NUMERICAL SIMULATION OF THE MAGNETIZATION REVERSAL WITHIN THE RF-SQUID MODEL WITH Φ0 JUNCTION DEPENDING ON THE EXTERNAL MAGNETIC FIELD PULSE

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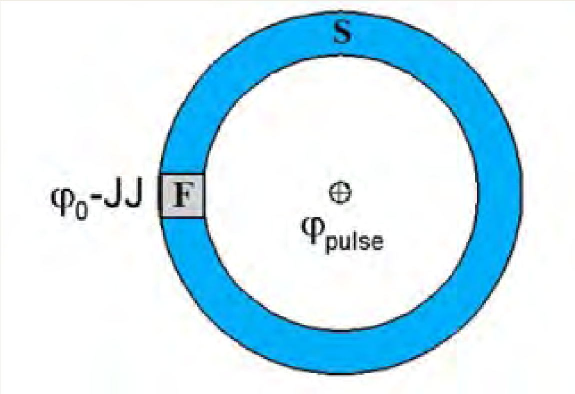
This work was supported by the Russian Science Foundation grant № 22-71-10022.

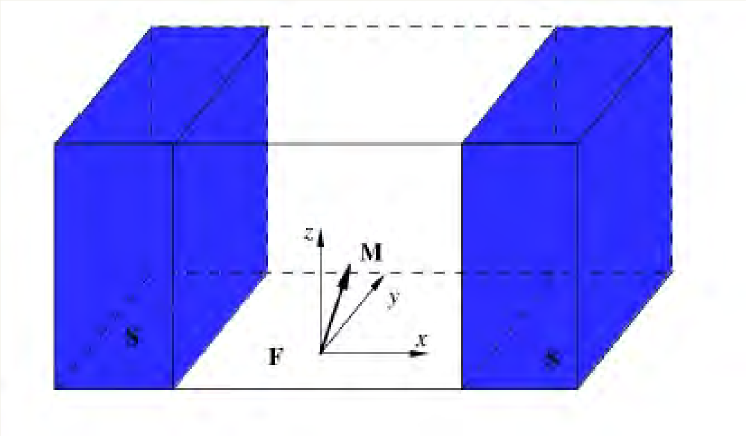
AYSS-2023, Dubna

Introduction



- Superconducting spintronics is one of the most intensively developing areas of condensed matter physics. An important place in this area is occupied by the study of Josephson junctions associated with magnetic systems.
- 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 to control magnetization by the Josephson current and vice versa Josephson current by magnetization, has attracted much recent attention.
- In this research we have investigated the peculiarities of the MR under the pulse of external magnetic field in the single junction superconducting quantum interference device (SQUID) with φ0-junction.

Introduction



- The magnetization reversal (MR) phenomena in SQUID with the single φ0 junction attracts an attention today due to the possibility of controlling magnetism by superconductivity that opens a perspective of different applications in quantum and nano-electronic technologies.
- Using 4th order Runge-Kutta 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.
- Parallel implementation allows one to significantly accelerate the simulations in the wide range of parameters of model.

Theoretical model

The dynamics of the magnetization *M* described by the Landau-Lifshitz-Gilbert equation[1,2], with the corresponding effective magnetic field H_{eff}.

$$\frac{dM}{dt} = -\frac{\Omega_F}{1+(M\alpha)^2}\{[M\,H_{eff}] + \alpha[M(MH_{eff}) - H_{eff}M^2]\}$$
$$H_{eff} = \frac{K}{M_0}[G_r \sin\left(\varphi - r\frac{M_y}{M_0}\right)e_y + \frac{M_z}{M_0}e_z] \qquad (1)$$

where Ω_F is ferromagnetic resonance frequency, α is Gilbert damping, K is anisotropic constant, $G=E_J / K_V$, E_J is Josephson energy, V is the volume of the ferromagnetic layer, $r= l\,(V_{SO} / V_{SF})$ -spin orbit coupling parameter, M_0 is magnetization saturation.

