Nonlinear regimes of current-induced domain wall motion.

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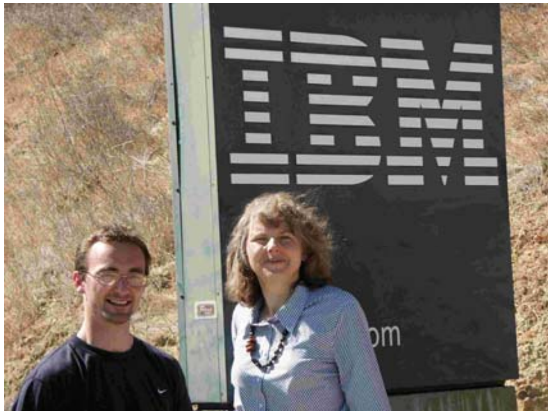

Alexander Joura (Georgetown U.),
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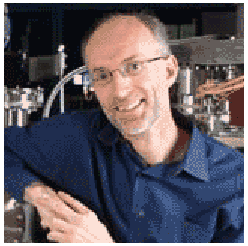


Stuart Parkin (IBM).

OUTLINE:

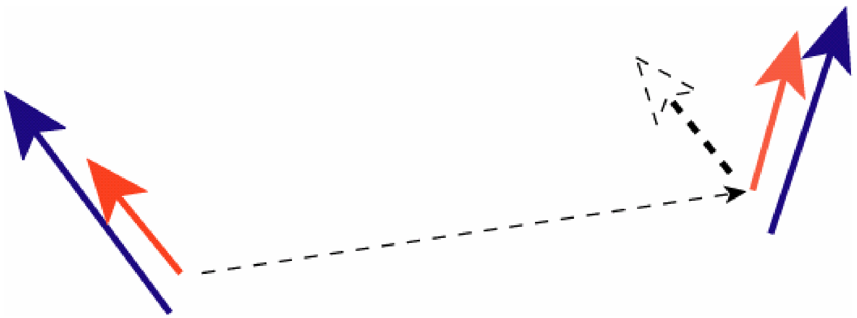
- spin-transfer effect
- spin-transfer in the case of domain walls
- rigid domain wall approximation
- motion in straight wires
- motion in shallow pinning potential
- domain walls with inner structure

<u>What happens if current flows through a non-uniform magnetic configuration:</u>

Spin = angular momentum

$$\mathbf{L} = \frac{\hbar}{2}\mathbf{s}$$

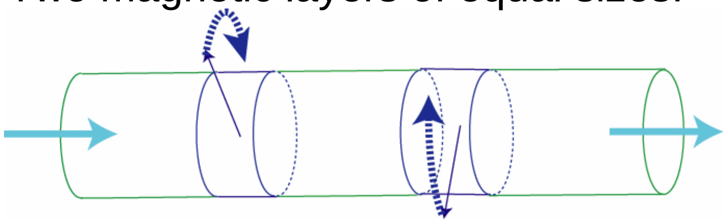
Electric current leads to rotation of the spin direction. Thus a torque must be acting on the spin



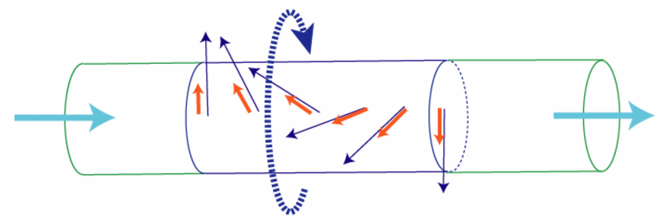
$U = J(\vec{s} \cdot \vec{M})$ - local interaction between itinerant spin ***s*** and local spin ***M***.

Discrete and continuous cases of spin-transfer:

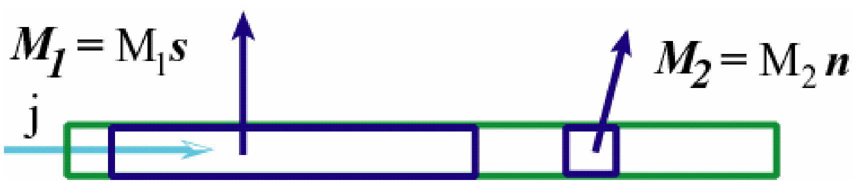
Two magnetic layers of equal sizes:



Current flowing through a spiral magnetization:



Large layer acting as a polarizer:



Torque Formula Slonczewski, JMMM, **159**, L1 (1996):

A magnet with **M** = M **n** experiences a torque

magnetic polarizer

$$\vec{T} = \left(\frac{\hbar j}{2e}\right) g((n \cdot s), P)[\vec{n} \times [\vec{s} \times \vec{n}]]$$

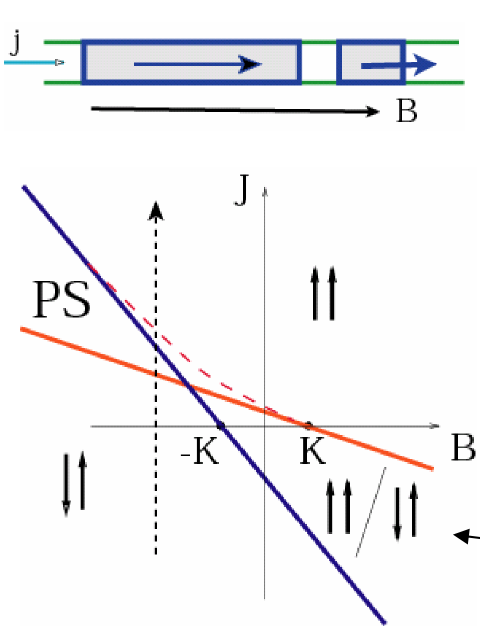
Degree of spin polarization

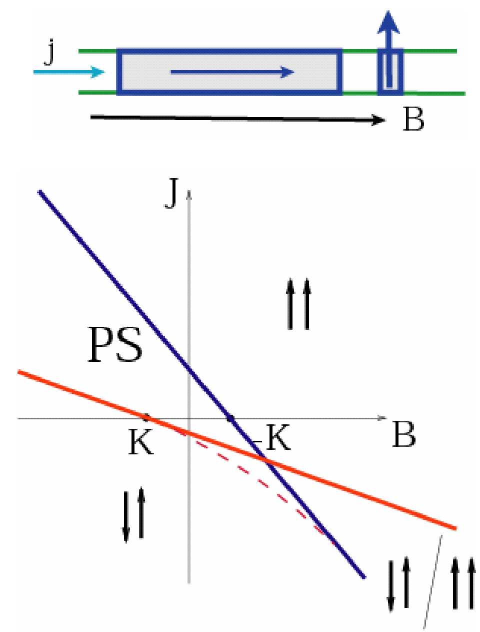
Spin-transfer is a non-equilibrium phenomena. The deviation from equilibrium is proportional to the current

Theoretical description – Landau-Lifshitz-Gilbert (LLG) equation

$$\dot{n}_i = \left[(H + \hat{K}\mathbf{n}) \times \mathbf{n}\right]_i + I g(P, \mathbf{sn})[\mathbf{n} \times [\mathbf{s} \times \mathbf{n}]]_i + \alpha[\mathbf{n} \times \dot{\mathbf{n}}]$$

Solutions for simple systems: “switching diagrams” of a free layer

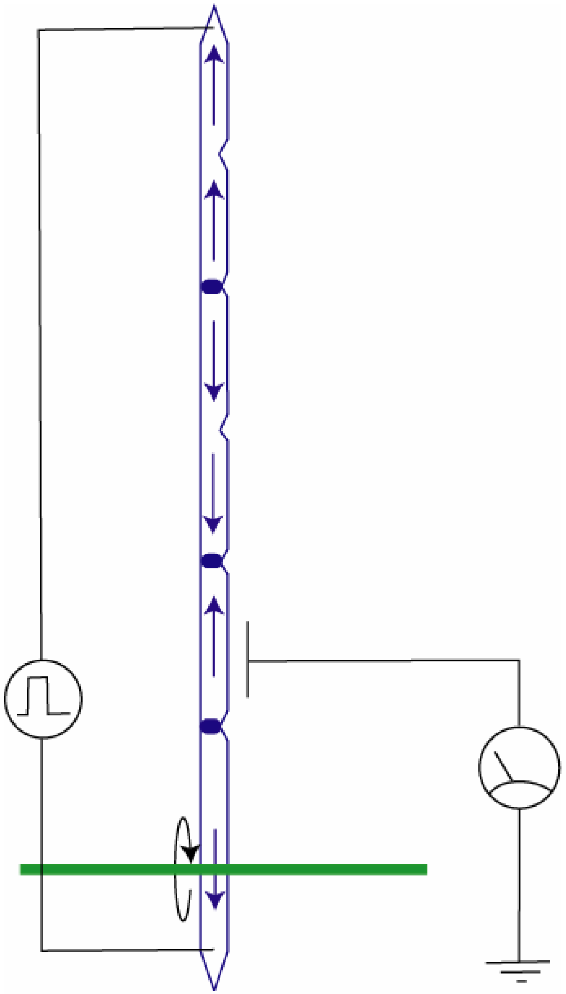




bistable regime
– memory cell.
MRAM writing!

Domain wall memory

Prototypes of MRAM based on individual spin valves are build, but the production costs are not competitive. If you have 30-50 information bits per cell, you get a very attractive figure per bit!



Spin-transfer effect in domain walls (DW):

Luc Berger, J. Appl. Phys. **49**, 2156 (1978)

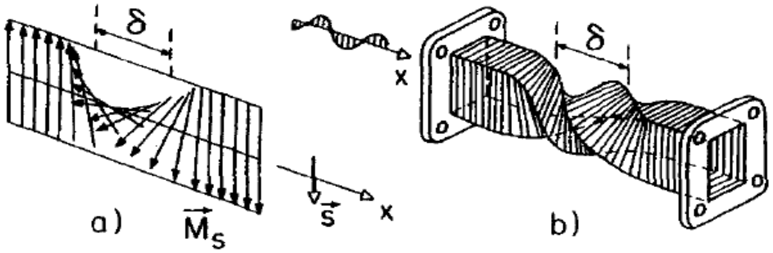


Fig. 1.a) A conduction electron of spin $\vec{s}$ crosses a 180° domain wall. b) Analogy with a linearly polarized microwave propagating along a twisted wave-guide.

