

Supplementary Materials for

Optical manipulation of magnetic vortices visualized in situ by Lorentz electron microscopy

Xuewen Fu*, Shawn D. Pollard, Bin Chen, Byung-Kuk Yoo, Hyunsoo Yang, Yimei Zhu*

*Corresponding author. Email: zhu@bnl.gov (Y.Z.); xfu@bnl.gov (X.F.)

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The PDF file includes:

Fig. S1. Occurrence frequency distribution of femtosecond laser pulse–induced magnetic structures in a circular Py disk at a fluence of 16 mJ/cm².

Fig. S2. Occurrence frequency distribution of femtosecond laser pulse–induced magnetic structures in a square Py disk at a fluence of 16 mJ/cm².

Fig. S3. Occurrence frequency distribution of femtosecond laser pulse–induced magnetic structures in a triangular Py disk at a fluence of 16 mJ/cm².

Fig. S4. Schematic of relative change to the sum of demagnetization and exchange energies associated with the transformation of the indicated state to a lower-energy state estimated by application of a magnetic field applied along the $\pm x$ or $\pm y$ directions, whichever is lowest.

Fig. S5. Typical magnetic structures in triangular Py disks (edge length of 1.7 μm) determined by micromagnetic simulation to show the pinning sites at the disk edge.

Fig. S6. Annular bright-field images of a circular Py disk after a femtosecond laser pulse quenching with different fluences to show the change of the inside crystallites.

Legends for movies S1 to S13

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/4/7/eaat3077/DC1)

Movie S1 (.avi format). Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a circular Py disk (diameter of 3 μm) at a fluence of 12 mJ/cm².

Movie S2 (.avi format). Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a square Py disk (edge length of 3 μm) at a fluence of 12 mJ/cm².

Movie S3 (.avi format). Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a triangular Py disk (edge length of 1.7 μm) at a fluence of 12 mJ/cm².

Movie S4 (.avi format). Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a circular Py disk (diameter of 1.7 μm) at a fluence of 12 mJ/cm².

Movie S5 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a single magnetic vortex structure in the triangular Py disk (edge length of 1.7 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S6 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with two magnetic vortices in the triangular Py disk (edge length of 1.7 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S7 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with three magnetic vortices in the triangular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S8 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a single magnetic vortex structure in the circular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S9 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with four magnetic vortices in the circular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S10 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with four magnetic vortices in the circular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

movie S11 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a single magnetic vortex structure in the square Py disk (edge length of 3 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S12 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with three magnetic vortices in the square Py disk (edge length of 3 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S13 (.avi format). Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with four magnetic vortices in the square Py disk (edge length of 3 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

