The influence of external radiation on the Josephson junction + nanomagnet system

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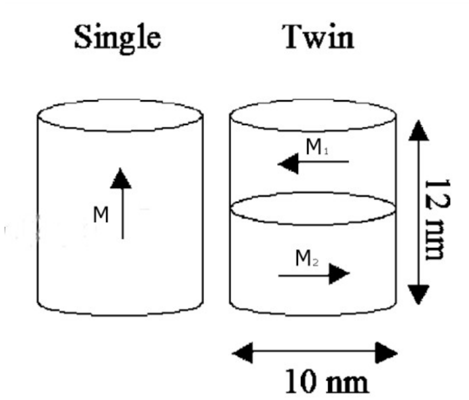
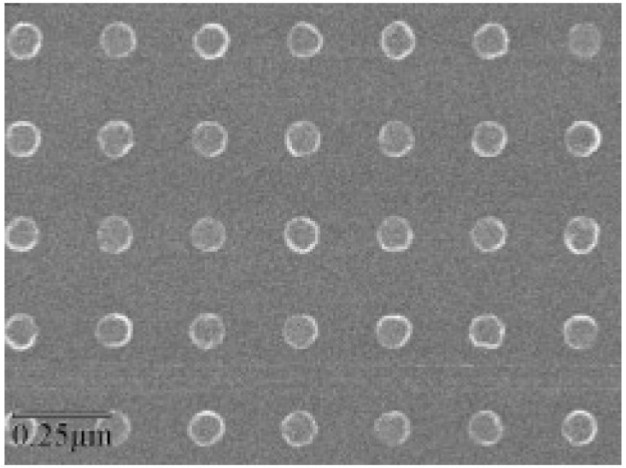
Nanomagnets



Single or twin domain nanoscale magnets. These so-called nanomagnets possess different magnetic properties from bulk material and may provide advanced replacements for hard disk media and computer memory chips.

A nanomagnet is analogous to a single giant atom of a new magnetic element; new artificial magnetic materials can be constructed from a lattice of these artificial atoms.



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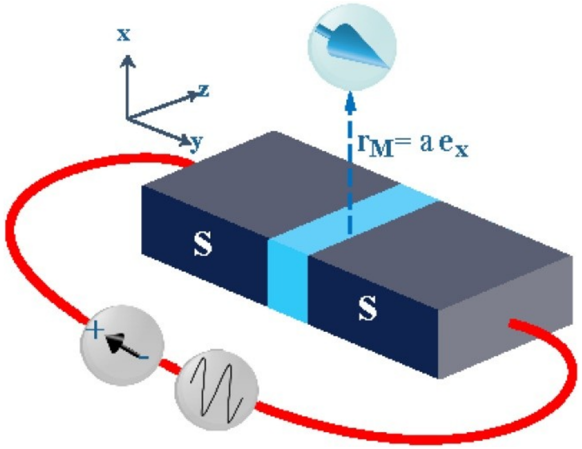
- L. Cai, D. A. Garanin, and E. M. Chudnovsky, ibid. 87, 024418 (2013).
- R. Ghosh, M. Maiti, Y. M. Shukrinov and K. Sengupta, Phys. Rev. B 96, 174517 (2017)

System of nanomagnet + Josephson junction



Effective magnetic field acting on the nanomagnet

$$\begin{aligned} h_x &= 0, \\ \boxed{h_y = m_y,} \\ h_z &= \boxed{\tilde{h}_z - \delta\epsilon k \dot{m}_z} \end{aligned}$$

$h_y = m_y$ → Easy axis

$\tilde{h}_z - \delta\epsilon k \dot{m}_z$ → AC Magnetic field generated by the Josephson junction

where

$$\tilde{h}_z = \epsilon[\sin(V\tau - km_z + \frac{A}{\Omega}\sin(\Omega\tau)) + (V + A\cos(\Omega\tau) - \beta_c A\Omega\sin(\Omega\tau))]$$

$k = (2\pi/\Phi_0)\mu_0 M_s l/a\sqrt{l^2 + a^2}$ → Coupling parameter

l → Length of the JJ

a → Disstance between nanomagnet and JJ

$\epsilon = Gk, \; G = \epsilon_J/K_{an}v$ → Josephson to magnetic energy ratio

o Yu. M. Shukrinov, M. Nashaat, I. R. Rahmonov, and K. V. Kulikov, JETP Letters, 110, 3, 160-165 (2019)