While reflection by a wall is negligible, another spin effect might conceivably be observed. In order to reverse the direction of $\vec{s}$, $\vec{M}_s$ must apply an exchange torque on $\vec{s}$. Inversely, $\vec{s}$ creates a reaction torque on the wall, equivalent to an exchange field applied to $\vec{M}_s$ and having a component H_x^{ex} in the x direction normal to the wall:

$$H_x^{ex} \simeq j\left(\frac{\hbar}{M_s\delta}\right)\left(\frac{Ph}{e^*}\right) \qquad (2)$$

Here j is the current density across the wall. We have assumed for simplicity that one group of carriers, having a well-defined charge $e^* = \pm 1.6 \times 10^{-19}$ C and well-defined spin polarization P = ±1, has a much higher mobility than others. This is reasonable in Ni-Fe, Ni-Co, and other alloys at low temperature. Also, h = ±1 is the wall "helicity" indicating whether $\vec{M}_s$ turns clockwise or anticlockwise as the wall is crossed. For $j = 10^9$ A/m^2, attainable in pure cobalt, Eq.(2) gives $|H_x^{ex}| \simeq 35$ A/m.

This exchange field tends to tip the wall $\vec{M}_s$

Ya. B. Bazaliy, B. A. Jones, S.-C. Zhang, PRB, **57**, R3213 (1998)

In case of continuous magnetization rotation in space, and nearly 100% spin polarizatoin, the LLG equation with current gets a form:

$$\dot{\vec{n}} = [H_{eff} \times \vec{n}] - A\left[\frac{\partial^2 \vec{n}}{\partial x^2} \times \vec{n}\right] - j\frac{\partial \vec{n}}{\partial x} + \alpha[\vec{n} \times \dot{\vec{n}}]$$

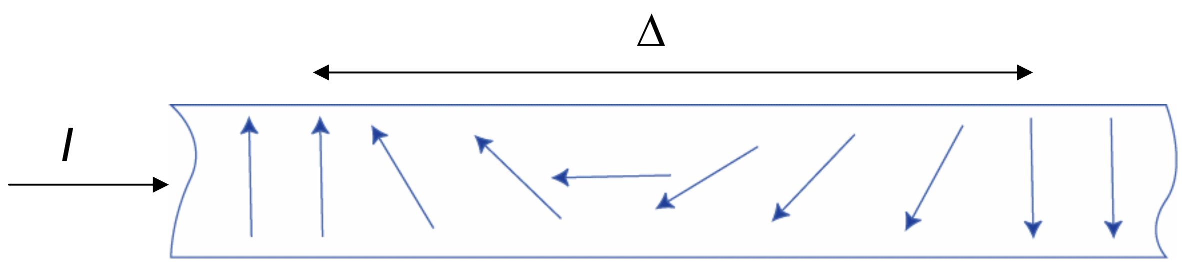
And is equivalent to conservation of angular momentum:

$$\begin{cases} \dot{\vec{n}} + \dfrac{\partial \vec{\Lambda}}{\partial x} = [\vec{H}_{eff} \times \vec{n}] + \alpha[\vec{n} \times \dot{\vec{n}}] \\ \vec{\Lambda} = A\left[\dfrac{\partial \vec{n}}{\partial x} \times \vec{n}\right] + j\vec{n} \end{cases}$$

angular momentum flux)

“Non-adiabatic” correction for P < 100%

S. Zhang, Z. Li, PRL, **93**, 127204 (2004)
A. Thiaville, Y. Nakatani, J. Miltat, Y. Suzuki, Europhys. Lett. **69**, 990 (2005)
However, this recent paper gives a different result:
J. Xiao, A. Zangwill, M.D. Stiles, cond-mat/0601172 (2006)



$$\beta \sim \lambda / \Delta$$

Modified LLG:

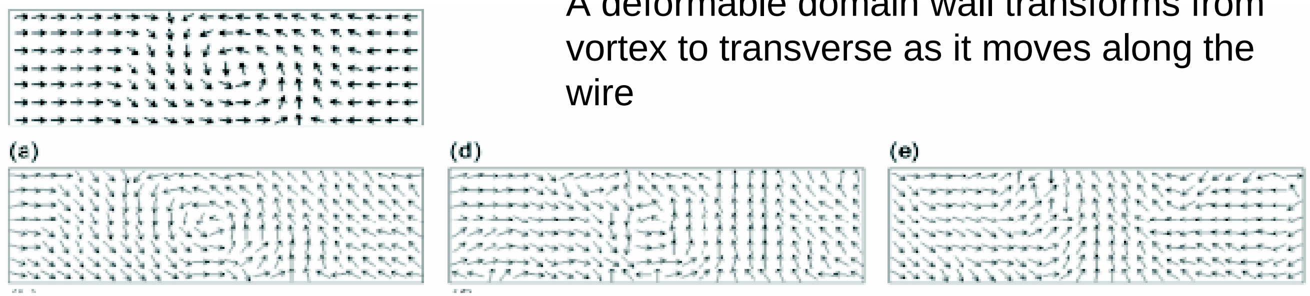
$$\dot{n} = [H_{eff} \times n] + \tilde{j}\frac{\partial n}{\partial x} + \beta \tilde{j}[n \times \frac{\partial n}{\partial x}] + \alpha[n \times \dot{n}]$$

Connection with discrete case:

$$\frac{\partial n}{\partial x} = [n \times [\frac{\partial n}{\partial x} \times n]] \Leftrightarrow [n \times [(s-n) \times n]] \Leftrightarrow [n \times [s \times n]]$$

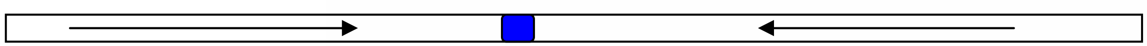
Rigid domain wall approximation:

M. Klaui et al., PRL, **95**, 026601 (2005)
A deformable domain wall transforms from vortex to transverse as it moves along the wire



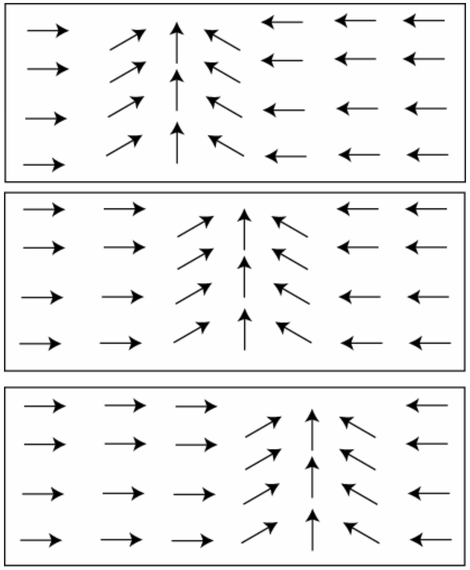
General description:
continuous field

$$\mathbf{M}(r,t)$$



$q(t)$

Motion of a deformable vortex wall



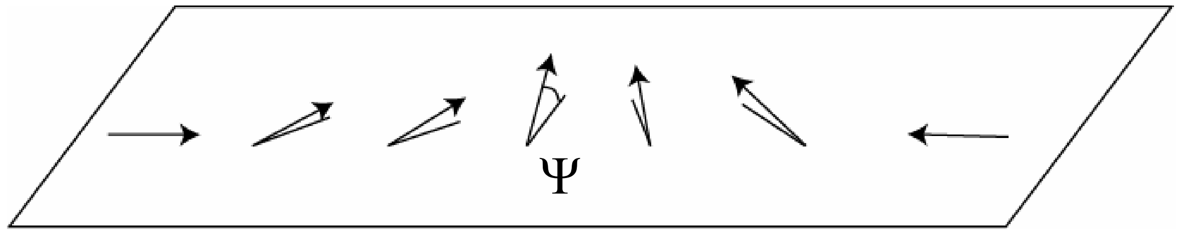
Rigid walls - move with minimal changes of their internal structure. <u>Only two</u> parameters are required:

$q(t)$ - position in the wire

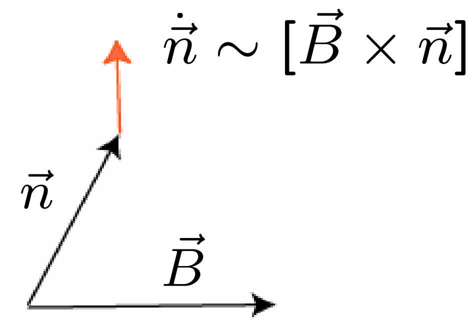
$\Psi(t)$ - out-of-plane angle

Walls loose rigidity when driving forces are too strong

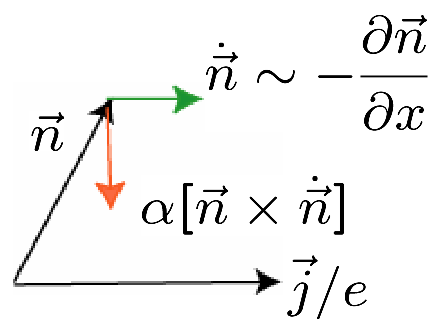
Why deflection Ψ ?



Moving the wall with magnetic field:

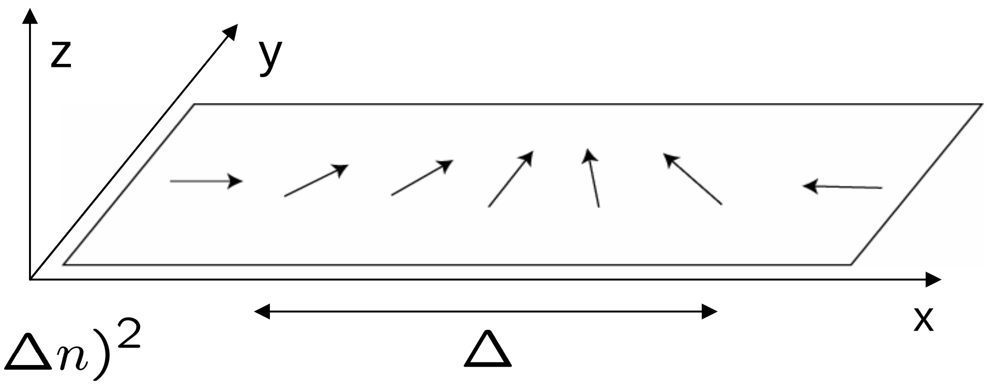


Moving the wall with current:



In both cases **n** cannot remain in-plane.
In the planar geometry Ψ has a meaning of the out-of-plane angle.

