

HIGH PERFORMANCE SIMULATION OF THE MAGNETIZATION REVERSAL PHENOMENON IN THE φ_0 -JOSEPHSON JUNCTION

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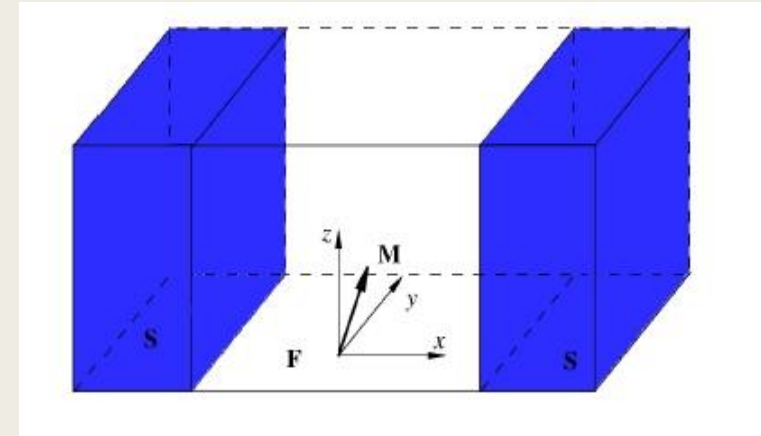
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Introduction



- In the superconductor-ferromagnetic-superconductor (SFS) structures, the spin-orbit coupling in ferromagnetic layer without inversion symmetry provides a mechanism for a direct (linear) coupling between the magnetic moment and the superconducting current. Such Josephson junctions are called ϕ_0 -junction. The possibility of controlling the magnetic properties by means of the superconducting current, and as well the effect of magnetic dynamics on the superconducting current attracts an intensive attention.
- Using implicit two-stage Gauss-Legendre method for numerical solution of a respective system of differential equations, one can obtain a detailed pictures representing the intervals of the damping parameter, relation of Josephson to magnetic energy and spin-orbit coupling parameter where the full magnetization reversal occurs.

Theoretical model

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

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

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

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

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

$$m_x(0)=0, m_y(0)=0, m_z(0)=1.$$

Theoretical model

The Josephson phase difference φ can be found using equation

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

where the pulse current is given by

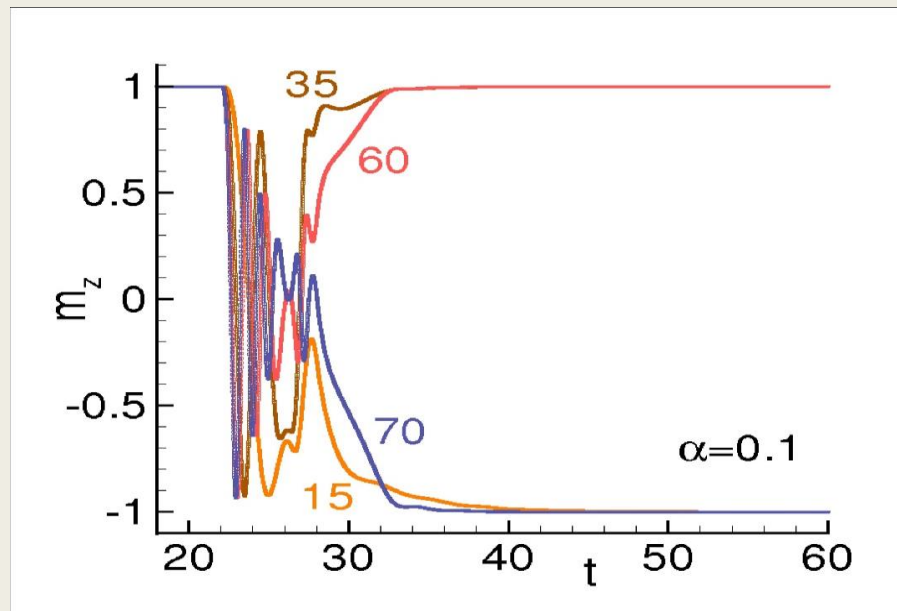
$$I_{pulse} = \begin{cases} A_s, & [t_0 - 1/2\Delta t, t_0 + 1/2\Delta t,] \\ 0 & \text{otherwise} \end{cases}. \quad (4)$$

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 the maximal amplitude.

