Title: Science Up to 100 Tesla

Author(s): L.J. Campbell

Submitted to: Spring Workshop on Basic Science Using Pulsed Power
Santa Barbara, CA - April 5-7, 1995

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Why 100 T?

What's so special about 100 tesla? Intrinsically, nothing — nature is indifferent to our arbitrary units and measuring systems. However, from the point of view of practical engineering limits, 100 T (± 10 T) is special as the highest attainable field that can be held for milli-sec in a non-destructive magnet. The strongest steels turn soft under stresses of 4 GPa, which is the magnetic pressure of 100 T. Therefore, the pressure (i.e., the magnetic field) in such a magnet must be spread over a large volume to allow the differential pressure change at any point to match the tensile strength of available materials. This large field volume implies high energy and also high power to transfer the energy quickly to avoid excessive Joule heating. Recent calculations at Los Alamos show that sufficient power and energy are available from the spinning rotor of the Laboratory's recycled nuclear power plant generator (1.4 GVA, continuous rating) to produce 100 T, non-destructively, with available materials. The stored field energy would be 140 MJ and the magnet, consisting of several independent coils, would be about 1 m in diameter and 1 m high. The bore diameter is 24 mm and the pulse length above 80 T is about 20 ms. The Europeans have recently arrived at a similar conclusion, i.e., non-destructive 100 T is achievable, and they are pressing ahead with a proposal for an ELMF (European Large Magnetic Field Facility) that will center around one or more 100 T, nondestructive, long pulse magnets.

Is there anything special about non-destructive 100 T for 20 ms in a 24 mm bore? After all, experiments that are non-destructive, at least to the sample, have been possible for years at fields over 200 T for μs in 6 mm bores. Indeed, condensed matter physicists see something quite special in ms time scales and 24 mm bores, namely, the chance to stretch thermodynamic
parameter space in two more dimensions (in addition to the high field dimension). At the National High Magnetic Field Laboratory in Los Alamos we recently installed a dilution refrigerator in a 50 T capacitor-driven magnet (24 mm bore, 20 ms time scale) and cooled the sample space below 30 mK. We also inserted a special diamond anvil cell into our 50 T magnet and verified that the field thoroughly penetrated during a pulse (i.e., the resistivity of the cell was high enough to prevent significant eddy current shielding). Therefore, the experimentalist can now look forward, for the first time, to measurements at 100 T and 30 mK or 100 T and 2 GPa. (No, we cannot yet put the diamond anvil cell into the dilution refrigerator!)

The 20 ms pulse length vs the 5 µs pulse length of existing single-coil 100 - 200 T magnets is also significant in that it allows a wider range experiments (with less dB/dt pick-up problems, less heating, more time for relaxation to equilibrium) and a wider range of samples (larger, more conductive metals and alloys). The use of dilution refrigerators and diamond anvil cells also requires ms pulse lengths, in addition to large bores.

Until there is a breakthrough in materials, magnets having all the low temperature and high pressure trimmings will be limited to about 100 T. Even if Phil Anderson's prediction of a 100 T superconducting magnet within 20 years turns out to be true, higher fields in large bores for long times will still be difficult. Within the field range 1 to 100 T far more resources are now devoted to producing the highest possible continuous fields (40 ± 5 T) than to producing longer pulsed fields above 50 T, even though a 100 ms flat-top at 60 T is now possible (and under construction at NHMFL). This again illustrates that the utility of the field can be more important than the strength of the field to researchers in condensed matter. Discoveries are typically made in new territory, but this can be new combinations of pressure, temperature, and magnetic field, or new probes and new materials.

Science Opportunities

If any activity has kept up with the proliferation of new experiments and new facilities in high magnetic field research it is the listing of experiments that could and should be done in high fields. Perhaps, there is a connection. However, the most interesting experiments
performed are often not those recommended a few years earlier, which I take as a healthy sign: if the proved reserves of worthy science keep increasing in spite of a high extraction rate then there is clearly a large undiscovered total reserve. Part of the reason for the vitality of high field research is that high fields provide a generic environment - you can stick almost anything into the field. As mentioned above, a magnetic field is just another independent thermodynamic parameter, so anything that may have an interesting thermodynamic state is fair game. And that 'anything' covers about everything in condensed matter physics. Compared to particle accelerators or plasma machines a high magnetic field laboratory is a setting for generic science, like synchrotron light sources or neutron scattering centers. (Although the latter two installations probe states, while a magnetic field typically creates a state.)

Because it is unrealistic to try to list all the science opportunities at high fields (and the best are not known, anyway) I will instead list sources for lists in the public domain, and give a few examples.

Blue Ribbon Panels — In the United States there have been two of these in the recent past. The first was the Panel on High Magnetic Field Research and Facilities (S. P. Keller, Chairman; J. K. Hulm, B D. McCombe, D. B. Montgomery, and R. L. Orbach, Subpanel Chairmen) which was convened by the National Research Council (Solid State Sciences Committee) in 1978. They saw 'significant new scientific opportunities in steady-state fields to 75 T', and recommended quasi-static field approaching 100 T. Among the highlights of scientific opportunities they listed

Transition to lower dimensionality and Wigner crystallization. Two-dimensional metals and semiconductors. This sort of work won a Nobel Prize for K. von Klitzing.

