JINR-India collaborative investigations of Josephson nanostructures

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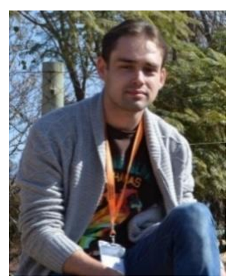


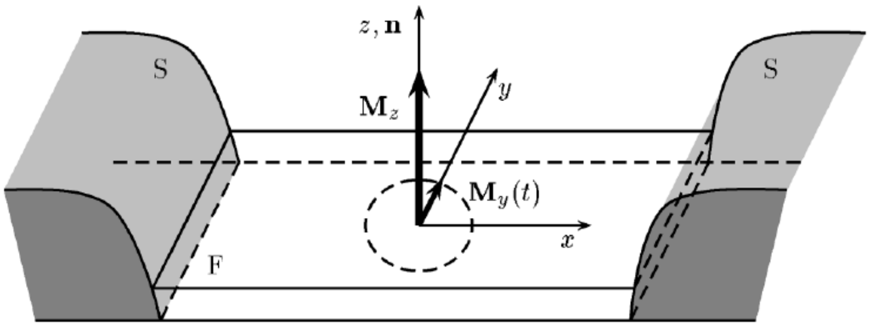
Dubna, 2023

Content

- **S/F/S φ_0-junction**
- **S/F/S Josephson junctions on top of 3D TI**
- **S/IF/S Josephson junctions on top of 3D TI**
- **Weyl and multi-Weyl semimetals Josephson junctions**

S/F/S φ_0-junction

Phi - 0 Josephson junction



$G = E_J/(K\mathcal{V}) \qquad r = l v_{so}/v_F$

Current phase relation

$$I = I_c \sin(\varphi - \varphi_0)$$

Landau Lifshits Gilbert equation

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

The effective field

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

Dynamical equations for Josephson junction

$$\frac{dV}{dt} = \frac{1}{\beta_c}[I - V - \sin(\varphi - r m_y)]$$

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

$$\beta_c = 2eI_cCR^2/\hbar$$

The appropriate candidate for experimental verification → **Permalloy doped with Pt or Pt/Co bilayer**, **MnSi** or **FeGe** (Ferromagnet without inversion symmetry)

r ~ 0.1 – 1, G ~ 0.1 – 100, ω_F ~ 10 GHz

A. Buzdin, Phys. Rev. Lett. 101, 107005 (2008).

F. Konschelle and A. Buzdin, Phys. Rev. Lett. **102**, 017001 (2009)

Ferromagnetic resonance

The system precess around the easy axis

$$Gr\alpha << 1 \; m_x, m_y << 1 \text{ и } m_z = 1 = const$$

The solution of the linearized system is given by:

$$m_y(t) = \frac{\omega_+ - \omega_-}{r}\sin(\omega_J t) - \frac{\gamma_+ + \gamma_-}{r}\cos(\omega_J t)$$

where

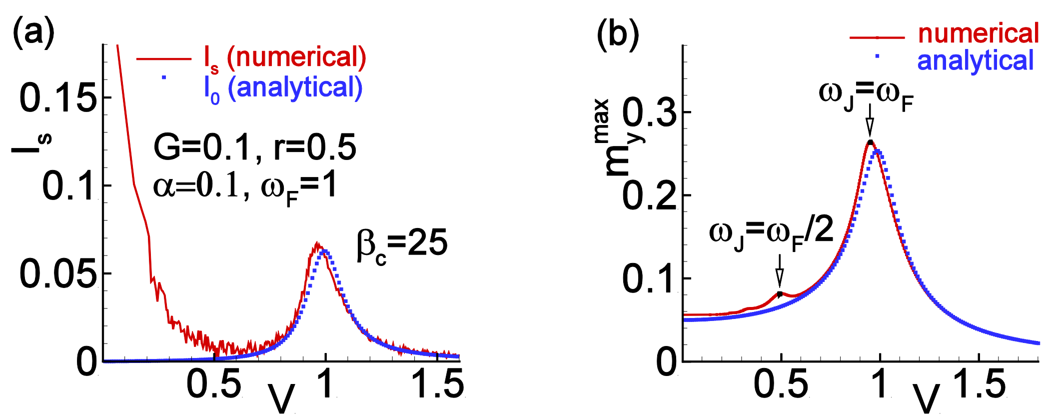
$$\omega_\pm = \frac{Gr^2\omega_F}{2}\frac{\omega_J \pm \omega_F}{\Omega_\pm} \qquad \gamma_\pm = \frac{Gr^2\omega_F}{2}\frac{\alpha\omega_J}{\Omega_\pm} \qquad \Omega_\pm = (\omega_J \pm \omega_F)^2 + (\alpha\omega_J)^2$$

