SUPPLEMENTARY INFORMATION: Dynamic Imaging of the Delay- and Tilt-Free Motion of Néel Domain Walls in Perpendicularly Magnetized Superlattices

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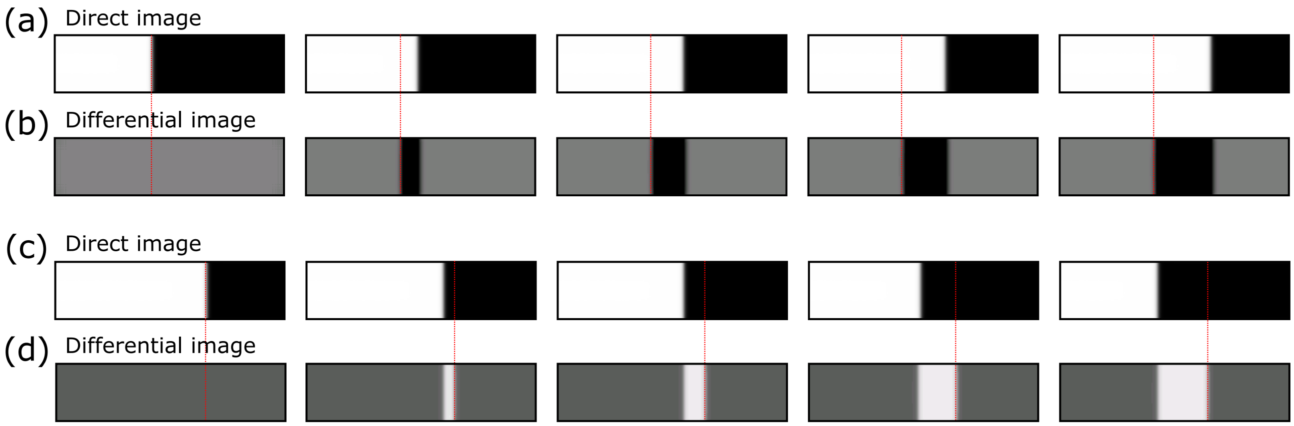

Figure S1. Schematic overview of the principle behind the differential imaging technique employed for the time-resolved images shown in the main manuscript. (a) and (c) show schematic XMCD images of the motion of a domain wall towards (a) the right and (c) the left of the page. (b) and (d) show the corresponding differential images, calculated by subtracting the first XMCD image from the following ones. In the case of a motion towards the right of the page, a growing region of dark contrast can be observed, whilst a growing region of bright contrast can be observed when the domain wall is displaced towards the left of the page. The red dashed line marks the position of the domain wall at the beginning of its motion. The images simulate the case of negative helicity imaging, as in the time-resolved images shown in the main manuscript.

DIFFERENTIAL TIME-RESOLVED IMAGING

The time-resolved images shown in Fig. 3 of the main manuscript and in the movies included with the supplementary information were acquired as differential images. Each frame in the differential time-resolved images shows the difference between the magnetic state at the given frame with respect to a defined magnetic state, which was selected to be the spin configuration just before the application of the exciting signal, i.e. the injection of a current pulse for the CIDWM, and the generation of a magnetic field pulse for the FIDWM. Each frame of the differential time-resolved image is calculated by subtracting the original magnetic configuration from each frame of the raw time-resolved image.

The principle behind the calculation of the differential time-resolved images is depicted in Fig. S1, which also shows their expected appearance for right- and left-moving domain walls when imaging with negative helicity x-rays.

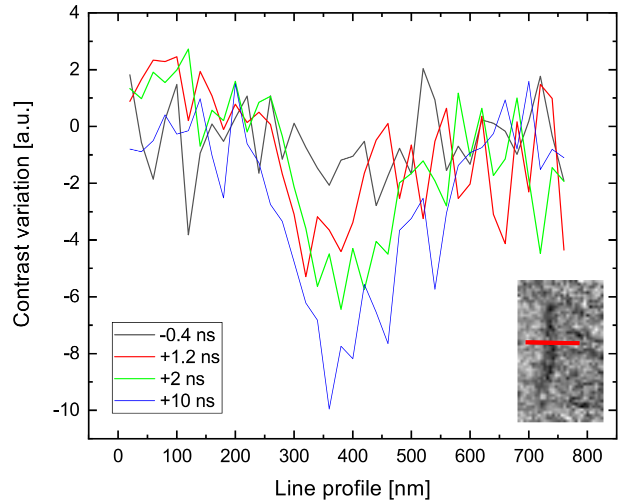

Figure S2. Variation of the magnetic contrast along the magnetic domain wall at different time steps (region of interest marked in the inset) during the injection of a current pulse. The motion of the domain wall can be observed from the change in the width of the region where a variation in the magnetic contrast can be observed for different time steps.

