OOMMF Tutorial
Part I: Introduction to Micromagnetics

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Online Spintronics Seminar

Professor Xin Fan (Univ. Denver)

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nanoHUB

Tanya Faltens (Purdue University)

IEEE Magnetics Society

- US Department of Commerce
  - National Institute of Standards and Technology (orig. NBS, 1901)
    - Information Technology Laboratory (ITL)
      - Applied and Computational Mathematics Division (ACMD)
        - Mathematical Software Group (Michael Donahue, Leader)
          - OOMMF: Original authors: Bob McMichael, Michael Donahue, Don Porter
          - OOF: Use micrographs to create grain-based finite-element models and run multi-physics simulations
          - DLMF: Successor to Abramowitz and Stegun, Handbook of Mathematical Functions

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OOMMF Tutorial
Part I: Introduction to Micromagnetics

Session schedule

- Thur, 21-May-2020: Intro to Micromagnetics
- Tues, 26-May-2020: OOMMF widgets and pitfalls
- Tues, 2-June-2020: MIF magic, writing an extension, batch processing
- Tues, 9-June-2020: Data analysis, pics, movies, dispersion curves, . . .

All sessions start at 12:00 noon EDT.

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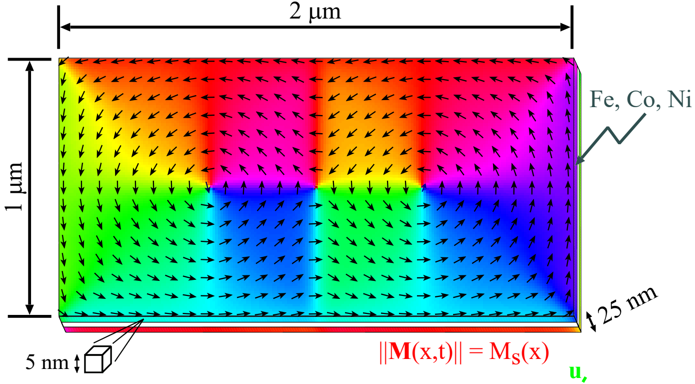
Part I: Introduction to Micromagnetics

Micromagnetics in a nutshell



$\|\mathbf{M}(x,t)\| = M_S(x)$

- Dipole-Dipole (demag)
- Anisotropy $\mathbf{u}$
- Exchange
- Zeeman $\mathbf{H}_{app}$

LLG: $(1+\alpha^2)\, d\mathbf{M}/dt = \gamma\, \mathbf{H}\times\mathbf{M} + (\alpha\gamma/M_S)\, \mathbf{M}\times\mathbf{H}\times\mathbf{M}$

$\Delta t \lesssim \text{ps}, \quad t \approx \text{ns}$

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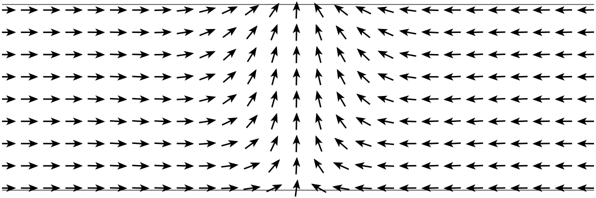
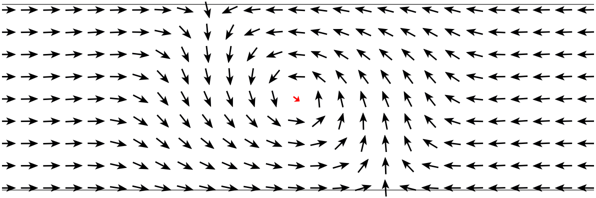
How can I use micromagnetics?

- Part design
- Experimental design
  - Is there anything to see?
  - Do the spatial and temporal scales match my apparatus?
  - Is the effect magnitude large enough?
- Explaining experimental results
- Understanding unexpected behavior