Electronic structure of exotic metals. Using de Haas - van Alphen and cyclotron resonance to probe the Fermi surface.

High-field Superconductors. Besides the technical interest, there are, still in 1995, fundamental questions on the role of composition, ordering, vacancy concentration,
dislocation density, etc. This was before the discovery of high temperature superconductivity.

Metallurgical phase transitions. Control and growth of martensite. Nucleation mechanism, etc. Application of a 100 T pulse on an α-FeNi alloy changes the martensitic transformation temperature by more than a few hundred degrees.

Chemical Reactions. Dynamics of chemical reactions in gases, in the condensed phase, and on surfaces are expected to be influenced uniquely by magnetic energy near kT at ambient temperatures.

Structure of biological systems. NMR spectroscopy at 75 T will yield substantial increases in resolving power. Reveal antibody-antigen interaction, hemoglobin structure and function, transfer RNA structure in solution, protein-lipid interaction, enzyme-complex assembly, etc.

Spectroscopy of atoms and molecules. Altered collision cross sections for resonant collisions. Insights into collision potential. Simulate conditions on surface of white dwarf stars.

The second blue ribbon panel was the NSF Panel on Large Magnetic Fields (F. Seitz and R. C. Richardson, Co-Chairmen) which issued its report in 1988. The principal recommendation of this panel was the establishment of a new National High Magnetic Field Laboratory, which was done. Not to be outdone by the previous National Research Council panel the NSF panel listed about three times as many science opportunities in three categories:

Condensed Matter. High temperature superconductors, heavy fermion compounds, neutral quantum fluids and solids, semiconductors, diluted magnetic semiconductors, artificially structured low-dimensional materials, one dimensional conductors, phase transitions, and magnetism.

Other Sciences. NMR, atomic and molecular physics, plasma physics, complex fluids, biophysics and biosciences, and magneto chemistry.
Technology and Engineering. Superconductivity, metallic superlattices, polymer science, magnetic resonance and imaging, magnetic materials, materials processing, and separations.

The report stated, 'The dream of all of us is the ready access in our own laboratories to a 100 T field.' Also, 'The Panel discovered that striking opportunities for new research discoveries exist in a broad variety of research areas.'

Conferences — There are about two large international conferences on high magnetic field research per year, whose proceedings are unerring guides to where the action is. In addition, the giant APS March Meeting covers most of condensed matter research, including that in high fields. I will mention only a few. First, the European Workshop on Science in 100 Tesla held in Leuven, Belgium, May 15-17, 1992, received reports from five scientific panels.

Low dimensional structures and semiconductors. Emphasis on the undisputed role of magnetic fields for elucidating electronic structure; a powerful tool for a tough and important problem.

Magnetism and metals. Better understanding of magnetic exchange interactions, especially as 100 T is large enough to lead to a significant perturbation of the atomic configuration of the magnetic moments, which can then be accurately measured.

Superconductors, heavy fermion systems and organic conductors. These are systems with highly correlated electrons and non-trivial elementary excitations. Also, rich behavior in high fields.

Atomic and molecular physics, plasma physics. Quantum chaos in Rydberg atoms, Faraday rotation to probe auto-ionizing resonances, energy transfer studies in molecules when the cyclotron frequency is commensurate with rotational or vibrational levels.

Complex fluids, chemistry and biology, NMR. Electronic origin of magnetic field effects such as ligand field splittings, exchange interactions, hyperfine couplings. Spectroscopy of forbidden transitions that become allowed in high fields. Reaction kinetics influenced
by electron spin as when a radical pair is a key intermediate. Field effect on conformation of molecules. Response of 'living matter.' NMR.

The statements following all the above (and below) topics are highly abbreviated, even in a qualitative sense. The point to be made is that 'science in high fields' is probably too large a topic today to be suggested realistically as a conference or a conference talk, even a 30 minute one. However, it is a difficult habit to overcome and even the NHMFL is hosting an international conference in May entitled, 'Physical Phenomena at High Magnetic Fields II,' which covers everything except psychic phenomena. The proceedings of the first such conference are in Physical Phenomena at High Magnetic Fields, ed. E. Manousakis, P. Schlottmann, P. Kumar, K. S. Bedell, and F. M. Mueller, (Addison-Wesley, Redwood City, CA, 1992).

Another recent conference I recommend was devoted to new results rather than science opportunities. This was the International Symposium on the Frontiers in High Magnetic Fields, Tokyo, 1994, and the proceedings are in Physica B, vol. 201, 1994.

**Magnet Laboratories, Annual Reports** — The following magnet laboratories publish annual reports which reveal the cutting edge, often before it appears in journals.

