

Central Lancashire Online Knowledge (CLOK)

Title	Boris computational spintronics—High performance multi-mesh magnetic and spin transport modeling software
Type	Article
URL	https://clock.uclan.ac.uk/id/eprint/36281/
DOI	https://doi.org/10.1063/5.0024382
Date	2020
Citation	Lepadatu, Serban (2020) Boris computational spintronics—High performance multi-mesh magnetic and spin transport modeling software. Journal of Applied Physics, 128 (24). p. 243902. ISSN 0021-8979
Creators	Lepadatu, Serban

It is advisable to refer to the publisher's version if you intend to cite from the work.
<https://doi.org/10.1063/5.0024382>

For information about Research at UCLan please go to <http://www.uclan.ac.uk/research/>

All outputs in CLOK are protected by Intellectual Property Rights law, including Copyright law. Copyright, IPR and Moral Rights for the works on this site are retained by the individual authors and/or other copyright owners. Terms and conditions for use of this material are defined in the <http://clock.uclan.ac.uk/policies/>

Boris computational spintronics—High performance multi-mesh magnetic and spin transport modeling software

Cite as: J. Appl. Phys. **128**, 243902 (2020); <https://doi.org/10.1063/5.0024382>

Submitted: 06 August 2020 . Accepted: 07 December 2020 . Published Online: 28 December 2020

 Serban Lepadatu

COLLECTIONS

 This paper was selected as an Editor's Pick



View Online



Export Citation



CrossMark

ARTICLES YOU MAY BE INTERESTED IN

A technique to measure spin-dependent trapping events at the metal-oxide-semiconductor field-effect transistor interface: Near zero field spin-dependent charge pumping
Journal of Applied Physics **128**, 244501 (2020); <https://doi.org/10.1063/5.0027214>

Reconfigurable and self-biased magnonic metamaterials
Journal of Applied Physics **128**, 240902 (2020); <https://doi.org/10.1063/5.0033254>

THz-range Faraday rotation in the Weyl semimetal candidate Co₂TiGe
Journal of Applied Physics **128**, 244303 (2020); <https://doi.org/10.1063/5.0033536>



Your Qubits. Measured.

Meet the next generation of quantum analyzers

- Readout for up to 64 qubits
- Operation at up to 8.5 GHz, mixer-calibration-free
- Signal optimization with minimal latency

Find out more



Boris computational spintronics—High performance multi-mesh magnetic and spin transport modeling software

Cite as: J. Appl. Phys. **128**, 243902 (2020); doi: [10.1063/5.0024382](https://doi.org/10.1063/5.0024382)

Submitted: 6 August 2020 · Accepted: 7 December 2020 ·

Published Online: 28 December 2020



Serban Lepadatu^{a)} 

AFFILIATIONS

Jeremiah Horrocks Institute for Mathematics, Physics and Astronomy, University of Central Lancashire, Preston PR1 2HE, United Kingdom

^{a)}Author to whom correspondence should be addressed: SLepadatu@uclan.ac.uk

ABSTRACT

This work discusses the design and testing of a new computational spintronics research software. Boris is a comprehensive multi-physics open-source software, combining micromagnetics modeling capabilities with drift-diffusion spin transport modeling and a heat flow solver in multi-material structures. A multi-mesh paradigm is employed, allowing modeling of complex multi-layered structures with independent discretization and arbitrary relative positioning between different computational meshes. Implemented micromagnetics models include not only ferromagnetic materials modeling, but also two-sublattice models, allowing simulations of antiferromagnetic and ferrimagnetic materials, fully integrated into the multi-mesh and multi-material design approach. High computational performance is an important design consideration in Boris, and all computational routines can be executed on graphical processing units (GPUs), in addition to central processing units. In particular, a modified 3D convolution algorithm is used to compute the demagnetizing field on the GPU, termed pipelined convolution, and benchmark comparisons with existing GPU-accelerated software Mumax3 have shown performance improvements up to twice faster.

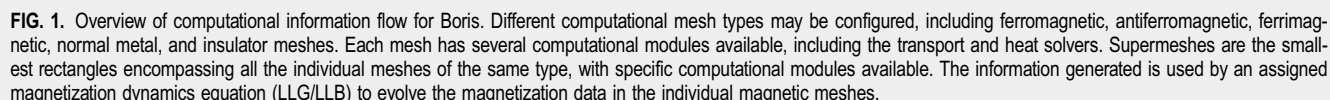
Published under license by AIP Publishing. <https://doi.org/10.1063/5.0024382>

I. OVERVIEW

Micromagnetics is a field of study concerned with understanding magnetization processes on the continuum scale and is an invaluable tool in interpreting experimental results, designing spintronics devices, testing analytical methods, and predicting new effects. Existing micromagnetics software includes open-source finite difference packages OOMMF,¹ Mumax3,² and Fidimag.³ A number of other micromagnetics packages are also available, including finite element/boundary element methods, both open-source and commercial, with a review given in Ref. 4.

Boris is a micromagnetics-oriented multi-physics research software. In contrast to the existing finite difference packages, it is specifically designed as a multi-mesh and multi-material software. Arbitrary geometries can be handled, where long-range interactions such as the magnetostatic interaction and Oersted field are calculated across all relevant computational meshes, and short-range interactions between neighboring meshes are treated using

appropriate composite media boundary conditions. An overview is given in Fig. 1. Magnetization dynamics are computed using the Landau–Lifshitz–Gilbert (LLG) equation⁵ or the Landau–Lifshitz–Bloch (LLB) equation,⁶ either of which may be augmented by thermal fluctuations (stochastic versions),^{7,8} Zhang–Li spin transfer torques (STTs),⁹ interfacial STT (ISTT),^{10,11} spin–orbit torques (SOTs) due to the spin–Hall effect (SHE),¹² Slonczewski spin torques,¹³ or spin torques computed self-consistently using a spin transport solver. The spin transport solver is based on a drift-diffusion model with circuit theory boundary conditions^{14–16} and self-consistently calculates charge currents, spin currents, and spin accumulations in multi-layer structures.¹⁷ In addition to obtaining spin torques self-consistently, several effects may be computed, including anisotropic magneto-resistance (AMR), current perpendicular to plane giant magneto-resistance (CPP-GMR),¹⁵ SHE and inverse SHE (ISHE),¹⁸ spin pumping,¹⁹ charge pumping, and the topological Hall effect.^{20,21} A heat solver is also available, allowing calculation of heat flow in response to ambient conditions as well



The computational meshes can be sized and discretized independently. One of the most difficult interactions to compute across several independent computational meshes is the magnetostatic interaction. A newly developed method, termed multi-layered convolution,²⁴ allows computation of demagnetizing fields for multiple meshes with arbitrary thicknesses, arbitrary relative positioning and spacings, without impacting on the computational performance. Other long-range interactions include the Oersted field, which is computed from the current density obtained using the transport

The software has a modular structure and is open-source,²⁹ facilitating community contributions of new computational modules. An extensive user manual³⁰ is included, together with many examples of both scripted simulations, as well as pre-configured simulation setups. The software is provided with a graphical user interface for interactive display of simulation data, with user control enabled through a graphical console allowing intuitive and interactive control of simulations. The software may also be controlled using Python scripts, which communicate with Boris through network sockets, thus allowing either local or remote user control. The software has been programmed mainly in C++17 and CUDA C, as well as Python. All computational routines can be executed on central processing units (CPUs), as well as graphical processing units (GPUs) using the CUDA framework.³¹ Supported operating systems include Windows 7, Windows 10, and Linux-based distributions; in the current version (2.9) Linux compilations of Boris do not include a graphical interface, only providing a basic text console; however, the software is otherwise fully functional and may be conveniently controlled using Python scripts, which is especially useful for controlling multiple

independent instances in a Linux cluster. The code-base size currently consists of ~ 130 k source lines of code (comments and trivial lines excluded) and is contained in ~ 800 source code files, including a purpose-written object-oriented finite difference vector calculus library for both CPU and GPU computations. External dependences include FFTW³² and CUDA.³¹ Material definitions are made available through an online database of material parameters.³³ The online materials database allows users to contribute new entries through a set of simple built-in protocols described in the manual. Material definitions used in this work are given in the online materials database.³³ Moreover, all the simulation scripts and files used to obtain the results presented here have been included in the Boris GitHub repository.²⁹

II. BASIC MICROMAGNETICS MODELING

In the continuum approximation, magnetization dynamics may be computed using the LLG equation,

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}. \quad (1)$$

Here, $\mathbf{m}$ is the normalized magnetization direction; $\gamma = \mu_0 g_{\text{rel}} |\gamma_e|$, where $\gamma_e = -g\mu_B/\hbar$ is the electron gyromagnetic ratio and g_{rel} is a relative gyromagnetic factor; α is the Gilbert damping factor,³⁴ and $\mathbf{H}_{\text{eff}}$ is an effective field that includes a number of interactions as additive field contributions. In a basic micromagnetics formulation, these include an applied field contribution, the magnetostatic or demagnetizing field interaction, and the direct exchange interaction. Depending on the material simulated, a magneto-crystalline anisotropy contribution may be included, either uniaxial or cubic, as well as bulk or interfacial DMI.^{25,26} Equations for these contributions implemented in Boris are given in Appendix A. A number of evaluation methods are available for the magnetization dynamics equations. These are the fixed step methods Euler (1st order), trapezoidal Euler (2nd order), and Runge–Kutta (RK4—4th order). Adaptive time step methods are the adaptive Heun (2nd order), the multi-step Adams–Bashforth–Moulton (2nd order), Runge–Kutta–Bogacki–Shampine (RK23—3rd order with embedded 2nd order error estimator), Runge–Kutta–Fehlberg (RKF45—4th order with embedded 5th order error estimator), Runge–Kutta–Cash–Karp (RKCK45—4th order with embedded 5th order error estimator), and Runge–Kutta–Dormand–Prince (RKDP54—5th order with embedded 4th order error estimator). For static problems, the steepest descent solver is available using Barzilai–Borwein stepsize selection formulas.^{35,36}

A widely used test for the validity and accuracy of LLG solvers is the μMAG Standard Problem #4.³⁷ Here, the magnetization response to a magnetic field is computed for a $\text{Ni}_{80}\text{Fe}_{20}$ rectangle with dimensions $500 \times 125 \times 3 \text{ nm}^3$, starting from a relaxed S-state. This is used as a test for correct implementation of the LLG equation and associated effective field terms (demagnetizing field, exchange interaction, and Zeeman term) as any errors result in significant deviations of the magnetization time dependence from accepted solutions. The results for the specified field 1 ($\mu_0 H_x = -24.6 \text{ mT}$, $\mu_0 H_y = 4.3 \text{ mT}$, $\mu_0 H_z = 0.0 \text{ mT}$) are shown in Fig. 2,

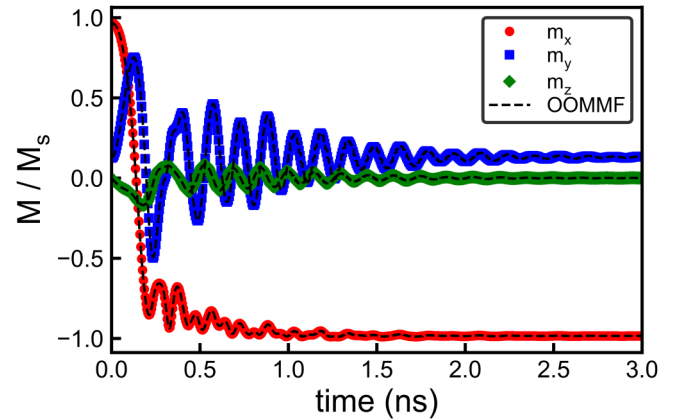


FIG. 2. Magnetization response computed for μMAG Standard Problem #4 using Field 1 specification, showing the normalized components of magnetization, compared to the magnetization response computed in OOMMF. Overall R^2 measure of 0.999 was obtained.

compared with the results obtained using OOMMF.¹ Excellent agreement throughout the switching process is obtained, with an overall R^2 measure between the two data sets of 0.999. A cellsize of 5 nm was used here, which is consistent with the exchange length in $\text{Ni}_{80}\text{Fe}_{20}$, $l_{\text{ex}} = \sqrt{2A/\mu_0 M_s^2} \cong 5.7 \text{ nm}$; however, Boris has been extensively tested using this problem with cellsize values down to 1 nm, thus including both 2D and 3D modes. Similarly, the specified field 2 ($\mu_0 H_x = -35.5 \text{ mT}$, $\mu_0 H_y = -6.3 \text{ mT}$, $\mu_0 H_z = 0.0 \text{ mT}$) was also tested. The results in Fig. 2 were computed using the RK4 method with a fixed time step of 500 fs; however, all the implemented evaluation methods were successfully tested using this problem, for both CPU and GPU computations in single and double floating point precision.

A further test that requires a more advanced external field stimulus consists in computing the spin wave dispersion as described in Ref. 38. Here, a $\text{Ni}_{80}\text{Fe}_{20}$ magnonic waveguide track with $1 \mu\text{m}$ length, 50 nm width, and 1 nm thickness is used, and spin waves are excited using a field pulse given by $H(t) = H_e \text{sinc}[k_C(x - x_0)] \text{sinc}[k_C(y - y_0)] \text{sinc}[2\pi f_C(t - t_0)]$. Boris has a provision for input stimuli specification using mathematical formulas, simultaneously allowing spatial and temporal dependences. Here, the excitation field amplitude was set to $H_e = 400 \text{ kA/m}$, frequency cutoff $f_C = 500 \text{ GHz}$, and wave-vector cutoff $k_C = 2\pi \times 0.1255 \text{ rad/nm}$, as specified in Ref. 38. Using the Nyquist criterion, a time sampling interval of 1 ps and a spatial sampling interval of 4 nm along the $1 \mu\text{m}$ long track were used. The excitation was applied in the center of the track for a duration of $2t_0$, with a temporal sinc pulse center $t_0 = 200 \text{ ps}$. Three spin wave geometries are possible, depending on the direction of the bias field, namely, (i) backward volume for the bias field along the length, (ii) forward volume for the bias field along the thickness, and (iii) surface spin waves for the bias field along the width. The wave-vector direction for this problem in all cases is along the length of the track, which is determined by the spatial sampling direction. Results for the backward

volume are shown in Fig. 3 for a damping value $\alpha = 0.01$, where a bias field $H_0 = 804$ kA/m was used, with the excitation field pulse applied along the width. The spin wave dispersion was obtained using a 2D Fourier transform from the y component of magnetization. The discretization cellsize was set to $1 \times 2 \times 1$ nm³, with periodic boundary conditions³⁹ used along the length only, and the RK4 method was used with a 50 fs time step. This results in excellent agreement between the computed spin wave dispersion and the analytical dotted lines given by $w = w_n + 2\gamma Ak^2/\mu_0 M_S$; here, w_n are the resonance frequencies obtained at $k = 0$ rad/m. Similar tests were performed for the two remaining spin wave geometries.

