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HESEB Soft X-ray Beamline ID11-L at SESAME: Performance and First User Experiments

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Abstract. The ID11-L HESEB Soft X-ray beamline and end station significantly enhance soft X-ray research capabilities. Operating in an energy range of 90–1800 eV, extendable to 70–2000 eV, the beamline achieves high performance with an energy resolution of $E/\Delta E > 8000$ and a photon flux of 10^{10} to 3.4×10^{12} photons/s. Its $500 \times 250\ \mu m^2$ beam spot size allows for precise measurements, including studies on magnetic materials using variable circular polarization. This paper presents the end station's design, including the receptacle, magnetic sample holder, and ambient pressure capabilities, along with experimental results that demonstrate the beamline's potential for diverse scientific applications.

1.Introduction

The ID11-L HESEB (Helmholtz-SESAME Soft X-ray Beamline) is the first soft X-ray beamline in the Middle East, funded and implemented by the Helmholtz Association. Five Helmholtz research centers—DESY, HZB, HZDR, FZJ and KIT—collaborated with SESAME to design the beamline in cooperation with FMB Berlin, who finished construction and installation in 2022. A key component, the undulator source, was donated by HZB and

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specifically refurbished for this beamline. Currently, HESEB features a soft X-ray absorption spectroscopy (XAS) end station. The first call for research proposals came in September 2023, and user operations began in February 2024. The beamline employs an APPLE II-type UE56 undulator and a plane grating monochromator (PGM) with 400 and 1200 grooves/mm gratings, plus a secondary mirror for beam branching. Further instrumentation details are available in [1]. A second branch, funded by the Turkish government, is under development and includes an X-ray Photoelectron Spectroscopy (XPS) end station. The project is carried out collaboratively by Bilkent University, Koç University, TARLA, and TENMAK.

This paper introduces the HESEB End Station and showcases its capabilities, including performance and first experimental data. Energy calibration and resolution were verified via the N_2 1s to π* electronic transition, while photon flux and beam size were measured using a photodiode. Example applications include XAS total electron yield measurements of h-BN powder and X-ray Magnetic Circular Dichroism (XMCD) studies.

2. Beamline Performance

2.1 Energy resolution and calibration

The HESEB beamline's energy calibration and resolution were assessed using the Franck-Condon features of N_2 gas. An ionization chamber filled with grade 4 N_2, positioned between the exit slit and refocusing mirror, was employed for this purpose. To monitor incident beam intensity (I_0), the photocurrent was measured from an 85% optically transparent gold mesh placed between the exit slit and ionization chamber, allowing accurate correction of beam intensity fluctuations during measurements. Beamline parameters were kept constant: the undulator gap was set at 32.5 mm, the aperture size was 3×3 mm^2 (horizontal × vertical), the 1200 grooves/mm grating of the PGM was used, the magnification parameter (Cff) was 10, and the exit slit aperture was 25 μm.

Figure 1a shows the characteristic 1s→π* transition peaks of N_2, used to evaluate energy resolution. These measurements confirm the beamline's high-resolution spectroscopic capabilities. Peak deconvolution, following a method in the literature [2], involved 9 Voigt peaks with fixed line widths, yielding a Lorentzian line width of 115 meV (FWHM) and a variable Gaussian line width, determined to be 50 meV at around 401 eV. This corresponds to an energy resolution ($E/\Delta E$) better than 8000, demonstrating the beamline's precision. Peak positions used for energy calibration aligned closely with values documented in the literature [3].

2.2. Photon flux and Beam size

Photon flux measurements at the HESEB beamline were conducted using an AXUV100G photodiode (Opto Diode) mounted on the manipulator inside the experimental chamber. Beamline parameters remained constant: a 3×3 mm^2 (hxv) aperture, 1200 grooves/mm grating, Cff of 10, and a 25 μm exit slit, optimized for energy resolution. The PGM was tuned to the undulator harmonic peak, and photocurrent readings were converted to photon flux using the photodiode's responsivity of 0.27 A/W, normalized to the standard 300 mA synchrotron current at SESAME.