Equations of the DW motion:



DW is described by the energy:

$$E = -\frac{1}{2}K_{||}n_x^2 + \frac{1}{2}K_{\perp}n_z^2 + A(\Delta n)^2$$

$$N \equiv \frac{M_s A \Delta}{\mu_B}$$

number of spins inside the DW

$$\begin{cases} \dot{q} - \alpha\Delta \cdot \dot{\Psi} = \Delta\left(\frac{\gamma}{M_s}\frac{K_{\perp}}{2}\sin 2\Psi\right) + \frac{\Delta}{N}\frac{I}{e} \\ \dot{\Psi} + \alpha\frac{\dot{q}}{\Delta} = -\frac{1}{N}\left(\frac{\gamma\Delta}{2}\frac{\partial V_{ext}}{\partial q}\right) + \beta\frac{I}{Ne} \end{cases}$$

"nonadiabaticity parameter" $\beta \sim \frac{\langle \text{electron wavelength} \rangle}{\Delta} \ll 1$

No electric current:

-Slonczewski, Malozemoff *"Magnetic domain walls in bubble materials"* (1979).

With current:

- G. Tatara and H. Kohno, PRL **92**, 086601 (2004).
- S. Zhang and Z. Li, PRL **93**, 127204 (2004) .
- A. Thiaville, Y. Nakatani, J. Miltat, Y. Suzuki, Europhys. Lett. **69**, 990 (2005)

Dimensionless form of DW equations:

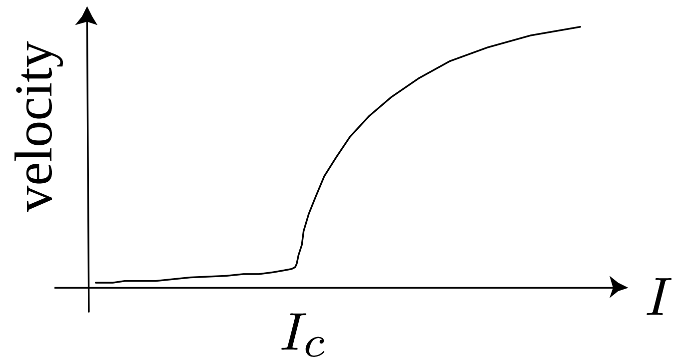
$$\frac{1}{\omega_K}\frac{\partial(x/\Delta)}{\partial t} = \alpha\left(f+\beta\frac{I}{I_c}\right)+\left(\sin 2\Psi+\frac{I}{I_c}\right)$$

$$\frac{1}{\omega_K}\frac{\partial\Psi}{\partial t} = \left(f+\beta\frac{I}{I_c}\right)-\alpha\left(\sin 2\Psi+\frac{I}{I_c}\right)$$

Potential: $V(x) = V_{pin}(x) - BMx \Longrightarrow f(x) = \frac{\Delta}{\hbar N\omega_K}\left(-\frac{\partial V}{\partial x}\right)$

Spin-torque: $I_c \sim eN\omega_K \sim 10^8\,\mathrm{A/cm^2}$ $\quad \beta \ll 1$

- Δ - DW width
- $N \sim 10^6 \div 10^8$ - number of spins in DW
- ω_K - FMR frequency of the wire
- $\alpha \sim 0.01$ - Gilbert damping constant



G. Tatara and H. Kohno, PRL **92**, 086601 (2004).

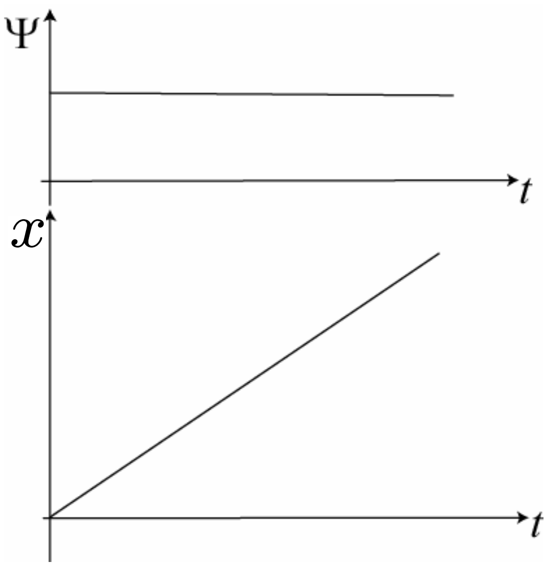
Static and dynamic regimes differ in the behavior of $\Psi(t)$:

$$\begin{cases} \frac{1}{\omega_K}\frac{\partial(x/\Delta)}{\partial t} = \alpha\left(f + \beta\frac{I}{I_c}\right) + \left(\sin 2\Psi + \frac{I}{I_c}\right) \\ \frac{1}{\omega_K}\frac{\partial \Psi}{\partial \tau} = \left(f + \beta\frac{I}{I_c}\right) - \alpha\left(\sin 2\Psi + \frac{I}{I_c}\right) \end{cases}$$

Static ("low drive"):

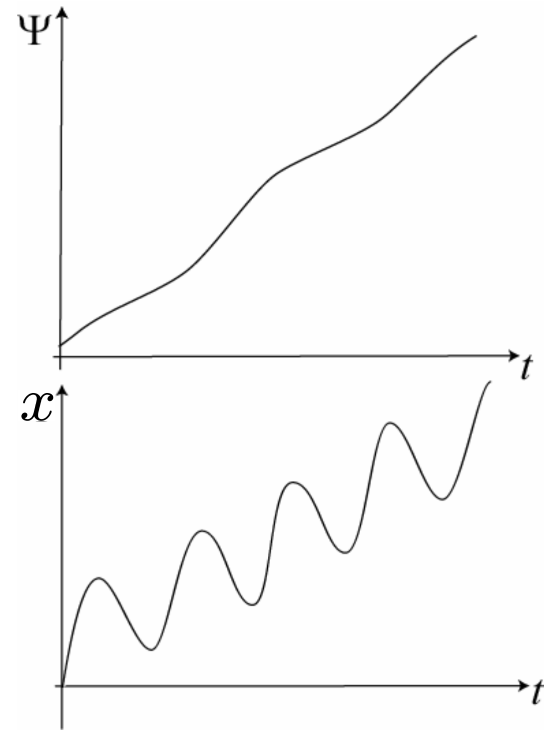
$\Psi = \Psi_0 = \text{const}$

DW moves along the force



Oscillatory ("high drive"):

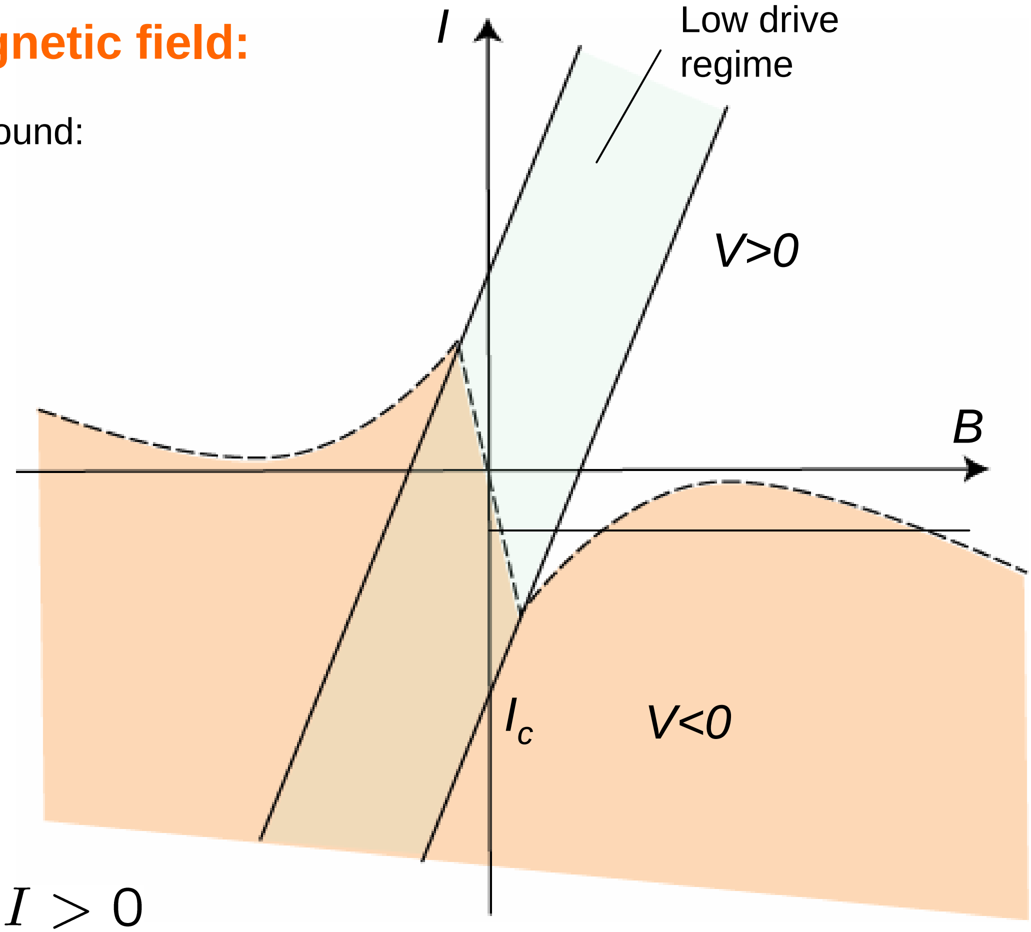
Ψ grows, making full 2π rotations,

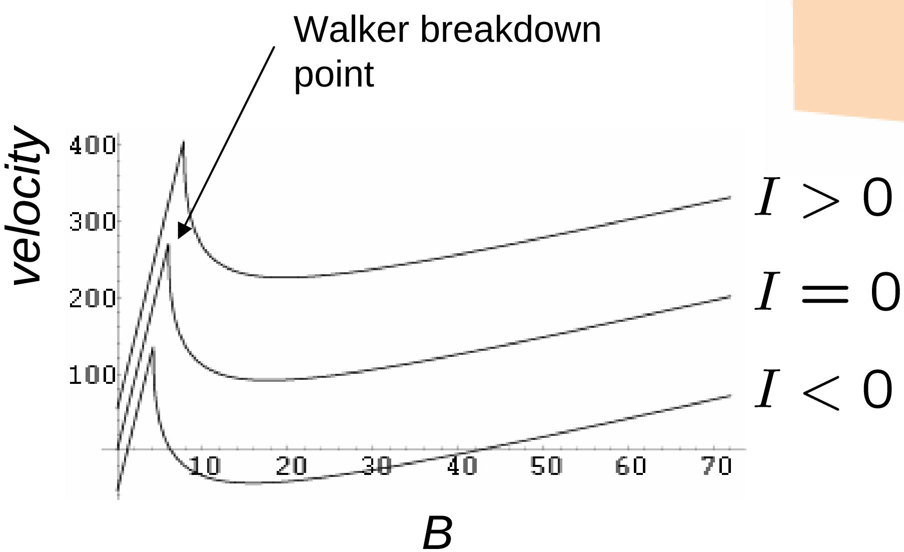


Velocity diagram, constant magnetic field:

Exact formula for average velocity can be found:

$$\begin{cases} v_{high} = \dfrac{b + \beta I/I_c}{\alpha} - \dfrac{\sqrt{\tilde{b}^2 - \alpha^2}}{\alpha} \\ \tilde{b} \equiv b + (\beta - \alpha)(I/I_c) \\ v_{low} = \dfrac{1}{\alpha}\left(b + \beta \dfrac{I}{I_c}\right) \end{cases}$$





At negative currents a window of reversed motion is observed already at $I \sim \alpha I_c << I_c$

PRL 96, 197207 (2006) PHYSICAL REVIEW LETTERS week ending 19 MAY 2006

Influence of Current on Field-Driven Domain Wall Motion in Permalloy Nanowires from Time Resolved Measurements of Anisotropic Magnetoresistance

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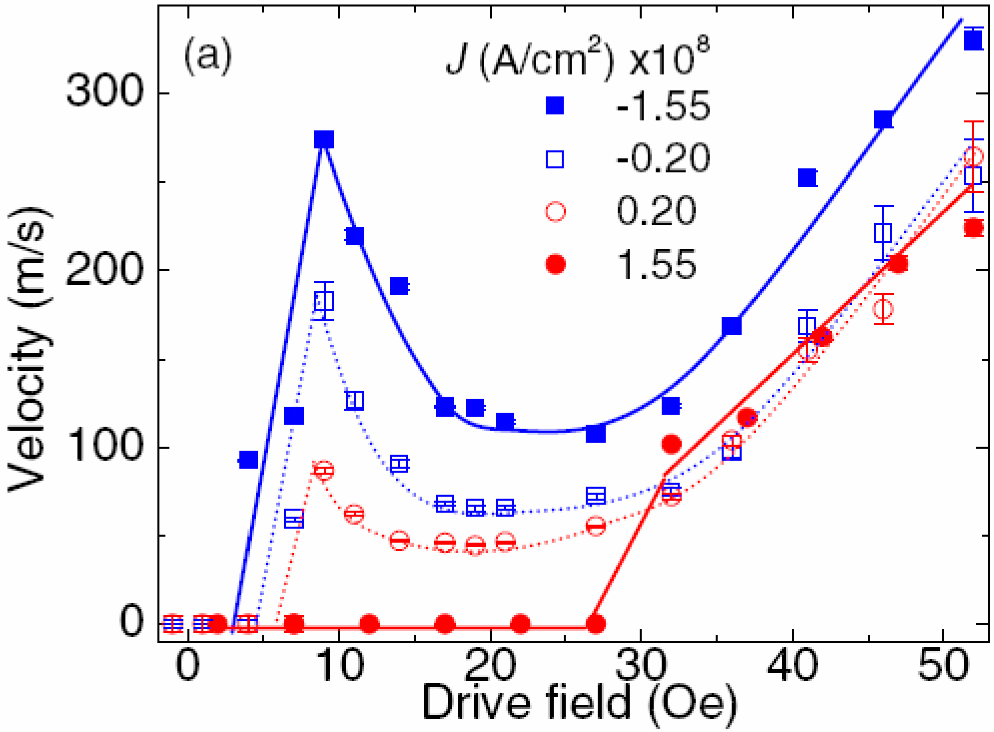
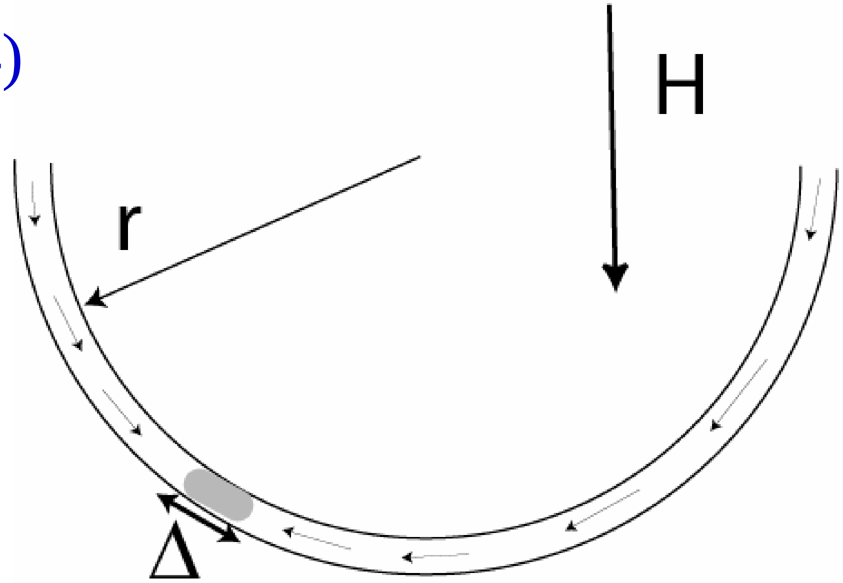
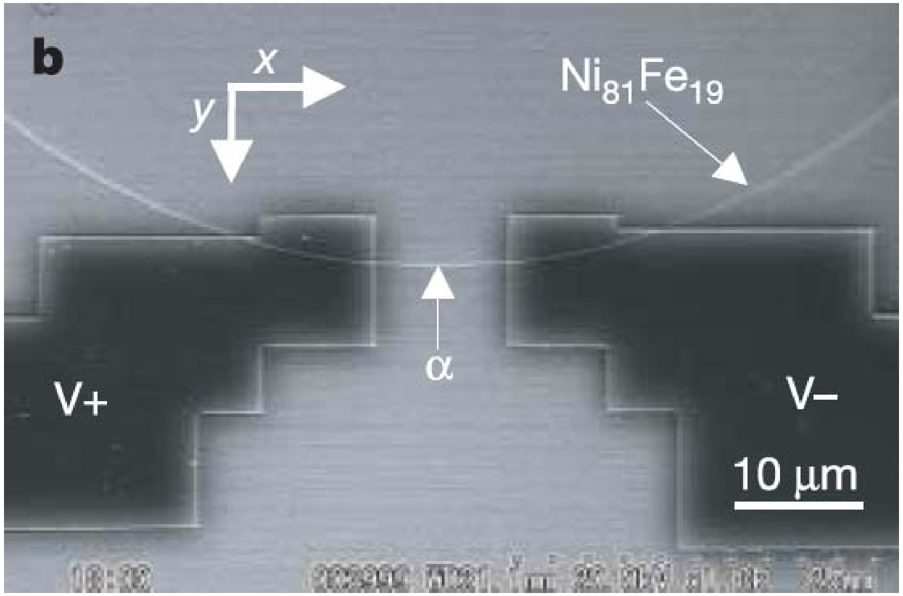
(Received 12 December 2005; published 18 May 2006)

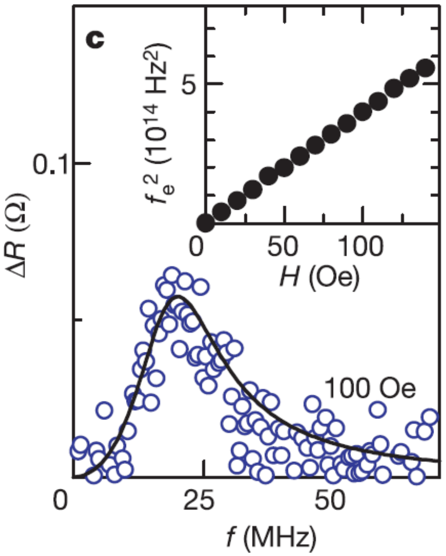
The motion of magnetic domain walls in permalloy nanowires is investigated by real-time resistance measurements. The domain wall velocity is measured as a function of the magnetic field in the presence of a current flowing through the nanowire. We show that the current can significantly increase or decrease the domain wall velocity, depending on its direction. These results are understood within a one-dimensional model of the domain wall dynamics which includes the spin transfer torque.



Saitoh *et al.*, Nature, **432**, 203 2004)



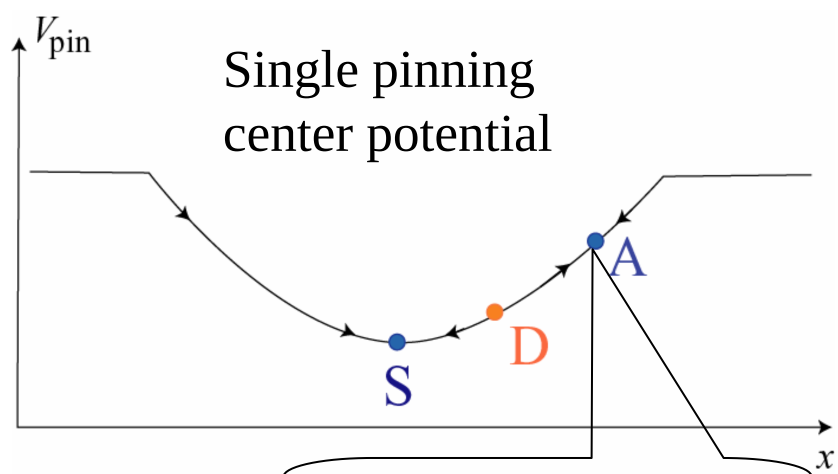




AC current induced oscillations of the domain wall inside the artificial pinning potential

Dynamic regime of a pinned DW in a wire with current:

"S" - static equilibrium at the bottom
"A" - stable dynamic equilibrium
(autogeneration regime)
"D" - dividing point

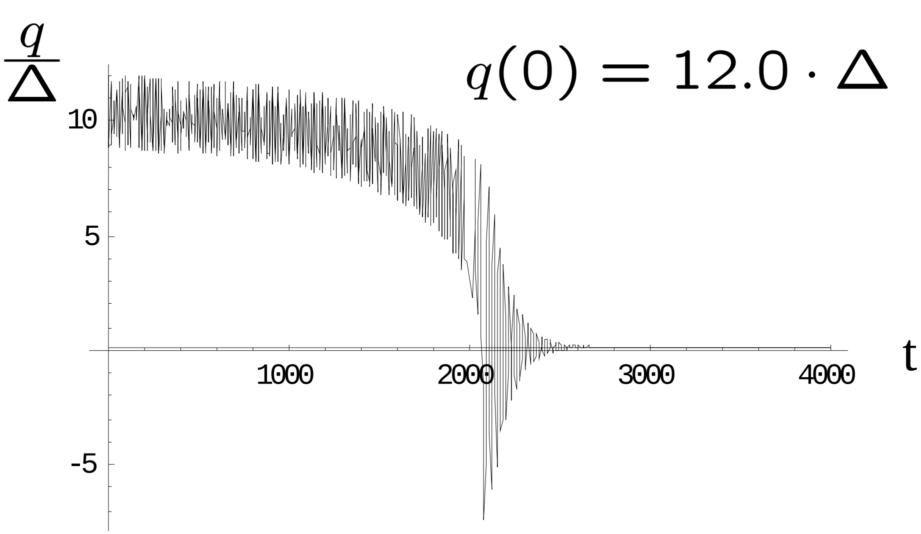


New state of the DW!

