High Magnetic Field Science and its Application in the United States: Current Status and Future Directions

Report prepared for the National Research Council

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Briefing to the NSF MPS Advisory Committee

by Bertrand Halperin, Chair, Report Committee

July 18, 2013

Statement of Task (abbv'd)

- Assess U.S. research community **needs for high magnetic fields**.
  - **Current science drivers, opportunities and challenges over the next ten years?**
  - **Current state of high-field magnet science, engineering, and technology in the U.S.; conspicuous needs?**
  - **Principal facilities outside the U.S.; U.S. roles in developing them; potentials for further international collaboration?**
- Based on this assessment, **provide guidance** for the future of magnetic-field research, technology development in the U.S.; by considering trends in the disciplinary makeup of the user base, **how should infrastructure be optimized** to meet the needs of the next decades?

Definition of High Magnetic Fields

- In line with previous studies, we define a high-field magnet as one whose construction tests the limits of our current capabilities.
- Definition takes into account physical size of high-field region, homogeneity and stability, as well as field strength.
- Report deals with research carried out in high field magnets, as well as their construction and operation.

Committee Membership

- 15 members, with expertise in research areas using high magnetic fields; in materials, instrumentation, and magnet technology; in international context, science policy, and program planning.

- Members from the UK, the Netherlands, and Japan, as well as the US.

Process

- Four Meetings: March – September 2012.
- Dear Colleague Letter sent out in May 2012; 23 responses received total.
- Final draft completed, report into review in mid-February 2013.
- Report cleared and released in May 2013
- Final editing and publication expected this summer.

Report Structure

- **Introduction/Overview**
- **Science Drivers**
  - **Condensed Matter and Materials Physics Science**
  - **High Magnetic Fields in Chemistry, Biochemistry, and Biology**
  - **Medical and Life Science Studies (MRI, FMRI, MRS)**
  - **Other High Field Magnet Applications**
- **Combining High Magnetic fields with Scattering and Optical Probes**
- **Magnet Technology Development**
- **International Landscape** of High Magnetic Field Facilities
- **Stewardship** of High Magnetic Field Science in the United States

Key Findings, Conclusions, and Recommendations

Centralized Facilities

- <u>Conclusion</u>: **There is a continuing need for a centralized facility like the NHMFL** because (1) it is a cost-effective national resource supporting user experiments and thus advancing the scientific frontiers; and (2) it is a natural central location containing expert staff enabling the development of the next generation of high-field magnets.
- **<u>Recommendation</u>: The National Science Foundation should continue to provide support for the operations of the NHMFL and the development of the next-generation of high-field magnets.**

Distributed Facilities

- **Conclusion: In some cases, there are benefits from decentralized facilities with convenient access to high magnetic fields for on-going scientific research.**

- **Recommendation: Taking into account, among other factors, the estimated costs and anticipated total and regional demand for such facilities, federal funding agencies should evaluate the feasibility of setting up some smaller regional facilities, ideally centered around 32 Tesla superconducting magnets as the technology becomes available, and with optimized geographic locations for easy user access.** These would be in addition to the premier centralized facility, which would remain, with its unique mission of expanding the frontiers of high magnetic field science.

Advancing NMR Spectroscopy

- Conclusion: Nuclear magnetic resonance (NMR) spectroscopy is one of the most important and widely used techniques for structural, dynamical, and mechanistic studies in the chemical and biological sciences. However, in recent years, U.S. labs have failed to keep up with advances in commercial NMR magnet technology. Continuation of this trend will likely result in loss of the U.S. leadership role, as scientific problems of greater complexity and impact will be solved elsewhere.

- Recommendation: New mechanisms should be devised for funding and siting high-field NMR systems in the United States. To satisfy the likely demand for measurement time in a 1.2 GHz system, at least three such systems should be installed over a two-year period. These instruments should be located at geographically separated sites . . . and planning for the next generation instruments, likely a 1.5 or 1.6 GHz class system, should be under way now to allow for steady progress in instrument development.

