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Controlling magnetic domain walls with supercurrents

arXiv:2606.19078

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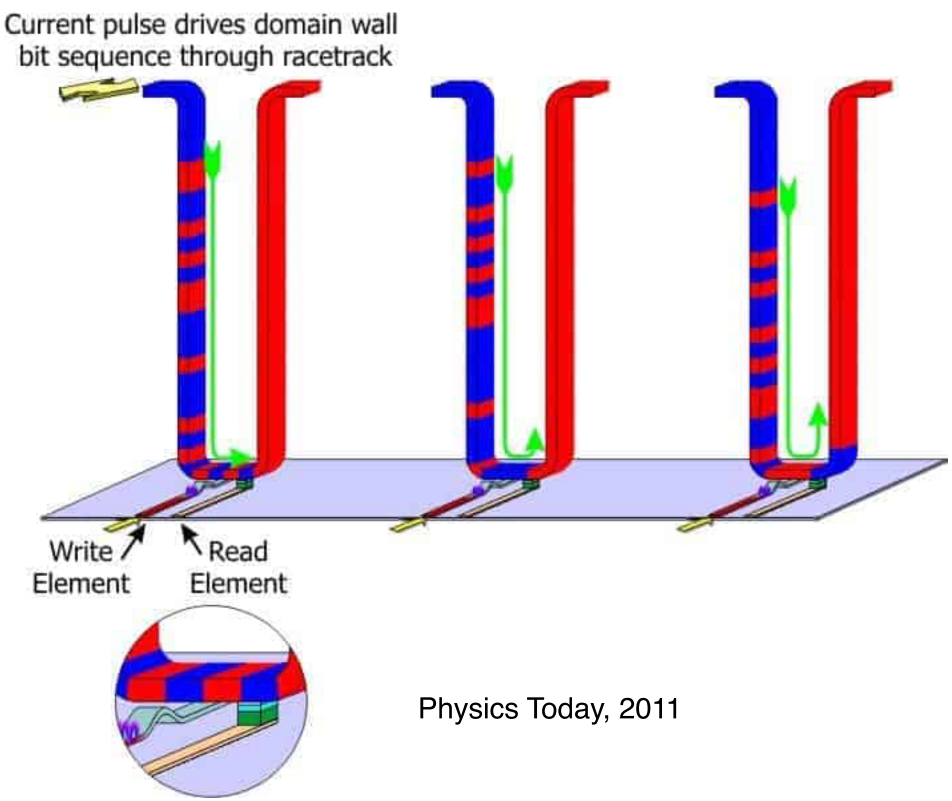
Supercurrent racetrack memory

Parkin, et al., 2004



Physics Today, 2011

Superconducting version:

- Low dissipation, heating
- Solution to missing cryogenic memory needed e.g., in next-stage QC

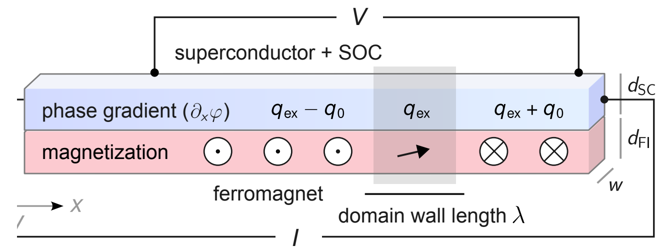
$$\dot{x}_{dW} = \beta I_S$$

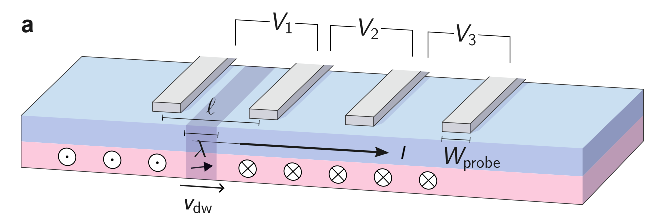
Open questions:

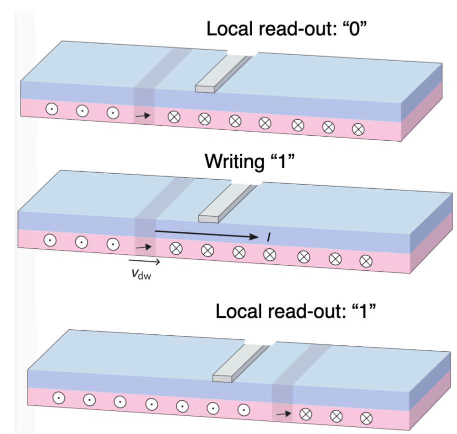
- How can *equilibrium* supercurrent maintain *dissipative* domain wall motion?
- Mechanism for supercurrent dw torque: what sets the sign and magnitude of β?

Contents

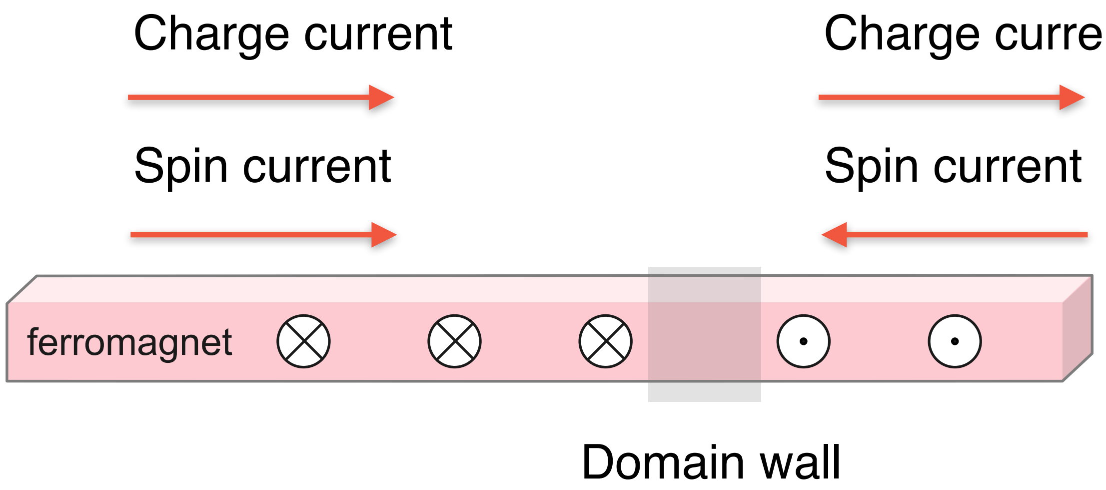
- Supercurrent domain wall torque from (inverse) spin galvanic effect
- Voltage generation from domain wall motion
- Use in cryogenic memory
- Materials requirements
- Power consumption, heating



