JOINT INSTITUTE FOR NUCLEAR RESEARCH

Bogoliubov Laboratory of Theoretical Physics (BLTP)

FINAL REPORT
ON STAGE 1 OF THE INTERNATIONAL STUDENT PRACTICE

"Computer simulation of tunneling characteristics of superconducting nanostructures"

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I. Abstract

The Josephson φ_0 junctions demonstrate a number of unique features important for superconducting spintronics and modern informational technologies. In the current study, a current sweep along IV characteristic of the φ_0 junction may lead to regular magnetization dynamics with a series of specific phase trajectories. The origin of these trajectories is related to a direct coupling between the magnetic moment and the Josephson oscillations in these junctions, and ferromagnetic resonance when Josephson frequency coincides with the ferromagnetic one. Several peculiarities in the maximal magnetic moment amplitude, obtained at each value of the bias current, which are correlated to the features of the IV-characteristics of the φ_0 junction. The transformation of the magnetization specific trajectories along the IV-curve is also demonstrated. Due to the relation between the IV-characteristics and features of m_y, the given results will pave a way for the experimental testing of the peculiar magnetization dynamics which characterize the φ_0 junction.

II. INTRODUCTION

Developing novel materials with definite properties is of a growing interest to physicists from various disciplines that mainly pertinent to material science. Recently, superconducting spintronics has been documented as one of the intensively developing fields of condensed matter physics, specially, what is so-called Josephson junctions (JJs) coupled to magnetic systems [1-6]. Particularly, the φ_0 JJs showed impressive ability to manipulate the magnetic properties by Josephson current. One of the most intriguing subclasses of φ_0 JJs is the superconductor-ferromagnet-superconductor (S-F-S) φ_0 JJs with non-centrosymmetric ferromagnetic interlayer and broken time-reversal symmetry. In S-F-S φ_0 JJ, the spin-orbit interaction in a ferromagnet without inversion symmetry provides a mechanism for a direct (linear) coupling between the magnetic moment and the super-conducting current. The current-phase relation (CPR) is obtained by $I = I_c \sin(\varphi - \varphi_0)$, where the phase shift φ_0 is proportional to the magnetic moment perpendicular to the gradient of the asymmetric spin-orbit potential [7].

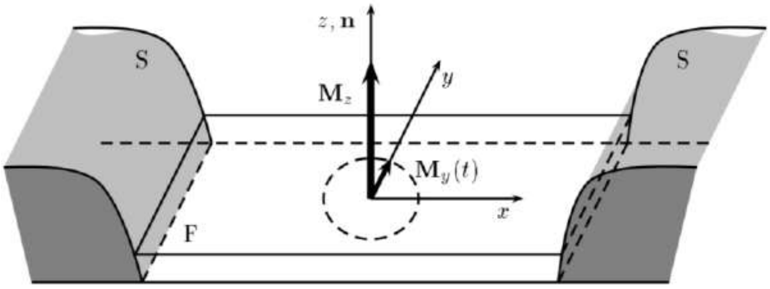

Figure 1. Geometry of the considered φ_0-junction. The ferromagnetic easy-axis is directed along the z-axis, which is also the direction **n** of the gradient of the spin-orbit potential. The magnetization component $\mathbf{M}_y$ is coupled with Josephson current through the phase shift term φ_0 α **n. (M ^ ∇ψ)**, where **ψ** is the superconducting order parameter (**∇ψ** is along the *x*-axis in the system considered here) (taken from Ref [8]).

In the presented work, the IV characteristics and magnetization dynamics of the S-F-S φ_0 JJ are thoroughly investigated. A more detailed investigation of the complicated dynamics that results from the unique interaction between the superconducting current and magnetic moment in the S-F-S φ_0 JJ is established by using the system of Landau-Lifshitz-Gilbert-Josephson equations. In certain ranges of bias current, there are stable states of the magnetization precession, at which the phase trajectories can be characterized by very specific shapes.

III. MODEL AND METHODS

In the S-F-S φ_0 JJ with a thin ferromagnetic layer, the superconducting phase difference and magnetization of the F layer are two coupled dynamical variables. The system of equations describing the dynamics of these variables is obtained from the Landau-Lifshitz-Gilbert (LLG) equation and Josephson relations for current and phase difference. The magnetization dynamics of the studied system can also be described by the LLG equation where the effective field depends on the phase difference.