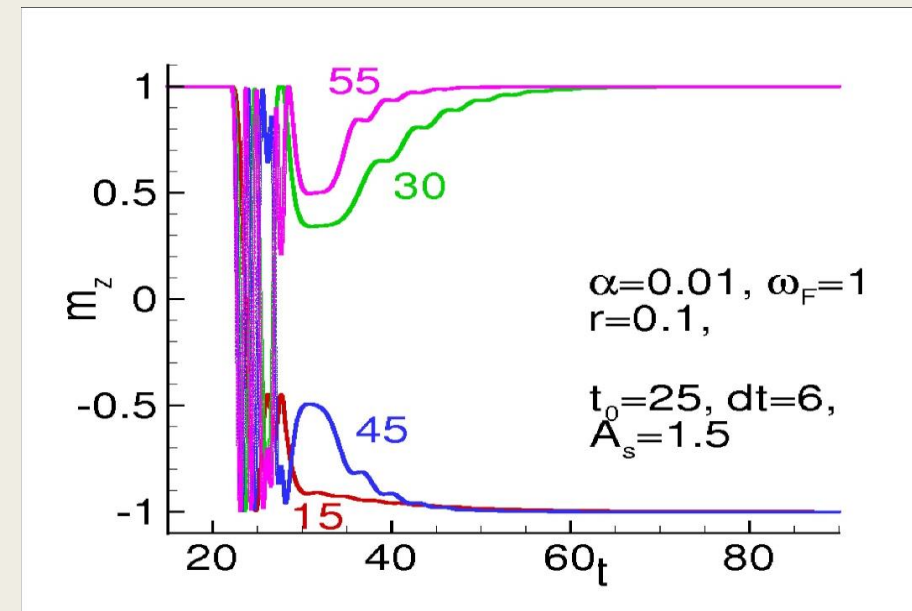
Thus, the system of equations (1) with effective field (2),(3) and with the pulse current (4) describes the dynamics of the φ_0 -junction.

Magnetic reversal

Magnetic reversal is an effect when m_z -component of the magnetic field changes the sign and takes the value -1 for a given initial value of $+1$. The pictures show the time dependence of m_z -component:



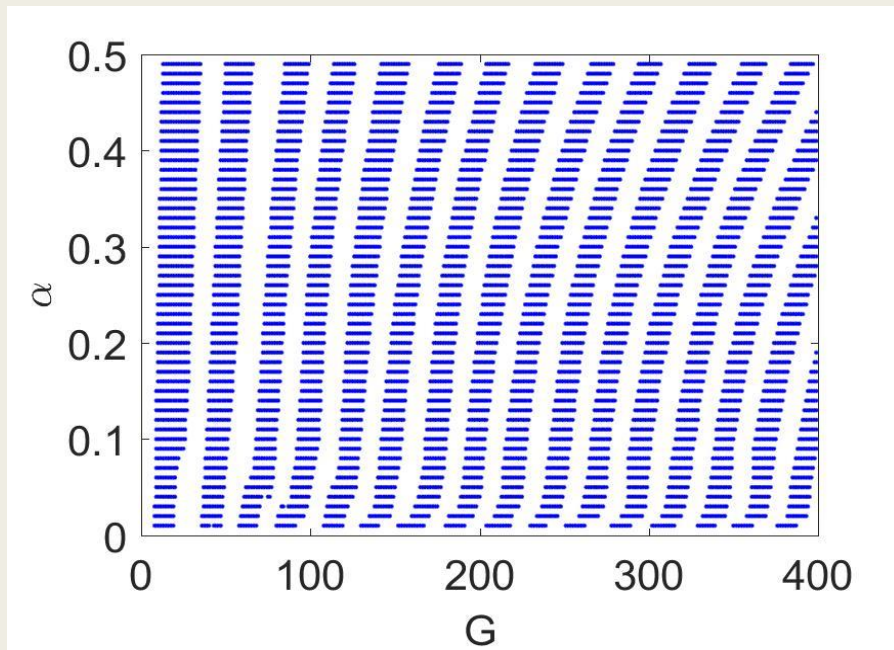
$\alpha=0.1$, $G=15$, $G=35$, $G=60$, $G=70$.
Magnetic reversal occurs for $G=15$ and 70 .



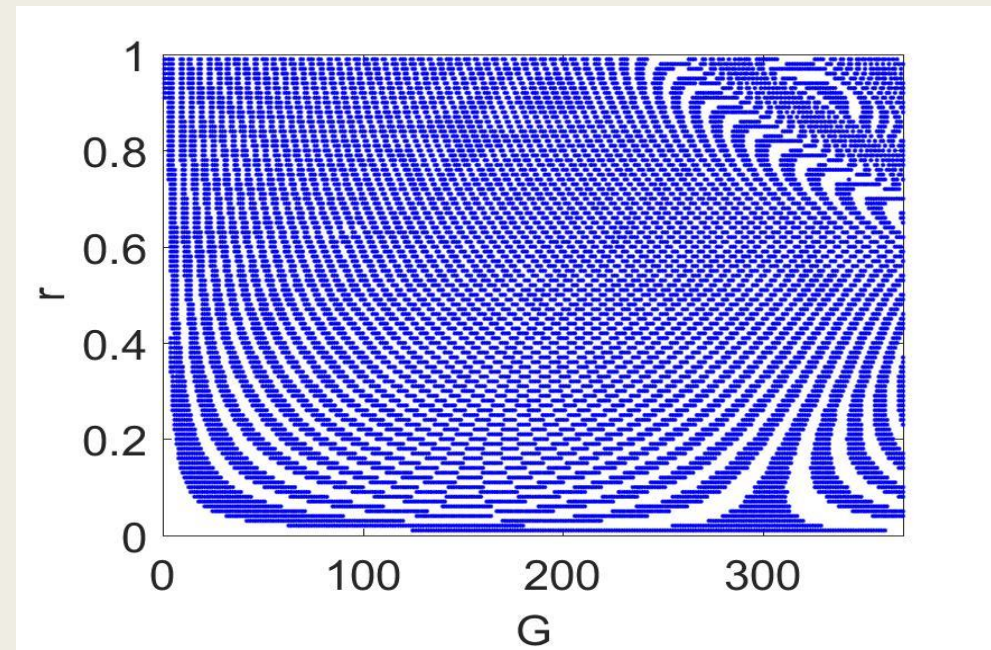
$\alpha=0.01$, $G=15$, $G=30$, $G=45$, $G=55$.
Magnetic reversal occurs for $G=15$ and 45 .