Head-to-head domain wall types

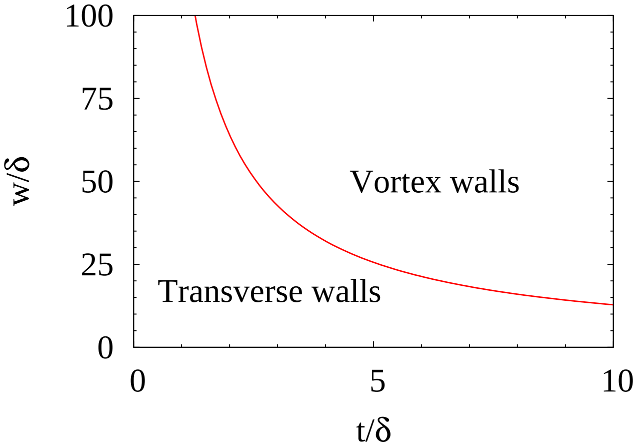


Transverse wall



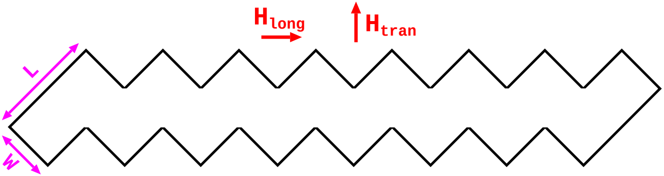
Vortex wall

Head-to-head phase diagram



R.D. McMichael & M.J. Donahue, *IEEE Trans. Magn.*, **33**, 4167 (1997).

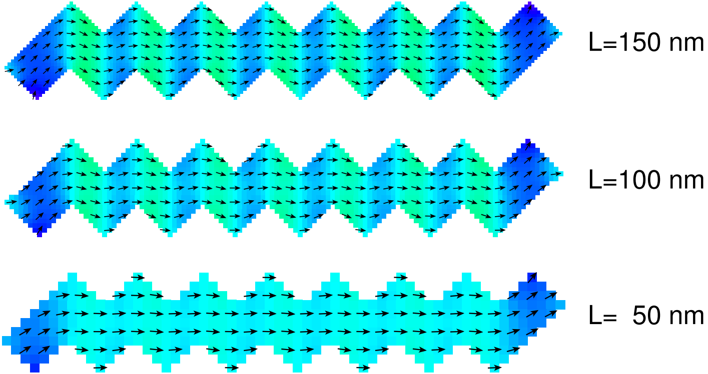
Size effect study



50 nm < L < 500 nm
W = 0.5 L
Thickness = 20 nm

Py material parameters:
A = 13 pJ/m
K = 0 J/m^3
M_s = 800 kA/m

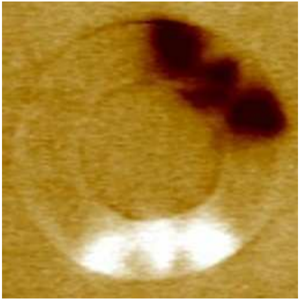
Size effect study (remanent state)



FCS da Silva, WC Uhlig, AB Kos, S Schima, J Aumentado, J Unguris & DP Pappas, “Zigzag-shaped magnetic sensors,” *APL*, **85**, 6025, (2004).

US Patent 7,450,353: Zig-zag shape biased anisotropic magnetoresistive sensor (2008).

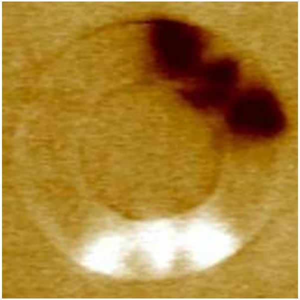
Py ring, D_O = 2 μm, t=65 nm



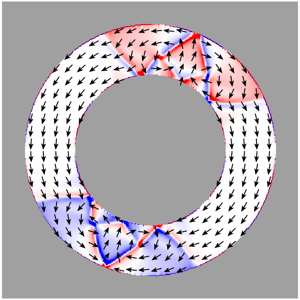
MFM image

MH Park, YK Hong, BC Choi, MJ Donahue, H Han & SH Gee, "Vortex head-to-head domain walls and their formation in onion-state ring elements," *Phys. Rev. B*, **73**, 094424 (2006).

Py ring, $D_O = 2\ \mu$m, t=65 nm



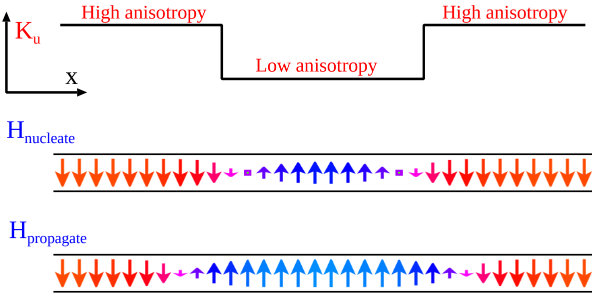
MFM image



Simulation, $\nabla \cdot M$

MH Park, YK Hong, BC Choi, MJ Donahue, H Han & SH Gee, “Vortex head-to-head domain walls and their formation in onion-state ring elements,” *Phys. Rev. B*, **73**, 094424 (2006).

