# Supporting Information: Imaging vortex magnetization configurations in ferromagnetic nanotubes

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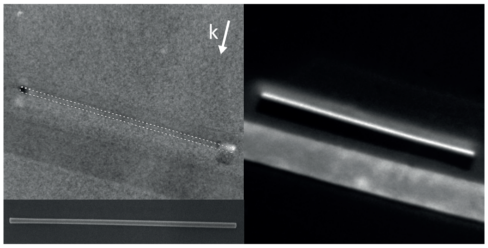
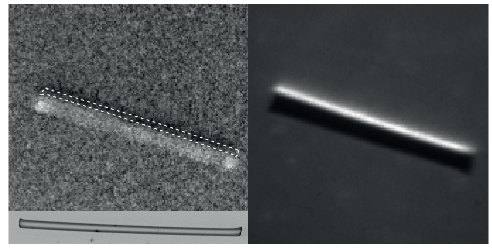
(Dated: May 16, 2017)

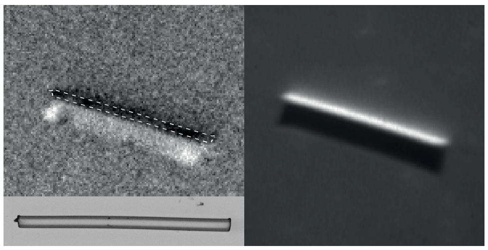
## XMCD-PEEM, PEEM, AND SEM IMAGES



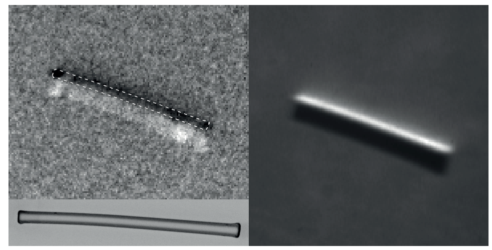

(a) ● : l = 11.3 $\mu$m, d = 300 nm.



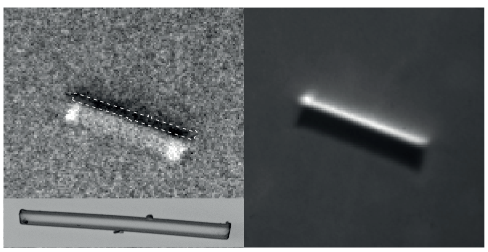
(b) ● : l = 7.24 $\mu$m, d = 265 nm.



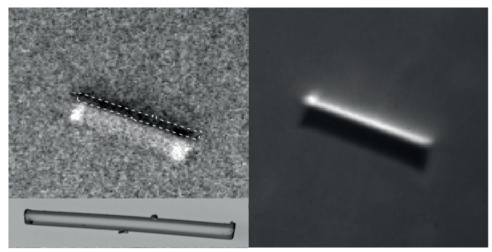
(c) ● : l = 5.15 $\mu$m, d = 314 nm.



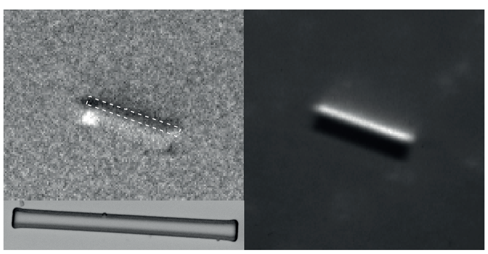
(d) ● : l = 5.09 $\mu$m, d = 276 nm.



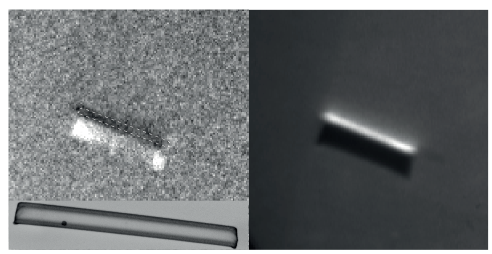
(e) ●: l = 4.06 $\mu$m, d = 305 nm.



