Single-pulse resonant magnetic scattering at FLASH

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Free-electron laser (FEL) sources based on self-amplified spontaneous emission (SASE)\textsuperscript{[?]} can provide intense and ultrashort (femtosecond) pulses from the vacuum ultraviolet (VUV) to the X-ray range. These sources have the potential to record a magnetic diffraction pattern from a sample within a few femtosecond exposure and thus to probe elementary magnetization dynamics such as spin-flip processes and their coupling to the electronic system on their intrinsic time scales in the femtosecond (fs) regime. At the same time nanometer spatial resolution and element-specific information is provided allowing to access the complex composition of technologically relevant magnetic media and devices.

However, the unprecedented peak power of FEL sources also implies that a considerable amount of energy is deposited in the sample. The radiation damage threshold defines the borderline between non-destructive and therefore repeatable pump-probe type of magnetic scattering experiments and high fluence destructive single-pulse experiments. Beam damage renders single-pulse scattering from magnetic samples especially challenging as one would ideally take femtosecond snapshots without modifying samples.

In order to address these issues, we performed single-pulse resonant magnetic diffraction experiments at the soft x-ray free electron laser FLASH in Hamburg. We demonstrated recently the first resonant magnetic scattering at FLASH by using the fifth harmonic of 8 nm to obtain magnetic scattering contrast at the Co L\textsubscript{3} edge [1]. Now, the fundamental wavelength was set to 20.8 nm (59 eV) which is in resonance with the Co M\textsubscript{2,3}-edge yielding magnetic scattering contrast. FLASH was operated in single-bunch mode with a repetition rate of 5 Hz. The pulse duration was 30 femtoseconds with an average pulse intensity of 2 \textmu J which corresponds to $2 \times 10^{11}$ photons per pulse on the sample in a beam size of 250 \textmu m. This results in a photon fluence of 4 mJ/cm\textsuperscript{2} and peak powers of about $1.3 \times 10^{11}$ W/cm\textsuperscript{2}. The experiment has been performed at beamline BL1 at FLASH which utilizes the direct FEL beam without monochromator. The natural bandwidth of the SASE radiation $\Delta E/E \approx 0.5$ \% - 1 \% is sufficiently small to allow for resonant scattering at the Co M-edge. A toroidal mirror produces a beam size of about 150 \textmu m in the focal plane. Our samples have been positioned slightly out of focus resulting in the beam size of around 250 \textmu m on the samples.

Co/Pt multilayer samples were grown via magnetron sputtering on a 50 nm thick Si\textsubscript{3}N\textsubscript{4} membrane. A 5 nm thick ECR sputtered Pt layer serves as seed layer, followed by 16 repeats of [Co(0.8nm)/Pt (1.4nm)] and a final Pt cap layer of 2 nm thickness, all prepared by DC magnetron sputtering [?]. The sample is mounted in such a way that the FEL beam is impinging on the membrane first before being scattered from the multilayer. In multilayer samples of this composition magnetic maze domains form with alternating up and down magnetization perpendicular to the sample surface.
The spatial correlation of the domains, being twice the domain size, is on the order of 200-300 nm leading to a pronounced magnetic small-angle scattering (SAXS) signal. Fig. 1 shows a resonant magnetic SAXS pattern recorded with a 30 fs long single FEL pulse of pulse energy 4 µJ. A subsequent illumination showed that the sample was not destroyed from the single-pulse exposure. The scattering ring reflecting the spatial correlation via \( \xi = 2\pi/Q_{\text{max}} \approx 200 \text{ nm} \) of the magnetic domains is clearly visible (see also Ref. [1]). The existence of magnetic scattering proves that the spin system temperature is below the Curie temperature of the multilayer sample during the exposure time. It is worth mentioning that even FEL pulse energies 10-20 times larger than the one applied here allowed us to record a single-pulse magnetic diffraction pattern. Those high pulse energies destroyed the sample although the spin system is still not quenched during the exposure time of 30 fs.

In conclusion, we demonstrated nondestructive resonant magnetic scattering using single pulses from the free-electron laser FLASH. Pulse energies of 4 mJ/cm\(^2\) are sufficient to record a magnetic diffraction pattern within 30 fs without destroying the sample. We observed that higher pulse intensities can lead to permanent changes of the magnetic properties of the magnetic multilayer but without macroscopically observable destruction. Below that threshold it is possible to record magnetic diffraction patterns without changing the magnetic domain size distribution.

![Figure 1: Resonant magnetic small-angle scattering pattern of a Co/Pt multilayer recorded with a single 30 fs FEL pulse of \( 1.3 \times 10^{11} \text{ W cm}^{-2} \). The photon wavelength was in resonance with the Co M\(_{2,3}\)-edge (20.8 nm) providing magnetic scattering contrast. The color scales indicates the number of scattered photons per pixel (4x4 binned image).](image)

References