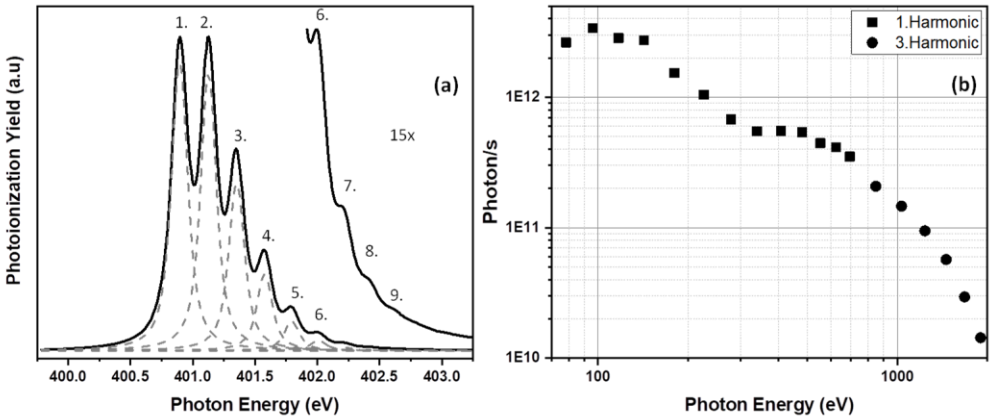

Figure 1. (a) Franck-Condon features of the 1s→π* transition in N_2 gas measured in the HESEB ionization chamber with a fixed undulator gap, 3×3 mm^2 aperture, Cff = 10, and 25 μm exit slit. (b) Photon flux measured for the respective maxima of the undulator harmonics.

Figure 1b shows the photon flux versus energy, indicating a decrease above 300 eV, likely due to carbon buildup on optical elements. Below 750 eV, measurements used the first undulator harmonic, while above 750 eV, the third harmonic optimized photon flux. The HESEB beamline spans 90–1800 eV (extendable to 70–2000 eV), delivering flux from 10^{10} to 3.4×10^{12} photons/s under these settings. Knife-edge scans determined the beam size as 500 × 250 μm^2 (h x v), when the beamline parameters were set for the energy resolution (E/ΔE) better than 8000, Cff was 10, using 1200 grove/mm and exit slit gap was 20μm.

3. HESEB end station

3.1 Chamber and Differential pumping capability

The HESEB end station features an analysis chamber developed at DESY, equipped with a motorized manipulator and an X-ray fluorescence detector. It connects to a load lock and pumping unit, both isolated by gate valves, and accommodates large samples up to 10×10×5 cm^3, suitable also for items which cannot be modified like cultural heritage artifacts. Figure 2 shows the HESEB analysis chamber, load lock, front end, and fluorescence detector. The entrance includes a slot for an optical capillary, which focuses the beam down to 20 μm at 5 mm beyond its exit (details in [1]). The figure also indicates the beam direction and positions of the capillary and manipulator.

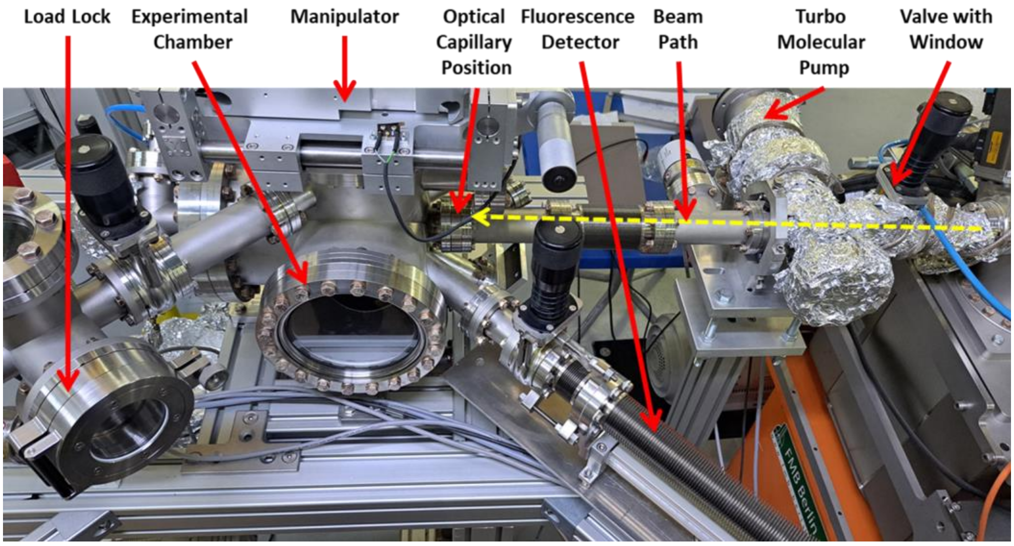

Figure 2. Close-up of the HESEB analysis chamber.

The optical capillary's differential pumping capability was tested with helium. When the chamber was pressurized to 1 bar of helium, the pressure between the capillary and window valves remained at 10^{-6} mbar, demonstrating that the chamber can operate in a 1-bar helium atmosphere, making it suitable for vacuum-sensitive samples such as in cultural heritage research.

