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HFM/EXED: The High Magnetic Field Facility for Neutron Scattering at BER II

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Abstract: An overview of the high magnetic field facility for neutron scattering at Helmholtz-Zentrum Berlin (HZB) is given. The facility enables elastic and inelastic neutron scattering experiments in continuous magnetic fields up to 26.3 T combined with temperatures down to 0.6 K.

1 Introduction

HFM/EXED – the high magnetic field facility for neutron scattering Figure 1 - consists of two main components: the High Field Magnet System (HFM) and the Extreme Environment Diffractometer (EXED) (Lieutenant et al., 2006; Peters et al., 2006; Prokhnenko et al., 2015; Smeibidl et al., 2010). The former is a continuous field hybrid magnet, built by the HZB in collaboration with the National High Magnetic Field Laboratory, Tallahassee, FL, USA (NHMFL) (Smeibidl et al., 2016). The latter is a time-of-flight instrument optimized for neutron scattering in the restricted angular geometry of the magnet. The facility has been installed in the second guide hall of the BERII research reactor and commissioned in the first half of 2015.

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The High Field Hybrid Magnet System

The HFM is a "first of its kind" hybrid system which is capable of reaching magnetic fields up to 26.3 T, making it by far the strongest continuous field available for neutron scattering experiments worldwide (Smeibidl et al., 2016). It is a series-connected magnet system with an outer superconducting coil and two inner resistive coils (Bird et al., 2009; Smeibidl et al., 2010). The total field of 26.3 T is achieved with a 4 MW insert coil set, which has the potential to be upgraded to 8 MW and a total field of 31 T. The magnet is designed taking into account the special geometric constraints of performing neutron-scattering experiments. As a result, the inner resistive coil provides a conical bore at each end to allow neutron-scattering to detectors up to $\pm15°$ off the field axis. The superconducting coil is a 13-Tesla, 500-mm cold bore coil consisting of Nb_3Sn cable-in-conduit conductor (CICC) and weights 5 tons (6 tons full cold mass including flanges, joints and piping) (Bonito Oliva et al., 2008; Dixon et al., 2009, 2010). The magnet central bore is horizontal so that it can align with the neutron beam axis. In addition, the magnet system sits on an instrument table so it can rotate $\pm15°$ for increased neutron scattering-angle. All cryogenic and electrical utilities port through an upper “turret” for interface with the supply systems (Dixon et al., 2015). The main technical parameters are listed in Table 1 and a vertical section of the magnet system is shown in Figure 2a.

Central Field	26.3 T (31) T
Bore	50 mm horizontal
Opening Angle	30°
Power Resistive Insert	4 MW (8 MW)
Field Homogeneity	< 0.5% (15 mm x 15 mm)
Operating Current	20 kA
Magnetic Field of Resistive Insert	13 T – 18 T (4 MW / 8 MW)
Magnetic Field of Superconducting Coil	13 T
Height	~5 m
Total Weight	~25 t
Cold Mass	~6 t

Table 1: Hybrid magnet system operating parameters.

Operation of the magnet system requires a dedicated technical infrastructure located in the separate technical building for the HFM beside the neutron guide-hall Figure 1a. The He-refrigerator system for the CICC coil and the 8 MW power supply as well as the high pressure water circulation required to cool the resistive insert magnet were constructed using standardised industrial components.
A specially designed horizontal continuous flow ^{3}He-sample-cryostat allows combining high fields with temperatures as low as ~0.6 K. The vacuum container of the cryostat has the shape of the magnet cone (Figure 2b). The sample size cross section inside the cryostat is limited to about 13 x 13 mm^2.

