Field & current-induced wall propagation in modulated-diameter cylindrical nanowires

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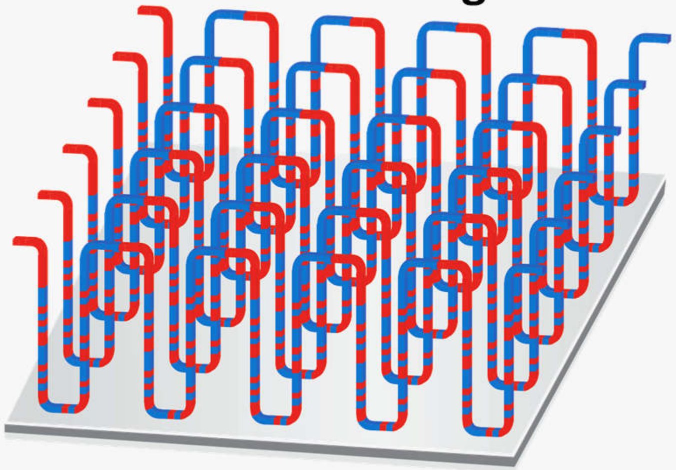
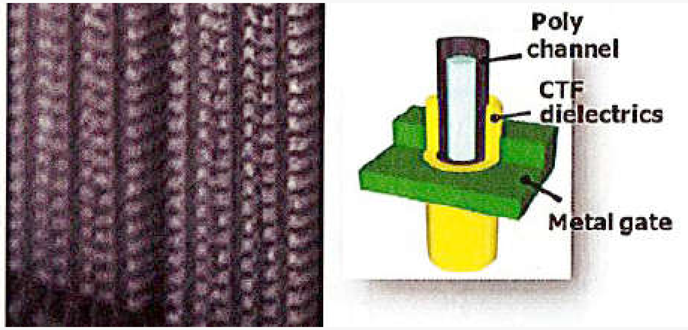
Dreams for a 3D storage device



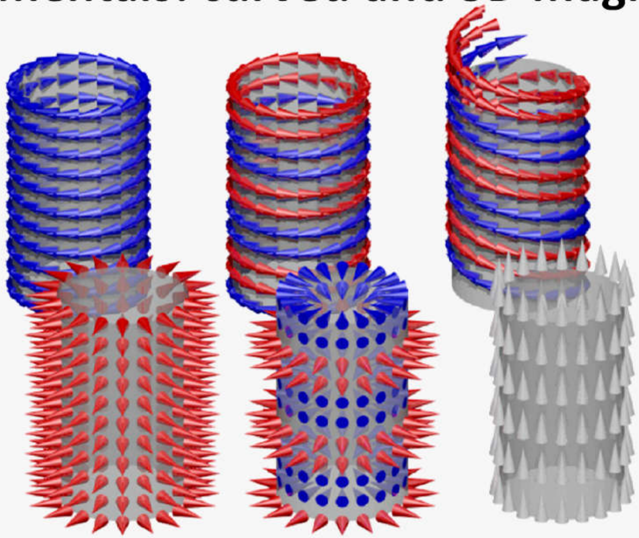
S. S. P. Parkin, Science 320, 190 (2008)
+ patents (IBM)

Note: 3D devices make the decision!