Combining magnetic fields with x-ray and neutron scattering facilities and with THz radiation sources

- **Recommendation: New types of magnets should be developed and implemented** that will enable the broadest possible range of **x-ray and neutron scattering measurements in fields in excess of 30 T.** Several steps have been recommended. **New partnerships will likely be required to fund, build, and operate these magnets.**
- **Recommendation: A full photon spectrum, covering at least all of the energies (from radio-frequency to far-infrared) associated with accessible fields, should be available for use with high magnetic fields for diagnostics and control.** Several options should be considered.

Magnetic Resonance Imaging

- <u>Recommendation</u>: A design and feasibility study should be conducted for the construction of a 20 T, wide bore (65 cm diameter) MRI magnet suitable for large animal and human subject research. The required homogeneity is 1 ppm or better over a 16 cm diameter sphere. The appropriate sponsorship might be multiple agencies (e.g., NIH, NSF, and DOE). In parallel, an engineering feasibility study should be undertaken to identify appropriate RF, gradient coils and power supplies that will enable MRI and MRS and an extension of current health and safety research currently being conducted at lower fields.

Goals for Higher –Field Magnets

- **Recommendation**: **A 40 T all-superconducting magnet** should be designed and constructed, building on recent advances in HTS magnet technology.
- **Recommendation**: **A 60T dc Hybrid Magnet** should be designed and built that will capitalize on the success of the current 45 T hybrid magnet at the NHMFL-Tallahassee.
- **Recommendation**: **Higher-field pulsed magnets should be developed, together with the necessary instrumentation,** in a series of steps, to provide facilities available to users that might eventually extend the current suite of thermal, transport, and optical measurements to fields of 150T and beyond.

Stewardship Issues: Recompetition of NHFML

- <u>**Conclusion**</u> **: Recompetition on time scales as short as 5 years places at risk the substantial national investment in high field research that is embodied in a national facility like NHMFL, and could have disastrous effects on the research communities that rely on uninterrupted access to these facilities.** Though this committee believes that recompetition of facilities is appropriate, it also believes a flexible approach should be taken in the implementation of this resolution to fulfill the role as a steward and to avoid potential negative consequences of a short time interval between recompetitions of the NHMFL.

- <u>**Conclusion**</u>**: This committee strongly endorses the consideration given to this matter by the Subcommittee on Recompetition of Major Research Facilities.**

Other Stewardship Issues

- **<u>Recommendation</u>:** The **NSF,** the **NHMFL, and other interested entities** that benefit from the use of high magnetic fields **should adopt the steward-partner model** as the basis for defining the roles in future partnerships in high magnetic field science. **For magnets not sited at NHMFL, the host institution is in most cases the natural steward** (especially for significant facility-specific infrastructure required for magnet operations)**. For magnets sited at the NHMFL, NSF should be the steward, although the partner organization could fund the construction and operation of these facilities.**

- **Recommendation: A High-Field Magnet Science and Technology School should be established in the United States.**

Questions?

Appendix:

Additional Information

International cooperation: Recommendations

- **Recommendation: High-field facilities worldwide should be encouraged to collaborate as much as possible to improve the quality of magnets and service for users.** This can be accomplished through the establishment of **a global forum for high magnetic fields that consists of representatives of the large magnetic field facilities from all continents.** Such a forum would further stimulate collaboration and the exchange of expertise and personnel, thereby providing better service to the scientific community and magnet technology development. The forum should establish a **roadmap** for future magnets and stimulate the realization of the defined targets on this roadmap.

- **Recommendation: Large high magnetic field facilities should also have strong collaborations with smaller regional centers, providing them with support and expertise.** Users of these regional centers may need the higher fields available in the large facilities, while users of the large facilities could be referred to the regional centers if their proposed experiments are better suited for those centers.