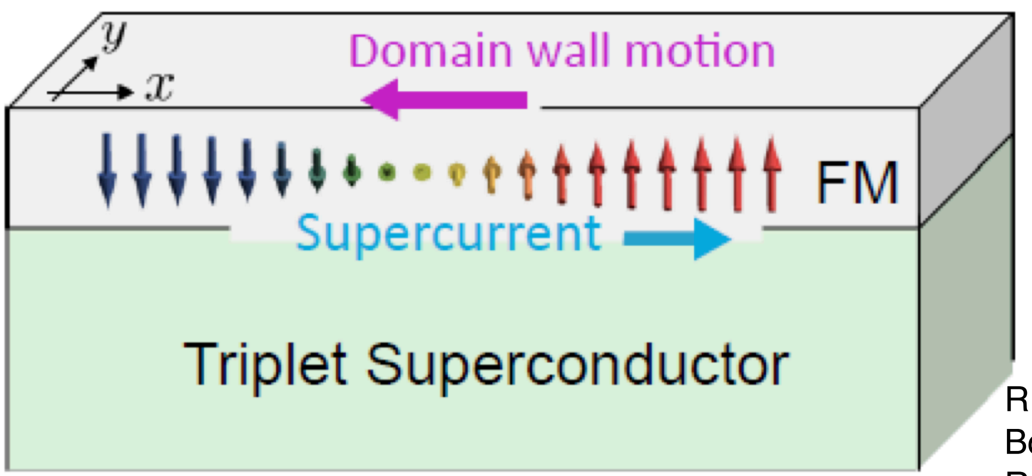




Current-induced domain wall motion



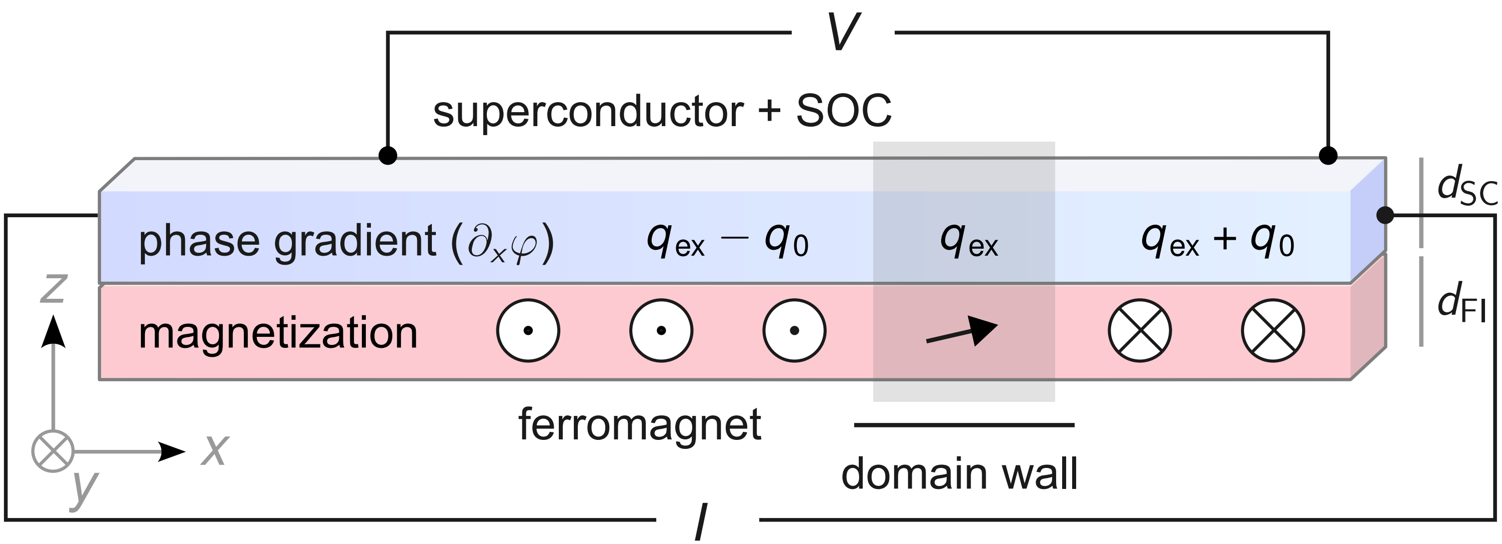
Difference between spin currents: torque on the domain wall



Supercurrent analogue: requires triplet supercurrent

R. Takashima, S. Fujimoto, T. Yokoyama, PRB 2017
Bobkova, Bobkov, Silaev, PRB 2018
Rabinovich, Bobkova, Bobkov, Silaev, PRL 2019

