Quasi-stable vortex magnetization structures in nanowires with perpendicular anisotropy

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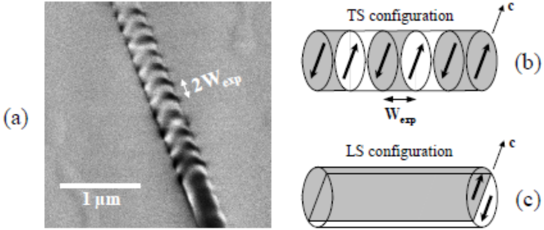
MFM of cobalt wires

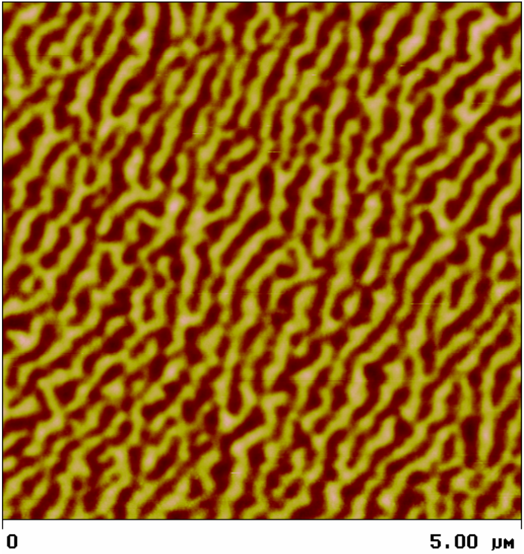
Experimental wire result and conjectured explanation:[†]



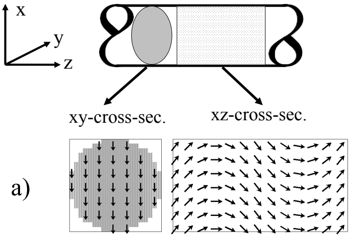
Wire radius: 50 nm

[†] Y. Henry, K. Ounadjela, et al., Eur. Phys. J. B **20**, 35 (2001).

200 nm Co film with perpendicular anisotropy



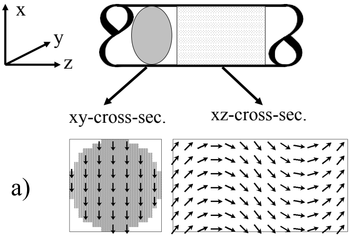
Analytic theory[‡]



Assume
$m(x,y,z) = m(z)$

[‡]G. Bergmann, J.G. Lu, et al., Phys. Rev. B **77**, 054415 (2008).

Analytic theory[‡]



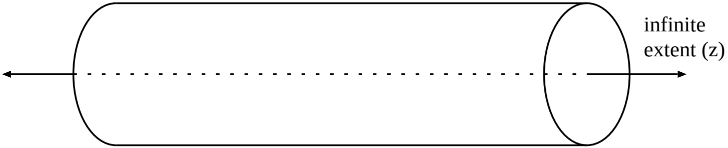
a)

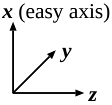
Assume
$m(x,y,z) = m(z)$

k_2/u_{00}	a_{ex}/u_{00} (10^{-2})	s_{min}	θ_{min}	u_{min}/u_{00}	$u[\mathbf{M}\|\hat{\mathbf{z}}]$	$u[\mathbf{M}\|\hat{\mathbf{x}}]$
0	0.68	2.3	0.7	0.333 88	0.34	0.5
0	1.36	1.75	0.3	0.341 37	0.34	0.5
0.083	0.68	2.1	1.0	0.378 83	0.425	0.5
0.083	1.36	1.6	0.8	0.396 9	0.425	0.5
0.125	0.68	2.1	1.0	0.397 04	0.47	0.5
0.125	1.36	1.5	0.9	0.417 71	0.47	0.5

[‡] G. Bergmann, J.G. Lu, et al., Phys. Rev. B **77**, 054415 (2008).

