AF-04

High Resolution Study of Discretization Effects in μMAG Standard Problem No. 1

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1901-2001
NIST CENTENNIAL

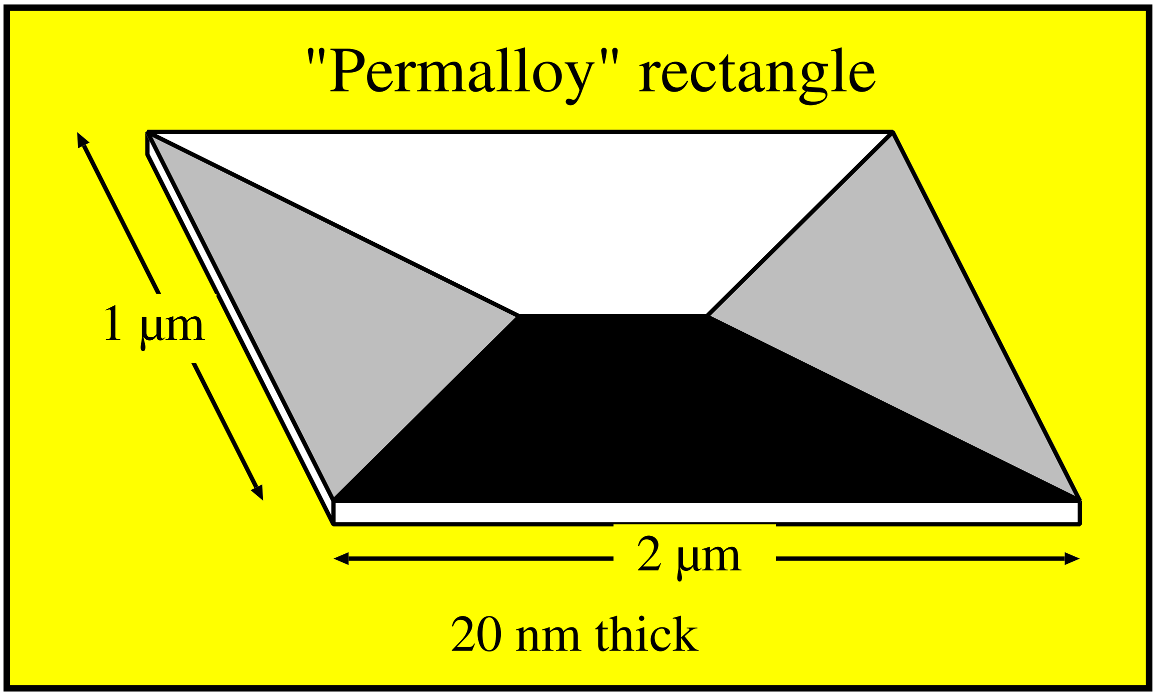
OOMMF

Object Oriented Micromagnetic Framework

- Portable, public domain package from NIST
  - http://math.nist.gov/oommf
- Fully 3D
- Regular, rectangular grids
- FFT-based demag
- Simple 6-neighbor exchange

μMAG Standard Problem No. 1

http://www.ctcms.nist.gov/~rdm/mumag.org.html



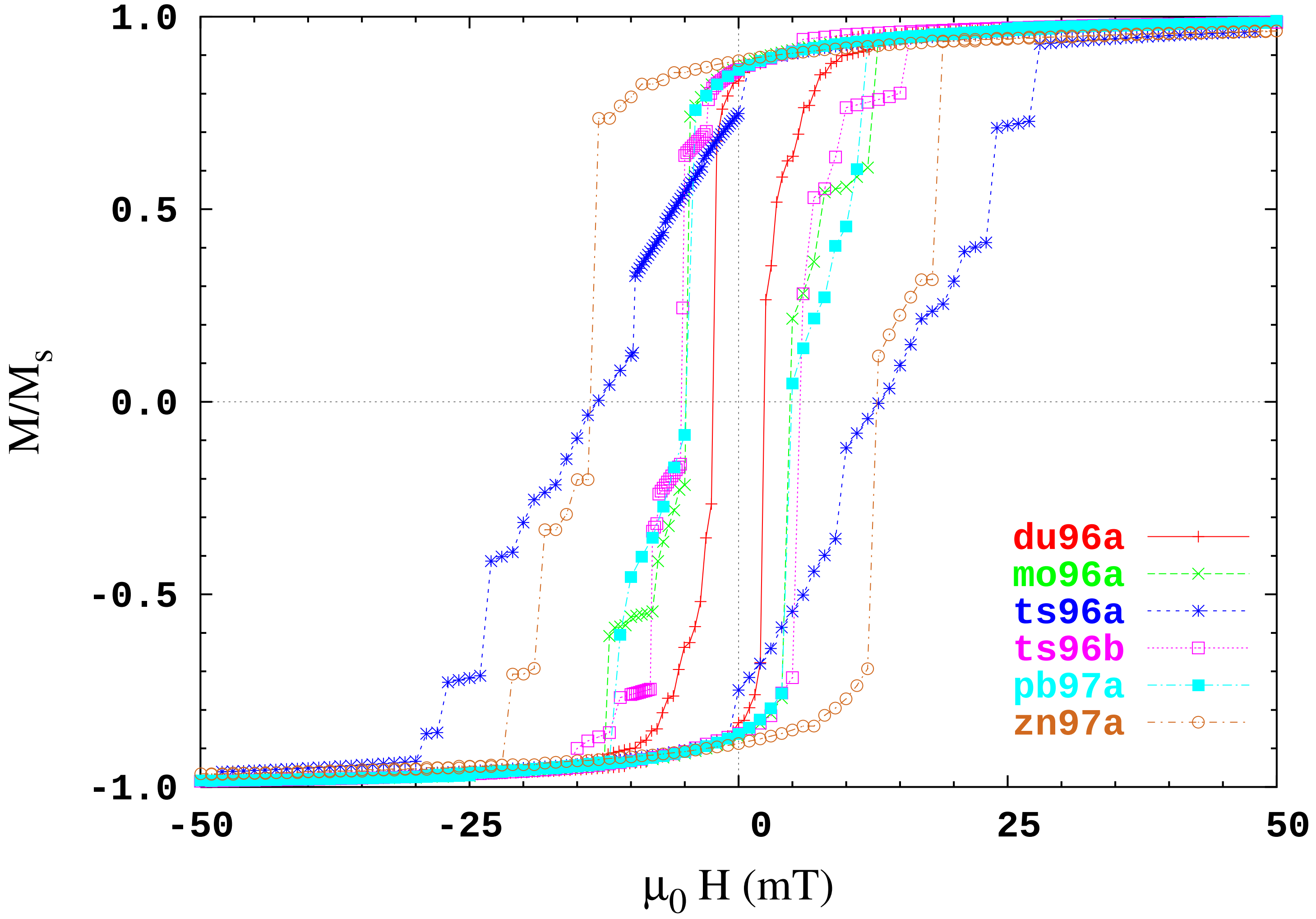
Material parameters:

$$
\begin{aligned}
\mathrm{A} &= 1.3 \times 10^{-11}\ \mathrm{J/m} \\
\mathrm{M}_s &= 8 \times 10^{5}\ \mathrm{A/m} \\
\mathrm{K} &= 5 \times 10^{2}\ \mathrm{J/m,\ easy} \parallel \mathrm{long\ axis}
\end{aligned}
$$

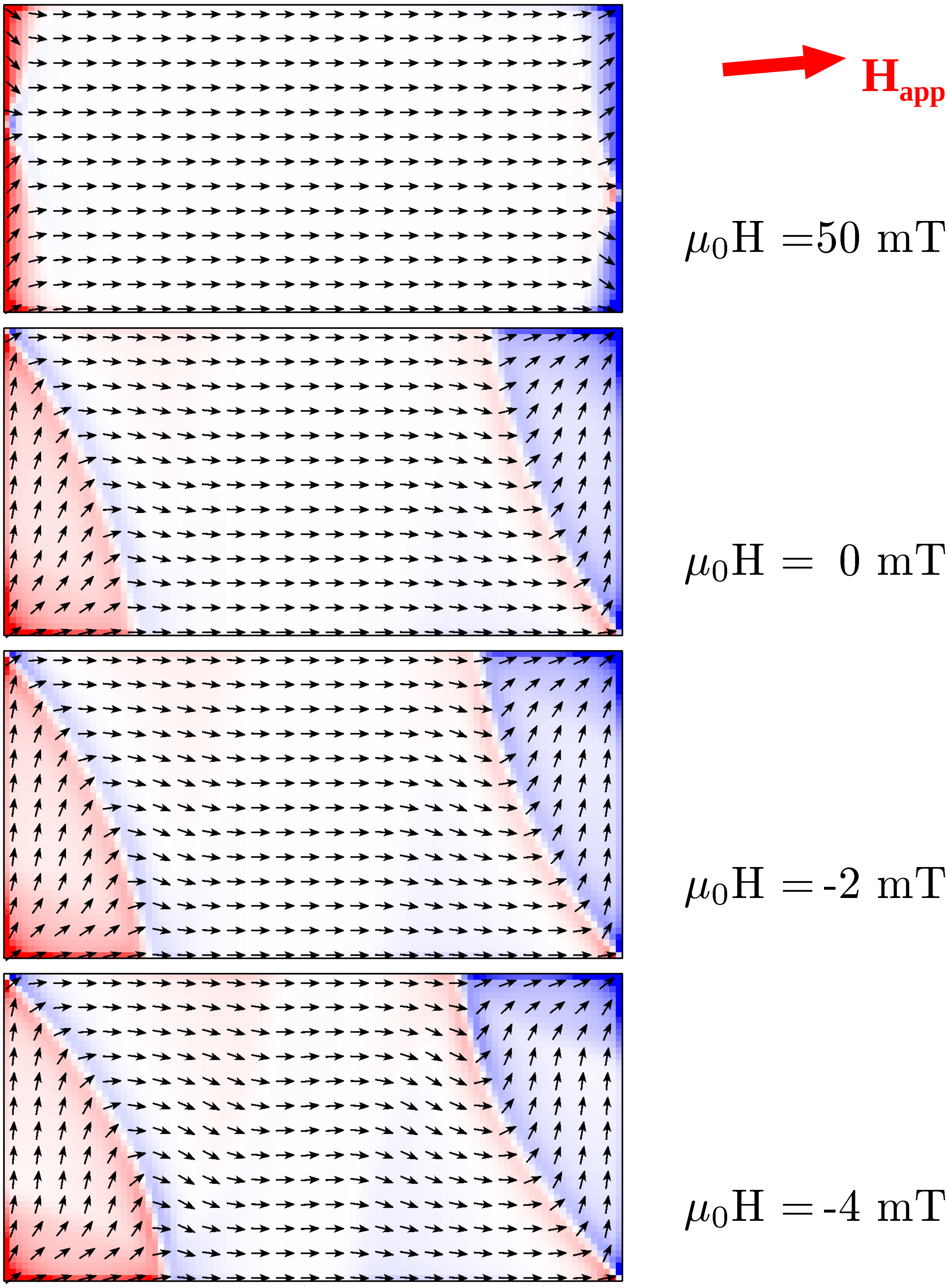
Field applied 1° ccw from particle axis.

Exchange length $\ell_{\mathrm{ex}} = \sqrt{\frac{2A}{\mu_0 M_s^2}} \doteq 5.7$ nm

