

Development of a Toolkit for Modeling of Cryogenic Memory Based on Controllable Magnetization Reversal in a Coupled Chain of φ_0 Junctions

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Tashkent, Uzbekistan

18-22 October

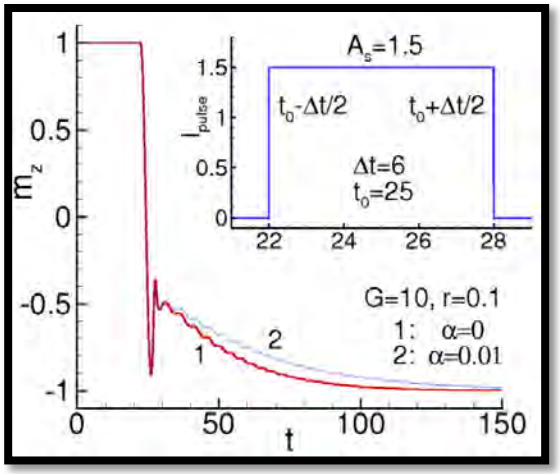
Anomalous Josephson Effect

- In SFS Josephson junction the spin orbit coupling in Ferromagnetic layer, leads to the direct coupling of magnetization dynamics and superconducting current.
- In the current phase relation of such junctions appears the phase shifting φ_0, and they called φ_0 junction and observed effect called Anomalous Josephson effect.

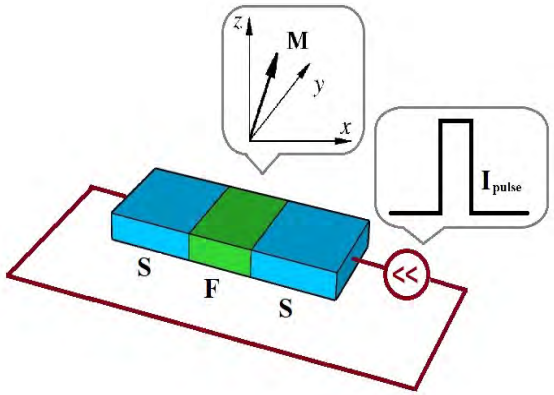
$$I_s = I_c \sin(\varphi - \varphi_0), \qquad \varphi_0 = r\frac{M_y}{M_0}$$

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

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



Time dependence of m_z in φ_0 -junction



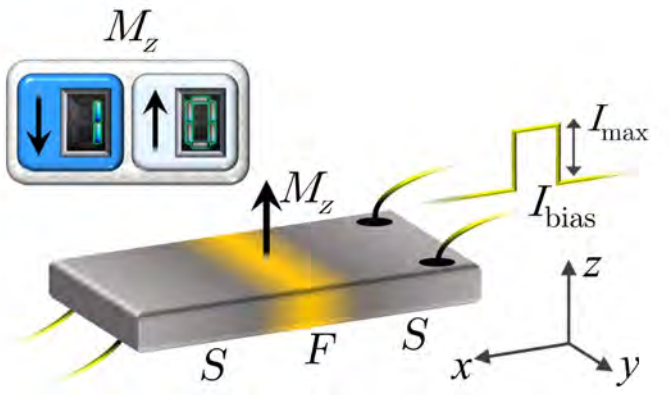
Scheme of SFS φ_0 - junction

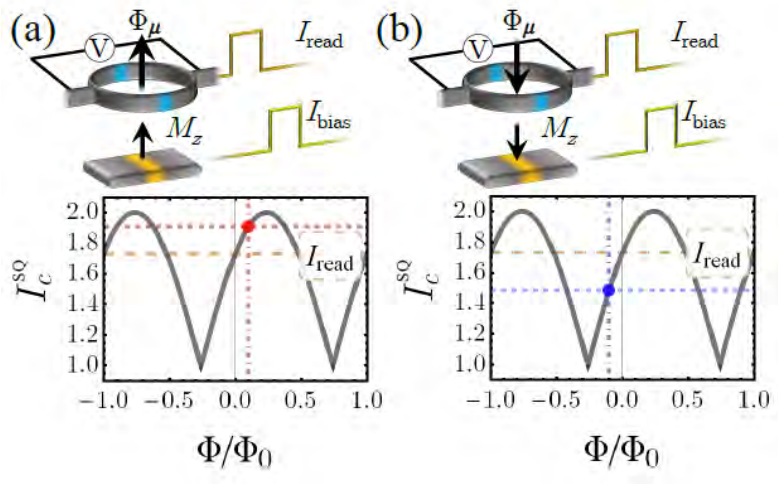
Yu. M. Shukrinov, I. R. Rahmonov, K. Sengupta, and A. Buzdin, Magnetization reversal by superconducting current in φ_0 Josephson Junctions, **Appl. Phys. Lett. 110, 182407 (2017)**