The LLG equation may be modified to include STT and, in particular, Boris implements Zhang–Li STT,^{9,40} which is given by

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{m} - \beta \mathbf{m} \times (\mathbf{u} \cdot \nabla) \mathbf{m}. \quad (2)$$

The spin-drift velocity $\mathbf{u}$ is given by

$$\mathbf{u} = \mathbf{J} \frac{Pg\mu_B}{2eM_s} \frac{1}{1 + \beta^2}, \quad (3)$$

where $\mathbf{J}$ is the charge current density, P is the current spin polarization, and β is the non-adiabaticity parameter. The LLG-STT equation is widely used for studying the effect of bulk STT on magnetization textures, including transverse domain walls, Bloch and Néel domain walls, vortices, and skyrmions. In particular, domain wall velocity dependence on spin drift velocity may be computed, including simulation of Walker breakdown phenomenon. Since this is a very common type of computation Boris implements a moving domain wall algorithm, which allows efficient simulation of domain wall movement using a finite track length. End magnetic charges are removed using the stray field computed from magnetic dipoles at each end, and spin waves are absorbed by

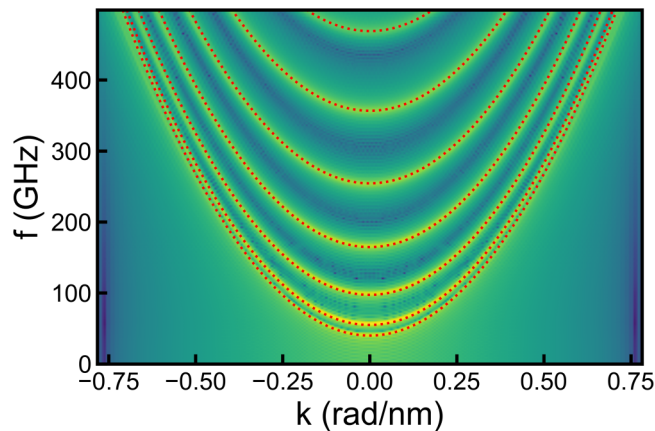


FIG. 3. Spin wave dispersion spectrum computed for the problem specified in Ref. 38, using a damping of 0.01. The dotted lines are obtained from the formula $w = w_n + 2\gamma Ak^2/\mu_0 M_S$, with w_n being the resonance frequencies obtained at $k = 0$ rad/m.

freezing the magnetization spins at the track ends. The domain wall is kept centered in the track and any domain wall displacement is recorded in a dedicated output parameter. This algorithm was tested previously,⁴¹ and it is straightforward to verify the expected relation $v/u = \beta/\alpha$,⁴² with v being the domain wall velocity far from Walker breakdown. Here, we show another test of the LLG-STT equation, based on the μ MAG Standard Problem #5.⁴³ A permalloy rectangle with dimensions $100 \times 100 \times 10$ nm³ is initialized with a vortex structure—Fig. 4(a)—and a constant current density resulting in a spin drift velocity $u = -72.35$ m/s is applied for a range of non-adiabaticity parameter values. Results for $\beta = 0.1$ are shown in Fig. 4(b), using a cubic cellsize of 2.5 nm, plotting the x and y components of magnetization as a function of time. Excellent agreement with results computed in OOMMF is obtained, with an overall R^2 measure between the two data sets of 0.999. Similar successful tests were performed for the remaining specified values of $\beta = 0, 0.05$, and 0.5.

As a further example, we apply the micromagnetics model to compute the vertices population in large-scale simulations of square artificial spin ice (ASI), as studied experimentally in previous studies.^{44,45} A part of the simulated ASI array is shown in Fig. 5(a), where the Ni₈₀Fe₂₀ islands have dimensions

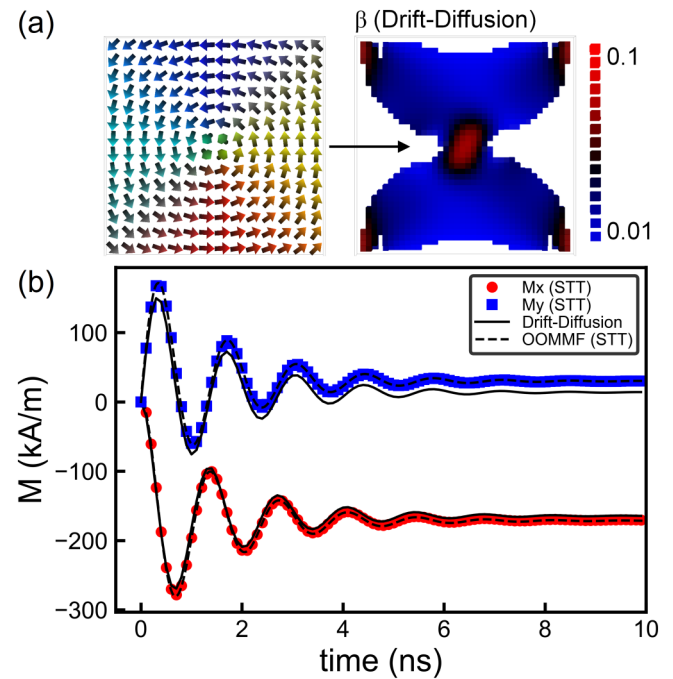


FIG. 4. Vortex dynamics computed for μ MAG Standard Problem #5 for $\beta = 0.1$. (a) Relaxed starting vortex state, also showing the fitted spatial dependence of non-adiabaticity parameter computed using the spin transport drift-diffusion solver. (b) Vortex dynamics are shown for the LLG-STT solver with constant non-adiabaticity, compared to results computed in OOMMF. Overall R^2 measure of 0.999 was obtained. Results obtained using the self-consistent bulk spin torque obtained from the drift-diffusion model, where β is no longer constant but varies due to in-plane spin diffusion, are also shown for comparison.

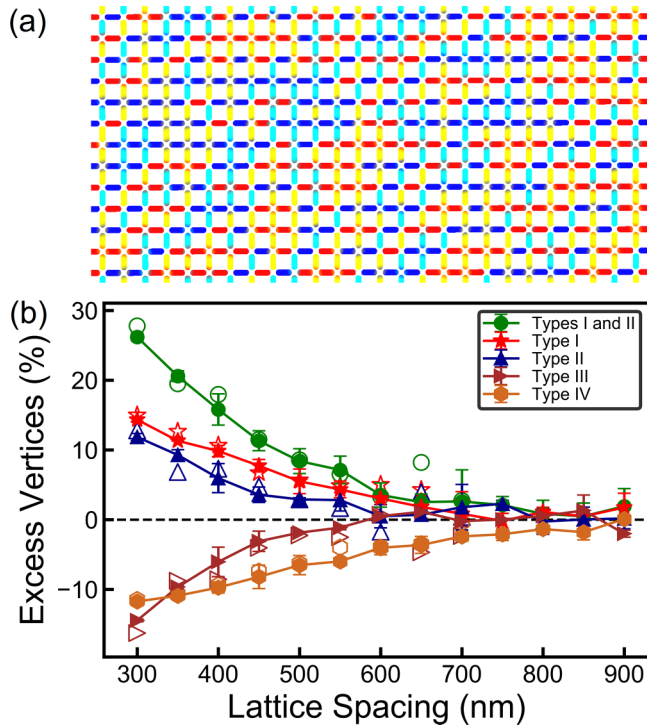


FIG. 5. Square ASI simulations with $220 \times 80 \times 25 \text{ nm}^3$ $\text{Ni}_{80}\text{Fe}_{20}$ elements, computed in both a 2D approximation and a 3D model, with in-plane periodic boundary conditions. For the 2D approximation, a maximum mesh size of $24 \mu\text{m} \times 24 \mu\text{m} \times 25 \text{ nm}$ was used with a 5 nm in-plane cellsize (up to 23M simulation cells). For the 3D model, a maximum mesh size of $6 \mu\text{m} \times 6 \mu\text{m} \times 25 \text{ nm}$ was used with a $2.5 \times 2.5 \times 5 \text{ nm}^3$ cellsize (up to 28.8M simulation cells). (a) Example part of simulated artificial spin ice array, with island direction color coded as blue: left, red: right, yellow: up, and cyan: down. (b) Calculated excess vertices for each vertex type as a function of lattice spacing, averaged over two simulation runs, comparable to results in Ref. 44. Solid symbols are used for the 2D approximation, and open symbols for the 3D model.

$220 \times 80 \times 25 \text{ nm}^3$, as used in Ref. 44. Due to the strong shape anisotropy and small island size, the magnetization is mostly in a single domain state, aligned to the longitudinal direction. Here, we distinguish four types of vertices, types I–IV, depending on the magnetization directions at each vertex, defined in Refs. 44 and 45. Due to magnetic frustration arising from dipolar interactions, the different vertex types have different energies—in particular, vertex types I and II have lower dipolar energy compared to vertex types III and IV, where particularly vertex type IV (all magnetization directions point in or all out) has a prohibitively large dipolar energy. Thus, compared to the expected random vertex population distribution in the absence of dipolar interactions (12.5%, 25%, 50%, and 12.5%, respectively), we expect to obtain an excess vertex population, dependent on the lattice spacing. Here, we compute this, by relaxation from a thermally demagnetized state, as a function of lattice spacing between 300 nm and 900 nm, using both a 2D approximation and a 3D model, shown in Fig. 5(b). These results are in good agreement with those obtained experimentally,⁴⁴

where increasing the lattice spacing causes the excess vertex populations to converge toward zero as the effect of dipolar interactions is reduced. These simulations have been completed on a GPU, automated using a single Python script available in the GitHub repository.²⁹

III. MULTI-MESH MICROMAGNETICS MODELING

Due to progress in experimental magnetism increasingly, devices are composed of complex multi-layered structures, including multi-layered stacks used to study skyrmions^{46–49} and synthetic anti-ferromagnetic structures.^{50–52} Such multi-layered structures, which cannot be discretized effectively using a single uniform finite difference mesh, are difficult to study using software packages which only implement a single computational mesh without introducing approximations or using unnecessarily small cellsize values. In Boris, a multi-mesh paradigm has been adopted from the outset, allowing computations using multiple meshes that can be arbitrarily positioned relative to each other and with independent discretization cellsize values. Thus, while still benefiting from computationally efficient finite difference discretization, multi-layered structures commonly found in experimental studies may be simulated without compromising accuracy or computational speed. This is accomplished using a new multi-layered convolution algorithm introduced in Boris,²⁴ which is used to compute demagnetizing fields for a collection of finite difference computational meshes. For a collection of meshes V_k ($k = 1, \dots, n$), the convolution sum may be written as

$$\mathbf{H}(\mathbf{r}'_{kl}) = - \sum_{\substack{i=1, \dots, n \\ \mathbf{r}_{ij} \in V_i}} \mathbf{N}(\mathbf{r}'_{kl} - \mathbf{r}_{ij}, \mathbf{h}_k, \mathbf{h}_i) \mathbf{M}(\mathbf{r}_{ij}), \quad (4)$$

$$k = 1, \dots, n; \quad \mathbf{r}'_{kl} \in V_k.$$

Here, $\mathbf{r}_{ij}$ is the cell-centered position vector of cell j in mesh i ($i = 1, \dots, n$), and $\mathbf{N}$ are inter- and intra-mesh demagnetizing tensors generalized from the Newell *et al.* formulas⁵³ in Ref. 24. With a single computational mesh, the usual approach to efficiently evaluate the convolution sum is to use the convolution theorem, which involves computing the forward Fourier transform of the magnetization, multiplying point-by-point with the Fourier transform of the demagnetizing tensor (kernel) in the transform space, and finally taking the inverse Fourier transform to obtain the demagnetizing field. With multiple input meshes, a similar approach may be taken to evaluate Eq. (4), with summation of inter-mesh contributions moved to the transform space. Full details, including validation tests, are given in Ref. 24. Here, we extend this algorithm to use periodic boundary conditions based on the multiple images method⁵⁴ and demonstrate the use of multi-layered convolution by simulating the hysteresis loop in a $[\text{Co}_{90}\text{Fe}_{10} (4.9 \text{ nm})/\text{Ru} (0.6 \text{ nm})/\text{Co}_{90}\text{Fe}_{10} (2.9 \text{ nm})/\text{Ru} (0.6 \text{ nm})]_{10}$ synthetic ferrimagnetic structure. Here, the layers preferentially align antiparallel due to RKKY interaction,^{55–57} as well as due to the magnetostatic field interaction between the layers. For two magnetic layers separated by a metallic spacer, the surface exchange

energy density and effective field are given as

$$\begin{aligned}\varepsilon &= -\frac{J_1}{\Delta} \mathbf{m}_i \cdot \mathbf{m}_j - \frac{J_2}{\Delta} (\mathbf{m}_i \cdot \mathbf{m}_j)^2, \\ \mathbf{H}_i &= \frac{J_1}{\mu_0 M_S \Delta} \mathbf{m}_j + \frac{2J_2}{\mu_0 M_S \Delta} (\mathbf{m}_i \cdot \mathbf{m}_j) \mathbf{m}_j.\end{aligned}\quad (5)$$

Here, J_1 and J_2 are the bilinear and biquadratic surface exchange coupling constants, respectively, with coupled magnetic moment directions given by $\mathbf{m}_i$ and $\mathbf{m}_j$, and Δ is the thickness of the ferromagnetic layer for which the $\mathbf{H}_i$ effective field contribution is calculated. The simulated structure is shown in the inset of Fig. 6, where we have used material parameters determined experimentally in Ref. 50 also available in the materials database³³ and, in particular, $J_1 = -1 \text{ mJ/m}^2$ with no biquadratic contribution. The simulated stack uses in-plane periodic boundary conditions, both for the differential operators—exchange field—and for the FFT-based convolution evaluation of the demagnetizing field. The simulated area is 300 nm^2 with an in-plane cellsize of 3 nm . A polycrystalline structure has been generated using in-plane Voronoi tessellation with 20 nm crystallites, where the uniaxial anisotropy easy axis varies randomly by $\pm 20^\circ$ around the x axis between the different crystallites. Results are shown in Fig. 6 with the field applied along the x axis direction. With a large external field, the magnetization in all the layers aligns along the field. Reduction of the field results in gradual rotation of the 10 thinner layers against the field direction, thus reducing the total energy as both the surface exchange and magnetostatic interactions result in preferentially anti-parallel alignment. As the field direction is reversed, all the thicker $\text{Co}_{90}\text{Fe}_{10}$ layers switch at once, with the thinner $\text{Co}_{90}\text{Fe}_{10}$ layer switching against the field due to the strong antiferromagnetic surface exchange interaction; further increasing the field results in gradual rotation of the 10 thinner layers toward the applied field direction. It should be noted that such a structure is very difficult to simulate using a single uniform finite difference computational mesh without introducing approximations, such as rounding the

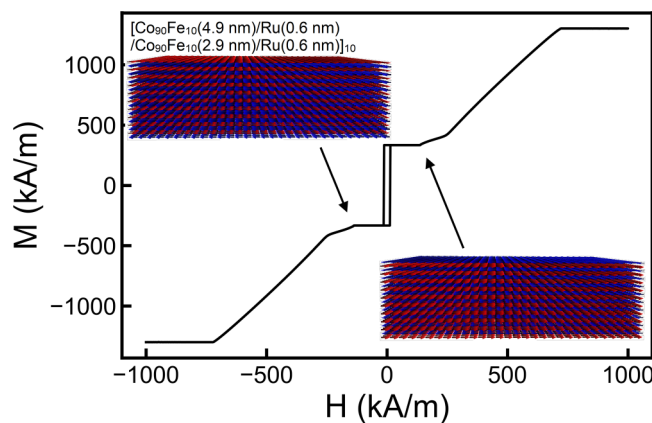


FIG. 6. Hysteresis loop in a synthetic ferrimagnetic 10-repetition multi-layered stack of $[\text{Co}_{90}\text{Fe}_{10} (4.9 \text{ nm})/\text{Ru} (0.6 \text{ nm})/\text{Co}_{90}\text{Fe}_{10} (2.9 \text{ nm})/\text{Ru} (0.6 \text{ nm})]_{10}$.

layer thicknesses, which become increasingly inaccurate as the number of repetitions increases. Even with the layer thickness rounded, for example, to $\text{Co}_{90}\text{Fe}_{10}$ (5 nm)/ Ru (1 nm)/ $\text{Co}_{90}\text{Fe}_{10}$ (3 nm), a discretization cellsize of 1 nm is still required along the z direction. With the multi-layered convolution algorithm in Boris, each layer can be considered a 2D mesh, rendering such simulations relatively trivial.