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M_0}\left(\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right)$$

$$\mathbf{H}_{\mathrm{eff}} = \frac{K}{M_0}\left[Gr\sin\left(\varphi - r\frac{M_y}{M_0}\right)\hat{\mathrm{y}} + \frac{M_z}{M_0}\hat{\mathrm{z}}\right]$$

where γ is the gyromagnetic ratio, α is a phenomenological damping constant, φ is the energy difference between the superconductors across the junction, $M_0 = \|\mathbf{M}\|$, $G = E_J/(K\upsilon)$, k is an anisotropic constant, υ is the volume of the ferromagnetic F layer, $r = l\upsilon_{so}/\upsilon_F$ is a parameter of spin-orbit coupling, υ_{so}/υ_F characterize the strength of the spin-orbit interaction, υ_F is fermi velocity, $l = 4hL/\hbar\upsilon_F$, L is length of the F layer, and the h denotes the exchange field in the ferromagnetic layer. The total system of LLG equations in normalized units is given as follows:

$$\dot{m}_x = \frac{\omega_F}{1+\alpha^2}\{-m_y m_z + Grm_z \sin(\varphi - rm_y) - \alpha[m_x m_z^2 + Grm_y m_z \sin(\varphi - rm_y)]\},$$

$$\dot{m}_y = \frac{\omega_F}{1+\alpha^2}\{m_x m_z - \alpha[m_y m_z^2 - Gr(m_z^2 + m_x^2)\sin(\varphi - rm_y)]\},$$

$$\dot{m}_z = \frac{\omega_F}{1+\alpha^2}\{-Grm_x \sin(\varphi - rm_y) - \alpha[Grm_y m_z \sin(\varphi - rm_y) - m_z(m_x^2 + m_y^2)]\},$$

$$\frac{dV}{dt} = \frac{1}{\beta_c}\left[I + A\sin(\omega_R t) - V - \sin(\varphi - rm_y) + \frac{rdm_y}{dt}\right],$$

$$\frac{d\varphi}{dt} = V$$

where $\beta_c = \frac{2eI_cCR^2}{\hbar}$ is the McCumber parameter (in our calculations we use $\beta_c = 25$), $m_i = M_i/M_0$for $i = x, y, z$ and $\omega_F = \Omega_F/\omega_c$ with the ferromagnetic resonance (FMR) frequency $\Omega_F = \gamma K/M_0$ and characteristic frequency $\omega_c = 2eRI_c/\hbar$. Here we normalize time in units of ω_c^{-1}, external current I in units of I_c, and the voltage Vin units of $V_c = I_cR$. The abovementioned system of equations solved numerically by the means of the fourth order Runge–Kutta method, yields $m_i(t)$, $V(t)$ and $\varphi(t)$ as a function of the external bias current I. After averaging procedure [9, 10], IV-characteristics can be obtained at the fixed parameters of the system and investigate the dynamics of magnetization along the IV-curve [11].

IV. RESULTS AND DISCUSSION

a. CHARACTERISTICS OF φ_0 JJ AT DIFFERENT G AND α

Here, the interactions between superconducting current and magnetic moment are thoroughly elucidated. In that spirit, the I–dependence of the maximal m_y component and IV characteristics are computed at different small values of the parameters G and α. Figure 2 shows the manifestation of the FMR in $m_{y,max}$ and IV characteristic for the φ_0 junction which geometry is displayed in the inset with superconductor(S) and ferromagnet (F). The utilized simulation parameters are G (0.1 and 0.5) and α (0.01, 0.001, and 0.0001) at fixed r = 0.2. The calculated one-loop IV curve that obtained by increasing and decreasing I and displays an expected hysteresis for βc = 25, are demonstrated in Figure 2. The IV characteristic at the chosen parameters of the system does not react practically on the changes in the magnetization dynamics.

As shown in Figure2, an increase of magnetization amplitude $m_{y,max}$ in the resonance region is conspicuously observed. Notably, prominent fluctuation regions are found through increasing the value of G parameter from 0.1 to 0.5. For highest values of α, plethora of harmonic and subharmonic regions are detected compared to the lower ones. The obtained findings consistently affirmed the crucial effect of the G and α parameters on the FMR peaks. Conspicuously, the peaks at the illustrated curves become more wider by decreasing the value of α. Moreover, the effect of increasing the value of G parameter is obviously noticed by the occurrence of the numerous subharmonic peaks.

