have been developed using Florida-Bitter magnet technology (shaped cooling-holes) (1994-96). Examples of notable advances made by the NHMFL include:

Powered (resistive) magnets

These include the 35 T (32 mm bore) 20 MW resistive magnets and the 31 T (52 mm bore) 20 MW resistive magnet. The Florida-Bitter technology has been adopted by most of the world's leading high magnetic field laboratories. These magnets are substantially better than earlier magnets of that type, and high field laboratories in other countries have installed NHMFL Bitter magnets in their facilities with NHMFL assistance.

Persistent (superconducting) magnets

These magnets are based on state-of-the-art cable-in-conduit magnets, coupled with Florida-Bitter magnets that serve as the insert coil to form a hybrid magnet. These hybrid magnets include:

(a) The 45 T hybrid magnet.

This magnet was commissioned in 2000 and has set the world record for DC magnetic fields.

(b) The 900 MHZ ultra wide bore (105 mm) NMR magnet.

A one-year commissioning phase for this magnet started in July, 2004. This magnet provides 21.1 T in an unprecedented 105 mm bore superconducting magnet that provides 1 ppb homogeneity for high-resolution state NMR (2005) and world-unique magnetic fields for magnetic resonance imaging (2005) and is expected to provide world-unique high pressure and/or high temperature materials chemistry NMR.

Pulsed magnets

A suite of highly engineered pulsed magnets has been developed (1998 – 2004). These include:

(a) The 60 T long pulse magnet with a stabilized 60 T field for 100 ms and a total pulse length of over 2 s.

This represents an almost two-fold increase of magnetic field for controlled pulse magnets and a five-fold increase in time-at-field for research in controlled pulsed field magnets.

(b) The 65 T short pulse magnet (2004).

This led to establishment of the 65 T NHMFL pulsed field magnet program (2004).

(c) A 100 T non-destructive 10 ms pulsed field magnet is under development.

The motivation for the development of this magnet was for studies of Pu, but it will add to the suite of magnets at the NHMFL-LANL facility.

These magnets form the core of the NHMFL facilities for the research programs of external and in-house research scientists. Some of the highlights of research accomplishments of the NHMFL utilizing these magnets are listed in Appendix D.

The NHMFL has strong interactions with other high magnetic field laboratories in Europe and Asia, and they share information and expertise in the design of high field magnets for a broad range of research applications. One of the important functions performed by the NHMFL involves the design, development, and construction of high field magnets for other research laboratories throughout the world.

Since its introduction in 1995 at the NHMFL, the Florida-Bitter technology has been adopted by four of the five largest dc field facilities worldwide. In addition to six designs in Tallahassee, the NHMFL developed a 30 T magnet for the Laboratory at Tsukuba in 1997 and some 33 T magnets for the Laboratory at Nijmegen in 2003. In addition, the laboratory at Sendai developed their own hybrid insert using Florida-Bitter technology, achieving 30 T in 1999. Finally, the laboratory at Tsukuba completed two Florida-Bitter inserts (32 and 52 mm bores) in 1999 and reached a record dc field of 37.3 T.

6. Design and development of magnets for special facilities

The NRC Committee on Opportunities in High Magnetic Field Science (COHMAG) strongly recommended the development of instrumentation that will make it possible for the community of U.S. scientists to use synchrotron radiation and neutrons to study the properties of materials at the highest possible magnetic fields. It is widely agreed and has long been understood that the scientific opportunities afforded by instrumentation of this kind are of the utmost importance. Nevertheless, the U.S.A. has fallen behind the rest of the world in this area even though it has excellent synchrotron light sources and a high magnetic field laboratory that is the acknowledged world leader, NHMFL, and is constructing a neutron source that will be second to none. The problem at this juncture is how best to bring high magnetic fields to synchrotron and neutron sources.

This panel was impressed that the management of the NHMFL has already begun to think about this problem, both at the magnet design level and from the point of view of its management. Whatever the solutions found to the technical problems, it is overwhelmingly likely that the NHMFL will be called upon to design and produce the magnets required. Furthermore, it is certain that those magnets will be installed at existing synchrotron light sources and neutron sources, rather than having a new hard X-ray light source and/or a new neutron source built at the NHMFL. Beyond this, the only point of clarity is the conviction that the top priority is construction of high field magnets at a neutron source.

This panel's recommendations regarding the organizational aspects of this problem bear directly on two of the questions it was asked to consider in its charge: (1) the wisdom of creating a "distributed magnet laboratory" in the U.S.A., and (2) the advisability of adding new sites to the NHMFL. This Committee's recommendation that the contract for the NHMFL not be rebid implies its opposition to the creation of a "distributed laboratory" that is different from, or does not include, the NHMFL. That said, it should be pointed out that the NHMFL is already a "distributed laboratory." It operates at three sites: Gainsville and Tallahasee, Florida, and at Los Alamos National Laboratory in New Mexico. It is likely to be able to manage additional sites should that become necessary.

7. Review new directions (see COHMAG)

The COHMAG report suggests that were the NHMFL to stop building new magnets and concentrate entirely on providing its users access to the instruments it already has, good science would continue to be done at the NHMFL for many years into the future. Many of its current users feel constrained by the limited instrumentation time they are able to obtain. Indeed, this Committee believes that the NHMFL would be wise to rebalance the way it uses its resources to favor user service over instrument development. Serious consideration should be given to altering the operating schedule of the Laboratory so that the scientific productivity of the facility is maximized. What might be possible within the constraints imposed by the current budget? What would it cost to relax those constraints?

The above not withstanding, it is vital that the NHMFL retain its magnet design and fabrication capabilities. The NHMFL presented to the panel some preliminary thoughts about how magnets that meet the specifications of the "challenge" magnets described in the COHMAG report might be built. This panel encourages such activities, but suggests that the NHMFL should develop a prioritized list of the magnets it is interested in developing, both those COHMAG suggested and others it might be considering. Which ones can be built using today's technology, and which ones are longer term development projects? Which ones would have the largest impact on the science being done by its user community.

With respect to NMR spectroscopy, the panel recommends against any immediate plans to construct a next-generation magnet for high-resolution solution NMR, e.g., the 1.3 GHz magnet discussed in the COHMAG report. At this point, substantial progress needs to occur in superconducting materials development before such a magnet, with the requisite homogeneity and stability, should be designed. The panel recommends that NMR-related efforts focus on exploiting the unique capabilities of the wide-bore 900 MHz magnet at the NHMFL and on adapting Bitter and hybrid magnet technology for magnetic resonance studies of systems and phenomena with less stringent homogeneity and stability requirements, e.g., inorganic and organic materials with technologically relevant properties, high-field phenomena in condensed matter physics, and solid state NMR of biological systems. A more detailed discussion of the NMR program at the NHMFL appears below.

8. Additional research activities in support of magnet development

Substantial progress in increasing the magnetic field produced by static high field magnets will eventually require increasing the critical field and critical current density of superconducting materials, as well as devising methods for using these materials in flexible wires or tapes of kilometer-scale lengths that are suitable for winding magnet coils. This has been accomplished with the brittle conventional superconductors such as Nb_3Sn by fabricating multi-filamentary wires through processes that have been developed over the course of several decades. Since the discovery of high T_c superconductivity in cuprates, multi-filamentary conductors of BSCCO have been prepared based on the "powder in tube" method that has been used for constructing superconducting magnets that operate at 77 K and produce magnetic fields of ~ 40 T. Substantial progress has been made on so-called YBCO "coated conductors," tapes of in-plane aligned YBCO crystallites on flexible Ni alloy substrates, that have enormous critical magnetic fields of ~ 100 T and critical current densities of 10^6 A/cm^2 that are not rapidly suppressed in applied magnetic fields. These developments have largely been carried out in national laboratories, notably Los Alamos and Oak Ridge, and represent significant progress towards making long conductors that will be suitable for technological applications of superconductivity, such as electrical power transmission lines, superconducting magnets for research, magnetic energy storage, magnetic levitation, and other applications, electrical generators, motors, etc. In addition, efforts are currently underway to increase flux pinning in coated conductors by introducing flux pinning centers. There are opportunities to explore various schemes for increasing flux pinning in the coated conductors and processing avenues to making longer conductor lengths that will have uniform superconducting properties, as well as to search for new superconducting materials with properties that surpass those of the presently known materials. The NHMFL facilities at Los Alamos and Tallahassee have played a role in the characterization of the coated conductors and the assessment of their performance. Research and development on new superconducting materials with the objective of developing the next generation of superconducting wires and tapes for magnet applications would constitute a very important component of the NHMFL program. Apparently, the NHMFL is currently exploring the possibility of initiating a superconducting materials research and development program under the leadership of a prominent scientist who works in this area.