A toolkit for simulation of magnetization reversal in the form of Jupyter Book has been developed:
http://studhub.jinr.ru:8080/books/intro.html

New memory element based on magnetization reversal in φ_0 - junction

Based on the magnetization reversal in φ_0 junction suggested the cryogenic memory element





S/F/S Josephson junction driven by a rectangular current pulse. The z-component of the magnetization, M_z, is the observable used to define the logic memory states 0 and 1.

SQUID-based memory readout and figure showing the critical current interference pattern of the SQUID, in the cases of both positive and negative orientation along the z-axis of the magnetization, see panel (a) and (b), respectively.

C. Guarcello and F.S. Bergeret, Cryogenic Memory Element Based on an Anomalous Josephson Junction, **Phys. Rev. Appl. 13, 034012 (2020)**

Patented memory element

(12) **United States Patent**
Naaman

(10) **Patent No.: US 10,650,884 B2**
(45) **Date of Patent: May 12, 2020**

(54) **SUPERCONDUCTING MEMORY WITH JOSEPHSON PHASE-BASED TORQUE**

(71) Applicant: **Microsoft Technology Licensing, LLC**, Redmond, WA (US)

(72) Inventor: **Ofer Naaman**, Santa Barbara, CA (US)

(73) Assignee: **Microsoft Technology Licensing, LLC**, Redmond, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/120,882**

2015/0094207	A1	4/2015	Herr et al.	
2015/0097159	A1*	4/2015	Apalkov	H01L 43/08 257/31
2018/0025775	A1*	1/2018	Ambrose	G11C 11/44 257/35

OTHER PUBLICATIONS

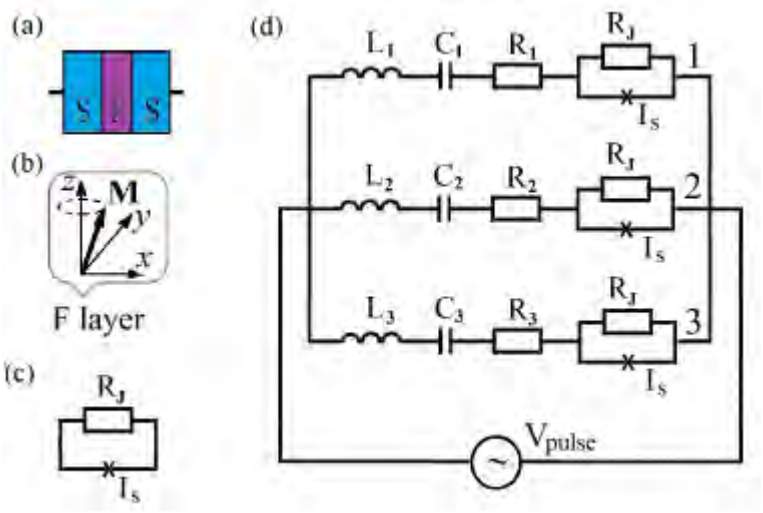
Dayton, et al., "Experimental Demonstration of a Josephson Magnetic Memory Cell with a Programmable π-Junction", In Journal of IEEE Magnetics Letters, vol. 9, Feb. 8, 2018, pp. 1-6.

Konschelle, et al., "Magnetic Moment Manipulation by a Josephson Current", In Journal of Physical Review letters, Jan. 5, 2009, pp. 1-5.