According to the SQUID theory and well known resistively shunted junction model expressions for total flux through the system can be written as

$$\frac{2\pi}{\Phi_0}\left[\Phi_{pulse} - L\left(\frac{I_c}{\omega_c}\frac{d\varphi}{dt} + I_C sin(\varphi - rm_y)\right)\right] = \varphi - rm_y, \qquad (2)$$

where $\Phi_0=h/2e$ is the flux quanta, Φ_{pulse} is the flux created by the external magnetic field pulse, L is the inductance of the superconducting loop, and I is the current through φ_0-junction, $\omega_c= 2\pi I_c R/\Phi_0$.

Theoretical model

Coupled system of equations in normalized variables takes form

$$\frac{dm_x}{dt} = -\frac{\omega_F}{1+\alpha^2}\{m_y m_z - Grm_z sin(\varphi - rm_y) + \alpha[Grm_x m_y sin(\varphi - rm_y) + m_x m_z^2]\} \quad (3)$$

$$\frac{dm_y}{dt} = -\frac{\omega_F}{1+\alpha^2}\{-m_x m_z + \alpha[Gr(m_y^2 - 1)sin(\varphi - rm_y) + m_y m_z^2]\} \quad (4)$$

$$\frac{dm_z}{dt} = -\frac{\omega_F}{1+\alpha^2}\{Grm_x sin(\varphi - rm_y) + \alpha[Grm_y m_z sin(\varphi - rm_y) + m_z(m_z^2 - 1)]\} \quad (5)$$

$$\frac{d\varphi}{dt} = \frac{\varphi_{pulse} - \varphi + rm_y}{L} - \sin(\varphi - rm_y)$$

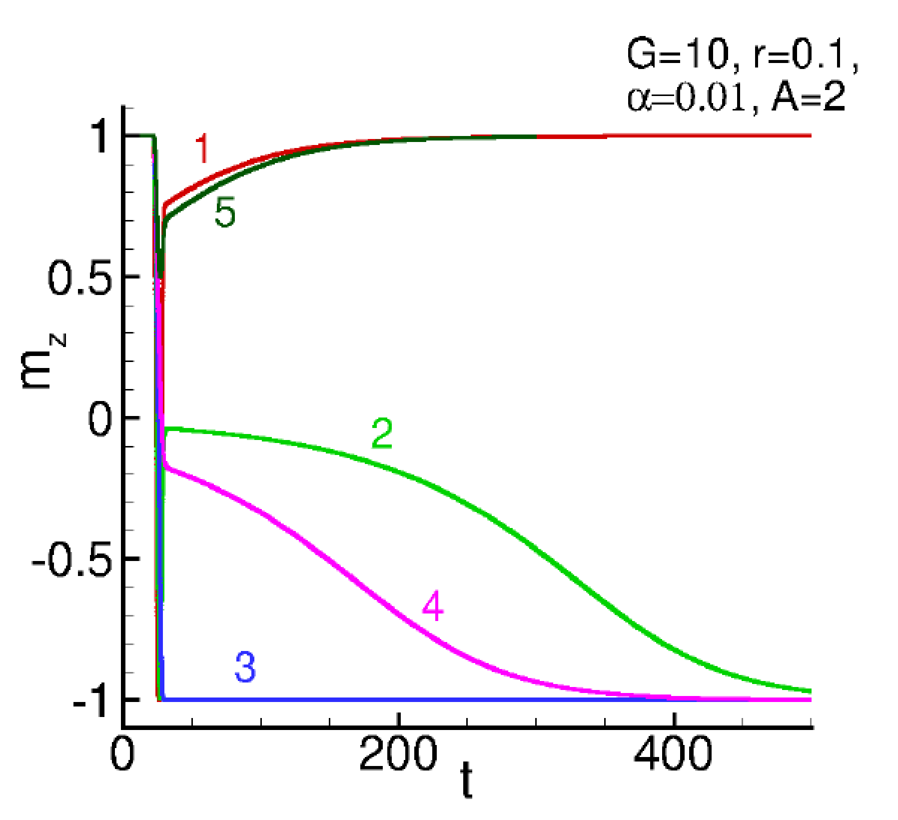
where m_i is magnetization components ($i = x, y, z$) normalised to M_0, ω_F is frequency of ferromagnetic resonance normalized to ω_c, $\varphi_{pulse}=(2\pi/\Phi_0)\Phi_{pulse}$ is normalized external magnetic flux. Here L is normalized to $L_0= \Phi_0/2\pi I_c$ and time to ω_c. The external flux pulse φ_{pulse} has rectangular form

$$\varphi_{pulse}(t) = \begin{cases} A, & t \in [t_0 - \Delta t/2, t_0 + \Delta t/2]; \\ 0 & \text{otherwise} \end{cases} . \quad (6)$$

where A and Δ_t are the pulse amplitude and width, respectively. The initial conditions for the LLG equation are the $m_x(0)=0$; $m_y(0)=0$; $m_z(0)=1$; $\varphi(0)=0$.