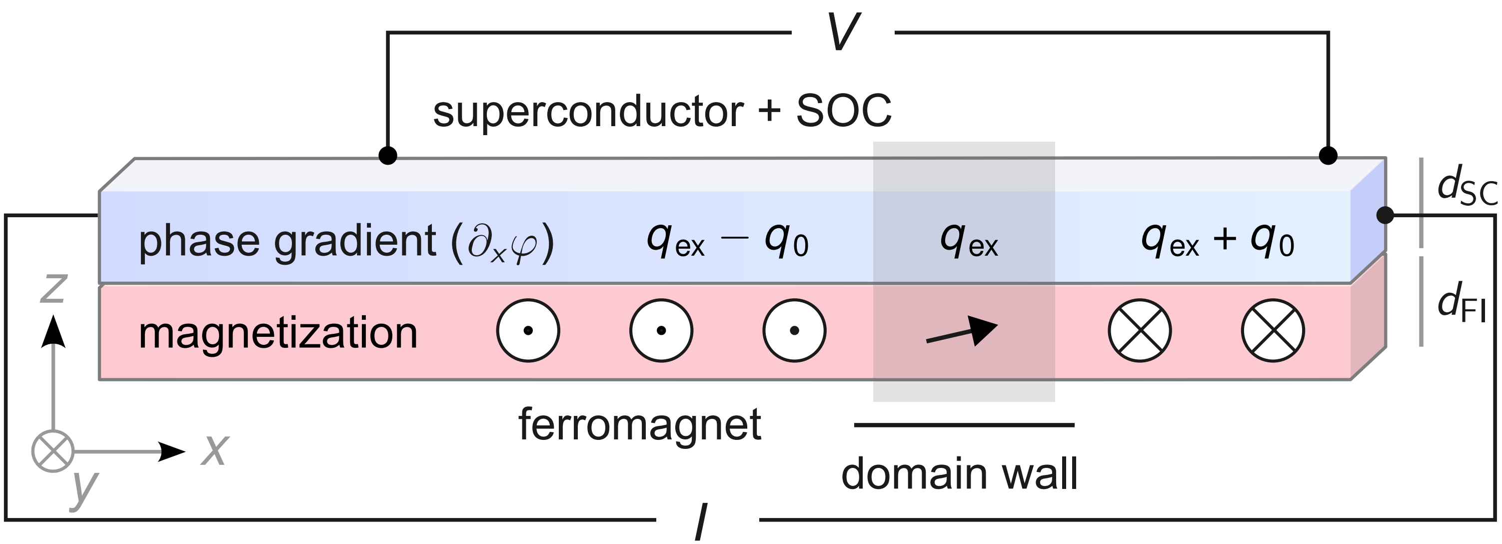
Our suggestion



Externally driven supercurrent: $q_{\rm ex}$
Spin galvanic effect (anomalous phase gradient): SOC+magnetization: q_0
Inverse spin galvanic effect: equilibrium spin $\mathbf{S} = S_0\hat{u}_y, S_0 \propto q_{\rm ex}$

Local precession of $\hat{m}$ around $\mathbf{S}$ at the DW + damping: domain wall motion

Our suggestion



Far from DW: $\mathbf{S} \propto \hat{m}$

$\Rightarrow$ no "long-range triplet"

$\Rightarrow$ Electron torque = domain wall torque, thus no net torque

Spin galvanic effect leads to helical superconductivity and diode effect

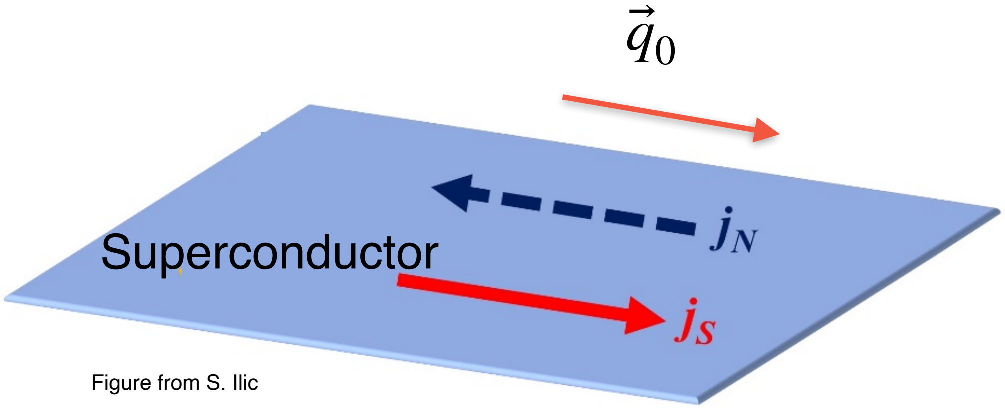


Figure from S. Ilic

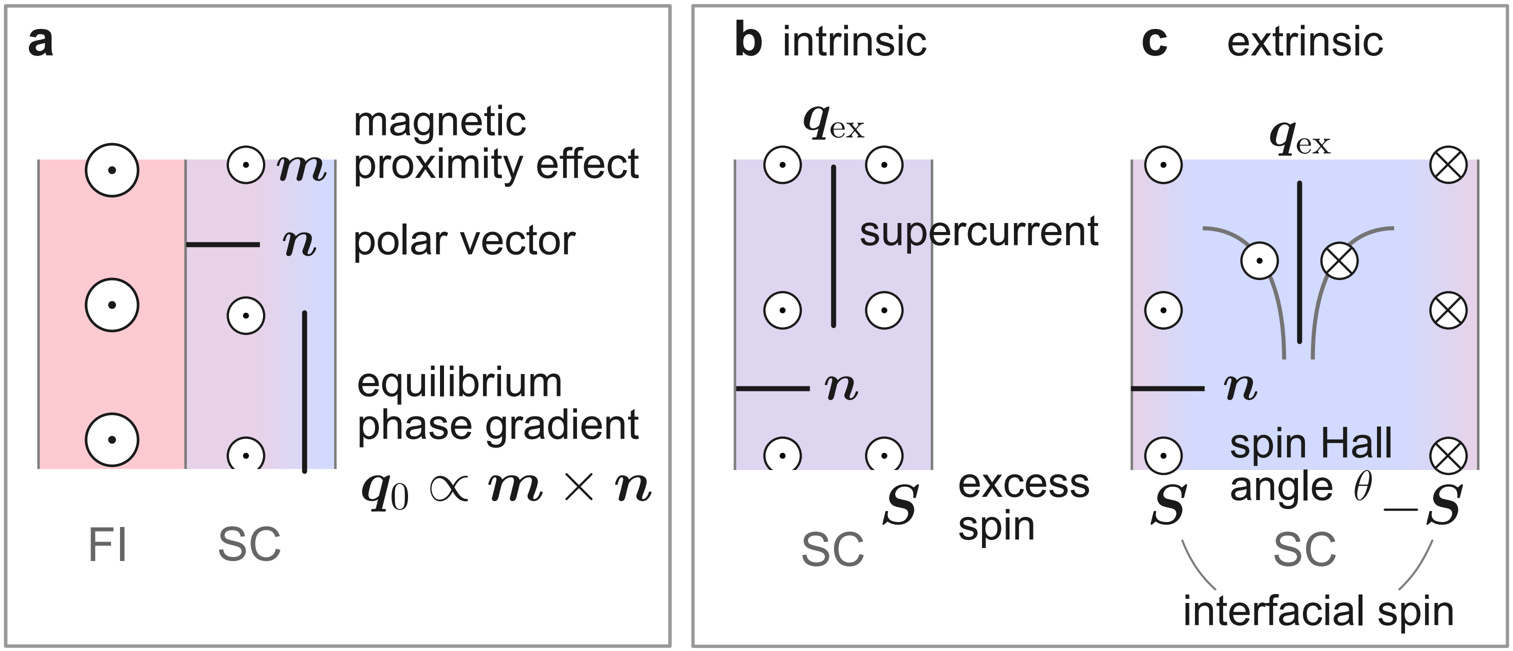
Superconductor:

- Helical superconductivity: $\Delta(\vec{r}) = \Delta_0 e^{i\vec{q}_0\cdot\vec{r}}$
- Superconducting diode effect: $j^+_{critical} \neq j^-_{critical}$

Agterberg and Kaur, PRB *75* (2007)
Smidman et al., Rep. Prog. Phys. 80 (2017)

Direct and inverse spin galvanic effect

Spin-galvanic effect | Inverse spin-galvanic effect



$$\mathbf{q}_0 \propto \mathbf{m} \times \mathbf{n}$$

$$\mathbf{S} \propto \mathbf{n} \times \mathbf{j}$$

(Also: Inverse Edelstein effect) (Also: Edelstein effect)

Background theory

Virtanen, Bergeret, Tokatly, PRB 2021
Kokkeler, Bergeret, Tokatly, PRL 2025

Keldysh non-linear sigma model (NLSM):

$$iS[Q, M] = iS_Q[Q] + iS_M[M] + iS_I[Q, M]$$

Disordered superconductor + SOC
(Saddle point gives the Usadel equation + spin Hall effect)

Ferromagnet
(Saddle point gives the Landau-Lifshitz-Gilbert equation)

Coupling
(Spin-mixing conductances, yield e.g., the induced exchange field)

Domain wall, collective coordinates x_0 and ϕ:

$$m_y^R \nu_s \partial_t x_0 - C_1 \nu_s \alpha \lambda \partial_t \phi + C_1 \nu_s \lambda K_\perp \sin 2\phi + \frac{\mathrm{T}[g]}{\hbar A_F} = 0$$

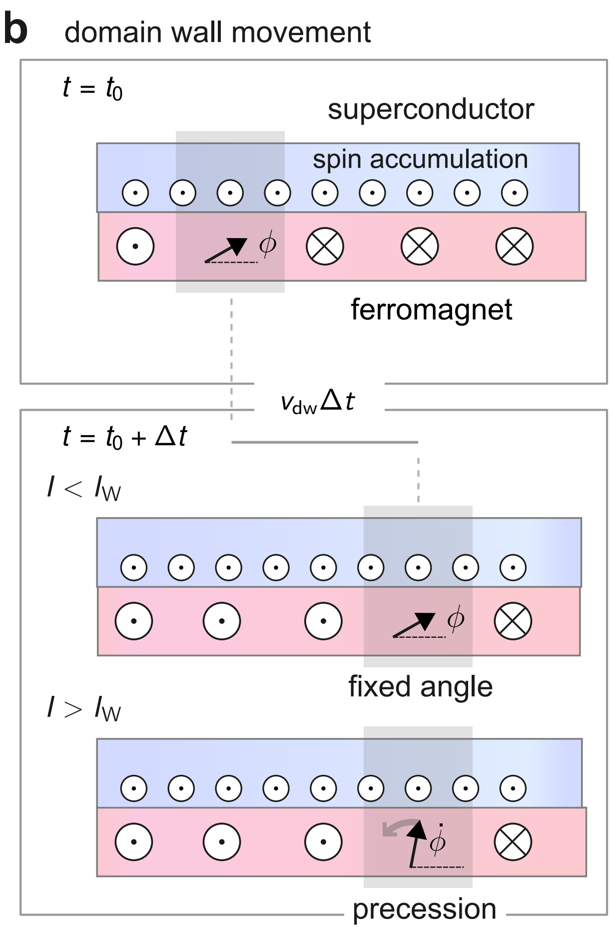
$$\mathrm{T} = \frac{G_i w}{2e^2 \nu_0} \int_{-\infty}^{\infty} dx\, \vec{S}(x) \cdot [\vec{m} \times \hat{\vec{y}}] \overset{\vec{m} \propto \hat{y}}{=} 0$$

Tatara, Kohno, Shibata, Phys. Rep. 2008

$$m_y^R \nu_s \partial_t \phi + C_2 \nu_s \frac{\alpha}{\lambda} \partial_t x_0 + \frac{F[g]}{\hbar A_F} = 0$$

$$F = \frac{G_i w}{2e^2 \nu_0} \int_{-\infty}^{\infty} dx\, \vec{S}(x) \cdot \partial_x \vec{m}$$

