New hybrid magnet system for structure research at highest magnetic fields and temperatures in the millikelvin region

Peter Smeibidl\textsuperscript{1}, Mark Bird\textsuperscript{2}, Hartmut Ehmler\textsuperscript{1} and Alan Tennant\textsuperscript{1}

\textsuperscript{1}Helmholtz Centre Berlin, Hahn-Meitner Platz 1, D-14109 Berlin, Germany
\textsuperscript{2}National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL, USA

E-mail: peter.smeibidl@helmholtz-berlin.de

Abstract. The Helmholtz Centre Berlin (HZB) is a user facility for the study of structure and dynamics with neutrons and synchrotron radiation with special emphasis on experiments under extreme conditions. Neutron scattering is uniquely suited to study magnetic properties on a microscopic length scale, because neutrons have comparable wavelengths and, due to their magnetic moment, they interact with the atomic magnetic moments. At HZB a dedicated instrument for neutron scattering at extreme magnetic fields and low temperatures is under construction, the Extreme Environment Diffractometer ExED. It is projected according to the time-of-flight principle for elastic and inelastic neutron scattering and for the special geometric constraints of analysing samples in a high field magnet. The new hybrid magnet will not only allow for novel experiments, it will be at the forefront of development in magnet technology itself. With a set of superconducting and resistive coils a maximum field above 30 T will be possible. To compromise between the needs of the magnet design for highest fields and the concept of the neutron instrument, the magnetic field will be generated by means of a coned, resistive inner solenoid and a superconducting outer solenoid with horizontal field orientation. To allow for experiments down to Millikelvin Temperatures the installation of a $^{3}$He or a dilution cryostat with a closed cycle precooling stage is foreseen.

1. Introduction
On the basis of their special expertise in experiments at lowest temperatures and world-wide highest magnetic fields the neutron scattering division at Helmholtz Centre Berlin (HZB) has driven the limits of neutron scattering research in high magnetic fields up to values of 15 T (in special cases up to 17 T by the use of ferromagnetic boosters) in the last years. One of the most important motivations for the combined projects High-Field-Magnet (HFM) and Extreme Environment Diffractometer (ExED) is a further development of the institute’s capabilities to offer experimental facilities for highest magnetic fields at lowest sample temperatures to the neutron user community. Further extension of the limit of magnetic fields will allow us to study by neutron scattering phenomena not yet accessible today, and will continue to provide outstanding scientific return on the effort invested.

2. Science
The special properties of the neutron, as an uncharged particle that carries a magnetic moment, provides remarkable possibilities in probing the magnetic state of materials. Magnetic ordering
can be measured via diffraction at the atomic level, and inelastic scattering measures the normal modes of excitation of the system and its fluctuations. So a full picture of the state, its interaction Hamiltonian, quasiparticles, and their statistics can be built up if one can control a system up to complete magnetic polarization where all other interactions are overcome by an extremely large field at low temperatures.

This vision of the powerful combination of extreme magnetic fields and neutron scattering led us to introduce fields up to 15 T at temperatures of 40 mK to the neutron scattering instrumentation at Helmholtz Centre Berlin. Breakthroughs in the understanding of metals and of the emergence of magnetic phases dominated by Heisenberg uncertainty of individual spin components have been made (see for example [1], [2]). The new serial hybrid magnet technology now provides a means to go beyond 15 Tesla and a development route to the highest possible steady fields above 30 T for neutrons, which we are now going on to build and install. Many materials and problems of outstanding scientific importance then, including field induced normal state in high-TC superconductors, lie beyond the 15 T technological barrier for split-coil superconducting magnets.

3. Neutron instrument ExED

To open up higher fields to neutron research requires a reinvented approach with fundamentally different magnet technology and neutron instrumentation. Just an increase of the maximum field using the existing superconducting magnet technology is not possible, because of the underlying principle of split-pair magnets. At HZB we have pioneered a special time-of-flight instrument (ExED) to allow diffraction and inelastic neutron measurements in the restricted geometries of an extreme field magnet.

![Figure 1](image_url)

**Figure 1.** Overview drawing of the most important components of the instrument ExED with the hybrid magnet at the scattering position. The neutron guide with a length of about 80 m is interrupted by different chopper systems (red and green circles). The magnet is surrounded by four rectangular area detectors for the analysis of the scattered neutrons.

For the first time it is necessary to build a special dedicated neutron instrument around a stationary magnet system. For the coil we have chosen the geometry of a solenoid with conical ends at both sides. To enhance the measurement capabilities for this limited geometry a unique multispectral neutron guide system for wave lengths between 0.7 to 15 Angstrom was installed in the new instrumentation building, the Neutron Guide Hall 2 at the research reactor BER-II.
The horizontal field magnet system with conical endings is well adapted for experiments in a large Q-space despite of its geometrical limitations for neutron scattering.