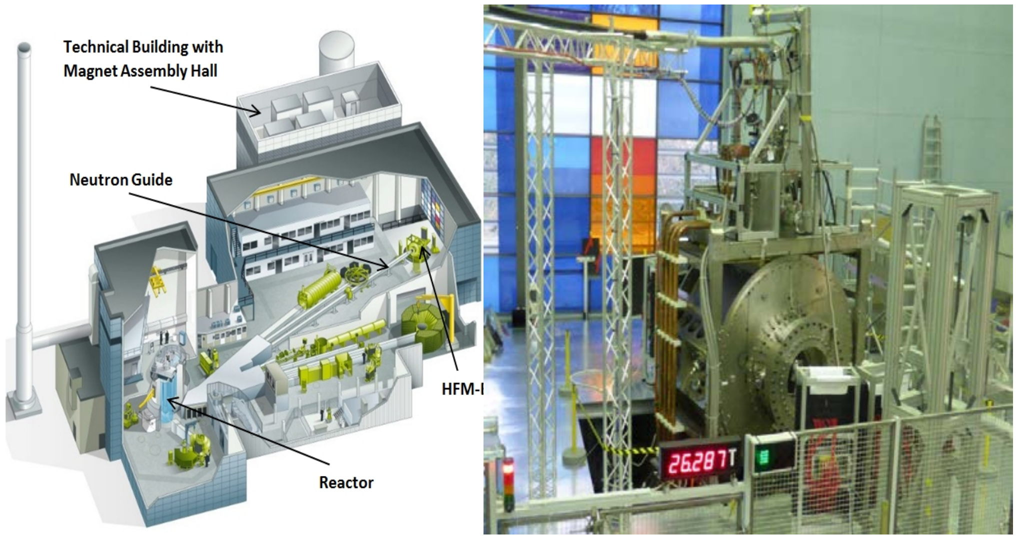

Figure 1:
a) BERII reactor, neutron instrument halls and HFM technical infrastructure building at the Helmholtz-Zentrum Berlin with the HFM/EXED facility.
b) Photograph of the HFM/EXED facility showing the magnet and the EXED instrument components around (neutron detectors and guide lifting device).

The Neutron Instrument EXED

The EXED shown in Figure 3 is a dedicated neutron instrument optimized to work with the restrictions imposed by the magnet geometry (Lieutenant et al., 2006; Peters et al., 2006; Prokhnenko et al., 2015) [2-4]. To achieve that it utilizes polychromatic (time-of-flight) technique. Equipped with a bispectral extraction system, EXED has an access to broad wavelength range. The supermirror guide (m = 1-3) with a cross section 100x60 mm^2 (H x W) transfers the neutrons from both thermal and cold moderators to the sample position located about 75 m away from the source (Figure 3). Before reaching the sample the neutron beam is compressed spatially in both directions by a factor of two by means of an elliptically converging focusing guide section. For applications requiring low beam divergence, the focusing section can be replaced by a pin-hole collimation section with variable apertures.

Flexibility of the primary instrument is ensured by three alternative systems that are available to create neutron pulses: a curved Fermi chopper for very high resolution (neutron pulse width, Δt ~6 μs at 600 Hz), a straight Fermi chopper for high resolution (Δt ~15 μs at 600 Hz) and a counter- or parallel-rotating double-disc chopper for medium to low resolution (Δt ~125 μs at 200 Hz). A number of single disc choppers (5-120 Hz) located downstream prevents the frame overlap and defines the bandwidth of interest. The chopper system allows operating the instrument with different wavelength bands, from narrow (~0.6 Å) to wide (~14.4 Å), centred at the region of interest, and easily trade resolution for intensity.

The secondary instrument is equipped with 12.7 mm diameter position-sensitive ^{3}He detector tubes. The effective length of the tubes is 0.9 m and position resolution is 1%. The tubes are combined in 4 detector banks that are positioned in forward- and backward scattering to reflect the geometry of the magnet. The typical sample-detector distance is about 2.5 m. A large Ar- or He-filled detector chamber allows positioning of two detector panels at 6 m away from the sample avoiding air scattering. Technical instrument characteristics are summarized in Table 2.