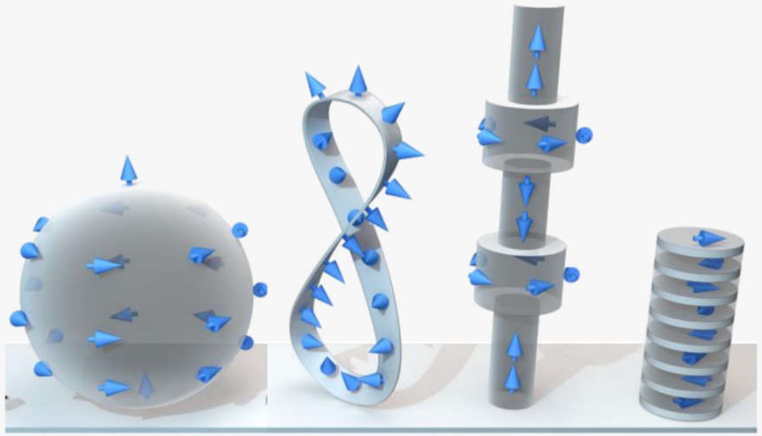


K. T. Park et al., IEEE J. Sol. State Circuits 50 (1), 204 (2015)

Fundamentals: curved and 3D magnetism

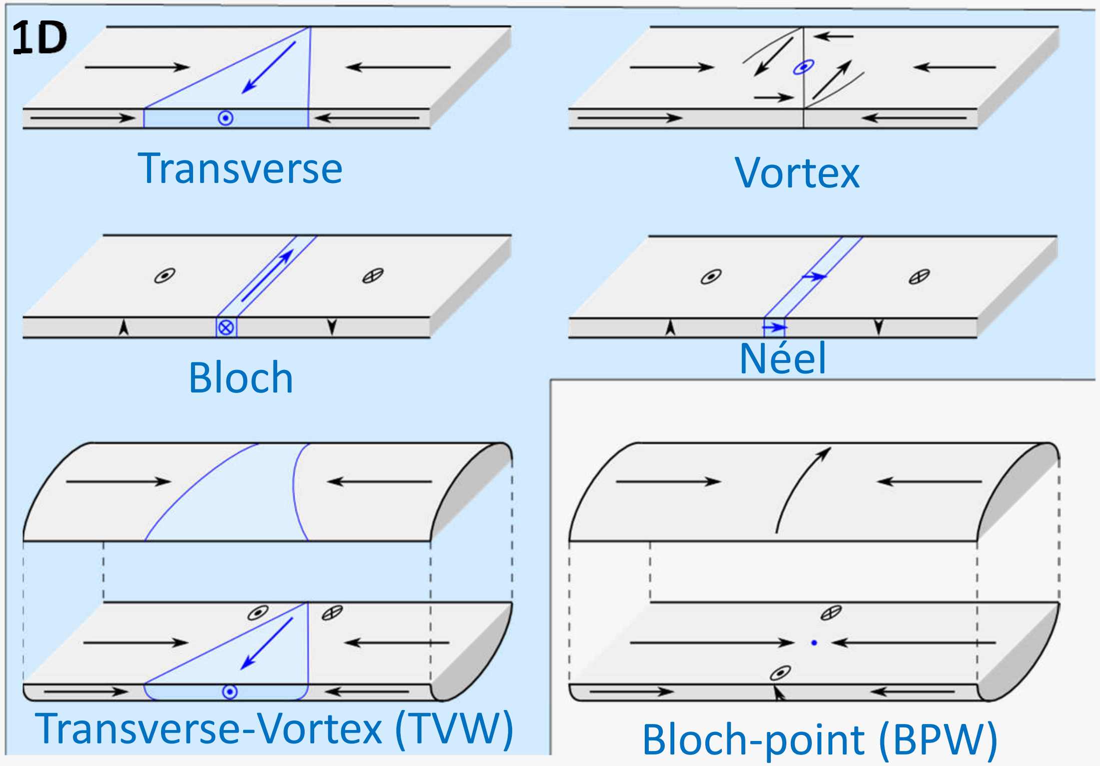


R. Streubel, J.Phys.D: Appl.Phys. 49, 363001 (2016)



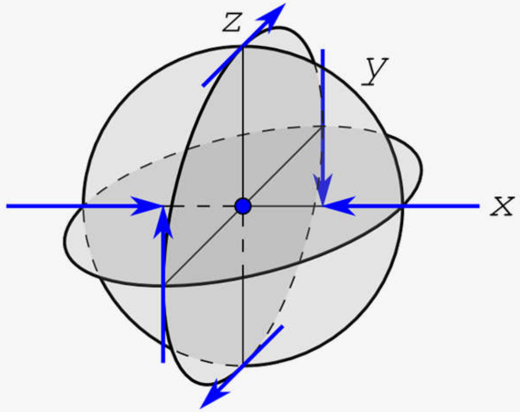
A. Fernandez-Pacheco, Nat. Comm. 8, 15756 (2017)

Domain wall topology of domain walls in 1D



H. Forster, JAP91, 6914 (2002); A. Thiaville, Spin dynamics in confined magnetic structures III, 101, (2006).

What is a Bloch point?



Magnetization texture with local vanishing of magnetization

R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

W. Döring,
J. Appl. Phys. 39, 1006 (1968)

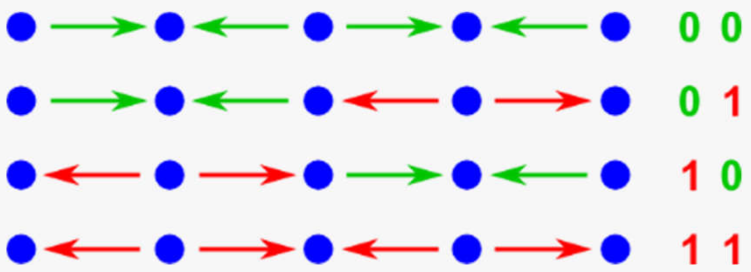
Review : S. Jamet, in Magnetic Nano- and Microwires, M. Vázquez Ed., Woodhead (2015) (arXiv:1412.0679)

- Transverse and vortex walls for IP have same topology: subject to Walker field
- Bloch-point walls have a different topology

