PARALLEL SIMULATION OF THE MAGNETIC MOMENT REVERSAL WITHIN THE JOSEPHSON JUNCTION SPINTRONIC MODEL USING MPI AND OPENMP IMPLEMENTATIONS

M.V. Bashashin[1,2], E.V. Zemlyanaya[1,2], I.R. Rahmonov[1,2]
[1]Joint Institute for Nuclear Research, Dubna
[2]Dubna State University, Dubna

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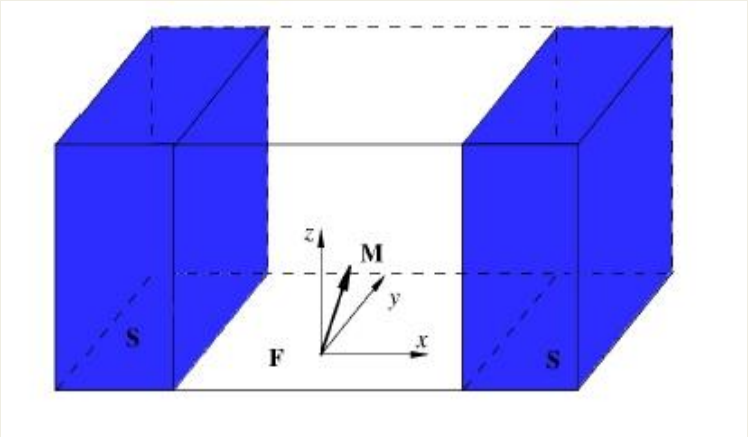
Introduction



- 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.
- This study is an extension of the study presented in:

Atanasova, P.K., Panayotova, S.A., Rahmonov, I.R. Shukrinov, Yu. M., Zemlyanaya E. V., Bashashin, M. V., Periodicity in the Appearance of Intervals of the Reversal of the Magnetic Moment of a ϕ_0 Josephson Junction, *JETP Letters*, 2019; 110(11):722-726. (In Eng.) DOI: https://doi.org/10.1134/S0021364019230073

Theoretical model

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

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

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

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

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

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

where the pulse current is given by

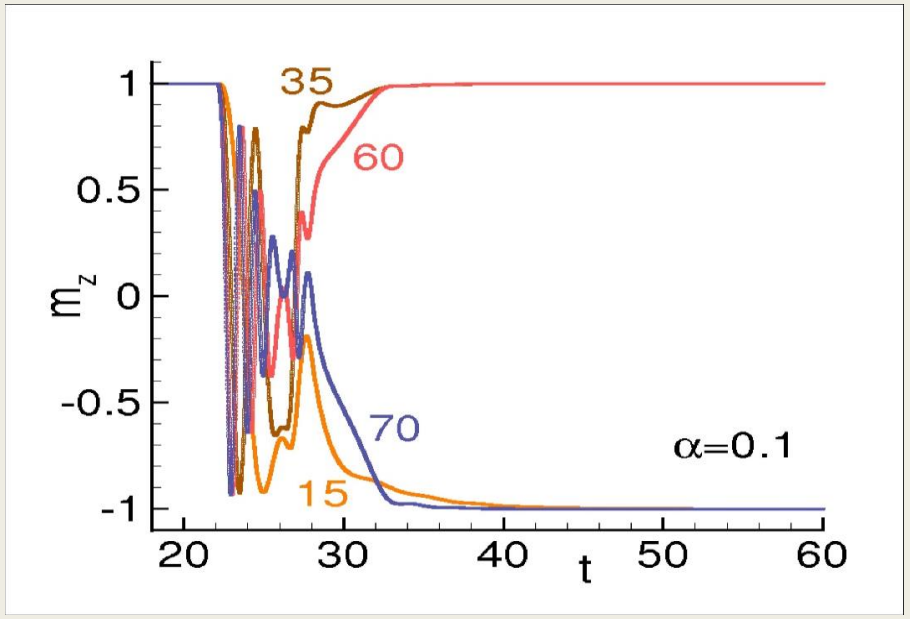
$$I_{pulse} = \begin{cases} A_S, & [t_0 - 1/2\Delta t, t_0 + 1/2\Delta t,] \\ 0 & \text{otherwise} \end{cases}. \tag{4}$$

