Mechanisms for the symmetric and antisymmetric switching of a magnetic vortex core: Differences and common aspects

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Three-dimensional micromagnetic simulations of the switching of a magnetic vortex core in a cylindrical nanodisk are performed, for excitations with out-of-plane fields (symmetric switching) or with various types of time-dependent in-plane fields (asymmetric switching). Although the switching mechanisms are different in detail, all switching events must involve the movement of a Bloch point through the disk, because the switching leads to a change of the Skyrmion number which is a topological invariant as long as there is no action of a Bloch point. The momentary magnetization configurations are different in different layers of the disk. Because of the three-dimensionality it is often difficult to decide whether the asymmetric switching is caused by the splitting of the dip close to the vortex core into a vortex-antivortex pair, and the annihilation of the original vortex with the antivortex (whereby a Bloch point moves). It is suggested that there are situations for which such a switching occurs by the formation of a Bloch point in a configuration which is already similar to a vortex-antivortex configuration, but by a movement of this Bloch point before the formation of a complete pair and without the annihilation of the original vortex with an antivortex.

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I. INTRODUCTION

A magnetic vortex is the magnetic ground state of a circular nanodisk of diameter $2R$ and thickness D. In this state the magnetization curls in the plane of the disk around a core with a diameter of only 10 to 20 nm [1]. Inside the core the magnetization rotates out of the plane, and it is perpendicular to the plane at the center of the core, either up or down, corresponding to the two vortex polarities $p = +1$ and $p = -1$. The polarity can be considered as a data bit (e.g., 1 for $p = +1$ and 0 for $p = -1$). Because the vortex polarity is very stable, such structures could be used in advanced information storage and data processing devices. For this it necessary to change the polarity in a short time. This switching can be performed in two ways. First, one can apply external magnetic fields which are antiparallel to the core magnetization and which are either static [2,3] or dynamic fields [4–6] in resonance with a radial spin wave mode. Second, one can apply dynamic in-plane fields (Refs. [7–13] and references quoted therein) or dynamic in-plane spin-polarized currents [14–16]. In the first case the spin configuration remains radially symmetric during the switching process, whereas in the second case the radial symmetry is broken. In Ref. [5] these two cases therefore have been denoted as symmetric and asymmetric switching. The scope of the present paper is to discuss the physical mechanisms behind these two switching scenarios in order to elucidate the question of whether there are common aspects although the mechanisms are different in detail. We will see that in both scenarios the switching results from the injection and propagation of a Bloch point (see Sec. II).

To investigate the switching mechanisms in detail, micromagnetic simulations of the magnetization dynamics have been done. For symmetric switchings three-dimensional simulations [4–6] have been used. For asymmetric switchings so far two-dimensional simulations have been performed in the literature (see Refs. [9,10,12] and references therein) for the case of excitations by rotating fields. For asymmetric switchings after excitation with two orthogonal monopolar in-plane pulses [13] three-dimensional simulations have been performed, which will be discussed in more detail in the present paper. Three-dimensional simulations are performed for the symmetric switching and for various types of asymmetric switching. It is shown that the three-dimensionality of the processes is essential in the sense that the magnetization dynamics is different in detail in different layers of the disk. The simulations for an excitation by a special type of dynamical in-plane field (see Sec. V A, counterclockwise excitation) give a hint to the fact that the asymmetric switching is not always performed by the mechanism in which a Bloch point moves through the disk during the annihilation of the original vortex with the antivortex of opposite polarization [17] resulting from a vortex-antivortex (VA) pair which is formed by the excitation. There may be also asymmetric switching events in which a magnetic structure similar to a VA pair is formed, but a Bloch point appears in this structure (which is energetically already favorable for this formation) and moves through the disk before the creation of a fully developed VA pair and hence without the annihilation of the original vortex with an antivortex.