The instrument commissioning for the diffraction setup was started in 2009. First experiments using smaller magnets were started in 2010. First small angle neutron scattering experiments were tested in 2010, too. The setup for inelastic scattering is not yet complete.

4. Hybrid magnet system

4.1. Magnet

Following our past experience only steady state fields are adequate to achieve the goals of this project. Pulsed resistive magnets can produce higher fields for a small fraction of a second. However, the duty factor of this type of magnets is very small. This implies a strong reduction of efficiency for their use in inherently intensity limited neutron scattering applications. This restricts the number of feasible experiments to an unacceptable degree. In particular inelastic scattering studies, which proved in the past to be most rewarding, would virtually be excluded when using pulsed magnets. Additional disadvantages are the strong decrease in lifetime with increasing field and the necessity to cool the coils to LN₂-temperature prior to every field pulse.

The basic configuration of the horizontal series-connected-hybrid magnet designed at the National High Magnetic Field Laboratory, Tallahassee, FL (NHMFL) is suited to HZB requirements for neutron scattering in high magnetic fields. A coil system based on a superconducting outsert and fitted with a conical resistive insert can produce fields above 25 T with a resistive insert of 4 MW, and fields above 30 T with a resistive insert of 8 MW, each for the HZB magnet specification (30 degree opening angle, 50 mm free room temperature bore), which is optimised for the underlying concept of the neutron instrument ExED [3].

With help of the used resistive insert coils (Bitter magnets) one can obtain fields above 30 Tesla, even in a limited geometry, optimised for the demands of neutron scattering. The required electric power of 8 MW is only 1/3 of an all resistive magnet of comparable field. Due to the conductor technology used for the superconducting outsert coil, - cable-in-conduit (CIC) - it is possible in a serial hybrid magnet system to connect a normal conducting and a superconducting coil in series and operate both at the same high current of 20 kA. The use of this setup allows considerable cost savings for design and construction, because of smaller force in case of a magnet quench and because of smaller local fields inside of the superconducting winding pack, compared with a conventional hybrid system with two independent power supplys. With this arrangement, the reduction in operating costs will be decisive compared to all-resistive coils, since a high portion of the total magnetic field is generated by the superconductor.

CIC conductor technology is a proven method, which is already used in magnet systems for fusion research, but careful design and testing of all components and fabrication procedures is still important [4]. We are planning to use three different types of conductor for different sections of the coil winding pack. Main drivers for this decision are internal field, forces which act on the conductor and cost of the superconductor material. All three conductors were tested successfully [5] [6]. All Nb₃Sn strand was cabled meanwhile and the final compaction of the superconductors is almost complete, too. Next steps will be coil winding, heat treatment of the Nb₃Sn and impreganition of the coil. It is planned to complete the fabrication of the cold mass by end of 2012.

A downsized conical resistive coil was successfully tested above 30 T at NHMFL. The design of the original coil is close to completion. The fabrication is simpler and faster compared with the superconducting CIC coil.

4.2. Magnet infrastructure

The He-refrigerator system for cooling of the CIC coil, the 8 MW, 20 kA DC power supply as well as the high pressure water circulation required to cool the heat loss from the insert
magnet, including the necessary cooling towers and the water treatment plant, are designed using standardised industrial components. The installation of the necessary infrastructure components in a separate building beside the Neutron Guide Hall is close to completion. The commissioning phase including various special operational tests without the magnet system will start in 2011.

4.3. Sample environment
The last challenge is to provide temperature regulation of the sample down into the millikelvin temperature region for all experiments. It is foreseen to install a cryostat and sample handling into the magnet cone. Critical issues are precise adjustment of the sample in the center of field and the limited access, which is possible only from the end of the two cones. Cold tests of the first components needed for the system were started in a test vacuum container of the same size and geometry as the original magnet cone.

References
[1] Khaykovich B et. al. 2003 Physical Review B 67 054501
[2] Lake B et. al. 2005 Nature Materials vol 4 558
[3] Bird M et. al. 2009 IEEE Transactions on Applied Superconductivity vol 19 num 3 1612
[4] Painter T et. al. 2010 IEEE Transactions on Applied Superconductivity vol 20 num 3 692
[5] Dixon I et. al. 2009 IEEE Transactions on Applied Superconductivity vol 19 num 3 2466
[6] Dixon I et. al. 2010 IEEE Transactions on Applied Superconductivity vol 20 num 3 1459