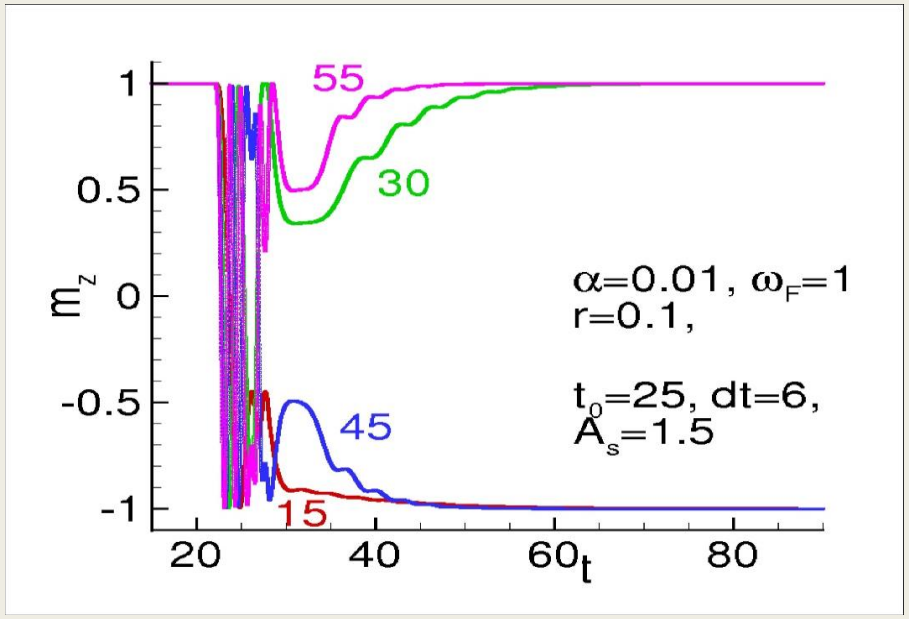
Here A_s is the amplitude of the pulse current, and Δt is the time interval, in which the pulse current is applied, t_0 is the time point the maximal amplitude.

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:





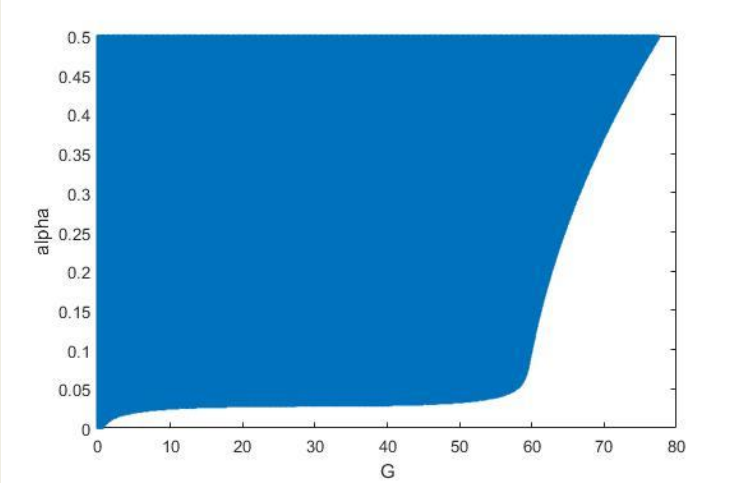
α=0.1, G=15, G=35, G=60, G=70.
Magnetic reversal occurs for G=15 and 70.

α=0.01, G=15, G=30, G=45, G=55.
Magnetic reversal occurs for G=15 and 45.

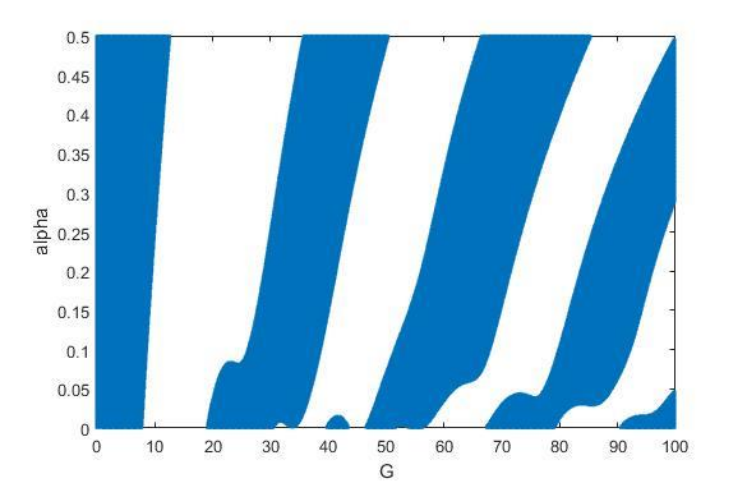
Magnetic reversal

- We investigate an influence of model parameters on the periodical structure of domains of the magnetization reversal.
- Here we present the (G, α)-plane diagram for different values of the normalized frequency of the magnetic resonance ω_F.
- The simulations have been performed in the time-interval $[0,T_{max}]$ where T_{max}=1000. At each pair of values of parameters G, α the magnetic reversal was indicated by means of condition $|m_z+1|<\varepsilon$. ε=0.0001