The NHMFL has a materials characterization and development program that consists of two major components. In the first, they have acquired a detailed understanding of the physics of magnets and established a materials characterization program to obtain information about the materials so that they can be used closer to their limits (e.g., mechanical properties, critical current density under stress and field, etc.) Efforts to develop tailored materials with more desirable characteristics have been initiated in collaboration with several companies. Unfortunately, these are long-term investments that are handicapped by the small volumes of materials involved.

The second phase is devoted towards the identification and development of new materials that will make it possible to construct magnets with higher fields. In so far as progress in the generation of magnetic fields is limited by mechanical properties of available materials, a significant amount of effort is being devoted towards improving the mechanical properties of materials of interest.

A description by Hans Schneider-Muntau and Ke Han of the NHMFL program on materials characterization and development is included in Appendix E.

9. Past, present, and future of NMR facilities

Current status

Nuclear magnetic resonance (NMR) is an extremely important set of experimental techniques, with applications in nearly all areas of physical and biological sciences. Among these applications are the identification of chemical structures in synthetic chemistry, the determination of full three-dimensional structures of high-molecular-weight biopolymers in biochemistry and structural biology, the elucidation of electronic and magnetic properties of new materials in solid state physics, and diagnostic magnetic resonance imaging (MRI) in medicine. As summarized in the COHMAG report, all types of NMR benefit from higher magnetic fields.

Higher fields generally increase the information content of NMR data, increase the size and complexity of systems that are amenable to NMR techniques, and increase the sensitivity of NMR measurements. Progress in NMR, which has continued at a steady pace for six decades, is driven in part by the development of very stable, very homogeneous magnets with ever-increasing field strengths. Progress in NMR also results from new ideas about how nuclear spin states can be manipulated by radiofrequency pulse sequences in the course of an NMR measurement, from the identification of new classes of systems and problems that are addressable by NMR, and from developments in ancillary technology.

NMR is a primary experimental tool for thousands of chemists, biologists, and physicists. NMR experiments are usually carried out in the laboratories or departments of individual scientists or groups of scientists, using their own magnets. NMR magnets up to 14 T are quite common. NMR magnets with 19 T fields are not unusual. Several 21 T NMR magnets have been installed recently in the U.S. These magnets are manufactured by several companies (Oxford, Bruker, Magnex). The fields of commercially available magnets have increased rather steadily since the 1960s. At least one commercial supplier is now advertising plans to build a 22.3 T NMR magnet.

Given that NMR (and MRI) is primarily a "local" technique, one must think carefully about how a national magnet laboratory such as the NHMFL can contribute to progress in NMR. It is particularly difficult for a national magnet laboratory to construct magnets with unique capabilities that will have a large impact on the use of NMR in chemistry and biology. This is because most chemical and biological applications require magnets with very high homogeneity and very high stability, and because the magnet companies produce superconducting magnets that are very close to the current technological limits for such magnets. The large market for state-of-the-art NMR and MRI magnets apparently makes it profitable for the magnet companies to continue pushing for higher fields. These companies have a great deal of expertise in superconducting magnet design and construction.

To date, the NMR program at the NHMFL has pursued several directions:

(a) The NHMFL in Tallahassee houses a variety of NMR magnets and spectrometers with standard capabilities for solution NMR and solid state NMR in fields from 7.05 T to 19.6 T. These magnets do not provide capabilities that are highly unusual, but they are heavily used both by the local NMR community (at FSU and UF) and by outside users who do not have their own high-field NMR instrumentation. Additional magnets at AMRIS in Gainesville include a wide-bore 17.6 T system for both solution NMR and MRI. The local NMR community includes several excellent research groups and NHMFL staff members who are widely recognized for their innovative work on NMR and MRI techniques as well as applications to specific problems. This part of the NMR effort at the NHMFL is similar in its purpose and impact to NMR facilities supported by the NIH at MIT (http://web.mit.edu/fbml/cmr.shtml), UCSD (http://nmrresource.ucsd.edu/index.html), and the University of Wisconsin (http://www.nmrfam.wisc.edu/) and by the DOE at PNNL (http://www.emsl.pnl.gov/hfmrf/homepage.html). Each of these facilities has a strong local NMR community and also services outside users who do not have their own local access to high field NMR instrumentation.

(b) A unique aspect of the NMR program at the NHMFL is the availability of 25 T resistive and 45 T hybrid magnets for NMR experiments. These magnets have significantly lower homogeneity (e.g., 12 ppm over 1 cm^3) for the 25 T magnet and lower stability (~3 ppm) than NMR-quality superconducting magnets. However, the higher fields have been shown to be useful both for solid state NMR of quadrupolar nuclei (e.g., ^{27}Al NMR in solid catalysts and minerals) and for studies of intrinsically high-field phenomena in condensed matter physics. These capabilities for NMR measurements at ultra-high fields (but with relatively low NMR spectral resolution) are unique in the U.S. and (in the case of the 45 T magnet) in the world.

(c) The NHMFL has constructed a 21.2 T (900 MHz proton NMR frequency) superconducting magnet with stability and homogeneity suitable for solution NMR, and with a uniquely large, 105 mm room-temperature bore diameter. Construction of this 21.2 T wide-bore magnet required more than 10 years of work. At a cost of approximately $17 M, this has been the most expensive magnet construction project at the NHMFL. The 21.2 T superconducting magnet has been operational for less than one year, so it is too soon to evaluate its eventual scientific impact. Possible areas of application include small-animal MRI for basic biological research, where the high field may permit improved spatial resolution and where a large bore is necessary to accommodate the animal and gradient coils, and low-temperature or high-pressure NMR of chemical or biochemical systems, where a large bore may be required to accommodate the cryostat or pressure system. One should keep in mind that, when construction of the 21.2 T magnet began, it seemed unlikely that magnet companies would succeed in producing their own 900 MHz NMR systems (with 54 mm room-temperature bore diameters, or 63 mm in the case of the PNNL magnet) as rapidly as they did.

Recommendations

The NHMFL should concentrate its NMR efforts in areas where it can provide truly unique and scientifically important capabilities. One obvious area is in the use of Bitter or hybrid magnets for NMR. It has already been demonstrated at the NHMFL and at Grenoble that these magnets are very useful for NMR studies of materials in solid state physics with field-dependent magnetic and electronic properties. These magnets should also be very useful in NMR studies of the molecular structure and dynamics of compounds with quadrupolar nuclei, in solid state chemistry and materials science, because the ability to resolve chemically inequivalent sites in NMR spectra of quadrupolar nuclei increases quadratically with field. The NHMFL should continue to support and expand the use of Bitter and hybrid magnets for NMR. According to the NHMFL staff, the stability of hybrid magnets can be improved substantially by implementation of a "series hybrid" design. NMR applications should be considered a strong motivation for the development of series hybrid magnets with fields above 30 T. At least one series hybrid magnet should be designed to have homogeneity and stability specifications that are consistent with NMR requirements. Magnets with homogeneities of 1-5 ppm (over a volume of approximately 30 mm^3) and stabilities of 1-5 ppm would be useful for many NMR measurements in solid state physics, solid state chemistry, and materials science. Such magnets would also be useful for certain solid state NMR experiments on biochemical systems. Although such magnets would not be immediately useful for most solution NMR applications (e.g., determination of full molecular structures of soluble proteins), it is possible that new spin physics phenomena that are relevant to high-field solution NMR may be discovered through the use of hybrid magnets.