Pinning by a simple defect



$$\boldsymbol{H}_{\text{propagate}} = (\boldsymbol{H}_{\text{u,bulk}} - \boldsymbol{H}_{\text{u,defect}})/4$$
$$\boldsymbol{H}_{\text{switch}} \geq \boldsymbol{H}_{\text{u,bulk}}/5$$

A. Aharoni, *Phys. Rev.*, **119**, 127 (1960).
M.J. Donahue, G. Vértesy, M. Pardavi-Horvath, *JAP*, **93**, 7038 (2003).

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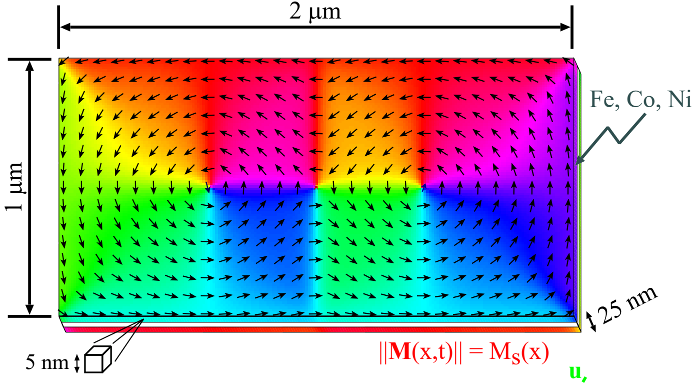
Micromagnetics in a nutshell



- Dipole-Dipole (demag)
- Anisotropy
- Exchange
- Zeeman

LLG: $(1+\alpha^2)\, d\mathbf{M}/dt = \gamma\, \mathbf{H}\times\mathbf{M} + (\alpha\gamma/M_S)\, \mathbf{M}\times\mathbf{H}\times\mathbf{M}$

$\Delta t \lesssim \text{ps},\quad t \approx \text{ns}$

Brown's equations

Energies:

$$E_{\text{exchange}} = \int_V \frac{A}{M_s^2}\left(|\nabla M_x|^2 + |\nabla M_y|^2 + |\nabla M_z|^2\right) d^3r$$

$$E_{\text{anisotropy}} = \int_V \frac{K_1}{M_s^2}(\boldsymbol{M}\cdot\boldsymbol{u})^2\, d^3r$$

$$E_{\text{demag}} = \frac{\mu_0}{8\pi}\int_V \boldsymbol{M}(\boldsymbol{r})\cdot\left[\int_V \nabla\cdot\boldsymbol{M}(\boldsymbol{r}')\frac{\boldsymbol{r}-\boldsymbol{r}'}{|\boldsymbol{r}-\boldsymbol{r}'|^3}\, d^3r' - \int_S \hat{\mathbf{n}}\cdot\boldsymbol{M}(\boldsymbol{r}')\frac{\boldsymbol{r}-\boldsymbol{r}'}{|\boldsymbol{r}-\boldsymbol{r}'|^3}\, d^2r'\right] d^3r$$

$$E_{\text{Zeeman}} = -\mu_0\int_V \boldsymbol{M}\cdot\boldsymbol{H}_{\text{applied}}\, d^3r$$

Constraints

$\boldsymbol{M}$ is piecewise smooth

and

$$\|\boldsymbol{M}(\boldsymbol{r},t)\| = \|\boldsymbol{M}(\boldsymbol{r})\| = M_s(\boldsymbol{r})$$

or equivalently

$$\|\boldsymbol{m}(\boldsymbol{r},t)\| = \boldsymbol{M}(\boldsymbol{r},t)/M_s(\boldsymbol{r}) = \|\boldsymbol{m}\| = 1.$$

W. F. Brown, Jr., *Micromagnetics.* (Interscience, New York, 1962).

Exchange lengths

Magnetocrystalline exchange length (for hard materials):

