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XMCD microscopy with synchronized soft X-ray and laser pulses at PETRA III for time-resolved studies

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Abstract. We present the setup of a new transmission X-ray microscope using zone plates at the soft X-ray beamline P04 at PETRA III, designed to utilize the X-ray magnetic circular dichroism (XMCD) contrast for imaging the magnetic orientation of nanostructured materials. We present the first results obtained with this setup at PETRA III using vacuum chambers with built-in multi-axis micropositioning stages that can be easily customized to mount a variety of components like condenser, samples, coils, zone plates etc. For further experiments the X-ray microscope will be equipped with a synchronized femtosecond laser system to implement a time-resolved detection of transient magnetic states in nanostructured media using a pump-probe scheme. The synchronization between laser and X-ray pulses has already been demonstrated at both the P04 and P11 beamlines at PETRA III with a jitter of $\sigma < 15$ ps.

1. Motivation and introduction

Studying nanoscale magnetic systems at their fundamental time- and length-scales is a fascinating and important research field with many applications in modern data storage technology. The performance of magnetic storage devices in terms of access times, data-density and stability may increase even more in the future with the development of new storage materials and ultra-fast physical mechanisms allowing the manipulation of magnetic nanostructures with femtosecond laser pulses [1–4]. Furthermore, the understanding of the fundamental physical properties and limitations in these processes may greatly contribute to the development of future computer concepts using magnetic nanostructures or even atoms instead of electronic elements as logical units (spintronic devices) [5, 6] or non-volatile memory technology [7–9].

Soft X-ray microscopy is a powerful and widely-used tool when it comes to imaging of magnetic nanostructures [10, 11] because it offers sufficient spatial resolution of a few 10 nm and it can be implemented in a pump-probe setup to add temporal sensitivity. Additionally,



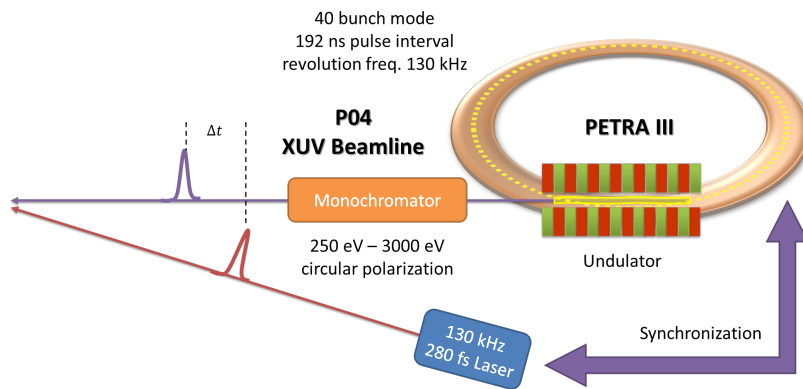


Figure 1. Schematic of the laser pump and soft X-ray probe experiment with a synchronized pulsed laser system at the P04 beamline of PETRA III at DESY.

soft X-ray microscopy enables a simultaneous detection of the magnetization via X-ray magnetic circular dichroism (XMCD) spectromicroscopy [12]. This contrast mechanism originates from the partly filled $3d$ shell of the transition metal elements because a difference in density of final states $\rho(E_f)$ in a magnetized medium acts as a detector for the magnetization component parallel to the propagation direction of the photons. For either spin-up or spin-down polarized electrons excited out of the initial $2p$ shell by the circular polarized light field [13, 14] the transition rate changes.

2. Experimental Setup

For time-resolved measurements, a magnetic system is excited by an ultrashort laser pulse and the magnetic response is successively probed by a soft X-ray pulse in the full-field transmission X-ray microscope (TXM). To perform a pump-probe experiment, the delay Δt between the pulses can be tuned electronically (figure 1).

The sample used here consists of cobalt-platinum (Co/Pt) multilayers with perpendicular magnetic anisotropy structured by electron-beam lithography and lift-off processing on a 200 nm thick silicon nitride (Si_3N_4) membrane.