μMAG Prob. 1: Long Axis Hysteresis Loops



Equilibrium states, Δ = 20 nm



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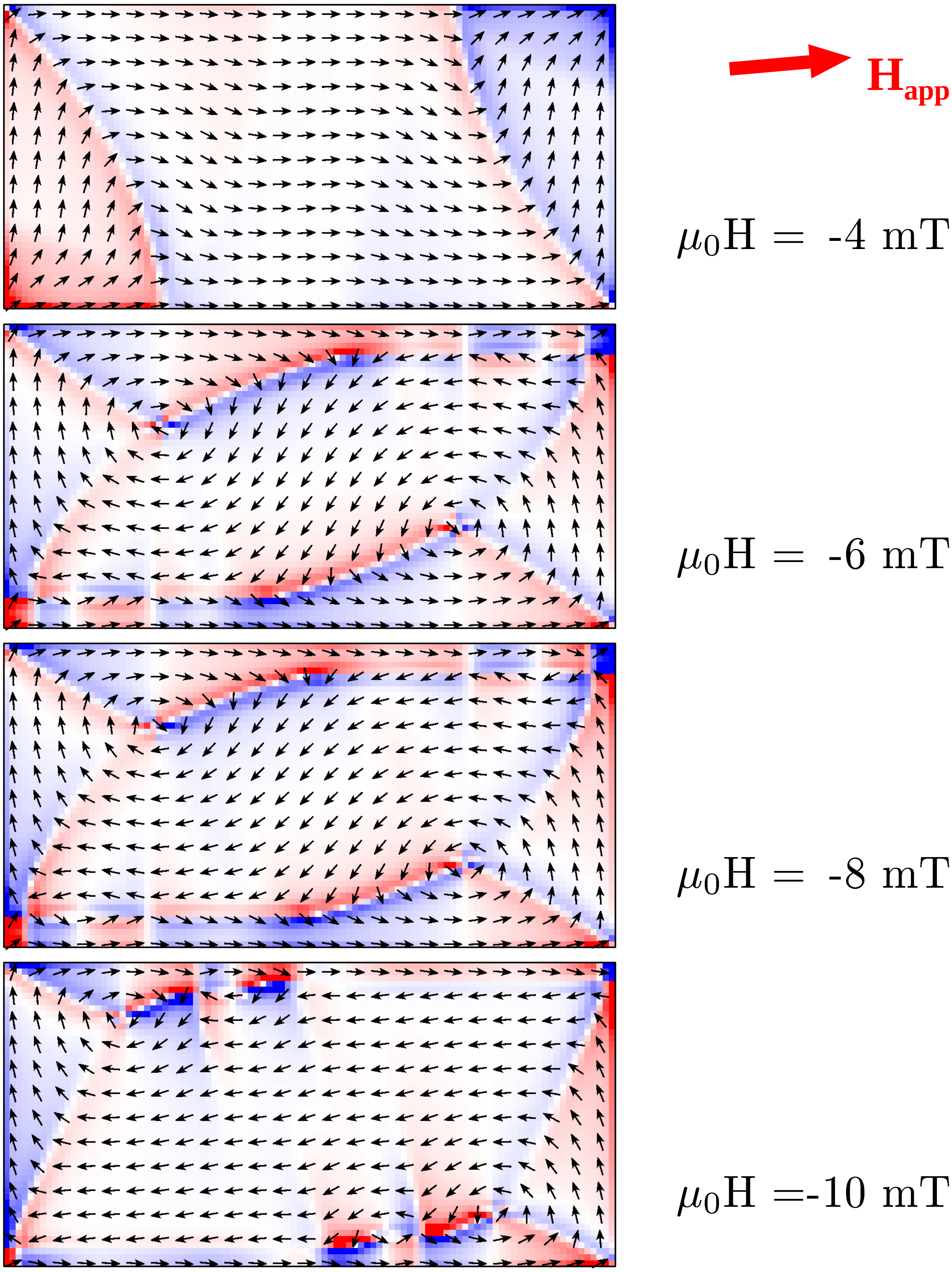

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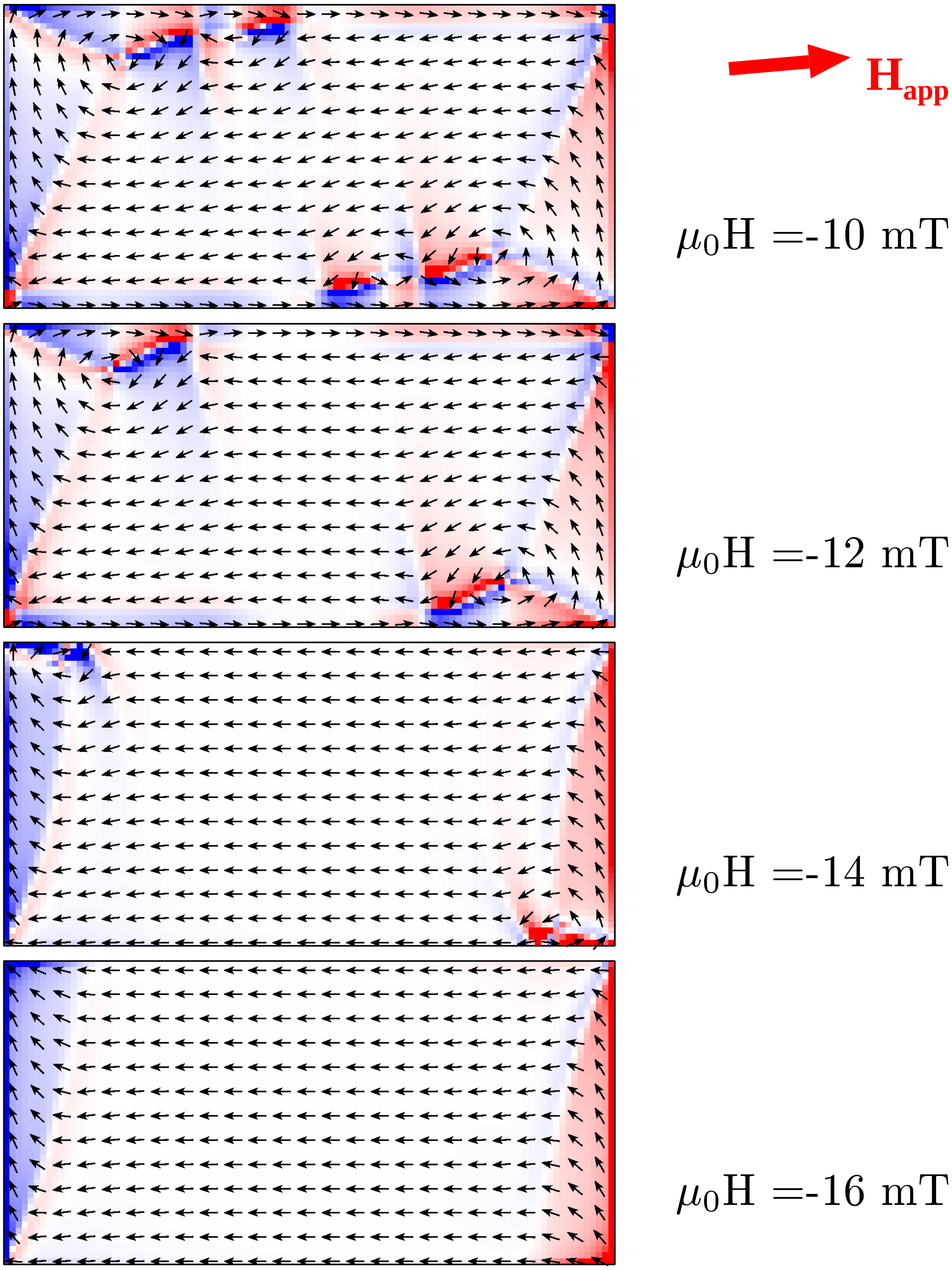
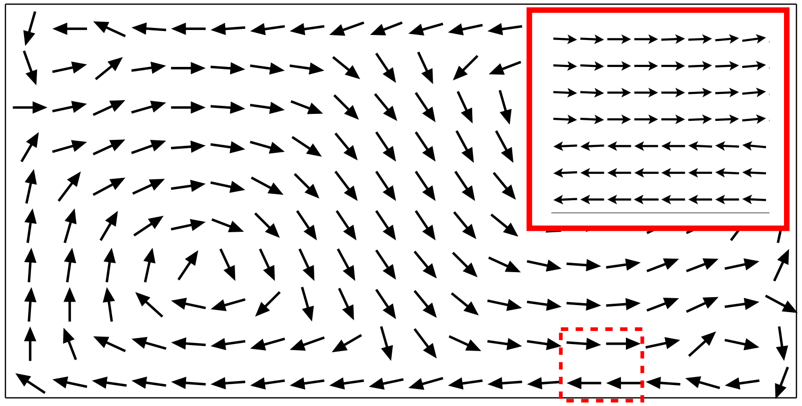
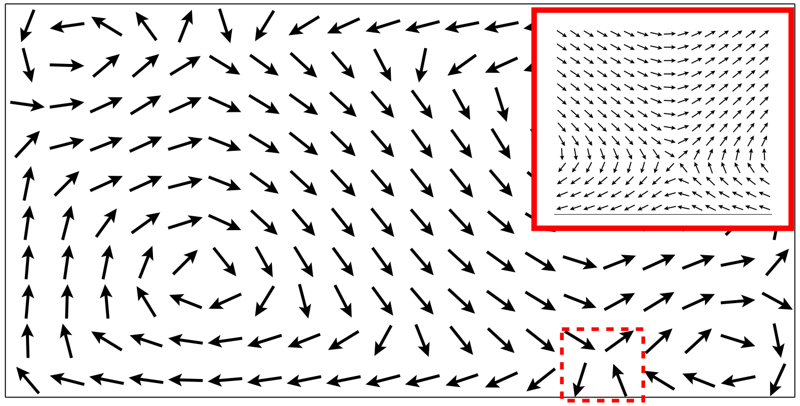