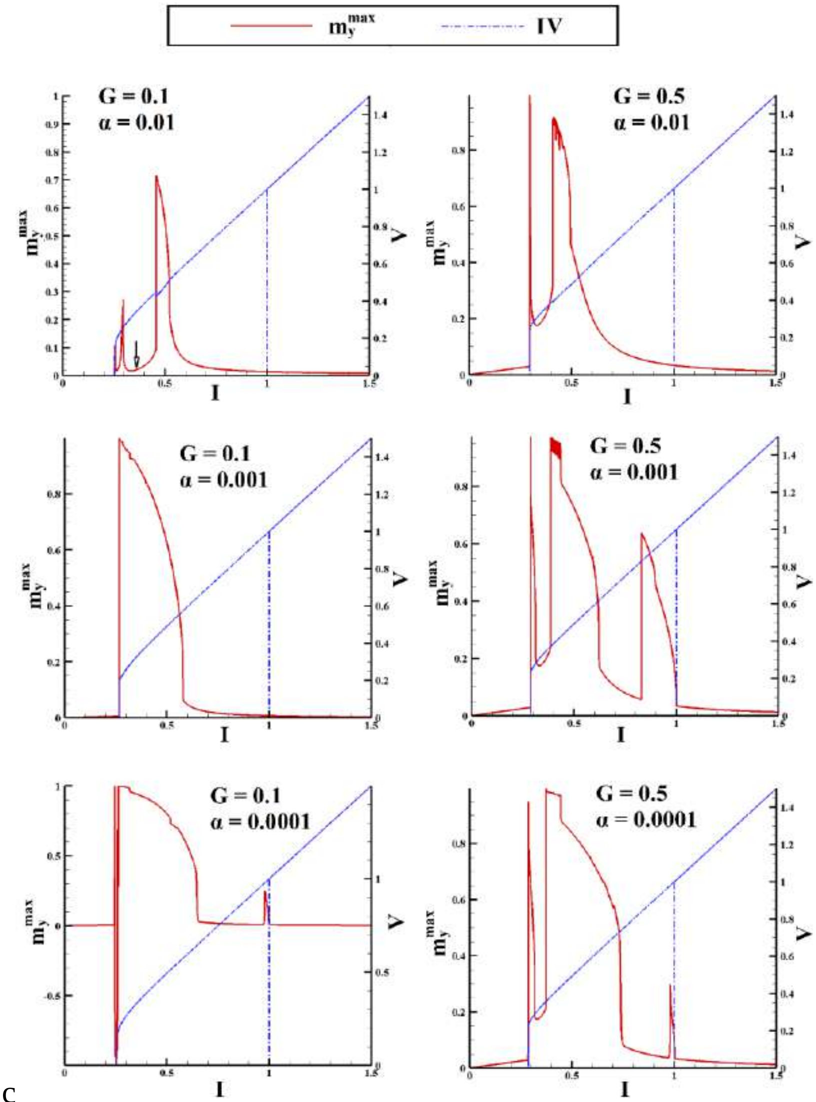

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Figure 2. Manifestation of the FMR in $m_{y,max}$ and IV characteristic for the φ_0 junction with S-F-S geometry and simulation parameters of G (0.1 and 0.5) and α (0.01, 0.001, and 0.0001) at fixed r = 0.2.

b. MAGNETIZATION DYNAMICS (TRAJECTORIES)

Versatile trajectories of the magnetic moment are characterized from the current intervals shown in Figure 2. The characteristic trajectories in the m_y–m_x, m_z–m_x, and m_z–m_y planes are demonstrated for different values of bias current in Figures 3-8.

