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X-ray imaging of nonlinear resonant gyrotropic magnetic vortex core motion in circular permalloy disks

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We report experimental evidence of nonlinear gyrotropic vortex core motion. Using soft x-ray transmission microscopy we observed the time-averaged dynamic response of a magnetic vortex core in a 2 1m diameter, 100 nm thick permalloy $(Ni_{80}Fe_{20})$ disk as a function of the amplitude and frequency of an applied RF magnetic field. At lower amplitude fields a single resonance was observed, but two distinct resonances, above and below the low amplitude resonance frequency, were observed when higher amplitude fields were applied. The results are discussed in the context of a nonlinear vortex energy potential.

Magnetic vortex structures, which form in micronsized circular permalloy $(Ni_{80}Fe_{20})$ disks,[1] consist of an in-plane circulating magnetic domain with two possible chiralities and an out-of-plane singularity in the center, the vortex core (VC), with two possible polarities.[2–4] The dynamic response of VCs to applied fields and currents has received significant attention[5,6] because of its relevance to future technologies,[6] and as a model system for fundamental studies of nanoscale magnetism.[7–9]

Recently it has been shown experimentally and theoretically that the core polarity can be flipped by an applied field or current pulse,[10] particularly when the VC is undergoing resonant gyrotropic motion. The gyrotropic resonance frequencies are usually several hundreds of MHz.[11,12] Open questions remain, especially concerning its driven motion for high amplitude driving fields.

Here we use soft x-ray transmission microscopy to examine the dynamic behavior of the VC in 2 1m diameter, 100 nm thick $Ni_{80}Fe_{20}$ disks. We record time-averaged images of the VC while applying a RF magnetic field to explore the gyrotropic VC motion as a function of driving magnetic field frequency and amplitude. For low amplitude applied fields we find the expected response of the core, that is, amplified motion at the gyrotropic resonance frequency. However, at higher driving magnetic amplitudes, there appear to be two distinct frequency ranges where the core has a dynamic response.

The experiments were conducted at XM-1, the full field transmission soft x-ray microscope at beamline 6.1.2 at the Advanced Light Source (ALS) in Berkeley, CA. XMCD provides an element-specific magnetic contrast mechanism.[14] Using Fresnel zone plate optics, XM-1 has achieved a betterthan 12 nm (Ref. 15) spatial resolution; for this experiment the resolution was about 25 nm.

Using e-beam lithography, a $Ni_{80}Fe_{20}$ disk with a 2 μm diameter and a thickness of 100 nm was fabricated on a gold waveguide structure on an x-ray transparent substrate, a 100 nm thick silicon nitride membrane. A RF current flowed through the waveguide, generating an in-plane oscillating magnetic field. The RF field was applied to the sample with various frequencies and amplitudes over the course of the experiment. The applied field peak amplitudes, H_0, ranged from 4 Oe to 10 Oe and typical frequencies were on the order of several hundred MHz. Images were taken with normal incidence, providing images with the core clearly shown as a dark or bright spot in the sample. An image of the sample with no field applied is shown in Fig. 1. The VC diameter is 52 nm, similar to previous VC studies.[4] Sample preparation and experimental technique are discussed in detail elsewhere.[16]

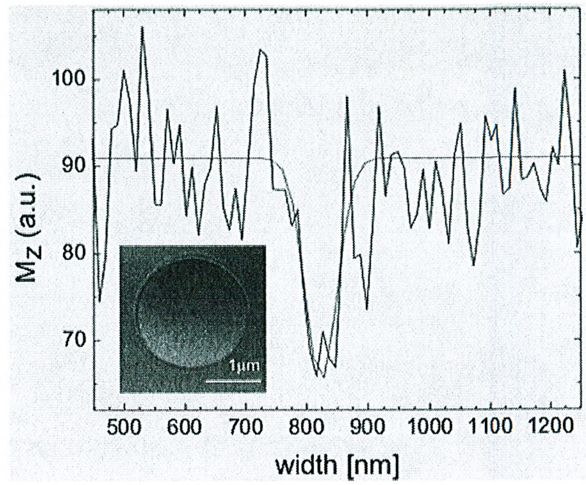

FIG. 1. (Color online) An image of the sample taken with no applied field. (Inset) The magnetization normal to the plane with respect to position on the sample. The vortex core is 52 nm in diameter.