Collapsed Néel Walls



25 nm cells

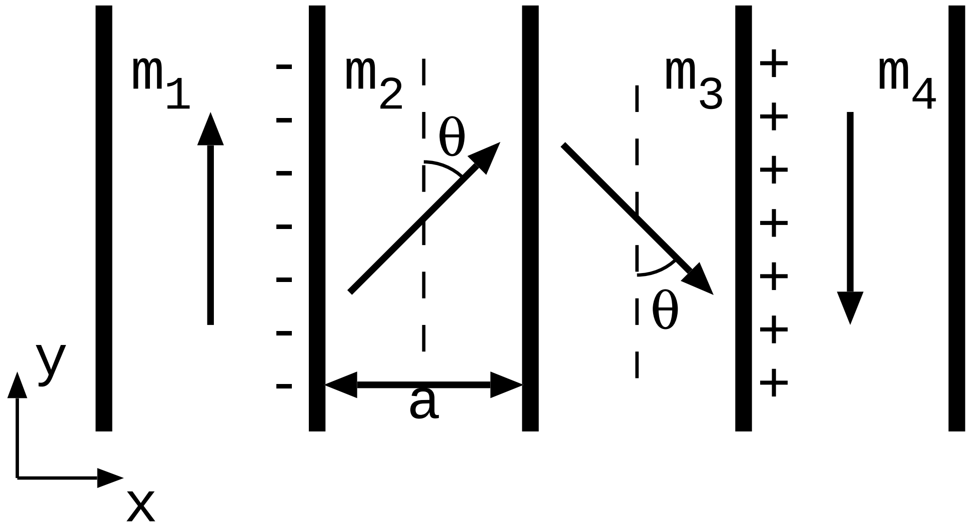


12.5 nm cells

Reference:

A Variational Approach to Exchange Energy Calculations in Micromagnetics, M. J. Donahue, *Journal of Applied Physics*, **83**, 6491–6493 (1998).

Simple discrete 1D Néel wall model.



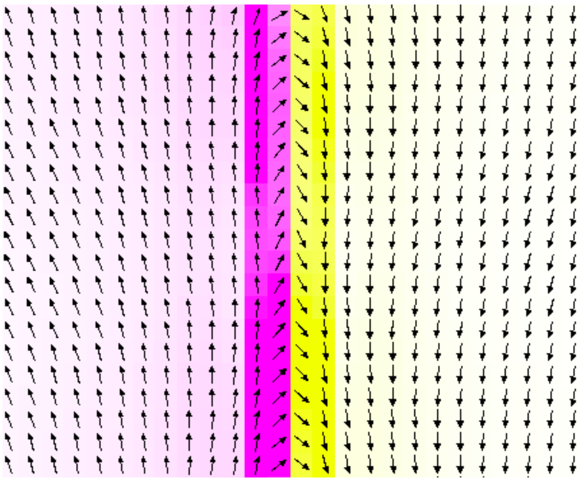
For thickness t, energy (exchange + demag) minimized at

$$\sec\theta = 2 - \frac{\mu_0 a^2 M_s^2 \left[\arctan\left(t/a\right) + \arctan\left(t/(3a)\right)\right]}{2A\pi}$$

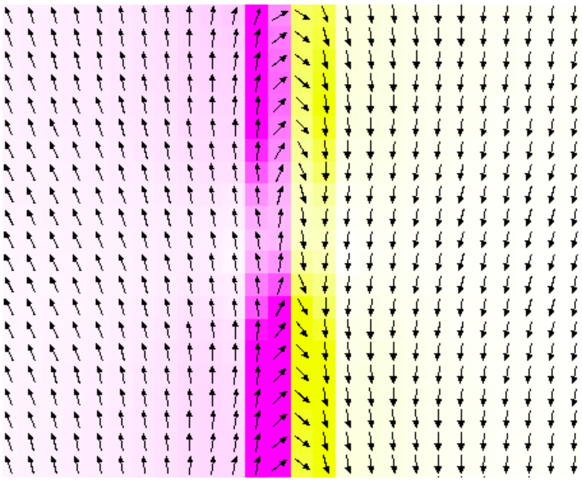
provided RHS > 1.