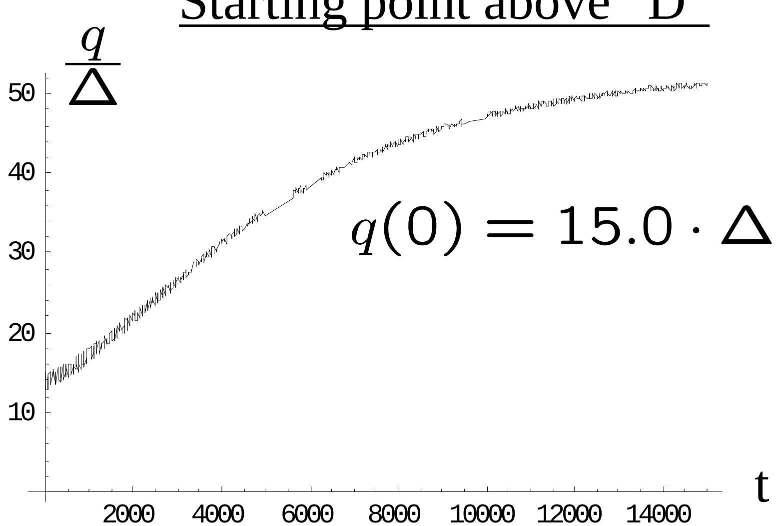
$$f = -r\frac{q}{\Delta},\ r \ll 1 \text{ (shallow potential)}$$

$$I = 0.05 I_c \text{ (spin-torque pushes the wall to the right)}$$

Starting point below "D"

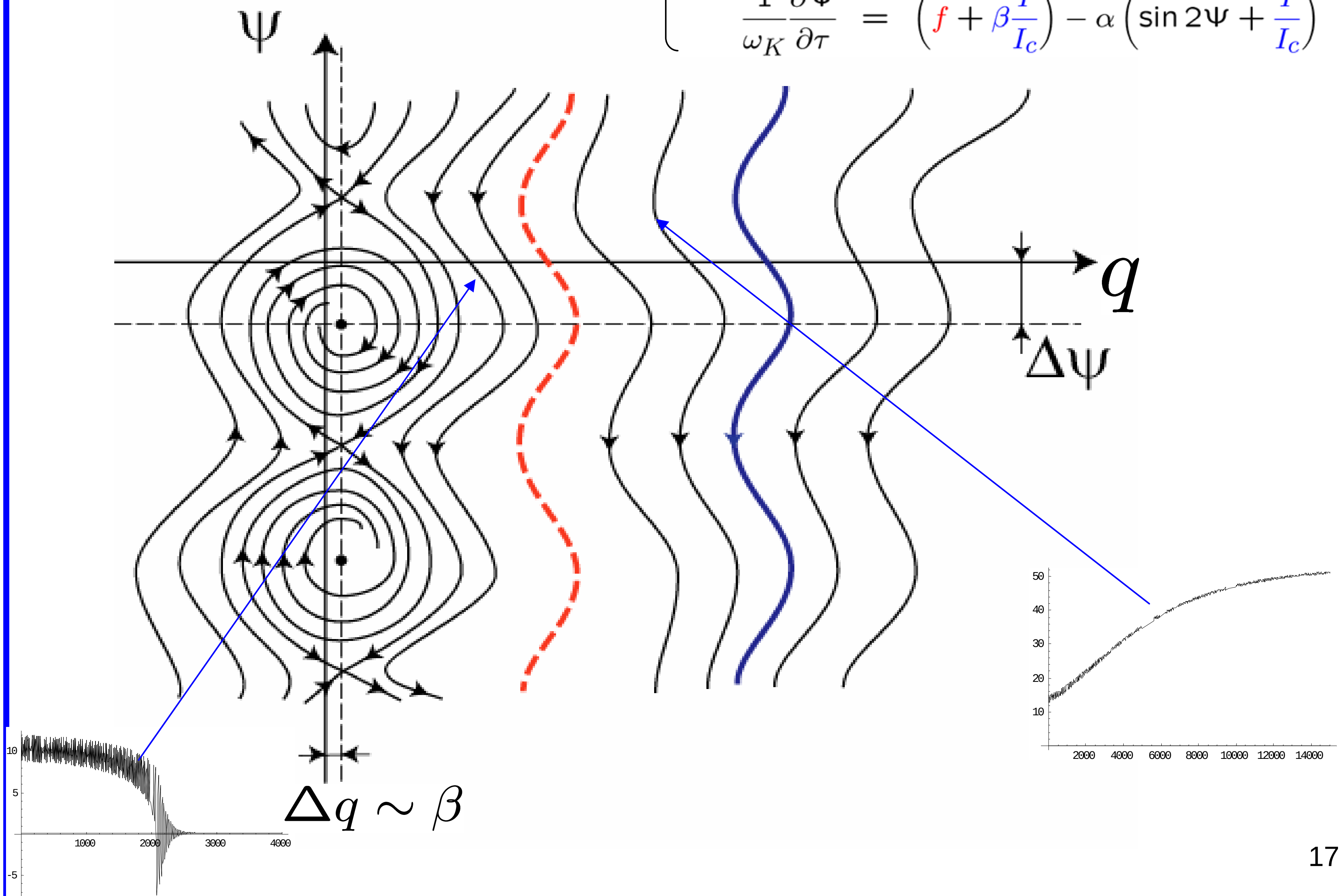


Starting point above "D"

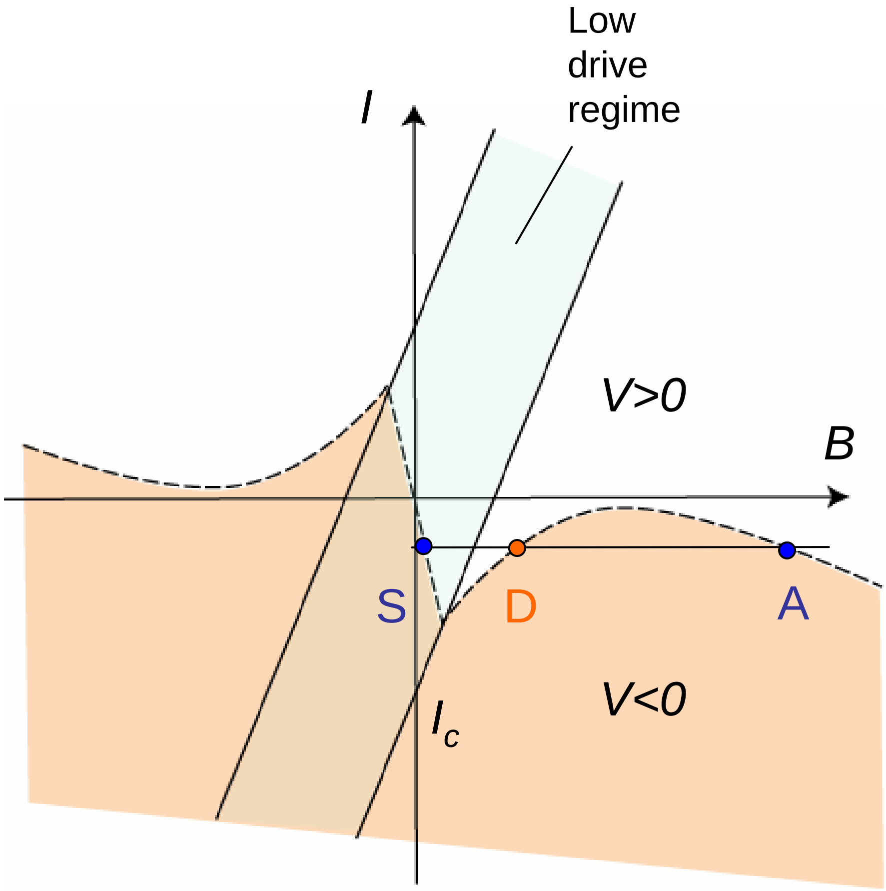


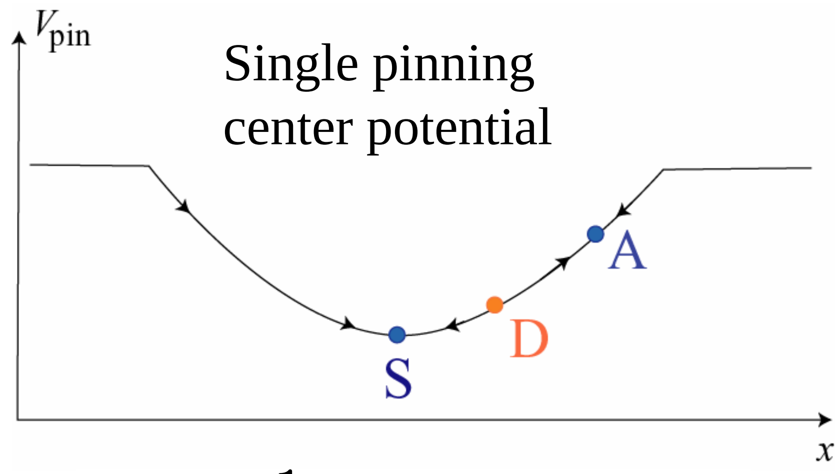
Phase portrait of the motion:

$$\begin{cases} \frac{1}{\omega_K}\frac{\partial(x/\Delta)}{\partial t} = \alpha\left(f + \beta\frac{I}{I_c}\right) + \left(\sin 2\Psi + \frac{I}{I_c}\right) \\ \frac{1}{\omega_K}\frac{\partial \Psi}{\partial \tau} = \left(f + \beta\frac{I}{I_c}\right) - \alpha\left(\sin 2\Psi + \frac{I}{I_c}\right) \end{cases}$$



Correspondence between the motions inside a pinning center potential and in constant external magnetic field