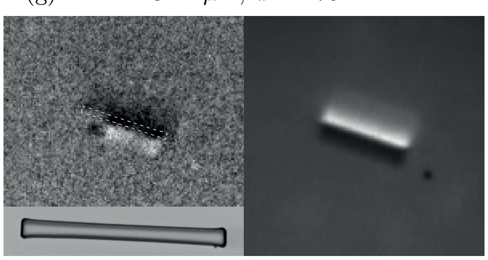
(f) ⊙ : l = 3.65 $\mu$m, d = 265 nm.



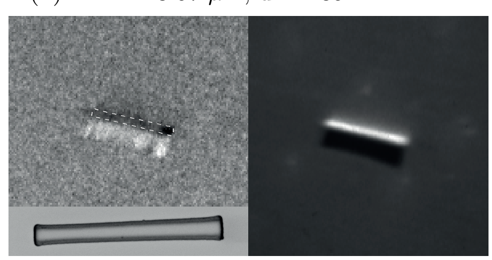
(g) ● : l = 3.14 $\mu$m, d = 270 nm.



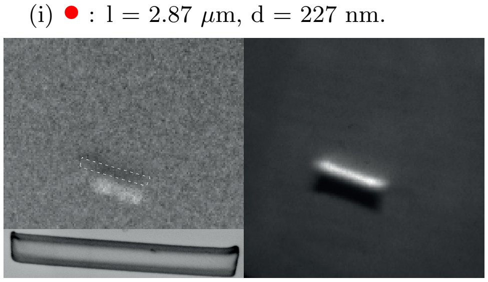
(h) ● : l = 3.07 $\mu$m, d = 285 nm.



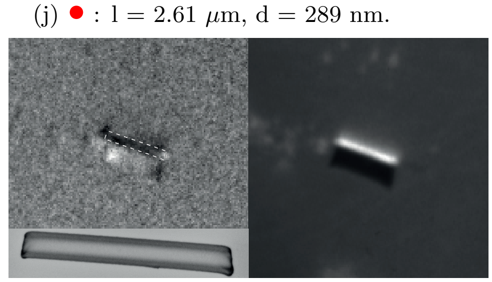
(i) ● : l = 2.87 $\mu$m, d = 227 nm.



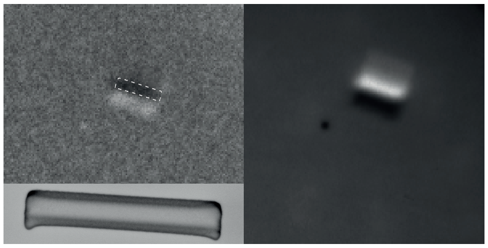
(j) ● : l = 2.61 $\mu$m, d = 289 nm.



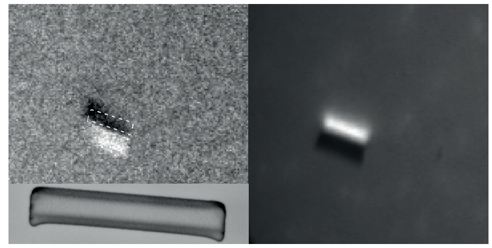
(k) ● : l = 2.18 $\mu$m, d = 279 nm.



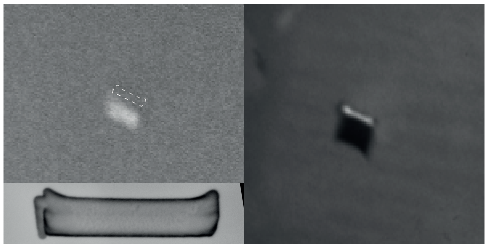
(l) ● : l = 2.03 $\mu$m, d = 272 nm.



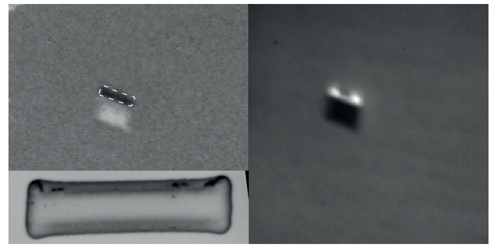
(a) ● : l = 1.57 $\mu$m, d = 283 nm.