II. ROLE OF TOPOLOGICAL INVARIANTS AND BLOCH POINTS

A topological invariant of a magnetization configuration $\boldsymbol{M}(\boldsymbol{r})$ is a quantity which does not change during a continuous

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deformation of the configuration. To change such an invariant quantity by one unit, a topological defect, i.e., a discontinuity of $\boldsymbol{M}(\boldsymbol{r})$, must move through the configuration. One topological invariant of a vortex or of an antivortex configuration is the winding number n which is the total variation of the angle of the projection of $\boldsymbol{M}(\boldsymbol{r})$ to the x-y plane of the disk relative to the x axis, divided by 2π. Independent of the polarity p, a vortex (antivortex) has the winding number $n = 1$ ($n = -1$). Another topological invariant is the Skyrmion number $q = \pm\frac{1}{2}np$ (+ sign for the top surface and − sign for the bottom surface). In thin-film elements, the Skyrmion number can be considered as a topological invariant for each surface. Alternatively, the total Skyrmion number S can be defined as the sum of the above-defined Skyrmion numbers for both surfaces, yielding $S = 0$ both for a vortex and for an antivortex.

When switching the polarity p from $p = +1$ to $p = -1$ the winding number n remains 1 (vortex) or -1 (antivortex) for the top surface, but q changes from $+\frac{1}{2}$ to $-\frac{1}{2}$ (vortex) or from $-\frac{1}{2}$ to $+\frac{1}{2}$ (antivortex). This requires the action of a topological defect, namely the injection of a Bloch point [18,19] at one surface and its movement to the opposite surface where it leaves the disk. The simplest example of a Bloch point [20] has the property that the magnetization vectors are radially oriented away from that point, so that no magnetization direction can be assigned to the center $\vec{r}_c$ of this configuration, yielding $\boldsymbol{M}(\boldsymbol{r}_c) = 0$. Independent of the question of how the switching mechanism looks in detail (see Secs. IV, V) the switching requires the movement of a Bloch point through the disk in a perpendicular direction which changes the Skyrmion number q by one unit (whereas n and S are conserved). This is a common aspect of all switching events.

III. DETAILS OF THE MICROMAGNETIC SIMULATIONS

The simulations are based on the Landau-Lifshitz-Gilbert equation [21], an equation of motion for the magnetization $\boldsymbol{M}(\boldsymbol{r},t)$ which has the mathematical form of the Landau-Lifshitz equation [22], but different prefactors, which ensure that the Landau-Lifshitz-Gilbert equation yields reasonable results also for infinite damping. The Landau-Lifshitz-Gilbert equation with a magnetization $\boldsymbol{M}(\boldsymbol{r},t)$ discretized in space and time is the basis for the MUMAX3 code [23]. The simulations discussed in this paper are performed on disk-shaped platelets of Permalloy with a diameter of 500 nm and a thickness of 50 nm and cubic simulation cells of volume $(1.5\text{ nm})^3$. Standard Permalloy material parameters are used: damping constant $\alpha = 0.007$, saturation magnetization $M_s = 690\,\text{kA}\,\text{m}^{-1}$, exchange constant $A = 13 \times 10^{-12}$ J/m, the Landau-Lifshitz gyromagnetic ratio $\gamma = 2.21 \times 10^5\,\text{m}\,\text{A}^{-1}\text{s}^{-1}$ which is the value for the free electron, because in Permalloy the contribution of orbital moments to the magnetization is very small, and the anisotropy constant K_1 (and all higher anisotropy constants) zero.

We note the following problems. As discussed in Sec. II, a switching of the vortex core requires the formation and movement of a Bloch point which is a topological defect with zero magnetization at the center of the Bloch point. Because the theory of micromagnetism assumes that $\boldsymbol{M}(\boldsymbol{r},t)$ varies as a continuous and smooth vector field with constant magnitude at any point, it can in principle not be used for the study of a Bloch point. It has been shown in Ref. [3] that, nevertheless, a micromagnetic treatment of a Bloch point is possible, whereby the Bloch point is always located between simulation cells. However, the results depend sensitively on the sizes of the simulation cells. Therefore, micromagnetic simulations of effects involving Bloch points have to be considered with some care.