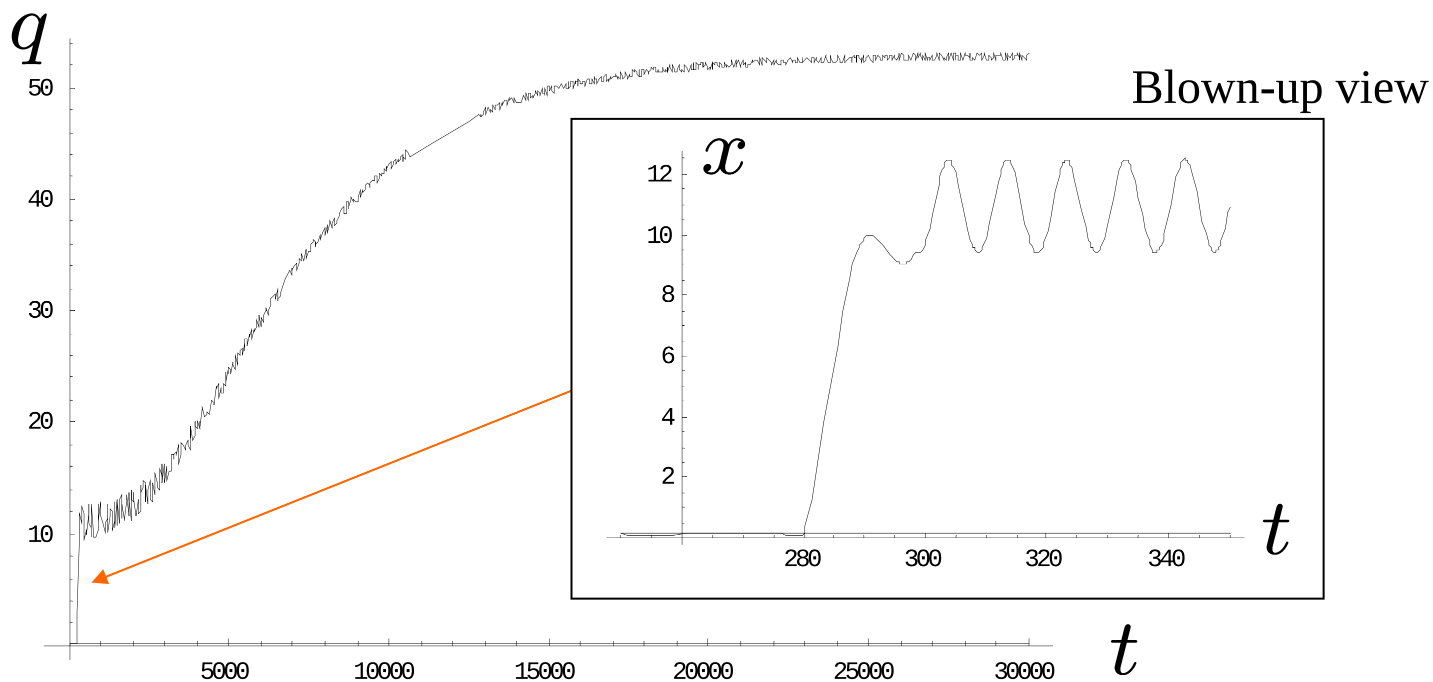


$$V_{pin} = \frac{1}{2} r q^2$$

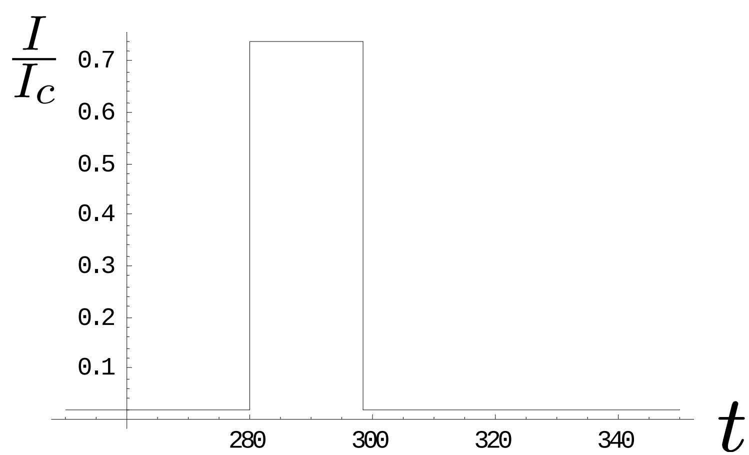
$$B_{eff}(q) = -\frac{\partial V_{pin}}{\partial q} = -rq$$

Effective magnetic field associated with the pinning potential

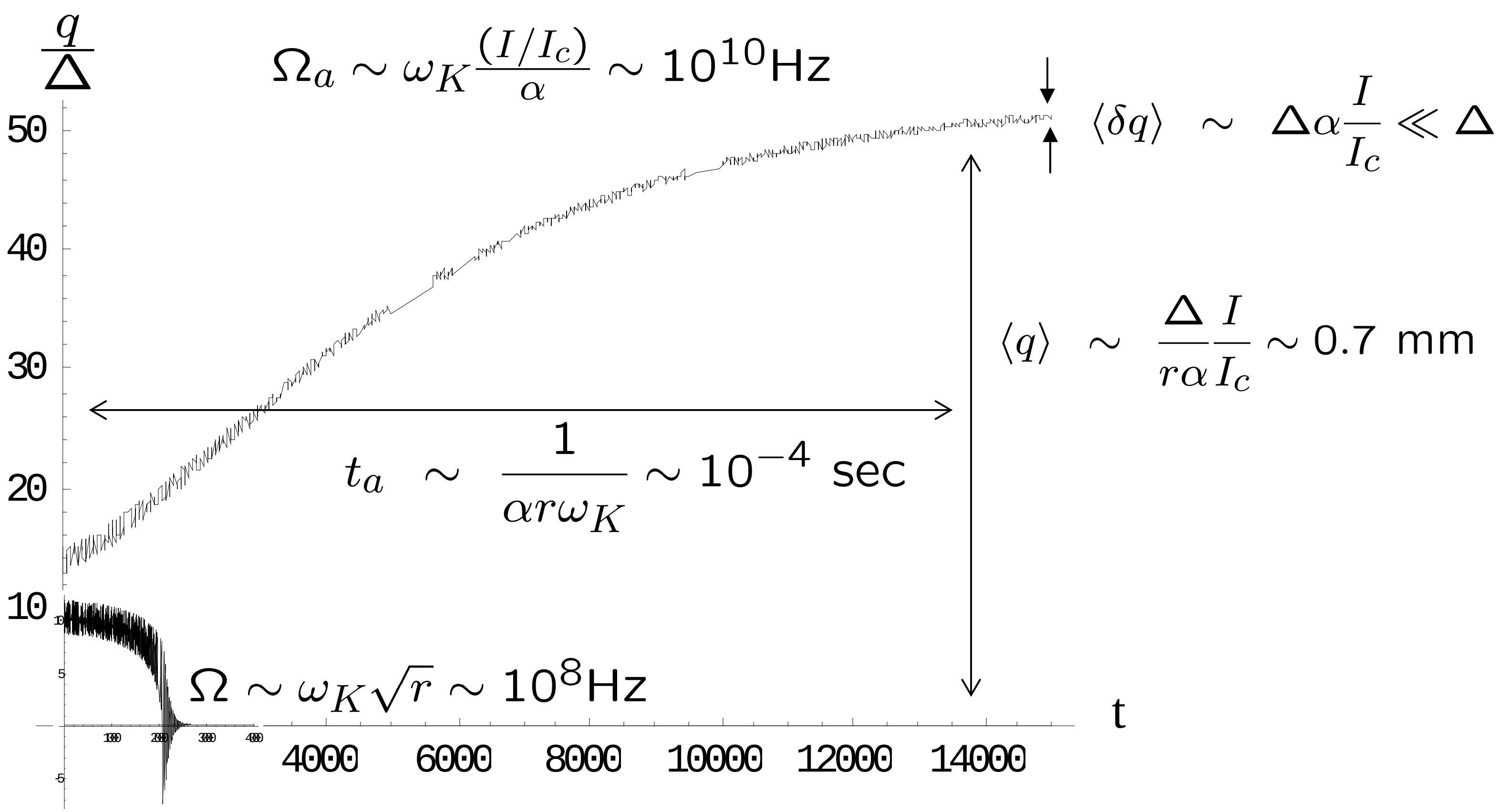
Reaching the autogeneration regime by a strong short pulse



$$\tau_{\text{pulse}} \sim \frac{2\pi}{\sqrt{2\omega_{pin}\omega_K}} \sim 10^{-6}\ \text{sec}$$

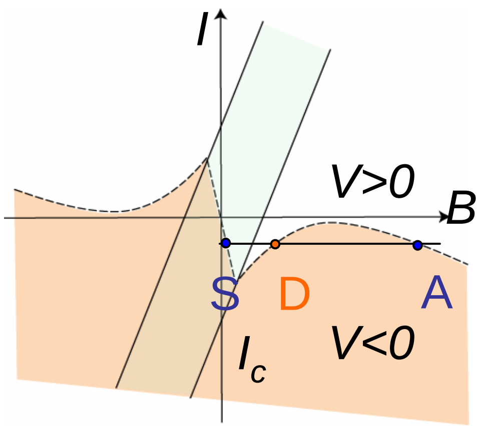


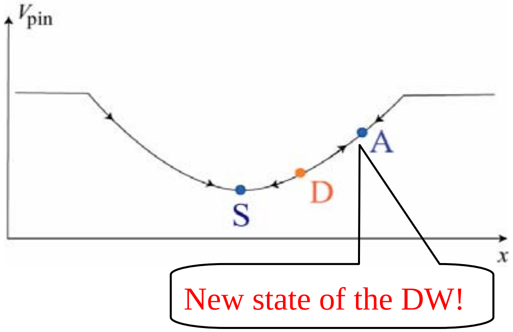
Estimates for the autogeneration regime and approach to it



Autogneration regime is <u>essentially nonlinear</u>, e.g. the oscillations frequency and effective damping are completely renormalized from their values for small oscillations.