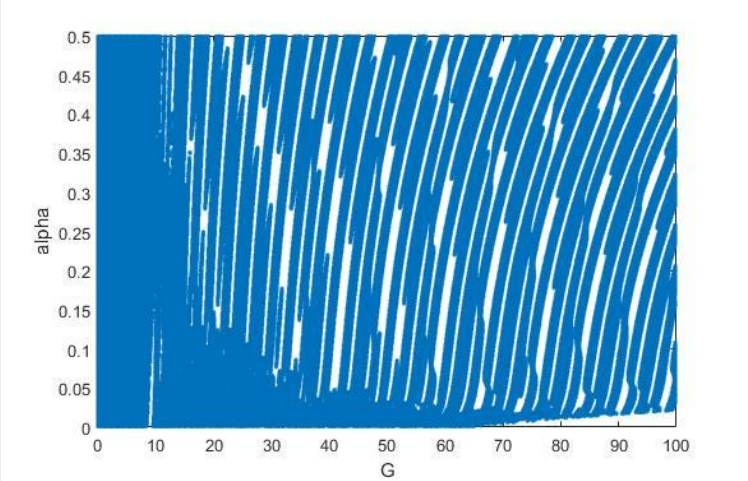
ω_F = 0.1



ω_F = 1



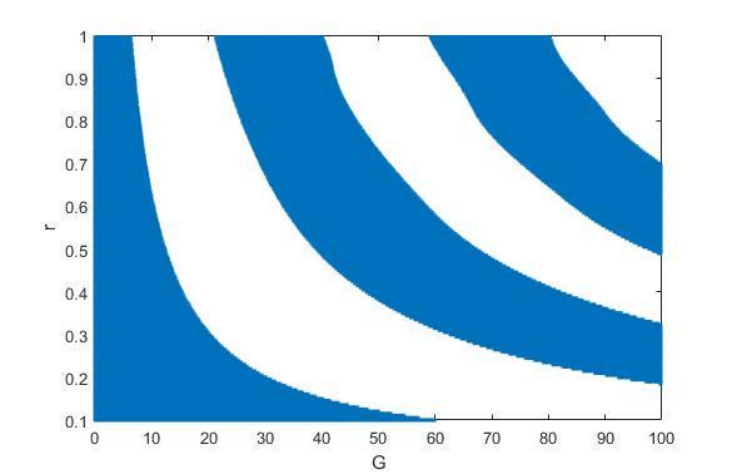
ω_F = 10



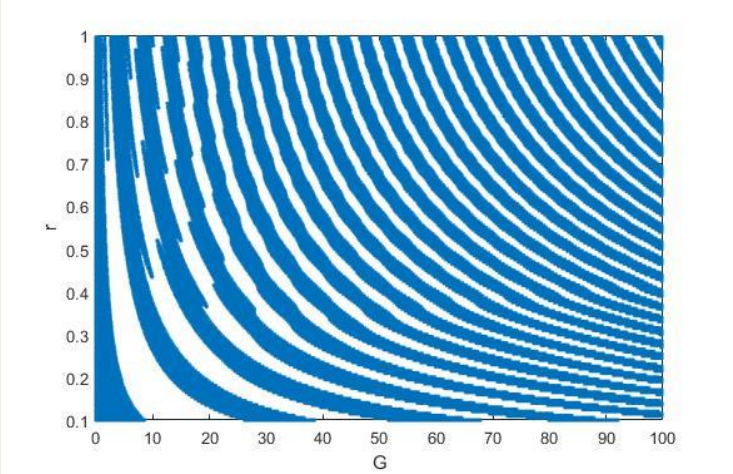
Intervals of complete magnetization reversal at (G, α)-plane. The results are obtained with G-stepsize ΔG=0.1, α-stepsize $\Delta\alpha$=0.001 at A_s = 1.5; r = 0.1; t_0 =25; Δt = 6.