Shukrinov, et al., "Magnetization reversal by superconducting current in ϕ0 Josephson junctions", In Journal of Applied Physics Letters, vol. 110, Issue 18, May 1, 2017, pp. 1-7.

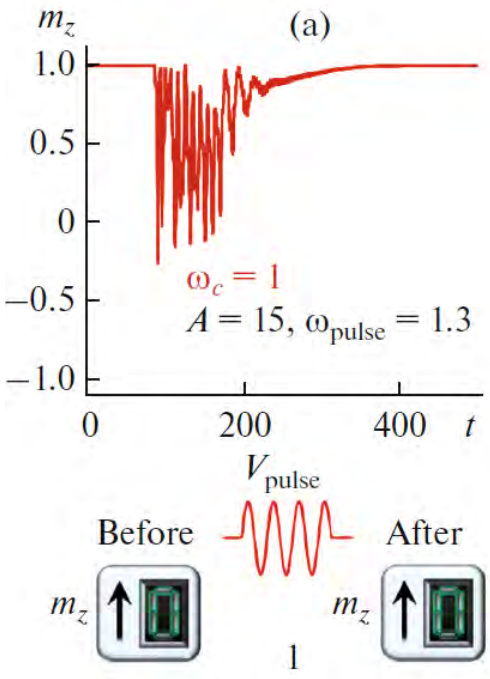
A patent based on the magnetization reversal phenomenon confirms its relevance.

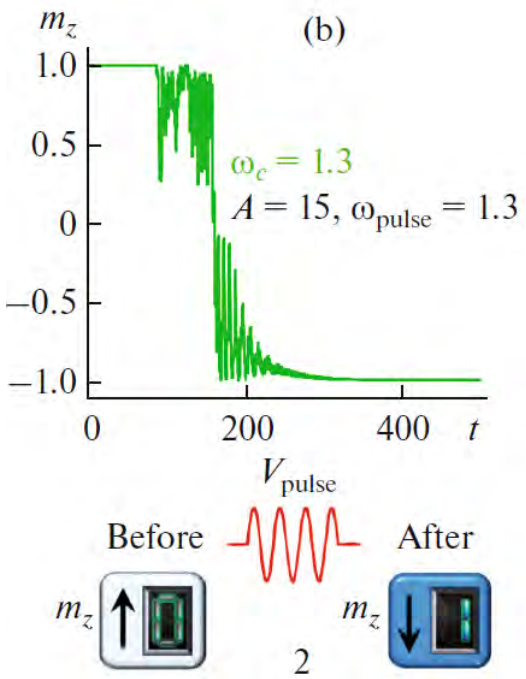
Controllable magnetization reversal

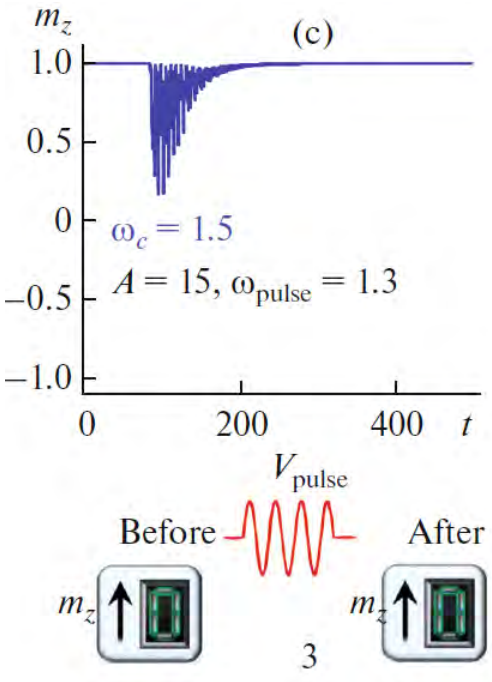


The possibility of a controllable magnetization reversal under the AC pulse is demonstrated