Model schematic

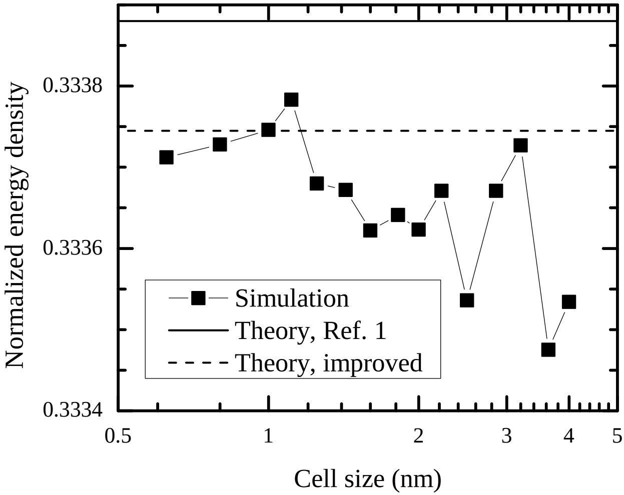




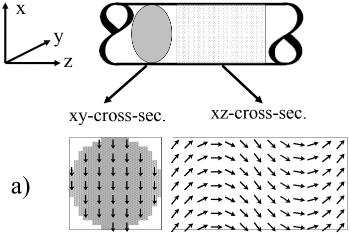
Model Parameters

M_s: 138 kA/m
K_1: 200 - 500 kJ/m^3
K_2: 0 - 150 kJ/m^3
A: 13 - 52 pJ/m
Radius: 30 - 200 nm

Discretization error for sinusoidal state



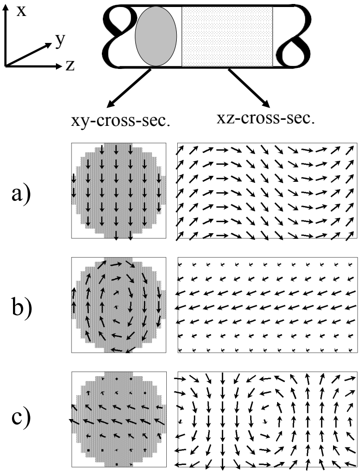
Analytic theory[‡]



Assume
m(x,y,z) = m(z)

[‡]G. Bergmann, J.G. Lu, et al., Phys. Rev. B **77**, 054415 (2008).

Micromagnetic simulations

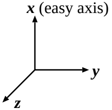


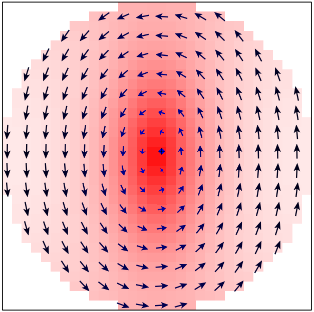
~~Assume m(x,y,z) = m(z)~~

z-vortex (non-periodic)

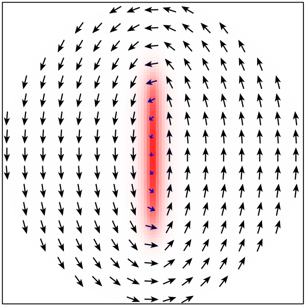
y-vortices (periodic)