The wide-bore 21.2 T magnet should continue to operate, and its utility in applications that benefit most from the large bore size (e.g., animal MRI, NMR spectroscopy at extreme temperatures and pressures) should continue to be explored. So far, the NHMFL staff and outside users have not demonstrated in real experiments that the 105 mm bore diameter permits measurements that can not be done in narrower-bore 21.2 T magnets. Identification and development of applications for this magnet that require the large bore should be a high priority of the NMR program at the NHMFL.

Other existing high-resolution magnets at the NHMFL should also continue to operate, as these magnets are important to the research programs of many local and outside users.

At this time, it does not seem appropriate for the NHMFL to embark on a new high-resolution NMR magnet construction project. The COHMAG report discusses the eventual construction of 30 T high-resolution NMR magnets. This discussion was intended by COHMAG to be a motivation for the development of new superconducting materials, wire fabrication processes, and other aspects of superconducting magnet design. A 30 T high-resolution NMR magnet was not intended to be an immediate goal, and was considered by COHMAG to be beyond our current capabilities (until significant progress in superconducting materials, etc., occurs). Although the NHMFL staff has begun to explore preliminary designs for a 30 T NMR magnet, it is unquestionably premature to begin designing or building this magnet in earnest at this time. It is still unclear which materials and which wire manufacturing processes should be used in such a magnet. On the other hand, it is very appropriate for NHMFL staff to conduct tests on small prototype coils of high-temperature superconducting materials, using wire obtained through collaboration with wire manufacturers or by a bidding process. These tests should be geared toward the eventual development of a 30 T NMR magnet. A research program at NHMFL in the area of high-field, high-stability magnets comprised of high-T_c materials would hasten the development of high-quality, high-critical-current wire needed.

10. Ion cyclotron resonance facility

The Ion cyclotron resonance (ICR) facility at Florida State University (FSU) operates as an exemplary user facility serving the high resolution mass spectrometry community superbly well. They have held for many years the world records for resolving power, resolution, mass accuracy, and dynamic range – singularly important parameters for mass spectrometry. Collectively, these instrumental achievements have enabled the analysis of some of the most complex mixtures presented by a variety of user communities from academic, industrial and government laboratories. Unlike most mass spectrometry facilities they have built their own instruments – purchasing only the magnet from commercial sources – developing critically important ancillary apparatus components such as vacuum systems, ion sources, inlets and data systems. This approach has kept them at or leading the state-of-the-art since inception of this facility rather than following the traditional saw-tooth pattern of purchasing commercial instruments, experiencing obsolescence and renewal at frequencies defined by funding sources.

The ICR facility recently brought on-line the highest field magnet fabricated for ICR purposes to date and the magnet design group at FSU is actively engaged in conceptual design of a much higher field magnet (21 T vs. 14.5 T for the recently installed system, with current commercial technology at 3 T, 7 T, 9.4 T and a just-introduced 12 T system). Interestingly, the mass accuracy of the new 14.5 T system required rewriting the code for data acquisition software in 64 bit/word rather than 32 bit/word used in the highest resolution commercial instruments. Clearly, they lead the field rather than relying on commercial developments; indeed, currently marketed instruments have important features originally demonstrated by the FSU facility.

Scientific and support staff at the ICR facility are outstanding and at least as important as the instrumentation; Alan Marshall is the first name that comes to mind for an authoritative review of ICR capabilities worldwide and for a current report of research by his group and collaborators using the facility. A metric of the value that his technical staff brings to ICR is that a substantial fraction of user publications – approximately 30% over the past 5 years – are research collaborations rather than analytical service. A steady stream of students and postdoctoral fellows benefit from the unique educational experience the ICR facility affords. The user community includes visiting scholars from industry and research centers located around the world are contributors and beneficiaries of their experience in this facility. An unique contribution is provision of plans, specifications and technical support for the fabrication of at least 20 ICR data stations deployed as an integral part of "home-built" ICR systems in other lead laboratories.

The mode of operation of this part of the NHMFL user facility extends the application of high magnetic field research to such diverse fields as fundamental ion chemistry and physics, biochemistry, petroleum chemistry, polymer chemistry, proteomics, protein structure and identification of biomarkers for presently intractable diseases. Many, but not all, of these applications and technology developments involve the characterization of high molecular weight species. To that end, the current design effort to step well beyond current state-of-the-art ICR magnetic fields is a very important development. Many performance parameters scale linearly or with the square of magnetic field strength. It is important to note that a 50% increase in field strength will enable a number of experiments not presently possible or possible only with "heroic" efforts. Further, one of the most important square law parameters is dynamic range, the ratio of most abundant to least abundant masses that can be measured. This may be crucial for discovery of protein biomarkers present as a very small number of copies in cells.

In summary, the FSU ICR Facility is a major contributor to the successful operation of the NHMFL. Leading the field in technology development and deployment, educational activities, outreach to a broad scientific community, and staff authorship of a continuing stream of publications in leading journals are signature strengths. Finally, it is a plausible prediction that future contributions from this group will have even greater impact.

11. Interrelationship between three components of existing NHMFL

The pulsed field facility at Los Alamos National Laboratory, the high B/T facility at the University of Florida and the high field magnets at FSU are three complementary components of the existing NHMFL currently operated within one overall structure. This arrangement now works very well. The three locations provide different capabilities with little overlap and the organizational structure provides coordination of the high field efforts in the United States.

The COHMAG report has recommended that high field capabilities be built at synchrotron and neutron sources, a recommendation that this panel endorses. In response to this recommendation, the NHMFL staff has already taken the lead in designing a 35 T magnet to meet the geometric requirements of these facilities, demonstrating the leadership required of the NHMFL. The operational structure needs to be examined. One way is to broaden the existing structure to include the new components. Other modes of operation are also possible and should be explored.

12. Improvement of instrumentation and assistance for users

1. Hard X-ray scattering

The COHMAG report correctly identifies the need to introduce probes that have lattice scale resolution, such as hard X-ray and/or neutron diffraction. Such techniques in combination with high magnetic fields will result in a more detailed and comprehensive understanding of the properties of materials at high field. To this end, it is laudable that the NHMFL has organized a workshop that addresses exactly this point. Both the highest brightness sources, the SNS for neutrons, and the APS for X-ray photons were represented at this workshop, and are the leading candidates for the sites of such a national facility. The science case that will be generated by this workshop will be an important tool in order to push forward to obtain the funding and support for the desired high field, high brightness facilities.

While this workshop is an excellent start, for the specific case of hard X-ray scattering, we see this as a problem that requires three parallel approaches. While two of the three approaches are being explored, the third requires some action by the NHMFL.

(a) High brightness sources combined with modest magnetic fields located at existing synchrotron and neutron sources. For example there are a number of superconducting magnets (~14 T) located at different synchrotron sources.

(b) The proposed high brightness source, high magnetic field facility mentioned above to be located at one of the brightest sources yet to be determined, and finally,

(c) Modest/low brightness "lab" sources combined with the highest fields to be located at one of the existing NHMFL laboratory sites, most likely in Tallahassee.

It is this last possibility that we would like to bring to the attention of the Magnet Laboratory management, and encourage the Laboratory to proceed to explore this option promptly, with modest exploratory funding, due to the potential immediate scientific payoff. Since this modest brightness/high field combination does not seem to have received much attention, we briefly elaborate on some technical issues below. In summary, a conventional lab or table-top X-ray sources, with careful attention to the optical path and the restricted experimental geometry due to the magnets, could help address some simple, but scientifically useful experiments.