The supercurrent in given by:

$$\begin{aligned} I_s(t) &= \sin\omega_J t - \frac{\omega_+ - \omega_-}{2}\sin 2\omega_J t \\ &+ \frac{\gamma_+ + \gamma_-}{2}\cos 2\omega_J t + I_0(\alpha) \end{aligned}$$

where $I_0 = \frac{\gamma_+ + \gamma_-}{2}$

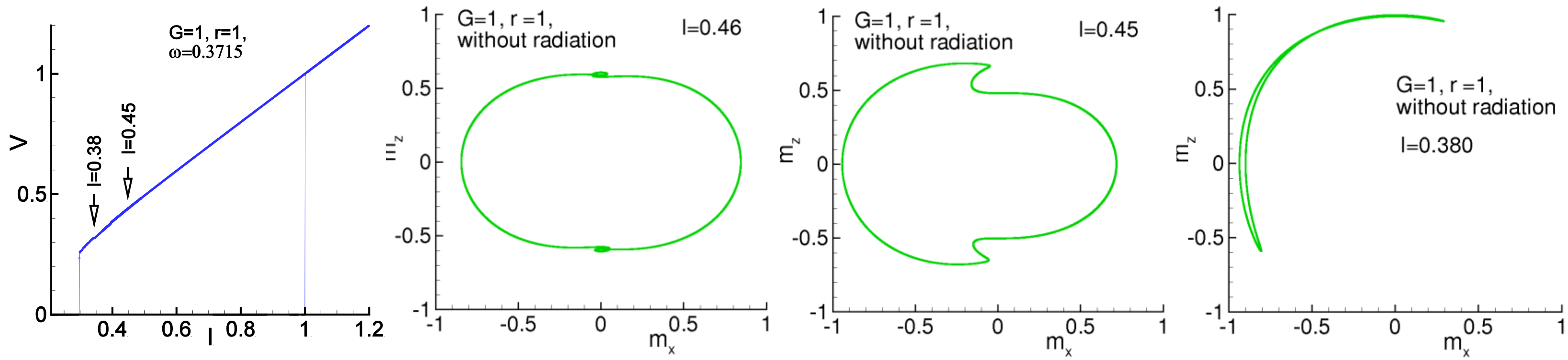
Damped resonance at $\boldsymbol{\omega}$ => 1



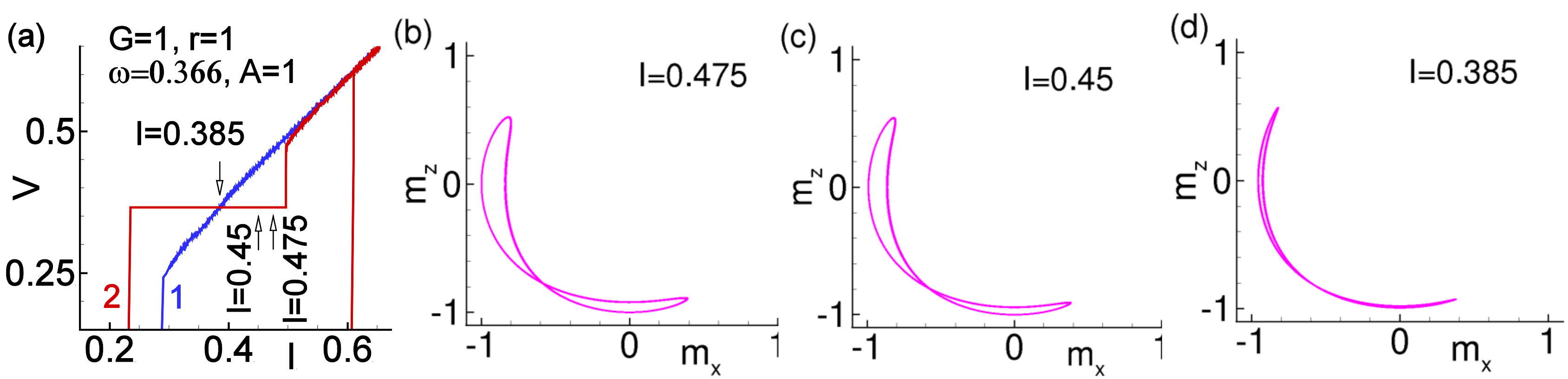
○ Yu.M. Shukrinov, I.R. Rahmonov, K. Sengupta, Physical Review B 99, 224513 (2019)

Effect of external electromagnetic radiation

Without radiation



Under radiation, W=0.366, A=1

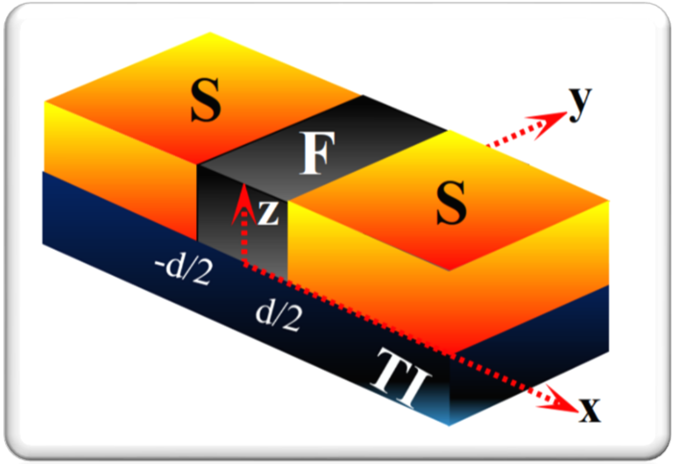


The transformation of precession trajectories under the influence of external periodic drive

- Yu.M. Shukrinov, I.R. Rahmonov, K. Sengupta, Physical Review B 99, 224513 (2019)

S/F/S Josephson junctions on top of 3D TI

SFS Junction on top of TI



The expression for the Josephson current is

$$J_s = J_c(m_x)\sin\left(\varphi - \frac{2h_y d}{v_F}\right),$$
$$J_c(m_x) = J_b \int_{-\pi/2}^{\pi/2} e^{\left[-\frac{2\pi T d}{v_F \cos\phi}\right]} \cos\left[\frac{2h_x d \tan\phi}{v_F}\right] \cos\phi d\phi,$$