z-vortex state, radius dependence



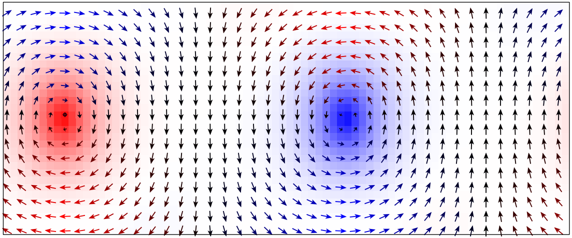


Radius: 30.4 nm

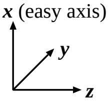


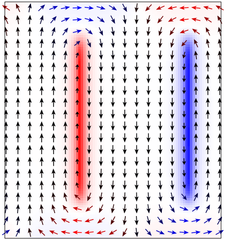
Radius: 200 nm

y-vortex states, radius dependence



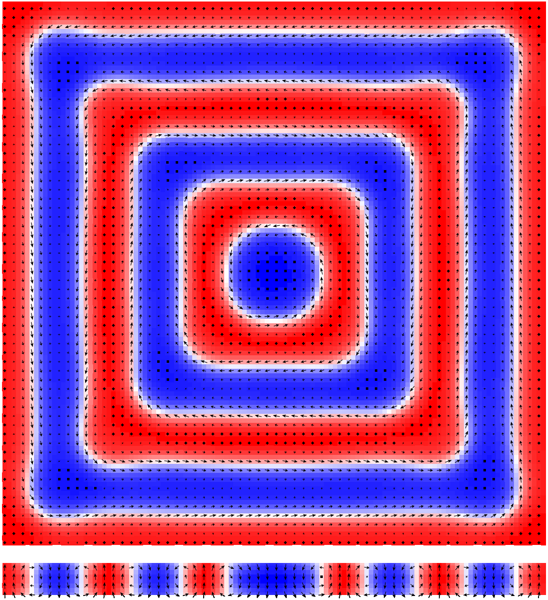
Radius: 30.4 nm





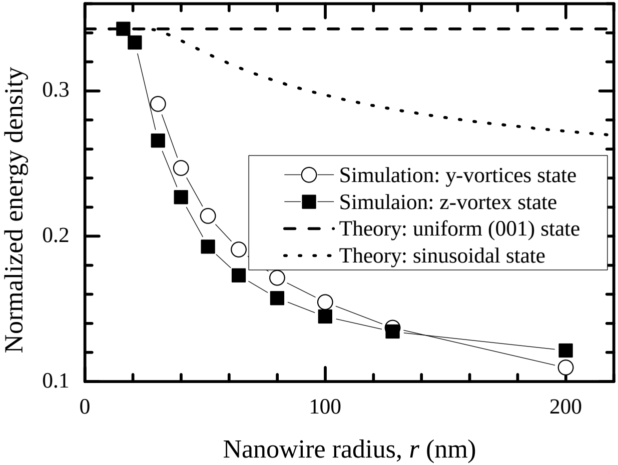
Radius: 200 nm

Thin film, micromagnetic simulation



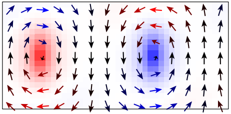
D.G. Porter and M.J. Donahue, HMM 2001.

Energy density for y-vortex state

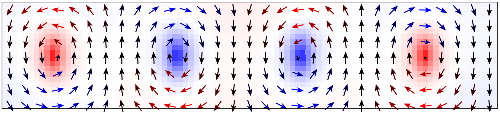


Multiple metastable y-vortex states

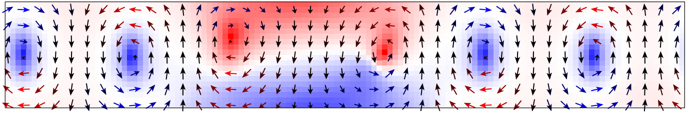
Radius: 40 nm.



Simulation length: 168 nm



Simulation length: 372 nm



Simulation length: 512 nm

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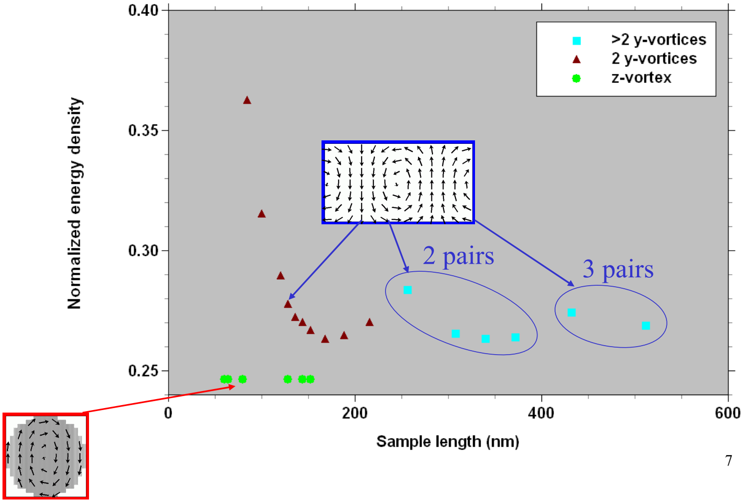
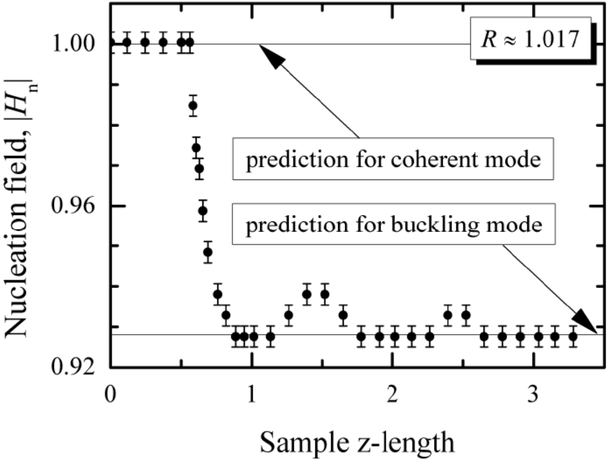
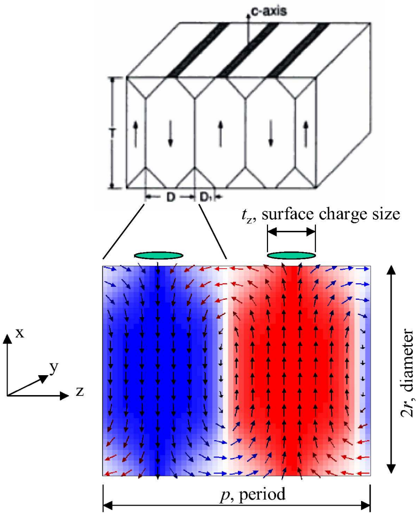
Relative energy densities (40 nm radius)