DETERMINATION OF THE POSITION OF THE MAGNETIC DOMAIN WALL

The position of the magnetic domain wall during its motion can be determined from the time-resolved images. One approach, shown in Fig. 4 of the main manuscript, is to calculate the time-resolved variation in the XMCD contrast across the entire region where the domain wall motion is observed. Another possible method that can be employed is to determine the profile of the magnetization across the domain wall for each of the time-steps in the time-resolved images. In this case, the motion of the domain wall can be detected from the width of the region where a variation in the XMCD contrast is visible, as shown in Fig. S2.

DETERMINATION OF THE DOMAIN WALL ACCELERATION

By determining the time-resolved variation of the XMCD contrast in the region of the magnetic domain wall (marked in Fig. 3 of the main manuscript), it was possible to determine that the CIDWM process occurs synchronously with the current pulse, and that the magnetic domain wall accelerates instantaneously to its final velocity. This conclusion can be obtained by observing that the XMCD contrast varies linearly during the application of the current pulse, and that the XMCD contrast remains constant after the end of the

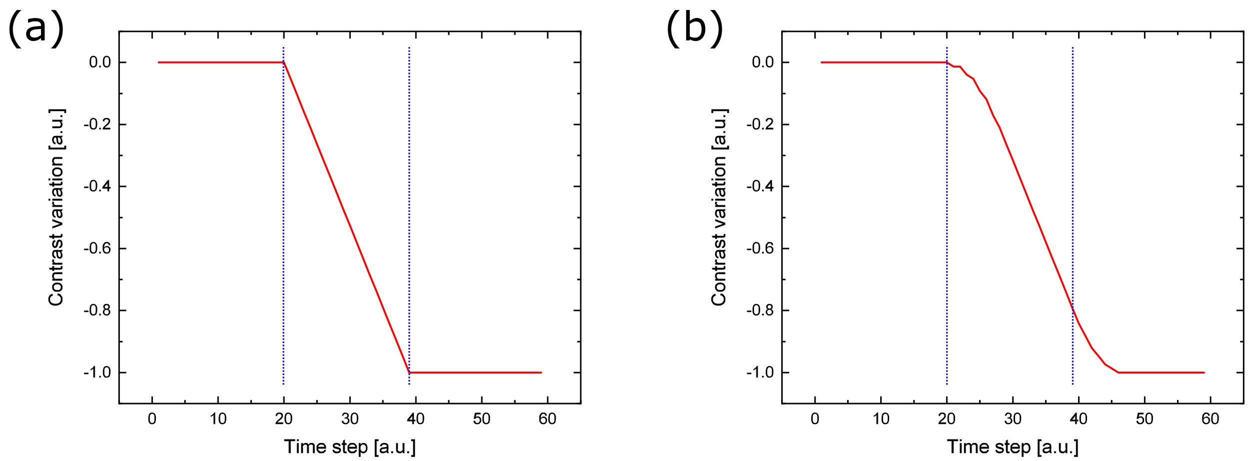

Figure S3. Schematic overview of the expected variation of XMCD contrast in the case of (a) a magnetic domain wall instantaneously accelerating to its final velocity and (b) a magnetic domain wall exhibiting a finite acceleration and deceleration time. A linear change of the magnetic contrast can be observed for (a), while a non-linear change of the magnetic contrast can be observed in (b) after the start and end of the excitation (marked with the blue dashed lines in the figure).

current pulse. If the domain wall exhibited a finite acceleration time to its final velocity (and a finite deceleration time when the current is removed), the variation of the XMCD contrast would show a non-linear behavior at the onset of the current pulse, indicating the acceleration of the domain wall, and a variation in the XMCD contrast would still be present after the end of the current pulse, during the deceleration of the domain wall (see Fig. S3 for a schematic overview of the difference between the case of an instantaneous and non-instantaneous acceleration of the magnetic domain wall).

SIMULATION OF THE MAGNETIC FIELD GENERATED BY THE Ω-SHAPED MICROCOIL

The distribution of the magnetic field generated by the injection of a current pulse across the Ω-shaped microcoil was simulated with the commercial finite element multiphysics simulation suite ANSYS. The results of the simulations are shown in Fig. S4.