The key characteristic of hard, as opposed to soft, X-ray photons is the ability to resolve the lattice structure from scattering measurements. Since typical lattice constants are of order 0.3 nm, the minimum photon energy required to resolve this lattice constant in the back-scattering geometry is of order 2 keV.

It is important to understand that the class of problems that could be addressed by such a laboratory-based system will naturally be restricted to a subset of those that succeed in a laboratory-based instrument. For example, feasible experiments include lattice strain measurements from charge scattering from millimeter sized single crystals and the determination of the broken symmetry due to a phase transition. In contrast, at the synchrotron sources, one can attempt more sophisticated measurements not feasible with laboratory sources such as magnetic scattering which has a smaller ($\sim 10^{-4}$) cross-section relative to the charge scattering cross-section, experiments with sub-micron sized beams, and chemically specific resonant scattering. However, a quick look through the recent NHMFL user reports turned up examples of experiments that would be improved by X-ray diffraction measurements of the field and temperature dependence of the crystal lattice. The most significant limitation for these experiments is the restricted geometry imposed by the typical magnet construction.

Careful choices must be made for sources and detectors for such an instrument. Typical X-ray tube sources such as commercial tube sources with efficient optical path are simple to use and might work in this application. However, there are alternative sources that could have special advantages in the high field environment, such as laser based plasma sources. Apparently, CCD detectors have already been used successfully at NHMFL, and there is one class of X-ray detectors based on the CCD technology, so there is at least one viable choice for detectors.

In summary, the potential scientific benefit is high. It is beyond the ability of most institutions, and the NHMFL should step in and evaluate the need and interest of the users. While the high brightness, high field facility will take some years to get funded and constructed, there will be a time window when the scientific needs will have to be met by the combination of low brightness sources at the NHMFL, and medium magnet fields at the existing synchrotron sources.

2. Operations and user equipment

One common theme from the users was the demand for more magnet time. We make here a few suggestions for the operations that we borrow from the synchrotron community.

The goals of our suggestions are to:

(a) Provide users more magnet time per assigned run.

(b) At the same time, reduce the intrusion on family life of the NHMFL support staff and scientists.

(c) Clarify the responsibilities of the staff to the users and, hence, set the expectations of the users, and the responsibilities of the users to the NHMFL.

We outline a particular scenario; however, we leave it completely to the NHMFL to formulate a plan of their own that meets the same goals.

Currently, users seem to come in on the Friday or the weekend before their week of assigned magnet time. They set up over the weekend, in order to be ready to run on Monday, and in the absence of any specific problems, they then typically use magnet time from Monday to Friday. The staff seems to come in on an informal basis on Sunday to help with the user set up.

Our suggestion is that one non-weekend day be assigned as a "Maintenance day," and on this day, with the full support of the Magnet Laboratory facilities, such as machine shops and staff, the user gets to set up the experiment. On the same day, the users get trained with respect to safety and operating procedures of the magnets and other pieces of NHMFL equipment they borrow. A checklist will keep track of all the completed training. Additionally, the checklist should provide the user a list of tested items that the NHMFL is providing to the user in good working order. Dewars that are not soft, connections that work in the specified field and temperature limits requested by the users, and a working lock-in could be typical items on the checklist that the NHMFL would be responsible to provide. On completion of the experiment, the user could be required to show that the borrowed equipment on the checklist has been returned in working order, or steps have been taken to get them back to working order. This entry/exit checklist, will make it easier for NHMFL staff to keep equipment in working order, and will provide fewer surprises for subsequent borrowers of the experimental equipment. Clearly, this checklist should be designed by the NHMFL with user input, and should help to set the expectations that the users have of the NHMFL.

Finally, since the insertion of a maintenance day could mean the loss of a day or segment of magnet time to the user, we suggest weekend operation to compensate. A minimum skeleton staff will be required to keep magnets running safely over the weekend. Our expectation is that the experiments should be fully functioning by the end of the week, and so the support required from the staff will be minimal. Note that not all experiments may be able to take advantage of the weekend hours; some magnets require intensive support and sophisticated staffing and, as such, it may be too expensive to provide weekend staffing for those magnets. Since the weekend staffing is minimal, any serious problems that develop on the weekend may have to wait until the weekday to be resolved. Even the skeleton crew we suggest here may require extra staffing for NHMFL, and the NSF should provide the extra funding if it would like to support the extra weekend hours.

To summarize: a clearly defined non-weekend day or time segment provided for a transition, well defined expectations of the staff and users, and extra operations time for resource-light experiments would greatly improve the user program of the NHMFL.

13. Recommendation of development of nearby housing for users

Housing is clearly a problem that has been articulated by users prior to this review, and also has been articulated by users in this review. The fact that there are two different "condos" associated with the NHMFL users is clear evidence of the mismatch between the existing commercial housing and the user needs. Due to the limited magnet time that users receive, it is important that every effort be made to minimize barriers for the users, in order to maximize the scientific output. One key issue here is that the housing should be located within a real or virtual walking distance from the NHMFL. By "virtual walking distance," we imply that for housing located outside a practical or safe walking distance, on demand transportation available at all hours of magnet laboratory operation. This transportation service could be as simple as a commercial taxi service. Since experimenters often need to spend time with no magnet field preparing their experiment for field, the transportation requirement could conceivably be required round the clock. One important reason to stress the "walking distance" requirement is that with the increasing internationalization of scientific personnel on experimental teams, a significant fraction of users, for example, beginning graduate students, will not have drivers licenses. It is also more difficult to obtain short-term drivers licenses, especially for scientists from countries identified by the Department of Homeland Security as sensitive countries.

Since housing is not an area of expertise for the NHMFL, one approach the panel suggests to improve the housing situation is for the director to try to nucleate commercial housing in the area that meets the NHMFL needs. The first step in this process would be to generate a realistic estimate of the total expected housing needs of the NHMFL; this would include the user load, and other visitors to the Laboratory. Next, the director could consult with the other institutions in the immediate vicinity, and see if, collectively, the total housing need of the NHMFL and the other local institutions would generate interest for commercial housing providers. The chance of success is low, but the payoff is high, and it is worth at least one attempt to generate commercial housing nearby.

Appendix A – Meeting agenda

NSF Advisory Panel on Future Support for High Magnetic Fields
Proposed Schedule
Meeting Agenda - March 16-17-18 (at NSF)

March 16: Dinner with Dr. Michael Turner, AD/MPS
Co-Chairs discuss charge to Panel with MPS/DMR

March 17:

8:00 am	Coffee / NSF Room TBD
8:15	Welcoming remarks - Michael Turner and/or Tom Weber
8:30	Sign-in. Review charge to panel.
8:45	Panel review of background and documentation provided by NSF
9:00	Peter Moore: Summary of the COHMAG Report
10:00	Break
10:15	Continue review of documentation; preliminary discussion of options
12:00 noon	Lunch / working
1:00 pm	Presentations by prominent users of high magnetic fields (NHMFL Staff and other speakers)
5:00	Adjourn

March 18:

8:00 am	Coffee
8:15 am	Discuss findings from previous day
10:00 am	Coffee
10:15am	Planning of site visits (LANL, FSU, UF, as needed) and writing assignments
12:00 noon:	Adjourn

Site visits by subgroups:

April 1st: Site Visit NHMFL Pulsed Field Lab
April 21-22: Site Visit NHMFL Tallahassee, DC field facility and ICR
April 23: Site Visit, NHMFL, AMRIS and High B/T University of Florida
April 28: Site Visit, NHMFL, FSU Materials effort
May 9: Site Visit NHMFL, FSU, NMR and Light sources and magnets

