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Neutron scattering in very high magnetic fields with the new hybrid magnet at Helmholtz Centre Berlin

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Abstract. At HZB a dedicated facility for neutron scattering at extreme magnetic fields and low temperatures is close to completion, the new High Field Magnet (HFM) on the Extreme Environment Diffractometer (EXED). To open up higher fields to neutron research HZB follows a new approach with completely different magnet technology. The aim is the construction of a multi purpose instrument which offers diffraction experiments as well as small angle neutron scattering and inelastic scattering. It is projected according to the special geometric constraints of analysing samples in a high field magnet. The potential scientific impact of the HFM-EXED facility is extraordinarily high. Key scientific questions, from unraveling competing interactions in high-T_C superconductors to the chirality of the molecules of life, are eagerly awaiting answers by using the combination of high magnetic fields and neutron scattering.

1. Introduction

Research in high magnetic fields in connection with elastic and inelastic neutron scattering provides a unique experimental tool to further improve our understanding of matter, and paves the way for the discovery of entirely new phenomena, and, subsequently, to the development of future technologies in general. However, to combine both techniques is challenging. Geometrical limitations imposed on the system due to the necessity to have sufficient angular access for the incoming and scattered neutron beam together with budgetary, energy, technological, and other practical constraints (such as the duty cycle and lifetime of pulse-field coils) usually lead to much lower maximum field strengths of magnets used for neutron research as compared to magnets used in specialized high-field facilities.

Up to now, technology that is based on superconducting coils such as Nb_3Sn led to portable magnet units limited to about 17 T capable of being used at different diffraction and/or scattering instruments that in turn can be optimized for a particular type of neutron diffraction/scattering technique. Any further increase of the magnetic field requires a significant modification of the technology. Besides the possibility of using high-temperature superconductor coils (high Tc's) such as YBCO tapes the only two other technologies are resistive magnets or pulsed magnets. While, at reactor sources, the latter can utilize only a negligible fraction of the neutrons that are available in the experiment, the former magnets require an enormous investment in infrastructure, especially in power and cooling systems. These enormous needs for electrical power can be reduced by a combination of a resistive insert with superconducting outsert leading, however, to an even higher degree of overall complexity. This way of producing higher magnetic fields has been selected at HZB. The resulting unique series-connected hybrid horizontal magnet with medium-wide angular access for scattered beams, is very heavy and not transferable to another instrument. Yet, a whole spectrum of scientific problems is expected to be tackled with such a magnet. This is enabled by the multipurpose neutron scattering instrument EXED on which the magnet will be situated that combines diffraction, inelastic scattering, and medium-small angle diffraction techniques.

2. Description of the facility

HZB, in collaboration with the National High Magnetic Field Laboratory, Tallahassee, FL, USA, is currently finalizing a project that combines a dedicated neutron scattering instrument (EXED) with a horizontal solenoid magnet with tapered cones (HFM) [1].

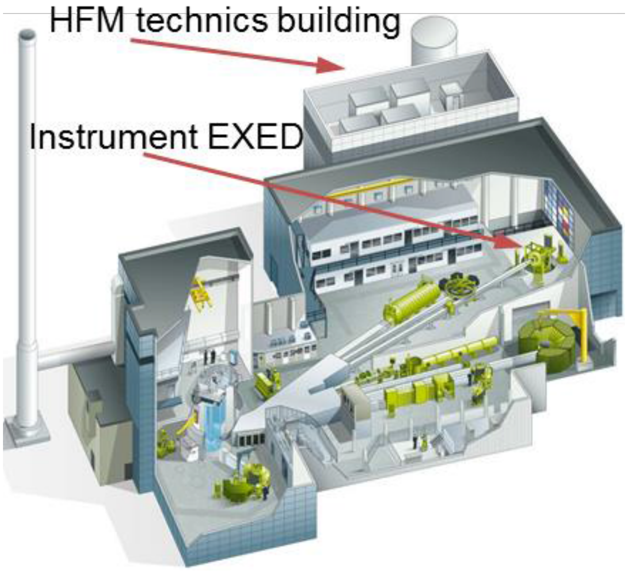

Figure 1. Neutron scattering facilities at HZB with hybrid magnet on instrument EXED

The magnet utilizes series-connected hybrid (resistive insert and superconducting outsert) technology and is capable of producing 25-31 T, depending on the power supplied to the resistive coils which can be between 4.0 and 8.0 MW.