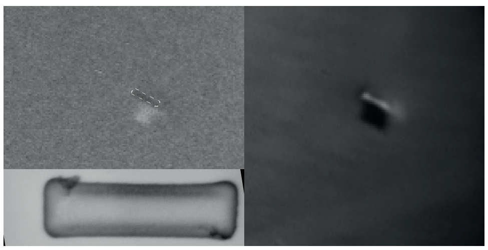
(b) ● : l = 1.57 $\mu$m, d = 285 nm.



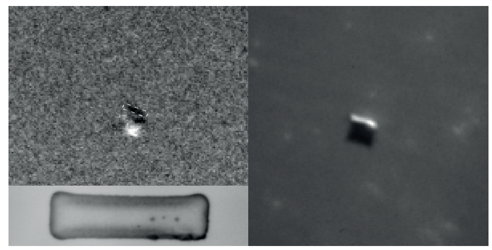
(c) ⊙ : l = 1.18 $\mu$m, d = 248 nm.



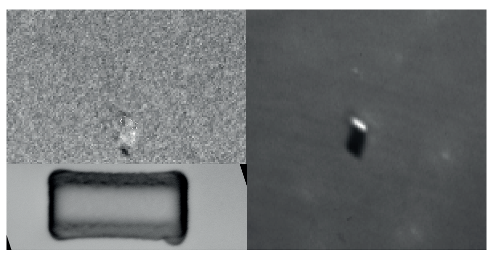
(d) ⊙ : l = 1.06 $\mu$m, d = 283 nm.



(e) ● : l = 0.83 $\mu$m, d = 236 nm.

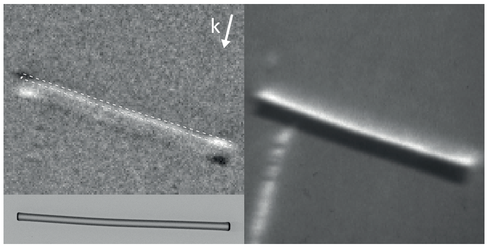


(f) ● : l = 0.80 $\mu$m, d = 228 nm.

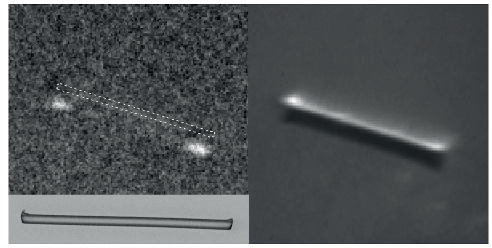


(g) ⊙ : l = 0.54 $\mu$m, d = 293 nm.

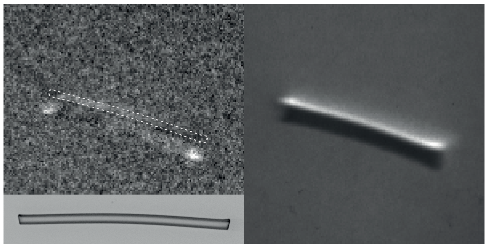
Figure S.2: XMCD-PEEM images (top left), SEMs (bottom left), and PEEM images (right) recorded with $\sigma^-$ polarized x-rays for each measured CoFeB NT. The dashed lines show the position of the NT as taken from SEM. The corresponding phase diagram is shown in Figure S.6 (a). ●: matching vortices. ●: opposing vortices. ●: relative vortex circulation switched after applying a field of ±40 mT along $\hat{n}$. ⊙: matching vortices before and after applying a field of ±40 mT along $\hat{n}$. ⊙: opposing vortex circulation before and after applying a field of ±40 mT along $\hat{n}$.



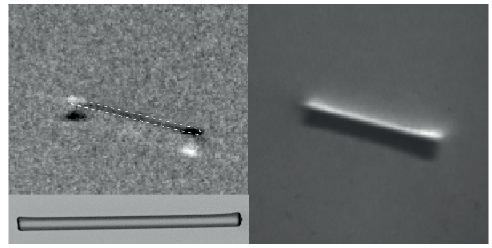

(a) ● : l = 6.90 $\mu$m, d = 243 nm.