June 30
Report due at NSF

Appendix B – Summary of site visits

April 1, 2005: National High Magnetic Field Laboratory Pulsed Field Facility Los Alamos National Laboratory

Attendees: M. Brian Maple, Jean Futrell, Lance W. Haworth

Agenda

Friday, April 1
9:00 a.m. Alex Lacerda will drive participants from Hotel (Holiday Inn Express) to NHMFL
9:30 a.m. **NHMFL / LANL overview presentation** – Alex Lacerda
10:00 a.m. **NHMFL Users' Program presentation** – Chuck Mielke
10:30 a.m. Coffee Break
11:00 a.m. **Single Turn Project laboratory tour** – Mielke, Singleton, Serna, Roybal, Goddard, and McDonald
12:00 – 1:30 p.m. Lunch Break – Katherine's Restaurant
1:45 p.m. **Tour of Optics laboratory** – Crooker, Gao, and Furis
2:30 p.m. **New Instrumentation tour** – Migliori, Balakirev, Betts
3:15 – 3:30 p.m. Afternoon Break
3:30 p.m. **Short Pulse tour** – Harrison, Rickel, Lashley, Jaime, Schillig, Balakirev, Mielke, Migliori Singleton, Coffey, Crooker, Drymiotis, Furis, Gao, Goddard, McDonald, Pantea, Sharma, Silhanek, Furis, and Zapf
4:30 p.m. **Large Magnets tour** – Rickel, Sims, Schillig, Gordon, and Paris
5:15 p.m. Q & A
6:30 p.m. Dinner – Katherine's Restaurant

April 21-22, 2005: National High Magnetic Field Laboratory, Tallahassee, Florida

Attendees: Bob Richardson, Myriam Sarachik, G. X. Tessema (NSF)

Agenda:

Thursday, April 21

7:30 AM	Panel Members and visitors picked up at Wingate Inn
8:00 AM	Breakfast at NHMFL
8:30 AM	Executive Session
9:00 AM	**Welcome** (NHMFL Director Greg Boebinger)

9:15 AM	**DC Field Facility Program Overview** (James Brooks)
10:00 AM	Break
10:15 AM	Tour of DC Field Facility, including User Cells, Millikelvin laboratory and discussions with users (Bruce Brandt)
11:30 AM	Series-Connected Hybrid Preliminary Findings Review
12:00 PM	Lunch
1:00 PM	**DC Field In-House Scientific Research** (Dragana Popovic)
1:30 PM	**NHMFL In-House Research Program** (Lloyd Engel)
2:00 PM	**EMR Facility Program Overview** (Louis-Claude Brunel OR Hans van Tol)
2:45 PM	Tour of EMR facilities, including discussions with users
3:30 PM	Roundtable with Condensed Matter Scholar Scientists
4:30 PM	Executive Session
5:30 PM	Dinner

FRIDAY, APRIL 22

7:30 AM	Panel Members and visitors picked up at Wingate Inn
8:00 AM	Breakfast at the NHMFL
8:30 AM	**ICR Program Scientific Overview** (Carol Nilsson)
9:00 AM	**ICR Techniques Overview** (Chris Hendrickson)
9:30 AM	Tour of ICR facilities, including discussions with users (Alan Marshall)

10:30 AM	Roundtable with ICR and EMR Scholar Scientists
11:30 AM	Blue Ribbon Panel Outbriefing
12:00 PM	Lunch [box lunches will be provided in the event of early flights]
1:00 PM	Adjourn

April 23, 2005 : University of Florida,

Attendees: Laura Greene, and G. X. Tessema (NSF)

Agenda:
SATURDAY , APRIL 23

8:45 AM	Panel Members and visitors picked up at Hotel
9:00 AM	Visit of the AMRIS Facility (Steve Blackband)
10:30 AM	Travel to the High B/T facility
11:00 AM	**Visit of the High B/T facility** (Yasu Takano and Yon Lee)
12:00 AM	**Adjourn**

APRIL 28: National High Magnetic Field Laboratory, Tallahassee, Florida

Attendees: M. Brian Maple, and G. X. Tessema

AGENDA:
THURSDAY, APRIL 28

7:30 AM	Greg Boebinger joins Brian Maple (University of California, San Diego and Blue Ribbon Panel member) and Guebre Tessema (National Science Foundation) for breakfast at Wingate Inn
8:00 AM	Drive to NHMFL
8:30 AM	NHMFL Overview Presentation, B210

(Greg Boebinger)

8:45 AM Tour of Facilities
Electron Microscope Lab, C124 (Ke Han, *et al.*)
Materials Characterization, C101 (Ke Han, *et al.*)
Materials Research, C213 (Justin Schwartz)
DC and Pulsed Magnet Construction, OP118 (Mark Bird, Chuck Swenson)
Magnet Cells, including new 31 T, 50 mm magnet (Bruce Brandt)
If time allows: Superfluid Counterflow (Steve Van Sciver)
End at Magnet Science & Technology Conference Room

10:30 AM Magnet Science & Technology Roundtable, A235
(John Miller, MS&T Project Leaders)

11:30 AM Lunch (out of the building)

1:00 PM Meeting with Eric Betzig (New Millennium Research, LLC, Okemos, Michigan), Harald Hess (KLA-Tencor, San Jose, California), and Mike Davidson (Optical Microscopy Program), atrium or B210

1:45 PM Tour of NMR in Millikelvin Lab, EMR Facilities, 900 MHz NMR Magnet
(Arneil Reyes, Louis-Claude Brunel, Bill Brey, Iain Dixon, *et al.*)

3:15 PM Adjourn

MAY 9, 2005: NATIONAL HIGH MAGNETIC FIELD LABORATORY TALLAHASSEE, FLORIDA

ATTENDEES: Kenneth Evans-Lutterodt, Robert Tycko, Adriaan de Graaf (NSF)

AGENDA

MONDAY, MAY 9 Kenneth Evans-Lutterodt, Brookhaven National Laboratory, BRP Member

Robert Tycko, National Institutes of Health, BRP Member
and Guebre Tessema, National Science Foundation

12:00 PM Lunch and NMR Roundtable
Brey, William, Assistant Scholar/Scientist
Bruschweiler, Rafael, Professor, Associate Director for Biophysics

Chekmenev, Eduard, Postdoc with Tim Cross
Cross, Timothy, NMR Program Director and Professor
*Dalal, Naresh, Professor and Chair, FSU Chemistry and Biochemistry
Fu, Riqiang, Associate Scholar / Scientist
Gan, Zhehong, Associate Scholar / Scientist
*Gao, Fei, Assistant Scholar / Scientist
*Greenbaum, Nancy, Associate Professor, Chemistry and Biochemistry
Kuhns, Philip, Associate Scholar Scientist
Locke, Bruce, Professor and Chair, FSU Chemical Engineering
Logan, Timothy, Associate Professor, Associate Director of NMR
*Long, Joanna, Assistant Professor, Biochemistry & Molecular Biology
Reyes, Arneil, Associate Scholar Scientist
Saha, Saikat, Postdoc with Bill Brey
*Shetty, Kiran, RF Technician
*Zhang, Fengli, Assistant Scholar / Scientist

1:00 – 5:00 PM

900 MHz NMR Magnet: Hands-on experience and operations
Dr. Tycko will be using the magnet during this period.

Dr. Evans-Lutterodt will be observing. A tour of the NMR probe design labs (Bill Brey) and condensed matter NMR lab (Arneil Reyes) will also be conducted at an opportune time.