Landau-Lifshiz-Gilbert equation

The dynamics of the nanomagnet magnetization components can be described by Landau-Lifshiz-Gilbert (LLG) equation, in the dimensionless quantities it is given by

$$
\begin{aligned}
\frac{dm_x}{dt} &= \frac{\Omega_F}{1+\alpha^2}[\alpha h_x(m_y^2+m_z^2)+h_y(m_z-\alpha m_x m_y)-h_z(\alpha m_x m_z+m_y)] \\
\frac{dm_y}{dt} &= \frac{\Omega_F}{1+\alpha^2}[-h_x(m_z+\alpha m_x m_y)+\alpha h_y(m_x^2+m_z^2)+h_z(m_x-\alpha m_y m_z)] \\
\frac{dm_z}{dt} &= \frac{\Omega_F}{(1+\alpha^2)D}[h_x(m_y-\alpha m_x m_z)-h_y(m_x+\alpha m_y m_z)+\alpha \tilde{h}_z(m_x^2+m_y^2)]
\end{aligned}
$$

$$
D = 1+\frac{\Omega_F \ \alpha\epsilon k}{1+\alpha^2}(m_x^2+m_y^2)
$$

$\Omega_F = \omega_F/\omega_c$ $\longrightarrow$ Normalized frequency of the ferromagnetic resonance

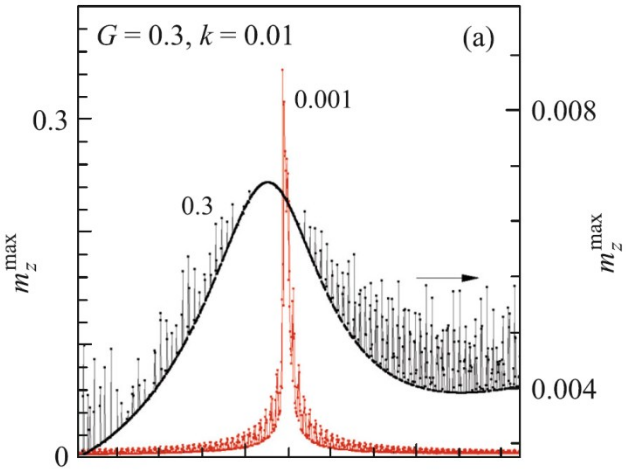
α $\longrightarrow$ Gilbert damping parameter

We solve this nonlinear stiff system of equations by the Gauss-Legendre integration scheme.

o Yu. M. Shukrinov, M. Nashaat, I. R. Rahmonov, and K. V. Kulikov, JETP Letters, 110, 3, 160-165 (2019)

Ferromagnetic resonance

Josephson oscillations in the junction excite the precession of the magnetic moment of the nanomagnet, which leads to the ferromagnetic resonance.



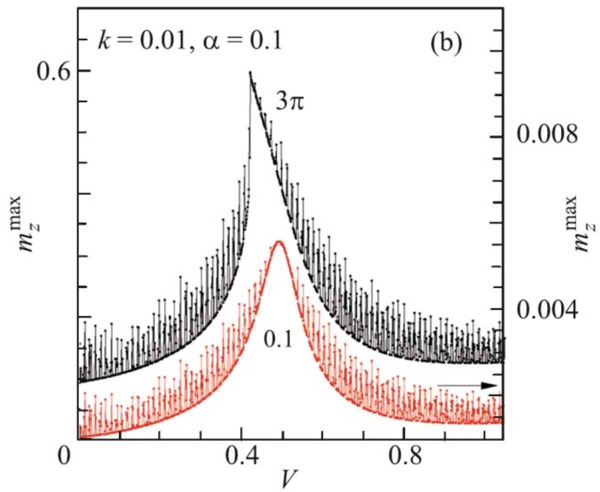
The positions of peaks can be obtained from the linearized Landau–Lifshitz–Gilbert equations.

$$\Omega_{\mathrm{Res}} = \sqrt{\frac{-a_2 + \sqrt{a_2^2 - 4a_1}}{2a_1}} \qquad a_1 = (\alpha^2 + \alpha k \Omega_{\mathrm{F}} \epsilon + 1)^2$$

$$a_2 = 2\alpha^2 + k^2 \Omega_{\mathrm{F}}^2 \epsilon^2 + 2\alpha k \Omega_{\mathrm{F}} \epsilon - 2$$

An enhancement of damping in the system leads to the broadening of the resonance and its shift toward lower frequencies.

