

# New High Field Magnet for Neutron Scattering at Hahn-Meitner Institute

**M Steiner, D A Tennant, P Smeibidl**

Hahn-Meitner Institute, Glienicker Str. 100, D-14109 Berlin, Germany

E-mail: [steiner@hmi.de](mailto:steiner@hmi.de), [tennant@hmi.de](mailto:tennant@hmi.de), [peter.smeibidl@hmi.de](mailto:peter.smeibidl@hmi.de)

**Abstract.** The Berlin Neutron Scattering Center BENSCH at the Hahn-Meitner-Institute (HMI) is a user facility for the study of structure and dynamics of condensed matter 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. Magnetic interactions and magnetic phenomena depend on thermodynamic parameters like magnetic field, temperature and pressure. At HMI special efforts are being made to offer outstanding sample environments such as very low temperatures or high magnetic fields or combination of both. For the future a dedicated instrument for neutron scattering at extreme fields is under construction, the Extreme Environment Diffractometer ExED. For this instrument the existing superconducting magnets as well as a future hybrid system can be used. The highest fields, above 30 T will be produced by the planned series-connected hybrid magnet system, designed and constructed in collaboration with the National High Magnetic Field Laboratory, Tallahassee, FL.

## 1. Introduction

The HMI project to achieve much higher magnetic fields in neutron scattering research is based on new paradigms both in neutron scattering instrumentation and in magnet design. The traditional approach is to install mobile high field magnets on general-purpose instruments for experiments requiring high fields. One magnet can be used on several instruments and in turn, it has to fit the geometrical constraints and needs of these instruments. For this reason the highest field magnets by now are vertical field split pair superconductors, i.e. with a horizontal gap between two coils with vertical axis. These magnets allow a large scattering range to be used, as conventional neutron scattering instruments generally cover a wide angular range (with the exception of most reflectometers and small angle scattering machines). The technical perspectives for future use of this approach are limited.

Therefore we plan for the new project to use immobile, solidly installed magnets and build up flexible, multifunctional neutron scattering instrumentation around the magnet. This enables us to build magnets without the constraints of a wide angular range of access for neutron scattering experiments. If we use novel neutron scattering instrument design concepts we get access to a large neutron scattering parameter range for a conveniently limited range of scattering angles.

## 2. Science

Magnetic field is a particularly valuable parameter, increasingly used to explore competing phases through bulk measurements in university laboratories, where steady fields of 20 T are commonly available. However, the understanding of the microscopic interactions has direct implication in the development of any realistic theoretical models, and this is often only possible by neutron scattering. In a survey of Science and Nature between 2001 and 2004 more than 20 % of the neutron related papers used high magnetic fields. Half of these came from the Hahn-Meitner Institut's Berlin Neutron Scattering Center.

In recent years a large effort in condensed matter research has focused on strongly correlated electron systems. In these materials the usual simplifying assumptions that allow the use of single electron wave functions, as for example in the case of the free electron model of a simple metal, cannot be made. The electrons interact strongly with each other and many-body effects that are far from being fully understood, determine their collective behaviour. Many materials are classed as strongly correlated electron systems, for example: high temperature superconductors (HTSC), quantum magnets, colossal magnetoresistive manganites, spintronic materials, spin frustrated systems, heavy fermion (HF) materials and the recently discovered nanomagnetic materials. Besides these areas, semiconductor physics will also benefit; for example the observed giant Zeeman splitting effect in (CdMn)Te is due to the exchange interaction of carriers with localised spins (i.e. spins of magnetic ions), and can cause a splitting as large as 100 meV in magnetic fields of 5 T. In the last years the interest in these materials has grown, partly because of their fascinating quantum nature, but also because there is significant potential for technological application. For example the work on ultrathin films and multilayer heterostructures has huge potential for application in hard disk media and in spintronic devices, whilst many bulk materials have applications in energy storage, solid state devices and future technology based on HTSC. These systems are characterised by a complex phase diagram where small changes in a given parameter can drive the system into a rich variety of exotic phases.

## 3. Neutron Scattering and High Fields

*Magnetic field is an important thermodynamic parameter.* The application of a magnetic field can control a phase transition: typical examples include field tuned quantum criticality and field induced superconductivity. Often the field couples directly to a ground or excited state, producing new exotic phases, such as the field induced Bose-Einstein condensation or Luttinger liquid phases in quantum magnets. Although such transformations may be revealed by laboratory magnetometry measurements, neutron scattering is much more incisive; mapping precise ordering vectors and revealing energy and momentum dependence of excitations as well as surface and interface roughness of heterostructures.

*Combining high fields and neutron scattering makes it possible to directly access a system's Hamiltonian.* [1] Even when it does not force a phase transition, an applied field controls the direction of the magnetic moments, resulting in a field-dependence of the: (i) diffraction intensities, (ii) spin-wave stiffness and mode softening, (iii) Zeeman splitting of triplet excitations in quantum magnets, (iv) characteristic wave vector and energy dependences of continua in quantum magnets, as well as (v) surface and interface roughness of heterostructures.