Further extensions to the micromagnetics model include topographical roughness and staircase corrections for the demagnetizing field, detailed previously²⁸ and tested experimentally,^{58–60} as well as magnetoelastic contributions.^{61,62} Finally, all the material parameters included in simulations may be assigned spatial and temporal dependences through user-supplied mathematical formulas, input data files, or built-in generators. This allows simulations using polycrystalline or granular structures, as well as material defects and impurities.

IV. TRANSPORT SOLVER

Inclusion of spin torques in modern micromagnetics solvers is an essential requirement, allowing modeling the effect of spin transfer torques on domain walls and skyrmions, spin-torque nano-oscillators,⁶³ and magnetic random-access memories.⁶⁴ In the simplest case, a uniform current density may be used, with the LLG equation augmented with appropriate spin torque terms. More advanced solvers also allow for non-uniform current densities, thus enabling simulations of structures with non-constant cross-sectional area. In Boris, the current density may be computed self-consistently for any given geometry and multi-layered structure without having to import a computed current density, using the successive over-relaxation method.⁶⁵

For charge transport only, this is given by $\mathbf{J}_c = \sigma \mathbf{E}$, where σ is the electrical conductivity and $\mathbf{E} = -\nabla V$ is the electric field obtained from the electrical potential V . Results in Fig. 4 made use of the LLG-STT equation with a uniform current density. Here, we further show computations with non-uniform current densities and, in particular, we compute the AMR in a $\text{Ni}_{80}\text{Fe}_{20}$ ellipse where a current density is generated by applying a potential drop across two 5 nm thick metallic contacts, which are included as separate computational meshes with Ru material and Dirichlet boundary conditions set at the ends. The contacts are placed on top of the ellipse, with the simulated geometry given in Fig. 7(a) showing the computed current density. Composite media boundaries between the ellipse and the contacts are treated using the continuity of flux (current density) and electrical potential. The AMR effect is included as $\sigma = \sigma_0 / (1 + r d^2)$, where σ_0 is the material base conductivity, r is the AMR ratio taken as 0.02 for $\text{Ni}_{80}\text{Fe}_{20}$, and $d = \mathbf{J}_c \cdot \mathbf{M} / |\mathbf{J}_c| |\mathbf{M}|$. The results are shown in Fig. 7(b) where the resistance is obtained as the potential drop across the entire simulated structure divided by the total current flowing into the circuit ground. The AMR loops show the typical behavior expected for longitudinal and transverse AMR loops, and it is noteworthy the computed resistance change is significantly lower than the input AMR parameter. This is mostly due to the inclusion of constant resistance of the simulated electrical contacts, but also due to non-uniformity of the current density. Test simulations with uniform current density and potential drop applied directly across a single ferromagnetic mesh reproduce the input AMR ratio accurately.

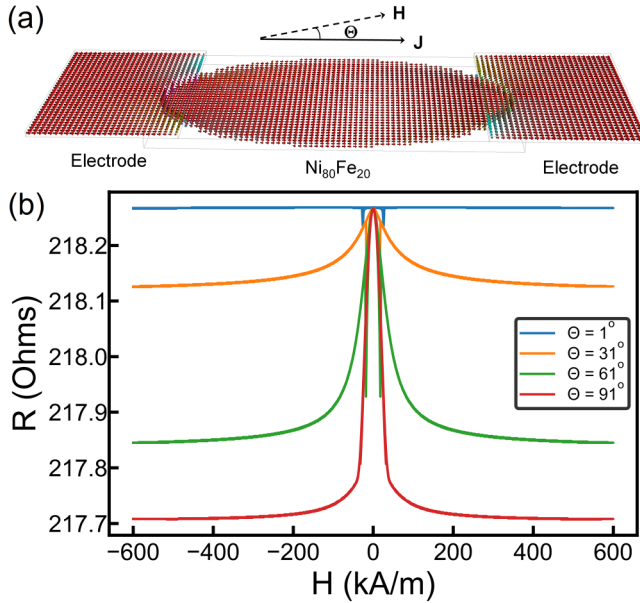


FIG. 7. Anisotropic magneto-resistance (AMR) in a $320 \times 160 \times 10 \text{ nm}^3$ $\text{Ni}_{80}\text{Fe}_{20}$ ellipse. (a) Simulation geometry showing the computed current density, and (b) AMR loops computed for different angles to the ellipse long axis.

An additional benefit of self-consistently computing current densities, an Oersted field can then be generated from it. This avoids having to compute the Oersted field externally and then importing it into the program, which apart from constant current densities is not trivial. Moreover, internal computation of the Oersted field allows simulations with the time-dependent Oersted field, for example, due to time-dependent current densities. Boris computes the Oersted field from the current density by evaluating the convolution sum with an Oersted tensor, using the formulas given in Ref. 66.

Additionally, Boris also allows computation of spin transport based on the drift-diffusion model,^{14,15} augmented with circuit theory boundary conditions.¹⁶ The full system of equations implemented is shown below,

$$\begin{aligned} \mathbf{J}_C &= \sigma \mathbf{E} + \beta_D D_e \frac{e}{\mu_B} (\nabla \mathbf{S}) \cdot \mathbf{m} + \theta_{SHA} D_e \frac{e}{\mu_B} \nabla \times \mathbf{S} + P \sigma \frac{\hbar}{2e} \mathbf{E}^\sigma - P \frac{\sigma^2 \hbar}{e^2 n} \mathbf{E} \times \mathbf{B}^\sigma, \\ \mathbf{J}_S &= -\frac{\mu_B}{e} P \sigma \mathbf{E} \otimes \mathbf{m} - D_e \nabla \mathbf{S} + \theta_{SHA} \frac{\mu_B}{e} \mathbf{E} \otimes \mathbf{S} \\ &\quad + \frac{\hbar \mu_B \sigma}{2e^2} \sum_i \mathbf{e}_i \otimes (\mathbf{m} \times \partial_i \mathbf{m}) + \frac{\hbar \mu_B \sigma^2}{e^3 n} (\mathbf{z} \times \mathbf{E}) \otimes (\partial_x \mathbf{m} \times \partial_y \mathbf{m}). \end{aligned} \quad (6)$$

The charge current density now additionally includes contributions due to (i) current perpendicular to plane giant magneto-resistance (CPP-GMR), where β_D is the diffusion spin polarization, D_e is the electron diffusion constant, and $\mathbf{S}$ is the spin accumulation. (ii) ISHE where θ_{SHA} is the intrinsic spin Hall angle, (iii) charge pumping, and (iv) topological Hall effect, where $\mathbf{E}_i^\sigma =$

$(\mathbf{m} \times \partial_i \mathbf{m}) \cdot \mathbf{m}$ and $\mathbf{B}^\sigma = \mathbf{z}(\partial_x \mathbf{m} \times \partial_y \mathbf{m}) \cdot \mathbf{m}$. Here, $\mathbf{E}^\sigma$ and $\mathbf{B}^\sigma$ are the directions of the emergent electric field due to charge pumping and emergent magnetic field due to the topological Hall effect, respectively.^{20,21} The spin current density tensor, where $\mathbf{J}_{Sij}$ indicates the flow of the j component of spin polarization in the direction i , includes contributions due to (i) drift, (ii) diffusion, (iii) SHE, where ϵ is the rank 3 unit antisymmetric tensor, (iv) charge pumping, and (v) the topological Hall effect where n is the itinerant electron density. The spin accumulation obeys the following equation of motion, where λ_{sf} is the spin flip length, λ_j is the exchange rotation length, and λ_ϕ is the spin dephasing length:

$$\frac{\partial \mathbf{S}}{\partial t} = -\nabla \cdot \mathbf{J}_S - D_e \left(\frac{\mathbf{S}}{\lambda_{sf}^2} + \frac{\mathbf{S} \times \mathbf{m}}{\lambda_j^2} + \frac{\mathbf{m} \times (\mathbf{S} \times \mathbf{m})}{\lambda_\phi^2} \right). \quad (7)$$

Solving for the spin accumulation allows computation of bulk spin torques, which may be included as an additional torque term in the LLG equation, as

$$\mathbf{T}_S = -\frac{D_e}{\lambda_j^2} \mathbf{m} \times \mathbf{S} - \frac{D_e}{\lambda_\phi^2} \mathbf{m} \times (\mathbf{m} \times \mathbf{S}). \quad (8)$$

It may be shown that under the assumption of negligible in-plane spin diffusion this expression is equivalent to Zhang-Li STTs as given in Eq. (2),^{9,17,67} where the non-adiabaticity parameter is constant and given by $\beta \cong \lambda_j^2 / \lambda_{sf}^2$ in the limit of long spin dephasing length and long domain walls. The assumption of negligible in-plane spin diffusion breaks down for rapidly varying magnetization textures such as vortices and skyrmions, and this can lead to spatially varying and enhanced non-adiabaticity. For example, it is known that vortex domain walls have a significantly larger non-adiabaticity compared to transverse domain walls,⁶⁸ arising mainly due to in-plane spin diffusion at large magnetization gradients, with contributions due to charge pumping and the topological Hall effect also recognized.⁶⁹ While it may still be possible to use the simple LLG-STT formulation of Eq. (2), the correct value of non-adiabaticity must be used when vortex domain walls are present, and this may be computed using the drift-diffusion model. This is shown in Fig. 4(a), where for $\text{Ni}_{80}\text{Fe}_{20}$ the relation $\beta \cong \lambda_j^2 / \lambda_{sf}^2$ gives $\beta = 0.04$ expected for a transverse domain wall with $\lambda_{sf} = 10 \text{ nm}$ and $\lambda_j = 2 \text{ nm}$. For the vortex domain wall in Fig. 4(a) however a much higher maximum value of 0.1 results for $\lambda_\phi = 2.1 \text{ nm}$, obtained by fitting the spin torque in Eq. (8) to the STT in Eq. (2) with β as a spatially varying fitting parameter. Thus, β is no longer a constant but has a spatial dependence with the maximum value reached at the vortex core as seen in Fig. 4(a). The μMAG Standard Problem #5 is repeated again, but this time the LLG equation is used with the spin torque from Eq. (8), i.e., the spin accumulation is solved at every time step to self-consistently compute the spin torque. The results are shown in Fig. 4(b) where a good agreement is obtained with the LLG-STT equation, despite the very different methods used to solve the problem.

At non-magnetic (N)/ferromagnetic (F) composite media boundaries, the following conditions are applied, obtained from circuit theory using the spin mixing conductance $G^{\uparrow\downarrow}$ and interface conductances for majority and minority carriers, $G^\uparrow$ and $G^\downarrow$:

$$\begin{aligned}
\mathbf{J}_C \cdot \mathbf{n}|_N &= \mathbf{J}_C \cdot \mathbf{n}|_F = -(G^\dagger + G^\perp)\Delta V + (G^\dagger - G^\perp)\Delta V_S \cdot \mathbf{m}, \\
\mathbf{J}_S \cdot \mathbf{n}|_N - \mathbf{J}_S \cdot \mathbf{n}|_F &= \frac{2\mu_B}{e} [\text{Re}\{G^{\dagger\perp}\} \mathbf{m} \times (\mathbf{m} \times \Delta V_S) + \text{Im}\{G^{\dagger\perp}\} \mathbf{m} \times \Delta V_S], \\
\mathbf{J}_S \cdot \mathbf{n}|_F &= \frac{\mu_B}{e} [-(G^\dagger + G^\perp)(\Delta V_S \cdot \mathbf{m})\mathbf{m} + (G^\dagger - G^\perp)\Delta V_S \mathbf{m}].
\end{aligned} \quad (9)$$

Interfacial spin torques are obtained as ($\hbar_F$ is the discretization cellsize of the F layer in the direction normal to the composite media boundary)

$$\mathbf{T}_S = \frac{g\mu_B}{eh_F} [\text{Re}\{G^{\dagger\perp}\} \mathbf{m} \times (\mathbf{m} \times \Delta V_S) + \text{Im}\{G^{\dagger\perp}\} \mathbf{m} \times \Delta V_S]. \quad (10)$$

Spin pumping may also be included on the N side of Eq. (9) as

$$\mathbf{J}_S^{\text{pump}} = \frac{\mu_B \hbar}{e^2} \left[\text{Re}\{G^{\dagger\perp}\} \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \text{Im}\{G^{\dagger\perp}\} \frac{\partial \mathbf{m}}{\partial t} \right]. \quad (11)$$

This results in a damping-like torque in Eq. (10), reproducing the expected enhancement in effective magnetization damping.¹⁷ As shown previously, when a heavy metal (HM)/F bilayer is simulated with the SHE enabled in the HM layer, the expected damping-like and field-like SOTs are obtained from Eq. (10).^{17,70} Moreover, when a spin accumulation is generated at magnetization

gradients, such as a skyrmion, the resulting imbalance in spin accumulation either side of the HM/FM interface generates vertical spin currents, which leads to an additional type of interfacial spin torque, termed interfacial STT (ISTT).^{10,11} In many cases, it is sufficient to run simulations with direct expressions for spin torques (e.g., STT and SOT) augmenting the LLG equation; however, the drift-diffusion spin transport solver is still useful for calculating the strength of these spin torques in the first place from spin transport parameters. Here, we further verify the spin transport solver reproduces the expected spin torques in a spin valve structure shown in Fig. 8(a). In a macrospin approximation, the total spin torque exerted on the free layer is given by a combination of Slonczewski and field-like spin torques as^{71,72}

$$\begin{aligned}
\mathbf{T}_S &= \frac{\mu_B J}{e d} \eta(\theta) [\mathbf{m} \times (\mathbf{m} \times \mathbf{p}) + r \mathbf{m} \times \mathbf{p}], \\
\eta(\theta) &= \frac{q_+}{A + B \cos(\theta)} + \frac{q_-}{A - B \cos(\theta)}.
\end{aligned} \quad (12)$$

Here, $\mathbf{p}$ is the polarization from the fixed layer, set to $\mathbf{p} = -\hat{\mathbf{x}}$. By varying the angle in the uniformly magnetized free layer, the angular dependence $\eta(\theta)$ in Eq. (12) is obtained by fitting the spin torque computed self-consistently in Eq. (10). The results are shown in Fig. 8(b), where we obtain $q_+ = 4.94$, $q_- = -0.05$, $A = 5.85$, $B = 3.83$, and $r = 0.19$. It should be noted that while a good agreement is obtained between Eqs. (10) and (12) for the angular dependence, the model above is strictly applicable for a macrospin only. During switching of the free layer, the magnetization is no longer uniform resulting in non-negligible spin diffusion effects. While the switching times computed with Eqs. (10) and (12), respectively, are approximately the same for the geometry in Fig. 8(a), the exact magnetization dynamics of the free layer differ between them. In this case, the self-consistent spin torque in Eq. (10) is a more accurate description, capturing the non-local nature of the spin torques.