Domain wall motion



Small current $I < I_W$:

$$v_{\mathrm{dw}} = \frac{f}{\eta}$$

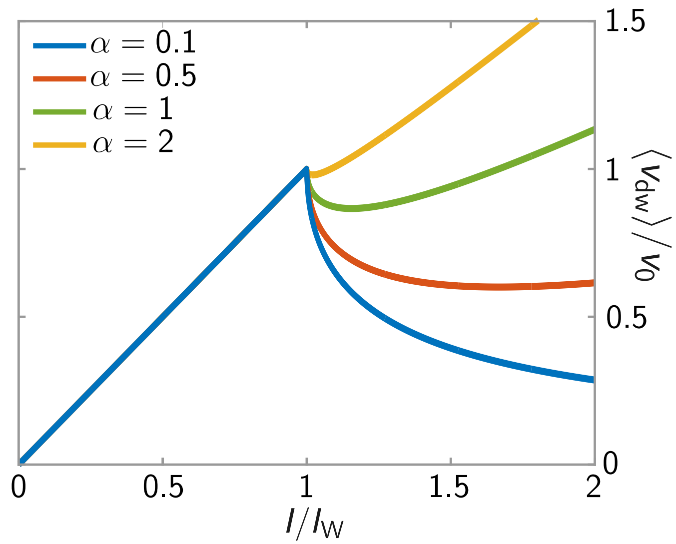
$$f = \frac{\hbar}{e} q_0 I$$

Force due to ISGE

$$\eta = C_2 \hbar \alpha \frac{\nu_s A_F}{\lambda}$$

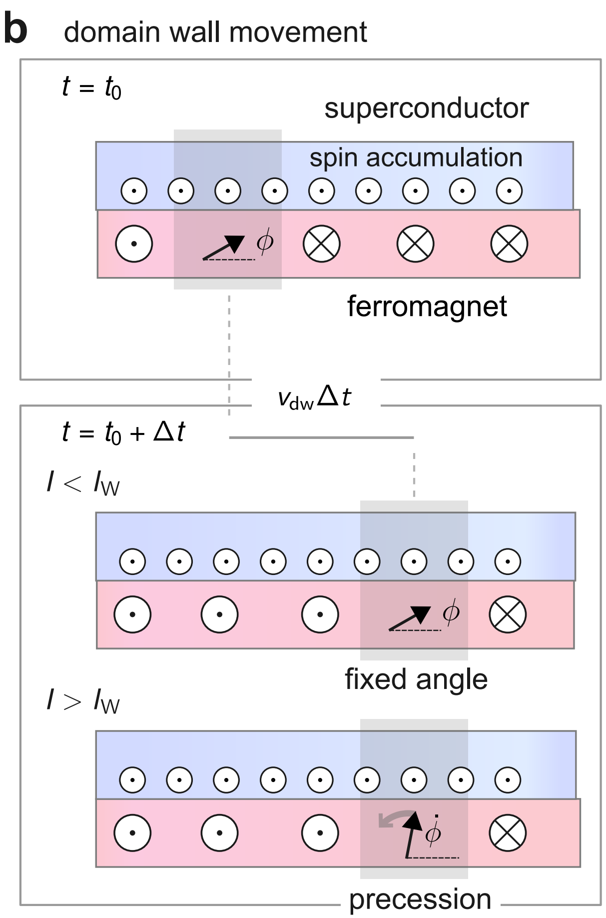
DW drag coefficient

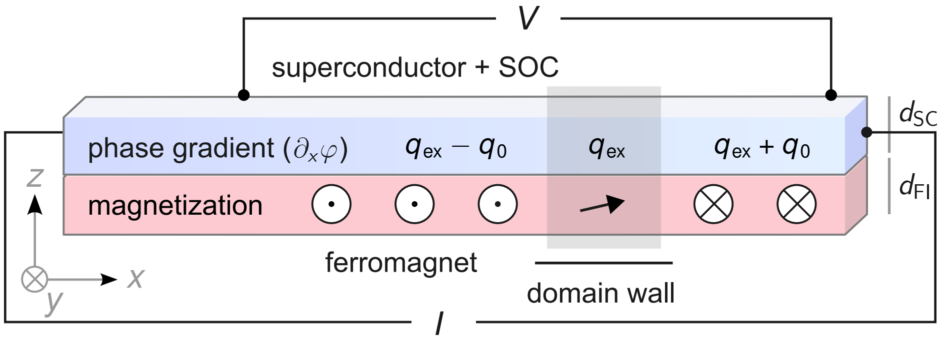
α: Gilbert damping

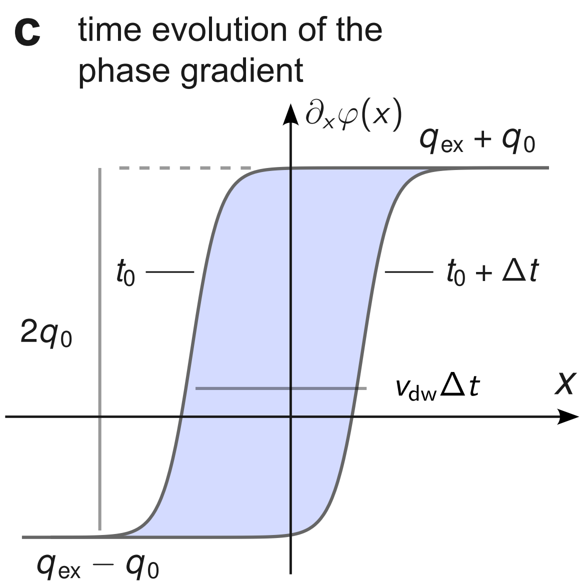


I_W: Walker breakdown current

Voltage from DW motion



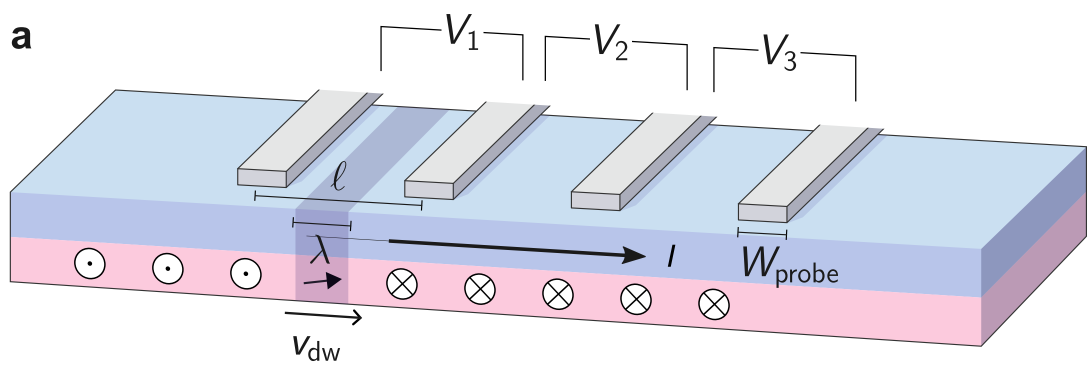