In the past years HMI has driven the limits of neutron scattering research in high magnetic fields from the previously available value of about 11 T to 15 T (in special cases up to 17 T by the use of Dy boosters) [2]. This led to extraordinary experimental results by most renowned scientists from all over the world, working in the fields of magnetism in general [3], superconductivity [4], metal-insulator transitions, Bose-Einstein condensation [5], etc. In macroscopic volumes 15 T field represents a huge energy in mechanical terms, however on the microscopic level it only corresponds to about 15 K temperature or 1.4 meV, very far from the energy scale of many other atomic phenomena such as the eV scale of electronic interactions.

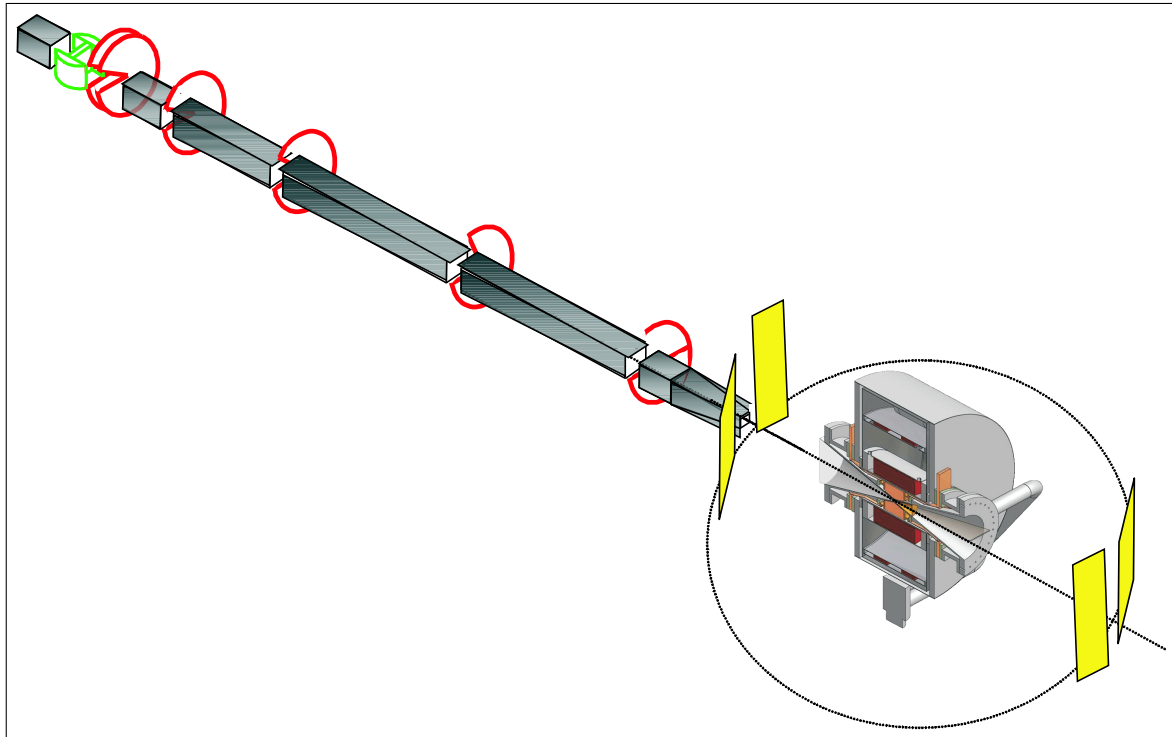
Further extension of the limit of magnetic fields will allow us to study new phenomena through neutron scattering, not yet accessible today and will continue to provide outstanding scientific return on the effort invested, as the relatively modest step from 11 T to 15 T did so convincingly in the past.

The 15 T world record performance was achieved by the conventional design of placing two superconducting solenoids close to each other with a common axis. Between the solenoids there is a small gap for the incoming neutrons on their way to the sample and allowing at the same time the scattered neutrons to come out in a wide angular range. Essentially due to the tremendous stresses in the gap region, for superconducting magnets the split pair magnet design came close to its technical limit at 15 T. For higher fields one needs to use a single solenoid in horizontal position, not a split coil configuration. This geometry severely restricts the range of accessible neutron scattering angles. By tapering the hole around the axis of the solenoid on both ends, scattering angles in the forward direction between 0 and 30 degrees and in the backward direction between 150 degrees and 178 degrees can be achieved, with the range in-between fully blocked. Our detailed technical analysis shows that in this case steady state fields above 30 T can be produced with the new approach of a series connected hybrid magnet system.

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 fraction of a second. However, the duty factor of this type of magnets is well below 1%. This implies a strong reduction of efficiency of their use in inherently intensity limited neutron scattering applications, which in turn restricts the number of feasible experiments to an unacceptable degree. In particular inelastic scattering studies, which proved to be most rewarding, would virtually be excluded when using pulsed magnets. Additional strong disadvantages are the strong decrease in lifetime with increasing field for magnets above 40 T and the necessity to cool the coils to liquid nitrogen temperature prior to every field pulse.