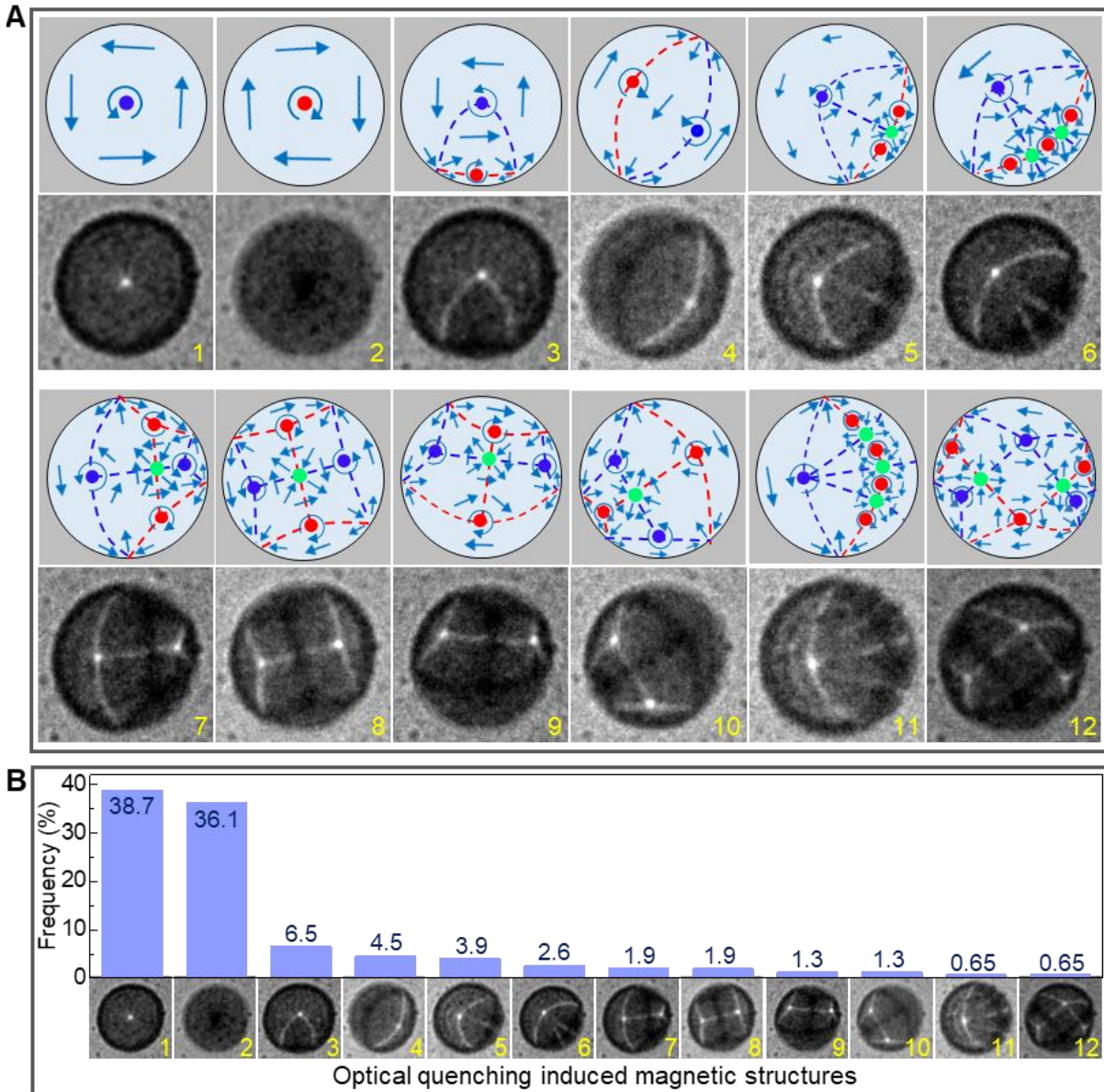


Fig. S1. Occurrence frequency distribution of femtosecond laser pulse–induced magnetic structures in a circular Py disk at a fluence of 16 mJ/cm^2 . (A) Bottom panel: Fresnel images of the observed magnetic structures in the circular Py disk (diameter of $3 \mu\text{m}$); Top panel: corresponding schematic magnetization configurations. (B) Occurrence frequency distribution of the fs-laser pulse induced different magnetic structures.