The Josephson energy reads as

$$E_s = \epsilon_J \left[1 - \cos\left(\Omega_J t - r m_y\right)\right]$$

The effective field components in LLG equation read as

$$\frac{dm}{d\tau} = -\frac{\Omega_F}{(1+\alpha^2)}\left(m \times h_{eff} + \alpha\left[m \times (m \times h_{eff})\right]\right).$$

$$h_x = \Gamma\left[\int_{-\pi/2}^{\pi/2} e^{-\tilde{d}/\cos\phi} \sin\phi \sin\left(r m_x \tan\phi\right) d\phi\right]\left[1 - \cos\left(\Omega_J t - r m_y\right)\right]$$
$$h_y = \Gamma\left[\int_{-\pi/2}^{\pi/2} e^{-\tilde{d}/\cos\phi} \cos\phi \cos\left(r m_x \tan\phi\right) d\phi\right] \sin\left(\Omega_J t - r m_y\right) + m_y$$
$$h_z = 0,$$

$$\Gamma = Gr/J_c^{m_x=0}, \text{ and } G = \epsilon_J / K_{an} V_F.$$

- M. Nashaat, I. V. Bobkova, A. M. Bobkov, Yu. M. Shukrinov, I. R. Rahmonov, K. Sengupta, Phys. Rev. B 100, 054506 (2019)

Easy axis splitting

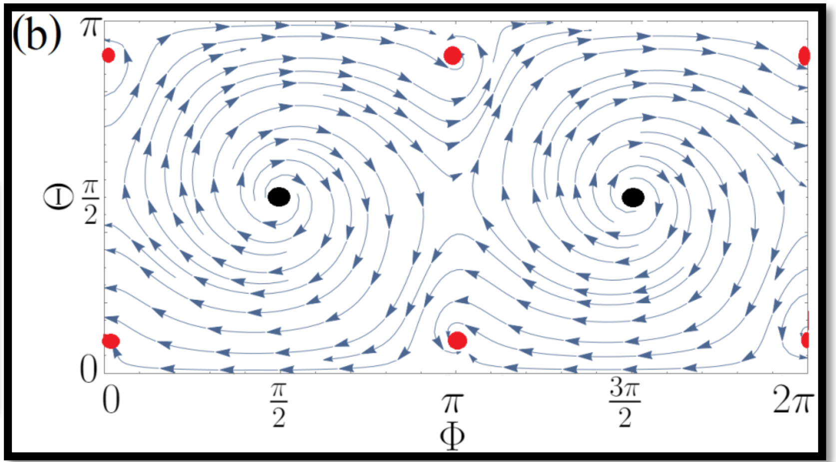
$$h_x = \Gamma\left[\int_{-\pi/2}^{\pi/2} e^{-\bar{d}/\cos\phi}\sin\phi\sin\left(rm_x\tan\phi\right)d\phi\right]\left[1-\cos\left(\Omega_J t - rm_y\right)\right]$$

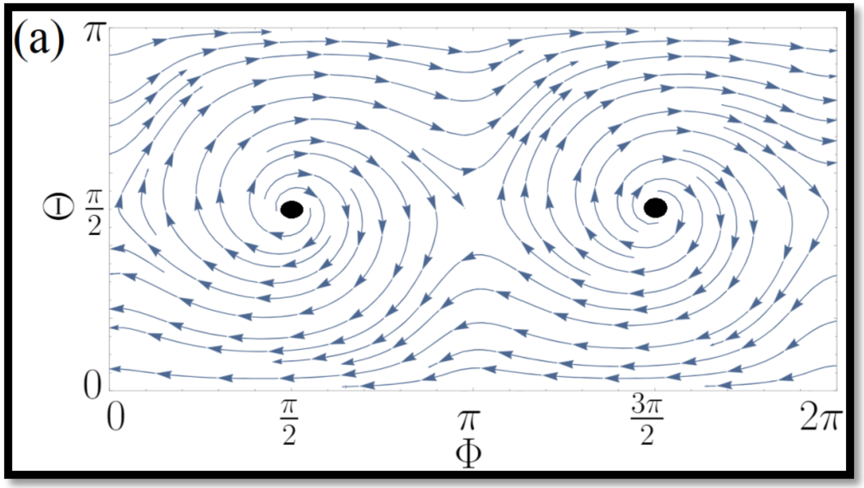
$$h_y = \Gamma\left[\int_{-\pi/2}^{\pi/2} e^{-\bar{d}/\cos\phi}\cos\phi\cos\left(rm_x\tan\phi\right)d\phi\right]\sin\left(\Omega_J t - rm_y\right) + m_y$$

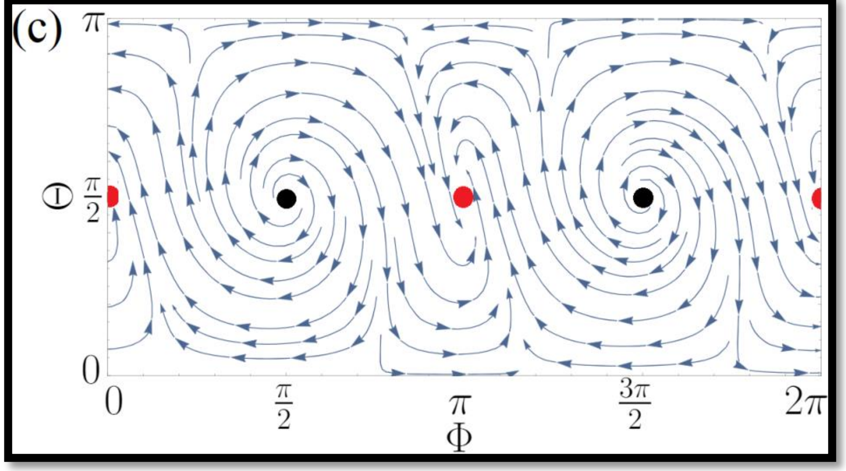
$$\boldsymbol{m} = (\sin\Theta\cos\Phi, \cos\Theta, \sin\Theta\sin\Phi).$$

$$\dot{\Theta} = \frac{\Omega_F}{\alpha^2+1}\left(-\alpha h_y\sin\Theta + h_x(\alpha\cos\Theta\cos\Phi + \sin\Phi)\right),$$

$$\dot{\Phi} = \frac{\Omega_F}{\alpha^2+1}\left(-\alpha h_x(\csc\Theta\sin\Phi + \cot\Theta\cos\Phi) - h_y\right).$$

