Parallel simulation of the magnetization reversal phenomenon in the φ0-Josephson junction

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- Superconducting spintronics based on the interaction of the superconducting current with the magnetic moment in Josephson superconductor-ferromagnet structures attracts attention nowadays, due to the possibility of controlling magnetism by superconductivity, which opens a perspective of different applications in quantum and nano-electronic technologies.
- Using the implicit two-stage Gauss-Legendre method for the numerical solution of a respective system of differential equations, one can obtain a detailed figure representing the intervals of the damping parameter, the relation of Josephson to magnetic energy and the spin-orbit coupling parameter where a full magnetization reversal occurs.
- The parallel implementation allows one to significantly accelerate simulations in a wide range of parameters of the model.
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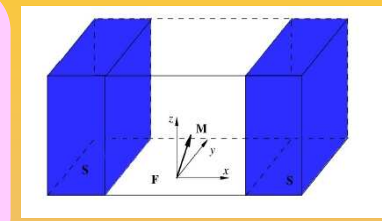


Theoretical model

The dynamics of the magnetization in the ferromagnetic layer in φ_0-Josephson junctions is described by the Landau-Lifshitz-Gilbert equation [1].

$$\frac{d\vec{m}}{dt} = -\frac{\omega_F}{1+M\alpha^2}\left([\vec{m}\times\vec{H}] + \alpha\vec{m}(\vec{m}\cdot\vec{H}) - \vec{H}\right), \quad (1)$$

where α is the damping parameter, ω_F is the normalized frequency of the ferromagnetic resonance. Here $\vec{H}$ is the effective magnetic field with the components

$$\begin{cases} H_x = 0 \\ H_y = Gr\sin\left(\varphi(t) - rm_y(t)\right) \\ H_z = m_z(t) \end{cases} \quad (2)$$

where G is the relation of Josephson energy to energy of magnetic anisotropy, r is the spin-orbit coupling parameter, $m_{y,z}$ is the y,z-component of the magnetic moment $\vec{m}$.

The Josephson phase difference φ can be found using the equation

$$\frac{d\varphi}{dt} = \frac{1}{\omega}\left(I_{pulse}(t) - \sin\left(\varphi - rm_y\right)\right), \quad (3)$$

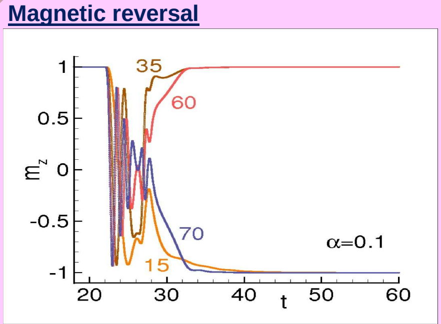
where the pulse current is given by

$$I_{pulse} = \begin{cases} A_S, & [t_0 - 1/2\Delta t, t_0 + 1/2\Delta t,] \\ 0 & \text{otherwise} \end{cases}. \quad (4)$$

Here A_s is the amplitude of the pulse current and Δt is the time interval, in which the pulse current is applied, t_0 is the time point of the maximal amplitude.

Thus, the system of the equations (1) with the effective field (2), (3) and the pulse current (4) describes the dynamics of the φ_0-junction.

Magnetic reversal

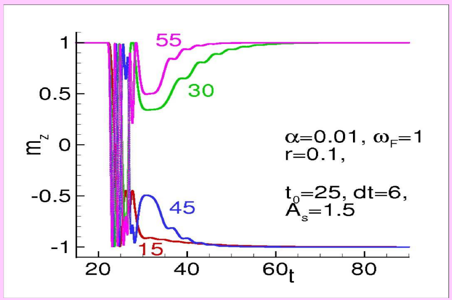


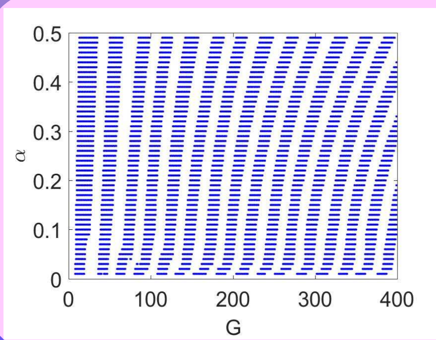
A magnetic reversal is an effect when the m_z–component of the magnetic field changes the sign and takes a value **-1** for a given initial value of **+1**.

The figures show the time dependence of the m_z–component:

Left panel: α=0.1, G=15, G=35, G=60, G=70. A magnetic reversal occurs for G=15 and 70.

Right panel: α=0.01, G=15, G=30, G=45, G=55. A magnetic reversal occurs for G=15 and 45.

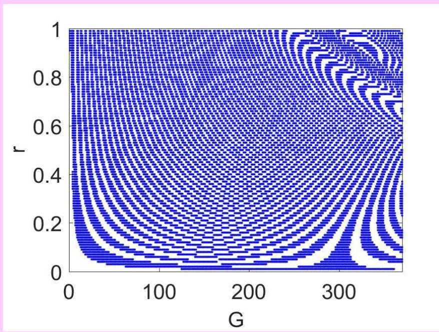




Left panel: Intervals of the complete magnetization reversal at the (α,G)-plane. The results are obtained with the G-stepsize ΔG=1, the α-stepsize $\Delta\alpha$=0.01 at A_s = 1.5; r = 0.1; t_0 =25; Δt = 6; ω_F = 1; h = 0.01.

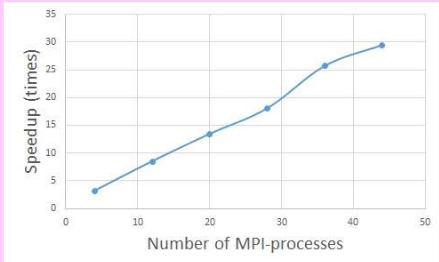
Right panel: Intervals of the complete magnetization reversal at the (r,G)-plane. The results are obtained with the G-stepsize ΔG = 1 and the r-stepsize Δr = 0.01 at A_s = 1.5; α = 0.5; t_0 =25; Δt = 6; ω_F = 1; h = 0.01.

- The simulations were performed in the time interval [0,T_{max}] where T_{max}=2000.
- At each pair of values of the parameters the magnetic reversal was indicated by means of the condition $|m_z+1|<\varepsilon$



Parallel implementation

- The execution time of a serial C++ program of modeling the magnetization reversal in the (r,G)-plane is 28 minutes.
- Parallelization is organized by distributing the points of the (r,G)-plane between MPI-processes.
- Interconnection between MPI-processes is needed only at the stage of formation of the final result.
- The maximal speedup of the MPI implementation is about 30 times.



Conclusion

- A parallel MPI program has been developed; it provides high-performance studies of the spintronics model in a wide range of parameters.
- The maximal speedup of the MPI version is about 30 times.
- In a wide range of parameters of the phase coupling G, the dissipation α and the spin-orbit coupling r, domains are obtained where the magnetic moment is reversed.
- The periodic structure of magnetic reversal domains is established. The further analysis in this field is required to explain this phenomenon.

References

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The calculations were performed on the HybriLIT cluster.