2.1. Extreme environment diffractometer EXED

The EXED instrument is currently a time-of-flight (TOF) instrument optimized for medium-SANS and diffraction under restricted geometrical conditions. An upgrade to increase its signal-to-noise ratio and to implement inelastic scattering capabilities is planned. This unique experimental setup will play a major role in high-field neutron diffraction and spectroscopy. It will also strengthen the leading position of HZB in magnetic field neutron scattering as it will offer by far the highest steady magnetic field for neutron research.

EXED is optimized for conducting powder and single-crystal experiments in restricted angular environments such as under the conditions of HFM, which has 30° neutron access in forward and backward scattering. Until the installation of the magnet, EXED complements HZB's diffraction-instrument suite by providing measurement characteristics typical for pulsed instruments e.g. high resolution in backscattering ($\Delta d/d \geq 10^{-3}$) and large dynamic range (0.4 - >100 Å). Variable wavelength resolution and wavelength band combined with 4 moveable detector banks make the instrument very flexible and continuously adjustable to the requirements of a particular problem. In its current configuration the instrument has no angular restrictions and is used with all types of standard sample environment available at HZB as well as user equipment.

As the design of HFM was further clarified it became clear that the EXED instrument has to cope with the complexity of the whole magnet project that comprises an extended infrastructure. This led to plans for an upgrade of EXED. In addition to improving the diffraction performance (signal-to-noise ratio and full angular coverage), it is especially important to complement the instrument portfolio by inelastic capabilities in the form of a direct time-of-flight (TOF) spectrometer. The upgrade will include four main components:

- an evacuated detector chamber for forward scattering with built-in
- ^{3}He detector array covering 30° in- and out- of plane and positioned 4.5 m away from the sample, and
- a new focusing guide section that accommodates
- a monochromating chopper assembly.

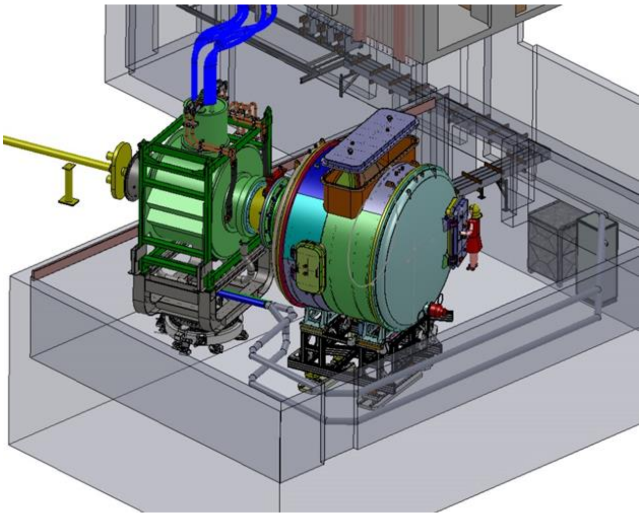

Figure 2. Hybrid magnet and new detector chamber

Limited sample size inside HFM and weak inelastic scattering cross sections imply the need for optimization for signal strength and low background conditions. The former is achieved by enhancing the flux at the sample using a novel focusing guide while the latter is provided by means of a shielded and evacuated detector chamber. After completion, the upgraded EXED will enable energy-resolved measurements over a limited Q-range < 3.25/λ (Å^{-1}) in addition to the existing elastic capabilities.

It is foreseen that all magnet and infrastructure tests will be finalized during the second half of 2014. At the end of this period, the magnet will be installed at the EXED instrument and instrument commissioning will be performed. According to current plans, the first friendly-user experiments could be performed in the second quarter of 2015.