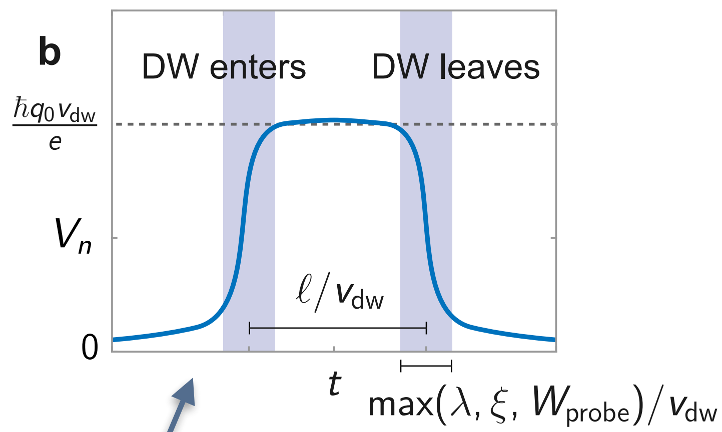


$$\partial_t \varphi = 2q_0 v_{dw} = \frac{2e}{\hbar} V$$

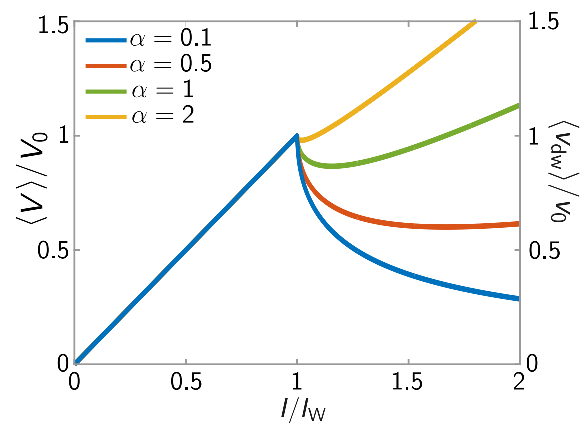
DW motion leads to electrical resistance!

Voltage allows tracking DW motion



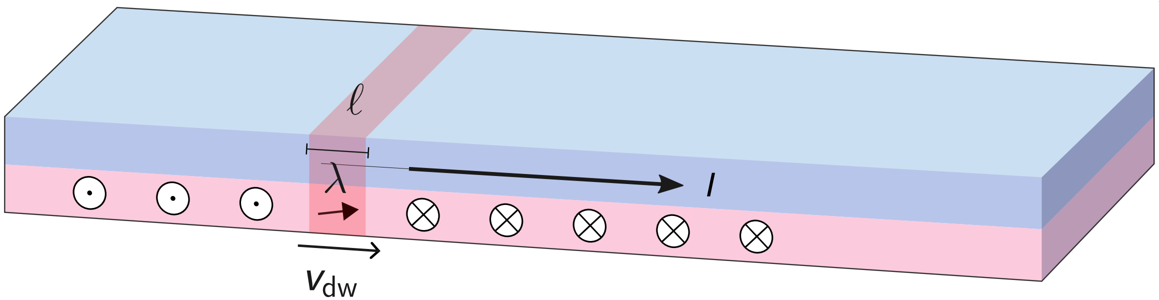


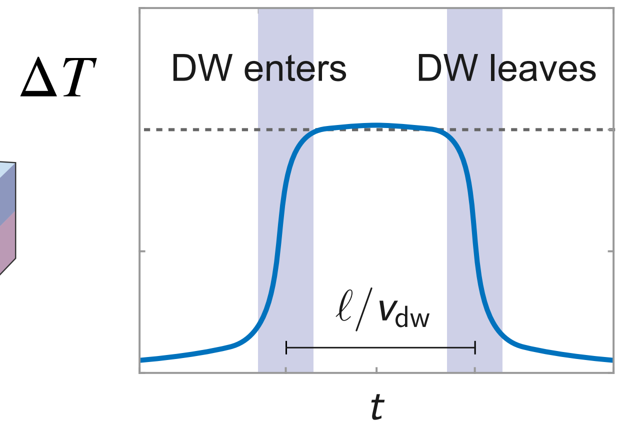
Charge
imbalance tail



Dissipation, heating

$$T = T + \Delta T(x,t)$$





Domain wall movement requires power $P_S = IV = \frac{\hbar^2}{e^2}\frac{q_0^2}{\eta}I^2$

Only from DW motion!