MOTIVATION FOR MODULATIONS

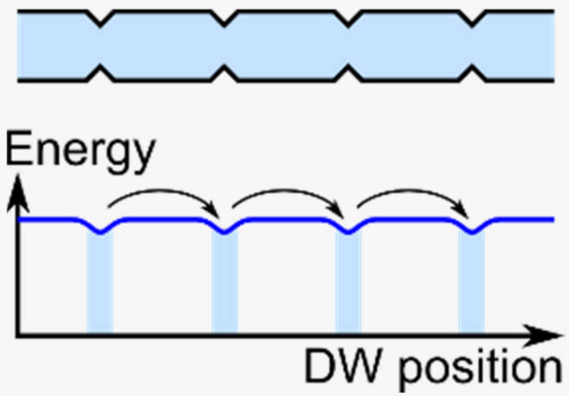
Devices

- Need for digital coding



Pathways

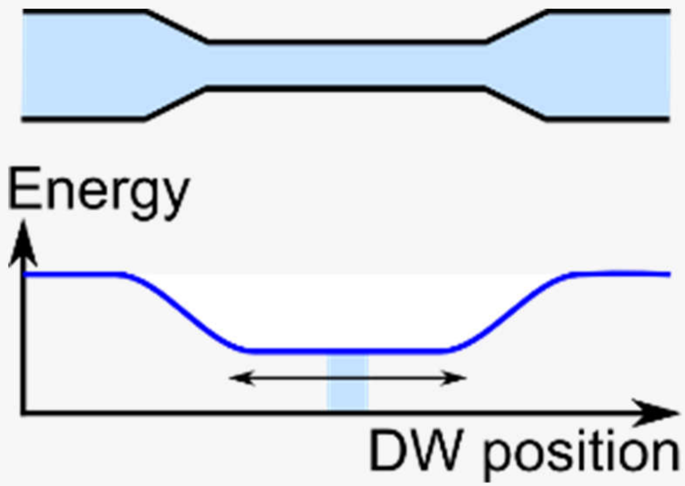
- Modulation of diameter



- Modulation of composition

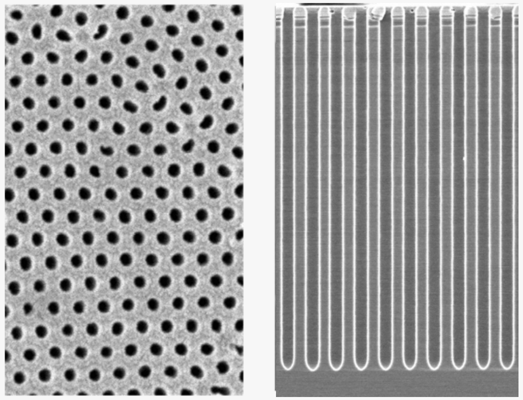
Physics: trap for domain wall

- Basis for pump-probe experiment and resetting the initial state



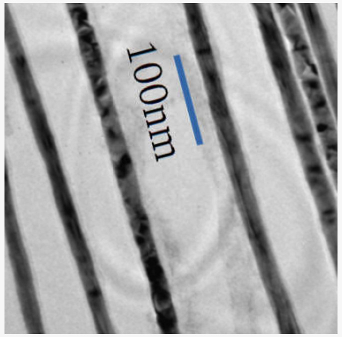
Standard processes

- Anodization of aluminum -> template



H. Masuda, Science 268, 1466-1468 (1995)

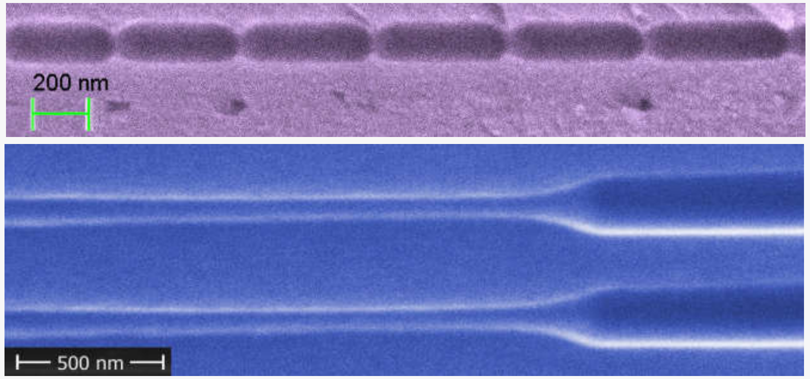
- Electroplating -> Magnetic wires



Simple metals and alloys : Co, Ni, $Fe_{20}Ni_{80}$, $Co_{20}Ni_{80}$

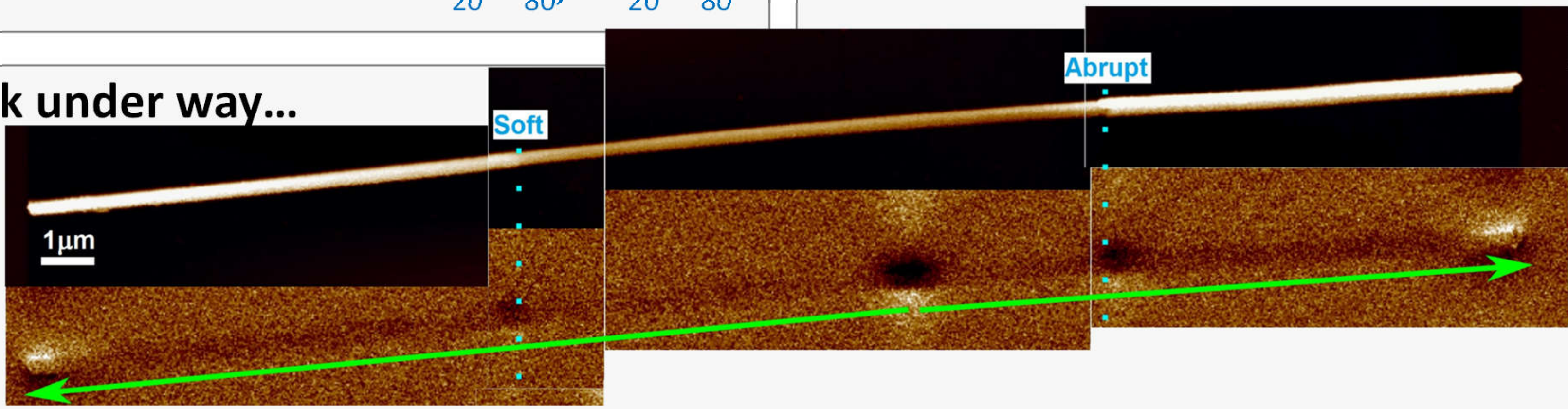
Specific aspects

- Pulsed or multi-steps anodization



S. Bochmann et al., submitted

Work under way…



Simulations / Theory

D. Allende, PRB80, 174402 (2009)

[S] Seminal work. Thick wires, domain walls fill part of the wire