V. LANDAU-LIFSHITZ-BLOCH EQUATION

Material parameters used in simulations may be assigned temperature dependences, either using a data file or with a user-supplied mathematical equation. This is particularly useful for computations where the temperature can change during the simulation. In this case, the (stochastic) Landau-Lifshitz-Bloch (LLB) equation⁸ is used, which is given by

$$\begin{aligned}
\frac{\partial \mathbf{M}}{\partial t} &= -\frac{\gamma}{1 + \tilde{\alpha}_\perp^2} \mathbf{M} \times \mathbf{H} - \frac{\tilde{\alpha}_\perp \gamma}{1 + \tilde{\alpha}_\perp^2} \frac{1}{|\mathbf{M}|} \mathbf{M} \\
&\times (\mathbf{M} \times (\mathbf{H} + \mathbf{H}_{\text{thermal}})) + \frac{\gamma \tilde{\alpha}_\parallel}{|\mathbf{M}|} (\mathbf{M} \cdot \mathbf{H}) \mathbf{M} + \boldsymbol{\eta}_{\text{thermal}}.
\end{aligned} \quad (13)$$

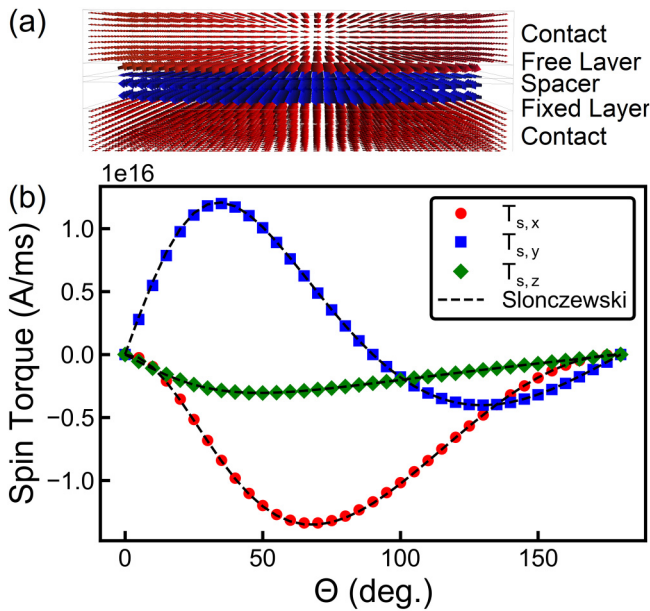


FIG. 8. Spin torques in a CPP-GMR spin valve structure for a current density of $\sim 10^{12}$ A/m². (a) Spin-valve geometry with dimensions 160×80 nm², 10 nm fixed layer thickness, 5 nm free layer thickness, 2 nm spacer thickness, and contacts of 20 nm thickness. (b) Computed spin torques in the free layer for uniform magnetization as a function of in-plane angle, with fitted Slonczewski and field-like spin torques.

Here, for $T < T_C$ (T_C is the Curie temperature), $\alpha_{\perp} = \alpha(1 - T/3T_C)$, $\alpha_{\parallel} = \alpha 2T/3T_C$, $\tilde{\alpha}_{\perp} = \alpha_{\perp}/m$, and $\tilde{\alpha}_{\parallel} = \alpha_{\parallel}/m$, where m is the magnetization length normalized to its zero temperature value, i.e., $m = |\mathbf{M}|/M_S^0$. For $T > T_C$, $\alpha_{\perp} = \alpha_{\parallel} = 2T/3T_C$. The effective field $\mathbf{H}$ must be complemented by a longitudinal susceptibility field given by

$$\mathbf{H}_l = \begin{cases} \left(1 - \frac{m^2}{m_e^2}\right) \frac{\mathbf{m}}{2\mu_0\tilde{\chi}_{\parallel}}, & T \leq T_C, \\ -\frac{\mathbf{m}}{\mu_0\tilde{\chi}_{\parallel}}, & T > T_C. \end{cases} \quad (14)$$

The field and temperature-dependent equilibrium magnetization, m_e , is obtained from the Curie–Weiss law as

$$m_e(T) = B\left[m_e \frac{3T_C}{T} + \frac{\mu\mu_0 H_{ext}}{k_B T}\right], \quad (15)$$

where $B(x) = \coth(x) - 1/x$ is the Langevin function and μ is the atomic moment. The longitudinal susceptibility is $\chi_{\parallel}(T) = \partial M / \partial H|_{H \rightarrow 0}$,^{6,8} and from this we obtain the relative longitudinal susceptibility (units T^{-1})

$$\tilde{\chi}_{\parallel}(T) = \frac{\mu}{k_B T} \frac{B'(x)}{1 - B'(x)(3T_C/T)} = \chi_{\parallel}(T)/\mu_0 M_S^0, \quad \text{with} \\ x = m_e 3T_C/T. \quad (16)$$

The components of the thermal field, $\mathbf{H}_{\text{thermal}}$, and torque, $\boldsymbol{\eta}_{\text{thermal}}$, follow Gaussian distributions with no correlations, zero mean, and standard deviations given, respectively, by

$$H_{\sigma} = \frac{1}{\alpha_{\perp}} \sqrt{\frac{2k_B T(\alpha_{\perp} - \alpha_{\parallel})}{\gamma\mu_0 M_S^0 V \Delta t}}, \\ \eta_{\sigma} = \sqrt{\frac{2k_B T \alpha_{\parallel} \gamma M_S^0}{\mu_0 V \Delta t}}. \quad (17)$$

Here, V is the computational cellsize and Δt is the integration time step. Stochastic equations are evaluated in Boris in the Stratonovich interpretation,⁷³ and applicable methods include the Euler and Heun methods (both fixed and adaptive time step)—the other previously mentioned higher order methods are not suitable for stochastic equations.

Temperature dependences of parameters may be adjusted by the user as explained above; however, when a Curie temperature is set the program computes a set of default temperature dependences, which are given as scaling laws on the base (zero-temperature) material parameter values. These are $M_S(T) = M_S^0 m_e(T)$ and $A(T) = A_0 m_e^2(T)$ for the exchange stiffness,⁷⁴ $D(T) = D_0 m_e^2(T)$ for the Dzyaloshinsky–Moriya exchange constant,⁷⁵ and $K(T) = K_0 m_e^3(T)$ for the anisotropy constants.^{76,77} It must be noted, however, the default temperature dependences are not always appropriate and may need to be adjusted depending on the material simulated, for example, see Refs. 78 and 79. For the full list of effective fields implemented, see Appendix A.

VI. HEAT SOLVER

In the simplest case, the electron temperature in the LLB equation is uniform. More advanced simulations also require non-uniform temperatures, and this calls for implementation of the heat equation, although an externally computed temperature distribution can also be loaded into Boris. For example, the authors in Ref. 22 investigated the AMR-induced magnonic spin-Seebeck effect, where Joule heating is included in the heat equation as the heat source $\mathbf{J}^2/\sigma$ (W/m^3). Due to the AMR of a transverse DW, the conductivity is higher at the DW, locally resulting in decreased Joule heating. This results in a temperature gradient between the center of the DW and its boundaries, and moreover when the DW is displaced due to STT the leading edge of the DW experiences a higher temperature compared to the trailing edge. Due to the magnonic spin-Seebeck effect,⁸⁰ this results in a significant enhancement of the DW velocity up to 15% for realistic material parameters.²² To reproduce such an effect, it is necessary to simultaneously solve both the LLB and heat equations, in addition to computing the current density using the transport solver. The heat equation implemented in Boris is shown below,

$$C(\mathbf{r})\rho(\mathbf{r}) \frac{\partial T(\mathbf{r}, t)}{\partial t} = \nabla \cdot K(\mathbf{r})\nabla T(\mathbf{r}, t) + S(\mathbf{r}, t) + \frac{\mathbf{J}(\mathbf{r}, t)^2}{\sigma(\mathbf{r})}. \quad (18)$$

Here, C is the total specific heat capacity, K is the thermal conductivity, ρ is the mass density, and S is the heat source. The material parameters in the heat equation are allowed to vary spatially, for example, if a temperature dependence is enabled. All material parameters, including the heat source S , in Boris may be assigned a temperature dependence, specified either through a data file or through a user-defined mathematical equation. The final term in Eq. (18) represents Joule heating, and the heat solver may be coupled to the transport solver as explained in relation to the example in Ref. 22. The heat equation is evaluated using the forward-time centered-space method. While this is a first-order method, so the time step required for stability is small, this is in many cases comparable to the time step required for evaluating the LLB equation; thus, a higher order scheme is not necessary.

For more advanced studies, which require separating the lattice and electron temperatures, a two-temperature model²³ is available, which is given as

$$C_e(\mathbf{r})\rho(\mathbf{r}) \frac{\partial T_e(\mathbf{r}, t)}{\partial t} = \nabla \cdot K(\mathbf{r})\nabla T_e(\mathbf{r}, t) - G_e(\mathbf{r})[T_e(\mathbf{r}, t) - T_l(\mathbf{r}, t)] + S(\mathbf{r}, t), \\ C_l(\mathbf{r})\rho(\mathbf{r}) \frac{\partial T_l(\mathbf{r}, t)}{\partial t} = G_e(\mathbf{r})[T_e(\mathbf{r}, t) - T_l(\mathbf{r}, t)]. \quad (19)$$

Here, C_e and C_l are the electron and lattice specific heat capacities, and G_e is the electron-lattice coupling constant, typically of the order $10^{18} \text{ W}/\text{m}^3 \text{ K}$. When used together with the LLB equation, the magnetization and magnetic parameters are coupled to the electron temperature ($T = T_e$).

Studies of ultrafast magnetization dynamics have revealed a large difference between electron and spin dynamics on time scales of the order 1 ps and below, explained in terms of a three-temperature model which includes the electron, spin, and lattice temperatures,⁸¹ and later formulated as a microscopic three-temperature model.⁸² This latter approach was shown to be equivalent to an LLB formulation,²³ which accounts for the different electron and lattice temperatures on ultra-short time scales. Within this formulation, the photon energy is absorbed by the delocalized electrons, which are coupled to the lattice electrons via the rate equations shown in Eq. (19). This allows simulations of ultrafast demagnetization due to heating by a laser pulse, by including an appropriate heat source S in Eq. (19). Here, we show an example of such a simulation by taking a Gaussian profile for a linearly polarized laser pulse as given below, where d and t_R are full-width at half-maximum values for the spatial and temporal widths,

$$S = P_0 \exp\left(\frac{-|\mathbf{r} - \mathbf{r}_0|^2}{d^2/4 \ln(2)}\right) \exp\left(\frac{-(t - t_0)^2}{t_R^2/4 \ln(2)}\right) \quad (\text{W/m}^3). \quad (20)$$

The geometry simulated is shown in Fig. 9(a), where we use a Co (2 nm)/Pt (8 nm)/SiO₂ (40 nm) structure, with in-plane dimensions of 512 nm² and periodic boundary conditions. For the Co layer, we also include the interfacial DMI contribution and

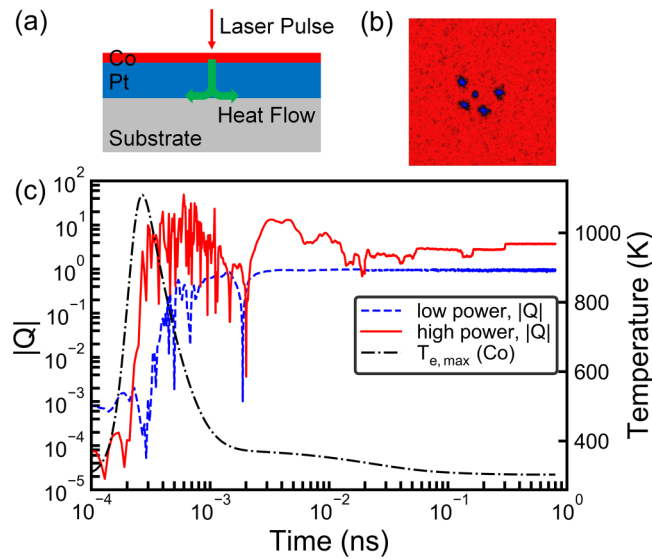


FIG. 9. Ultrafast demagnetization and Néel skyrmion creation in a 2 nm thick Co layer on Pt (8 nm) and SiO₂ substrate (40 nm). (a) Simulated trilayer structure. (b) State after 800 ps for a high power laser pulse ($T_{\max} \cong 2T_C$, $T_C = 500$ K) and out-of-plane field of 100 kA/m, showing the z component of magnetization and five created skyrmions. (c) $|Q|$ plotted as a function of time for two different pulse strengths (high $T_{\max} \cong 2T_C$, low $T_{\max} \cong 1.5T_C$) and $d = 400$ nm, $t_R = 100$ fs. The maximum Co temperature reached for the high power laser pulse is also plotted.

uniaxial anisotropy with easy axis out of the plane. The two-temperature model is computed for the Co and Pt layers, while the one-temperature heat equation is computed for the SiO₂ substrate. Continuity of heat flux and temperature is assumed at the interfaces, and Robin boundary conditions are used on the exposed surfaces of the magnetic layer and substrate with ambient temperature set to room temperature. For a high power laser pulse ($P_0 = 4 \times 10^{21}$ W/m³) with $d = 400$ nm and $t_R = 100$ fs, the computed maximum Co electron temperature is plotted in Fig. 9(c), showing ultrafast heating up to $T_{\max} \cong 2T_C$ ($T_C = 500$ K), followed by rapid cooling as the electron and lattice temperatures equilibrate. The temperature decays back to room temperature on a longer time scale. For this problem, we solve the stochastic LLB in Eq. (13) and compute the topological charge (which takes on values ± 1 for a single skyrmion) using⁸³

$$Q = \frac{1}{4\pi} \int_A \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) dx dy. \quad (21)$$

Thus, by plotting $|Q|$ as a function of time, the number of skyrmions present can be monitored. As the magnetization order recovers for $T < T_C$ following ultrafast demagnetization, Néel skyrmions begin to emerge under the action of DMI, as observed experimentally.⁸⁴ The mean number of skyrmions formed is dependent on the laser power and follows a Poisson counting distribution as discussed in Ref. 85. Two examples are shown in Fig. 9(c): the low power pulse results in a single skyrmion formed in this case, while the high power pulse results in five skyrmions formed, with the final state indicated in Fig. 9(b). The integration of a multi-layered heat solver with the magnetization dynamics solver is thus a powerful feature, allowing detailed studies with non-uniform and non-constant temperatures and heat sources.