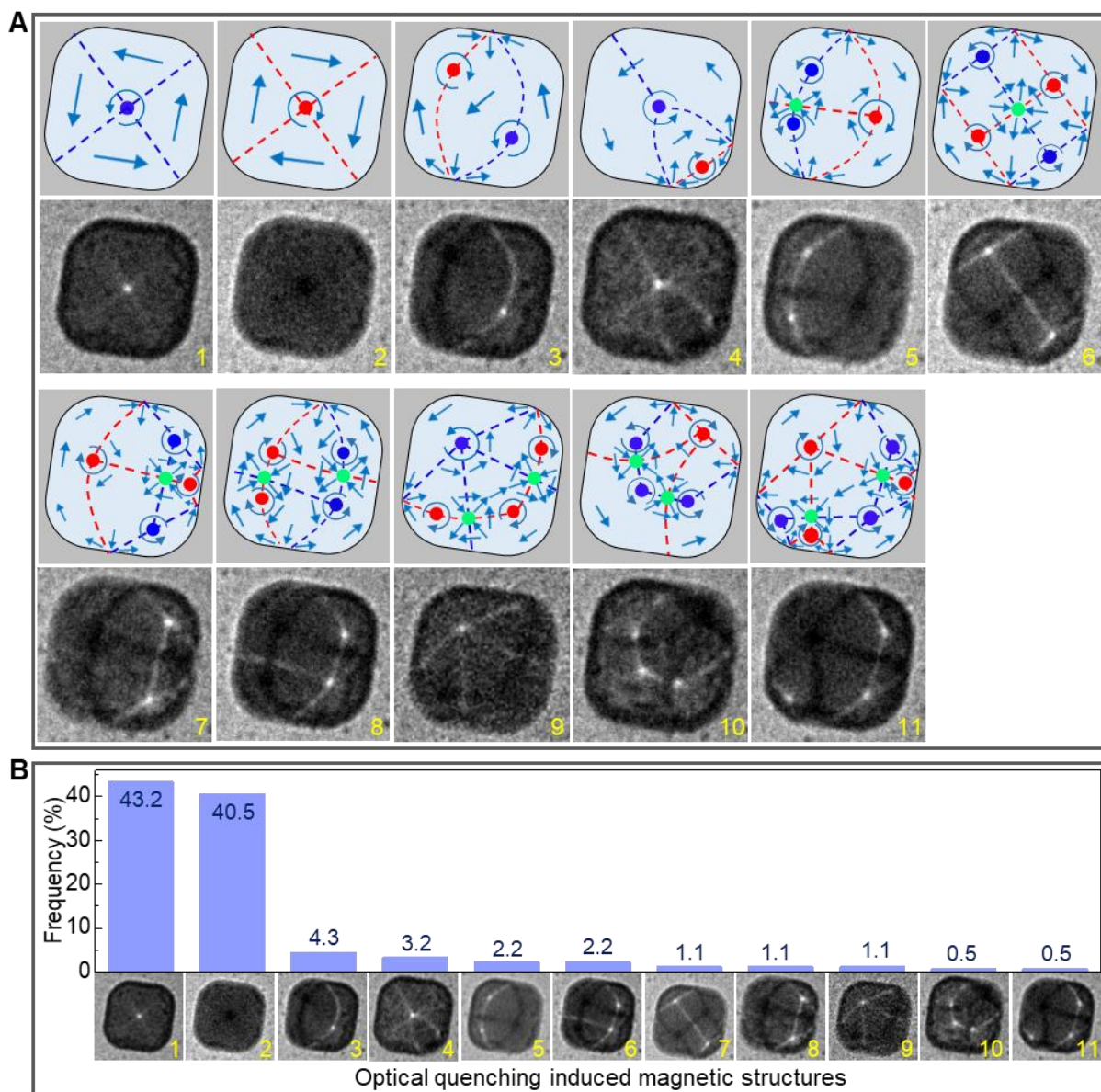


Fig. S2. Occurrence frequency distribution of femtosecond laser pulse–induced magnetic structures in a square Py disk at a fluence of 16 mJ/cm^2 . (A) Bottom panel: Fresnel images of the observed magnetic structures in the square Py disk (edge length of $3 \mu\text{m}$); Top panel: corresponding schematic magnetization configurations. (B) Occurrence frequency distribution of the fs-laser pulse induced different magnetic structures.