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*.



We analyze effect of the SQUID inductance *L* on MR. In figure the time dependence of the m_z for values of the *L = 1, 2, 3, 4, 5* for the pulse parameters *A=3* and $\Delta_t=6$. The numbers in figure show the value of corresponding *L*.

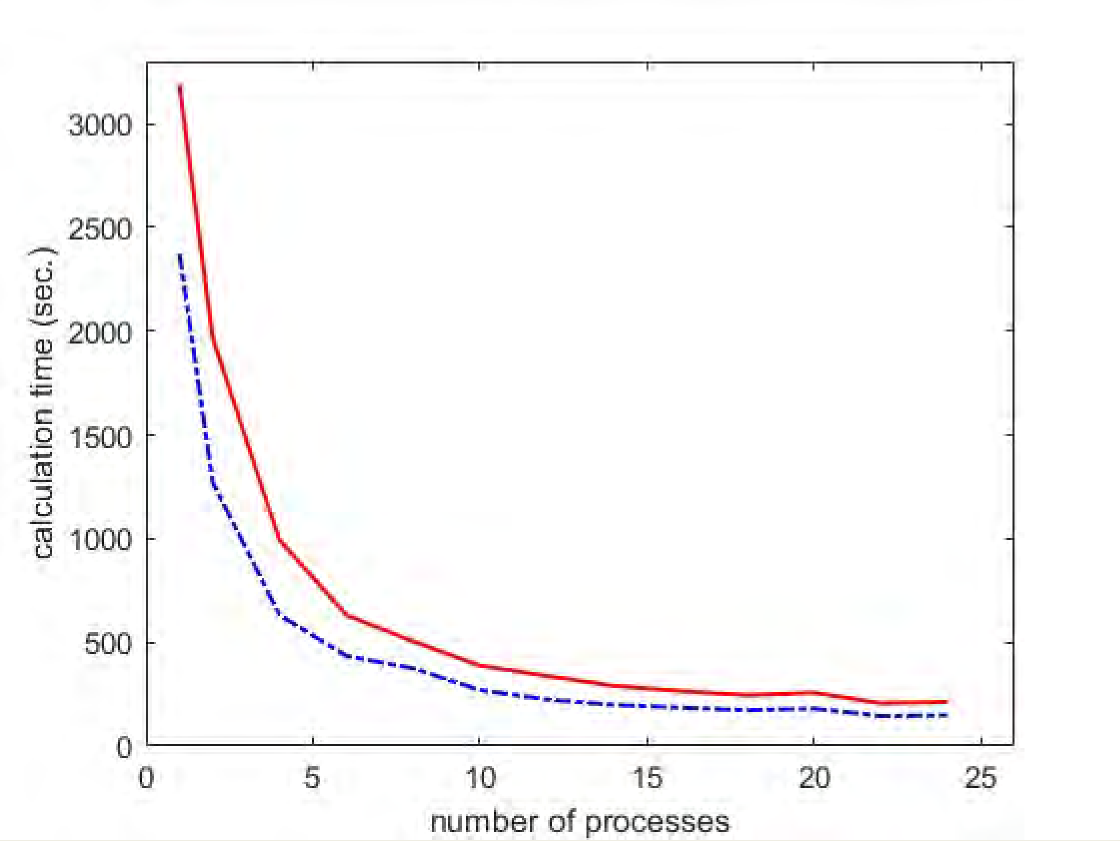
- In case of *L = 1* there no reversal, at *L = 2* MR is realized and complete reversal realized at *t = 500*.
- At *L = 3* the fast MR is realized, i.e. already during the acting of pulse.
- In case of the *L = 4*, like the case of *L = 2*, the MR takes long time (about *t = 400*).
- At *L = 5* again we can see that MR is not realized.