Effects of simulation window size





Infinite Plate*

Infinite Rod

$\alpha = (p - t_z)/2p$

*H. Kronmuller and M. Fähnle, *Micromagnetism and the Microstructure of Ferromagnetic Solids* (Cambridge, 2003).

Variation of t_z with r

r (nm)	t_z (nm)
30	46
40	52
50	51
64	56
80	54
100	62
128	68
200	70

In this range,

$$\alpha = (p - t_z)/2p \in [0.25, 0.4]$$

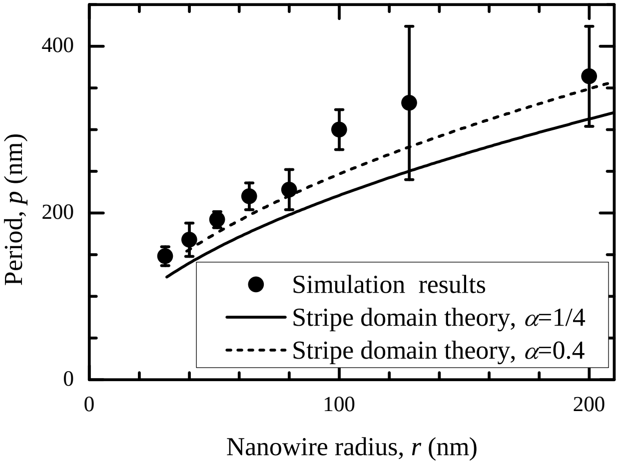
Periodicity formula

$$p(r) = 2\sqrt{\frac{8r\sqrt{AK_1}}{f(\alpha)4\mu_0 M_s^2/\pi^3 + 2\alpha^2 K_1}}$$

here

$$\alpha = 0.25 \implies f(\alpha) \approx 0.5259$$
$$\alpha = 0.4 \implies f(\alpha) \approx 0.130887$$

y-vortex period



Summary table

Material constants			Sinusoidal state			Vortex-like states		
K_1 (MJ/m^3)	K_2 (MJ/m^3)	A (pJ/m)	s_{sin}	θ_{sin}	u_{sin}	u_{zvort}	u_{yvort}	p (nm)
0.41	0.0	26	2.24	0.6849	0.3344	0.2268	0.247	168
0.41	0.0	52	1.75	0.3212	0.3422	0.2832	0.307	220
0.41	0.1	26	2.09	0.9555	0.3788	0.2463	0.263	168
0.41	0.1	52	1.57	0.8499	0.3972	0.3094	0.322	216
0.41	0.15	26	2.09	1.0251	0.3972	0.2551	0.270	176
0.41	0.15	52	1.53	0.9452	0.4179	0.3213	0.323	216
0.20	0.03	13	-	-	-	0.1274	0.148	144
0.50	0.0	13	2.73	1.0409	0.3687	0.2062	0.221	150

Summary

- Wide range of material constants and wire radii considered.
- Lowest non-saturated energy in z-vortex and periodic y-vortices states.
    - y-vortex periodicity in rough agreement with experiment
- Z-vortex and periodic y-vortices have comparable energy.
- y-vortex period described using simple quasi-stripe domain theory.