D. Allende, PRB83, 174452 (2011)

[T] Seminal work. Complex analytics. No scaling law.

A. A. Ivanov, Phys. Sol. State 53, 2441 (2011)

[T] Fluctuations of diameters, link with Kondorski model. Not single item

M. Franchin, PRB84, 094409 (2011)

[S] Particular case. No general view

D. Salazar-Aravena, JMMM346, 171 (2013)

[S] Wires and tubes. Interesting, however no scaling law.

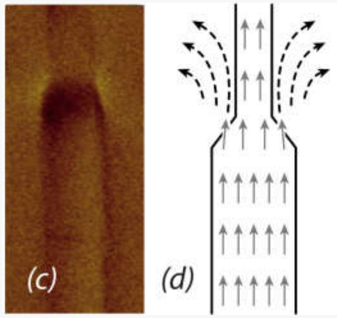
Experiments

K. Pitzschel, JAP109, 033907 (2011)

Global M(H)

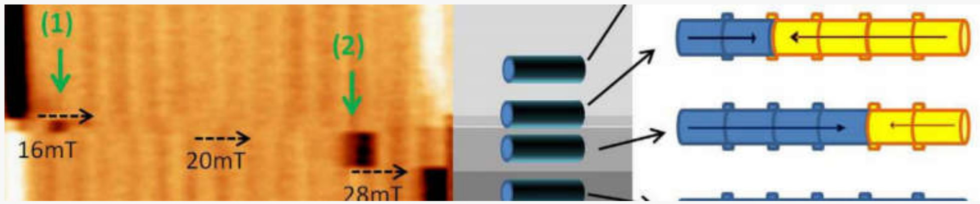
Imaging stray field at modulations

No domain wall



E. Berganza, Sci. Rep. 6, 29702 (2016)

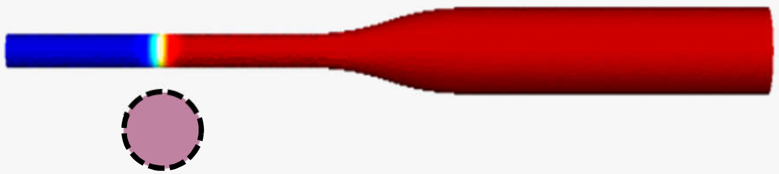
First hint of wall motion. No trend extracted



Our goal here:

- Tractable analytics -> Scaling law for trends, although not perfect
- Simulations -> Confirm scaling law, and quantitative approach