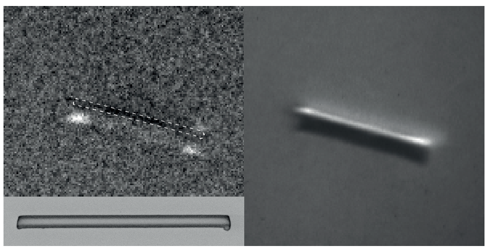
(b) ● : l = 5.13 $\mu$m, d = 234 nm.



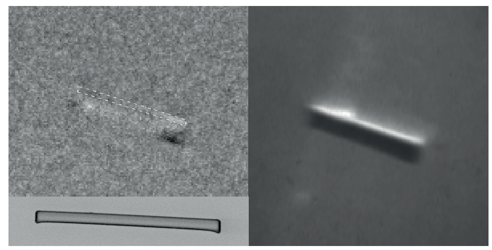
(c) ● : l = 5.10 $\mu$m, d = 242 nm.



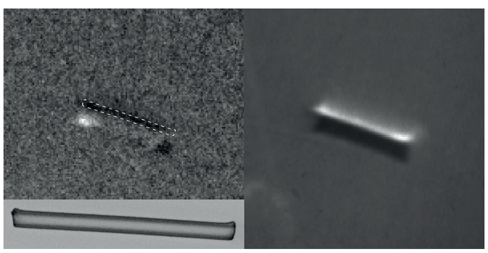
(d) ● : l = 4.34 $\mu$m, d = 239 nm.



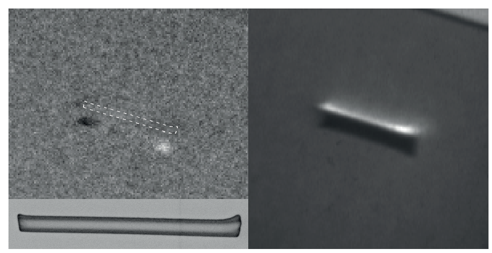
(e) ● : l = 4.15 $\mu$m, d = 258 nm.



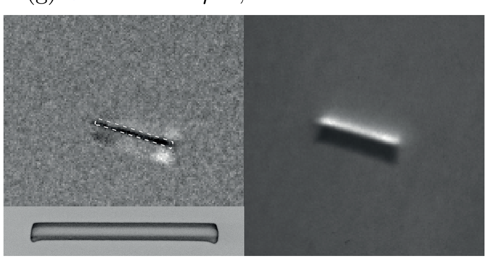
(f) ● : l = 3.63 $\mu$m, d = 212 nm.



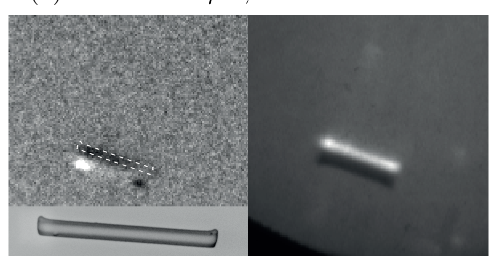
(g) ⊙ : l = 3.07 $\mu$m, d = 228 nm.



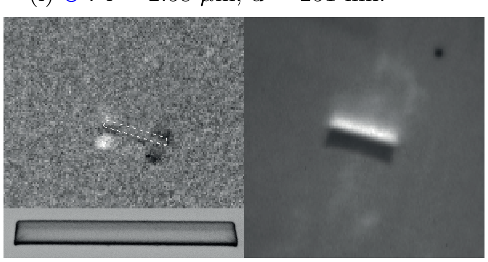
(h) ● : l = 3.05 $\mu$m, d = 223 nm.



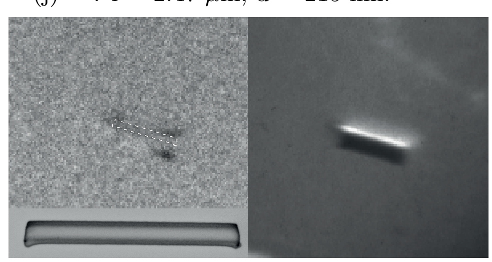
(i) ⊙ : l = 2.58 $\mu$m, d = 251 nm.