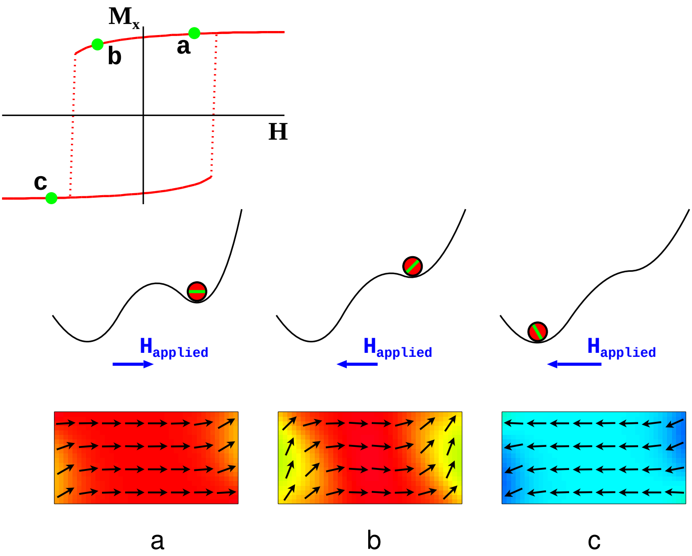
$$\ell_{\text{ex,K}} = \sqrt{\frac{A}{K_u}}$$

Magnetostatic exchange length (for soft materials):

$$\ell_{\text{ex,Ms}} = \sqrt{\frac{2A}{\mu_0 M_s^2}}$$

- Don't mesh any coarser than smaller of these two values!

Quasi-static simulations



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Magnetization dynamics

Landau-Lifshitz-Gilbert:

$$\frac{d\boldsymbol{M}}{dt} = \frac{|\gamma_0|}{1+\alpha^2}\boldsymbol{H}_{\text{eff}} \times \boldsymbol{M} + \frac{\alpha\,|\gamma_0|}{(1+\alpha^2)M_{\text{s}}}\boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} \times \boldsymbol{M}$$

where

$$\boldsymbol{H}_{\text{eff}} = -\frac{1}{\mu_0}\frac{\delta E_{\text{total}}}{\delta \boldsymbol{M}}$$

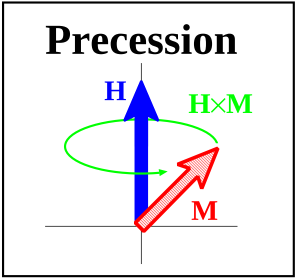
γ_0 = gyromagnetic ratio

α = damping coefficient

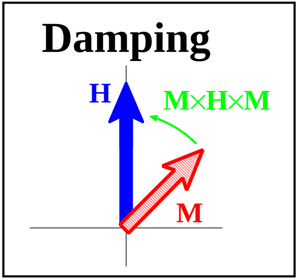
Magnetization dynamics

Landau-Lifshitz-Gilbert:

$$\frac{d\boldsymbol{M}}{dt} = \frac{|\gamma_0|}{1+\alpha^2}\boldsymbol{H}_{\text{eff}} \times \boldsymbol{M} + \frac{\alpha\,|\gamma_0|}{(1+\alpha^2)M_s}\boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} \times \boldsymbol{M}$$



No energy change



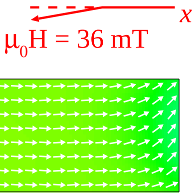
Loses energy

$$\left\|\frac{d\boldsymbol{M}}{dt}\right\| = \frac{|\gamma_0|}{\sqrt{1+\alpha^2}}\,\|\boldsymbol{H}_{\text{eff}} \times \boldsymbol{M}\|$$