As the Josephson-to-magnetic energy ratio increases, the resonance frequency decreases and the resonance peak becomes asymmetric.



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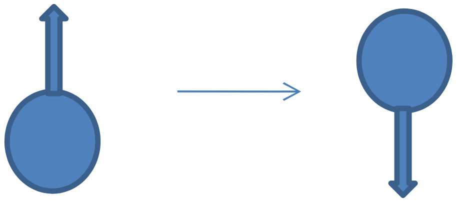
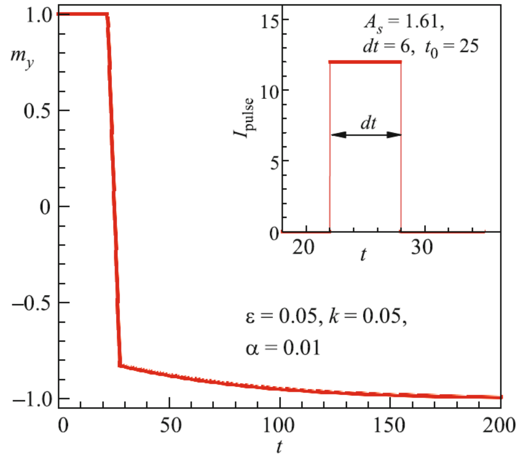
Methods of magnetization control

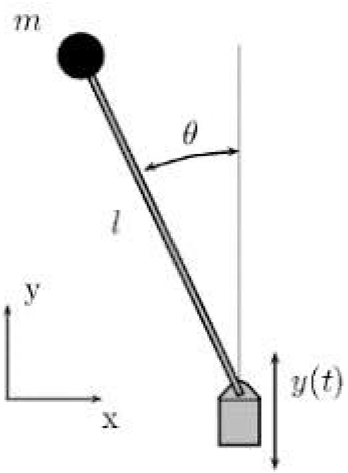
Magnetization reversal

Demonstration of the magnetization flip by the current pulse through the Josephson junction.





Kapitsa pendulum features

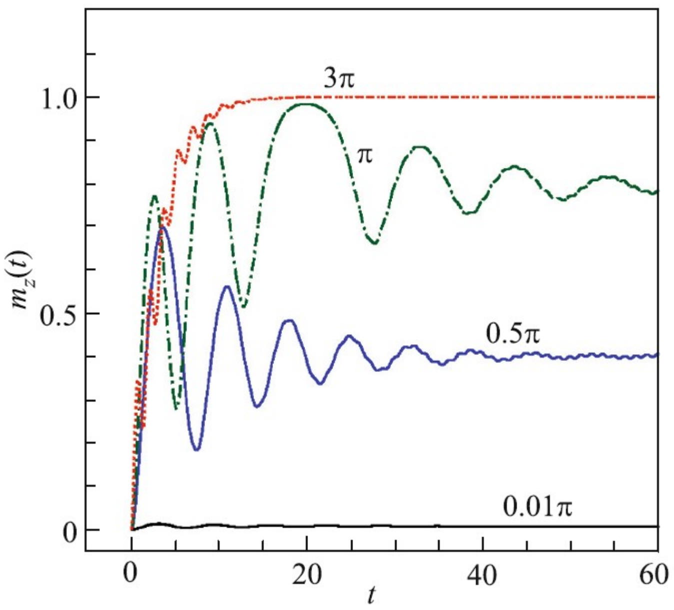


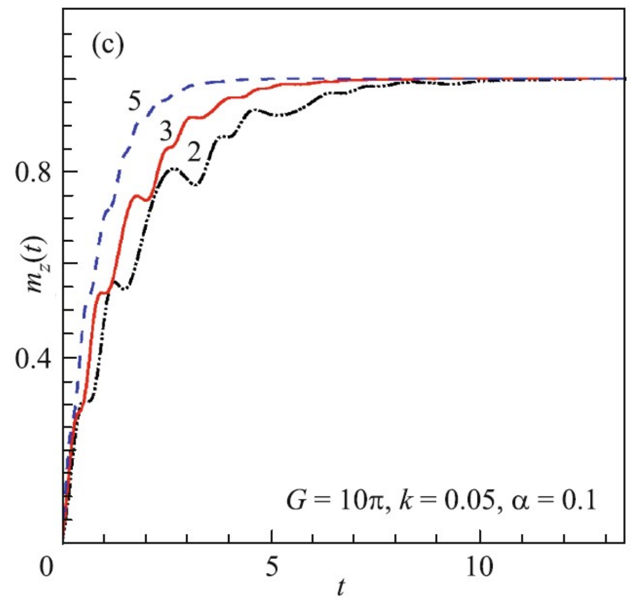
In a pendulum with a vibrating point of suspension, the external sinusoidal force can invert the stability position of the pendulum if the vibrations of the suspension point oscillate at a high frequency. In this case the unstable fixed point can become dynamically stable.