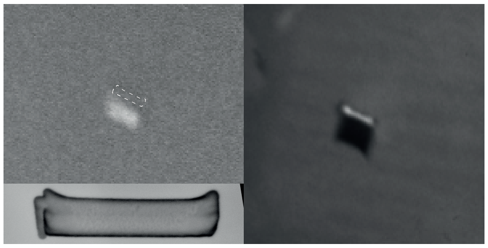
(j) ● : l = 2.47 $\mu$m, d = 215 nm.



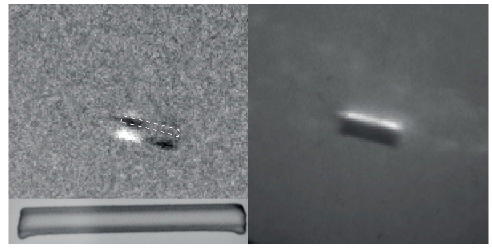
(k) ● : l = 2.13 $\mu$m, d = 212 nm.



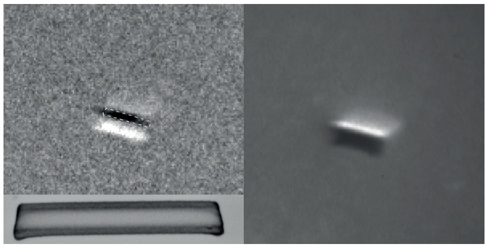
(l) ● : l = 2.07 $\mu$m, d = 225 nm.



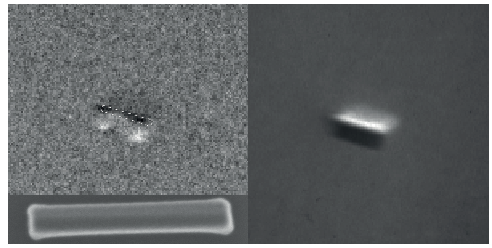
(a) ●: l = 1.86 $\mu$m, d = 209 nm.



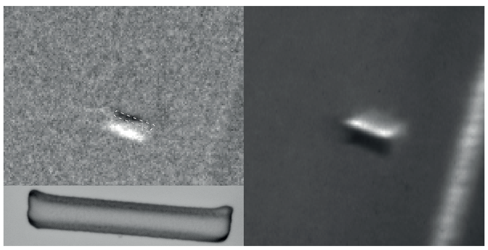
(b) ●: l = 1.85 $\mu$m, d = 211 nm.



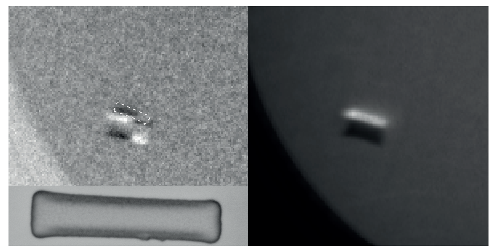
(c) ● : l = 1.53 $\mu$m, d = 237 nm.



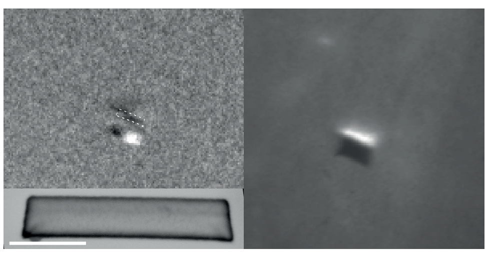
(d) ⊙ : l = 1.53 $\mu$m, d = 215 nm.



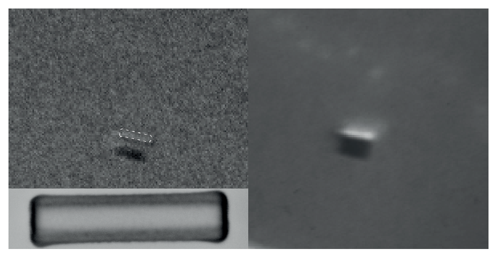
(e) ⊙ : l = 1.33 $\mu$m, d = 215 nm.