The first experiments will use only the diffraction and small-angle capabilities of EXED. The INS option upgrade is in the phase of preparation and should be implemented in 2015/2016, so that the first INS user experiments could be performed in 2016.

2.2. Hybrid magnet

The new hybrid magnet, a 'first of its kind system' with horizontal field orientation, designed and constructed in collaboration with NHMFL, will not only allow for novel experiments, it will be at the forefront of development in magnet technology for neutron scattering experiments. With a set consisting of a superconducting cable-in-conduit coil and different resistive coils of conical shape at both ends of the system, maximum fields between 25 T - 31 T will be possible with cooling power between 4 MW - 8 MW for the resistive part.

A sectional view of the magnet system is pictured in Fig. 3. The primary technical parameters are provided in Table 1.

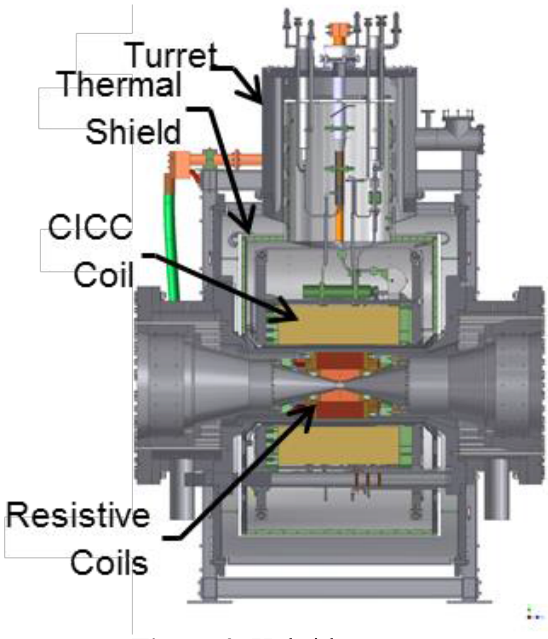

Figure 3. Hybrid magnet system

Table 1. Magnet specification data

Hybrid Magnet Operating Parameters	
Central field	26 T
Power resistive coil	4 MW / 8 MW
B resist. 4 MW / 8 MW	 13 T / 18 T
B supercond.	13 T
Warm bore (center)	50 mm
Scattering angle	30°
Operating current	20 kA
Ramp time	30 min
System height	~ 5 m
Total weight	~ 25 t
Cold mass	~ 6 t

The resistive coils in the center have a conically shaped inner diameter to conform to the bore. It is series connected to a single superconducting coil with Nb_3Sn CICC conductor. The entire magnet system has the bore horizontal so it can align with the neutron beam axis. In addition, the magnet system will sit on an instrument table so it can rotate +/- 15° for exposure of samples to the neutron beam.

All cryogenic and electrical utilities port through an upper “turret” for interface with the technical utilities. The thermal shields are cooled via the helium refrigerator at nominally 40 K.

A large part of the functional requirements of the cryostat stem from the electromagnetic interactions between the superconducting and resistive coils. Features are designed to accommodate potential axial and radial misalignments and axially offsetting fault forces created from a fast shut down of the resistive coils.

For the first project phase a continuous ^3He cryostat combined with a closed cycle precooling cryostat is planned for sample cooling. The sample cryostat is a separate independent unit which has to be inserted into the magnet cone.

Another option is to remove the inner coil altogether and keep just the superconducting outsert, which would provide a field of 13T over a large warm bore of almost 0.5m diameter at almost zero electrical cost. This feature of the magnet is truly unique. No other magnet has such a large available space. It should be mentioned that the large warm bore of HFM would allow complex sample environments. Usually only 1 or 2 sample environments are used together during any particular measurement e.g. temperature and magnetic field. Here the large available space allows magnetic fields of 13T to be used simultaneously with temperature, pressure, electric field, laser light, etc. Of particular importance are Paris-Edinburgh pressure cells. The higher pressure cells are too bulky to be placed inside available magnets preventing the combination of field with pressures above ~2.5GPa.