Magnetic reversal

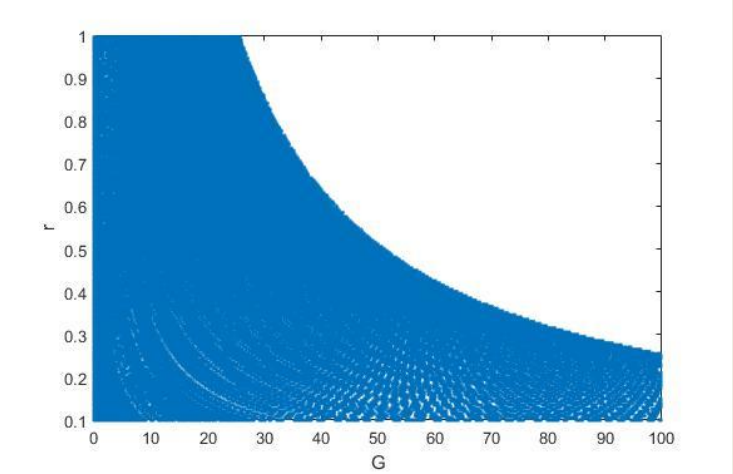
$\omega_F = 0.1$



$\omega_F = 1$



$\omega_F = 10$



Intervals of complete magnetization reversal at (G, r)-plane. The results are obtained with G-stepsize $\Delta G = 0.1$ and r-stepsize $\Delta r = 0.005$ at $A_s = 1.5$; $\alpha = 0.1$; $t_0 = 25$; $\Delta t = 6$; $h = 0.01$.

Parallel implementation

For the numerical solution of the system of equations, the implicit two-step Gauss – Legendre method was used.

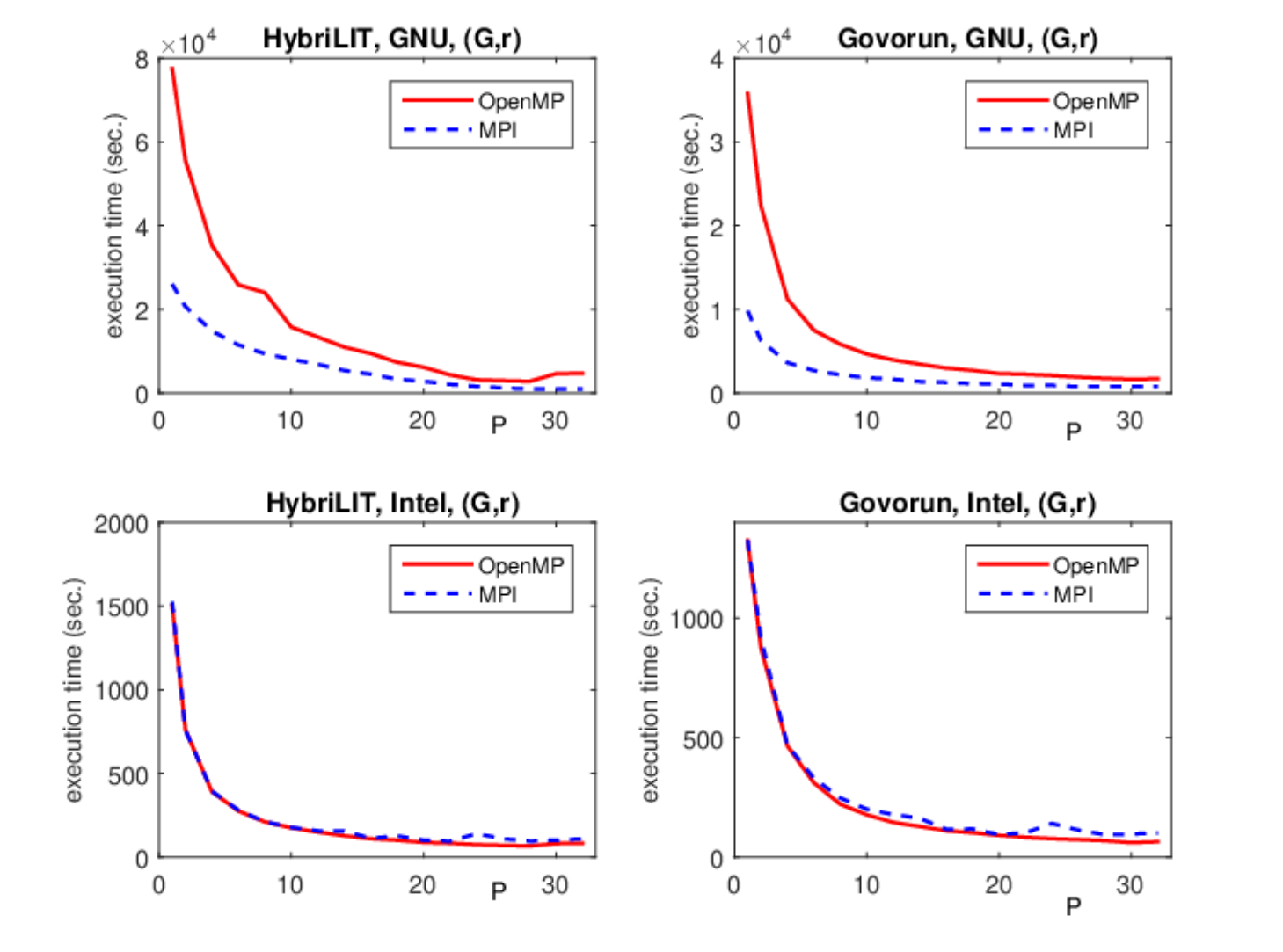
The execution time of a serial C++ program of modeling magnetization reversal in the (G, r)-plane is 25 minutes (using Intel compiler).