Graphical representation

Furthermore, in a three-dimensional simulation the magnetic configurations are different in different layers. Therefore, it is often more difficult than in two-dimensional simulations to identify and represent important features of the investigated processes, for example VA pairs, which appear momentarily in some but not in all layers or a Bloch point with a inherently threedimensional structure. We therefore extracted the features important for core reversal. In the following figures, the lines indicate the positions of the cores of the original vortex "up" (red line) and of the vortex (blue line) and antivortex (gray line) "down" of the VA pairs with "down" polarity. At these lines, the magnetization points exactly out of the plane. The lines are obtained from the intersection of the isosurfaces with $M_x = 0$ and $M_y = 0$ as described in Ref. [17]. The "tubes" around these lines represent the isosurfaces with $M_z/M_S = -0.8$ (blue) and

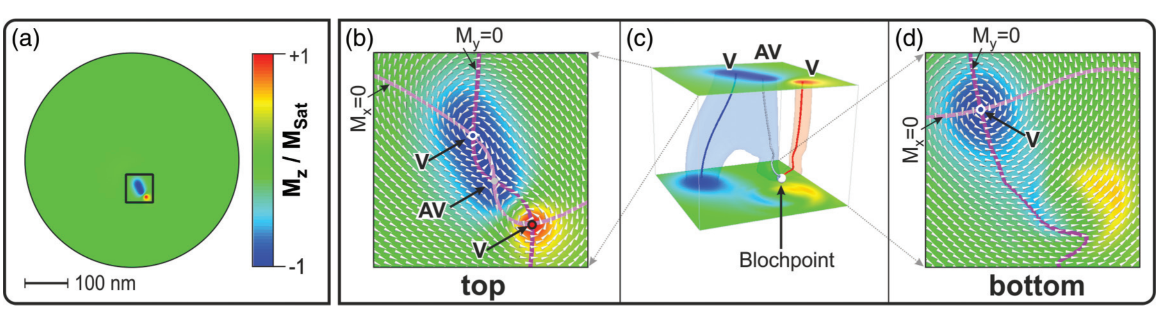

FIG. 1. (Color) Magnetization configuration during vortex core reversal by excitation of the vortex gyrotropic mode [color coding represents out-of-plane magnetization; the white arrows in (b) and (d) indicate the orientation of the in-plane magnetization]. The region of the core and the dip close to the core as marked in (a) is shown in detail in (b)–(d). At the top (b) exists a vortex (V)/antivortex (AV) pair "down" and a vortex "up" while at the bottom (d) only a vortex "down" exists. Inside the sample, a Bloch point is located where the cores of the antivortex "down" and vortex "up" meet (c). The vortices and the antivortex are located at the intersections of the isosurfaces $M_x = 0$ and $M_y = 0$ [(b), (d)].

$M_z/M_S = +0.8$ (red) to show the width of the vortices or antivortices. Bloch points are represented as white spheres and their positions are determined by the intersection of the three isosurfaces $M_x = 0$, $M_y = 0$, and $M_z = 0$. Additionally, the z component of the magnetization at the top and the bottom surface of the disk are shown. In all cases, only that part of the system is shown which contains the core of the original vortex and the dip region close to the core where the VA pair is formed [see Fig. 1(a)].

IV. SYMMETRIC SWITCHING

It has been shown in Ref. [3] by micromagnetic simulations that the vortex switching by the application of a static external magnetic field antiparallel to the core magnetization involves the nucleation of a Bloch point at one surface of the sample, followed by its displacement along the sample thickness. The nucleation of the Bloch point requires a certain amount of energy which is provided by rather large external fields of about 0.5 T in Permalloy disks. These values are higher than the experimental values [2] probably [3] due to the assistance of thermal excitations or interactions with defects for the nucleation of the Bloch point in a real sample. In a thin-film element of thickness D, a useful analytical estimate of the energy E_{BP} of a Bloch point structure can be obtained from an analytic integration over its exchange energy density within a sphere of radius $D/2$, yielding [24] $E_{\mathrm{BP}} = 4\pi AD$ where A is the exchange constant. This value is equal to one-half of the numerically determined energy threshold $E_{\mathrm{VAV}} = 8\pi AD$ for the formation of a vortex-antivortex pair in the case of vortex core switching by asymmetric excitation [25]. Hence, once a vortex-antivortex pair is created, the system has already accumulated sufficient energy to generate a Bloch point.

The nucleation of a Bloch point can also be caused by pumping energy into the system by oscillating external magnetic fields which are in resonance with a radial spin-wave mode and which are applied perpendicularly to the disk plane. It was found by three-dimensional micromagnetic simulations [5,6] that the threshold fields required for the vortex core switching are thereby an order of magnitude smaller than those of static perpendicular fields. The switching times could be reduced below 200 ps for small disk thicknesses of about (1–30) nm and diameters of 300 nm.