Science Drivers

- **Condensed Matter and Materials Physics**
  - Materials near a quantum Critical Point
  - Quantum magnets
  - Superconductors
  - Semiconductors and semimetals
  - Topological phases
  - Soft condensed matter

Science Drivers

- **Chemistry, Biochemistry, and Biology**

  - **NMR** in chemistry and biology
  - **FT-ICR** Mass spectrometry
  - Electron **P**aramagnetic **R**esonance

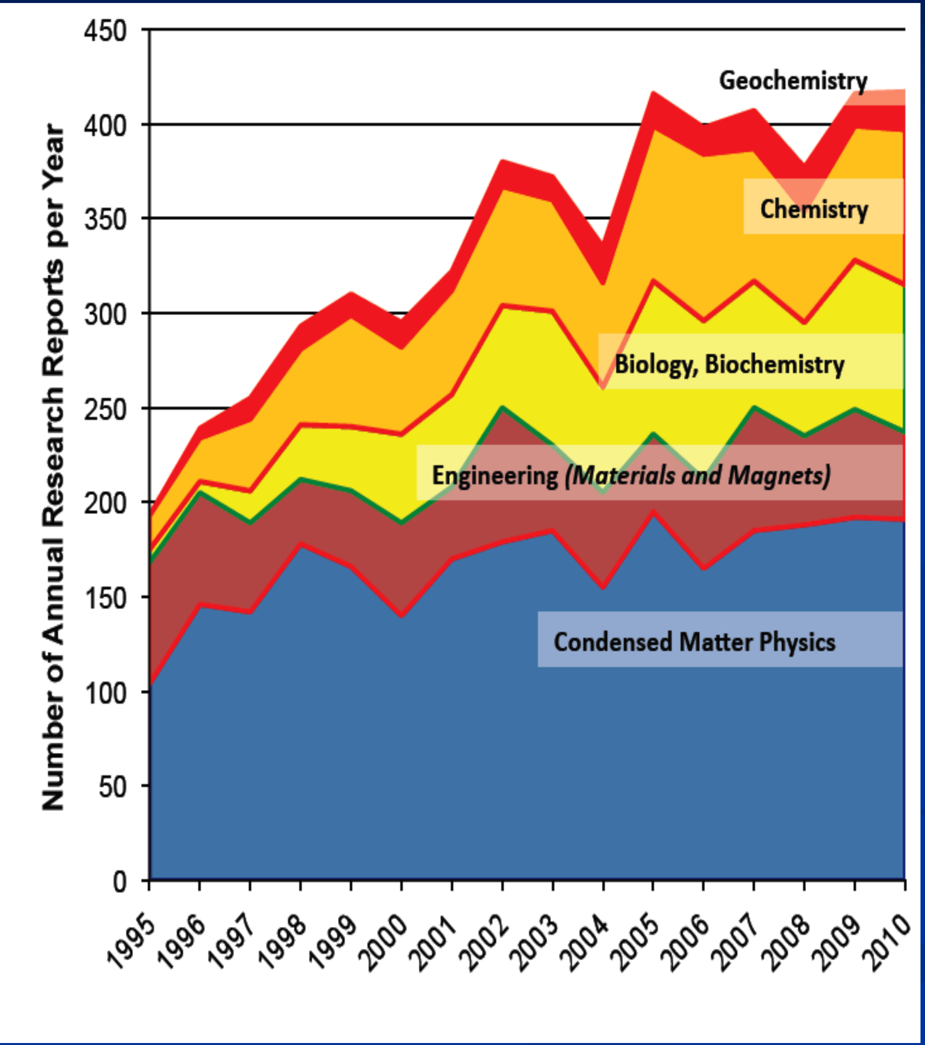
Science Drivers

- **Medical and Life Sciences**
  - **M**agnetic **R**esonance **I**maging **for humans** and large animals.
  - Magnetic Resonance Spectroscopy
  - Functional MRI
  - What might be learned by going to much higher fields