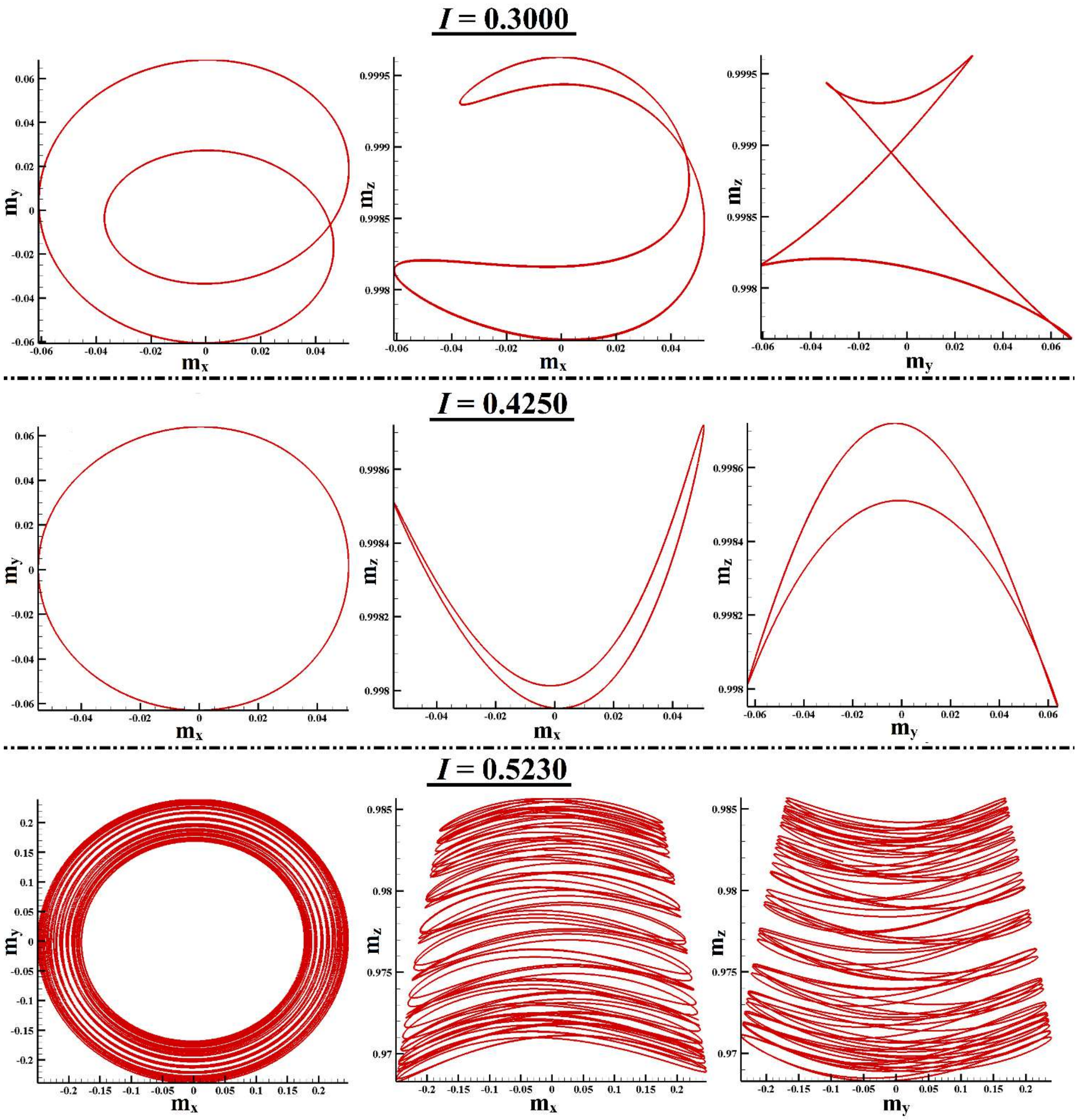

Figure 3. Magnetization trajectories in the m_y–m_x, m_z–m_x, and m_z–m_y planes at different values of bias current for the φ_0 junction with S-F-S geometry and simulation parameters of G = 0.1, r = 0.2 and α = 0.01.