Principle

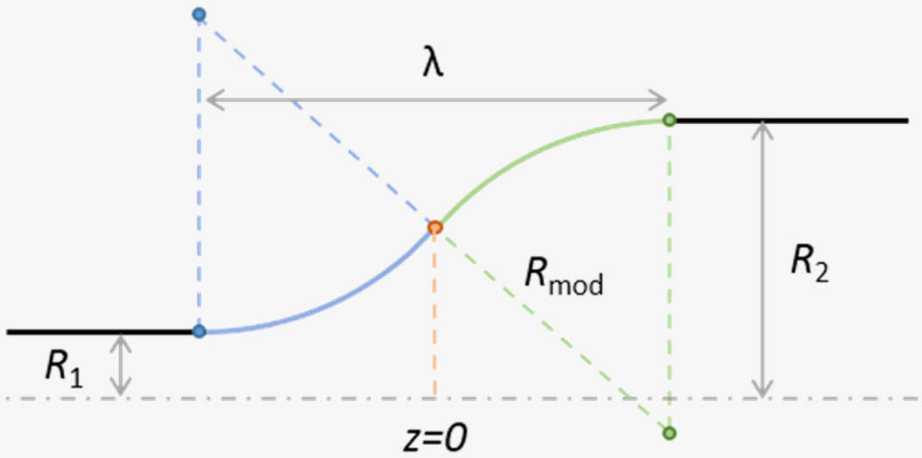


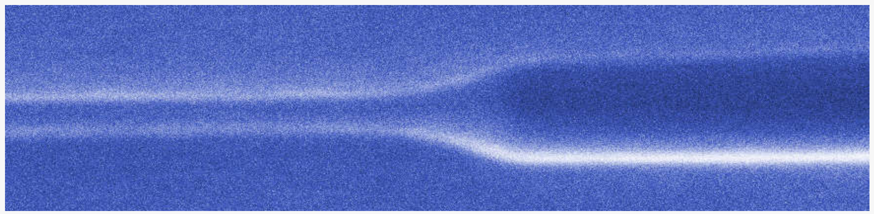
- Domain wall modelled as a sphere (reasonable for moderate diameter)
- Dipolar energy $(3\pi/5)\mu_0 M_s^2 R^3$
- Exchange energy $A(\pi^3/3)R$
- Zeeman energy