5:00 PM

Discussion of future of NMR magnets and capabilities
Bruschweiler, Rafael, Professor, Associate Director for Biophysics
Cross, Tim, NMR Program Director and Professor
Markiewicz, Denis, Scientist, MS&T
Miller, John, Director, MS&T
Schwartz, Justin, MS&T and Professor, Mechanical Engineering

6:00 PM

Adjourn

Appendix C – Panel membership

Members of the NSF Advisory Panel on Future Support for High Magnetic Fields

March 16-17, 2005

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Appendix D

Ten Major Scientific Accomplishments during the First Ten Years of the National High Magnetic Field Laboratory (Greg Boebinger)

Emphasizing successes of the NHMFL user programs, including highly-cited and particularly prominent scientific publications that helped pioneer new areas of high magnetic field research.

1. Powered (Resistive) Magnet Developments

The Florida-Bitter (shaped-cooling hole) technology (1994-1996) enabled magnets with much higher power density and Lorentz forces than (round-cooling hole) Bitter magnets:

33T (32mm bore) 20 MW Resistive Magnets, and the

31T (52mm bore) 20MW Resistive Magnet, the workhorses of the NHMFL's DC magnet program.

"*A New Concept in Bitter Disk Design*", by B.J. Gao, et al, IEEE Transactions Magn., **32** (1996) 2503. Due of its unique advantages, including a power density as high as 12W/mm^2 and a 3
0-50% reduction in hoop stress, the Florida-Bitter technology has been adopted by most of the world's leading high magnetic field laboratories.

Bright future: The uniquely-large 195 mm bore of the NHMFL's 20T Large Bore Resistive Magnet (1998) provided the background field into which was inserted the NHMFL 5T High-T_c Superconducting Solenoid (2003) yielding a world record and key milestone in the development of High-T_c magnets.

2. Persistent (Superconducting) Magnet Developments

State of the art cable-in-conduit superconducting magnet design, coupled with Florida-Bitter magnet design for the insert coil of a hybrid magnet resulted in the NHMFL's

45T Hybrid Magnet (2000), the world-record for DC magnetic fields.

July 2004 marked the beginning of the one-year commissioning phase for the NHMFL's

900MHz ultra wide bore (105mm) NMR magnet.

This magnet provides 21.1T in an unprecedented 105mm bore superconducting magnet, providing:

1ppb homogeneity for high-resolution solution state NMR (2005)

world-unique magnetic fields for magnetic resonance imaging (2005)

and is expected to provide:

world-unique high pressure and/or high temperature materials chemistry NMR

Bright future: The Michigan State Sweeper Magnet, an NHMFL "work-for-others" project, is a non-axisymmetric large-gap superconducting dipole that represents the NHMFL entry into uniquely-difficult accelerator magnets, a developing market that now includes initial design work on superconducting undulator magnets, a key technology for future, brighter X-ray sources.

3. Pulsed Magnet Developments

Highly-engineered pulsed magnets (1998-2004) introduced engineering science to the suite of these NHMFL 'applied metal fatigue' magnets, including the NHMFL's

> **60T long-pulse magnet**, providing a stabilized 60T field for 100msec and a total pulse length of over two seconds, representing:
>
> a near doubling of the magnetic field for controlled-pulse magnets and
>
> a factor of five increase in time-at-field for research in controlled-pulsed magnets
>
> **the 75T short-pulse magnet** (2004), which
>
> established the 65T NHMFL pulsed magnet user program (2004), and
>
> makes feasible the 100T non-destructive 10msec pulsed magnet (2006).

Bright future: The recent National Academy of Sciences report on Research Opportunities in High Magnetic Fields made the scientific case for future development of a 30T NMR magnet, a 60T DC Hybrid Magnet and, perhaps most difficult of all, a 100T long-pulse magnet with pulse durations and pulse-shaping rivaling the 60T long-pulse magnet. Each of these magnets requirse significant new magnet technology and materials development and, thus, represent even bigger challenges than the original three magnets called for by the 1988 Seitz-Richardson Report.

4. Advances in Strongly Correlated Matter through Magnetotransport and Magnetization.

Unusual superconductors increasingly require high magnetic fields to provide sufficiently large energy scales to adequately probe the physics underlying superconductivity:

"Superconductivity in an organic insulator at very high magnetic fields", by Balicas et al.; Physical Review Letters **87** (2001) 067002. A well-cited paper presenting a unique case of magnetic-field-induced superconductivity, in which superconductivity exists only between 25T and 40T.

"Metal-to-insulator crossover in the low-temperature normal state of Bi2(Sr,La)2CuO6", by S. Ono, et al; Physical Review Letters **85** (2000) 638. Research seeking an eventual understanding of high-temperature superconductivity includes this paper nearing 100 citations, a representative of high-Tc research programs that include magnetotransport, thermopower, and nuclear magnetic resonance experiments.

The suite of NHMFL quantum oscillation experiments continue to develop as a flexible and accurate probe of both Fermi Liquid and non-Fermi Liquid behaviors:

"A coherent three-dimensional Fermi surface in a high-transition-temperature superconductor", by NE Hussey et al; Nature **425** (2003) 814. This 45T hybrid magnet experiment is still the only

full three-dimensional solution of the Fermi surface of a high-temperature superconductor, a tour-de-force application of angular dependent magneto-resistive oscillations, a technique broadly applicable to low-dimensional systems.

"Development of the high-field heavy-fermion ground state in (Ce,La)B6 intermetallics", by RG Goodrich, et al. Physical Review Letters **82** (1999) 3669. The Kondo problem, especially in heavy-mass f electron systems, is a newly fruitful area of research using sensitive quantum oscillation techniques adapted to the NHMFL's pulsed magnetic fields. These particularly intense magnetic fields are uniquely suited to studies of heavy mass and disordered systems, such as the (Ce,La)B6 alloy series reported in this paper.

5. Novel Phases of Matter Realized Through Application of Intense Magnetic Fields

The NHMFL's High B/T facility is particularly well-suited to study ground state properties and complex phase diagrams in the quantum limit. By combining nuclear demagnetization with large superconducting magnets, experiments at 16T can remain below 1mK (holding the electron temperature between 5mK and 10mK) for up to four months. Two examples from quantum liquids are:

"New evidence for zero-temperature relaxation in a spin-polarized Fermi liquid", by H.Akimoto, et al. Physical Review Letters **90** (2003) 105301.

"Exact quantization of the even-denominator fractional quantum Hall state at ν=5/2 Landau level filling factor", by W. Pan, et al, Physical Review Letters **83** (1999) 3530. The two-dimensional electron system displays an exactly quantized Hall plateau at an even denominator filling fraction only at extremely low electron temperatures of ~4mK. The composite fermions that give rise to the conventional fractional quantum Hall effect apparently pair at 5/2 filling, in loose analogy to the formation of Cooper pairs in superconductivity, creating a new collective energy gap reported in this >50 citations paper.

"Closing the spin gap in the Kondo Insulator Ce3Bi4Pt3 at high magnetic fields", by M. Jaime, R. et al. Nature **405** (2000) 160. The controlled pulse waveforms of the NHMFL's 60T Long-Pulse Magnet enabled new techniques previously only available in DC magnetic fields, including specific heat and, in the near future (2006), terahertz spectroscopy, thermal conductivity and resonant ultrasound measurements.

"Spatially resolved electronic structure inside and outside the vortex cores of a high-temperature superconductor", by VF Mitrovic et al.; Nature **413,** 501 (2001). The NHMFL's 45T hybrid magnet enabled this study of the vortex state in a high-temperature superconductor, revealing both the electronic structure of a vortex core and the hexagonal structure of the vortex lattice.

Bright future: The NHMFL is developing single-turn pulsed magnets to deliver magnetic fields of 150-250T for several microseconds. While magnetotransport becomes troublesome in such an environment, recent NHMFL magnetization experiments of quantum oscillations suggest a scientific goldmine from precise phase diagram and Fermi surface measurements throughout a phase space made three- to four-fold larger by these dramatically more intense magnetic fields.