A sequence of images taken with a lower amplitude field applied to the sample, Ho ~ 4 Oe, is shown in Fig. 2. Each image is formed by dividing two images taken with opposite x-ray polarizations. Such an image pair takes about 2 min of illumination to record, which corresponds to $\sim 10^{10}$ VC gyrations. Between each image the RF current was disconnected from the waveguide, adjusted to the next frequency, and then reconnected to the waveguide. The VC can be seen in most of the images as a dark spot at the center of the disk. Here, the VC is in motion, but the amplitude is less than the microscope resolution. However, the VC is not discernible at all frequencies (Fig. 2(c)), which pinpoints; the frequencies at which the VC has a resonant dynamic response. This "core disappearance" could happen for several reasons. For low amplitude excitations, the VC has been shown to follow a circular trajectory at resonance. This would spread out the XMCD signal; hence the blurring in Fig. 2(c) could indicate that the VC is in motion. Reduced contrast could also occur if the core polarity were rapidly flipping, averaging out the dark and light contrast into a gray background, or if both lateral motion and polarity flipping were occurring. At Ho ~ 4 Oe the VC was consistently imaged as a dark spot above and below resonance, suggesting that for small Ho the blurring is due to core motion rather than VC polarity reversal. The disappearance, or blurring, was observed repeatedly. For the critical highest and lowest amplitude fields a full set of frequencies was scanned in sequence at least five times. This was a reproducible effect and we thus infer that the core blurring was caused by a change in the magnetization of the sample rather than an experimental artifact.

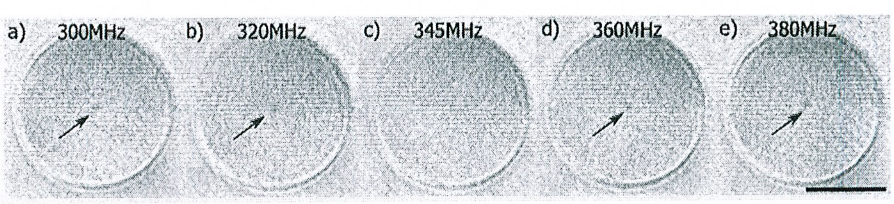

FIG. 2. (Color online) A representative sequence of images taken with a lower amplitude oscillating field of Ho 4 Oe. Sample imaged at (a) 300 MHz, (b) 320 MHz, (c) 345 MHz, (d) 360 MHz, and (e) 380 MHz. Red arrows highlight the images of the dark VC. The VC is not visible in (c). Scale bar is μ m.

In Fig. 2, the dynamic change in the core occurs around 345 MHz. This is ~0.7 times the expected resonant frequency[11]; other experiments have seen similar deviations from theory.[13] Hence the blurring of the core to gray in Fig. 2(c) corresponds to resonant gyrotropic motion.

Next, magnetic fields of several amplitudes were applied (Fig. 3). For Ho of about 8 Oe, the frequency range where the VC blurs appears to broaden slightly. A significant change is seen for Ho around 10 Oe, where there appear to be two distinct regions of dynamic motion of the VC (Fig. 4). We are able to image the core near 345 MHz, while at 320 MHz and 360 MHz the core is not visible in the images. This suggests that dynamic behavior is now occurring on either side of the original resonance frequency. The comparatively sharp image of the core at the original resonance frequency suggests that the core is not changing or gyrating between the two new dynamic frequency ranges.

In Fig. 4(c) the VC is bright rather than dark, indicating that the core polarity switched during the dynamics at frequencies before and after the stable image at 345 MHz, unlike the images for lower H_0 where the VC was consistently dark. From time-averaged images alone it is impossible to tell whether the core polarity flipped just once while at resonance, or if the polarity was continually undergoing rapid flipping, ending by chance with a particular contrast. Nevertheless, the core images at the highest and lowest frequencies applied to the sample at $H_0 =$ 10 Oe indicate that core flipping does occur for this H_0. To further investigate the core polarity flipping, single-shot imaging of VC dynamics would be needed; however, at present no snapshot magnetic imaging technique is available with sufficient spatial resolution. The polarity did not switch when changing between frequencies where the core could be clearly imaged. Switching was only observed after moving from a frequency where the core was blurred. For the 10 Oe RF field, the images with the indistinct core are likely the result of both core motion and switching; previous studies have indicated that core flipping is facilitated at resonance.