The authors Wang and Dong [4] did not see in their simulations the movement of a Bloch point (in contrast to Ref. [5]), and it was claimed that the core switching was generated by the movement of a Néel wall. This would be in contrast to the general knowledge that the vortex core switching requires the action of a Bloch point, and we therefore think that the statement of Ref. [4] results from an artifact of the simulations or of their analysis. In fact, in a later publication Dong, Wang, and Wang [6] considered a slightly different system with a spin-wave potential well obtained by setting up a cylindrical cavity in the center of the sample, and by this the vortex could be reversed well below 200 ps and for a wide range of frequencies of the perpendicularly applied fields. In the corresponding micromagnetic simulations the authors used smaller simulation cells than in Ref. [4] and found the action of a Bloch point as in Ref. [5].

We have performed our own three-dimensional micromagnetic simulations for the vortex core switching by oscillating magnetic fields perpendicular to the disk plane for parameters very similar to those of Ref. [4]. The radial spin wave excited by the oscillating external field has an oscillating out-of-plane component of the magnetization. This leads to an oscillation of the local exchange energy at the core with a maximum amplitude when the magnetization of the spin wave is opposite to the one of the core. When the energy is high enough, a Bloch point is formed and core reversal occurs. In contrast to Ref. [4] we found a moving Bloch point during the switching of the vortex. When continuing the excitation 30 ps after the first switching the core was inverted back to the original vortex polarity by a second symmetric switching process. Thereafter, we observed a breaking of the radially symmetric situation with the formation of two VA pairs and the switching of the vortex polarity due to the annihilation of the original vortex with one of the antivortices (as for switching processes after excitation with dynamical in-plane fields). Our assumption is that the breaking of the radial symmetry arises from the use of a cubic discretization net in the simulation code, which intrinsically breaks the radial symmetry. It should be noted that in a real experiment generally the radial symmetry is also broken. A first possible reason is a nonperfect radial symmetry of the sample shape or the existence of structural defects and surface roughnesses. A second reason is that it is impossible to generate experimentally for these nanodisks oscillating magnetic fields which have exactly an out-of-plane orientation, there are always at least small in-plane components. Altogether, small effects seem to destabilize the radially symmetric magnetization dynamics leading to an asymmetric switching mechanism.

V. ASYMMETRIC SWITCHING

As discussed in the introduction, an asymmetric switching of the vortex polarity can be performed by sinusoidal [7] or rotating [9,10,12] radio frequency (RF) in-plane magnetic fields, by excitations with two orthogonal monopolar pulses [11,13], or by dynamical in-plane spin-polarized currents [14–16]. The in-plane RF fields can be in resonance with the gyrotropic eigenmode [7,9] of the vortex core with an eigenfrequency typically in the range of 100 MHz to 1 GHz, or in resonance with azimuthal spin waves at higher GHz frequencies [10], or it can be a nonresonant excitation by short multi-GHz rotating field bursts down to one-period bursts [12]. By excitation with higher GHz rotating fields the core can be switched [12] in about 200 ps with field amplitudes of a few mT for disks of diameter 1600 nm and thickness of 50 nm. By use of two orthogonal pulses the switching time can be reduced [13] to below 100 ps, but then the switching fields are about 20 − 30 mT for disks of diameter 500 nm and thickness 50 nm.

For the switching by rotating in-plane fields so far only two-dimensional micromagnetic simulations have been performed. In all these simulations the switching occurs via the formation of a local out-of-plane magnetized dip region close to the vortex core with magnetization opposite to the core magnetization. The dip splits into a VA pair with a polarity opposite to the one of the original vortex, and the switching is performed via annihilation of the antivortex with the original vortex. Because the magnetic configurations during this process are not radially symmetric, we have an asymmetric switching. In the present paper three-dimensional simulations are performed for various types of in-plane excitations.