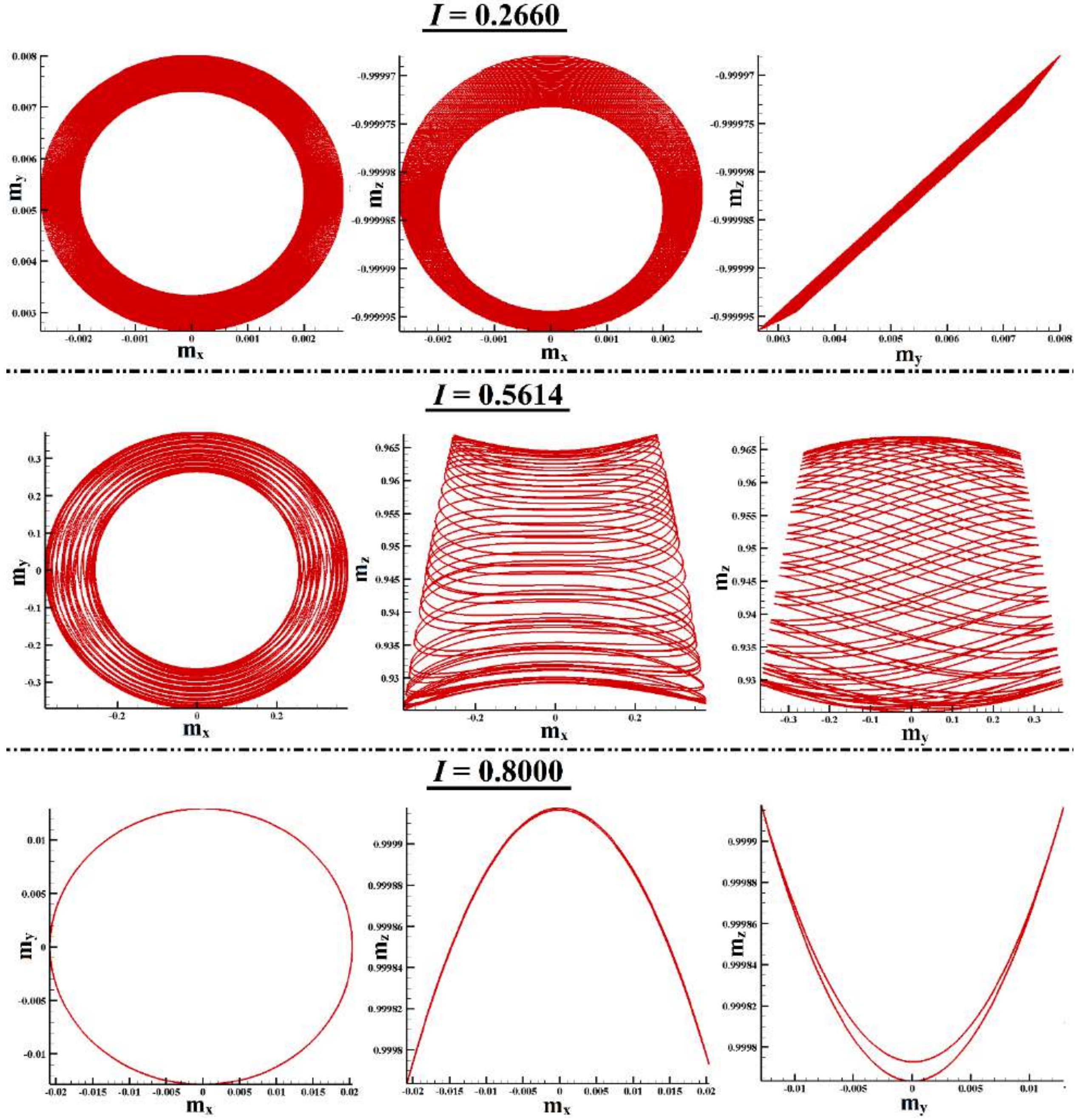

Figure 4. Magnetization trajectories in the m_y–m_x, m_z–m_x, and m_z–m_y planes at different values of bias current for the φ_0 junction with S-F-S geometry and simulation parameters of G = 0.1, r = 0.2 and α = 0.001.

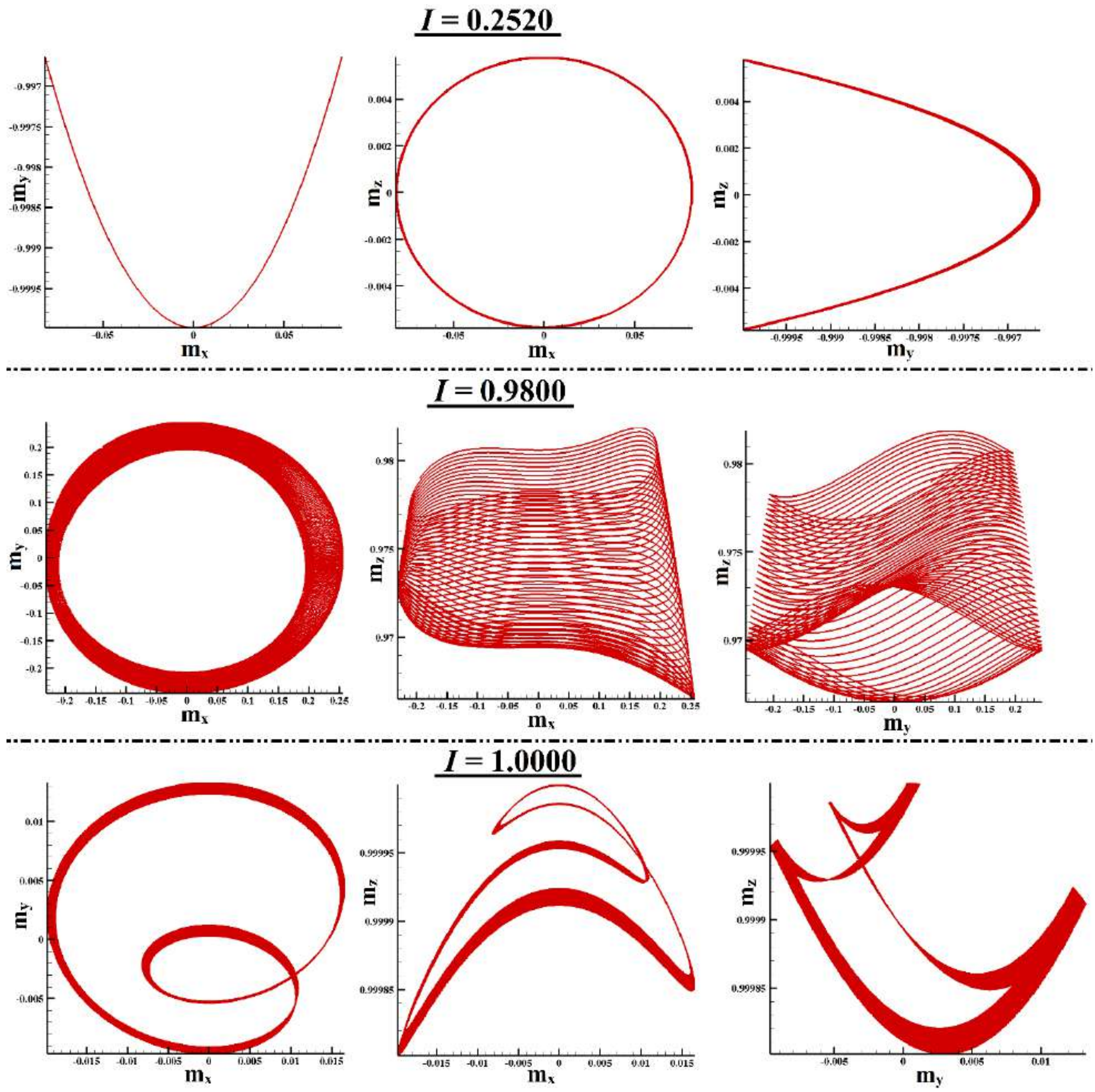

Figure 5. Magnetization trajectories in the m_y–m_x, m_z–m_x, and m_z–m_y planes at different values of bias current for the φ_0 junction with S-F-S geometry and simulation parameters of G = 0.1, r = 0.2 and α = 0.0001.