A. R. Rahmonova, O. I. Streltsova, I. R. Rahmonov, M. I. Zuev, Physics of Particles and Nuclei, 56, 1592 - 1598 (2025).





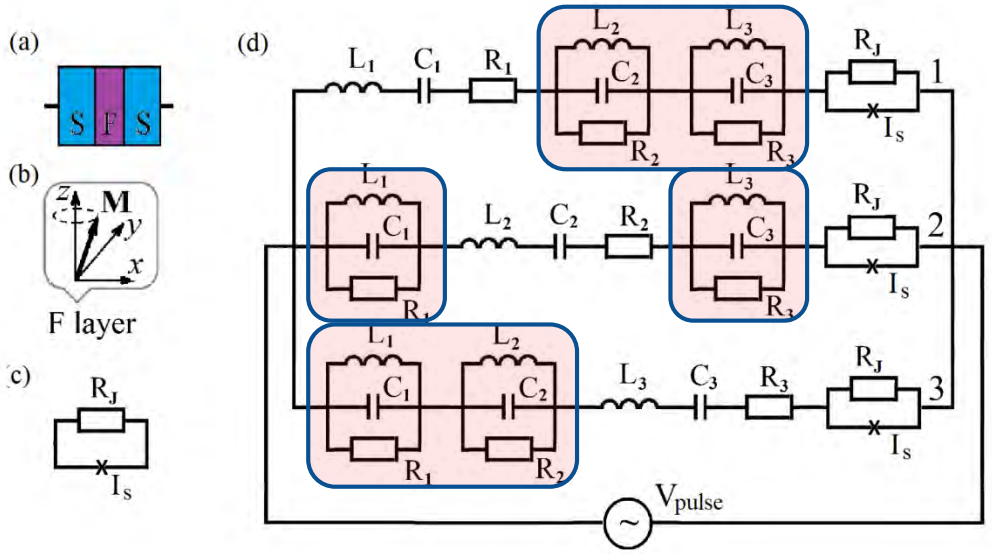


Motivation

Main question: In case of realization of controllable magnetization reversal occurs parasitic magnetization reversal.

How to eliminate this parasitic magnetization reversal?

Equivalent scheme of considered system



(a) SFS junction; (b) magnetization direction relative to the coordinate axes (z – easy axis); (c) equivalent scheme of φ_0 –junction; (d) scheme of considered system with filters.

We consider 3 φ₀ junctions, each of which is connected in series to the one serial and two parallel LCR-circuits. Each of LCR-circuits has its own eigenfrequency, which can be find by expression $\omega_{c,ij} = \sqrt{\frac{1}{LC}}$, in case of $i = j$ eigenfrequency corresponds to the serial circuit and in case of $i \neq j$ to the parallel circuit.

The parallel circuits plays role of filters and reduces the possibility of parasitic.

Mathematical modeling of a controllable magnetization reversal

$$\frac{dm_{xi}}{dt} = -\frac{\omega_F}{1+\alpha^2}\{m_{yi}h_{zi} - m_{zi}h_{yi} + \alpha[m_{xi}(m_{xi}h_{xi} + m_{yi}h_{yi} + m_{zi}h_{zi}) - h_{xi}]\},$$

$$\frac{dm_{yi}}{dt} = -\frac{\omega_F}{1+\alpha^2}\{m_{zi}h_{xi} - m_{xi}h_{zi} + \alpha[m_{yi}(m_{xi}h_{xi} + m_{yi}h_{yi} + m_{zi}h_{zi}) - h_{yi}]\},$$

$$\frac{dm_{zi}}{dt} = -\frac{\omega_F}{1+\alpha^2}\{m_{xi}h_{yi} - m_{yi}h_{xi} + \alpha[m_{zi}(m_{xi}h_{xi} + m_{yi}h_{yi} + m_{zi}h_{zi}) - h_{zi}]\},$$

$$\frac{d\varphi_i}{dt} = I_i - \sin(\varphi_i - rm_{yi}) + r\frac{dm_{yi}}{dt},$$

$$\frac{dI_i}{dt} = \frac{1}{L_i}\left[V_{pulse} - R_iI_i - \frac{q_i}{C_i} - \sum_{j=1(j\neq i)}^{3} u_{ij} - \frac{d\varphi_i}{dt}\right],$$