VII. TWO-SUBLATTICE MODEL

Recent years have seen an increased interest in antiferromagnetic spintronics,^{86–88} with the real prospect of antiferromagnetic memories⁸⁹ in sight, and applications to terahertz technologies.⁹⁰ Thus, micromagnetics research software is needed to support future efforts in this area. Following the multi-mesh and multi-material paradigm, Boris has been extended with a two-sublattice model, allowing modeling of antiferromagnetic and ferrimagnetic materials, for example, applicable to studies of ferrimagnetic skyrmions.⁹¹ This allows studying not only antiferromagnetic and ferrimagnetic materials devices on their own, but also complex multi-layered devices including both antiferromagnetic and ferromagnetic materials—one obvious application here is to the study of exchange bias.⁹²

Here, we show the two-sublattice stochastic LLB equation implemented in Boris, based on the LLB equation from Refs. 93 and 94 applicable for antiferromagnetic, ferrimagnetic, and binary ferromagnetic alloys. This is given in Eq. (22) in terms of the macroscopic magnetization, where we denote the two sublattices as $i = A, B$,

$$\frac{\partial \mathbf{M}_i}{\partial t} = -\tilde{\gamma}_i \mathbf{M}_i \times \mathbf{H}_{\text{eff},i} - \tilde{\gamma}_i \frac{\tilde{\alpha}_{\perp,i}}{M_i} \mathbf{M}_i \times (\mathbf{M}_i \times (\mathbf{H}_{\text{eff},i} + \mathbf{H}_{\text{th},i})) + \gamma_i \frac{\tilde{\alpha}_{\parallel,i}}{M_i} (\mathbf{M}_i \cdot \mathbf{H}_{\parallel,i}) \mathbf{M}_i + \mathbf{n}_{\text{th},i} \quad (i = A, B). \quad (22)$$

The reduced gyromagnetic ratio is given by $\tilde{\gamma}_i = \gamma_i / (1 + \tilde{\alpha}_{\perp,i}^2)$, and the reduced transverse and longitudinal damping parameters by $\tilde{\alpha}_{\perp(\parallel),i} = \alpha_{\perp(\parallel),i} / m_i$, where $m_i(T) = M_i(T) / M_{S,i}^0$, with $M_{S,i}^0$ denoting the zero-temperature saturation magnetization and $M_i \equiv |\mathbf{M}_i|$. The exchange field now includes not only intra-lattice contributions, but also homogeneous and non-homogeneous inter-lattice contributions given as

$$\mathbf{H}_{\text{ex},i} = \frac{2A_i}{\mu_0 M_{e,i}^2} \nabla^2 \mathbf{M}_i - \frac{4A_{h,i}}{\mu_0 M_{e,i} M_{e,j}} \hat{\mathbf{m}}_i \times (\hat{\mathbf{m}}_i \times \mathbf{M}_j) + \frac{A_{nh,i}}{\mu_0 M_{e,i} M_{e,j}} \nabla^2 \mathbf{M}_j \quad (i = A, B, i \neq j). \quad (23)$$

The effective field includes a number of contributions, as for the ferromagnetic model, namely, demagnetizing field computed for $(\mathbf{M}_A + \mathbf{M}_B)/2$, external field, magneto-crystalline anisotropy, as well as DMI or interfacial DMI terms. The formulas given in Appendix A are now applicable to the two sublattices separately.

The relative longitudinal susceptibility, $\tilde{\chi}_{\parallel,i} = \chi_{\parallel,i} / (\mu_0 M_{S,i}^0)$, now becomes⁹⁴

$$k_B T \tilde{\chi}_{\parallel,i} = \frac{\mu_i B'_i (1 - 3\tau_j \tilde{T}_N B'_j / T) + \mu_j 3\tau_{ij} \tilde{T}_N B'_i B'_j / T}{(1 - 3\tau_i \tilde{T}_N B'_i / T)(1 - 3\tau_j \tilde{T}_N B'_j / T) - \tau_{ij} \tau_{ji} B'_i B'_j (3\tilde{T}_N / T)^2}, \quad (24)$$

where $B'_i \equiv B'_{m_{e,i}} [(m_{e,i} \tau_i + m_{e,j} \tau_{ij}) 3\tilde{T}_N / T]$ ($i = A, B$). Here, $m_{e,i}$ are magnetization temperature scaling laws, and τ_i, τ_{ij} are dimensionless coupling parameters between the effective exchange parameters and the phase transition temperature, which allow convenient specification of materials for two-sublattice micromagnetic simulations. Full details, including the longitudinal relaxation field expression, and examples are given in Appendix B.

Here, we test the two-sublattice model by computing the antiferromagnetic resonance (AFMR) as a function of antiferromagnetic exchange and uniaxial anisotropy. The predicted

resonance frequency is given by the Kittel formula⁹⁵ as $f_0 = \sqrt{H_A(2H_E + H_A)}$ at zero external field, where $H_A = 2K_1 / (\mu_0 M_S)$, and $H_E = 4|A_h| / (\mu_0 M_S)$. We compute the resonance frequency for a generic antiferromagnetic material with $M_S = 800$ kA/m and $A = 13$ pJ/m on each sublattice, as a function of homogeneous antiferromagnetic exchange and uniaxial anisotropy constant, by applying a uniform sinc pulse and taking the Fourier transform to obtain a frequency-swept AFMR peak. The excitation is applied perpendicular to the easy axis with amplitude 1 kA/m. Results are plotted in Fig. 10(a), showing a good agreement with the Kittel formula over a wide range of values. We further compute the spin wave dispersion with the same method used to compute the ferromagnetic spin wave dispersion in Fig. 3. Here, we set $A = 5$ pJ/m, $A_h = -20$ MJ/m³, $K_1 = 50$ kJ/m³ and also set a nonhomogeneous exchange constant $A_{nh} = -10$ pJ/m, with a damping constant of 0.002. The $n = 0$ spin wave mode analytical formula is given as

$$w_0(k) = \gamma \sqrt{\left(2H_E + H_A + \left(\frac{2A + |A_{nh}|}{\mu_0 M_S}\right) k^2\right) \left(H_A + \left(\frac{2A + |A_{nh}|}{\mu_0 M_S}\right) k^2\right)}. \quad (25)$$

The results are plotted in Fig. 10(b), showing an excellent agreement with Eq. (25).

The two-sublattice model in Eq. (22) also includes stochastic terms, which is similar to the stochastic LLB equation having zero spatial, vector components, and inter-lattice correlations, and whose components follow Gaussian distributions with zero mean and standard deviations given by

$$H_{\text{th},i}^{\text{std}} = \frac{1}{\alpha_{\perp,i}} \sqrt{\frac{2k_B T (\alpha_{\perp,i} - \alpha_{\parallel,i})}{\gamma_i \mu_0 M_{S,i}^0 V \Delta t}}, \quad (26)$$

$$\eta_{\text{th},i}^{\text{std}} = \sqrt{\frac{2k_B T \alpha_{\parallel,i} \gamma_i M_{S,i}^0}{\mu_0 V \Delta t}}.$$

Similarly to the approach in Ref. 8, it can be shown that the magnetization length distribution follows a Boltzmann probability distribution. For the two-sublattice case, in general, this distribution is a function of the magnetization length of both sublattices, m_A and m_B , and is shown below for the isotropic case (see Appendix B for further definitions),

$$P_i(m_A, m_B) \propto m_i^2 \exp \left\{ -\frac{M_{S,i}^0 V}{4\mu_i m_{e,i} k_B T} \left[\frac{(m_i^2 - m_{e,i}^2)^2 (\mu_i + 3\tau_{ij} k_B T_N \tilde{\chi}_{\parallel,j})}{m_{e,i}} + \frac{(m_j^2 - m_{e,j}^2)}{m_{e,j}} 3\tau_{ij} k_B T_N m_i^2 \right] \right\} \quad (i, j = A, B, i \neq j). \quad (27)$$

We test this by computing a two-sublattice histogram for the magnetization length as a function of temperature, taking

the generic antiferromagnetic material of Fig. 10(a) with a Néel temperature $T_N = 500$ K. A temperature is set and a cubic block

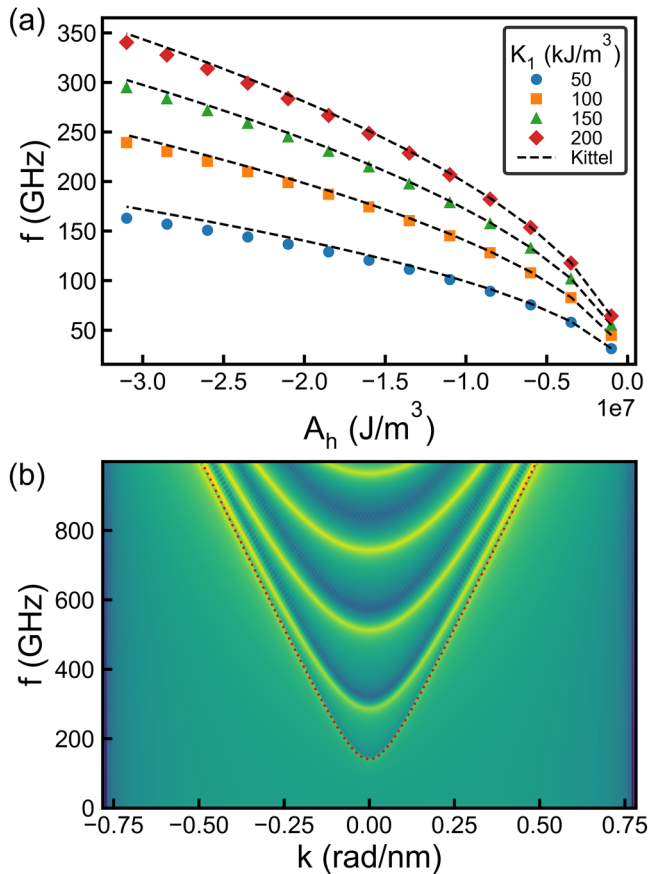


FIG. 10. (a) Antiferromagnetic resonance computed as a function of homogeneous antiferromagnetic exchange and uniaxial anisotropy, compared to the Kittel formula. (b) Antiferromagnetic spin wave dispersion computed for the same geometry in Ref. 38 with $A = 5 \text{ pJ/m}$, $A_h = -20 \text{ MJ/m}^3$, $A_{nh} = -10 \text{ pJ/m}$, and $K_1 = 50 \text{ kJ/m}^3$, using a damping factor of 0.002, compared to Eq. (25) for $n=0$ mode (dotted line).

of antiferromagnetic material (400 nm side) with periodic boundary conditions in all directions is allowed to relax for a set time (20 ps or longer). The computed two-sublattice probability distribution is shown in Fig. 11 for $T/T_N = 0.99$ as a color map. A very good agreement is obtained with the two-sublattice Boltzmann distribution from Eq. (27), plotted as a wire-frame. Similar tests were repeated over a wide range of temperatures. This shows that the implemented stochastic two-sublattice LLB model correctly reproduces the expected stochastic properties.

Exchange bias may also be modeled by simulating a bilayer consisting of an antiferromagnetic and a ferromagnetic mesh. The effective exchange bias field, first observed by Meiklejohn and Bean,⁹⁶ coincides with the bilinear surface exchange field of Eq. (5); thus, exchange bias may be included by enabling the surface exchange fields at the interface between antiferromagnetic and ferromagnetic meshes.⁹⁷ By including

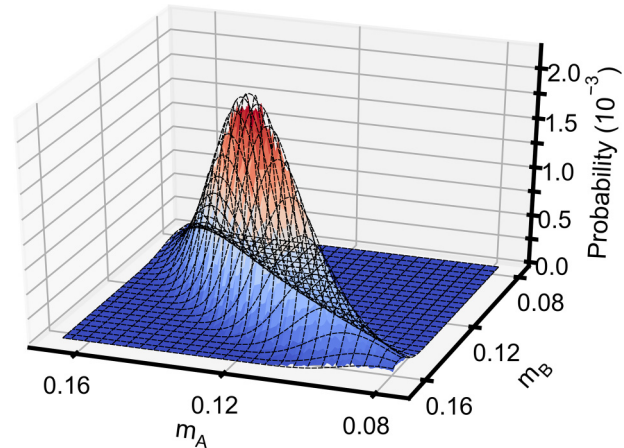


FIG. 11. Two-sublattice antiferromagnetic magnetization length probability distribution at $T/T_N = 0.99$, showing the computed distribution as a color map, with the wire frame showing the predicted two-sublattice Boltzmann probability distribution.

such coupling terms between the ferromagnetic spins and one or both antiferromagnetic sublattices, uncompensated spins as well as compensated spins⁹⁸ may be simulated. This subject, however, is beyond the scope of the current work and will be addressed in a separate publication.

VIII. PERFORMANCE AND BENCHMARKING

Large-scale micromagnetics simulations require significant computational resources. An important advancement is the use of GPUs, which result in significant speed-up factors compared to CPUs,² typically over an order of magnitude. All the computational routines in Boris may be executed on the CPU as well as on the GPU, either with single or double floating point precision. For CPU computations, Boris has been designed to run on shared memory devices with parallelization based on OpenMP. Fast Fourier transforms (FFTs) are computed using the FFTW3 library,³² configured to use threading. For GPU computations, Boris uses the CUDA toolkit,³¹ including for FFTs. Currently, true distributed computing in a cluster is not possible with Boris, although in a future work the possibility of using multiple GPUs for a single simulation will be explored. It should be noted that finite element/boundary element method codes are available for distributed computations, particularly suitable for curved geometries due to increased accuracy compared to finite difference codes,⁹⁹ for example, Magpar has shown near-linear performance scaling.¹⁰⁰ Boris can be controlled by using remote Python scripts; thus, execution and control of multiple independent remote Boris instances (for example, in a Linux cluster) is possible.

By far, the most expensive term to evaluate is the demagnetizing field, which involves evaluating a convolution sum over the entire mesh—see Eq. (4)—and normally takes 75% or more of the computation time in each iteration. The convolution sum may be

evaluated very efficiently using the convolution theorem: a (2)3D FFT algorithm is used on the input magnetization; this is then multiplied with the demagnetizing kernel in the transform space, and an inverse (2)3D FFT algorithm is used to obtain the output demagnetizing field. The computational complexity of this approach increases as $N \log(N)$, compared to N^2 for the naïve evaluation of the convolution sum; thus, several orders of magnitude improvement may be achieved for a large number of computational cells N . The simplest method of implementing the 3D convolution algorithm consists of computing 1D FFTs along the x , y , and z directions, performing the point-by-point multiplication, then computing the z , y , and x inverse 1D FFTs in this order. With CUDA³¹ implementations of GPU computations, these seven steps are most easily implemented using separate CUDA kernel launches. In particular, the z FFTs, point-by-point multiplications and z inverse FFTs are done in three separate steps. This can be inefficient for a small number of cells along the z direction. In Boris, a new approach is taken, termed pipelined convolution, where the z (inverse) FFTs and point-by-point multiplications are done using a single CUDA kernel launch, simultaneously for all three vector components. This involves manually coding the FFT algorithm and results in significant performance improvement over the non-pipelined approach due to more efficient use of GPU instruction bandwidth, up to a certain number of computational cells along the z direction.