Vortex/Cross-tie Nucleation Detail
(Δ=10 nm)

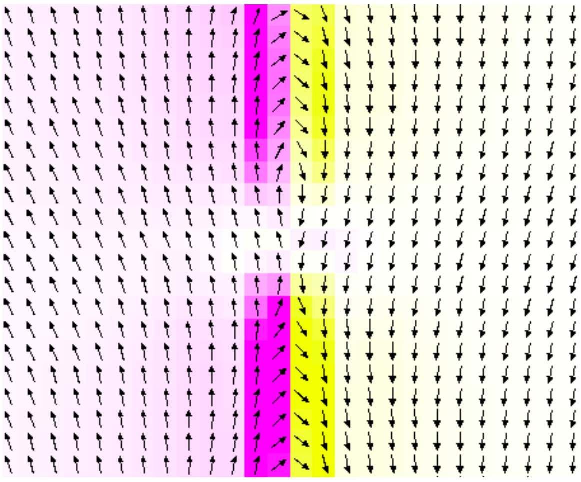
$\mu_0 H$ = 8.5 mT



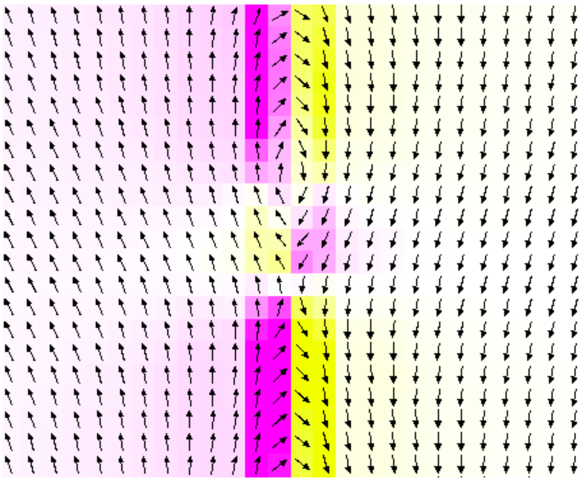
Iteration = 0



Iteration = 10

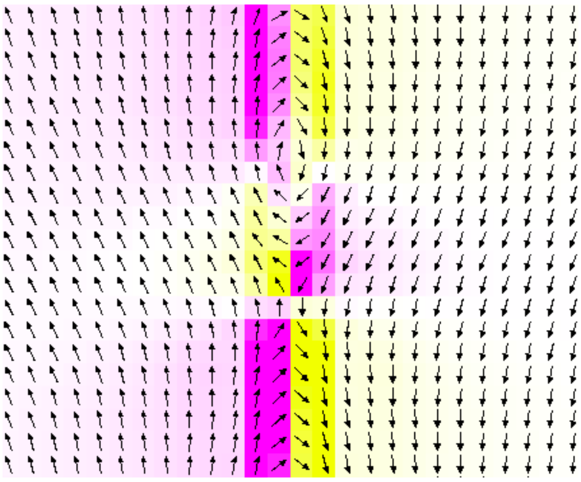


Iteration = 20

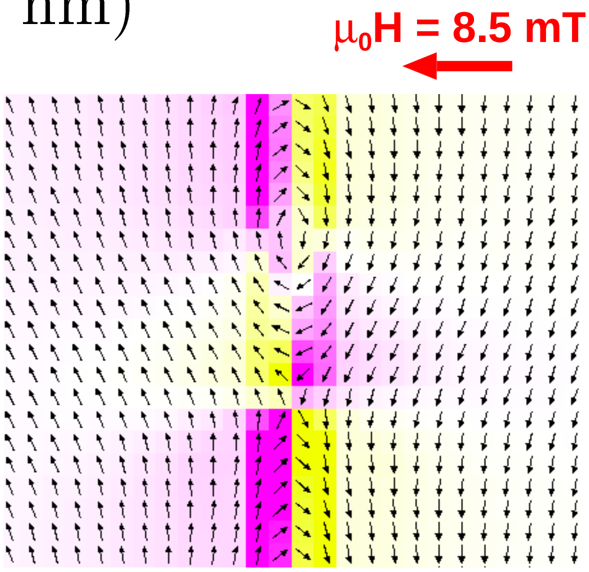


Iteration = 30

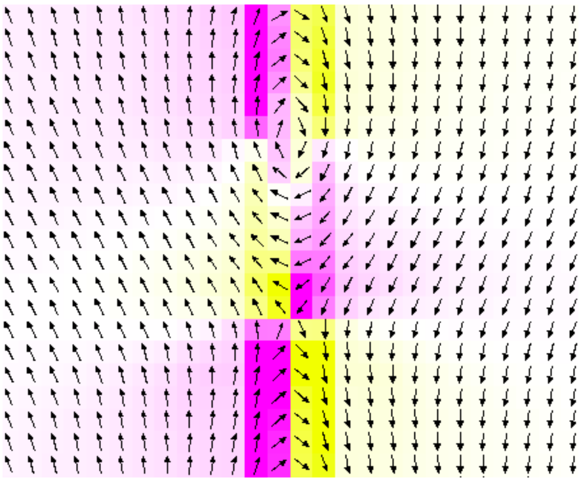
Vortex/Cross-tie Nucleation Detail (Δ=10 nm)