Summary up to this point:





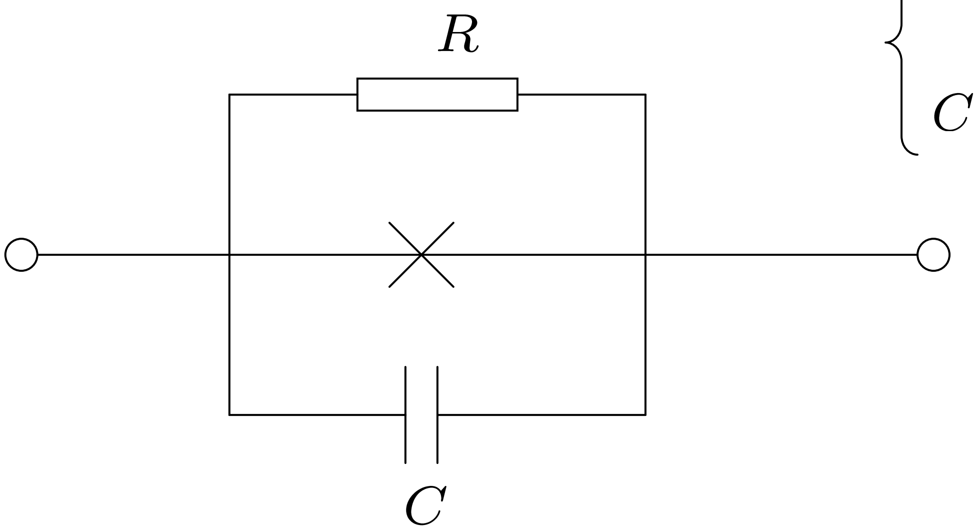
- Interesting phenomena happen at I << I_c when both current and field are applied.

- Velocity reversal in magnetic field

- Dynamic state in the shallow pinning center

Dynamic DW equilibrium with periodic currents: an analogue of Josephson effect.

Equivalent circuit for a Josephson junction



$$\begin{cases} \dot{\phi} = \frac{2e}{\hbar} V \\ C\dot{V} = -\frac{V}{R} + I - I_c \sin\phi \end{cases}$$

Josephson effect (x = Voltage)

$$\begin{cases} \dot{\phi} = \frac{2e}{\hbar} V \\ C\dot{V} = -\frac{V}{R} + I - I_c \sin\phi \end{cases}$$

$$\begin{cases} \phi' = rx \\ x' = -x - (\sin\phi - i) \end{cases}$$

Domain wall (x = displacement)

$$\begin{cases} x' = -\alpha(rx - \beta v) + (\sin 2\Psi + v) \\ \Psi' = -(rx - \beta v) - \alpha(\sin 2\Psi + v) \end{cases}$$

Analogy with Josephson effect was considered before for <u>very sharp pinning potential</u>, where DW displacement was assumed to be negligible.

<u>Luc Berger, PRB, **33**, 1572 (1986)</u>

Possible existence of a Josephson effect in ferromagnets

L. Berger
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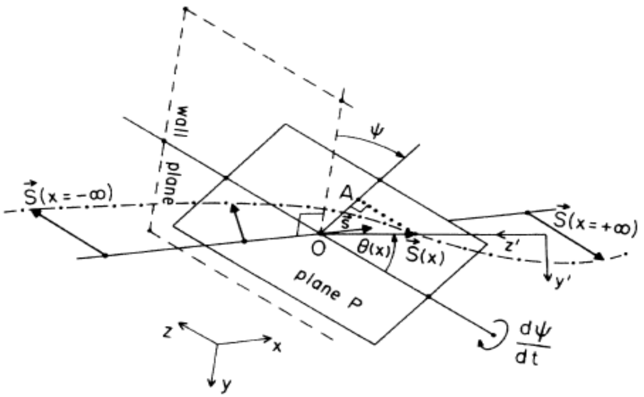
(Received 11 July 1985)

When a current density j_x crosses a 180° domain wall in a metallic ferromagnet, the spin **s** of each conduction electron exerts an s-d exchange torque on the localized wall spins. Hence, the wall moment of a Bloch wall is canted out of the wall plane by an angle ψ, given by $j_x=(eC/\hbar)\sin(2\psi)$, where C is the maximum restoring torque at $\psi=45°$. This equation is the exact analog of the dc Josephson effect, and 2ψ is the analog of the superconducting phase difference ϕ across a junction. For $|j_x| > eC/\hbar \simeq 10^6$ A/cm^2, the s-d exchange torque overcomes the restoring torque, and the wall moment precesses with a frequency $\omega = d(2\psi)/dt$. A dc voltage δV is expected to appear across the wall, satisfying the famous ac Josephson relation $2e\delta V = -\hbar\omega$. This wall precession can be described as a translation of Bloch lines, and the Bloch lines are the exact analog of superconducting vortices. The electric current exerts a transverse force on Bloch lines.

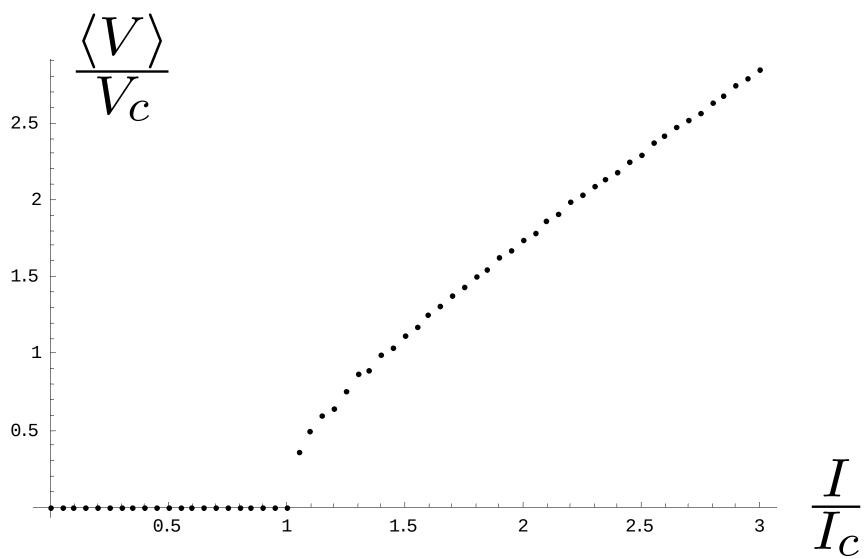


Shapiro steps in Josephson junctions

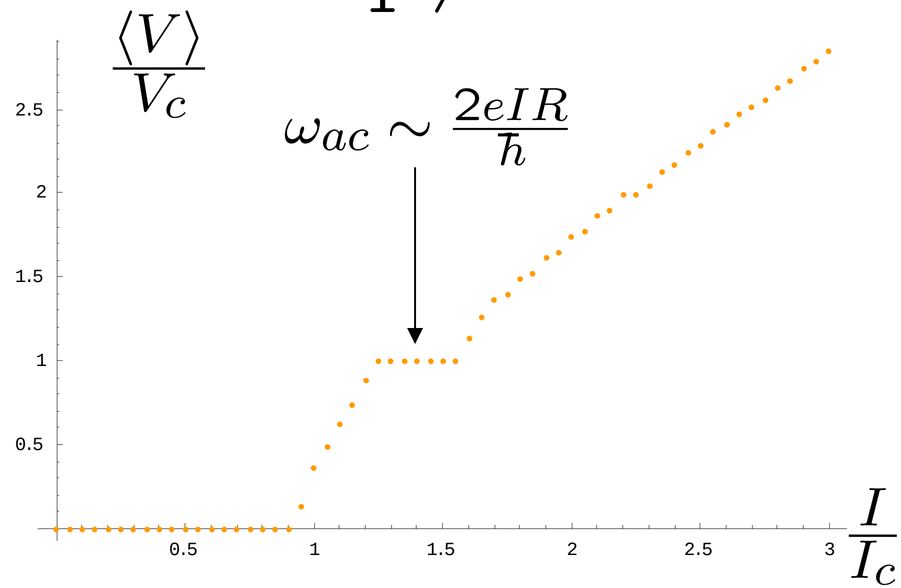
$$i = i_0 + i_1 \sin(\omega_{ac} t)$$

Apply AC current with fixed frequency and amplitude. Vary the DC bias and measure the average voltage on the junction.

$i_1 = 0$



$i_1 \neq 0$



Explanation of the steps:

$$x = \frac{1}{r}\phi' \Rightarrow \langle x \rangle = \frac{1}{T}\int_0^T \frac{\phi'(\tau)}{r} d\tau = \frac{2\pi}{rT(i_0)} = \frac{\omega_{ac}}{r} n$$

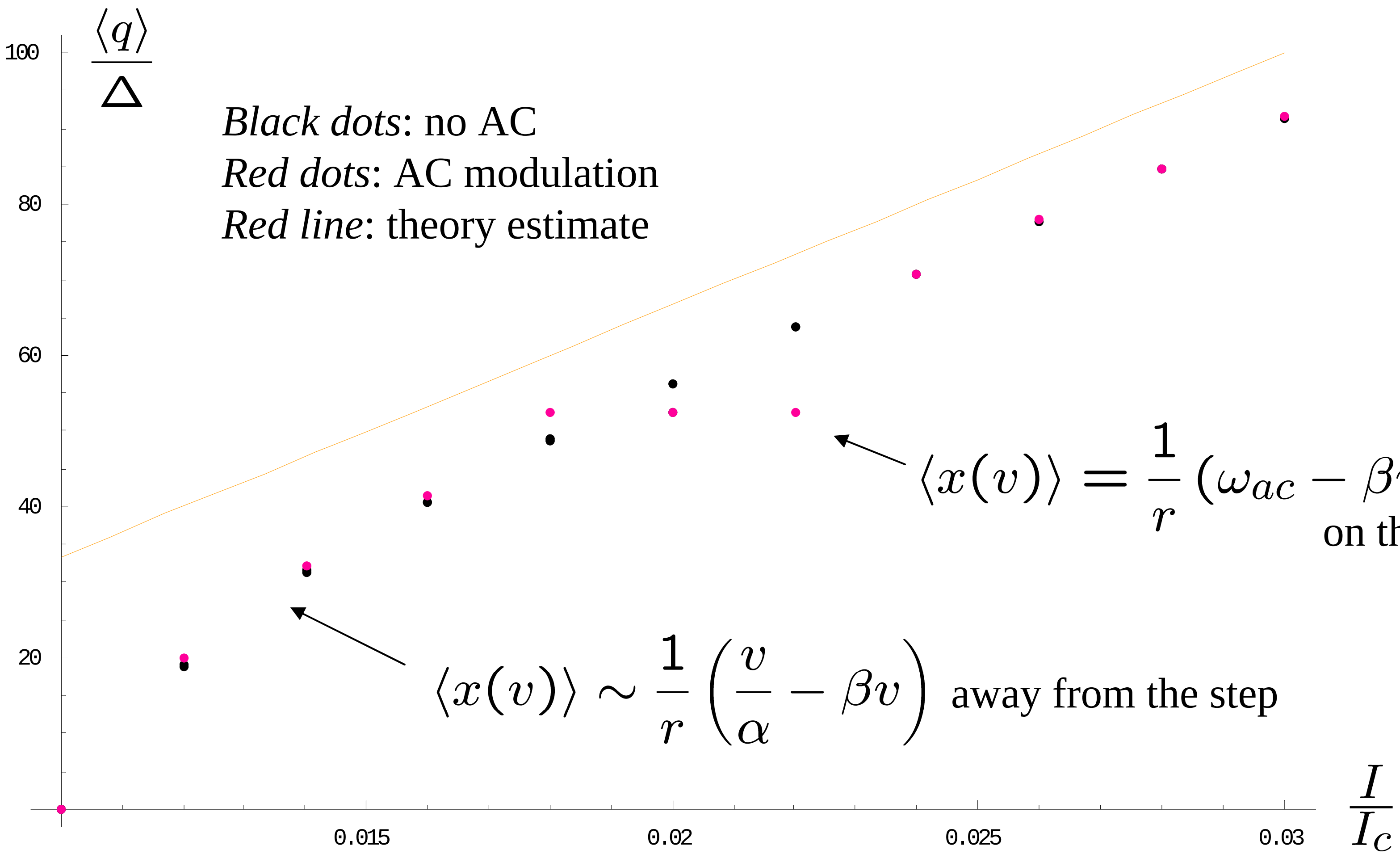
On the step, $T = 2\pi/\omega_{ac}$ independent of i_0