Magnetization dynamics

Time

0 ps

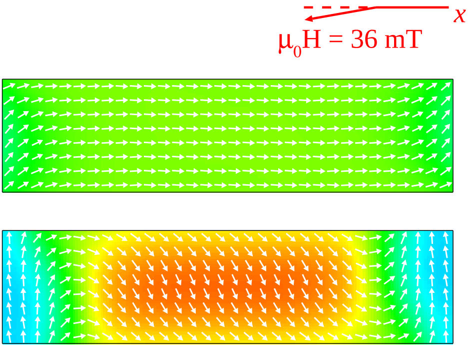


Magnetization dynamics

Time

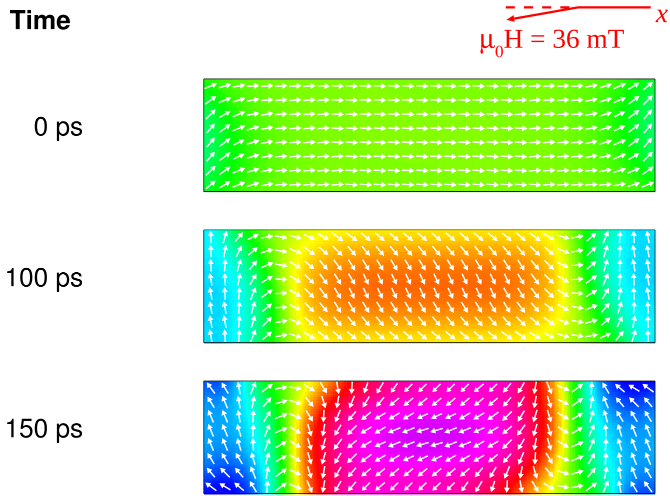
0 ps

100 ps



Magnetization dynamics

Time



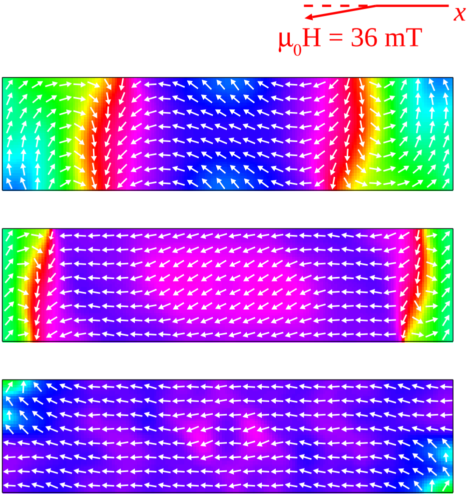
Magnetization dynamics

Time

350 ps

450 ps

750 ps

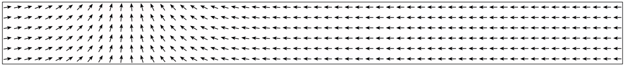


RD McMichael, MJ Donahue, DG Porter & J Eicke, “Switching dynamics and critical behavior of standard problem no. 4,” *JAP*, **89**, 7603 (2001).