To test the efficient implementation of computational routines in Boris, benchmark comparisons with Mumax3² have been performed. A testing platform consisting of a GTX 980 Ti GPU in single floating precision mode on Ubuntu 20.04 was used. An identical simulation was configured for both programs, consisting in computing the magnetization response to a perpendicular magnetic field, with effective field contributions of demagnetizing field, exchange interaction, and applied field. The RK4 evaluation method was used, and the time per evaluation was measured, noting the RK4 method consists of four evaluations per time step iteration. The benchmarking scripts for both programs are available in the Boris GitHub repository.²⁹ Typical results are shown in Fig. 12(a), for both 2D and 3D modes, showing the time per evaluation as a function of a total number of simulation cells N . In the 2D mode, the computational performance of Boris and Mumax3 is comparable; however, in the 3D mode Boris is found to run significantly faster. More information is obtained by plotting the speedup factor ($t_{\text{Mumax3}}/t_{\text{Boris}}$) as a function of number of z cells for a wide range of total number of computational cells, shown in Fig. 12(b). The pipelined convolution algorithm has been implemented up to 2^4 cells along the z direction, thus for FFTs of up to 32 points, noting the circular convolution theorem requires doubling the input data size by zero padding when not using periodic boundary conditions. This approach is found to be significantly faster compared to Mumax3, with the speedup factor also increasing with the total number of computational cells. Above 2^4 cells along the z direction, the pipelined convolution algorithm becomes less efficient than the non-pipelined algorithm; thus, 2^4 is the largest value for which Boris implements the pipelined convolution approach, although speedup factors above 1 are still obtained for the non-pipelined convolution mode in all 3D cases.

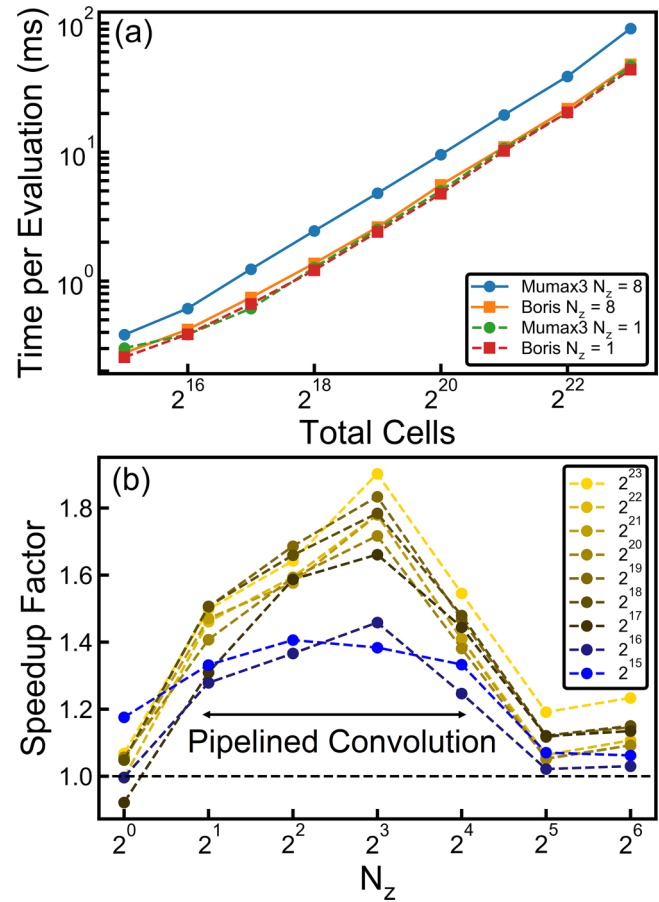


FIG. 12. Comparison of computational performance with Mumax3, for single floating point precision CUDA computations, benchmarked on a GTX 980 Ti GPU under Ubuntu 20.04. (a) Time per evaluation as a function of a total number of simulation cells for $N_z = 1$ (2D mode) and $N_z = 8$ (3D mode). (b) Speedup factor, defined as the ratio of time per evaluation as $t_{\text{Mumax3}}/t_{\text{Boris}}$, as a function of N_z and a total number of computational cells. In Boris, 3D computations up to 16 cells along the z direction (80 nm thickness for a 5 nm cellsize) are handled using an efficient pipelined convolution algorithm, resulting in significant speedup factors compared to non-pipelined convolution in Mumax3, up to nearly twice faster on this platform for large simulations containing over 8×10^6 computational cells.

Finally, we test the performance scaling at fixed problem sizes for different GPUs as a function of available floating point operations per second (Flops), using the same simulation procedure explained above. The results are shown in Fig. 13 for the GTX 1050 Ti, GTX 980 Ti, RTX 2080 Super, and RTX 2080 Ti GPUs, using GTX 1050 Ti as a reference. Normally strong scaling as a function of number of available processors is described by Amdahl's law;¹⁰¹ however, for the results in Fig. 13, where not only the number of CUDA cores changes, but also the operating frequency, memory bandwidth, and microarchitecture changes, we simply indicate the ideal scaling of 1:1 increase with

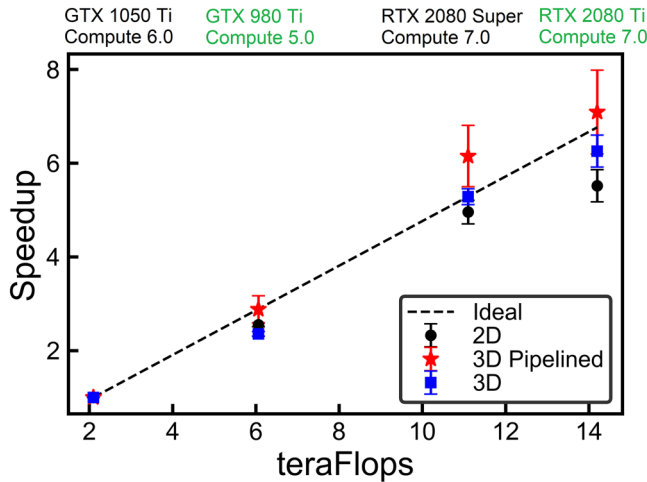


FIG. 13. Scaling at fixed problem size as a function of available single precision (FP32) floating point operations per second (Flops), across three different CUDA Compute major versions (5.0, 6.0, 7.0), for the 2D, pipelined 3D, and standard 3D simulation modes. The GTX 1050 Ti GPU was taken as a reference when computing the speedup factors, and these have been averaged for fixed problem sizes with 2^{20} , 2^{21} , 2^{22} , and 2^{23} number of simulation cells.

available Flops for comparison. The performance increase is comparable to the ideal case on average. We note the most recent Ampere microarchitecture, with CUDA Compute 8.0, has GPUs with available Flops in the range of 20–40 teraFlops; however, we have not tested Boris in this range yet, although the code can also be compiled on this microarchitecture.

IX. CONCLUSIONS AND OUTLOOK

Here, we have presented the main mathematical models implemented and testing of a new comprehensive computational magnetism research software. This represents a significant addition to the body of modeling capabilities introduced in other comparable open-source software, including OOMMF,¹ Mumax3,² and Fidimag.³ Thus, in addition to the existing micromagnetics modeling software, a new multi-mesh modeling paradigm is introduced, allowing complex simulations with multiple independently discretized computational meshes and materials. This allows simulations of multi-material structures, including ferromagnetic, antiferromagnetic, ferrimagnetic, and non-magnetic and substrate materials, without the constraint of fitting the computations on a single uniformly discretized finite difference mesh, while still preserving the computational performance associated with finite difference methods. In addition to magnetization dynamics models, including LLG, LLB, and stochastic and two-sublattice models, Boris also implements a drift-diffusion spin transport solver in ferromagnetic materials, as well as a heat flow solver in multi-layered structures.

While the implemented spin transport solver is only applicable to ferromagnetic materials, a future development consists in

extending the drift-diffusion model implementation to a two-sublattice model, for example, as introduced in Ref. 102 with appropriate boundary conditions. Magnetoelastic effects may be modeled in Boris either using a uniform stress or by importing an externally computed strain or mechanical displacement, similar to the approach implemented in an OOMMF extension.¹⁰³ A future development will implement both a multi-layered elastostatics solver and an elastodynamics solver,¹⁰⁴ allowing complex simulations with non-uniform and time-dependent strains, including magnetoelastic and magnetostriction-related dynamical effects. Finally, a basic atomistic modeling¹⁰⁵ capability has already been introduced in Boris, with a view to implementing true multi-scale simulations^{106,107} in the multi-mesh paradigm, although this was not discussed in the current work and will be treated in a separate publication.

ACKNOWLEDGMENTS

The author would like to thank Callum Robert Mackinnon for help with benchmarking the performance scaling of Boris.

APPENDIX A: MICROMAGNETICS EFFECTIVE FIELD TERMS

Effective field terms for various interactions are included as additive terms in $\mathbf{H}_{\text{eff}}$ in either the LLG or LLB equations. These are usually obtained from their corresponding energy density terms using the relation $\mathbf{H} = \frac{-1}{\mu_0 M_S} \frac{\partial \mathcal{E}}{\partial \mathbf{m}}$. The main terms implemented in Boris not already given in the main text are shown in Table I. Parameter definitions are not repeated here if given in the main text.

APPENDIX B: LANDAU-LIFSHITZ-BLOCH TEMPERATURE DEPENDENCES

For the two-sublattice model, we introduce convenient dimensionless micromagnetic parameters τ_i and $\tau_{ij} \in [0, 1]$. These are coupling parameters between exchange parameters and the phase transition temperature, where $|J_{0,i}| = 3 \tau_i k_B T_N$, $|J_{0,ij}| = 3 \tau_{ij} k_B T_N$. Here, $J_{0,i(j)}$ is the effective exchange parameter for intra-lattice ($i = A, B$) and inter-lattice ($i, j = A, B$, $i \neq j$) coupling, respectively, obtained from the exchange parameters as given in Ref. 94. For a simple prototypical antiferromagnet, we have $\tau_A = \tau_B = \tau_{AB} = \tau_{BA} = 0.5$ ($J_{0,ij} < 0$). For $\tau_A = 1$, $\tau_B = 0$, $\tau_{AB} = \tau_{BA} = 0$, the temperature dependences given below, as well as the two-sublattice LLB equation, reduce to the ferromagnetic LLB case. Thus, here we give the general case in terms of τ parameters.

The damping parameters are continuous at T_N —the phase transition temperature—and are given by

$$\begin{aligned} \alpha_{\perp, i} &= \alpha_i \left(1 - \frac{T}{3(\tau_i + \tau_{ij} m_{e, j} / m_{e, i}) \tilde{T}_N} \right), \quad T < T_N, \\ \alpha_{\parallel, i} &= \alpha_i \left(\frac{2T}{3(\tau_i + \tau_{ij} m_{e, j} / m_{e, i}) \tilde{T}_N} \right), \quad T < T_N, \\ \alpha_{\perp, i} &= \alpha_{\parallel, i} = \frac{2T}{3T_N}, \quad T \geq T_N. \end{aligned} \quad (\text{B1})$$

TABLE I. Effective field terms implemented in Boris, not already given in the main text.

Term	Formulas
Uniaxial anisotropy	$\mathcal{E} = K_1[1 - (\mathbf{m} \cdot \mathbf{e}_A)^2] + K_2[1 - (\mathbf{m} \cdot \mathbf{e}_A)^2]^2$ $\mathbf{H} = \frac{2K_1}{\mu_0 M_S} (\mathbf{m} \cdot \mathbf{e}_A) \mathbf{e}_A + \frac{4K_2}{\mu_0 M_S} [1 - (\mathbf{m} \cdot \mathbf{e}_A)^2] (\mathbf{m} \cdot \mathbf{e}_A) \mathbf{e}_A$ where $\mathbf{e}_A$ is the symmetry axis.
Cubic anisotropy	$\mathcal{E} = K_1[\alpha^2\beta^2 + \alpha^2\gamma^2 + \beta^2\gamma^2] + K_2\alpha^2\beta^2\gamma^2$ $\mathbf{H} = -\frac{2K_1}{\mu_0 M_S} [\mathbf{e}_1\alpha(\beta^2 + \gamma^2) + \mathbf{e}_2\beta(\alpha^2 + \gamma^2) + \mathbf{e}_3\gamma(\alpha^2 + \beta^2)] - \frac{2K_2}{\mu_0 M_S} [\mathbf{e}_1\alpha\beta^2\gamma^2 + \mathbf{e}_2\alpha^2\beta\gamma^2 + \mathbf{e}_3\alpha^2\beta^2\gamma]$ $\alpha = \mathbf{m} \cdot \mathbf{e}_1$, $\beta = \mathbf{m} \cdot \mathbf{e}_2$, and $\gamma = \mathbf{m} \cdot \mathbf{e}_3$, where $\mathbf{e}_3 = \mathbf{e}_1 \times \mathbf{e}_2$.
Direct exchange	$\mathcal{E} = A \left[\left(\frac{\partial \mathbf{m}}{\partial x} \right)^2 + \left(\frac{\partial \mathbf{m}}{\partial y} \right)^2 + \left(\frac{\partial \mathbf{m}}{\partial z} \right)^2 \right]$ $\mathbf{H} = \frac{2A}{\mu_0 M_S} \nabla^2 \mathbf{m}$ Homogeneous Neumann boundary condition: $\frac{\partial \mathbf{m}}{\partial \mathbf{n}} = 0$
DM exchange	$\mathcal{E} = D \mathbf{m} \cdot (\nabla \times \mathbf{m})$ $\mathbf{H} = -\frac{2D}{\mu_0 M_S} \nabla \times \mathbf{m}$ The non-homogeneous Neumann boundary condition is used: $\frac{\partial \mathbf{m}}{\partial \mathbf{n}} = \frac{D}{2A} \mathbf{n} \times \mathbf{m}$
Interfacial DM exchange	$\mathcal{E} = -D \mathbf{m} \cdot ((\nabla \cdot \mathbf{m}) \hat{\mathbf{z}} - \nabla m_z)$ $\mathbf{H} = \frac{2D}{\mu_0 M_S} ((\nabla \cdot \mathbf{m}) \hat{\mathbf{z}} - \nabla m_z)$ For single lattice models, the non-homogeneous Neumann boundary condition is used: $\frac{\partial \mathbf{m}}{\partial \mathbf{n}} = \frac{D}{2A} (\hat{\mathbf{z}} \times \mathbf{n}) \times \mathbf{m}$ For two-sublattice models, the boundary conditions become¹⁰⁸ $\frac{\partial \mathbf{m}_i}{\partial \mathbf{n}} = \frac{D_i}{2A_i(1-c_i^2)} [(\hat{\mathbf{z}} \times \mathbf{n}) \times (\mathbf{m}_i - c_i \mathbf{m}_j)], \quad (i, j = A, B, \quad i \neq j)$ where $c_i = A_{nh}/2A_i$.
Demagnetizing field	$\mathbf{H}(\mathbf{r}_0) = -\sum_{\mathbf{r}} \mathbf{N}(\mathbf{r} - \mathbf{r}_0) \mathbf{M}(\mathbf{r})$ $\mathbf{N}$ computed using formulas in Ref. 53
Oersted	$\mathbf{H}(\mathbf{r}_0) = \sum_{\mathbf{r}} \mathbf{K}(\mathbf{r} - \mathbf{r}_0) \mathbf{J}_C(\mathbf{r})$ $\mathbf{K}$ computed using formulas in Ref. 66
Magneto-optical	$H_{MO} = \sigma^\pm H_{MO}^0 f_{MO}(\mathbf{r}, t) \hat{\mathbf{z}}$
Roughness	$\mathbf{H}(\mathbf{r}_0) = -\left[\sum_{\mathbf{r} \in V} \mathbf{N}(\mathbf{r} - \mathbf{r}_0) G(\mathbf{r}, \mathbf{r}_0) \right] \mathbf{M}(\mathbf{r}_0) \quad (\mathbf{r}_0 \in V)$ G is computed using formulas in Ref. 28
Magnetoelastic	$\mathcal{E}_{mel,d} = B_1 [(\mathbf{m} \cdot \mathbf{e}_1)^2 (\mathbf{S}_d \cdot \mathbf{e}_1) + (\mathbf{m} \cdot \mathbf{e}_2)^2 (\mathbf{S}_d \cdot \mathbf{e}_2) + (\mathbf{m} \cdot \mathbf{e}_3)^2 (\mathbf{S}_d \cdot \mathbf{e}_3)]$ $\mathcal{E}_{mel,od} = 2B_2 \left[(\mathbf{m} \cdot \mathbf{e}_1)(\mathbf{m} \cdot \mathbf{e}_2)(\mathbf{S}_{od} \cdot \mathbf{e}_3) + (\mathbf{m} \cdot \mathbf{e}_1)(\mathbf{m} \cdot \mathbf{e}_3)(\mathbf{S}_{od} \cdot \mathbf{e}_2) \right. \\ \left. + (\mathbf{m} \cdot \mathbf{e}_2)(\mathbf{m} \cdot \mathbf{e}_3)(\mathbf{S}_d \cdot \mathbf{e}_1) \right]$ where B_1 and B_2 are magnetoelastic constants, $\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$ are cubic anisotropy axes, and $\mathbf{S}_d$ and $\mathbf{S}_{od}$ are diagonal and off-diagonal strain tensor terms