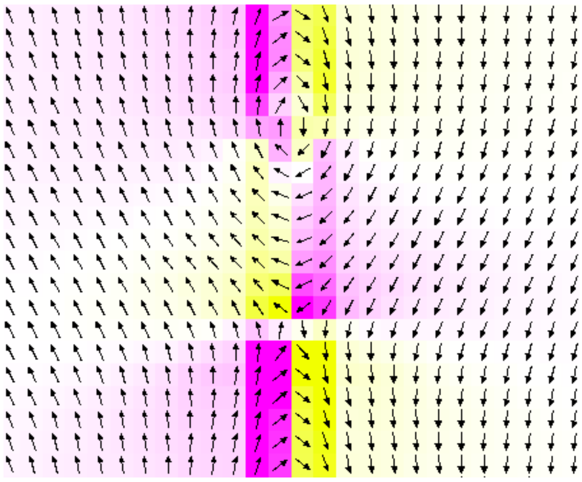
Iteration = 40



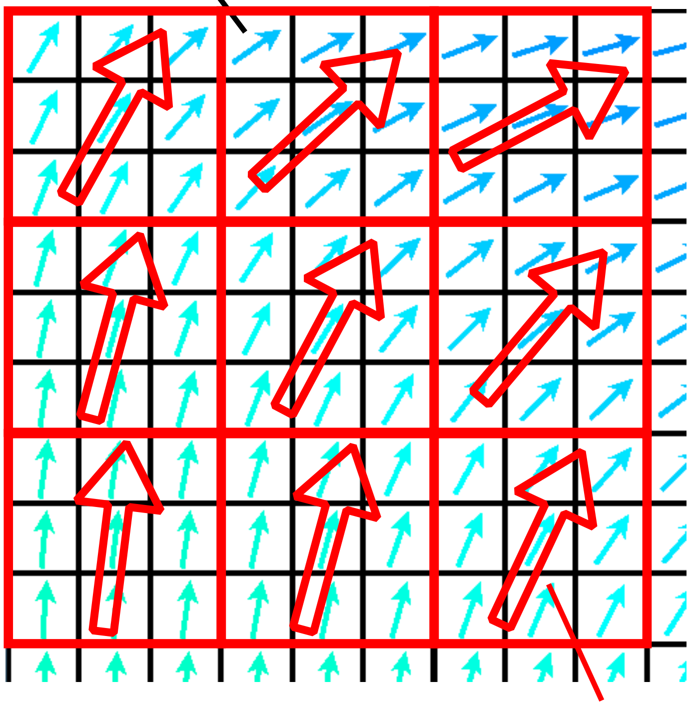
Iteration = 50



Iteration = 60



Iteration = 70



1. $M_{IJ} = \dfrac{1}{9} \sum_{i=3I}^{3I+2} \sum_{j=3J}^{3J+2} m_{ij}$

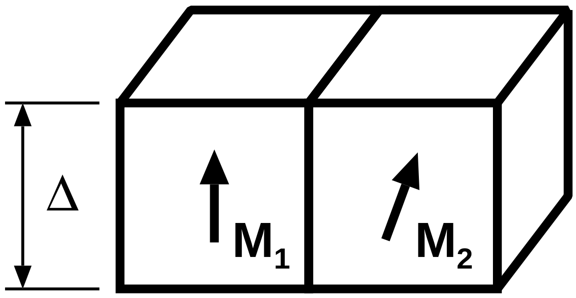
2. $(M_{IJ}) \Rightarrow$ FFT Demag $\Rightarrow (H_{IJ})$

3. $h_{ij} = H_{IJ}$ where $i = \lfloor I/3 \rfloor$, $j = \lfloor J/3 \rfloor$

Note: Preserves

$$h_{ij} = -\mu_0^{-1} \frac{\partial E}{\partial m_{ij}}$$

Near-Field Demag Error



$$H_{21}^{\text{exch}} = \frac{2A}{\mu_0 M_s \Delta^2} \qquad\qquad H_{21}^{\text{demag}} \doteq -0.0675\ M_s$$

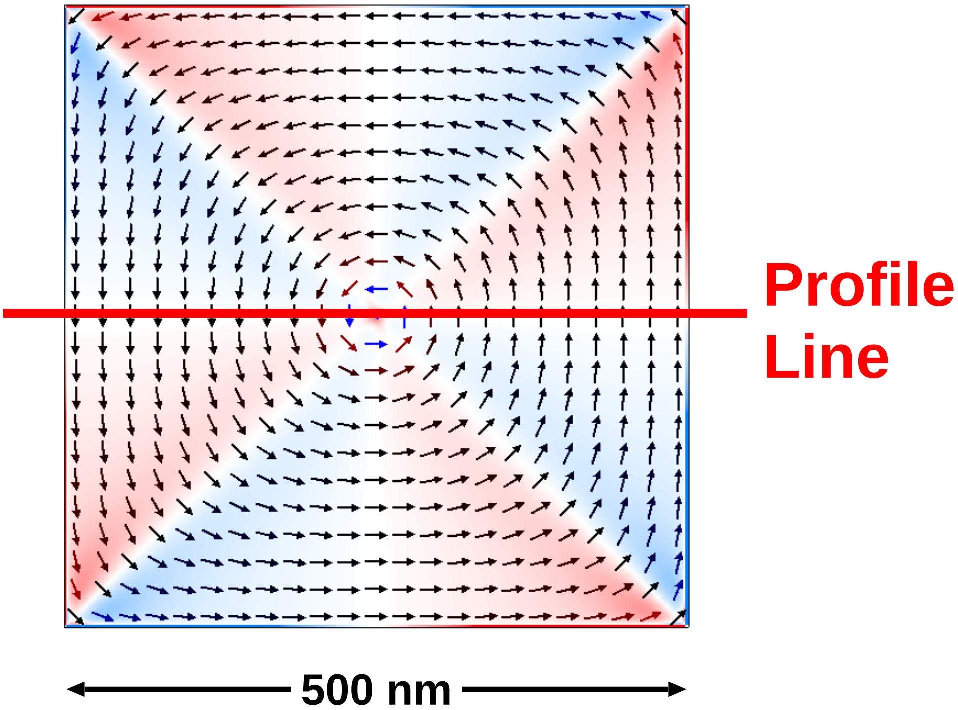
Setting

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

yields

$$H_{21}^{\text{demag}} \doteq \left(\frac{\Delta}{3.85\ \ell_{\text{ex}}}\right)^2 H_{21}^{\text{exch}}$$