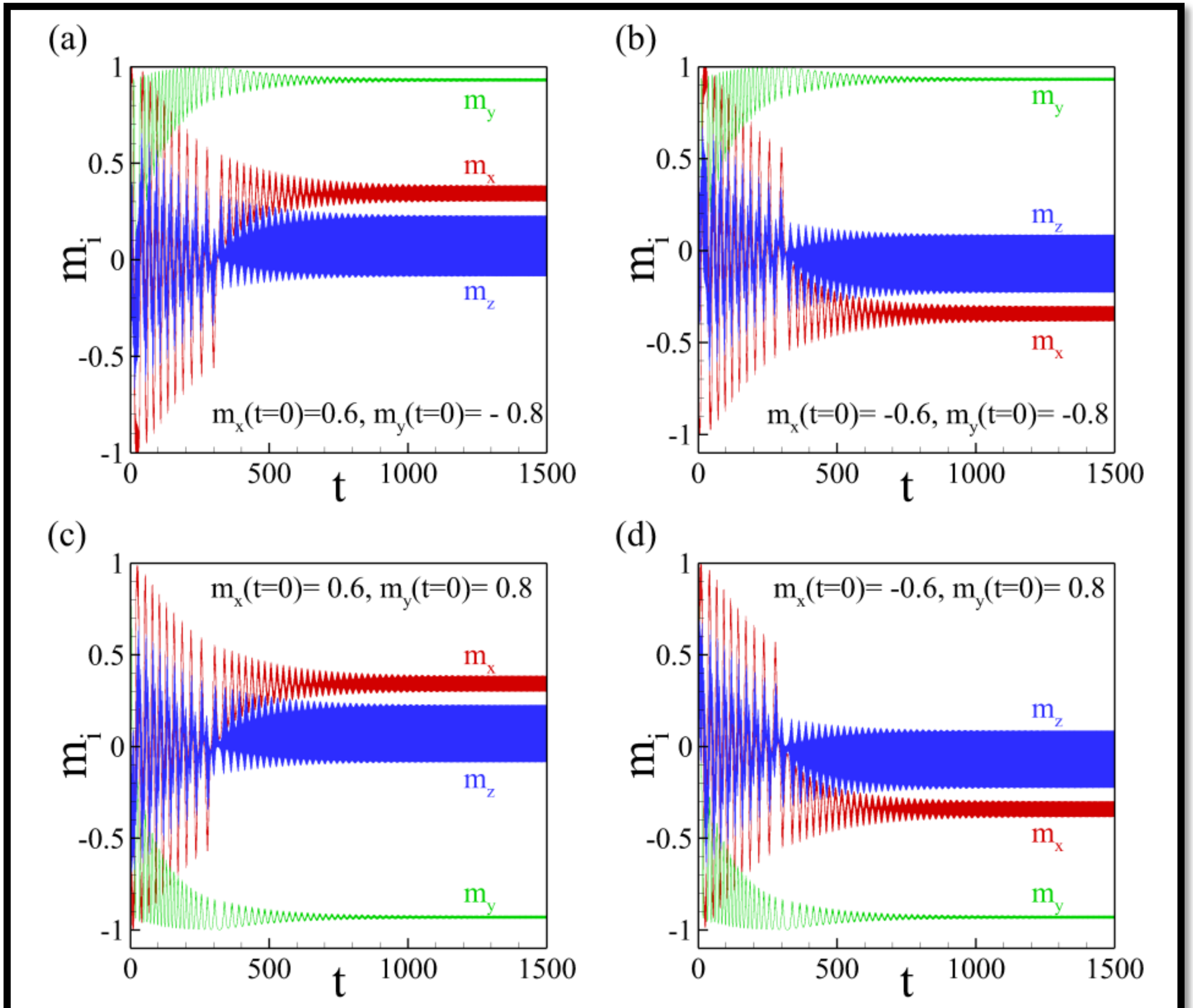






○ M. Nashaat, I. V. Bobkova, A. M. Bobkov, Yu. M. Shukrinov, I. R. Rahmonov, K. Sengupta, Phys. Rev. B 100, 054506 (2019)

Magnetization Dynamics



Time evolution of the magnetization starting from different initial conditions.