o Yu. M. Shukrinov, M. Nashaat, I. R. Rahmonov, and K. V. Kulikov, JETP Letters, 110, 3, 160-165 (2019)

Kapitsa pendulum

The Kapitsa pendulum could be introduced as a mechanical analogy for the nanomagnet + JJ system.





- The magnetic moment value depends on the Josephson-to-magnetic energy ratio and the Josephson frequency.
- The stabilization in dynamics for the magnetic moment components occurs at the "maximum" value of voltage which indicates to the complete reorientation of the magnetic moment.
- The time of reorientation decreases with increasing in the Josephson-to-magnetic energy ratio.

o Yu. M. Shukrinov, M. Nashaat, I. R. Rahmonov, and K. V. Kulikov, JETP Letters, 110, 3, 160-165 (2019)

Kapitsa pendulum

LLG equations in spherical form are given by:

$$\dot{\theta} = -\frac{\Omega_F}{(1+\alpha^2)} \frac{\sin\theta}{\left(1+\frac{\Omega_F \alpha\epsilon k}{1+\alpha^2}\sin^2\theta\right)} \left[\alpha\tilde{h}_z - \sin\phi(\cos\phi + \alpha\cos\theta\sin\phi)\right],$$

$$\dot{\phi} = \frac{\Omega_F}{\alpha^2+1} \frac{1}{1+\frac{\alpha\epsilon k\Omega_F\sin^2\theta}{\alpha^2+1}} \left[\tilde{h}_z - \left(-\sin^2\theta\cos\phi\epsilon k\Omega_F + \sin\phi\cos\theta - \alpha\cos\phi\right)\sin(\phi)\right]$$

- K. V. Kulikov, D. V. Anghel, A. T. Preda, M. Nashaat, M. Sameh, Yu. M. Shukrinov, arXiv:2107.01882

Here we separate θ and φ into fast and slow variables by introducing the notations

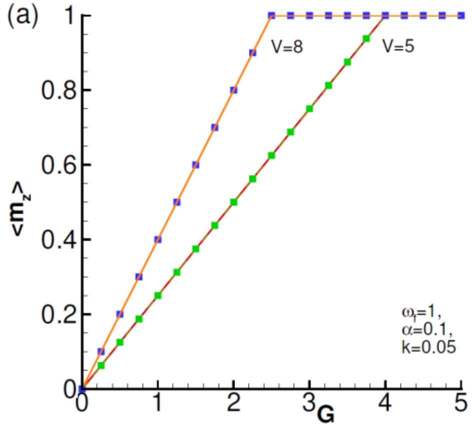
$$\theta \equiv \Theta + \xi \qquad \text{and} \qquad \phi \equiv \Phi + \zeta$$

Here, Θ and Φ describe the “slower” motion, relevant on longer time scales, whereas the variables ξ and ζ describe the “fast” oscillations of the system.

Stability position in the case without periodic drive (when $A = 0$) are given by:

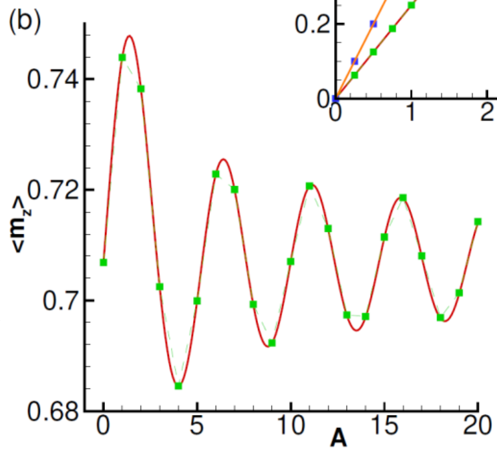
$$\Phi = \pi/2 \qquad \text{or} \qquad \Phi = 3\pi/2$$

$$\langle m_z\rangle = \cos\Theta = \epsilon\delta V + \frac{\alpha\epsilon^2 k\sin^4\Theta\Omega_F}{2V(1+\alpha^2+\delta\alpha\epsilon k\sin^2\Theta\,\Omega_F)^2}$$