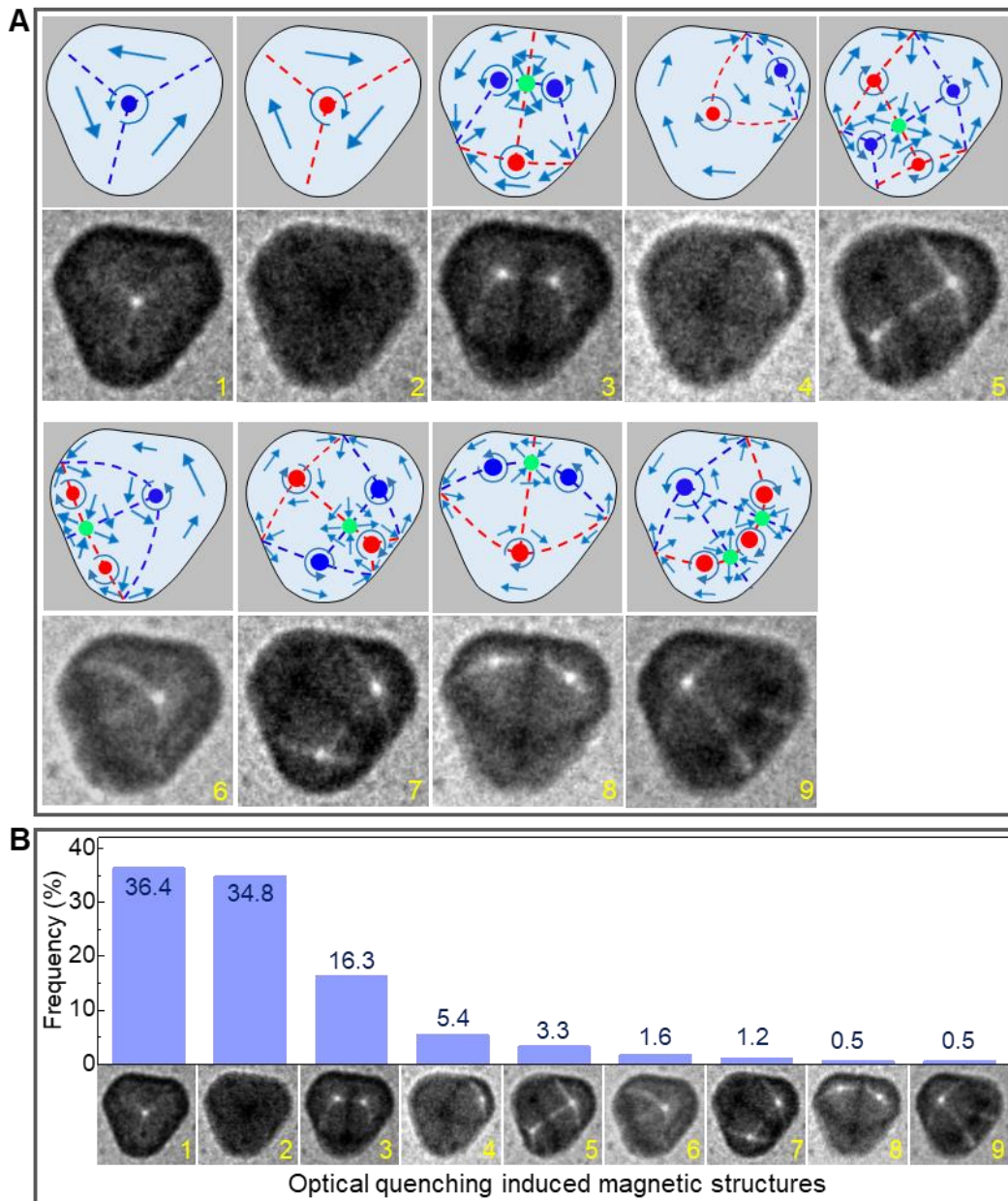


Fig. S3. Occurrence frequency distribution of femtosecond laser pulse–induced magnetic structures in a triangular Py disk at a fluence of 16 mJ/cm^2 . (A) Bottom panel: Fresnel images of the observed magnetic structures in the triangular Py disk (edge length of $1.7 \mu\text{m}$); Top panel: corresponding schematic magnetization configurations. (B) Occurrence frequency distribution of the fs-laser pulse induced different magnetic structures.