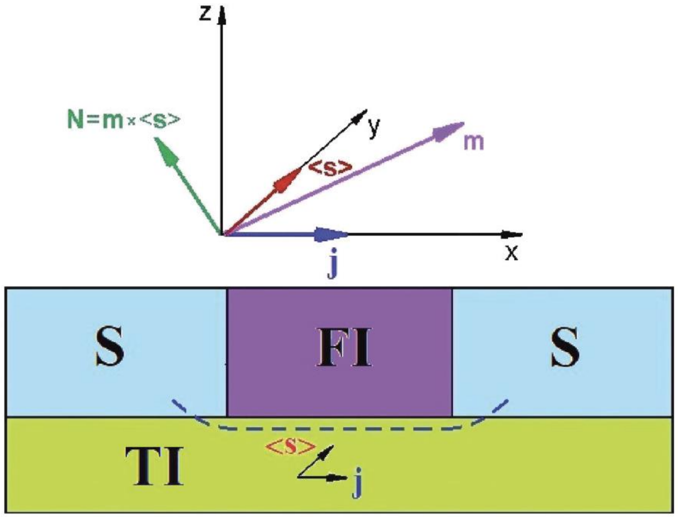
Four panels correspond to four possible stable states, which are reached by the system at large t.

Γ = 1.57, r = 0.5, $\tilde{d}$= 0.3, α = 0.01, Ω_F /Ω_J = 0.2, time is measured in units of Ω_J^{-1}

○ M. Nashaat, I. V. Bobkova, A. M. Bobkov, Yu. M. Shukrinov, I. R. Rahmonov, K. Sengupta, Phys. Rev. B 100, 054506 (2019)

S/IF/S Josephson junctions on top of 3D TI

S/IF/S Josephson junctions on 3D TI



The dashed line represents a schematic trajectory of the current flow.

The LLG equation:

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} + \frac{\alpha}{M} \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial t} + \frac{J_{\text{ex}}}{d_F} \boldsymbol{M} \times \langle \boldsymbol{s} \rangle,$$

The effective exchange field

The effective field components in LLG equation read as

$$\boldsymbol{H}_{\text{eff}} = -\frac{K}{M} m_z \boldsymbol{e}_z + \frac{K_u}{M} m_x \boldsymbol{e}_x,$$

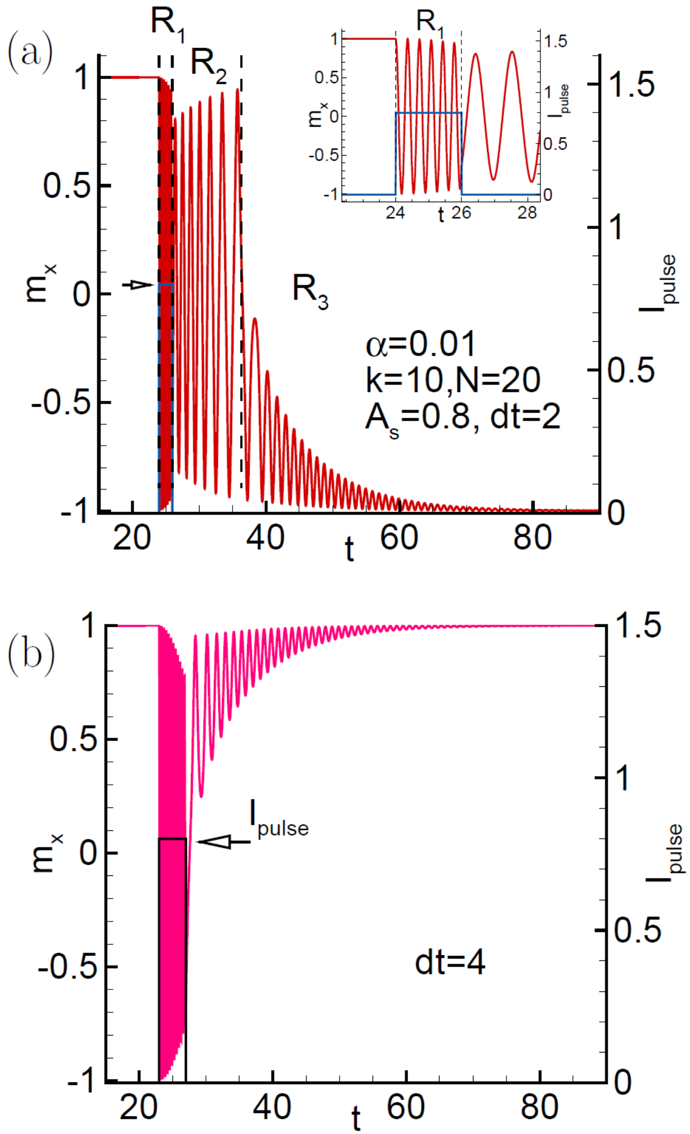
where K and K_u → hard axis and easy axis anisotropy constants

The expression for the Josephson current is $j = j_c \sin(\chi - \chi_0) + \frac{1}{2eR_N}(\dot{\chi} - \dot{\chi}_0)$

The induced electron spin polarization <s> lies in the TI surface plane and is perpendicular to the current.

- I. V. Bobkova, A. M. Bobkov, I. R. Rahmonov, A. A. Mazanik, K. Sengupta, and Yu. M. Shukrinov, Physical Review B, 102, 134505 (2020)

Magnetization reversal



The ratio of the hard-axis and easy-axis anisotropies → $k = K/K_u$

It is seen that the magnetization dynamics consists of three different regimes R1, R2 and R3 in panel (a).