$$2\mu_0 M_S H\pi \int_{-L/2}^{z} R^2(z')\,\mathrm{d}z'$$

Modeling the modulation

- Two arcs of circles

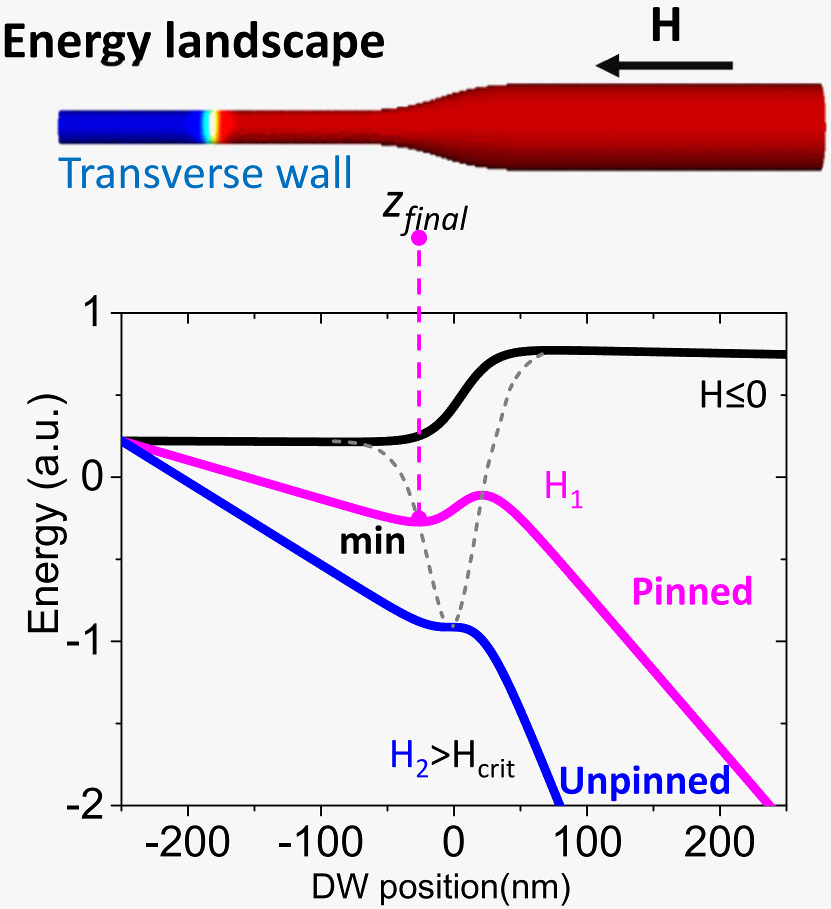




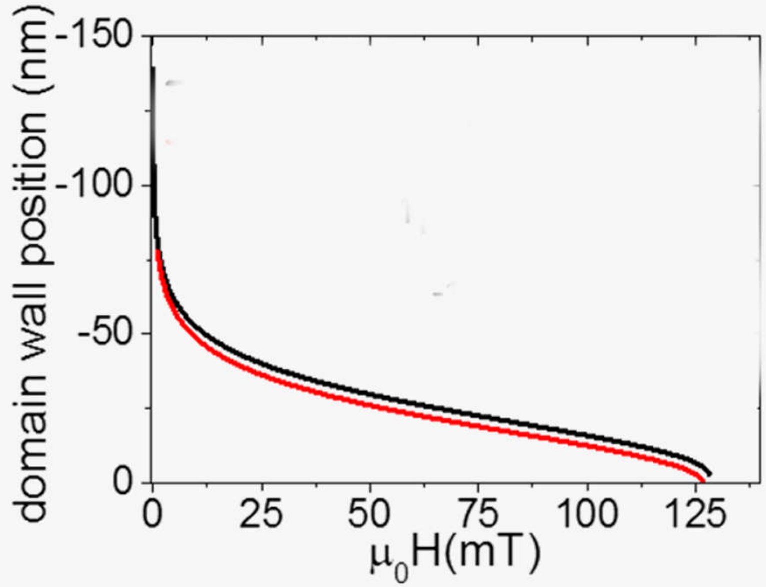
J. Fernandez-Roldan, submitted

Analytics: results

Energy landscape



Wall position and depinning



Depinning field

$$H_{crit} \quad \left(\frac{R_2 \quad R_1}{\lambda}\right)\frac{9M_S}{5}\left(1+\frac{10 l_{ex}^2\pi^2}{27(R_1+R_2)^2}\right)$$

Textbook case of the Becker-Kondorski model:

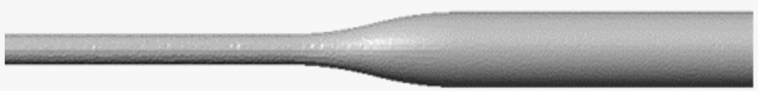
R. Becker, Phys. Z.S. 33, 905 (1932)

E. Kondorski, Phys. Z. Sowjetunion 11, 597 (1937)

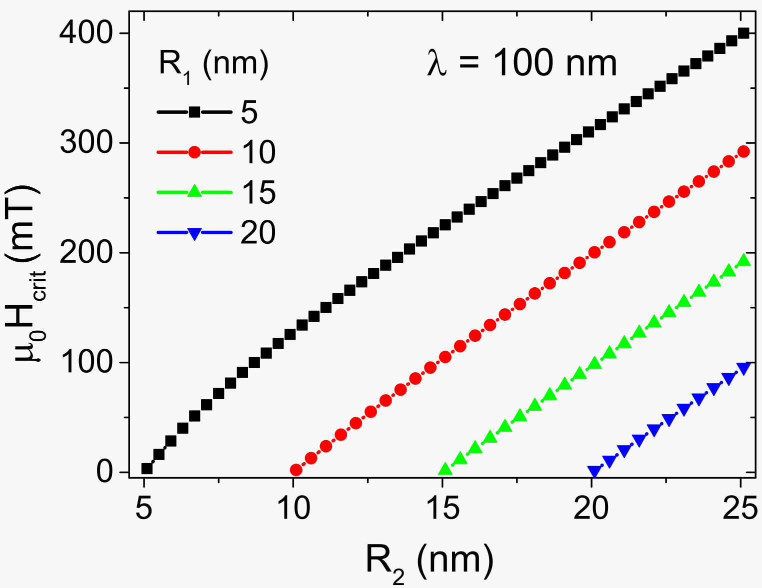
$$H_c \quad Slope \cdot M_s$$

Critical field

H_{app}



$$H_{crit} = \left(\frac{R_2 \quad R_1}{\lambda}\right)\frac{9M_S}{5}\left(1+\frac{10 l_{ex}^2 \pi^2}{27(R_1+R_2)^2}\right)$$