Let us first discuss the asymmetric switching as it is found in the two-dimensional simulations from the viewpoint of Skyrmion numbers. We start with a vortex with polarity $p = +1$, which has $q = +\frac{1}{2}$ $(-\frac{1}{2})$ for the top (bottom) surface and $S = 0$. The polarity of the VA pair is $p = -1$, leading to $q = +\frac{1}{2}$ $(-\frac{1}{2})$ for the antivortex with $n = -1$ (for the new vortex with $n = +1$) at the top surface, as well as $q = -\frac{1}{2}$ $(+\frac{1}{2})$ for the antivortex (for the new vortex) at the bottom surface, with $S = 0$ (0). The switching occurs by the annihilation of the original vortex with the antivortex, whereby a Bloch point moves through the disk (of course the movement of the Bloch point is not seen in two-dimensional simulations). A three-dimensional simulation of the switching process, for example by excitation of the vortex gyrotropic mode, shows that after the complete splitting of the dip into a VA pair the annihilation of the antivortex with the original vortex starts for instance at the bottom layer while in the top layer both the VA pair and the original vortex are still there (Fig. 1). This means that at the bottom layer [Fig. 1(d)] a vortex with opposite polarity $p = -1$ and with $q = +\frac{1}{2}$ remains; i.e., the Skyrmion number q changes from $-\frac{1}{2}$ to $+\frac{1}{2}$, while it is still unchanged in the top layer [Fig. 1(b)]. This already proves the presence of a Bloch point in the current magnetization configuration, which can be indeed found in the simulation [Fig. 1(c)]. After the movement of the Bloch point we have the final vortex with $q = -\frac{1}{2}$ $(+\frac{1}{2})$ at the top (bottom), so both q values changed, and this is caused by the action of the Bloch point. This description also applies to thin disks with thicknesses in order of the exchange length; however, the Bloch point traverses the sample typically in less than 1 ps.

In the following we represent the results of our three-dimensional simulations for different types of excitation.

A. Excitation with two orthogonal monopolar pulses

We first discuss in detail the results of our three-dimensional simulations for the switching of the vortex by an excitation with two orthogonal monopolar pulses as demonstrated experimentally [13]. The insets of Fig. 2 show the pulse sequence used for these simulations. The excitation consists of two orthogonal monopolar magnetic in-plane field pulses of Gaussian shape with pulse amplitude B, pulse length T (full width at half maximum of the Gaussian), and with a delay of $T/2$ between the pulses. For a counterclockwise (clockwise) excitation the first pulse is in x direction (y direction) and the second pulse is in y direction (x direction). At the beginning of the simulation the polarity of the vortex is $p = +1$, the chirality is $C = +1$, and the vortex core is at rest in the center of the disk.

For a counterclockwise (CCW) excitation with $B = 29$ mT the simulations yield a switching in agreement with observations of the time-resolved scanning transmission x-ray microscopy [13]. For a clockwise (CW) excitation even at higher amplitudes $B = 35$ mT the simulations do not show a switching, which corresponds to the experiments where the switching threshold in the CW case is systematically higher. This unidirectionality of the switching process has been explained in Ref. [13] by the coupling of the azimuthal spin waves excited by the pulse sequence with the gyrotropic vortex mode, which for $p = +1$ always has a CCW sense of rotation. Because of this coupling the response of the magnetization on the excitation depends on whether the sense of rotation of the excited spin-wave mode (which has the sense of rotation of the excitation) is the same or opposite to the sense of rotation of the gyromode. This leads to different trajectories of the center of the vortex core and to different gyrofields [26]. The gyrofields are responsible for the formation of the dip region discussed above which precedes the possible switching of the vortex.

For the CCW excitation the simulations show [Fig. 2(a)] that the dip splits into a VA pair with "down" polarity. Then the AV approaches the original V "up". At $t = 211.2$ ps a Bloch point is injected at the bottom surface of the disk, exactly at the position of the original vortex. In contrast to the previously discussed case of the vortex gyrotropic mode, the splitting of the dip into a VA pair is not complete along the thickness of the disk, but the V and AV are still connected at the point C. At BP injection, the distance between AV and the original V "up" is approximately 2 nm. 0.5 ps later they connect leading to the V-AV annihilation ($t = 212$ ps). This means that the original V and AV merge to one line with $M_x = M_y = 0$. The attachment point moves from the bottom to the top when the Bloch point moves in this direction; i.e., the V-AV annihilation progresses upwards. Due to the only partial splitting of the VA pair, the AV disappears when annihilation reaches the height of the attachment point C of the VA pair. The vortex "down" is now attached to the original vortex at the position of the Bloch point. The inversion is completed when the Bloch point leaves the disk at the top surface. This is a hint of the fact that also asymmetrical switching processes do not necessarily need the annihilation of the original V with the AV of a VA pair, but that there may be an alternative scenario in which a Bloch point moves through the disk before the formation of a completely developed VA pair (see Sec. V C.).