We denote $\tilde{T}_N$ the re-normalized transition temperature as

$$\tilde{T}_N = \frac{2T_N}{\tau_A + \tau_B + \sqrt{(\tau_A - \tau_B)^2 + 4\tau_{AB}\tau_{BA}}}. \quad (\text{B2})$$

The normalized equilibrium magnetization functions $m_{e,i}$ are obtained from the Curie–Weiss law as

$$m_{e,i} = B[(m_{e,i}\tau_i + m_{e,j}\tau_{ij})3\tilde{T}_N/T + \mu\mu_0 H_{ext}/k_B T], \quad (\text{B3})$$

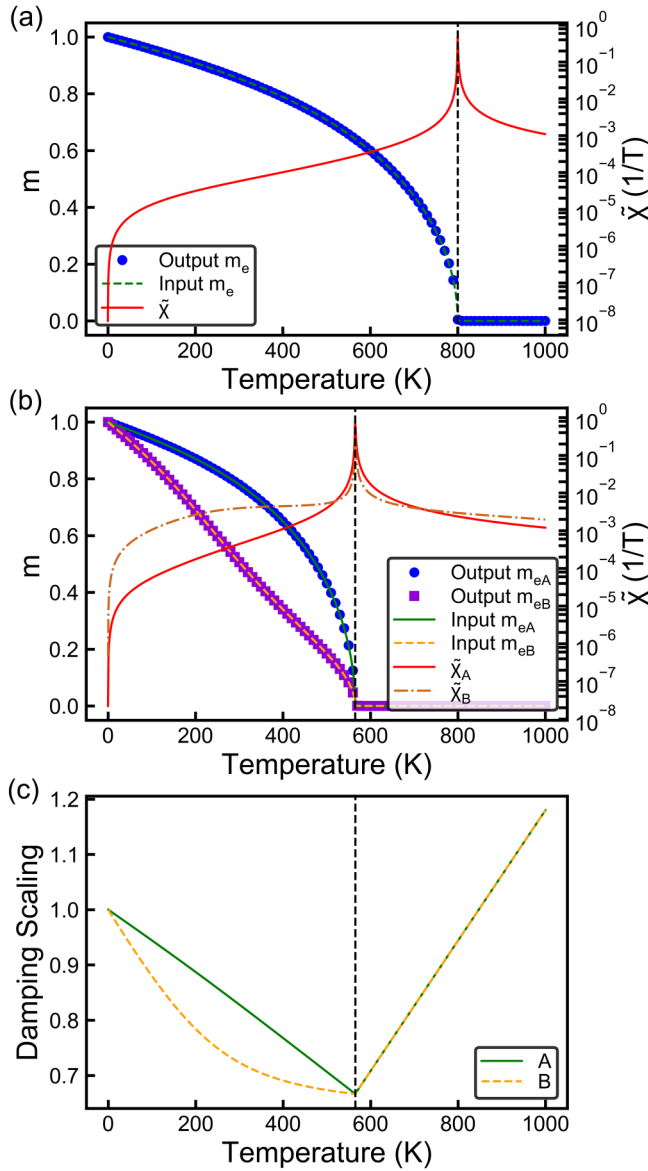


FIG. 14. Temperature dependences of magnetization scaling functions and relative longitudinal susceptibilities, showing both the model input functions and output computed functions for (a) one lattice LLB model with $T_C = 800$ K, $\mu = 1\mu_B$ and (b) two-sublattice LLB model with parameters obtained from Ref. 94 for $\text{Gd}_{25}(\text{FeCo})_{75}$, namely, $T_C = 565$ K, $\mu_A = \mu_{\text{FeCo}} = 1.92\mu_B$, $\mu_B = \mu_{\text{Gd}} = 7.63\mu_B$, $\tau_A = 0.958$, $\tau_B = 0.127$, $\tau_{AB} = 0.111$, $\tau_{BA} = 0.333$. (c) Damping scaling functions for the two-sublattice model with $\text{Gd}_{25}(\text{FeCo})_{75}$ parameters.

where $B(x) = \coth(x) - 1/x$ and μ_i is the atomic magnetic moment.

The longitudinal relaxation field that includes both intra-lattice and inter-lattice contributions is given by

$$\mathbf{H}_{||,i} = \left\{ \frac{1}{2\mu_0\tilde{\chi}_{||,i}} \left(1 - \frac{m_i^2}{m_{e,i}^2} \right) + \frac{3\tau_{ij}k_B T_N}{2\mu_0\mu_i} \right. \\ \times \left. \left[\frac{\tilde{\chi}_{||,j}}{\tilde{\chi}_{||,i}} \left(1 - \frac{m_j^2}{m_{e,i}^2} \right) - \frac{m_{e,j}}{m_{e,i}} (\hat{\mathbf{m}}_i \cdot \hat{\mathbf{m}}_j) \left(1 - \frac{m_j^2}{m_{e,j}^2} \right) \right] \right\} \mathbf{m}_i, T < T_N, \\ \mathbf{H}_{||,i} = - \left\{ \frac{1}{\mu_0\tilde{\chi}_{||,i}} + \frac{3\tau_{ij}k_B T_N}{\mu_0\mu_i} \left[\frac{\tilde{\chi}_{||,j}}{\tilde{\chi}_{||,i}} - \frac{m_{e,j}}{m_{e,i}} (\hat{\mathbf{m}}_i \cdot \hat{\mathbf{m}}_j) \right] \right\} \mathbf{m}_i, T > T_N. \quad (\text{B4})$$

Here, $\hat{\mathbf{m}}_i = \mathbf{m}_i/m_i$, and the relative longitudinal susceptibility is given in Eq. (24).

Similarly to the ferromagnetic case, the default magnetization temperature scaling is given as $M_{e,i} = m_{e,i} M_{S,i}^0$. The anisotropy constant follows the temperature dependence $K_{1,i} = K_{1,i}^0 m_{e,i}^3$. The intra-lattice exchange stiffness A_i has the temperature dependence $A_i = A_i^0 m_{e,i}^2$, while the inter-lattice exchange stiffnesses have the temperature dependences $A_{i(nh),i} = A_{i(nh),i}^0 m_{e,i} m_{e,j}$. The DMI exchange parameter follows the temperature dependence $D_i = D_i^0 m_{e,i}^2$. Note these temperature dependences can be adjusted depending on the material simulated where appropriate, for example, using $m_{e,i}$ exponents computed using an atomistic model.

We further show examples of magnetization temperature scaling laws as well as relative longitudinal susceptibility temperature dependences in Fig. 14. In Fig. 14(a), we take a simple ferromagnet with $\mu = 1\mu_B$ and $T_C = 800$ K, plotting the computed relative susceptibility above and below T_C based on Eq. (16). The input m_e function—Eq. (15)—is also plotted for an applied external field of 10 kA/m, and we test the correct implementation by computing the output magnetization temperature dependence using the LLB equation; as expected the input and output m_e scalings are virtually identical. Next, we consider the two-sublattice LLB model using the parameters for $\text{Gd}_{25}(\text{FeCo})_{75}$ given in Ref. 94. From these, we obtain the dimensionless coupling parameters $\tau_A = 0.958$, $\tau_B = 0.127$, $\tau_{AB} = 0.111$, and $\tau_{BA} = 0.333$ for $T_C = 565$ K. Again, we plot the relative longitudinal susceptibilities—Eq. (24)—for the two sublattices ($A = \text{FeCo}$, $B = \text{Gd}$) in Fig. 14(b), as well as the input $m_{e,i}$ functions from Eq. (B3)—as for the ferromagnetic case, these are virtually identical to the magnetization temperature scaling computed using the two-sublattice LLB model as expected. The damping parameter temperature scaling functions—Eq. (B1)—are plotted in Fig. 14(c).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request and the scripts used to obtain the data are available at <https://github.com/SerbanL/Boris2/tree/master/BorisArticle> Ref. 29.

REFERENCES

- ¹M. J. Donahue and D. G. Porter, OOMMF User's Guide, Version 1.0. Interagency Report NISTIR 6376, 1999.
- ²A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia-Sanchez, and B. Van Waeyenberge, "The design and verification of Mumax3," *AIP Adv.* **4**, 107133 (2014).

- ³M.-A. Bisotti, D. Cortés-Ortuño, R. Pepper, W. Wang, M. Beg, T. Kluyver, and H. Fangohr, "Fidimag—A finite difference atomistic and micromagnetic simulation package," *J. Open Res. Softw.* **6**, 22 (2018).
- ⁴J. Leliaert and J. Mulders, "Tomorrow's micromagnetic simulations," *J. Appl. Phys.* **125**, 180901 (2019).
- ⁵T. L. Gilbert, "A Lagrangian formulation of the gyromagnetic equation of the magnetic field," *Phys. Rev.* **100**, 1243 (1955).
- ⁶D. A. Garanin, "Fokker-Planck and Landau-Lifshitz-Bloch equations for classical ferromagnets," *Phys. Rev. B* **55**, 3050 (1997).
- ⁷D. A. Garanin and O. Chubykalo-Fesenko, "Thermal fluctuations and longitudinal relaxation of single-domain magnetic particles at elevated temperatures," *Phys. Rev. B* **70**, 212409 (2004).
- ⁸R. F. L. Evans *et al.*, "Stochastic form of the Landau-Lifshitz-Bloch equation," *Phys. Rev. B* **85**, 014433 (2012).
- ⁹S. Zhang and Z. Li, "Roles of nonequilibrium conduction electrons on the magnetization dynamics of ferromagnets," *Phys. Rev. Lett.* **93**, 127204 (2004).
- ¹⁰S. Lepadatu, "Effect of inter-layer spin diffusion on skyrmion motion in magnetic multilayers," *Sci. Rep.* **9**, 9592 (2019).
- ¹¹C. R. MacKinnon, S. Lepadatu, T. Mercer, and P. R. Bissell, "Role of an additional interfacial spin-transfer torque for current-driven skyrmion dynamics in chiral magnetic layers," *Phys. Rev. B* **102**, 214408 (2020).
- ¹²M. I. Dyakonov and V. I. Perel, "Possibility of orienting electron spins with current," *JETP Lett.* **13**, 467–469 (1971).
- ¹³J. C. Slonczewski, "Current-driven excitation of magnetic multilayers," *J. Magn. Magn. Mater.* **159**, L1–L7 (1996).
- ¹⁴M. I. Dyakonov, "Magnetoresistance due to edge spin accumulation," *Phys. Rev. Lett.* **99**, 126601 (2007).
- ¹⁵S. Zhang, P. M. Levy, and A. Fert, "Mechanisms of spin-polarized current-driven magnetization switching," *Phys. Rev. Lett.* **88**, 236601 (2002).
- ¹⁶A. Brataas, Y. U. V. Nazarov, and G. E. W. Bauer, "Finite-element theory of transport in ferromagnet-normal metal systems," *Phys. Rev. Lett.* **84**, 2481 (2000).
- ¹⁷S. Lepadatu, "Unified treatment of spin torques using a coupled magnetisation dynamics and three-dimensional spin current solver," *Sci. Rep.* **7**, 12937 (2017).
- ¹⁸J. E. Hirsch, "Spin Hall effect," *Phys. Rev. Lett.* **83**, 1834 (1999).
- ¹⁹Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, "Enhanced Gilbert damping in thin ferromagnetic films," *Phys. Rev. Lett.* **88**, 117601 (2002).
- ²⁰Y. Tserkovnyak and M. Mecklenburg, "Electron transport driven by nonequilibrium magnetic textures," *Phys. Rev. B* **77**, 134407 (2008).
- ²¹S. Zhang and S. S.-L. Zhang, "Generalization of the Landau-Lifshitz-Gilbert equation for conducting ferromagnets," *Phys. Rev. Lett.* **102**, 086601 (2009).
- ²²S. Lepadatu, "Interaction of magnetization and heat dynamics for pulsed domain wall movement with Joule heating," *J. Appl. Phys.* **120**, 163908 (2016).
- ²³U. Atxitia and O. Chubykalo-Fesenko, "Ultrafast magnetization dynamics rates within the Landau-Lifshitz-Bloch model," *Phys. Rev. B* **84**, 144414 (2011).
- ²⁴S. Lepadatu, "Efficient computation of demagnetizing fields for magnetic multilayers using multilayered convolution," *J. Appl. Phys.* **126**, 103903 (2019).
- ²⁵I. Dzyaloshinsky, "A thermodynamic theory of 'weak' ferromagnetism of anti-ferromagnetics," *J. Phys. Chem. Solids* **4**, 241–255 (1958).
- ²⁶T. Moriya, "Anisotropic superexchange interaction and weak ferromagnetism," *Phys. Rev.* **120**, 91 (1960).
- ²⁷B. Heinrich *et al.*, "Bilinear and biquadratic exchange coupling in bcc Fe/Cu/Fe trilayers: Ferromagnetic-resonance and surface magneto-optical Kerr-effect studies," *Phys. Rev. B* **47**, 5077 (1993).
- ²⁸S. Lepadatu, "Effective field model of roughness in magnetic nano-structures," *J. Appl. Phys.* **118**, 243908 (2015).
- ²⁹See <https://github.com/SerbanL/Boris2> for source code repository; accessed 3 August 2020.
- ³⁰User manual, https://www.researchgate.net/publication/331715880_Boris_Computational_Spintronics_User_Manual, DOI:10.13140/RG.2.2.31496.88322/1; accessed 3 August 2020.
- ³¹J. Nickolls, I. Buck, M. Garland, and K. Skadron, "Scalable parallel programming with CUDA," *ACM Queue* **6**, 40–53 (2008).
- ³²M. Frigo and S. G. Johnson, "The design and implementation of FFTW3," *Proc. IEEE* **93**, 216–231 (2005).
- ³³See <http://www.boris-spintronics.uk/online-materials-database/> for material parameters; accessed 3 August 2020.
- ³⁴T. L. Gilbert, "A phenomenological theory of damping in ferromagnetic materials," *IEEE Trans. Magn.* **40**, 3443 (2004).
- ³⁵L. Exl *et al.*, "Labonte's method revisited: An effective steepest descent method for micromagnetic energy minimization," *J. Appl. Phys.* **115**, 17D118 (2014).
- ³⁶J. Barzilai and J. M. Borwein, "Two-point step size gradient methods," *IMA J. Numer. Anal.* **8**, 141–148 (1988).
- ³⁷See <https://www.ctcms.nist.gov/~rdm/std4/spec4.html> for NIST micromagnetic modeling activity group (μ MAG) website; accessed 22 July 2020.
- ³⁸G. Venkat *et al.*, "Proposal for a standard micromagnetic problem: Spin wave dispersion in a magnonic waveguide," *IEEE Trans. Mag.* **49**, 524–529 (2013).
- ³⁹K. M. Lebecki, M. J. Donahue, and M. W. Gutowski, "Periodic boundary conditions for demagnetization interactions in micromagnetic simulations," *J. Phys. D Appl. Phys.* **41**, 175005 (2008).
- ⁴⁰Z. Li and S. Zhang, "Domain-wall dynamics driven by adiabatic spin-transfer torques," *Phys. Rev. B* **70**, 024417 (2004).
- ⁴¹S. Lepadatu, "Interaction of magnetization and heat dynamics for pulsed domain wall movement with Joule heating," *J. Appl. Phys.* **120**, 163908 (2016).
- ⁴²A. Thiaville, Y. Nakatani, J. Miltat, and Y. Suzuki, "Micromagnetic understanding of current-driven domain wall motion in patterned nanowires," *Europhys. Lett.* **69**, 990–996 (2005).
- ⁴³See <https://www.ctcms.nist.gov/~rdm/std5/spec5.shtml> for NIST micromagnetic modeling activity group (μ MAG) website; accessed 22 July 2020.
- ⁴⁴R. F. Wang *et al.*, "Artificial 'spin ice' in a geometrically frustrated lattice of nanoscale ferromagnetic islands," *Nature* **439**, 303–306 (2006).
- ⁴⁵J. P. Morgan, A. Stein, S. Langridge, and C. H. Marrows, "Thermal ground-state ordering and elementary excitations in artificial magnetic square ice," *Nat. Phys.* **7**, 75–79 (2011).
- ⁴⁶S. Woo *et al.*, "Observation of room-temperature magnetic skyrmions and their current driven dynamics in ultra-thin metallic ferromagnets," *Nat. Mater.* **15**, 501–506 (2016).
- ⁴⁷W. Legrand *et al.*, "Room-temperature current-induced generation and motion of sub100 nm skyrmions," *Nano Lett.* **17**, 2703–2712 (2017).
- ⁴⁸K. Litzius *et al.*, "Skyrmion Hall effect revealed by direct time-resolved X-ray microscopy," *Nat. Phys.* **13**, 170–175 (2017).
- ⁴⁹A. Hrabec *et al.*, "Current-induced skyrmion generation and dynamics in symmetric bilayers," *Nat. Commun.* **8**, 15765 (2017).
- ⁵⁰S. Lepadatu *et al.*, "Very low critical current density for motion of coupled domain walls in synthetic ferrimagnet nanowires," *Sci. Rep.* **7**, 1640 (2017).
- ⁵¹A. Hrabec *et al.*, "Velocity enhancement by synchronization of magnetic domain walls," *Phys. Rev. Lett.* **120**, 227204 (2018).
- ⁵²S.-H. Yang, K.-S. Ryu, and S. Parkin, "Domain-wall velocities of up to 750 ms⁻¹ driven by exchange-coupling torque in synthetic antiferromagnets," *Nat. Nanotechnol.* **10**, 221–226 (2015).
- ⁵³A. J. Newell, W. Williams, and D. J. Dunlop, "A generalization of the demagnetizing tensor for nonuniform magnetization," *J. Geophys. Res. Solid Earth* **98**, 9551–9555, (1993).
- ⁵⁴H. Fangohr, G. Bordignon, M. Franchin, A. Knittel, P. A. J. de Groot, and T. Fischbacher, "A new approach to (quasi) periodic boundary conditions in micromagnetics: The macrogeometry," *J. Appl. Phys.* **105**, 07D529 (2009).
- ⁵⁵M. A. Ruderman and C. Kittel, "Indirect exchange coupling of nuclear magnetic moments by conduction electrons," *Phys. Rev.* **96**, 99–102 (1954).
- ⁵⁶T. Kasuya, "A theory of metallic ferro- and antiferromagnetism on Zener's model," *Prog. Theor. Phys.* **16**, 45–57 (1956).
- ⁵⁷K. Yosida, "Magnetic properties of Cu-Mn alloys," *Phys. Rev.* **106**, 893 (1957).
- ⁵⁸M. M. Vopson, J. Naylor, T. Saengow, E. G. Rogers, S. Lepadatu, and Y. K. Fetisov, "Development of flexible Ni80Fe20 magnetic nano-thin films," *Phys. B Condens. Matter* **525**, 12 (2017).