$$\frac{dq_i}{dt} = I_i,$$

$$\frac{du_{ij}}{dt} = \frac{1}{C_j}\left[I_i - \frac{u_{ij}}{R_j} - I_{L,ij}\right],$$

$$\frac{dI_{L,ij}}{dt} = \frac{u_{ij}}{L_j}, i \neq j.$$

Effective field components

$h_{xi} = 0$

$h_{yi} = Gr\sin(\varphi_i - rm_{yi})$

$h_{zi} = m_{zi}$

G - relation of Josephson energy to magnetic energy

ω_F - Ferromagnetic resonance frequency

r - spin orbit coupling parameter

α - Gilbert damping parameter

L_i - inductance

R_i - resistance

C_i -capacitance

Initial condition

$$m_{xi}(0) = 0, m_{yi}(0) = 0, m_{zi}(0) = 1,\ \varphi_i(0) = 0, I_i(0) = 0, q_i(0) = 0, I_{L,ij}(0) = 0, u_{ij}(0) = 0$$

m_{xi}, m_{yi}, m_{zi} - components of magnetization

φ_i - phase difference

$I_{L,ij}$ - current trhougth inductance of parallel circuit

I_i - current through the i-th branch

q_i - charge in capacitance of serial circuit

u_{ij} - voltage in parallel circuits

$i = 1, 2, 3$ - number of circuit branch

Expression for external AC voltage pulse

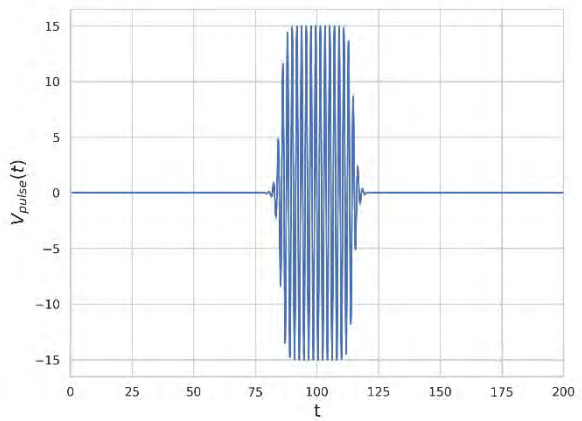
Here V_{pulse} is the AC voltage pulse and defined as following

$$V_{pulse} = \frac{A}{2}\sin(\omega_p t)\left[\tanh\left(\frac{t - t_{on}}{w}\right) - \tanh\left(\frac{t - t_{off}}{w}\right)\right]$$

$[t_{on}, t_{off}]$ - time interval, where is applied pulse

w - time duration of pulse rise and fall ω_p - frequency of pulse

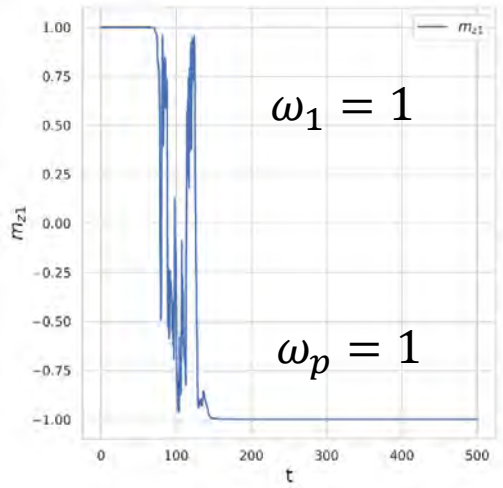
A - Amplitude of pulse



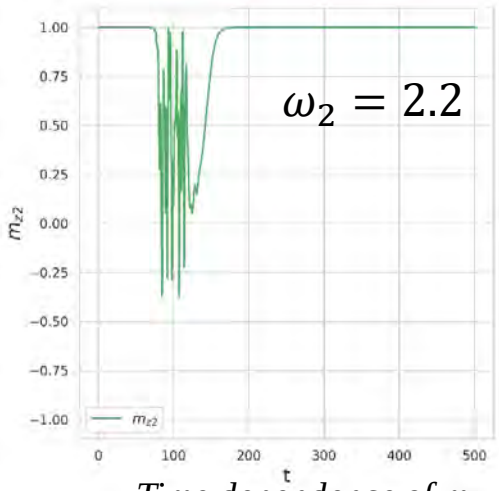
Time dependence of AC voltage pulse

We have numerically solved system of equations using Fourth order Runge-Kutta method, where time step size was $\Delta t=0.005$.