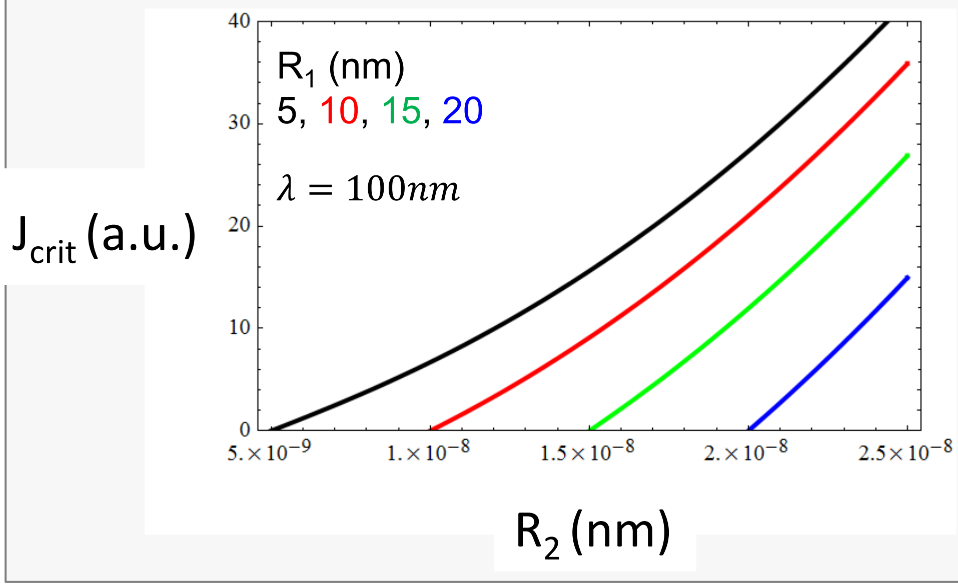


- Almost linear with R_2-R_1

Critical current (local)

J_{app} e⁻

$$J_{crit} \quad \frac{\alpha\gamma_0(R_2+R_1)}{(1+\alpha\beta_{NA})}\left(\frac{R_2 \quad R_1}{\lambda}\right)\frac{9eM_S^2}{5P\mu_B}\left(1+\frac{10 l_{ex}^2 \pi^2}{27(R_1+R_2)^2}\right)$$



- Further $(R_1/R_2)^2$ reduction against j_0

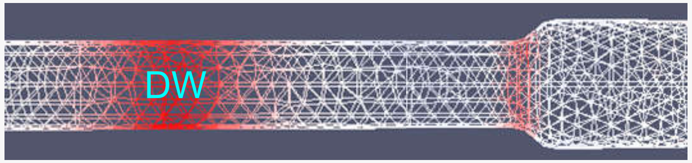
Tools

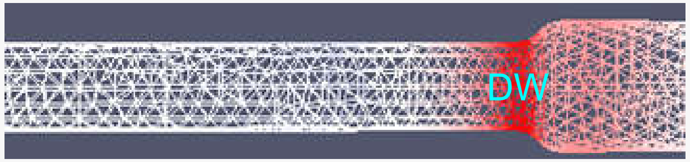
- Modified LLG $\alpha = 1$ For quasistatics (energy landscape)

$$\frac{\partial \mathbf{m}}{\partial t} = \gamma_0(\mathbf{H}_0 \times \mathbf{m}) + \alpha(\mathbf{m} \times \partial_t \mathbf{m}) + \frac{\mu_B P \sigma}{e M_S}(\nabla\varphi \cdot \nabla)\mathbf{m} \quad \beta_{NA}\frac{\mu_B P \sigma}{e M_S}\mathbf{m} \times (\nabla\varphi \cdot \nabla)\mathbf{m}$$

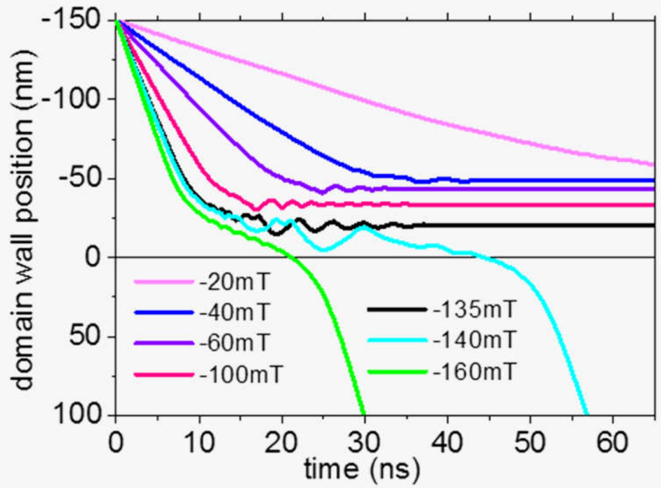
effective field   damping   driving force due to spin transfer torque