Uniquely this magnet is able to accommodate the larger Paris Edinburgh cells allowing pressures of up to 30 GPa with 13T magnetic fields at low or high temperatures.

Another task of the project HFM-EXED, is the design, construction, and installation of the technical infrastructure for safe and reliable operation of the magnet system during user service. The construction, installation, commissioning and test activities of the building for the three big infrastructure components needed for magnet operation, high-pressure water cooling for the resistive coil, 4 K helium cooling of the superconducting coil and 20 kA power supply were complete by end 2013.

The installations of a control system for the operation of the magnet along with the technical infrastructure and the neutron instrument EXED were finished.

3. Magnet system assembly

The system assembly was an international achievement with the cold mass being completed at the NHMFL in the USA, cryostat to cold mass interfaces made at Criotec Impianti in Italy, and final assembly at the HZB in Germany.

Fabrication of the superconducting cable-in-conduit coil and cold-mass assembly was completed at the National High Magnetic Field Laboratory. The cold mass then was transported to Criotec Impianti in Italy where Paschen and leak tests were conducted as part of acceptance qualifications and the major components of the cryostat were assembled around it. Subsequently, the coil with cryostat was transported to the “magnet assembly and test hall” at the HZB for the final assembly. After rotation to have the magnet axis horizontal, the remaining assembly tasks including all cryogenic and electrical utilities were completed.

Figure 4. Cold mass

Figure 5. Assembly of vacuum container around cold mass

Figure 6. Rotation of magnet to orient magnet axis horizontal

The fabrication of the resistive coil was completed at NHMFL in January 2014. The installation in the room temperature bore of the magnet cryostat was completed by end May 2014 as the last step of system installation.

4. Magnet commissioning and test

After completion of the last assembly task the system was connected to all infrastructure facilities and to the data acquisition and control systems and the testing was started with the resistive coil alone.

All operating data (coil stress and cooling performance) were in agreement with our expectations. On June 23 the full field of 13.1 T at 20 kA and 4 MW was attained for the first time.

The next step was the connection of the superconducting coil to the He refrigerator via the flexible transfer lines and the cool down of the 6 t cold mass to 4 K. The base temperature was reached on August 8. Since then the full hybrid system commissioning was performed. At first a complete check of all interfaces and data acquisition systems of the central control system was executed. The checks of the system safety include the interlocks of all peripheral systems for the operation of the power supply and the adjustment and fine tuning of the coil protection systems for the resistive and superconducting coils. With increasing system current the performance data have to be verified and for each limit overrun of operating data the emergency shutdown procedures have to be tested. The impact on the operation of all system components for the magnet and the technical infrastructure needs to be checked.

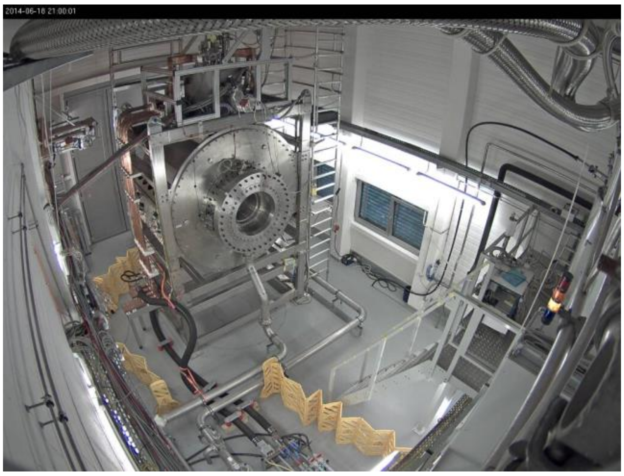

Figure 7. Series-connected hybrid magnet under test

On 16 October 2014 the full field of the hybrid system of 26.28 T at the maximum design current of 20 kA was reached for the first time. The system operates stable within the calculated operational parameters.

To conclude, the HFM-EXED facility is a unique combination of a hybrid magnet dedicated to and optimised for neutron scattering offering the highest static magnetic fields for neutron science in the world. The field is much higher than those available elsewhere and will remain so for years.

References

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