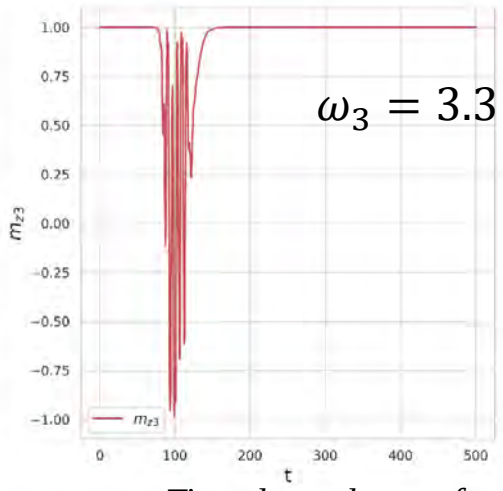
Results of simulation



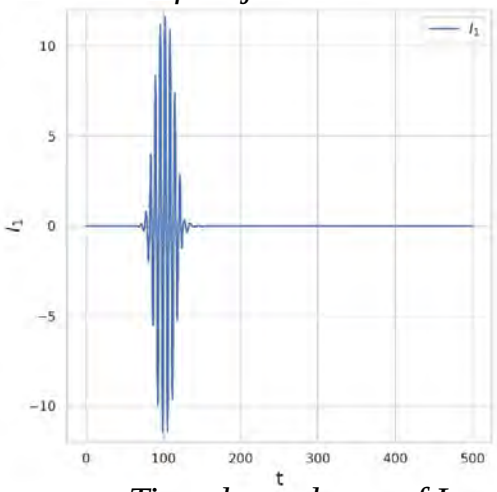
Time dependence of m_z in first junction



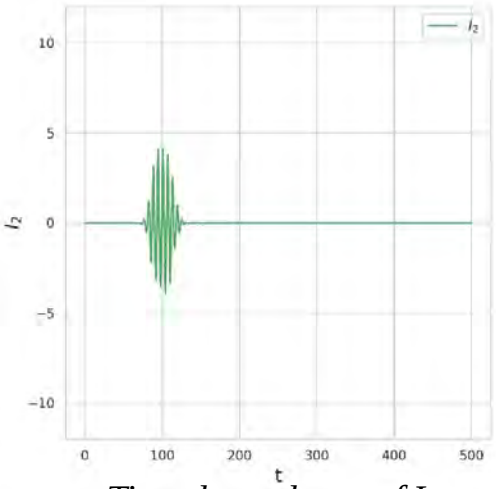
Time dependence of m_z in second junction



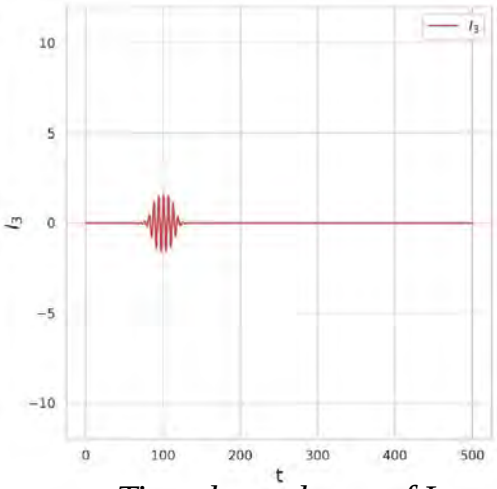
Time dependence of m_z in third junction