- ⁵⁹M. Belusky, S. Lepadatu, J. Naylor, and M. M. Vopson, "Evidence of substrate roughness surface induced magnetic anisotropy in Ni80Fe20 flexible thin films," *J. Magn. Magn. Mater.* **478**, 77 (2019).
- ⁶⁰M. Belusky, S. Lepadatu, J. Naylor, and M. M. Vopson, "Study of roughness effect in Fe and Co thin films prepared by plasma magnetron sputtering," *Physica B* **574**, 411666 (2019).
- ⁶¹M. M. Vopson and S. Lepadatu, "Solving the electrical control of magnetic coercive field paradox," *Appl. Phys. Lett.* **105**, 122901 (2014).
- ⁶²S. Lepadatu and M. Vopson, "Heat assisted multiferroic solid-state memory," *Materials* **10**, 991 (2017).
- ⁶³T. Chen *et al.*, "Spin-torque and spin-Hall nano-oscillators," *Proc. IEEE* **104**, 1919–1945 (2016).
- ⁶⁴J. Åkerman, "Toward a universal memory," *Science* **308**, 508–510 (2005).
- ⁶⁵J. W. Thomas, *Numerical Partial Differential Equations: Finite Difference Methods* (Springer-Verlag, 1995).
- ⁶⁶B. Krüger, "Current-driven magnetization dynamics: analytical modeling and numerical simulation," Ph.D. dissertation, University of Hamburg, 2011, Appendix D, p. 118.
- ⁶⁷C. Abert *et al.*, "A three-dimensional spin-diffusion model for micromagnetics," *Sci. Rep.* **5**, 14855 (2015).
- ⁶⁸D. Claudio-Gonzalez, A. Thiaville, and J. Miltat, "Domain wall dynamics under nonlocal spin-transfer torque," *Phys. Rev. Lett.* **108**, 227208 (2012).
- ⁶⁹A. Bisig *et al.*, "Enhanced nonadiabaticity in vortex cores due to the emergent Hall effect," *Phys. Rev. Lett.* **117**, 277203 (2016).
- ⁷⁰K. Ando *et al.*, "Electric manipulation of spin relaxation using the spin Hall effect," *Phys. Rev. Lett.* **101**, 036601 (2008).
- ⁷¹J. Xiao, A. Zangwill, and M. D. Stiles, "Boltzmann test of Slonczewski's theory of spin-transfer torque," *Phys. Rev. B* **70**, 172405 (2004).
- ⁷²J. Xiao, A. Zangwill, and M. D. Stiles, "Macrospin models of spin transfer dynamics," *Phys. Rev. B* **72**, 014446 (2005).
- ⁷³J. L. García-Palacios and F. J. Lázaro, "Langevin-dynamics study of the dynamical properties of small magnetic particles," *Phys. Rev. B* **58**, 14937 (1998).
- ⁷⁴U. Atxitia, D. Hinzke, O. Chubykalo-Fesenko, U. Nowak, H. Kachkachi, O. N. Mryasov, R. F. Evans, and R. W. Chantrell, "Multiscale modeling of magnetic materials: Temperature dependence of the exchange stiffness," *Phys. Rev. B* **82**, 134440 (2010).
- ⁷⁵L. Rozsa, U. Atxitia, and U. Novak, "Temperature scaling of the Dzyaloshinsky-Moriya interaction in the spin wave spectrum," *Phys. Rev. B* **96**, 094436 (2017).
- ⁷⁶H. B. Callen and E. Callen, "The present status of the temperature dependence of magnetocrystalline anisotropy, and the power law," *J. Phys. Chem. Sol.* **27**, 1271–1285 (1966).
- ⁷⁷P. Asselin, R. F. L. Evans, J. Barker, R. W. Chantrell, R. Yanes, O. Chubykalo-Fesenko, D. Hinzke, and U. Nowak, "Constrained Monte Carlo method and calculation of the temperature dependence of magnetic anisotropy," *Phys. Rev. B* **82**, 054415 (2010).
- ⁷⁸R. Moreno, R. F. L. Evans, S. Khmelevskyi, M. C. Muñoz, R. W. Chantrell, and O. Chubykalo-Fesenko, "Temperature-dependent exchange stiffness and domain wall width in Co," *Phys. Rev. B* **94**, 104433 (2016).
- ⁷⁹R. Tomasello, K. Y. Guslienko, M. Ricci, A. Giordano, J. Barker, M. Carpentieri, O. Chubykalo-Fesenko, and G. Finocchio, "Origin of temperature and field dependence of magnetic skyrmion size in ultrathin nanodots," *Phys. Rev. B* **97**, 060402 (2018).
- ⁸⁰D. Hinzke and U. Nowak, "Domain wall motion by the magnonic spin Seebeck effect," *Phys. Rev. Lett.* **107**, 027205 (2011).
- ⁸¹E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot, "Ultrafast spin dynamics in ferromagnetic nickel," *Phys. Rev. Lett.* **76**, 4250 (1996).
- ⁸²B. Koopmans *et al.*, "Explaining the paradoxical diversity of ultrafast laser-induced demagnetization," *Nat. Mater.* **9**, 259 (2010).
- ⁸³N. Nagaosa and Y. Tokura, "Topological properties and dynamics of magnetic skyrmions," *Nat. Nanotechnol.* **8**, 899 (2013).
- ⁸⁴S.-G. Je *et al.*, "Creation of magnetic skyrmion bubble lattices by ultrafast laser in ultrathin films," *Nano Lett.* **18**, 7362 (2018).
- ⁸⁵S. Lepadatu, "Emergence of transient domain wall skyrmions after ultrafast demagnetization," *Phys. Rev. B* **102**, 094402 (2020).
- ⁸⁶C. Marrows, "Addressing an antiferromagnetic memory," *Science* **351**, 558 (2016).
- ⁸⁷T. Jungwirth, X. Marti, P. Wadley, and J. Wunderlich, "Antiferromagnetic spintronics," *Nat. Nanotechnol.* **11**, 231 (2016).
- ⁸⁸T. Jungwirth, J. Sinova, A. Manchon, X. Marti, J. Wunderlich, and C. Felser, "The multiple directions of antiferromagnetic spintronics," *Nat. Phys.* **14**, 200–203 (2018).
- ⁸⁹P. Wadley *et al.*, "Electrical switching of an antiferromagnet," *Science* **351**, 587–590 (2016).
- ⁹⁰S. Baierl *et al.*, "Nonlinear spin control by terahertz-driven anisotropy fields," *Nat. Photonics* **10**, 715–718 (2016).
- ⁹¹S. Woo *et al.*, "Current-driven dynamics and inhibition of the skyrmion Hall effect of ferrimagnetic skyrmions in GdFeCo films," *Nat. Commun.* **9**, 959 (2018).
- ⁹²J. Nogués and I. K. Schuller, "Exchange bias," *J. Magn. Magn. Mater.* **192**, 203–232 (1999).
- ⁹³U. Atxitia, P. Nieves, and O. Chubykalo-Fesenko, "Landau-Lifshitz-Bloch equation for ferrimagnetic materials," *Phys. Rev. B* **86**, 104414 (2012).
- ⁹⁴P. Nieves, U. Atxitia, R. W. Chantrell, and O. Chubykalo-Fesenko, "The classical two-sublattice Landau-Lifshitz-Bloch equation for all temperatures," *Low Temp. Phys.* **41**, 739 (2015).
- ⁹⁵F. Keefer and C. Kittel, "Theory of antiferromagnetic resonance," *Phys. Rev.* **85**, 329 (1952).
- ⁹⁶W. H. Meiklejohn and C. P. Bean, "New magnetic anisotropy," *Phys. Rev.* **102**, 1413 (1956).
- ⁹⁷M. M. Vopson, M. Belusky, and S. Lepadatu, "Diamagnetic coupling for magnetic tuning in nano-thin films," *Appl. Phys. Lett.* **116**, 252402 (2020).
- ⁹⁸R. L. Stamps, "Mechanisms for exchange bias," *J. Phys. D Appl. Phys.* **33**, R247–R268 (2000).
- ⁹⁹C. Abert, L. Exl, G. Selke, A. Drews, and T. Schrefl, "Numerical methods for the stray-field calculation: A comparison of recently developed algorithms," *J. Magn. Magn. Mater.* **326**, 176–185 (2013).
- ¹⁰⁰W. Scholz, J. Fidler, T. Schrefl, D. Suess, R. Dittrich, H. Forster, and V. Tsiantos, "Scalable parallel micromagnetic solvers for magnetic nanostructures," *Comput. Mater. Sci.* **28**, 366 (2003).
- ¹⁰¹G. M. Amdahl, "Validity of the single processor approach to achieving large scale computing capabilities," in *AFIPS Conference Proceedings* (ACM Digital Library, 1967), Vol. 30, pp. 483–485.
- ¹⁰²A. Manchon, "Spin diffusion and torques in disordered antiferromagnets," *J. Phys. Condens. Matter* **29**, 104002 (2017).
- ¹⁰³Y. Yahagi, B. Harteneck, S. Cabrini, and H. Schmidt, "Controlling nanomagnet magnetization dynamics via magnetoelastic coupling," *Phys. Rev. B* **90**, 140405 (2014).
- ¹⁰⁴A. G. Gurevich and G. A. Melkov, *Magnetization Oscillations and Waves* (CRC Press, 1996).
- ¹⁰⁵R. F. L. Evans *et al.*, "Atomistic spin model simulations of magnetic nanomaterials," *J. Phys. Condens. Matter* **26**, 103202 (2014).
- ¹⁰⁶A. De Lucia, B. Krüger, O. A. Tretiakov, and M. Kläui, "Multiscale model approach for magnetization dynamics simulations," *Phys. Rev. B* **94**, 184415 (2016).
- ¹⁰⁷É. Méndez, M. Poluektov, G. Kreiss, O. Eriksson, and M. Pereira, "Multiscale approach for magnetization dynamics: Unraveling exotic magnetic states of matter," *Phys. Rev. Res.* **2**, 013092 (2020).
- ¹⁰⁸L. Sánchez-Tejerina, V. Puliafito, P. K. Amiri, M. Carpentieri, and G. Finocchio, "Dynamics of domain-wall motion driven by spin-orbit torque in antiferromagnets," *Phys. Rev. B* **101**, 014433 (2020).