Our observations suggest there are two resonant frequencies of the VC when relatively large amplitude RF fields are applied, one above the low amplitude resonance frequency and the other below. This behavior is consistent with previous microwave absorption spectra recorded for arrays of magnetic vortices.[7] For low amplitude excitations, the vortex gyromode is known to occur at a single resonance frequency and the VC motion has been found to be well described by the Thiele equation:[11]

$$-\vec{G}\times\frac{d\vec{X}}{dt} - D\frac{d\vec{X}}{dt} + \frac{\partial W(\vec{X})}{\partial \vec{X}} = 0,$$

where G~ is the gyrovector,x~ is the displacement of the core, D is the damping coefficient, and W(~x) is the potential

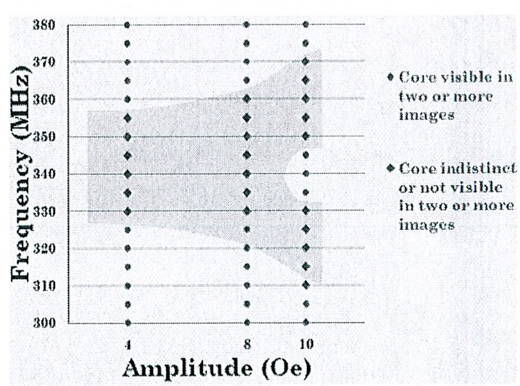

FIG. 3. (Color online) A summary of the images taken over a range of frequencies and amplitudes. The blue circles indicate a frequency and amplitude where the core was visible, and the red diamonds a frequency and amplitude where the core was indistinct or not visible in at least two images. The pink overlay emphasizes the general trend of the data: a single resonance splitting to two at higher applied fields.

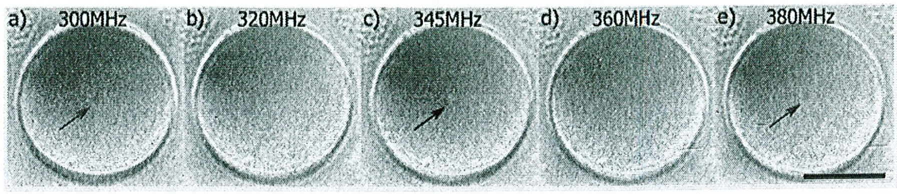

FIG. 4. (Color online) A representative sequence of images taken with a higher amplitude oscillating field of H_0 10 Oe. Sample imaged at (a) 300 MHz, (b)320 MHz, (c) 345 MHz, (d) 360 MHz, and (e) 380 MHz. Arrows highlight the visible VC in(a), (c), and (e). The red arrows ((a) and (e)) point toward a darkVC while the blue arrow (c) points out a light VC in (c), indicating a change in core polarity before and after the 345 MHz image was taken. Scale bar is 1 μm.

(mainly dipolar) energy of the vortex. $W(\tilde{X})$ is approximately assumed proportional to $\tilde{X}^2$; a more precise description of the potential requires higher order terms.[5,17] More recently, the concept of a critical velocity-energy-displacement of the VC has been proposed, beyond which the VC becomes unstable and undergoes dynamic polarity reversal. The VC critical velocity has been calculated,[18] and measured experimentally.[19] A model for the VC motion that combines the gyrotropic motion with a critical velocity predicts a general broadening of the frequency range of dynamics with increased driving field. At high driving fields, the amplitude of the core motion exceeds the critical displacement at frequencies near the original resonance frequency, leading to core instability. This leads to two separate dynamic peaks that are associated with the leading and falling edges of the original gyromode.[20] Between the two dynamic peaks, the VC never reaches a steady state; micromagnetic simulations show a repeated building of the VC amplitude followed by a core reversal event and abrupt drop in the amplitude of its motion.[7] Time-resolved experiments show both non-steady state dynamics and lower time-averaged amplitude in this region.[21]