Time dependence of I through the first branch



Time dependence of I through the second branch

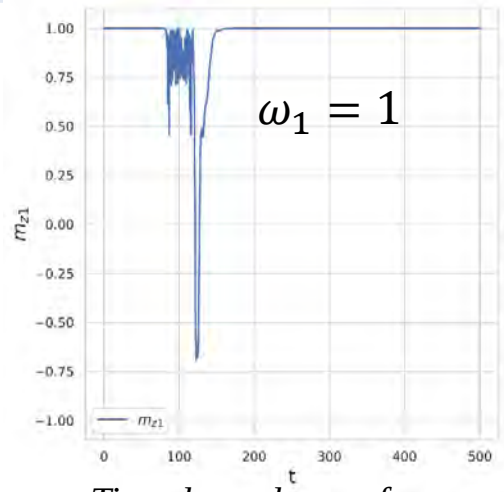


Time dependence of I through the third branch

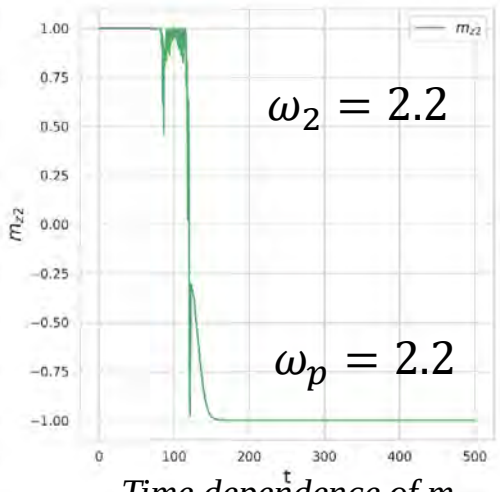
Here we applied voltage pulse with frequency corresponding to the eigenfrequency of first LCR-circuit and obtain magnetization reversal of first φ0 junction

$A = 15, L_i = 1, R_i = 0.1, \omega_F = 1, G = 15, r = 0.1, \alpha = 0.1.$

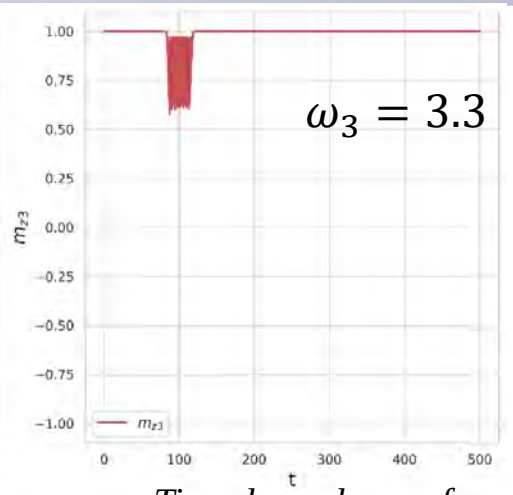
Results of simulation



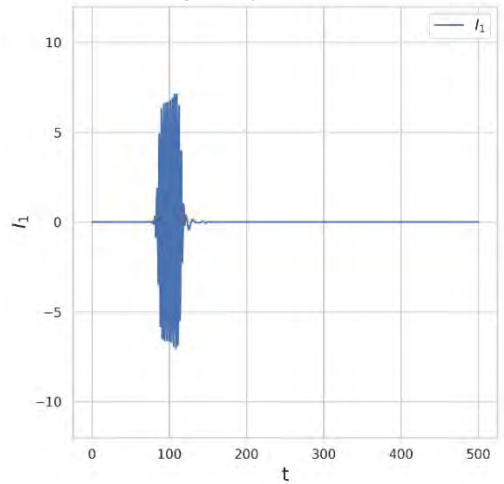
Time dependence of m_z in first junction



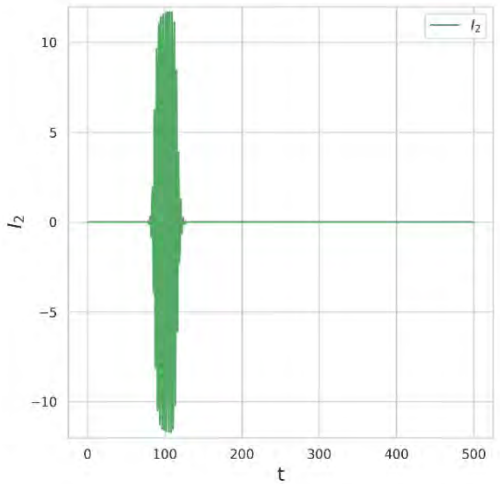
Time dependence of m_z in second junction