The size and weight of magnets for fields above 25 T and the restricted domain of available scattering angles make their use incompatible with conventional neutron scattering techniques. At HMI we have developed a number of new methods to overcome this difficulty. In view of the reduced angular access the full required neutron scattering parameter space can only be explored by using a very broad band of neutron wavelengths. This will be made available by the novel multispectral beam extraction technique, which can combine both the thermal and the cold neutron spectra in the same beam. On this basis, a ballistic neutron guide delivering an intense neutron beam spectrum stretching over 0.7 - 20 Å wavelengths was built as the centrepiece of the second neutron guide hall at the HMI reactor. HMI has also developed and tested an advanced neutron beam chopper system for variable resolution diffraction work using the time-of-flight principle with a broad wavelength band. This technique opens up the way for unrestricted neutron scattering work at the restricted angular access of the immobile high field magnets. The method can be extended to perform inelastic scattering spectroscopy too, small angle scattering and reflectometry experiments under favourable neutron intensity conditions, always based on the time-of-flight approach. The final commissioning of the instrument ExED will be about spring 2007.

In sum, over the past few years HMI has acquired unique experience with the use of high magnetic fields in neutron scattering research and it has developed the novel neutron scattering techniques needed to accommodate the restricted angular access and mobility of the highest field tapered solenoid magnets conceivable today. It is proposed in this project to use this broad know-how together with state-of-the-art magnet design technology to open up a whole field of new scientific opportunities by realizing the quantum jump of taking the limits of neutron scattering work in high magnetic fields from the current 15 T to above 30 T.



**Figure 1.** One can see a sketch of the beam line with the magnet system. On the left side there is the neutron guide with the Fermi chopper, the double disc chopper, 3 frame overlap choppers and the wavelength band chopper (from left to right). On the right side one sees the hybrid magnet system surrounded by four detectors for forward scattering and backscattering experiments.

#### 4. The Magnet System

The magnetic field at the instrument ExED in our new neutron guide hall will be produced by a high field magnet in the horizontal direction. Fields up to 25 T could in principle be generated by purely superconducting magnets with use of HTSC material. At the moment magnets with geometries necessary for neutron scattering experiments can reach maximum fields of only 22.5 T, because HTSC material cannot be used in superfluid helium.

The second option is the so called "Series-Connected-Hybrid System", which is now planned to be incorporated in the described new neutron instrument in collaboration with the National High Magnetic Field Laboratory, Tallahassee, FL. This system will allow the reduction of running cost to 1/3 compared to a purely resistive approach. Resistive insert coils (Bitter magnets) in the room temperature bore of a superconducting magnet can produce fields above 25 T in the first expansion stage of the hybrid magnet. In the second expansion stage it is planned to reach fields above 30 T by increasing the power. At the maximum field the magnet stores an energy up to 50 MJ. Because of the use of "Cable-in-Conduit" (CIC) conductors it is possible to connect superconducting and resistive coil in series and drive both with the same high current. CIC conductors are approved in the construction of fusion magnets.

In combination with time-of-flight neutron scattering we get the best possible compromise between the needs of neutron scattering and magnet construction.

#### 4.1. Technical needs for the operation of the magnet system

The problem with technical production of highest magnetic fields is the very high current, in the coils. Magnetic fields exert forces on moving charges, and therefore very high forces are affecting conductors with high electrical current. We face the challenge to find materials with extreme stability, which can transport very high current.

At the moment only water cooled, resistive coils can produce fields clearly above 20 T. To reduce high running cost we plan to build a hybrid system to produce part of the field by a superconducting magnet, which then has to be cooled by a liquid helium refrigerator system.

To supply both coils (superconducting outsert and resistive insert coil) of the planned hybrid magnet at maximum field one needs:

- controlled DC current of max. 20 kA (stability: 100 - 500 ppm);
- coil voltage up to max. 400 V;
- electrical power of 8 MW;
- water cooling according to 8 MW for the insert coil.

During the first phase of construction we will realise a hybrid system for the power of 4 MW and maximum field above 25 T in a clear bore of 50 mm. By increasing the power up to 8 MW in the final construction phase fields above 30 T are achievable. Further increase of the power does not result in significant increase of the maximum field.

#### 4.2. Planned user service at the instrument ExED

The user service at the Berlin Neutron Scattering Center is determined by the reactor cycles of the research reactor BER II. This results in a maximum amount of about 5500 running hours per year. To estimate the energy cost one should use a mean value of about 70% of the maximum field. This results in an overall mean value of 2 MW for the electrical magnet power.

### 5. Impact on the Mission of HMI

The instrument ExED with the planned series-connected-hybrid magnet system offers not only experiments in high magnetic fields, but also at low temperatures or high pressures at the same time. In combination with existing measurements of physical properties for sample characterisation, the new experimental capabilities ensure a crucial improvement of the HMI user service. Future top level research will be attracted. In this combination the instrument ExED will be a worldwide unique research instrument. It will enrich structural research with neutrons by results on atomic interaction in condensed matter from model quantum systems or high temperature superconductors to biological systems. There is also potential for development of new experimental methods in structural research, even in materials science.

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