3.2 Manipulator and Receptacle Part

The motorized manipulator at the HESEB end station, an HPM300 from Omnivac, provides four degrees of freedom: movement along the x, y, and z axes, plus rotation around the y-axis, with a reproducible motion resolution of 1 µm. The sample holder receptacle, shown in Figure 3a, was fabricated at FZJ and is made of stainless steel, electrically isolated and thermally conductive due to anodized alumina. It connects to a hollow arm tube serving as a liquid nitrogen reservoir. The receptacle includes three specialized slots:

a) Cooling Slot: Positioned nearest to the liquid nitrogen reservoir, it holds a 14×14 mm^2 sample holder. A thermocouple at the back measures temperature, reaching a minimum of 170 K after 3 hours of LN_2 exposure.

b) Magnetic Slot: Designed for a 20×20 mm^2 sample holder, it features an electromagnet from FZJ capable of producing a magnetic flux up to 180 mT. A thermocouple on the electromagnet (Figure 3a, upper right part of the magnetic slot) recorded a minimum temperature of 200 K after 3 hours of LN_2 cooling.

c) Heating Slot: Accommodates a 14×14 mm^2 sample holder and includes a button heater (HT-02 from Momentive Technologies) capable of reaching 1000°C in air.

The receptacle also integrates a photodiode (AXUV100G from Opto Diode) for diagnostics and a knife-edge scan mechanism for beam profiling.

Additionally, the HESEB end station includes a sample holder designed at FZJ, generating an in-plane magnetic field of approximately 1 T using permanent magnets, ideal for XMCD measurements on samples with in-plane magnetic domains. Figure 3b shows the assembly and magnetization axis direction. The magnet accommodates samples up to 2×2 mm^2 and is compatible with both the cooling and heating slots.

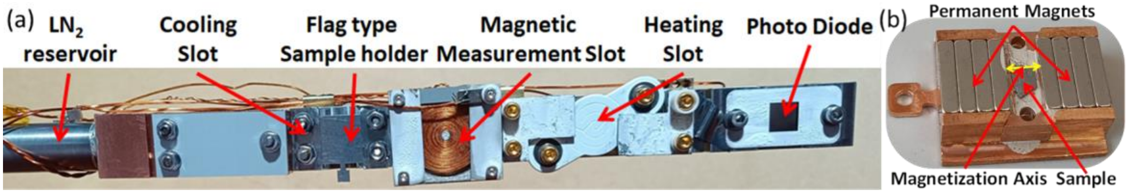

Figure 3. (a) Receptacle featuring designated slots. (b) Sample holder assembly for applying an in-plane magnetic field.

4. Total electron Yield (TEY) and XMCD Examples

4.1 TEY Example: h-BN Spectra

The HESEB end station's performance was validated through XAS measurements on commercially available hexagonal boron nitride (h-BN) powder from Merck, using the TEY detection method. The drain current from the refocusing mirror (M4) was used for incident beam flux (I_0) correction to compensate for fluctuations in beam intensity. Figure 4a and b display the B and N K-edge XAS spectra, respectively, which align with literature values [4]. The 1s to π^* electronic transitions were observed at 191.9 eV for Boron and 401.8 eV for Nitrogen, confirming the accuracy of the energy calibration and the system's capability for reliable XAS measurements.