Magnetic reversal

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



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



Intervals of complete magnetization reversal at (r, G) -plane. The results are obtained with G -stepsize $\Delta G = 1$ and r -stepsize $\Delta r = 0.01$ at $A_s = 1.5$; $\alpha = 0.5$; $t_0 = 25$; $\Delta t = 6$; $\omega_F = 1$; $h = 0.01$.

Parallel implementation

For the numerical solution of the system of equations, the implicit two-step Gauss – Legendre method was used using the method of successive approximations at each time step.

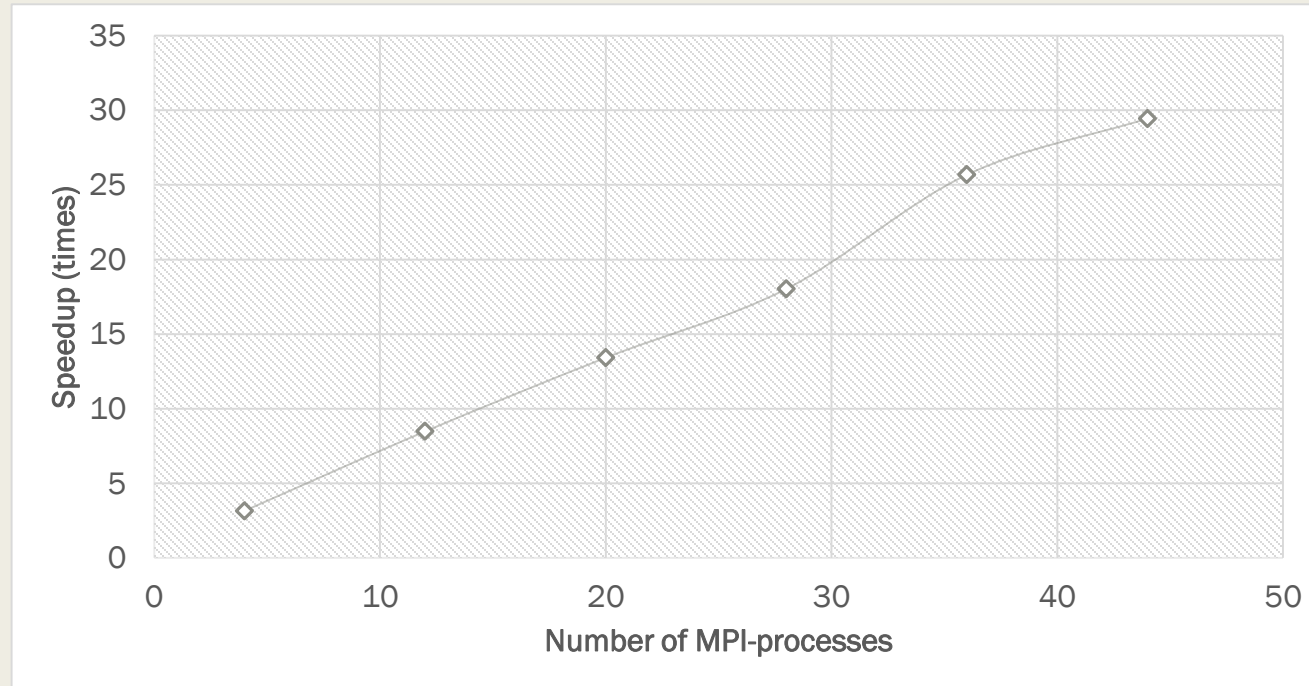
The execution time of a serial C++ program of modeling magnetization reversal in the (r, G)-plane is 28 minutes.

For mass calculations in a wide range of parameter changes, the implementation in C++ using MPI technology for organizing calculations in parallel mode is more effective.

The parallelization process is based on the distribution of the points of the (r, G)-plane between parallel MPI-processes. For the convenience of the MPI-exchange, a new data type was constructed. The values of r, G where the condition $|m_z(T_{max})+1| < \epsilon$ is satisfied, are saved and then joined in one process for writing to the output file.

The same parallelization scheme was used in case of simulations at the (α, G)-plane.

Parallel implementation



Speedup of calculations depending on the number of MPI-processes.

Calculations performed on HybriLIT platform

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Conclusions

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



THANKS FOR
ATTENTION