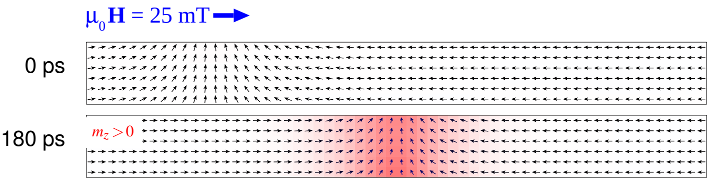
Thin film simulation

$\mu_0 \mathbf{H} = 25$ mT →

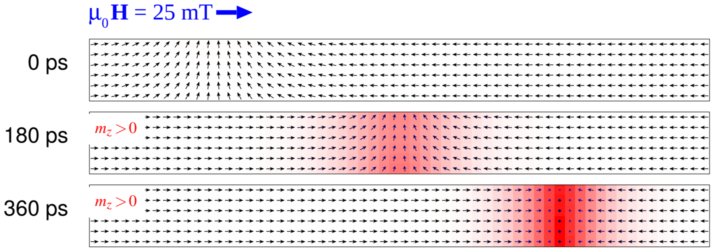
0 ps



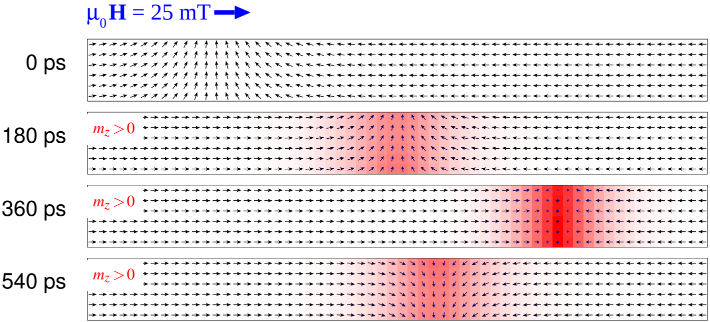
Thin film simulation



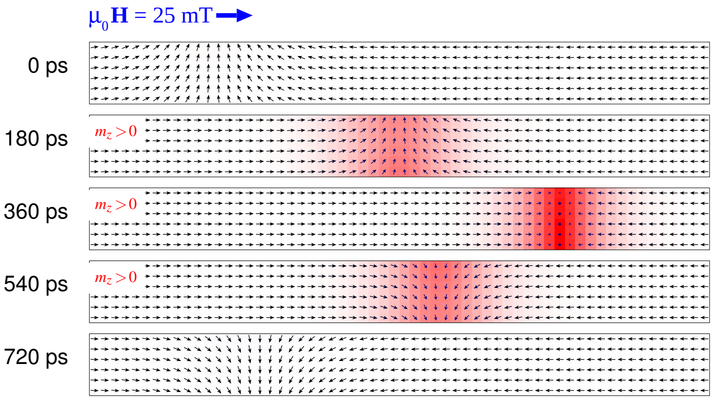
Thin film simulation



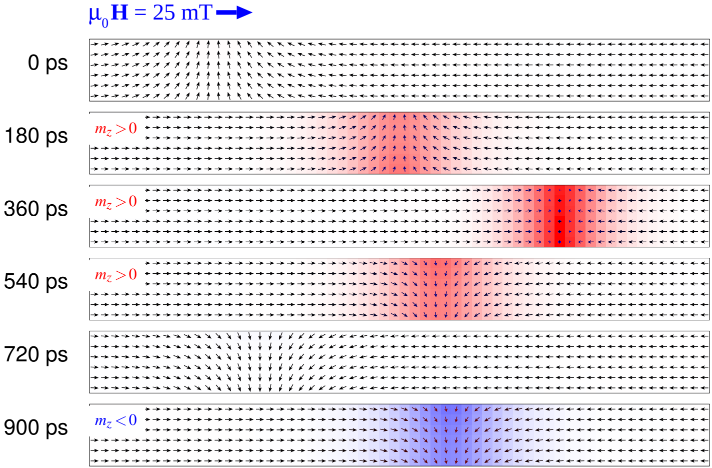
Thin film simulation



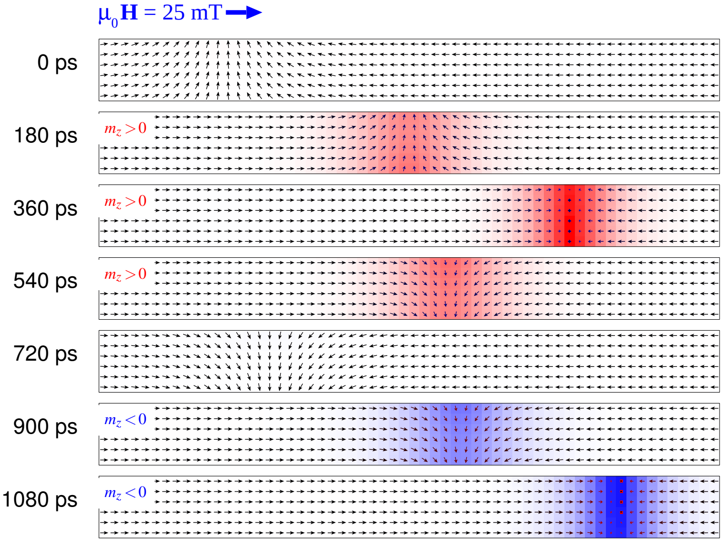
Thin film simulation



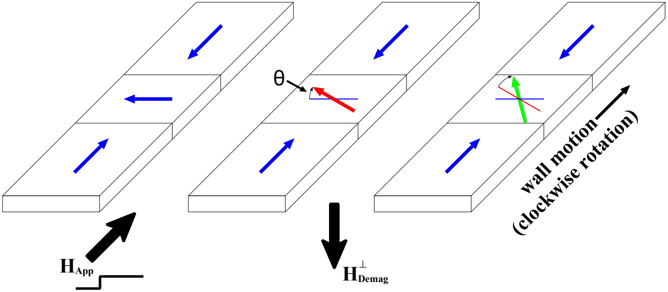
Thin film simulation



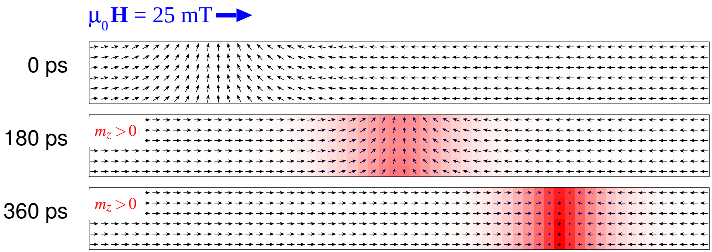
Thin film simulation



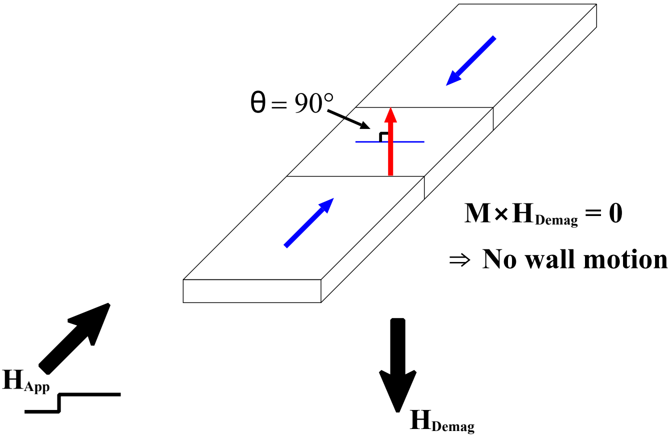