6. Electron Magnetic Resonance in the Highest Magnetic Fields

"Resonant Magnetization Tunneling in the Trigonal Pyramidal Mn[IV]Mn[III]3 Complex [Mn4O3Cl(O2CCl3)3(dbm)3]", by S.M.J. Aubin, et al. Journal of the American Chemical

Society **120** (1998) 4991. This electron magnetic resonance (EMR) paper with over 100 citations is a landmark demonstration of the value of high magnetic fields in the study of single molecule magnets, which do not give a signal at low frequencies due to zero-field level splitting. Other systems require high-field EMR to overcome large crystal field splittings, including the biologically important metallo-enzymes.

Bright future: The NHMFL is facilitating the rapid development of time-domain EMR, in which multiple high-frequency EMR measurements study interactions operating on different time scales and spin labeling studies the structure and carrier dynamics of normally-diamagnetic macromolecules. Pulsed EMR using double-electron electron spectroscopy requires the highest magnetic fields to provide inter-electron distance measurements out to 8nm, a distance scale well beyond the range of NMR structural studies and a unique capability of high-field EMR.

7. Nuclear and Electron Magnetic Resonance in Powered Magnets from 25T to 45T

Field strength has long been the "enabling technology" for new NMR applications, providing a powerful increase in sensitivity and resolution. The NHMFL is developing unique capabilities for NMR and EMR to be conducted in the powered (resistive) magnets. In 1998, the NHMFL realized an entirely new design goal for resistive magnets, optimizing the magnetic field homogeneity of the Florida-Bitter magnet design to achieve 12ppm homogeneity over a centimeter-sized region. In addition to pioneering new techniques for high resolution solution NMR spectra in otherwise unachievable fields, this hundred-fold improvement in homogeneity at 25T opened new avenues for condensed matter physics and chemistry EMR, including research on photosynthetic processes and motional molecular dynamics. These techniques were rapidly extended to the 45T hybrid magnet.

”*High-Resolution, >1 GHz NMR in Unstable Magnetic Fields” by* Y.-Y. Lin, S. Ahn, N. Murali, W. Brey, C. R. Bowers, and W. S. Warren, Physical Review Letters **85** (2000) 3732. By combining high-resolution magic-angle spinning and a technique for compensating magnetic field fluctuation (HENPEC), 40 ppb resolution has been achieved at 25T opening new possibilities for high resolution NMR at field strengths above the highest superconducting NMR magnets The researchers exploit a recently discovered source of "zero quantum" coherence in NMR to achieve a resolution enhancement of ~100, for the first time enabling high resolution NMR in the inhomogeneous and unstable field of a resistive magnet.

”*Seeking higher resolution and sensitivity for NMR of quadrupolar nuclei at ultrahigh magnetic fields.* Z. Gan, P. Gor'kov, T. Cross, A. Samoson, D. Massiot. J. American Chemical Society **124** (2002) 5634. This paper demonstrates the increasing resolution of quadrupolar resonances by solid state NMR at high magnetic fields up to 40T. The reduction of the second-order quadrupolar broadening and increasing chemical shift resolution result in a quadratic gain on spectral resolution despite the less homogenous magnetic fields of these powered magnets compared to superconducting NMR magnets.

Bright future: The design work to date on an NHMFL Series Connected Hybrid holds promise of realizing 1ppm homogeneity at 36T magnetic fields, an accomplishment that will further expand the applicability and success of magnetic resonance experiments using the NHMFL’s unique suite of powered magnets. A magnetic field of 36T corresponds to a 1THz frequency for electron magnetic resonance, pushing time-resolution for EMR into the picosecond regime.

8. Membrane Protein Nuclear Magnetic Resonance

"Structure of the Transmembrane Region of the M2 Protein H+ Channel" by J. Wang, S. Kim, F. Kovacs, and T.A. Cross, Protein Science **10**:2241-2250 (2001).

"Imaging Membrane Protein Helical Wheels", by J. Wang, J.K. Denny, C. Tian, F.A. Kovacs, Z. Song, R. Fu, J.R. Quine, and T.A. Cross, Journal of Magnetic Resonance **144**:162-167 (2000). In the 2000 paper, cited more than 80 times, Wang et al. discovered that helical structures in cell surface proteins could be imaged directly in NMR spectra. For the first time, it became possible to achieve detailed structural information on a biological macromolecule without assigning all of the spectral signals to specific atomic sites in the protein. The subsequent work, which appeared in 2001 as a cover story in Protein Science, used this methodology to help solve the protein backbone structure of the transmembrane domain of the M2 Protein from the Influenza A virus. This important drug target has eluded detailed structural analysis for more than a decade, despite extensive research employing all previously known experimental protocols. This landmark NMR structural characterization represents a major step toward enhanced pharmaceuticals against Influenza A and is a testimony of future applications of high magnetic field NMR to solve biological macromolecules that are not amenable to crystallization and X-ray diffraction, including the huge class of functionally important membrane proteins.

9. Ion Cyclotron Resonance

"External Accumulation of Ions for Enhanced Electrospray Ionization Fourier Transform Ion Cyclotron Resonance Mass Spectrometry", by M.W. Senko, et al. Journal of the American Society of Mass Spectrometry **8** (1997) 970. This paper has been cited more than 200 times because it provides the preferred solution to the problem of interfacing an ion source (initially, electrospray, but later extended to several other ionization methods) to FT-ICR MS detection. The trick is to accumulate ions in an electric ion trap located outside the superconducting magnet containing the ICR ion trap, and then inject the ions quickly for ICR analysis. ICR detection can then occur SIMULTANEOUSLY with ion accumulation, selection, dissociation, and/or reaction of the next batch of ions. The improvement in duty cycle was a factor of 10, with corresponding improvement in detection limit, scan rate, and/or signal strength. Faster scan rate led to efficient coupling with liquid chromatography and other separation methods. All three FT-ICR MS vendors (Bruker, Thermo, and IonSpec) have adopted external accumulation and the subsequently-developed hybrid quadrupole-FT-ICR mass spectrometers, which offer improved dynamic range, mass accuracy (by "counting" the ions delivered to the ICR trap), and tandem mass spectrometry for molecular structure characterization. Virtually all FT-ICR science since 1997 makes use of external ion accumulation, including:

"Biomolecule Mass Spectrometry," by F. W. McLafferty et al., Science **284** (1999) 1289. Protein characterization is typically performed by enzymatic digestion into smaller protein fragments (peptides) followed by chromatographic separation (to simplify the mixture) and mass analysis. This article, cited over 85 times, features a 191,000 Da protein digest mass spectrum in which (time-consuming and tedious) prior wet chemical separation was eliminated by high resolution FT-ICR mass spectrometry. A computer algorithm was able to identify a world-record 600 resolved peptides, some as large as 30,000 Da. High dynamic range was achieved by rapid signal averaging made possible by external ion accumulation.

"Identification of Novel Interactions in HIV-1 Capsid Protein Assembly by High-Resolution Mass Spectrometry," by J. Lanman et al., Journal of Molecular Biology **325** (2003) 759-772. The active RNA of the AIDS virus is encapsulated and protected in a mesh-like bag formed of interlocking hexamers of a "capsid" protein. Identification of the contact surfaces between such hexamers is a first step in the design of drugs to disrupt those contacts, resulting in collapse of a

virulent virus particle or inhibition of virus capsid formation, thus rendering the virus non-infective. This cover article, already cited 32 times, reports liquid chromatography FT-ICR mass analysis (possible only with external ion accumulation) to measure HIV-1 capsid protein amide hydrogen-deuterium exchange rates for the protein monomer and assembled hexamer. Differences in exchange rate between the monomer and hexamer identified points of contact in the hexamer structure, to help elucidate the full three-dimensional hexamer structure. Such structural knowledge is increasingly the key to rational drug design.