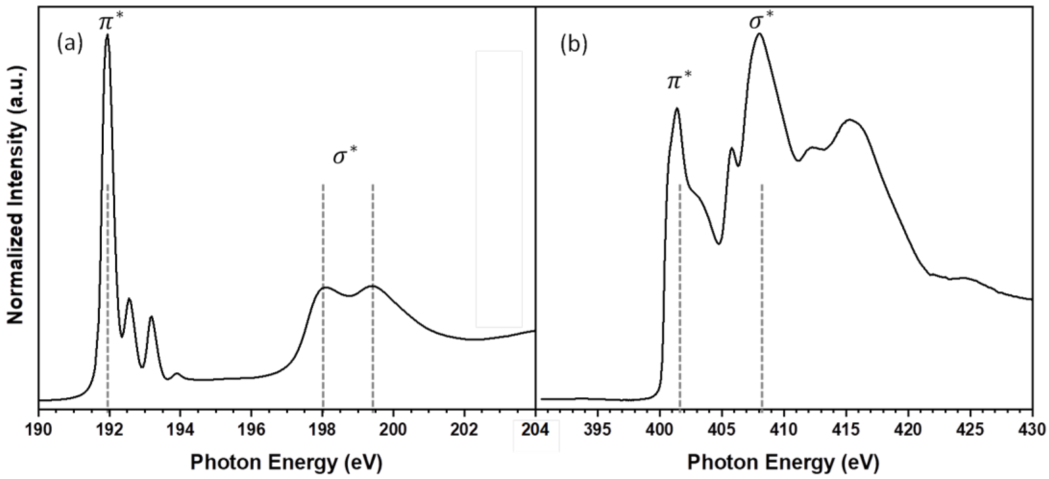

Figure 4. Total Electron Yield data of h-BN at (a) Boron K-edge and (b) Nitrogen K-edge

4.2 XMCD Example: Gd $M_{4,5}$ Edge

As an example of XMCD measurement, a magnetic compound produced at FZJ was studied. The beamline parameters were: undulator gap of 34 mm, undulator shift of ±19.80 mm, 3×3 mm^2 aperture, Cff value of 10, 1200 grooves/mm grating, and a 25 µm exit slit, using the third harmonic. A magnetic sample holder, designed for an in-plane magnetic field (Figure 3b), was used. Absorption was measured via the Fluorescence Yield technique with a Silicon Drift Detector (XFlash, Bruker) detecting the Gd Mα line at 1185 eV.

Figure 5 shows the X-ray absorption spectra and XMCD signal for the gadolinium-based compound at the $M_{4,5}$ edges. Spectra were taken with the beam at a 50° angle to the sample's surface normal, with the photon spin reversed by changing the undulator shift from +19.80 mm to -19.80 mm. In Figure 5a, normalized absorption spectra for both right and left circular polarization reveal peaks at the $M_{4,5}$ edges (3d→4f transitions) around 1183 eV and 1213 eV. Weak features beyond the main peaks are consistent with the GdNi alloy literature [5]. Figure 5b shows the XMCD signal, derived by subtracting the absorption spectra, displaying significant positive and negative peaks at the M_5 and M_4 edges, indicating a net magnetic moment in the 4f states of gadolinium.

The XAS and XMCD data agree well with previous studies [5, 6], confirming the HESEB undulator's ability to produce circularly polarized light, essential for magnetic materials research.

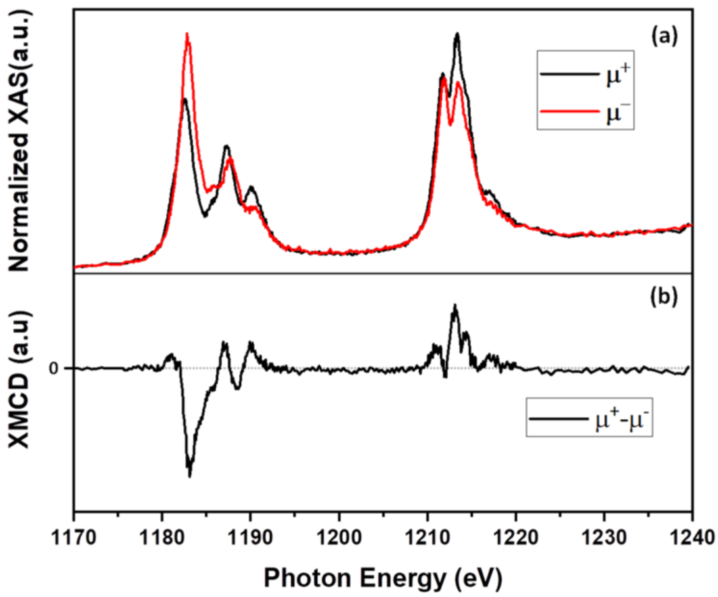

Figure 5. (a) Fluorescence yield XAS data of the Gd $M_{4,5}$ edges, and (b) the corresponding XMCD data obtained from the measurement.

5. Conclusion

The ID11-L HESEB beamline is now fully operational, covering an energy range of 90–1800 eV with a photon flux of 10^{10} to 3.4×10^{12} photons/s, a beam size of 500×250 μm², and an energy resolution of $E/\Delta E > 8000$. Its high performance makes it well-suited for a broad spectrum of research fields, including cultural heritage studies, magnetic materials, and catalysis.

6. Acknowledgment

We would like to express our sincere gratitude to Yishui Zhou, Jülich Centre for Neutron Science at the Heinz Maier-Leibnitz Zentrum, Munich, Germany, for the production of Gd containing magnetic sample used in to demonstrate XMCD measurement capability of the HESEB beamline

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