Thin film wall dynamics, $m_z \geq 0$



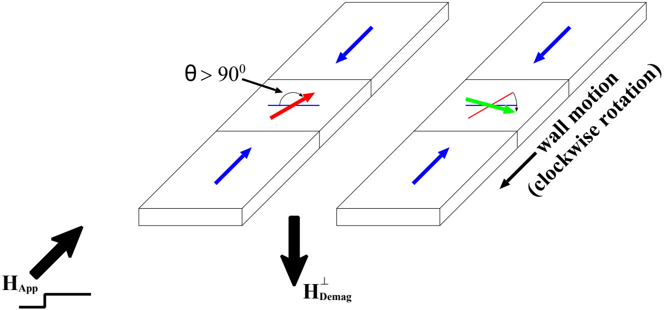
Thin film simulation



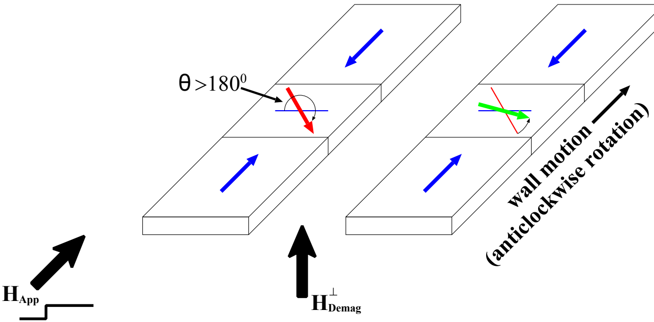
Thin film wall dynamics, $m_z \geq 0$



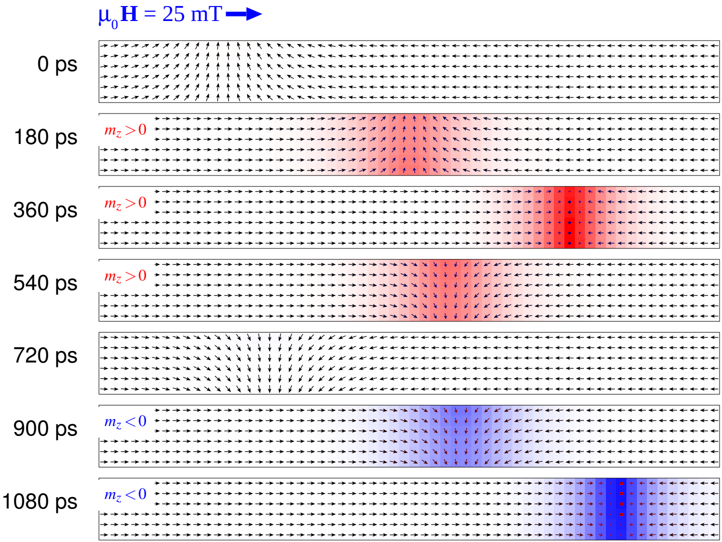
Thin film wall dynamics, $m_z \geq 0$



Thin film wall dynamics, $m_z \leq 0$



Thin film simulation



DG Porter & MJ Donahue, "Velocity of transverse domain wall motion along thin, narrow strips," *JAP*, **95**, 6729 (2004).

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Installation demonstrations

- nanoHUB
- Windows
- macOS