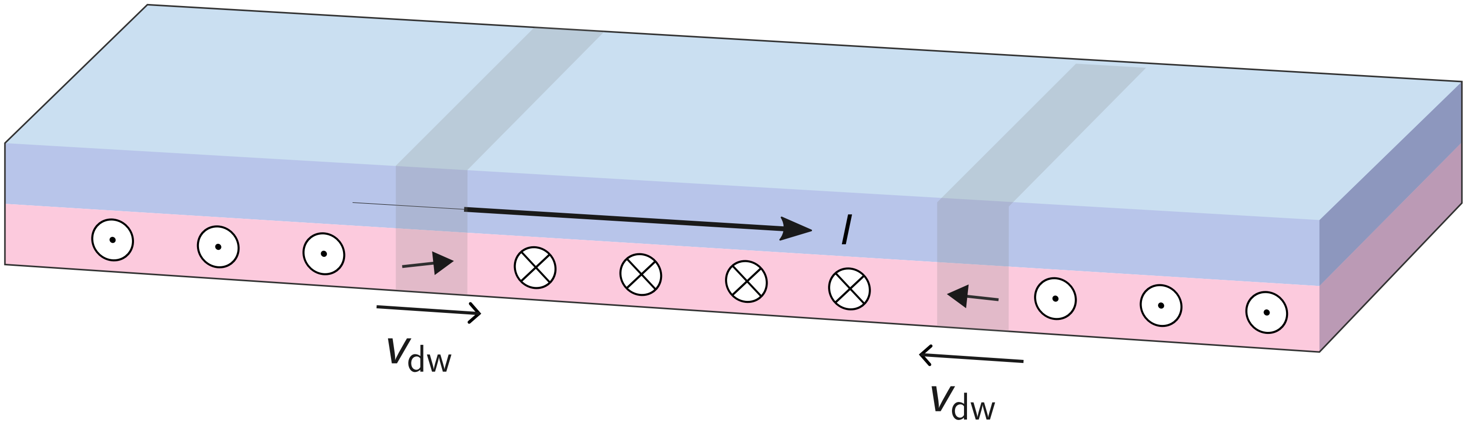
Heating: heat balance equation

$$\kappa_{\mathrm{FI}}\partial_x^2\Delta T - \rho c_p v_{\mathrm{DW}}\partial_x T = -\frac{P}{A_F}\delta(x) + \frac{\mathscr{K}}{d_{\mathrm{FI}}}\Delta T$$

$$\Delta T \approx \frac{P_S}{A_F}\left[\frac{4\kappa_{\mathrm{FI}}\mathscr{K}}{d_{\mathrm{FI}}} + \left(\rho c_p v_{\mathrm{DW}}\right)^2\right]^{-\frac{1}{2}}$$

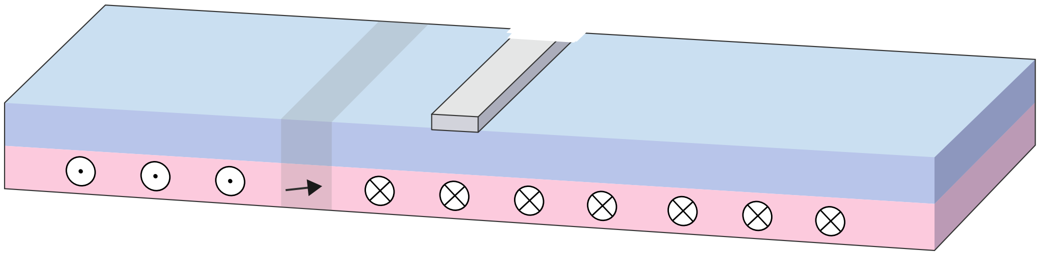
Many domains

Supercurrent tries to shrink the “minority” wall (depends on sign of I): not a racetrack with only dc current pulses

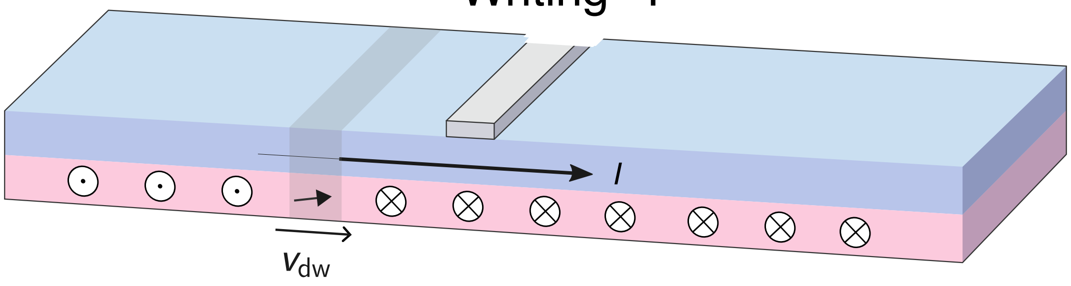


Memory with fast writing

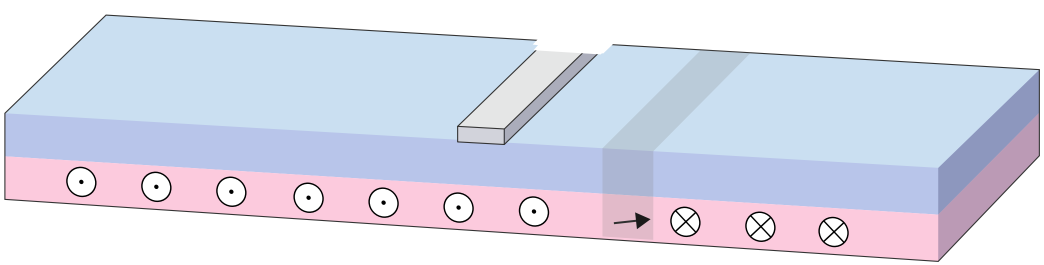
Local read-out: “0”



Writing “1”