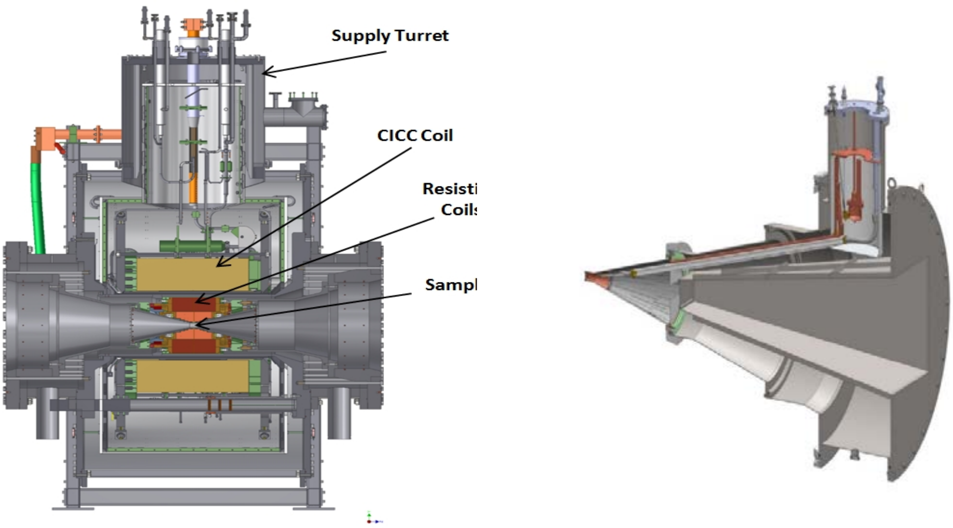

Figure 2:
a) Cross-section through HFM showing the superconducting CICC coil and resistive insert coils. The cryogenic and electrical utilities enter through the upper supply turret.
b) Dedicated ^{3}He sample-cryostat that can be installed into one of the magnet cones to combine high fields with low temperatures.

Modes of Operation
In order to enable a broad range of scientific applications using unique combination of neutron scattering and high magnetic fields, EXED has several modes of operation which are described below.

Elastic Neutron Scattering is represented by diffraction and low-Q modes. The former is the main mode at the moment and is used to study single crystal and powder samples in high fields. The mode is characterized by high resolution in backscattering ($\Delta d/d \geq 2{\cdot}10^{-3}$) and large dynamic range (0.5 – 100 Å). The low-Q mode offers small angle scattering capabilities. It extends the low Q-range beyond 10^{-2} $Å^{-1}$ using a 6 m-long pin-hole collimation combined with sample-detector distance of 6 m. The latter enables studies of matter on mesoscales in high magnetic fields such as e.g. vortex state in type-two superconductors.

Inelastic Neutron Scattering: A major development took place to complement the instrument portfolio by inelastic capabilities turning EXED into a direct TOF spectrometer (Bartkowiak et al., 2015). The upgrade includes an evacuated detector chamber for forward scattering with a built-in ^{3}He detector array covering 30° in- and out- of plane and positioned 4.5 m away from the sample, a new focusing guide section that accommodates a monochromating chopper assembly and an inelastic doppler system which is at 2.5 m distance from the sample, the upgraded EXED will enable energy-resolved measurements over a limited Q-range < $3.25/\lambda$ ($Å^{-1}$) and energy range < 25 meV in addition to the existing elastic capabilities.

2 Instrument application

Typical applications are:

- Quantum magnets and quantum phase transitions
- Superconductivity
- Multiferroic and magnetoelectric materials
- Correlated electrons in 3d, 4f and 5f metal compounds

- Spin, charge and lattice degrees of freedom in transition metal oxides
- Frustrated magnets
- Novel states of matter