In addition to the version of the program developed in 2019 by the MPI, an OpenMP version was developed in 2022. Both versions are based on the C++ programming language.

The parallelization process is based on the distribution of the points of the (G, r)-plane between parallel threads. The values of G, r where the condition $|m_z(T_{max})+1|<\varepsilon$ is satisfied, are saved in output structure and writing to the output file.

The same parallelization scheme was used in case of simulations at the other planes.

Parallel implementation

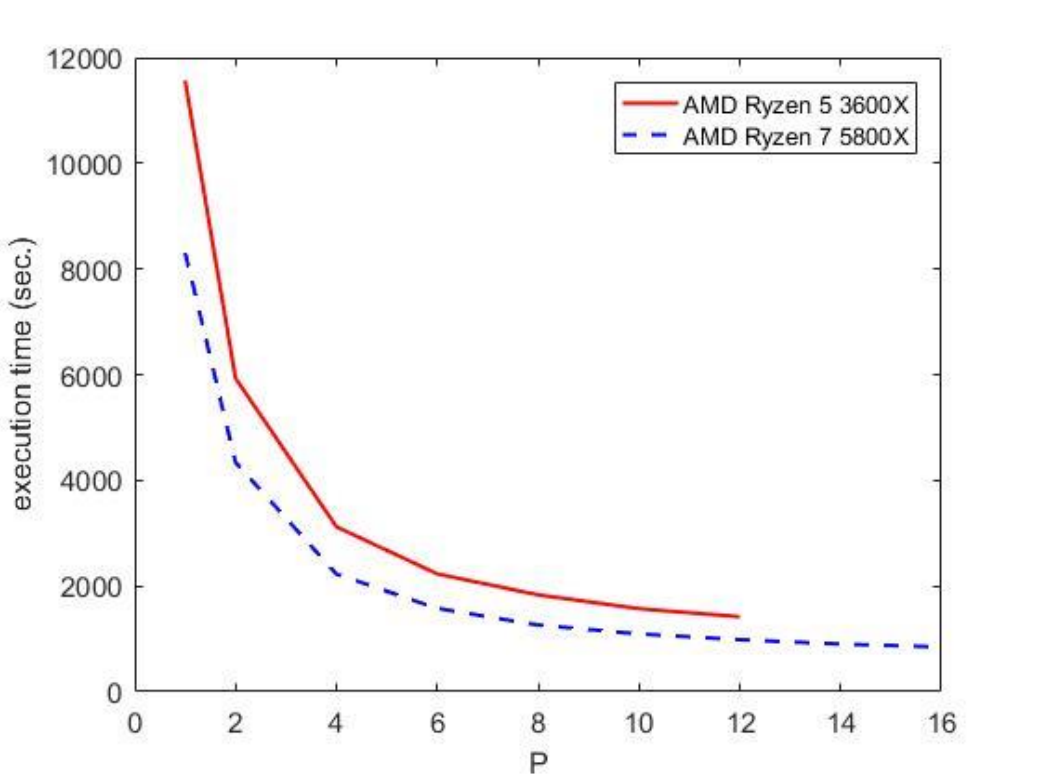


Time of calculations depending on the number of MPI-processes/ OpenMP threads.

Calculations performed on HybriLIT platform

Parallel implementation Windows

Due to the cross-platform nature of the OpenMP technology, the software implementation was tested on general-purpose personal computers. OpenMP implementation was compiled using Microsoft Visual Studio on Windows 10 operating system. Testing was carried out using AMD Ryzen 5 3600X (6 cores 12 threads) and AMD Ryzen 7 5800X (8 cores 16 threads) processors.



Conclusions

- A parallel MPI and OpenMP program has been developed that provides high-performance studies of the spintronics model in a wide range of parameters.
- Maximal speedup of the MPI and OpenMP versions 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.
- The effect of the normalized frequency of the magnetic resonance ω_F on the magnetization reversal process is shown.
- Periodic structure of the magnetic reversal domains is established. Further analysis in this field is required to explain this phenomenon.

THANKS FOR ATTENTION