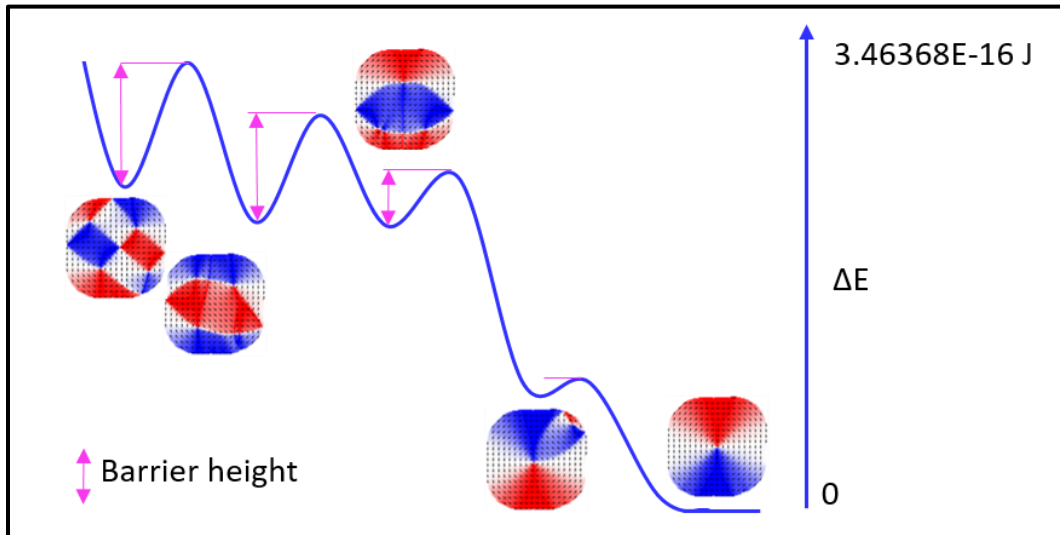


Fig. S4. Schematic of relative change to the sum of demagnetization and exchange energies associated with the transformation of the indicated state to a lower-energy state estimated by application of a magnetic field applied along the $\pm x$ or $\pm y$ directions, whichever is lowest. This is distinct from the energy barrier between two states, as this includes modifications to the entire structure, not just the energy required for depinning one vortex/antivortex. However, it may be used to gauge the comparative stability of each measured state. The magnetic structure containing two vortices has the lowest barrier associated with transformation to a single vortex state.

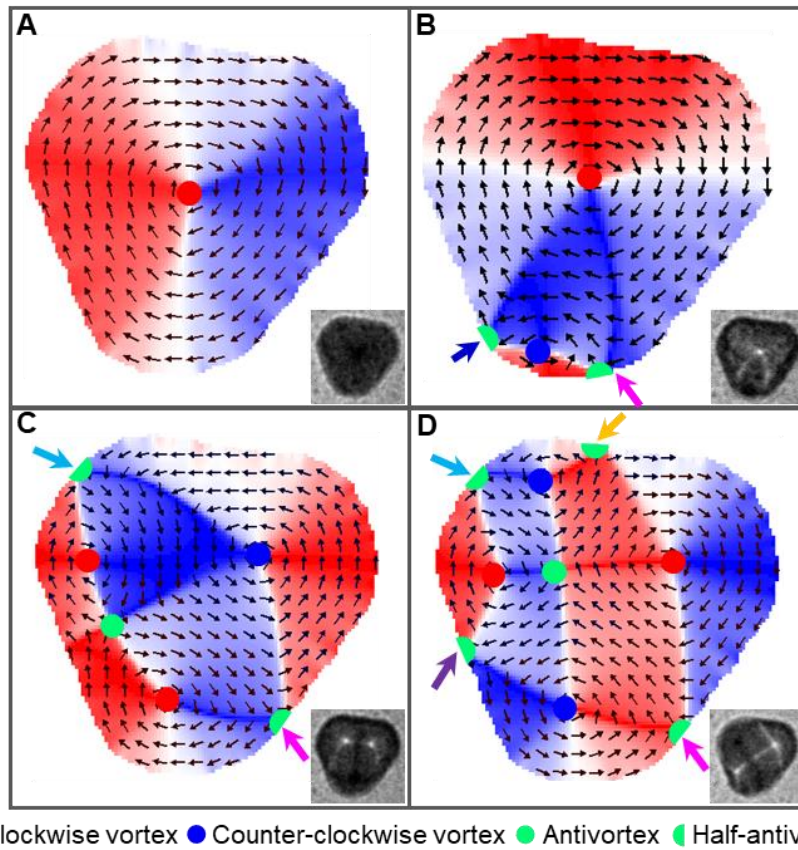


Fig. S5. Typical magnetic structures in triangular Py disks (edge length of 1.7 μm) determined by micromagnetic simulation to show the pinning sites at the disk edge. The colored arrows at the disk edge show the pinning sites. The insets show their corresponding Fresnel images.