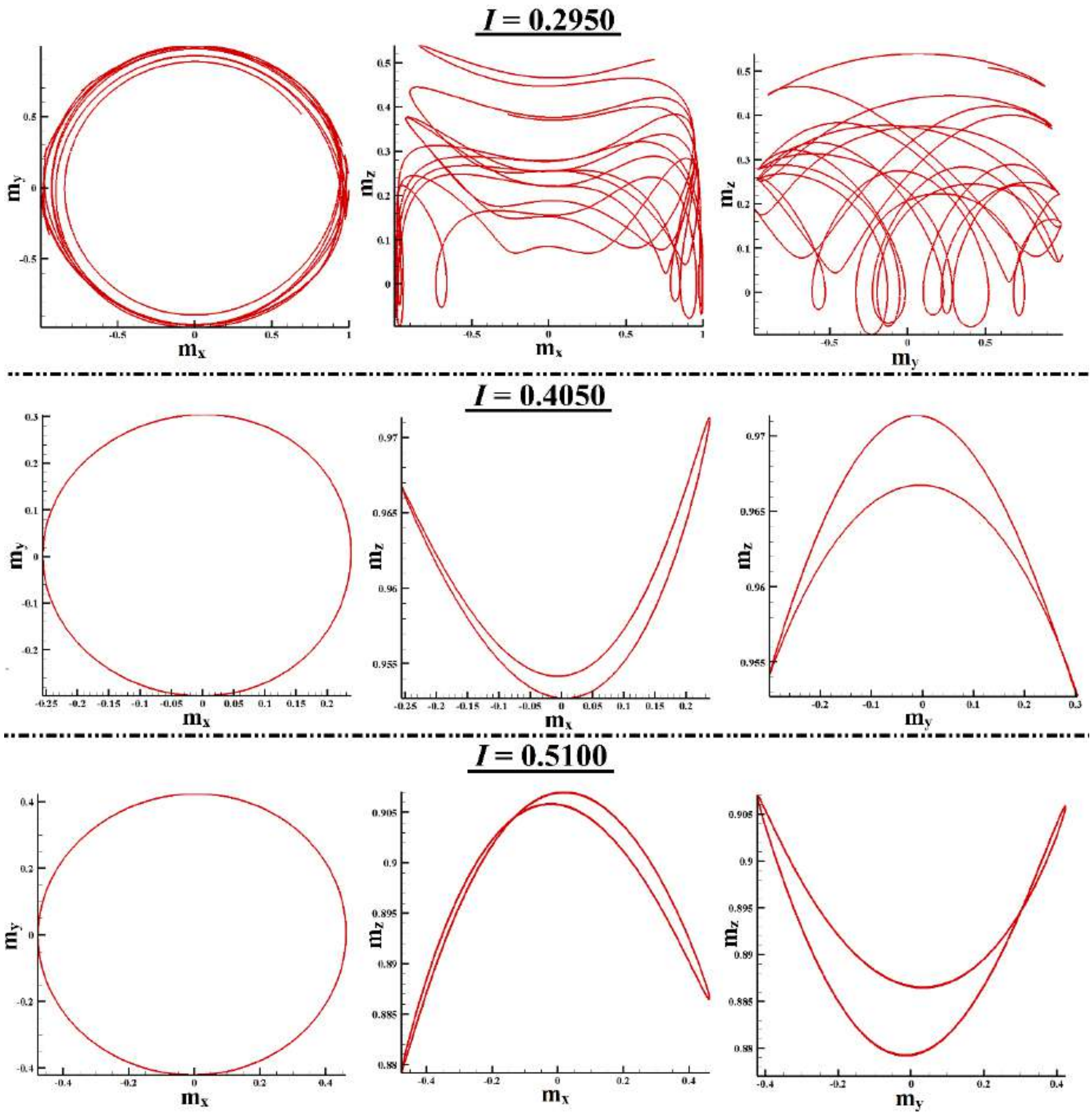

Figure 6. Magnetization trajectories in the m_y–m_x, m_z–m_x, and m_z–m_y planes at different values of bias current for the φ_0 junction with S-F-S geometry and simulation parameters of G = 0.5, r = 0.2 and α = 0.01.