The vacuum chambers in this experiment are part of an endstation system which can be adapted for different applications in, for example, imaging, spectroscopy or nonlinear physics at synchrotron radiation facilities, free-electron lasers (FEL) or in a laboratory. It features up to three vacuum chambers on a rail with viewports and large rectangular flanges for accessing the inner components (figure 2). The micropositioning stages inside can hold a variety of components like condenser, samples, coils, zone plates etc. and are designed for long travel ranges and high precision positioning.

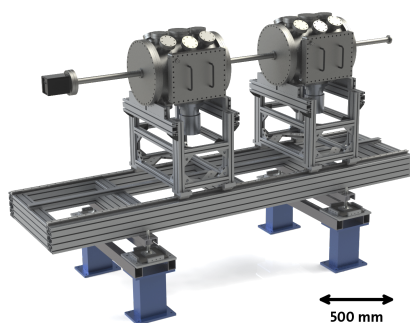


Figure 2. CAD image of the modular vacuum system.

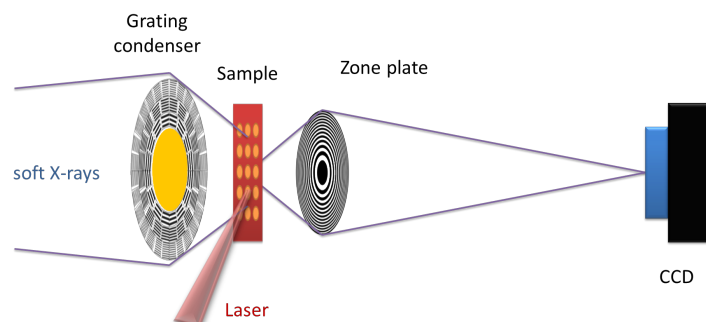


Figure 3. Setup of the TXM consisting of a grating condenser with gold central stop and a micro zone plate.

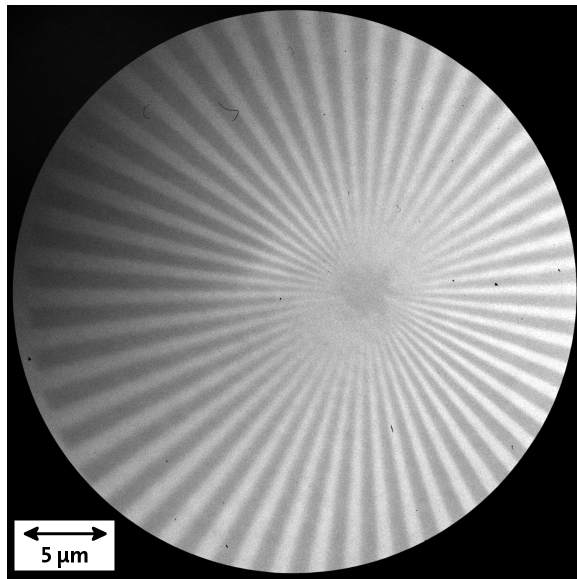


Figure 4. Siemens star with transmission of $\approx 75\%$, diameter of $D = 40\ \mu\text{m}$ and $n = 50$ spokes imaged with the TXM (dark image subtracted).

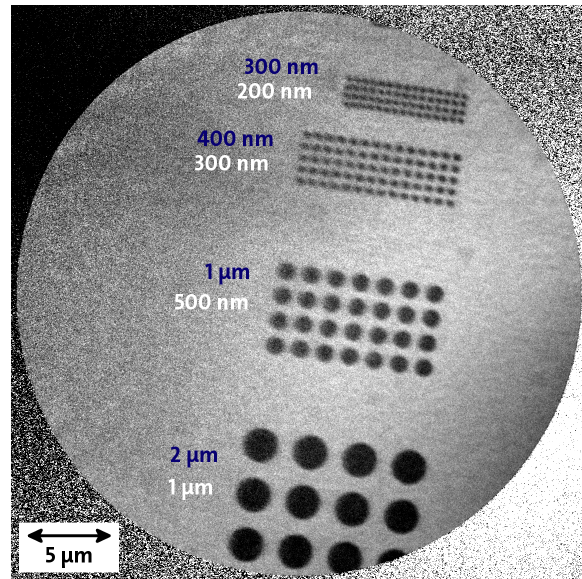


Figure 5. Flatfield corrected TXM image of a nanostructured magnetic cobalt-platinum (Co/Pt) multilayer system. The blue labels indicate the dot diameter while the white labels specify the minimum distance between two dots.