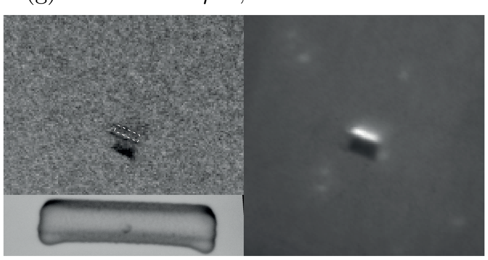
(f) ● : l = 1.24 $\mu$m, d = 265 nm.



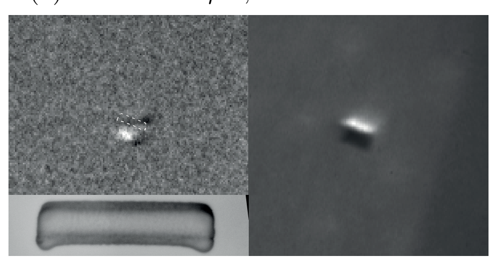
(g) ● : l = 1.09 $\mu$m, d = 211 nm.



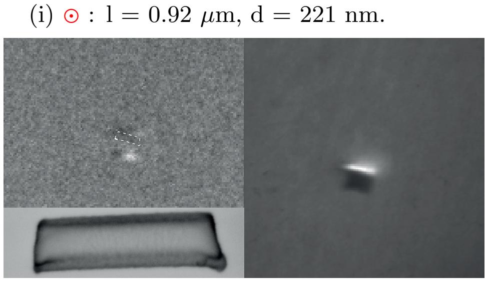
(h) ● : l = 1.02 $\mu$m, d = 259 nm.



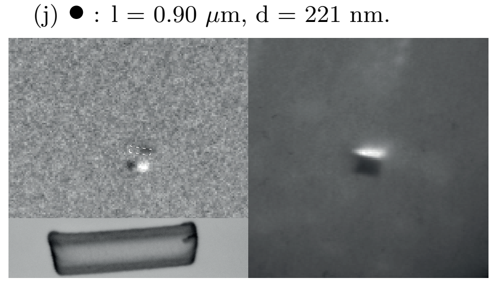
(i) ⊙ : l = 0.92 $\mu$m, d = 221 nm.



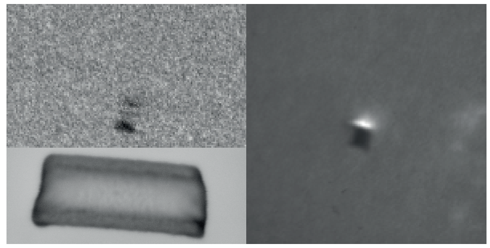
(j) ● : l = 0.90 $\mu$m, d = 221 nm.



(k) ⊙ : l = 0.77 $\mu$m, d = 237 nm.



(l) ● : l = 0.73 $\mu$m, d = 221 nm.



(a) ⊙: l = 0.58 $\mu$m, d = 244 nm.

Figure S.5: XMCD-PEEM images (top left), SEMs (bottom left), and PEEM images (right) recorded with $\sigma^-$ polarized x-rays for each measured Py NT. The dashed lines show the position of the NT as taken from SEM. The corresponding phase diagram is shown in Figure S.6 (b). ●: matching vortices. ●: opposing vortices. ●: relative vortex circulation switched after applying a field of ±40 mT along $\hat{n}$. ⊙: matching vortices before and after applying a field of ±40 mT along $\hat{n}$. ⊙: opposing vortices before and after applying a field of ±40 mT along $\hat{n}$.