Bright future: This capability is partly responsible for the high growth rate in FT-ICR MS since 1997. FT-ICR MS is currently growing at twice the rate of the entire mass spectrometry market, which is in turn the fastest among all kinds of spectrometers (Spectroscopy, March 1, 2005)

10. Magnetic Resonance Imaging

Building on the track record of its researchers in MRI 'firsts', the NHMFL MRI program has been the first to acquire NMR spectra on a single neuron and multicomponent diffusion on single neuron The acquisition of the first imaging of an isolated perfused brain slice has led to more recent work:

"Observation of Significant Signal Voids in Images of Large Biological Samples at 11.1 Tesla", by B.L. Beck, Magnetic Resonance Medicine **51**(6) (2004) 1103

"Numerical Modeling of 11.1T MRI of a Human Head Using a MoM/FDTD Method", by F. Liu, et al. Magnetic Resonance Engineering **24B**(1) (2005) 28. MRI continues to employ ever stronger magnetic fields to make better images. However it is known that image inhomogeneities can arise from wave effects as the field strength (and thus frequency) increases. Researchers at the AMRIS facility of the NHMFL have utilized the world's first 11.1T/40cm MRI magnet to observe image inhomogeneities to be large enough to give rise to signal voids on both a fixed human brain as well as a fresh cadaver head. While these limitations could greatly impact the future imaging potential of high field MRI, more recent modeling of the observed effects and experimentation are exploring possible solutions to this problem.

Bright future: Magnetic Resonance Images of the mouse brain have already been acquired using the NHMFL's ultra-wide-bore 900MHz magnet, a world-unique capability around which the NHMFL is developing new instrumentation and hiring new staff in biology, biophysics and biomedical engineering.

Bright future: Rapid and multidisciplinary advances in MRI promise a growing database 'atlas' of the structure and function for model systems, beginning with defining the 'normal' mouse and extending to transgenic mice and, eventually, humans. The achievement of real-time imaging of cellular processes is a distinct possibility, including the real-time tracking and function of metabolites, pharmaceuticals and disease processes.

Appendix E

Materials Characterization and Development Program at the NHMFL: A Vision into the Future.

By Hans J. Schneider-Muntau and Ke Han

Introduction

In 1991, when we started the magnet development program of the NHMFL from scratch, we were confronted with the task of developing a vision on how to advance magnet technology. Based on the Seitz-Richardson report, the NSF charged us with building a wide range of next generation magnets. The program required an enormous progress in the generation of magnetic fields far beyond the start-of-the-art at that time (1990); from 20 T to 25 T for superconducting magnets, from 600 MHz to 1 GHz for NMR magnets, from 25 T to 35 T for resistive magnets, from 30 T to 45 T and 50 T for hybrid magnets, and from 50 T to 75 T in pulsed magnets. To this impressive list we added two new pulsed magnet systems enabled through the cooperation with the Los Alamos National Laboratory and the availability of a 600 MJ generator; a 60 T magnet with a flat top of 100 ms, and a 100 T system.

The program had two major components: development of a detailed understanding of the physics of magnets, and establishment of a materials characterization program. We argued that the precise knowledge of the materials used in the magnets would allow us to exploit them closer at their limits. We installed facilities that provide the information necessary for magnet design and construction, i.e., material testing systems for tensile, shear, fatigue, fracture toughness and resistivity measurements and impact tests between room and cryogenic temperatures, critical current measurements under strain and field, and optical microscopes, SEM, and TEM for microstructure examinations. Of special concern were the spread in the data, the unreliability or inconsistency in the delivery of standard products, and the non-achievement of the specifications. We also started development programs with several companies to deliver better or tailored materials (CuNb, MP35N, $CuAl_2O_3$, 316LN mod), which are, however, long-term investments and handicapped by the small volumes involved.

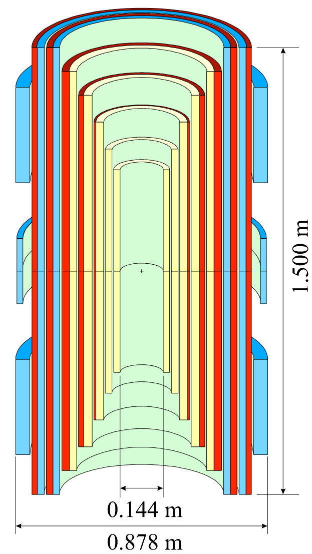
The present situation

The laboratory has now gone into its second phase. All magnet systems have achieved the promised specifications. A detailed understanding of the physics of magnets has been achieved, and new design ideas, such as the Florida-Bitter disk, have optimized magnet performance.

With the present materials, for *resistive magnets*, an increase in magnetic fields can only be achieved by augmenting the electric power level. At present, the NHMFL boosts its power in the frame work of an overhaul of the technical infrastructure by 20 %. Because of the inefficiency of materials and the basic power-field relationship, this will translate into a field increase of less than 10%, i.e., from 35 T to about 38 T.

For *pulsed magnets* the limit is at present at 100 T for pulses in the range of 1-10 ms our users are interested in. This limit is practically independent of the size of the energy source, because there are no materials available that could withstand these extreme Lorentz forces.

High-field *superconducting magnets* are not limited by the current density but the conductor strength. Almost half of the volume of the 900 MHz NMR magnet consists of reinforcement. A conductor of appropriate strength would reduce magnet volume correspondingly. Another example are the superconducting coils of the 45 T hybrid magnet. Only a small fraction is superconductor (5-10%), most of the volume is reinforcement (33-38%), insulation (16-20 %), stabilizer (21-25%) and cooling space (15-20%). An increase of the current density of the superconductor would, therefore, help very little, and any improvement would require even more reinforcement, diluting these efforts (for a more detailed description of this and other related questions see the attached article "Material Research for Advanced Magnets").



900 MHz magnet

In summary, we conclude that progress in the generation in magnetic fields is limited by the mechanical properties of the available materials.

NHMFL's future needs in material research

An appropriate materials program would consist of three major activities: a) characterization, b) application studies, and c) development of new materials.

The ***characterization of materials*** would be a continuation of the existing, well justified and very successful activity. More than 250 engineering reports have been created over the years with invaluable information for the magnet designer. Some upgrading and modernization of the equipment are required.

Application studies would consist of combining known materials with known conductors for improved performance. An example would be the integration of high-strength steel or fibers into a superconductor to improve its strain behavior. Another example would be Zylon braiding of conductors for pulsed magnets for higher strength and better insulation. Cooperation with industry (such as the Bochvar Institute) for new and better conductor geometries is recommended.

Studies of this kind would also involve investigating and adapting materials traditionally not used in magnet design but with a high potential for improved characteristics. An example is the intended use of Haynes alloys for cable-in-conduit conductors.

The ***development of new materials*** would include several efforts.

(1) Establishment of fabrication routes for newly developed processes. An example is cold working of Cu and Cu alloys at cryogenic temperatures, which introduces nanotwins and high density dislocations. This process has been investigated at the

NHMFL; it was funded through an IHRP, and has shown very promising results. The necessary next step is the construction of a facility where long lengths of such a conductor could be fabricated.

(2) Development of new processes. There are many developing techniques which improve material characteristics, such as equal channel angular extrusion, multilayer lamination, cryogenic cold work, cryogenic ball milling, thin-layer electro deposition of Cu, high pressure torsion and friction stirring. These processes would have to be explored, by themselves and in combination, for their usefulness for magnet materials and up-scalability. A focused development activity would have to follow.

(3) Development of new materials. There is a strong need for alloys with high Young's modulus. Nano-structured materials, nanotubes (carbon and other elements), bulk glassy alloys, and high-strength fibers are the most promising candidates for new materials. Of special interest is the combination of nano-structured Cu with CNTs. The research efforts are considerable. An association or coordination with other laboratories would be useful, such as MST at LANL, Carnegie Mellon, Harvard, Drexel University, or industry, such as Toyobo. These activities would not only be useful for building the next generation of high field magnets, but also have a broad impact on material science, other technologies