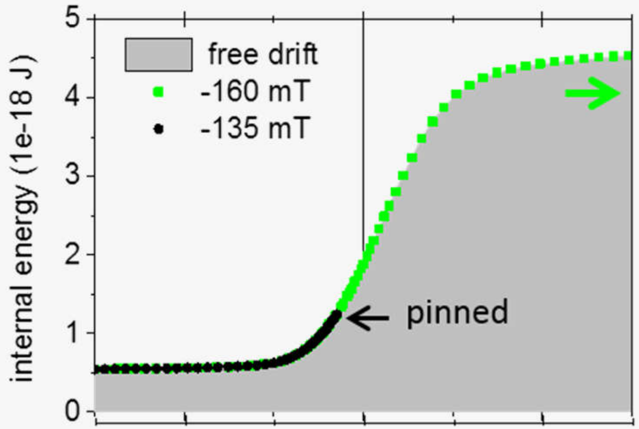
- Finite elements for smooth description of the wire   http://feellgood.neel.cnrs.fr/





Typical experiment





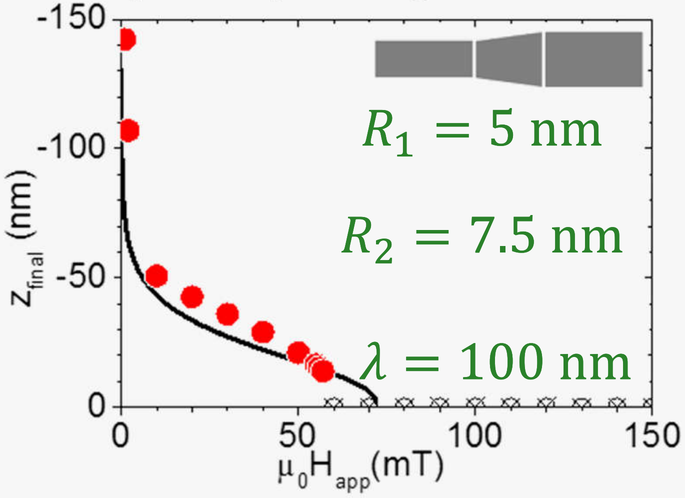
$R_1 = 5\ \mathrm{nm}$

$R_2 = 12.5\ \mathrm{nm}$

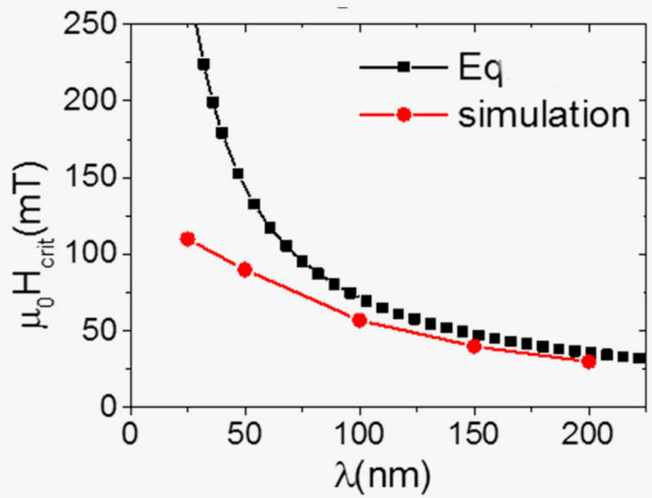
$\lambda = 100\ \mathrm{nm}$

Simulations versus model

Principle of pinning

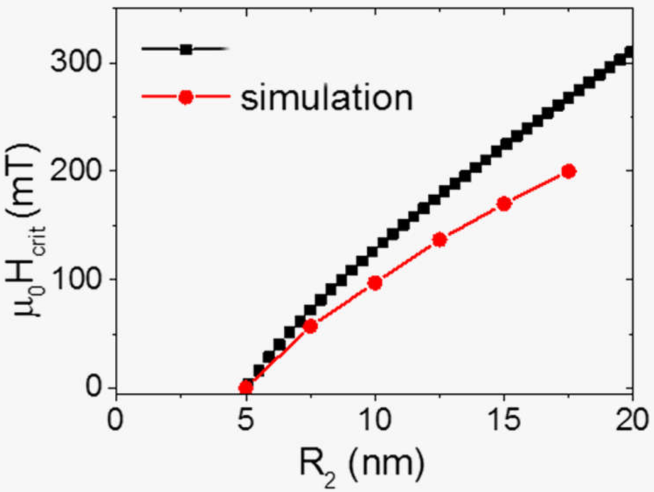


Modulation length



J. Fernandez-Roldan, submitted

Modulation strength



- Analytics reasonably valid, except for short modulations
- Scaling law valid: $H_c \quad Slope \cdot M_s$
- Under way
  - Finite-length modulation
  - Current-induced depinning

ACKNOWLEDGEMENTS

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- ICMM-CSIC, Madrid J. Fernandez-Roldan

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Thank you for your attention !

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