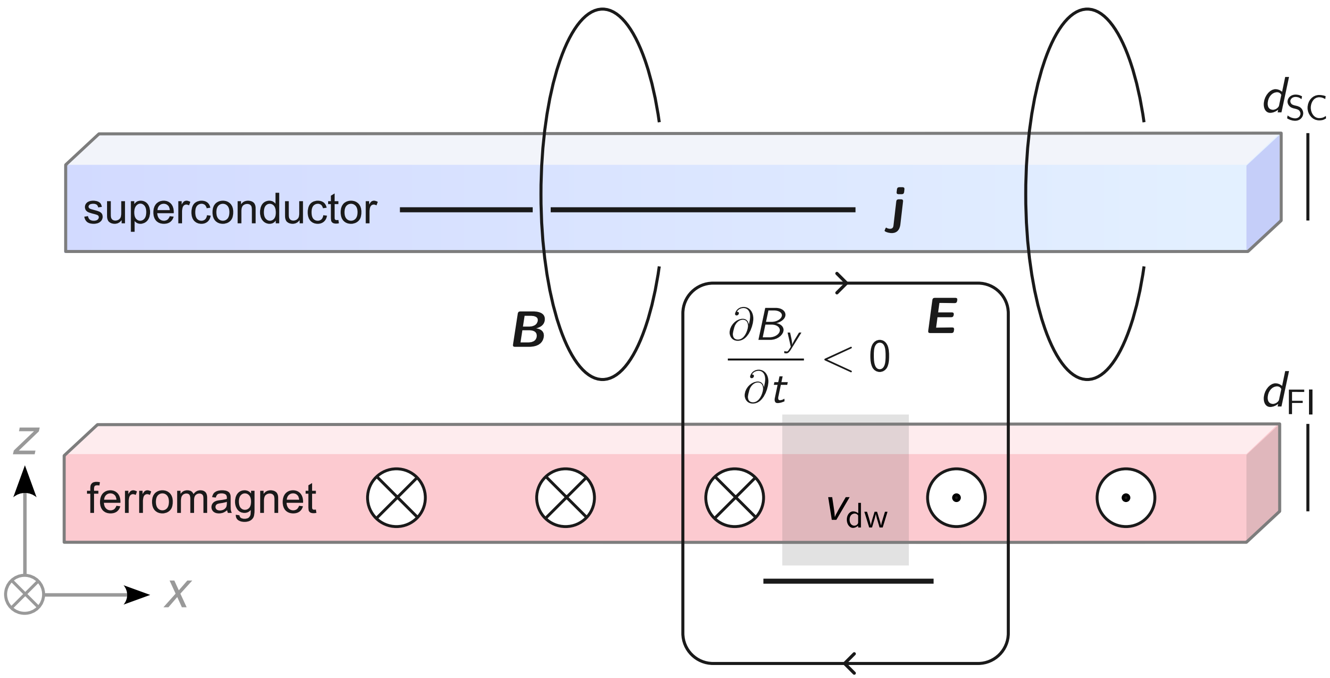
Local read-out: “1”



Writing 0: reverse current

Voltage can be used for determining when the wall passed the memory region

Oersted field effect



Quite similar physics…

Spin-orbit mechanism dominates for $$\theta \frac{G_i l_{so}}{\sigma} \frac{2\pi\hbar}{e\mu_0 MA \ln(1 + \frac{d_{FI}}{d_{SC}})} > 1$$

Oersted field: leads to cross-talk

Materials

Requirements:

- superconductors with a large spin-Hall angle (strong SOC) or superconductor/semiconductor hybrids together with
- ferromagnetic insulators with well-defined easy axis, homogeneous anisotropy
- good interfaces with large G_i

Examples: Al/InAs/EuS, NbSe2/CrI3, …

Estimates

Assumptions:

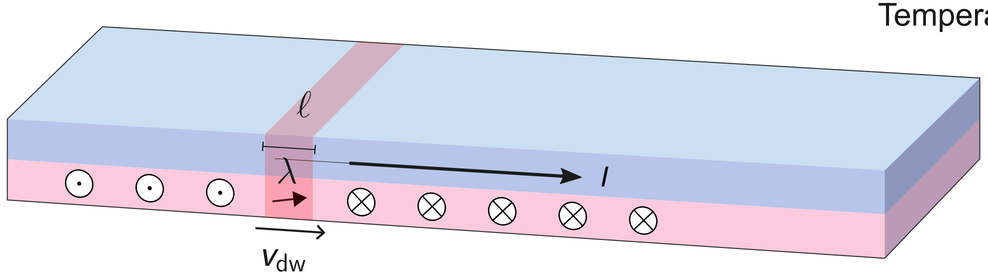
λ=10 nm, $\alpha = 10^{-3}$, $d_S \approx d_{\mathrm{FI}}$ = 10 nm, $q_0 \sim \hbar\,(\mu\mathrm{m})^{-1}$

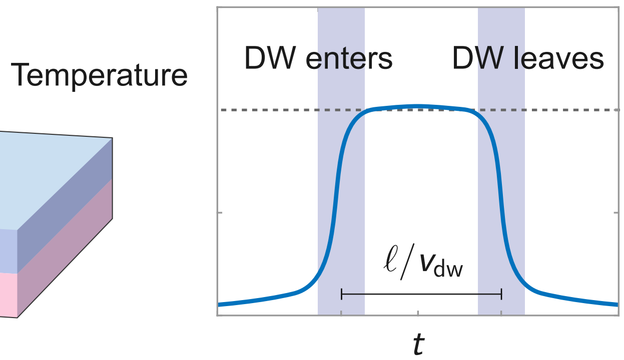
Reaching $v_{\mathrm{DW}} = 100$ m/s requires $j = 10^9$ A/m^2 and yields $V = 0.1\mu$V

Adiabatic limit: $v_{\mathrm{DW}} \ll \lambda\Delta/\hbar$, for $\Delta \sim 0.1$ meV it is $\ll 10^3$ m/s

Dissipation, heating

$$T = T + \delta T$$





Domain wall movement requires power $P_S = IV = \dfrac{\hbar^2}{e^2}\dfrac{q_0^2}{\eta} I^2$ Only from DW motion!

Heating: primarily heating of the phonons in the ferromagnetic (electrons decoupled)

$$\Delta T \approx \frac{P_S}{A_F}\left[\frac{4\kappa_{\mathrm{FI}}\mathscr{K}}{d_{\mathrm{FI}}} + \left(\rho c_p v_{\mathrm{DW}}\right)^2\right]^{-\frac{1}{2}}$$

Our estimate ($T = 1$ K), EuS
$\Delta T \approx 1$ mK

Comparison to normal domain wall torque

	DW motion in N state	DW motion in S state
Damping mechanisms	Gilbert damping due to electrons and phonons, thus much larger α	Gilbert damping due to phonons only
Power dissipation	Mainly from wire resistance, small correction from DW motion	Only from DW motion
Heating	Electrons heat everywhere and a lot	Only around the DW and due to much less power
Pinning	Problem	Problem (?)
Fluctuations	Brownian motion due to high electron temperature	Fluctuations small due to weak dissipation and low T

Summary

arXiv:2606.19078