Stability under external drive and the zeroth order resonances (when $V + m_0\Omega = 0$)

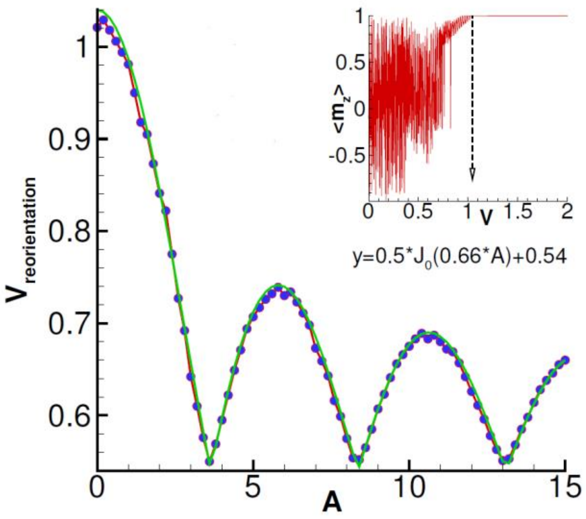
$$\cos\Theta = \epsilon\delta V - \epsilon\,\mathrm{sign}^{m_0}(m_0) J_{m_0}\left(\frac{A}{\Omega}\right)\sin(k\cos\Theta)$$

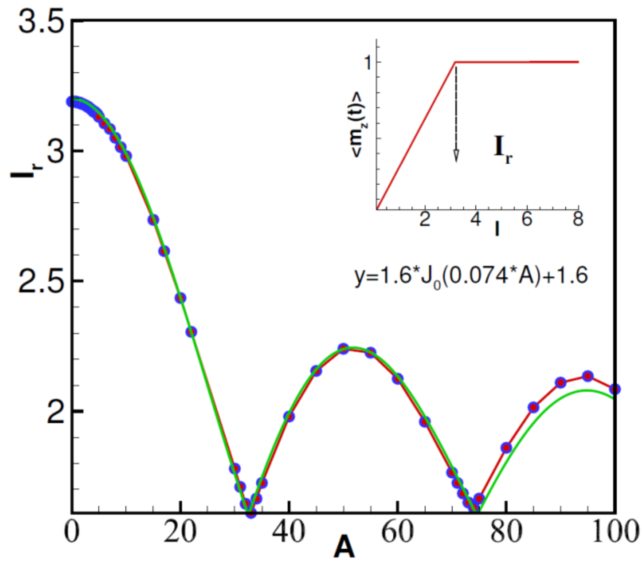


Influence of external radiation

- Previously, it has been shown that the presence of ac voltage leads to more steps in IVC whose positions are accurately predicted by the theoretical analysis.
- The position of the Shapiro steps are also shifted by the influence of the nanomagnet magnetization.

○ R. Ghosh, M. Maiti, Y. M. Shukrinov and K. Sengupta, Phys. Rev. B 96, 174517 (2017)





The reorientation voltage and current changes as the Bessel function with the amplitude of external radiation.

○ K. V. Kulikov, D. V. Anghel, A. T. Preda, M. Nashaat, M. Sameh, Yu. M. Shukrinov, arXiv:2107.01882

Summary

- It has been shown that a ferromagnetic resonance can occur when the frequency of Josephson oscillations becomes equal to the eigenfrequency of the magnetic system.

- It has been shown that a current pulse can flip the magnetic moment of the nanomagnet, which opens new prospects for the application of this system in superconducting spintronics.

- It has been demonstrated that the magnetic moment of the nanomagnet is reoriented at an increase in the Josephson-to-magnetic energy ratio, as well as in the coupling parameter and in the frequency of Josephson oscillations.

- It has been shown that the dependence of the average value of the magnetic moment component mz on the amplitude of external drive A is described by the Bessel function. **This result considerably expands the possibilities of controlling the dynamics of magnetization.**

- It has been shown that the reorientation voltage and current changes as the Bessel function with the amplitude of external radiation

Thank you for attention.