Science Drivers

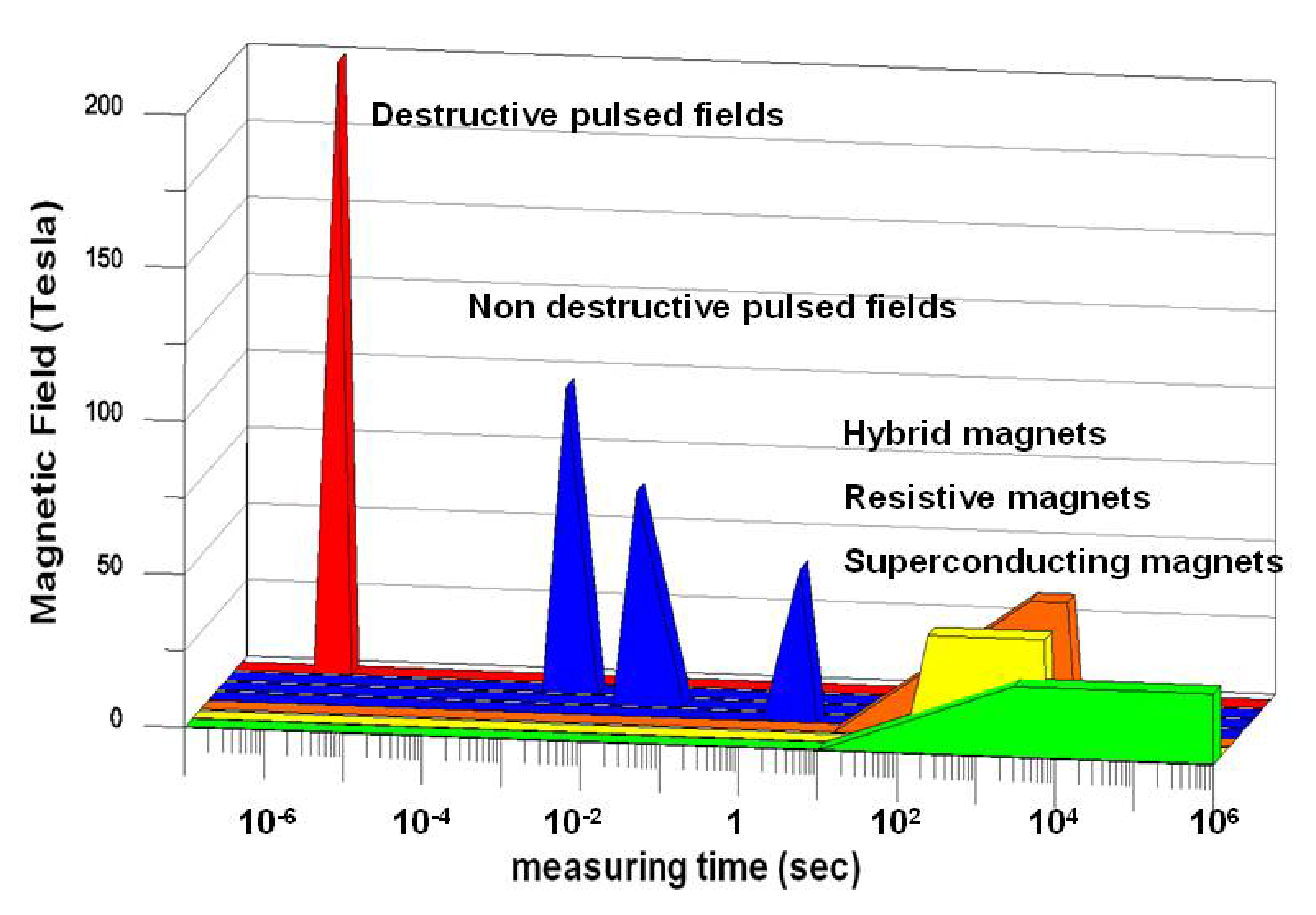
- **Other Applications**
  - **High-energy physics:** Accelerators and detectors.
  - Plasma physics: **Controlled nuclear fusion**
  - Particle astrophysics
  - Radiotherapy using charged particles

Science Drivers at NHMFL



Research reports resulting from projects using high-field magnets at the National High Magnetic Field Laboratory (NHFML) from 1995 to 2010, classified by field of research.

State of High-Field Magnetic Technology



An overview of magnetic fields available with different technologies, showing the corresponding rise times for the fields and the times during which experiments in these fields van be performed.
SOURCE: Graph courtesy of Jan Cornelis Maan, Radboud University Nijmegen.