**PHASE DIAGRAMS**

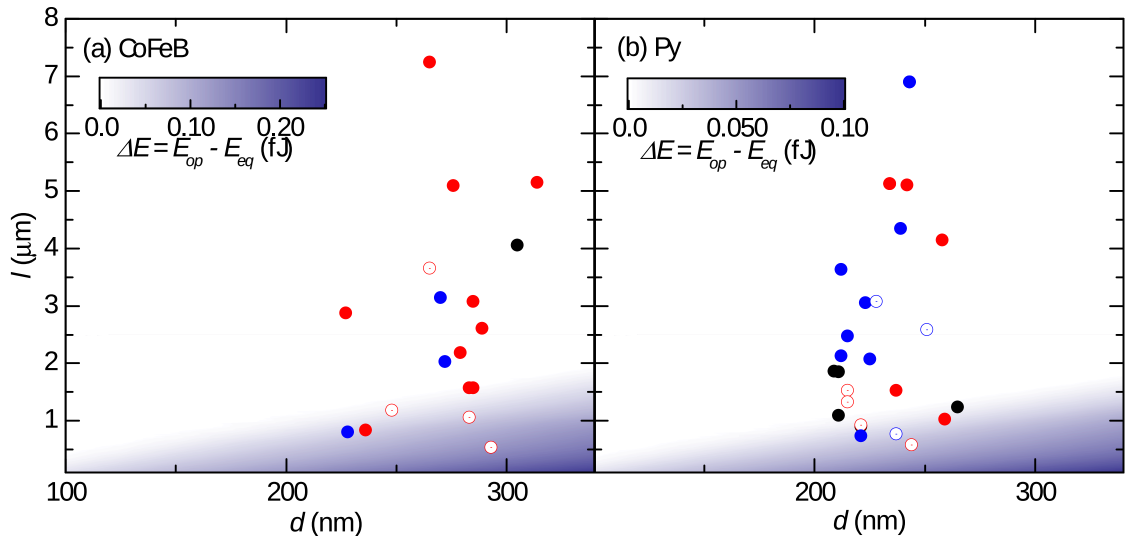



Figure S.6: Phase diagrams of relative vortex circulation for (a) CoFeB and (b) Py. Numerically calculated $\Delta E = E_{op} - E_{eq}$ is plotted in the color scale as a function of NT diameter $d$ and length $l$. $E_{op}$ ($E_{eq}$) represents the energy of an equilibrium configuration with opposing (matching) circulation. Regions of $\Delta E > 0$ (shaded) show where end vortices with matching ciruclation are likely, while regions of $\Delta E \simeq 0$ (white) show where vortices with matching or opposing circulation are equally likely. Data points represent remnant states measured in real NTs by XMCD-PEEM. ●: matching vortices. ●: opposing vortices. ●: relative vortex circulation switched after applying a field of ±40 mT along $\hat{n}$. ⊙: matching vortices before and after applying a field of ±40 mT along $\hat{n}$. ⊙: opposing vortices before and after applying a field of ±40 mT along $\hat{n}$.