For a CW excitation [Fig. 2(b)] the dip splits again into a VA pair ($t = 62$ ps), starting at the top and progressing to the bottom (white arrow), while the AV approaches the original V now at the top as indicated by the black arrow. When AV and V come together a Bloch point is injected at the meeting point ($t = 120$ ps). The pair of the original V and AV merge to one joint line $M_x = M_y = 0$, connected by the Bloch point and the BP point moves from the top to the bottom (black arrow). Simultaneously, the V and the AV of the VA pair approach each other at the bottom of the disk (white arrows) and merge to one line $M_x = M_y = 0$. The attachment point moves upwards ($t = 130$ ps, left arrow) while the BP moves downwards (right arrow). This results in a similar situation as in the CCW case at $t = 114$ ps. However, the dip region which is present in the CCW case has disappeared here due to the asymmetry described above. Therefore the Bloch point moves to the top and leaves the disk and the old vortex remains. This means that although the dip splits at the beginning into a VA pair and a Bloch point is injected, there is no final reversal of the polarity of the original vortex. Note that for both CW and CCW pulsed excitation at higher amplitudes more complex scenarios were observed, including the creation of multiple Bloch points.

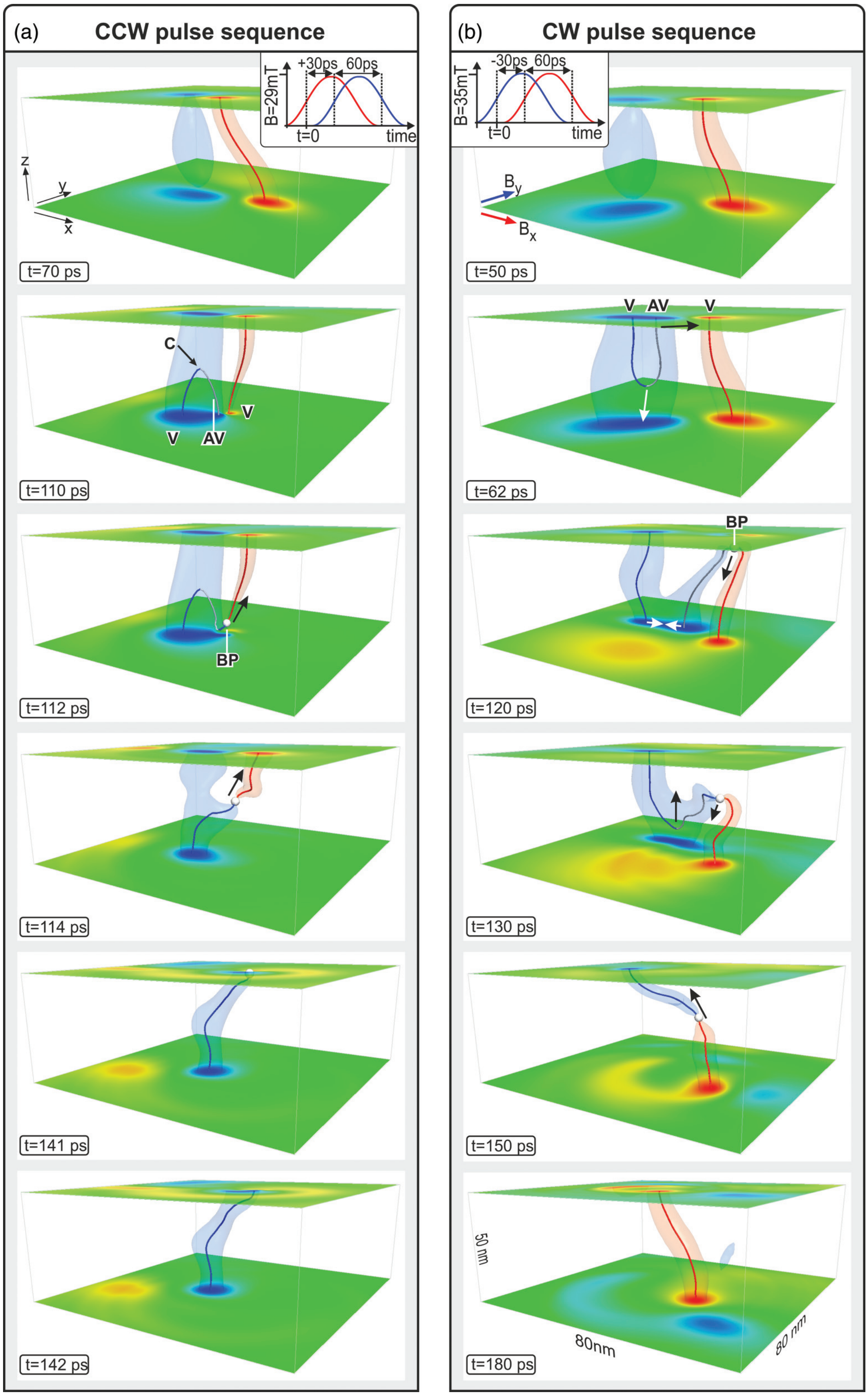

FIG. 2. (Color) Unidirectional vortex core reversal by pulsed excitation (see insets). Although the pulse amplitudes are higher for the CW excitation (b) and a Bloch point (BP) is injected, the reversal is not completed for this excitation. The core is only switched in the CCW case (a). There, a VA pair is present during BP injection ($t = 112$ ps), but this pair is transformed in vortex "down" only and the switching is completed without the presence of an AV ($t = 114$ ps). (For a detailed description of the dynamics see text.)

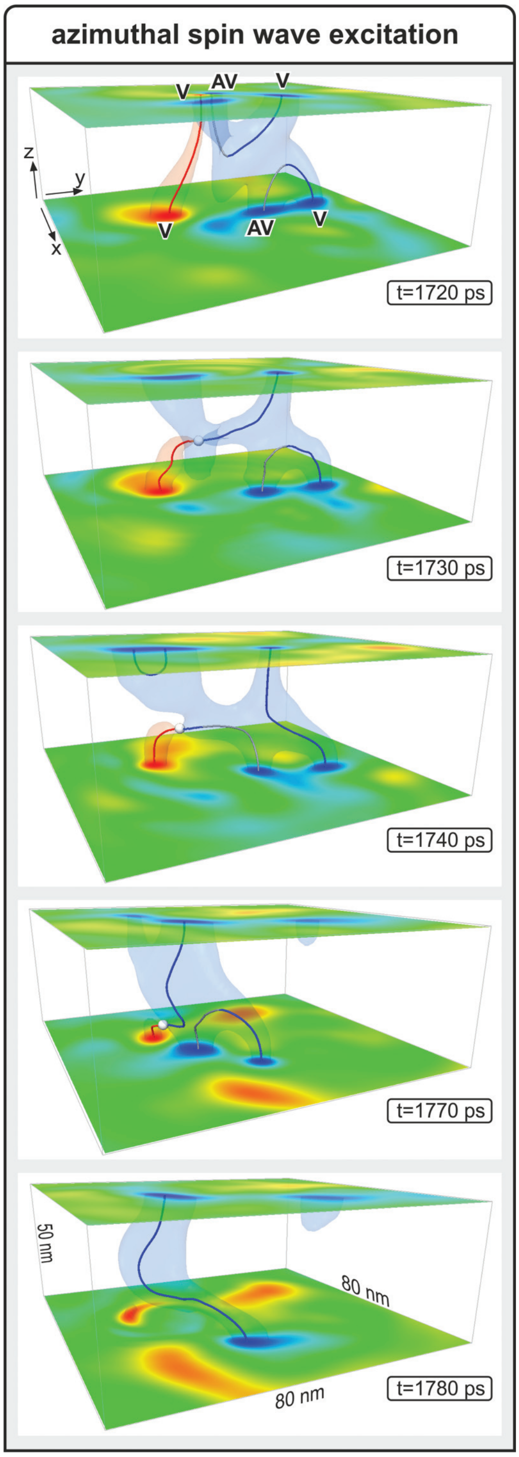

FIG. 3. (Color) Vortex core switching due to resonant excitation of an azimuthal spin wave. Here, two partial VA pairs are formed ($t = 1720$ ps). Reversal starts with the AV of the top VA pair. Between $t = 1730$ ps, $t = 1740$ ps, and $t = 1770$ ps the configuration of the vortices and the antivortex changes twice before the inversion is complete at $t = 1780$ ps.