Steps in the DW average position

$$\langle x(v)\rangle = \frac{\langle \Psi' \rangle - \beta v}{r}$$

In the mode-locking situation $\langle \Psi' \rangle = \omega_{ac}$

Without mode-locking $\langle \Psi' \rangle \sim \frac{v}{\alpha}$



Luc Berger, J. Appl. Phys, **69**, 4683 (1991)

Prediction of Shapiro steps in the dc voltage across a magnetic domain wall traversed by a dc current and exposed to high-frequency magnetic fields

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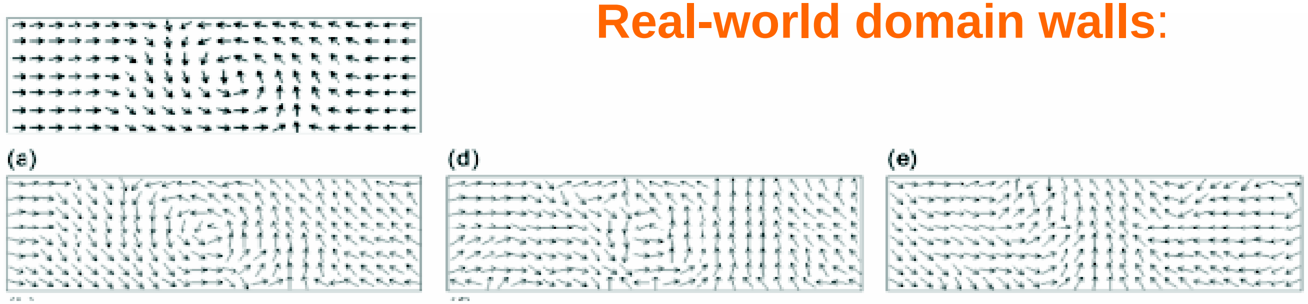
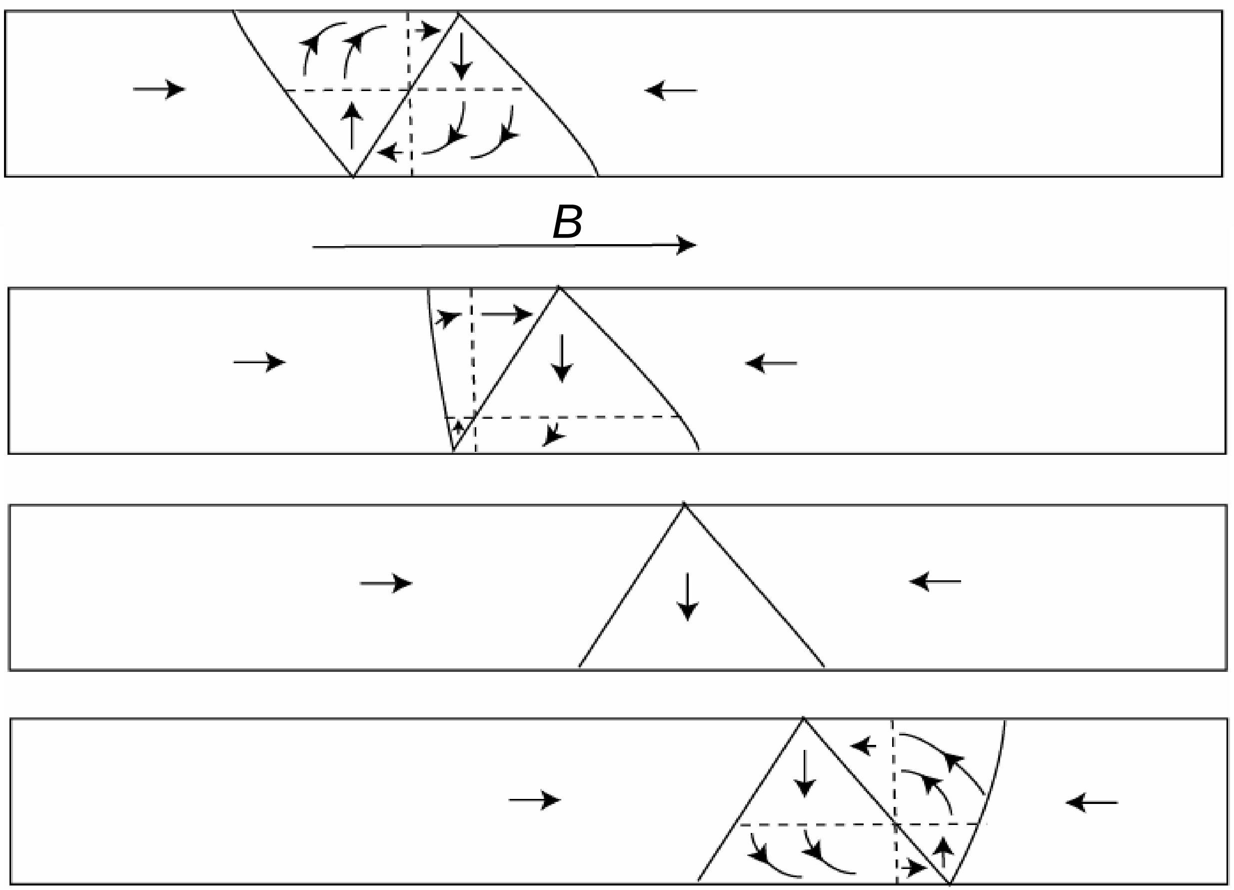
In metallic ferromagnets, a current of electrons traversing a domain wall exerts a torque on the wall spins through the *s-d* exchange interaction. This torque may induce a precession of the wall spins around the easy axis. In turn, the wall precession at a rate ω_0 generates a dc voltage δV across the wall, given by the formula $e\delta V = \hbar\omega_0$ similar to the Josephson equation for superconducting junctions. In the present theoretical work, a high-frequency (hf), in-plane, hard-axis magnetic field is also applied. For a certain range of values of the dc current density, the rate of wall precession is synchronous with that of the hf drive field. In other ranges, precession is asynchronous, or there is no precession. As a result, the voltage δV has a stepwise dependence on the current density. This is the analog of the well-known Shapiro steps for the superconducting Josephson voltage.

In a sharp pinning potential mode locking (= Shapiro steps) is suggested to be observable in a voltage measurement.

Real-world domain walls:





Vortex domain walls have more degrees of freedom. Their reduced description has involve more parameters.

Is the vortex motion equivalent to cyclic variable Ψ?

Conclusions:

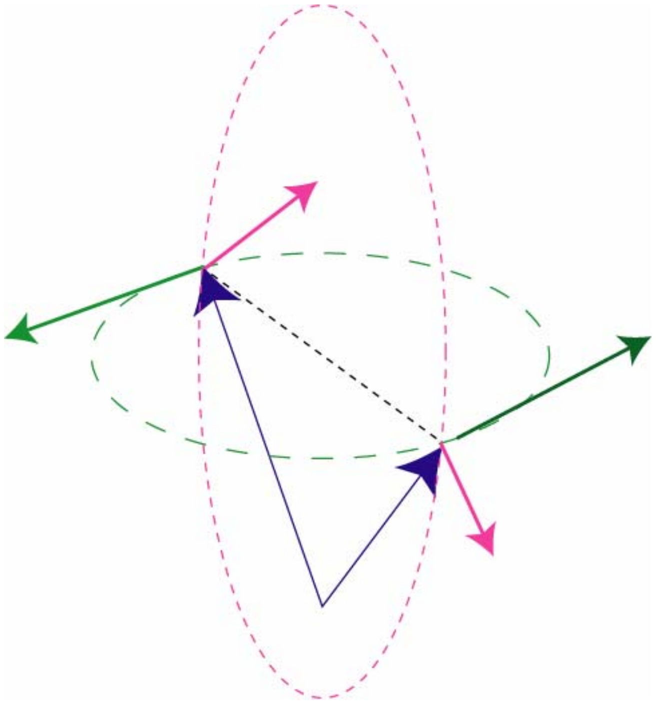
Observed: Small current ($I \ll I_c$) can be effective in the presence of magnetic field;

Coming soon (?): New dynamic state in the shallow pinning potential;

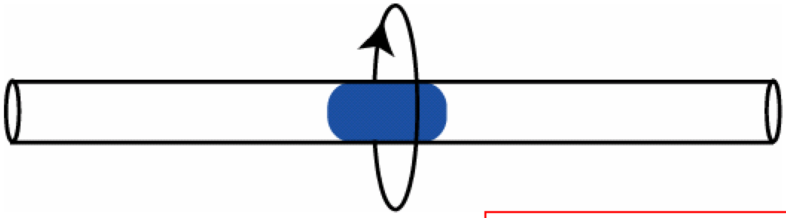
Future: Magnetic Josephson effect: Shaprio steps.

Spin-Transfer and RKKY exchange

1. Spin-transfer torque lies in the (s,n) plane. RKKY exchange creates a torque perpendicular to this plane.
2. RKKY is an equilibrium phenomena
3. RKKY decays on the mean free path length *l*. Spin-transfer persists up to the spin diffusion length, with $l_{sd} >> l$



Spin-transfer and circular magnetic field:



$$T_B \sim B\mathcal{M} \propto (jR)(MR^2L)$$

$$T_{ST} \propto jR^2$$

$$R < \frac{a^3}{r_0 L} \sim 100 \text{ nm},$$

$$a \sim 3\mathring{A}, \quad r_0 \sim 10^{-5}\mathring{A} \ .$$