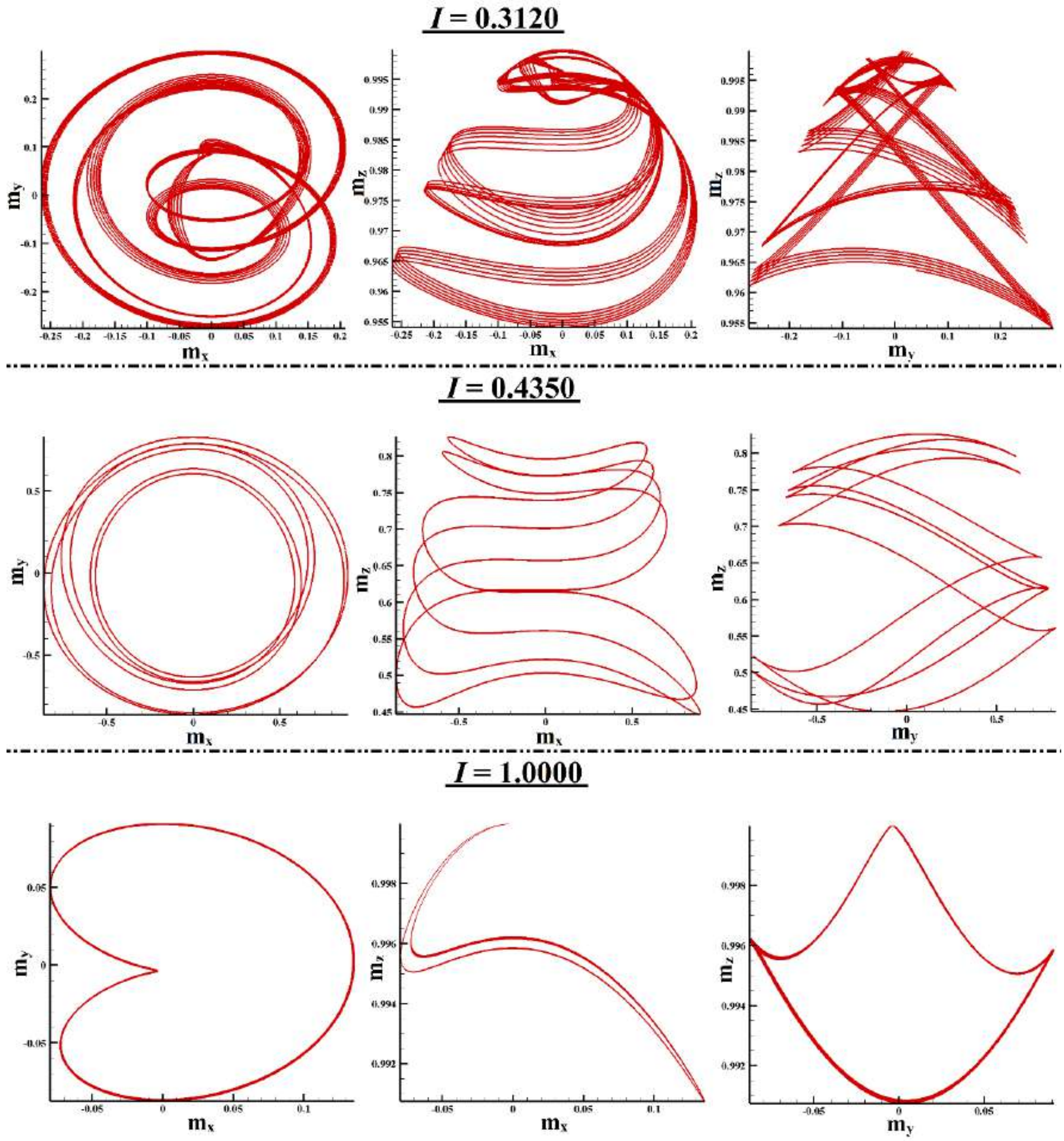

Figure 7. Magnetization trajectories in the m_y–m_x, m_z–m_x, and m_z–m_y planes at different values of bias current for the φ_0 junction with S-F-S geometry and simulation parameters of G = 0.5, r = 0.2 and α = 0.001.