Recommendation –

Combining magnetic fields with scattering facilities

- **Recommendation: New types of magnets should be developed and implemented** that will enable the broadest possible range of **x-ray and neutron scattering measurements in fields in excess of 30 T.** Recommended steps **:**
- **1) procure modern 10-16T magnet/cryostat systems for US facilities;**
- **2)develop a 40 T pulsed field magnet with a repetition rate of 30 seconds or less;**
- **3) develop a wider-bore 40 T superconducting DC magnet specifically for use in conjunction with neutron scattering facilities.**
- **New partnerships will likely be required to fund, build, and operate these magnets**

Recommendation –
Combining magnetic fields with THz radiation

- **Recommendation: A full photon spectrum, covering at least all of the energies (from radio-frequency to far-infrared) associated with accessible fields, should be available for use with high magnetic fields for diagnostics and control.** At any point in the spectrum, transform-limited pulses of variable amplitude, allowing access to linear and non-linear response regimes, should be provided. **Consideration should be given to a number of different options including (1) providing a low-cost spectrum of THz radiation sources at the NHMFL, (2) construction of an appropriate FEL at NHFML, or (3) providing an all-superconducting, high-field magnet at a centralized FEL facility with access to the THz radiation band.**
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Summary of topics for findings, conclusions, and recommendations

- Centralized and Distributed Facilities;
- Advancing NMR Spectroscopy;
- Combining magnetic fields with scattering facilities, THz radiation;
- Specific goals for higher field magnets;
- 20 T research magnet for human MRI;
- Stewardship;
- International cooperation.

Committee Membership

- **Bertrand I. Halperin**, *Chair* (Harvard University)
- **Gabriel Aeppli** (University College of London)
- **Yoichi Ando** (Osaka University)
- **Meigan Aronson** (Stony Brook University)
- **Dimitri Basov** (University of California at San Diego)
- **Thomas F. Budinger** (University of California, Berkeley)
- **Robert Dimeo** (NIST)
- **John C. Gore**(Vanderbilt University)
- **Frank Hunte** (North Carolina State University)
- **Chung Ning (Jeanie) Lau** (University of California, Riverside)
- **Jan Cornelis Maan** (Radboud University Nijmegen)
- **Ann McDermott** (Columbia University)
- **Arthur P. Ramirez** (University of California, Santa Cruz)
- **Zlatko B. Tesanovic** (Johns Hopkins University) (deceased – July 26, 2012)
- **Robert Tycko** (NIH)

Expertise in research areas using high magnetic fields; in materials, instrumentation, and magnet technology; in international context, science policy, and program planning.

Community Input: Dear Colleague Letter

- A broad call for community input to the committee was issued in spring 2012 as a dear colleague letter, shortly after the committee's second meeting. The announcement was sent by email to the users of the NHMFL, colleagues of committee members, and appeared on the committee's public Web page. A portion of the dear colleague letter is excerpted below.

"…With this message, the MagSci committee invites you to send it any information or opinions you feel should be taken into account during its deliberations…Specifically, how have high magnetic fields had an impact on your research? What scientific advances might your research lead to? How have you taken advantage of facilities at the National High Magnetic Field Laboratory (NHMFL) or other high-field magnet centers? Have you utilized international high magnet field facilities for your research? What new facilities or new capabilities would be most valuable to you? In what new areas of research are high magnetic fields likely to have a large impact? Are the challenges related to the current status of high magnetic field science impacting your research? Do you have any other comments? How does support for magnetic field research compare with support elsewhere?..."

- The MagSci committee is distributing this message to as many members of the high magnetic field community as possible, using several different organizations, because it wants to be sure that all voices have been heard before it issues its report. We apologize if you have received multiple copies of this letter.

Community Input: 23 Responses Received

David Valentine
William P Halperin
Gavin Morley
Sang-Wook Cheong
Michael Harrington
En-Che Yang
Juliana D'Andrilli
Michael S Chapman
K.-P. Dinse
Bertaina Sylvian
Jeffrey Hoch

Tatyana Polenova
Jack H Freed
Mei Hong
James McKnight
Núria Aliaga-Alcalde
Joshua Telser
Raphael Raptis
Patrick van der Wel
Trudy Lehner
Ayyalusamy Ramamoorthy
Dan Reger
Joe Zardrozny