1. Hochfeld-Magnetlabor, 25 Av. des Martyrs-166x, F38042, Grenoble Cedex, France. (The Grenoble magnet lab is a joint French and German effort.)
2. Amsterdam-Nijmegen Magnet Laboratory, Postbus 9010, NL-6500 GL Nijmegen. The Netherlands. (The Amsterdam and Nijmegen laboratories specialize in pulsed and continuous fields, respectively, but have common support and a common report.)
3. Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139-4307.
4. National High Magnetic Field Laboratory, Florida State University, 1800 East Paul Dirac Drive, Tallahassee, FL 32306-4005. (NHMFL has facilities at Tallahassee, Gainesville, and Los Alamos which, broadly speaking, specialize in continuous fields, low temperature, and pulsed fields, respectively.)

**Examples from Science Program Committee** — For up-to-date science opportunities I will list a few views from the Science Program Committee of the NHMFL. (Members include J. R.

Quantum fluids and solids.
- Broad range of physical phenomena accessible at high fields and temperatures below 0.1 K; unconventional superfluidity, unusual magnetic ordering, Bose-Einstein condensation, Kosterlitz-Thouless transitions
- Superfluid $^3$He. Spin triplet ordering (hard core repulsion), enhanced ferromagnetic correlations favor spin triplet pairing. Properties in high field; spin polarized Fermi liquids; polarization dependence of magnetic susceptibility; magnetic equation of state.
- Solid $^3$He. Quantum solid with large zero-point motion and multiple exchange interactions. Determine critical field for transition from high field phase to disordered phase, and nature of phase transition. Nuclear spin glasses - geometric frustration of multiple spin exchange mechanisms combined with applied disorder for 2D layers of $^3$He could lead to new 2D nuclear spin glasses with glassy ordering for very low nuclear spin entropies.
- Spin-polarized atomic hydrogen. Seek simplest example of Bose-Einstein condensation by production of sufficiently dense polarized atomic H ($\approx 10^{19}$ atoms/cm$^3$ at 0.1 K)


Artificial structures.
- Quantum Hall effect (QHE). Why are some values of the quantized Hall resistance not observed? Investigate the 'composite fermion theory' of the fractional QHE by preparing Landau level filling fraction $\nu = 1/2$ in high field. Look at high mobility double-layer systems and wide single quantum wells. Expected long-range coherence in quantum Hall state $\nu = 1$.
- Magnetic multilayers. Metallic and insulating.
- High field permanent magnets. Enhance field intensity by appropriately combining magnetically hard and soft phases.
- Magnetic semiconductors
Examples from DOE 100 tesla meeting, Los Alamos, February 16-17, 1995. This meeting considered the feasibility and applications of the 100 T magnet described earlier. John Wilkins prepared a summary, which includes the following comments about science opportunities. The source of the idea, whether DOE lab or university scientist, is indicated in square brackets.

**High temperature superconductors.** The upper critical field $H_c2$ is central to both the phenomenology and potential technology of cuprate superconductors. The estimates of the low-temperature $H_c2(0)$ are based on order-of-magnitude extrapolation from measurements made with existing magnets. The 100 tesla magnet would extend these measurements into the technological interesting range where some applications might occur [Ames, ANL, LANL, LBL, ORNL]. Irreversible effects that might compromise potential technology could be discriminated from the upper critical field. [B. Maple]

**Heavy Fermions.** A rebirth of interest has increased the range of heavy fermion systems such as 'Kondo insulators.' Of particular interest are materials with several magnetic phases [Ames, LANL], magnetic field dependent specific heat [G. Stewart] and the breakdown of the conventional Fermi-liquid description [B. Maple].

**New phases of matter.** Recently it has been realized that the correlations associated with the metal-insulator transition can be probed in a magnetic field. To probe close to the collapse of the energy gap in the metal-insulator transition requires large magnetic fields. [M. Aronson] Novel phase transitions - such as, Landau-level induced reentrant superconductivity - require very large fields. [M. Salamon]

**Nanoscale physics.** Dilutely magnetic doped semiconductor nanostructures show a giant Faraday rotation, while concentrated doping yields a 100-fold increase and unusual spin dynamics. [Sandia] The Coulomb staircase observed in single-electron tunneling can be appreciably split in 100 tesla, thus offering a new way to tune this phenomenon. [S. Ruggiero].

**Restricted dimensional materials.** The measurement of the technological-important magnetic anisotropy of surfaces, multilayers, and ultrathin films is currently limited by the magnetic field strength. [C. Falco] In quasi-one- and two-dimensional, single-crystal, pure organic materials the properties change dramatically as the cyclotron radius $[250 \, \text{Å}/\sqrt{B(Tesla)}]$ becomes smaller than the sample size. [C. Agosta]

The applications of magnetic fields below 100 T to science are becoming so widespread that the usefulness of associating the science with the magnetic field is rapidly diminishing. Magnetic fields up to 100 T are becoming a commodity in the scientific economy.