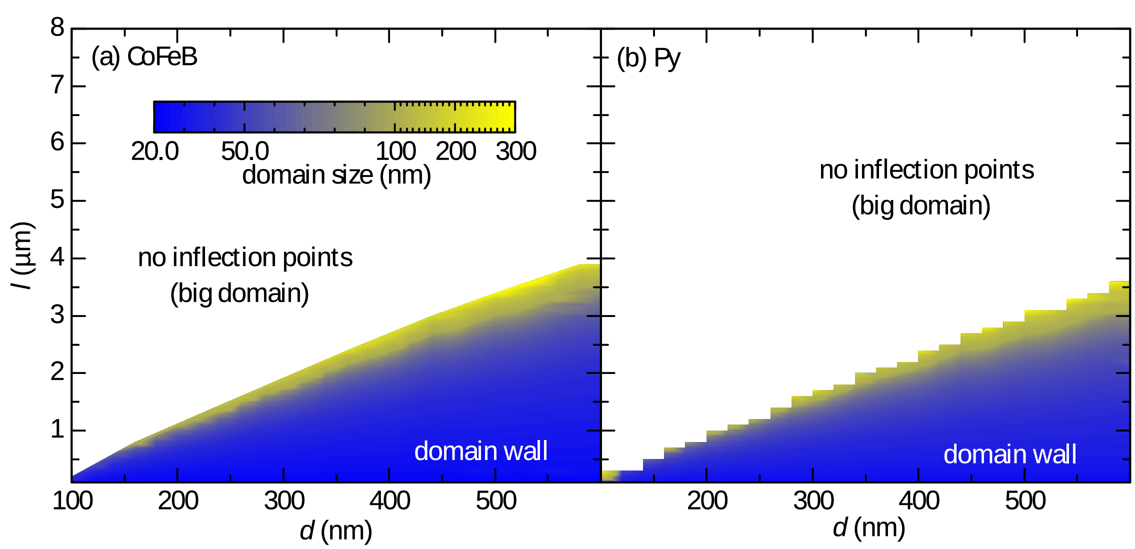



Figure S.7: Phase diagrams for (a) CoFeB and (b) Py NTs considering only opposing circulation magnetization configurations. The size of the central axial domain is plotted in the color scale and is calculated using the distance between inflection points in the order parameter $M_n/|\mathbf{M}|$ along $\hat{n}$. A clear boundary between a mixed state with opposing vortex circulation and an opposing vortex state can be identified.

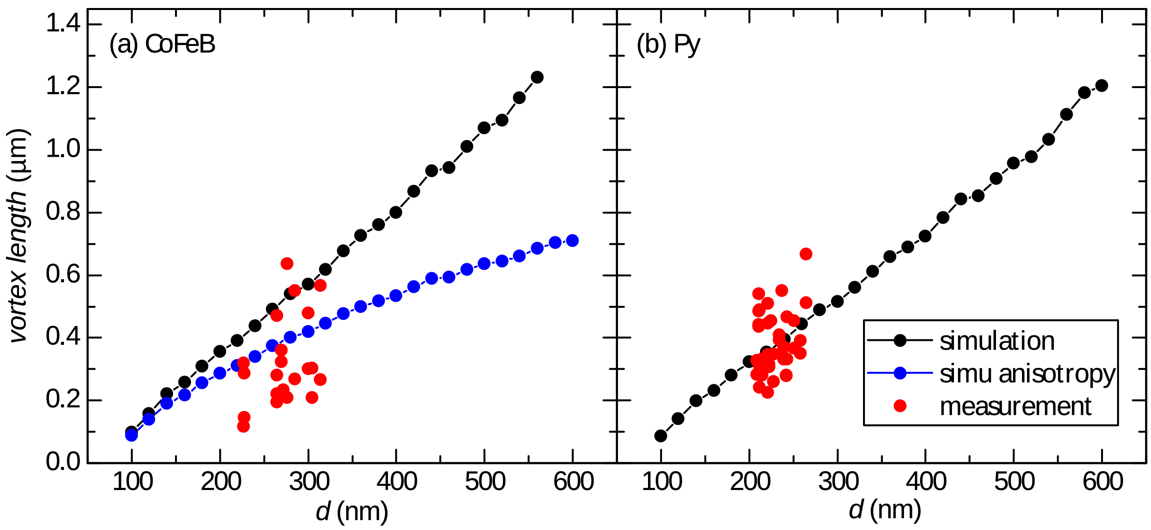



Figure S.8: Length of the end vortices for (a) CoFeB and (b) Py. Black points: Simulated vortex length for $l = 3.9\,\mu\text{m}$ and matching vortex circulation ($l$ does not significantly influence the size of the vortices.) Blue points: Simulation for CoFeB including a growth induced anisotropy postulated by Baumgaertl et al. to explain their magneto-transport results [1]. The simulation considers a uni-axial anisotropy with $K_u = 5\,\text{kJ/m}^3$ with a different axis for each facet. Each axis is tilted by 55° towards the $z$ axis with respect to the facet's surface normal. Red points: Length of the vortices extracted from XMCD-PEEM images. The vortex length is determined by the following procedure: We take 10% of the maximum intensity over the background to determine the beginning and end of a vortex. The difference is the length of the vortex. The general trend of increasing vortex length as a function of tube diameter is also predicted by Landeros et al. [2].

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[1] K. Baumgaertl, F. Heimbach, S. Maendl, D. Rueffer, A. Fontcuberta i Morral, and D. Grundler, Applied Physics Letters **108** (2016), http://dx.doi.org/10.1063/1.4945331.
[2] P. Landeros, O. J. Suarez, A. Cuchillo, and P. Vargas, Phys. Rev. B **79**, 024404 (2009).