B. Excitation of azimuthal spin waves

For the resonant excitation of azimuthal spin-wave modes the effects are even more complicated (Fig. 3). For instance, for a switching by the excitation of an $n = 1$, $m = +1$ CW spin-wave mode $f = 6.45$ GHz a VA pair is generated both at the bottom and at the top of the disk. Then the original V and the new AV of the VA pair at the top approach each other until a Bloch point is injected. Similarly to the description for pulsed excitation, the upper AV disappears ($t = 1730$ ps). During the reversal, the configuration of vortices and the antivortex changes repeatedly: While the original vortex is connected to the upper vortex "down" at $t = 1730$ ps and $t = 1770$ ps, it is connected to the bottom antivortex at $t = 1770$ ps. At $t = 1780$ ps, the Bloch point has left the sample and the other vortex with the reversed polarity remains. It should be noted that for slightly different frequencies or excitation fields the details of the switching process are sometimes somewhat different and similar situations to those described in Fig. 2(b) can occur where switching is initiated but not completed.

C. Possible switching scenario without involvement of a vortex-antivortex pair

We now want to introduce the idea that for special situations (disk geometry, frequency, excitation amplitude, etc.) it might be that an asymmetric switching occurs before the dip splits into a VA pair, i.e., not via annihilation of the original V with an AV, simply because a Bloch point moves (possibly on a nonstraight path) through the disk. The VA annihilation (which is accompanied by the movement of a Bloch point) is a possible scenario for the vortex-core annihilation, but it is not the only possible scenario. However, in all cases a switching is related to the movement of a Bloch point (see Sec. II), either during the annihilation of the original vortex with the antivortex of the formed VA pair, or, alternatively, without the formation of a VA pair. The formation of a Bloch point requires energy. When applying a static out-of-plane field antiparallel to the vortex-core magnetization, it requires large field amplitudes to form the Bloch point (see Sec. III). In the above-discussed alternative scenario the Bloch point is formed in a magnetic configuration which is already similar to the configuration of a VA pair and which is energetically favorable for the formation of a Bloch point. Therefore, the required field amplitudes for the excitation are similarly small for the two scenarios. Thus we do not discuss two completely different scenarios, but scenarios which are very similar in the sense that both are related to dips in which a VA pair has already formed completely in the first scenario or is on the way to be formed in the alternative scenario. The only difference is the precise time at which the Bloch point is formed and moves through the disk.

VI. CONCLUSIONS

We have performed three-dimensional micromagnetic simulations (with the MUMAX3 code based on the Landau-Lifshitz-Gilbert equation of motion) for the switching of a magnetic vortex core in a cylindrical disk. We investigated two cases, one in which a symmetric switching was initiated by excitation with dynamic out-of-plane fields and another case which is antisymmetric and occurs for excitations with various types of dynamic in-plane fields. By discussing the role of topological invariants, it becomes clear that irrespective of the complexity of the details of the switching process, a Bloch point always moves through the disk when the core switches. This is an important common aspect of different switching mechanisms. In all cases of dynamical excitation, this Bloch point is created by a large local exchange energy caused by a region close to the core with out-of-plane components opposite to the core magnetization. This is another common aspect.

It is shown that in general a three-dimensionality of the magnetization dynamics appears; i.e., the momentary magnetization configurations are different in different layers of the disk. In all asymmetric switching processes a dip with out-of-plane components of the magnetization develops which is in opposite direction to the out-of-plane magnetization of the vortex core. This is a second common aspect. It is generally assumed that for strong enough excitations the dip splits into a VA pair, and that the switching occurs via the annihilation of the original vortex with the antivortex (whereby a Bloch point moves through the disk). In three-dimensional simulations the pairs do not develop simultaneously in all layers, and therefore it is more difficult than in two-dimensional simulations to see them. There may be also situations in which a switching occurs, but no fully developed VA pair is seen, even when using small simulation cells and short time steps. It is suggested that the switching by the annihilation of the original vortex with the antivortex is a possible switching scenario, but that it is not the only possible scenario. It might be that there are situations for which an asymmetric switching occurs via a slightly different scenario, in which a Bloch point is formed in the dip which started to develop a VA pair but which has not yet completed the formation of this pair, and that it moves through the disk without an annihilation of the original vortex with an antivortex.

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