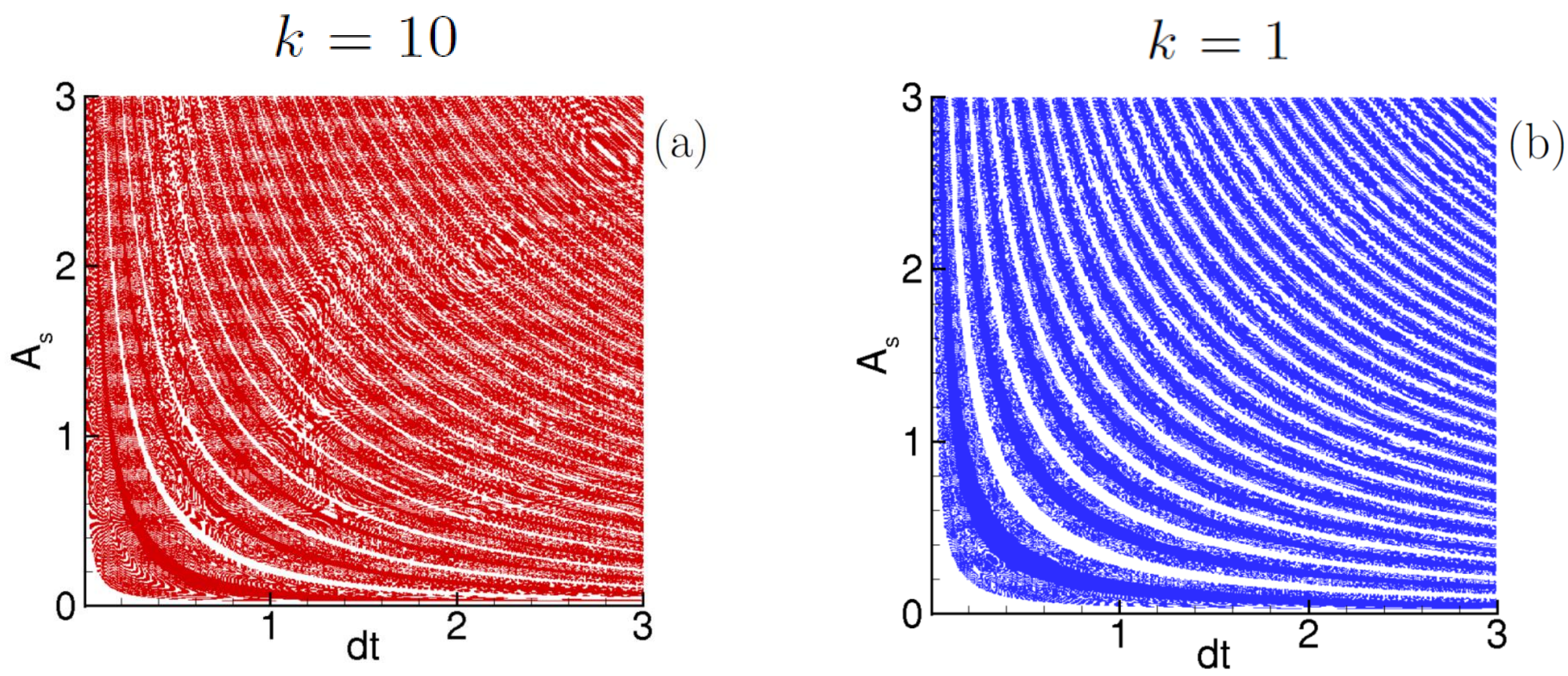
The regime R1 corresponds to the dynamics during the current pulse.

Regime R2 differs from R3 by the fact that the final state of the magnetization is not determined yet in this regime.

Regime R2 is not necessary realized in the system. Such an example is illustrated in panel (b).

○ I. V. Bobkova, A. M. Bobkov, I. R. Rahmonov, A. A. Mazanik, K. Sengupta, and Yu. M. Shukrinov, Physical Review B, 102, 134505 (2020)

Reversal diagram



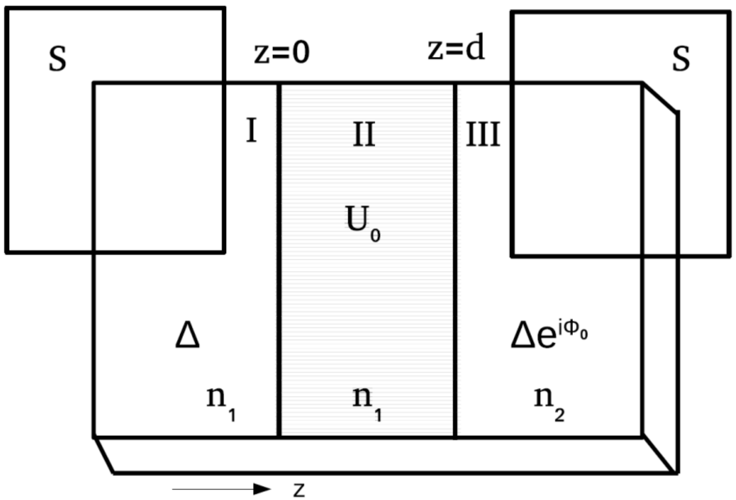
The regions, where the reversal occurs are colored and where it does not occur are white.

They are separated by the white/colored striped regions, which represent an "uncertainty" regime.

- I. V. Bobkova, A. M. Bobkov, I. R. Rahmonov, A. A. Mazanik, K. Sengupta, and Yu. M. Shukrinov, Physical Review B, 102, 134505 (2020)

Weyl and multi-Weyl semimetals Josephson junctions

Josephson junctions of Weyl and multi-Weyl semimetals



The expression for the Andreev bound states

$$E_{\pm}(\phi_0) = \pm\Delta_0\sqrt{1 - T_N \sin^2(\phi_0/2)}$$

The expression for the Josephson current is

$$I_J = \frac{I_0}{4n_1}\left(\frac{Lk_F}{2\pi}\right)^2 \int_0^{\pi/4} d\theta \int_0^{2\pi} d\phi \times (\sin 2\theta)^{2/n_1 - 1} \cos 2\theta \frac{T_N \sin\phi_0}{\sqrt{1 - T_N \sin^2(\phi_0/2)}}$$

$$G_N = \left(\frac{e^2}{hn_1}\frac{Lk_F}{2\pi}\right)^2 \int_0^{\pi/4} d\theta \times \int_0^{2\pi} d\phi (\sin 2\theta)^{2/n_1 - 1} \cos 2\theta \; T_N$$