Both the broadening of the resonance frequency range and the existence of two resonant peaks, fit well with the experimental results. The observation of different core polarities for the highest value of H_0 indicates that core flipping is associated with the two distinct resonance peaks of the VC. A key difference, however, between theory and experiment is the image of the static VC seen in Fig. 4(c). Micromagnetic simulations suggest that between the two resonance peaks the VC would follow a circular spiral outwards, then flip in polarity with a reduction in displacement, spiral outwards again, and so on,[7] whereas these experiments suggest that there is minimal or no motion of the VC between the two dynamic peaks. One possible reason for this discrepancy is that the sample studied here is much thicker than those typically considered which, according to numerical simulations, should lead to a pronounced dependence of the VC width through the thickness that could influence the dynamics at high H_0.[22]

In summary, we have observed the driven dynamic response of a VC in a $Ni_{80}Fe_{20}$ disk under applied RF magnetic fields. At low amplitude fields the core responds as expected, showing a single resonance, while at higher amplitude fields the core images indicate that there are two distinct resonances separated by a stable, non-dynamic state. Changes in the VC contrast indicate that the high amplitude dynamics and observed mode splitting are related to core instability and polarity reversal.

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[1]R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, M. E. Welland, and D. M. Tricker, Phys. Rev. Lett. 83, 1042 (1999).
[2]T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science 289, 930 (2000).
[3]A. Wachowiak, J. Wiebe, M. Bode, O. Pietzsch, M. Morgenstern, and R. Wiesendanger, Science 298, 577 (2002).
[4]P. Fischer, M. Y. Im, S. Kasai, K. Yamada, T. Ono, and A. Thiaville, Phys. Rev. B 83, 212402(2011).
[5]K. S. Lee and S. K. Kim, Appl. Phys. Lett. 91, 132511 (2007).
[6] S. K. Kim, Y. S. Choi, K. S. Lee, K. Y. Guslienko, and D. E. Jeong, Appl. Phys. Lett. 91, 082506 (2007).
[7]K. S. Buchanan, M. Grimsditch, F. Y. Fradin, S. D. Bader, and V. Novo- sad, Phys. Rev. Lett. 99, 267201 (2007).
[8]A. Barman, S. Barman, T. Kimura, Y. Fukuma, and Y. Otani, J. Appl. Phys. D 43,422001(2010).
[9]H. Jung, Y. S. Yu, K. S. Lee, S. K. Kim, M. Y. Im, P. Fischer, L. Bocklage, A. Vogel, M. Bolte, and G. Meier, Appl. Phys. Lett. 97, 222502 (2010).
[10]Y. Liu, S. Gliga, R. Hertel, and C. M. Schneider, Appl. Phys. Lett. 91, 112501 (2007).
[11]K. Y. Guslienko, B. A. Ivanov, V. Novosad, Y. Otani, H. Shima, and K. Fukamichi, J. Appl. Phys. 91, 8037 (2002).
[12] S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, and T. Ono, Phys. Rev. Lett. 97, 107204 (2006).
[13]K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, and T. Ono, Nature Mater. 6,269(2007).
14P . Fischer, AAPPS Bull. 18, 12 (2008).
[15]W. Chao, J. Kim, S. Rekawa, P. Fischer, and E. H. Anderson, Opt. Express 17, 17669 (2009).

[16]B. L. Mesler, K. Buchanan, M. Y. Im, E. Anderson, and P. Fischer, J. Vac. Sci. Technol. B 28, 198 (2010).
[17]K. S. Buchanan, P. E. Roy, M. Grimsditch, F. Y. Fradin, K. Yu. Guslienko, S.D. Bader, and V. Novosad, Phys. Rev. B 74,064404 (2006).
[18]K. S. Lee, S. K. Kim, Y. S. Yu, Y. S. Choi, K. Y. Guslienko, H. Jung, and P. Fischer, Phys. Rev. Lett. 101, 267206(2008).
[19]X. M. Cheng, K. S. Buchanan, R. Divan, K. Y. Guslienko, and D. J. Keavney, Phys. Rev. B 79, 172411 (2009).
[20]K. Y. Guslienko, R. H. Heredero, and O. Chubykalo-Fesenko, Phys. Rev. B 82, 014402 (2010).
[21]T. Y. Chen and P. A. Crowell, IEEE Trans. Magn. 46, 1457 (2010).
[22]T. Y. Chen, M. Erickson, A. Galkiewicz, C. Leighton, and P. Crowell, "Thickness dependence of the gyrotropic mode of a single magnetic vortex," J. Appl. Phys. (these proceedings), Abstract No. BD-05.

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