To investigate magnetic nanostructures, a full-field TXM based on a grating condenser [15] for Köhler-like illumination with an included gold central stop, a micro zone plate and a soft X-ray CCD (figure 3) has been set up and commissioned. The theoretical resolution of the microscope operating at the cobalt L_3 edge (778 eV) with 660X magnification is limited to $\Delta l = 1.22 \cdot \Delta r = 61\ \text{nm}$ according to the outermost zone width of the micro zone plate measuring $\Delta r = 50\ \text{nm}$. For best imaging results, the numerical apertures of condenser and zone plate are matched.

A phase-locked loop (PLL) synchronized chirped pulse amplification (CPA) laser system has been set up based on the commercial diode-pumped Yb:KGW laser PHAROS operating at a high repetition rate of 130 kHz (equal to the revolution frequency of the storage ring PETRA III) with a pulse duration of 280 fs and an output power of 6 W. The fundamental output wavelength of 1030 nm can be converted into the spectral range of 210 nm - 2700 nm via harmonic generation or optical parametric amplification (OPA). The laser system is mounted onto a mobile laser table with a footprint of only 1.2 m x 0.9 m.

3. Results

The TXM has been set up and tested successfully and in the first images (figure 4 and 5) features down to 130 nm can be resolved. The discrepancy to the expected theoretical resolution of 61 nm can be explained by drifts based on mechanical instabilities that have been overcome by now and an improved resolution could be demonstrated in a recent beam time (data not shown). The remaining gradient in the illumination in figure 4 was due to a misalignment of the condenser optic but can be fully eliminated via flat field correction.

As depicted in figure 6, the synchronization of the laser system has been demonstrated at beamline P11 with a residual jitter of $\sigma < 15\ \text{ps}$ (presumably limited by the photodiode) by measuring the delay of ≈ 7000 shots of the laser and the synchrotron pulses on the same photodiode. Given the fact that this jitter is short in comparison to the root mean square (RMS)

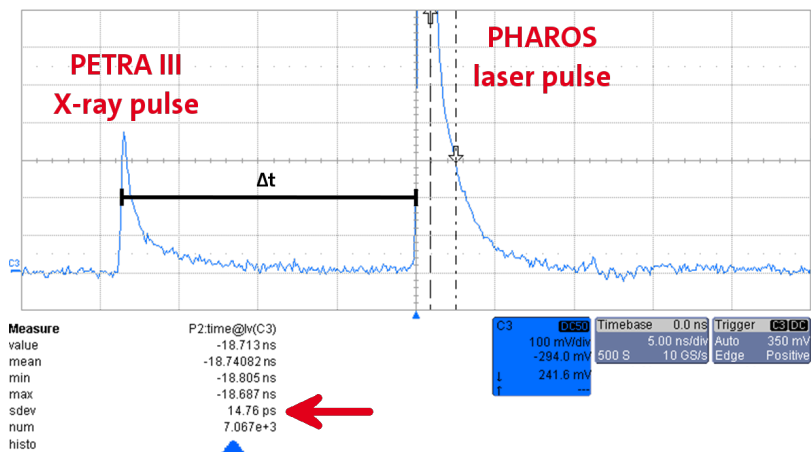


Figure 6. PHAROS (3rd harmonic) and PETRA III pulses synchronized on the same photodiode. The time scale is 5 ns/div and the voltage scale is 100 mV/div.

pulse length of the PETRA III pulses of about 44 ps [16], pump-probe experiments reaching a temporal resolution limited only by the synchrotron pulse duration become possible. Recent measurements suggest an even smaller jitter in the range of a few picoseconds (data not shown).

4. Summary and Outlook

We have set up and commissioned a new full-field TXM at the P04 beamline of PETRA III as well as a synchronized femtosecond laser system. The next steps are heading for the theoretical resolution and recording XMCD contrast images of magnetic nanostructures with the improved P04 beamline parameters offering a better beam profile and a higher resolving power $\frac{\lambda}{\Delta\lambda}$.

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