Convergence Study



$A = 1.3 \times 10^{-11}$ J/m

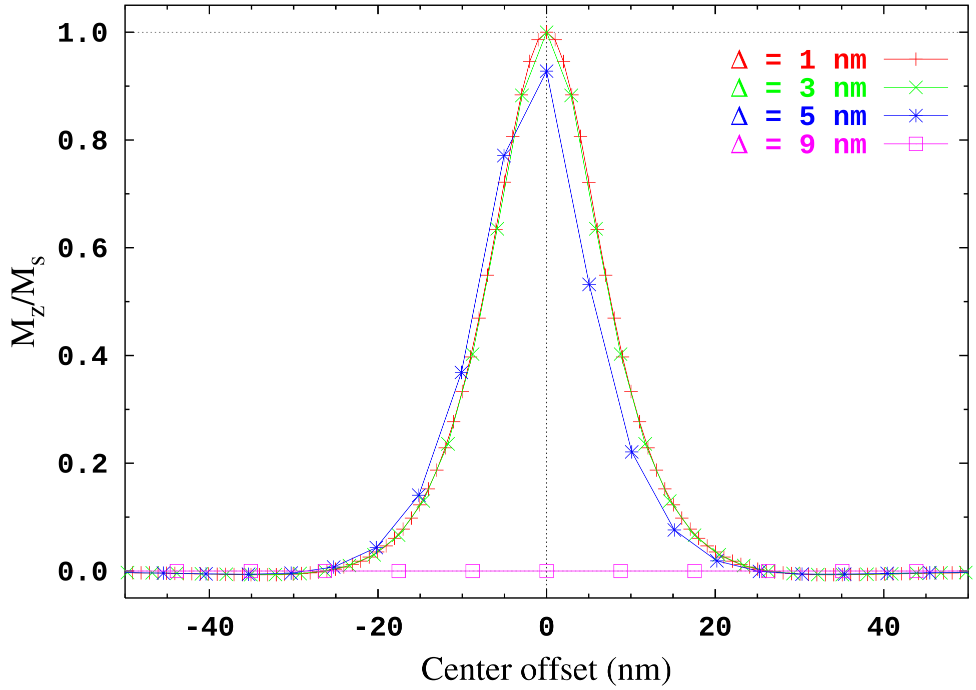
$M_s = 8 \times 10^{5}$ A/m

10 nm thick

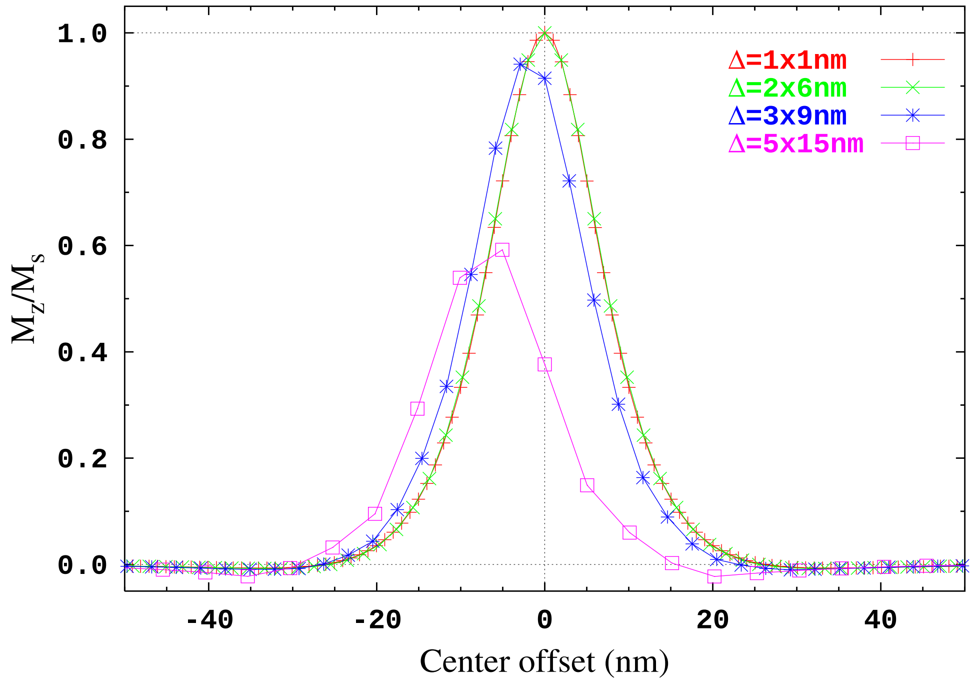
Test:

- Effects of refinement
- Effectiveness of coarse demag

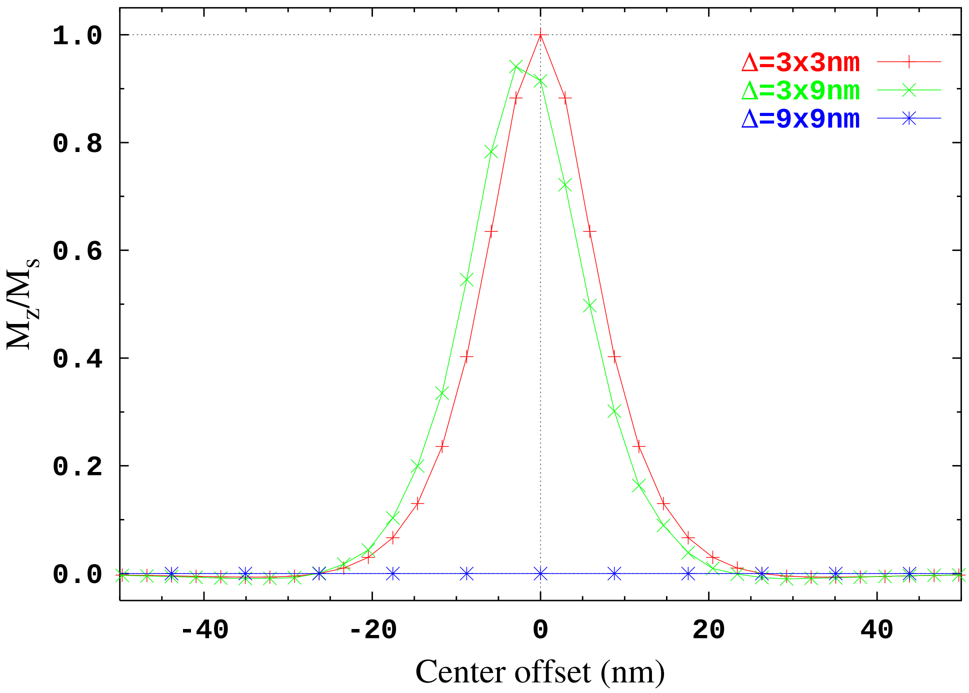
Single Mesh Convergence



Coarse Demag Mesh Convergence

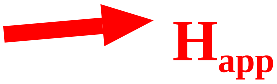


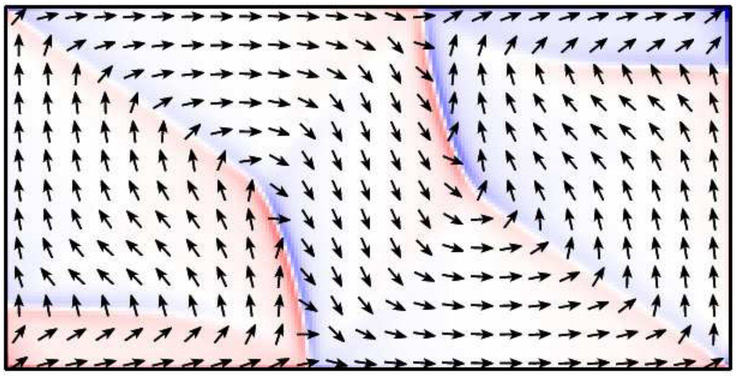
Mesh Convergence Comparison



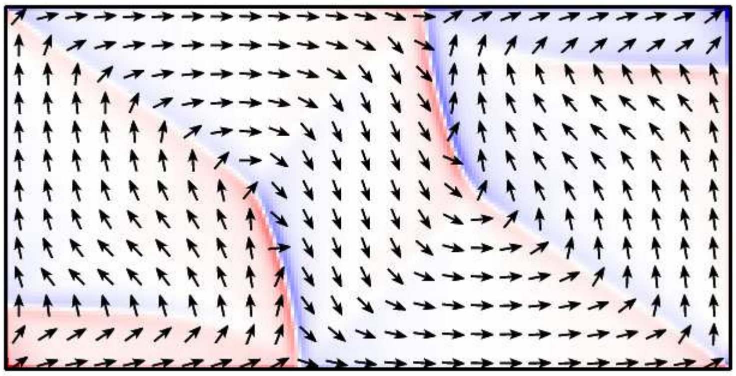
Fine Mesh (nm)	Coarse Mesh (nm)	Time/field eval (secs)
$2{\times}2{\times}2$	—	130.
$3{\times}3{\times}3.3$	—	63.
$5{\times}5{\times}10$	—	1.9
$9{\times}9{\times}10$	—	0.13
$15{\times}15{\times}10$	—	0.13
$2{\times}2{\times}3.3$	$6{\times}6{\times}10$	2.4
$3{\times}3{\times}3.3$	$9{\times}9{\times}10$	0.41
$5{\times}5{\times}3.3$	$15{\times}15{\times}10$	0.22

Non-equilibrium states, H_{applied} = -8.5 mT

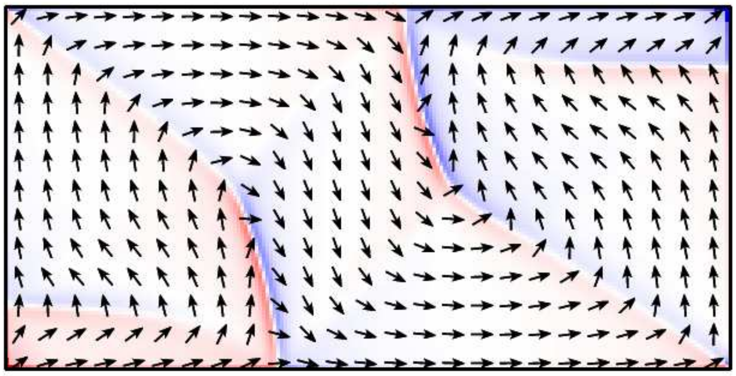




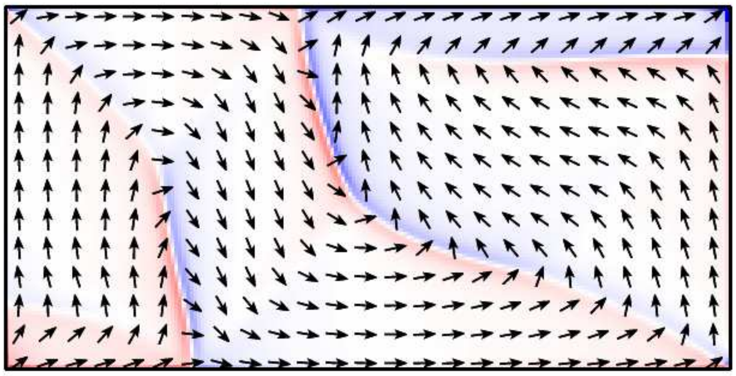
Iteration 0



Iteration 7000



Iteration 14000



Iteration 21000

Conclusions

Coarse Demag:

- Easy to implement
- Proper far field
- Near field errors
  - Exchange effects
  - Local corrections?
- Good bang for the buck

μMAG Standard Problem No. 1:

- $\Delta \geq 10$ nm allows false cross-tie nucleation
- Track max angle at all times
- Non-stable equilibrium; requires symmetry breaking
- μMAG Standard Problem No. 1 is evil.

References

A Variational Approach to Exchange Energy Calculations in Micromagnetics, M. J. Donahue, *Journal of Applied Physics,* **83**, pp 6491–6493 (1998).

Exchange Energy Representations in Computational Micromagnetics, M. J. Donahue and R. D. McMichael, *Physica B,* **233**, pp 272–278 (1997).

A Generalization of the Demagnetizing Tensor for Nonuniform Magnetization, A. J. Newell, W. Williams, and D. J. Dunlop, *J. Geophysical Research–Solid Earth,* **98**, pp 9551–9555 (1993).

OOMMF User's Guide, Version 1.0, M. J. Donahue and D. G. Porter, Interagency Report **NISTIR 6376,** National Institute of Standards and Technology, Gaithersburg, MD (Sept 1999).

Web Pages

- OOMMF:

  http://math.nist.gov/oommf/

- μMAG:

  http://www.ctcms.nist.gov/~rdm/mumag.org.html