→ The normal state junction conductance

The expression for tunneling conductance is given by

$$T_N = \frac{2\cos\theta_1\cos\theta_3}{1 + \cos\theta_1\cos\theta_3 - \sin\theta_1\sin\theta_3\cos((n2 - n1)\phi + 2\chi)}$$

where

$$\cos\theta_1 = \sqrt{1 - \frac{k_p^{2n1}}{\mu_s^2}}$$

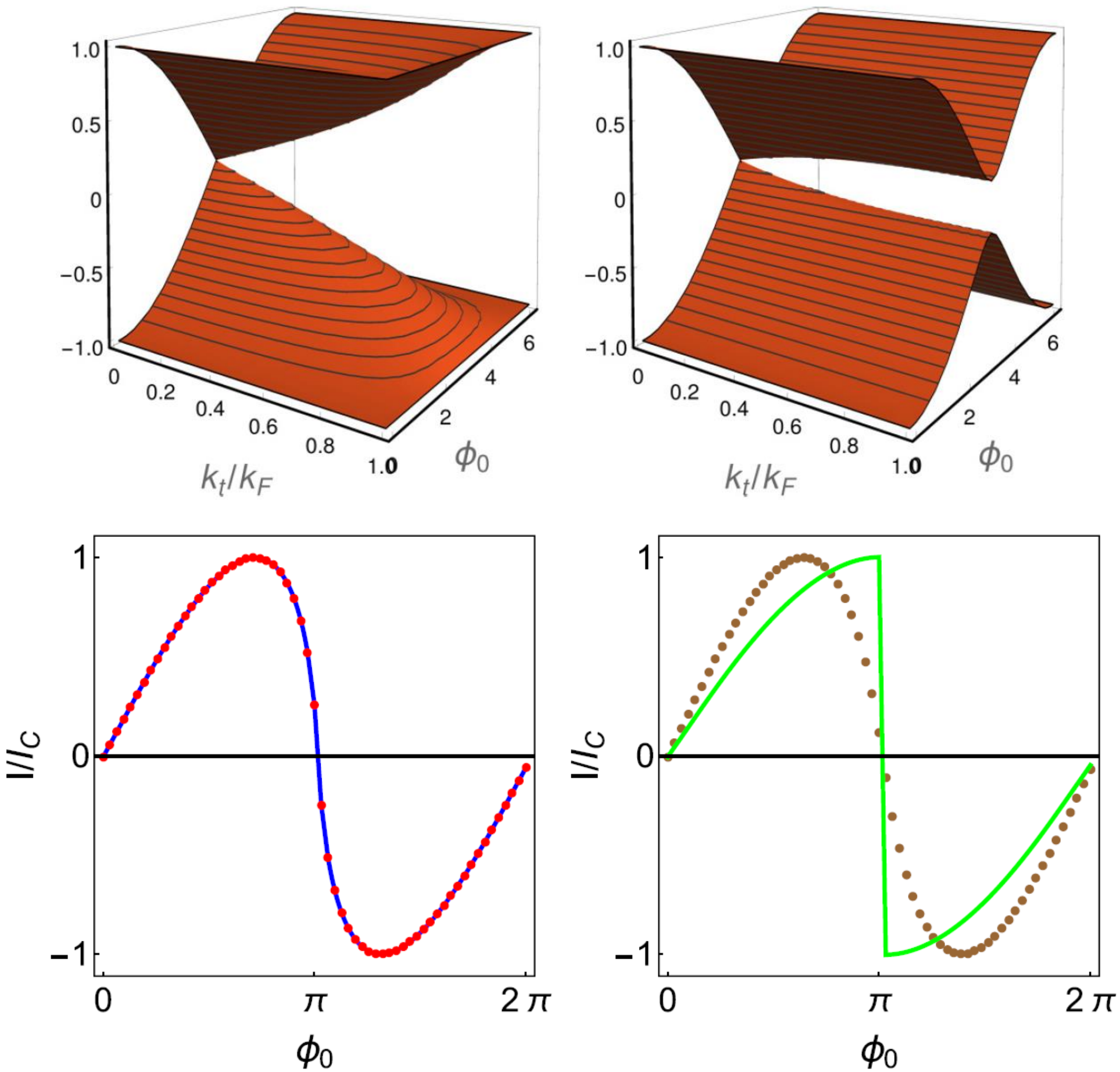
$$\cos\theta_3 = \sqrt{1 - \frac{k_p^{2n2}}{\mu_s^2}}$$

$$\chi = U_0 d/(\hbar v_F)$$

→ The barrier parameter

○ Kirill Kulikov, Debabrata Sinha, Yu. M. Shukrinov, K. Sengupta, Phys. Rev. B 101, 075110 (2020)