The performed analysis allows us to conclude that MR has a periodic behavior by the changing of the value of SQUID inductance.

Parallel implementation

- For the numerical solution of the system of equations, 4th order Runge-Kutta method was used.
- The execution time of a serial C++ program of modeling magnetization reversal in the (G, α)-plane is 53 minutes (using Intel compiler).
- The parallelization process is based on the distribution of the points of the (G, α)-plane between parallel threads. The values of G, α where the condition $|m_z(T_{max})+1|<\varepsilon$ is satisfied, are saved in output structure and writing to the output file.
- Maximal speedup of MPI implementation is about 15.5 times.
- The same parallelization scheme was used in case of simulations at the other planes.
- Also, using a parallel implementation, the influence of the AVX-512 vector instructions built into the latest versions of Intel server processors was tested. These processors are available on the Govorun supercomputer.

Parallel implementation



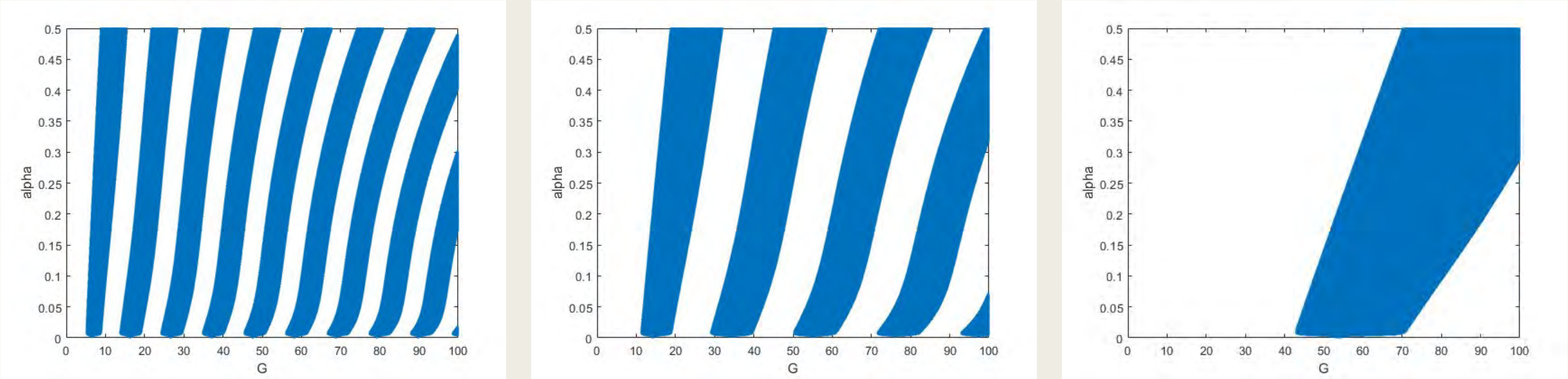
Time of calculations depending on the number of MPI-processes.

Red line: MPI realization with basic compiler options;

Blue line: MPI realization with AVX-512 options, further speed up by 1.3-1.6 times.

Calculations performed on Govorun supercomputer.

Magnetic reversal



Intervals of complete magnetization reversal at (G, α)-plane. The results are obtained with G-stepsize ΔG=0.1, α-stepsize $\Delta\alpha$=0.001 at A_s = 1.5; r = 0.1; t_0 =25; Δ_t = 6; ω_F = 1.

Left panel: L = 0.1. Central panel: L=2. Right panel: L = 10.

- The simulations have been performed in the time-interval [0, T_{max}] where T_{max}=1000.
- At each pair of values of parameters the magnetic reversal was indicated by means of condition $|m_z+1|<\varepsilon$. ε=0.0001.

Conclusions

- The influence of the inductance parameter on the width of magnetization reversal domains was revealed. Shown that an increase in the inductance parameter leads to an increase in the width of the MR bands.
- Using AVX-512 instructions allows us to further speed up the program by 1.3-1.6 times in comparison with the standard MPI-version.
- Maximal speedup of MPI + AVX-512 implementation is about 22 times compared to the single-thread calculation.

THANKS FOR ATTENTION