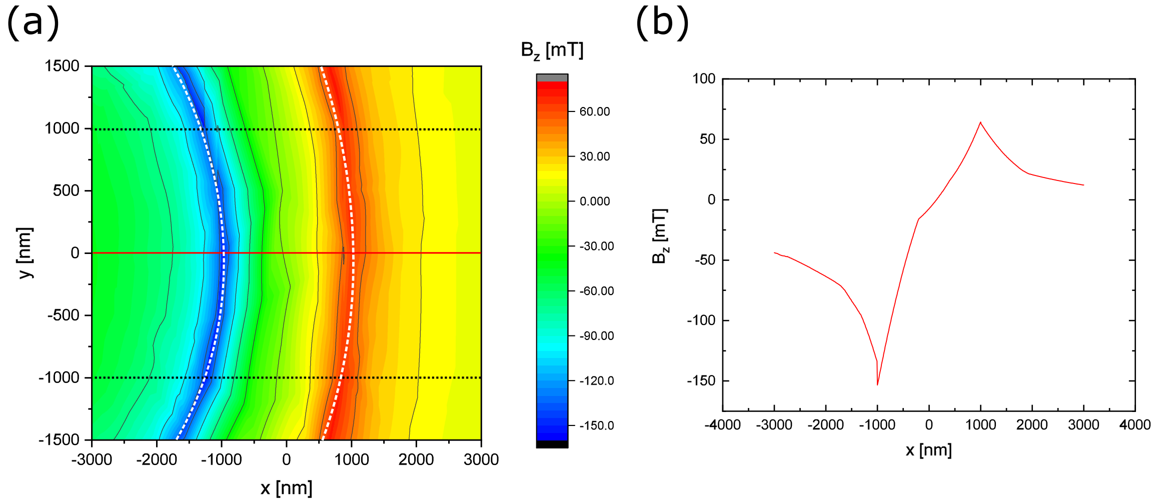

Figure S4. Finite element simulation of the magnetic field generated by the Ω-shaped coil, with an injected current of 350 mA. (a) Field distribution at the region of interest for the experiments presented in the main manuscript. The white dashed lines indicate the edges of the Ω-shaped coil, and the black dashed lines indicate the edges of the microwire. (b) Linescan across the line marked by the red continuous line in (a).

ONE-DIMENSIONAL ZEEMAN ENERGY MODEL

In the main manuscript, it is stated that the field-induced domain wall motion (FIDWM) process stops once the magnetic domain wall has reached the energetic minimum. This energetic minimum is found below the Ω-shaped coil, due to the distribution of the z component of the magnetic field generated by the coil. A finite element simulation of the magnetic field generated by the coil is shown in Fig. S4(a).

To demonstrate that the minimum of the Zeeman contribution to the magnetic free energy of the system occurs when the domain wall is at the position where the z component of the magnetic field changes sign, we can consider a simplified one-dimensional model for the magnetic configuration, where we adopt the simplest possible description for the domain wall, i.e. according to the following relation:

$$m_z(x, a) = -\mathrm{sign}(x - a), \tag{1}$$

where $\mathrm{sign}(x)$ represents the sign function, and a represents the position of the magnetic domain wall. As shown in Fig. S4(b), the one-dimensional description of the z component of the magnetic field generated by the coil is given by a function $\mu_0 H_z(x) = B_z(x)$ that is positive for $x < 0$, and negative for $x > 0$, being $x = 0$ the position where the magnetic field $B_z(x)$ changes sign (see Fig. S4(b)). Therefore, the one-dimensional version of the Zeeman contribution to the magnetic free energy can be written as follows:

$$F_Z(a) = -\mu_0 \int_{\Re} H_z(x) m_z(x,a) \mathrm{d}x = \mu_0 \int_{\Re} H_z(x) \mathrm{sign}(x-a) \mathrm{d}x. \tag{2}$$

If we assume, for simplicity, $a \geq 0$, then Eq. (2) can be rewritten as follows:

$$F_Z(a) = -\mu_0 \int_{-\infty}^{0} H_z(x) \mathrm{d}x - 2\mu_0 \int_{0}^{a} H_z(x) \mathrm{d}x + \mu_0 \int_{0}^{\infty} H_z(x) \mathrm{d}x, \tag{3}$$

which, knowing that $H_z(x)$ is positive for $x < 0$ and negative for $x > 0$, results in the following relation:

$$F_Z(a) = -\mu_0 \int_{-\infty}^{0} |H_z(x)| \mathrm{d}x + 2\mu_0 \int_{0}^{a} |H_z(x)| \mathrm{d}x - \mu_0 \int_{0}^{\infty} |H_z(x)| \mathrm{d}x = -A + B(a) - C. \tag{4}$$

All three integrals (labeled for simplicity A, $B(a)$, and C) yield positive results, and it is therefore easy to demonstrate that the minimum in the Zeeman contribution to the magnetic free energy will be given when $B(a) = 0$, i.e. when $a = 0$. The same argument can be easily extended for the case of $a \leq 0$, demonstrating that the minimum in the Zeeman contribution to the magnetic free energy is given, in this simplified one-dimensional model, when the magnetic domain wall is positioned at the change of sign in the z component of the magnetic field generated by the Ω-shaped coil.

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