3 Instrument layout

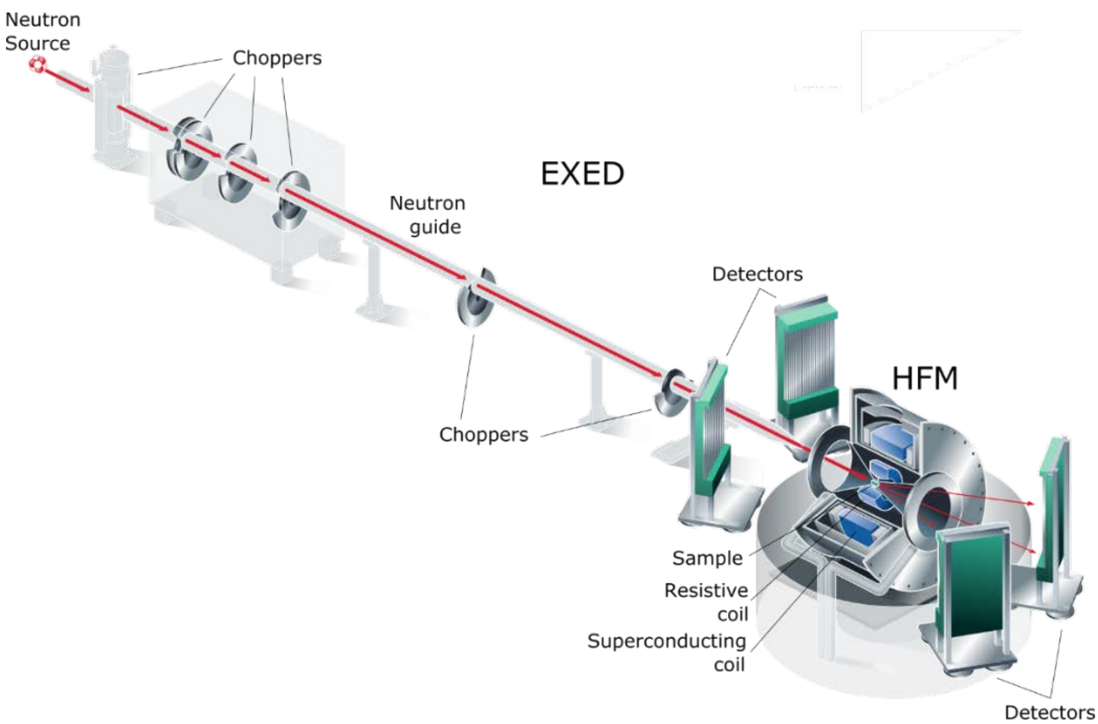

Figure 3: Schematic view of HFM/EXED.

4 Technical Data

Beam tube	NL 4A, 75 m long ballistic multispectral guide: a straight section (60 x 100 mm^2) with a kink and a 7.5 m long focusing section at the end (elliptically tapered down to 30 x 50 mm^2)
Collimation	i) None (standard configuration with the focusing guide) ii) 6 m long pin-hole collimation (low-Q configuration without the focusing section)
Wavelength	$0.7 < \lambda < 15$ Å
Flux	~10^9 n/cm^2/s - continuous flux
Range of scattering angles	Elastic 0 – 30°, 150° – 170° Inelastic 0 – 30°
Range of lattice spacing	Forward scattering: 1.5 < d < 1000 Å Backward scattering: 0.5 < d < 7 Å
d-resolution	Forward scattering: $\Delta d/d > 2 \cdot 10^{-2}$ Backward scattering: $\Delta d/d \geq 2 \cdot 10^{-3}$
Sample size	<13 x 13 mm^2
Detector	192 ^{3}He linear position sensitive detectors combined in 4 sections, each containing 48 detector tubes of 900 mm effective length and 12.7 mm diameter
SInstrument options	Elastic: Diffraction; Low-Q Inelastic: direct TOF spectrometer (under construction)
Sample environment	B = 26.3 T (B||ki ± 15°) T = 0.6 K – RT
Software	Egraph (event recording data reduction) Mantid (TOF data reduction)
Chopper speed range	5 – 600 Hz (Fermi chopper) 5 – 215 Hz (double disc choppers) 5 – 120 Hz (single disc choppers)
Sample-detector distance	2.5 - 6 m

Table 2: Technical parameters of HFM/EXED.

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