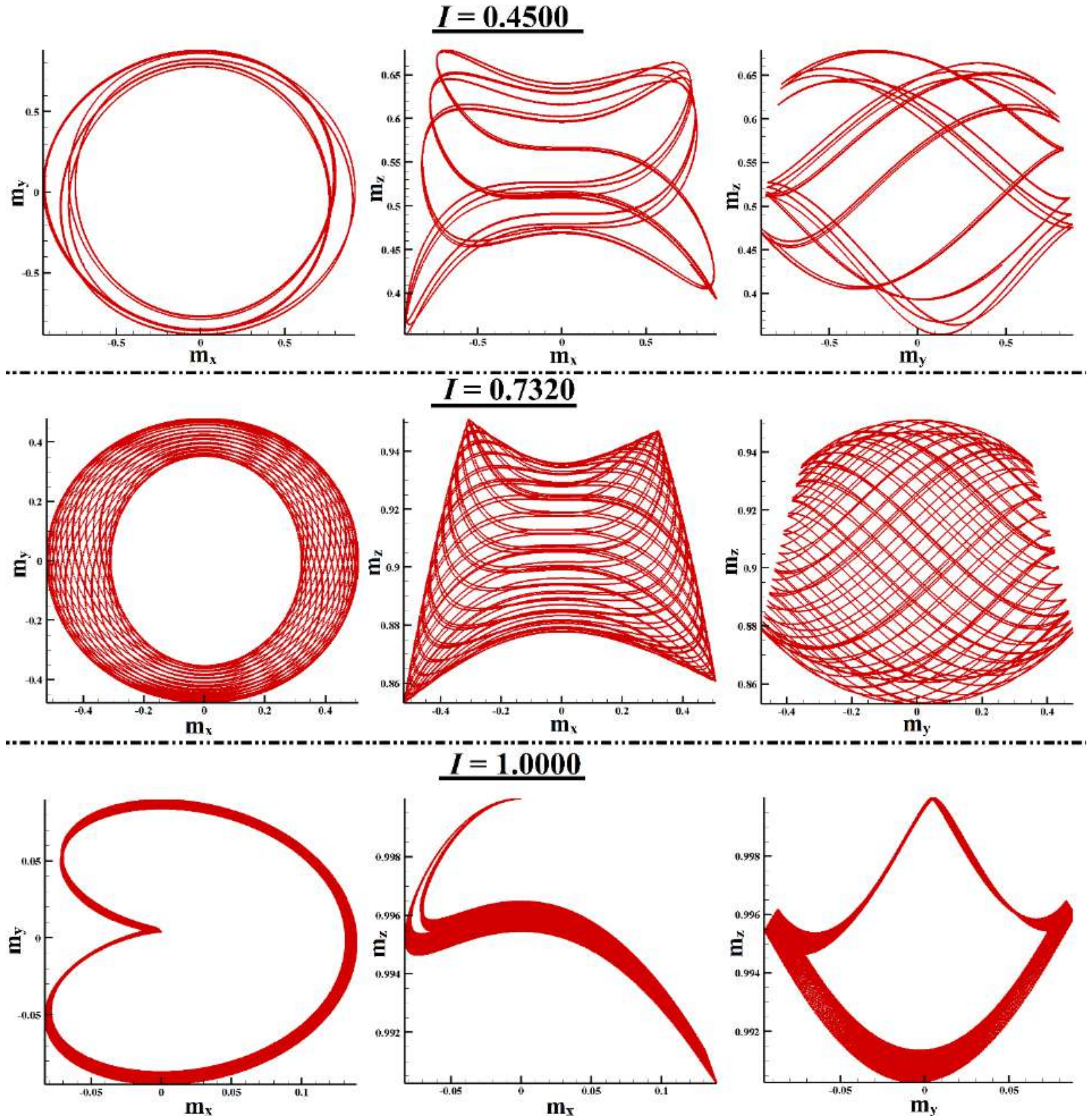

Figure 8. Magnetization trajectories in the m_y–m_x, m_z–m_x, and m_z–m_y planes at different values of bias current for the φ_0 junction with S-F-S geometry and simulation parameters of G = 0.5, r = 0.2 and α = 0.0001.

According to the depicted Figures, various distinguishable trajectories are observed, highlighting a prominent possibility of dominating the magnetization dynamics via external bias current. At different values of current, the studied φ_0 junction are found with versatile dynamics that ensure the correlation between the value of utilized current with magnetization of the system.

According to the trajectories displayed in Figure 3, the m_y–m_x plan exhibited double behavior when we inspect current with value of 0.30000 compared to that of 0.4250. An obvious donate shape is observed in the case of I with value of 0.5230. In the case of I = 0.4250, m_z–m_x and m_z–

m_y planes show reversed patterns. The thickness of the above-mentioned planes increases by increasing the value the bias current as demonstrated in the case of I with value of 0.5230.

We can observe from the trajectories illustrated in Figure 4 that the thickness of the donates shape of the studied m_y–m_x plane decreases by increasing the value of the utilized bias current. In the case of I with values of 0.5614 and 0.8000, m_z–m_x and m_z–m_y planes show reversed patterns.

IV. CONCLUSIONS

An in-depth insight into the IV-characteristics of the φ_0 JJ is herein obtained. The interactions between superconducting current and magnetic moment are accordingly unveiled. Also, the I–dependence of the maximal m_y component and IV characteristics are computed at different small values of the parameters G and α. Subsequently, different types of magnetization trajectories are generated by sweeping current along the IV-characteristics of the φ_0 JJ due to a direct coupling between the magnetic moment and the Josephson current.

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I would like to express my special thanks of gratitude to the Egyptian Academy of scientific research and technology (ASRT) and the Joint Institute for Nuclear Research (JINR) for give me such golden opportunity to do this wonderful project. I would like to express my sincere thanks to Prof. Yu. M. Shukrinov who directed me and give me an outstanding push in starting and finalizing this project within the limited time frame. Much obliged for efforts of Dr. M. Nashaat who helped me a lot in this project. At each step of my life, I express proudly my special gratitude to my role model, Dr. Mahmoud A. A. Ibrahim, for his consistent support and guidance since my academic career start in the "CompChem-Talented Students Incubator Program" at CompChem Laboratory.

VI. FUTURE WORK

Through our work in the presented project, Prof. Yu. M. Shukrinov suggested to provide full physical and chemical insights into the features of the superconducting nanostructures under high temperature. The proposed project will be executed from the pure physical and chemical points of view in the BLTP laboratory at JINR, Russia and computational chemistry (CompChem) laboratory in Minia University, Egypt, respectively.

VII. REFERENCES

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