Energy and superconducting current dependencies

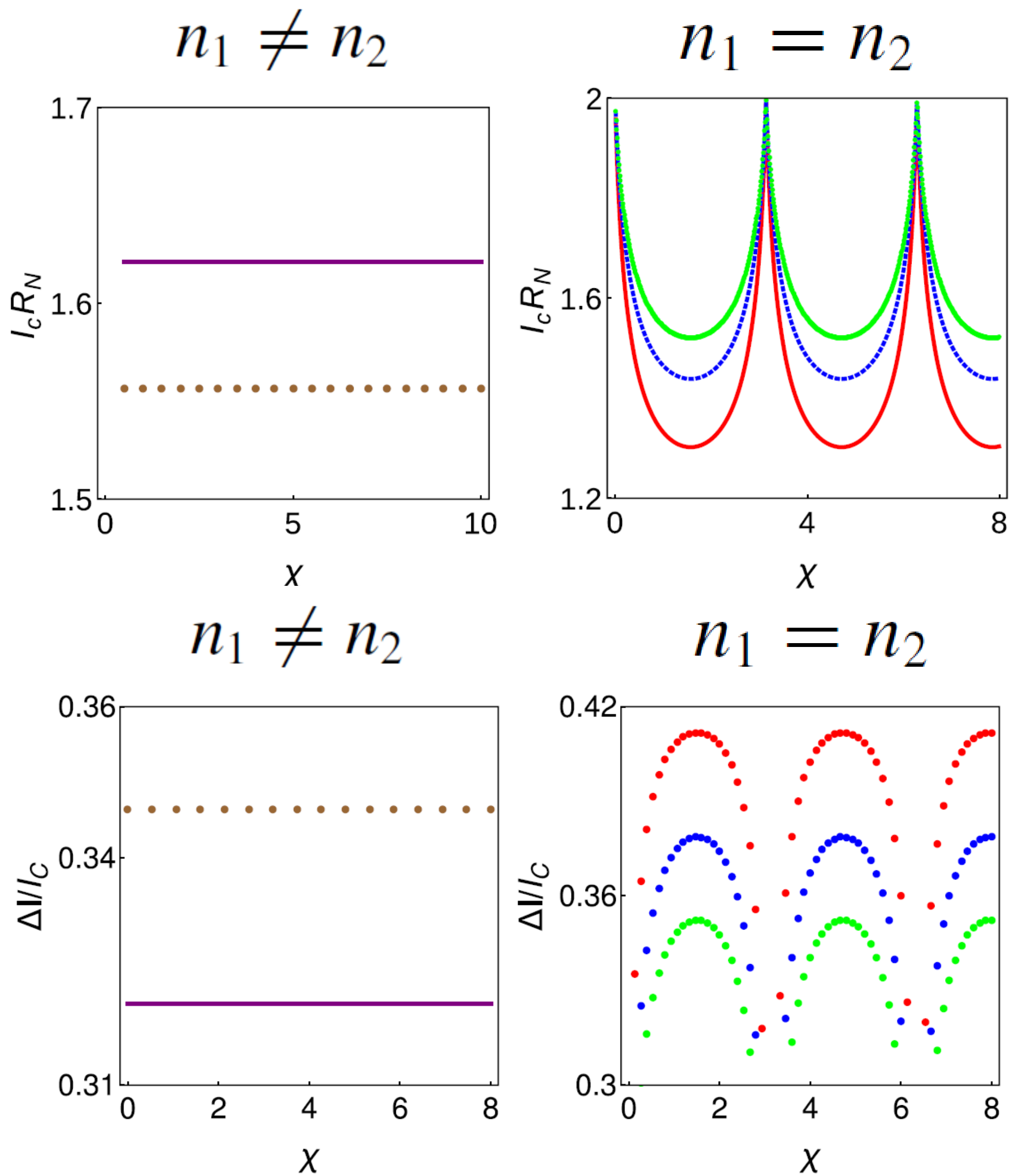


Energy as a function of the relative phase and the transverse momentum

Note that I/Ic becomes independent of χ in the thin-barrier limit for $n1 = n2$ (left panel) but depends substantially on χ if $n1 = n2$ (right panel).

○ Kirill Kulikov, Debabrata Sinha, Yu. M. Shukrinov, K. Sengupta, Phys. Rev. B 101, 075110 (2020)

System of nanomagnet + Josephson junction



The barrier independent of *IcRN* for *n*1 ≠ *n*2 for several choices of *n*1 and *n*2. We find *c* = 1.56 (1.62) for *n*1 = 1 and *n*2 = 2 (3)

$$I_c R_N = \frac{\pi \Delta_0}{2e}\frac{\mathcal{I}_1}{\mathcal{I}_2} = \frac{\pi \Delta_0}{2e} c$$

In contrast, *c* is an oscillatory function of *χ* for *n*1 = *n*2 as shown in the right panel

IcRN starts to oscillate with the barrier strength. However, the magnitude of this oscillation decreases rapidly with decreasing the barrier thickness.

- Kirill Kulikov, Debabrata Sinha, Yu. M. Shukrinov, K. Sengupta, Phys. Rev. B 101, 075110 (2020)

Summary

- It was shown that an external electromagnetic field allows to control the magnetic moment dynamics and can lead to a transformation of precession trajectories.

- The splitting of the ferromagnet's easy-axis which can lead to stabilization of an unconventional four-fold degenerate ferromagnetic state was demonstrated .

- It was demonstrated that strong spin-momentum locking in the TI surface states provides a possibility of efficient reversal of the magnetic moment by current pulse with amplitude lower than the critical current, that results in strongly reduced energy dissipation.

- It was shown that the product of the critical current on the normal-state resistance for Weyl semimetal based junctions, has a universal value independent of the barrier potential, which is a consequence of change in topological winding number across the junction.

Future plans

We plan to continue our collaborative work investigating higher-order topological superconductors. This year we submitted a joint Russian-India project to RSF with the title: *"Temperature Driven Emergent Phases and Novel Transport Signatures in Higher-order Topological Materials"*

Thank you for attention.