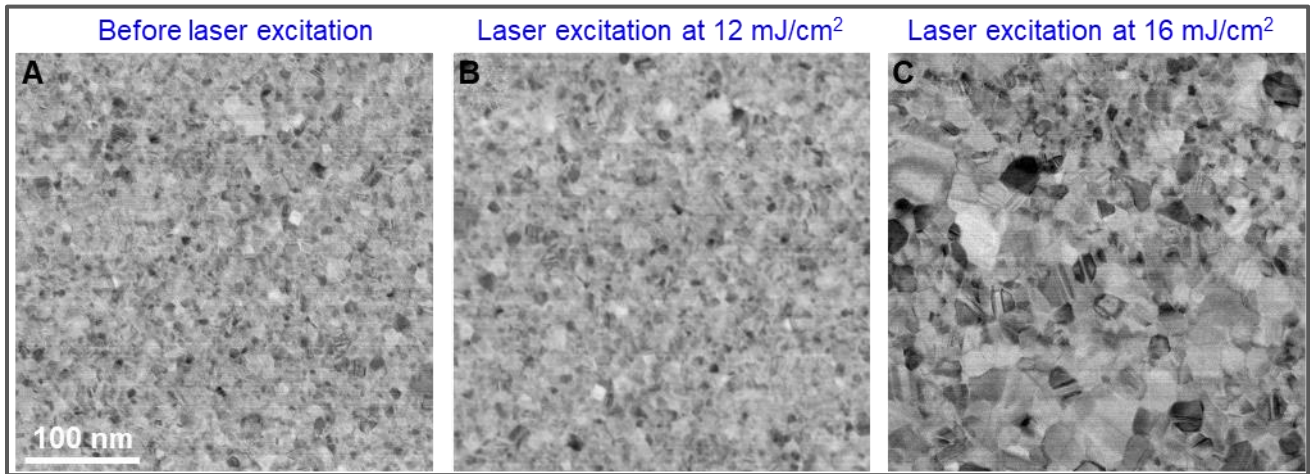


Fig. S6. Annular bright-field images of a circular Py disk after a femtosecond laser pulse quenching with different fluences to show the change of the inside crystallites. The crystallites in the Py disk show no obvious change under the excitation fluence of 12 mJ/cm² (B), while exhibit apparent growth after the fs-laser pulse excitation with the fluence of 16 mJ/cm² (C). The fs-laser pulse induced growth of crystallites induces large grain boundaries in the Py disk, which may cause more pinning sites and result in more complex magnetic structures.

Movie S1. Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a circular Py disk (diameter of 3 μm) at a fluence of 12 mJ/cm^2 .

Movie S2. Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a square Py disk (edge length of 3 μm) at a fluence of 12 mJ/cm^2 .

Movie S3. Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a triangular Py disk (edge length of 1.7 μm) at a fluence of 12 mJ/cm^2 .

Movie S4. Fresnel imaging of femtosecond laser pulse quenching–induced magnetic structure change in a circular Py disk (diameter of 1.7 μm) at a fluence of 12 mJ/cm^2 .

Movie S5. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a single magnetic vortex structure in the triangular Py disk (edge length of 1.7 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S6. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with two magnetic vortices in the triangular Py disk (edge length of 1.7 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S7. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with three magnetic vortices in the triangular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S8. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a single magnetic vortex structure in the circular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S9. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with four magnetic vortices in the circular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S10. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with four magnetic vortices in the circular Py disk (diameter of 3.0 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S11. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a single magnetic vortex structure in the square Py disk (edge length of 3 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S12. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with three magnetic vortices in the square Py disk (edge length of 3 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).

Movie S13. Micromagnetic simulation on the magnetization relaxation dynamics of the formation of a magnetic structure with four magnetic vortices in the square Py disk (edge length of 3 μm) after a femtosecond pulse quenching (fluence of 12 mJ/cm^2).