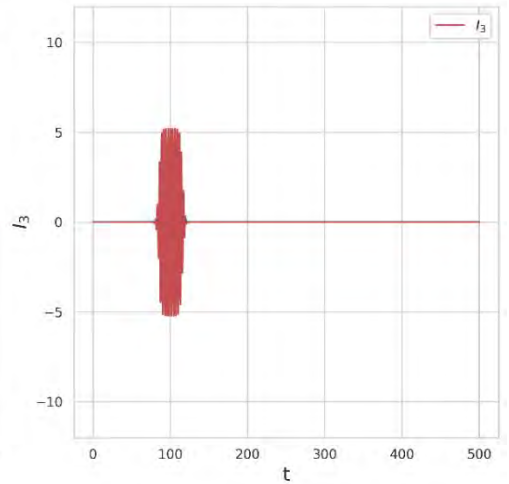
Time dependence of m_z in third junction



Time dependence of I through the first branch



Time dependence of I through the second branch

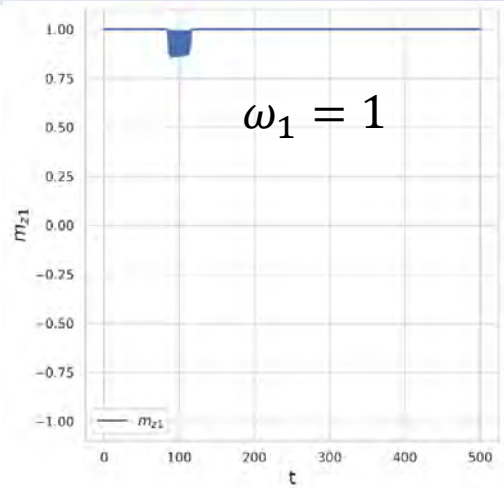


Time dependence of I through the third branch

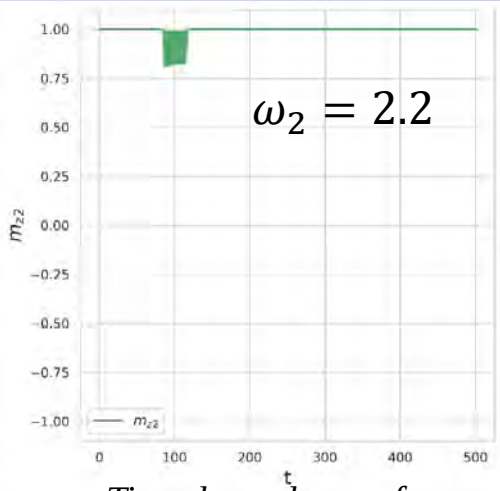
Here we applied voltage pulse with frequency corresponding to the eigenfrequency of second LCR-circuit and obtain magnetization reversal of second φ₀ junction

$A = 15, L_i = 1\ , R_i = 0.1, \omega_F = 1, G = 15, r = 0.1, \alpha = 0.1.$

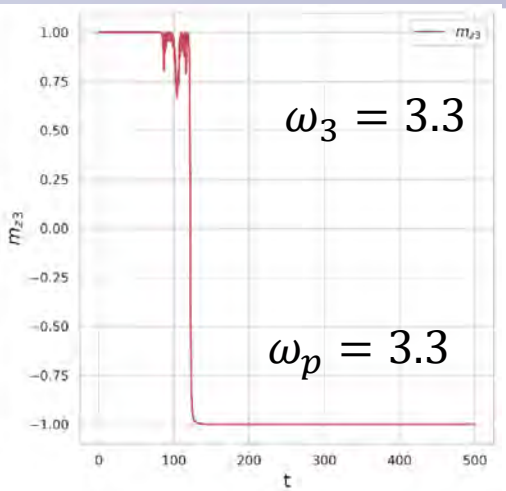
Results of simulation



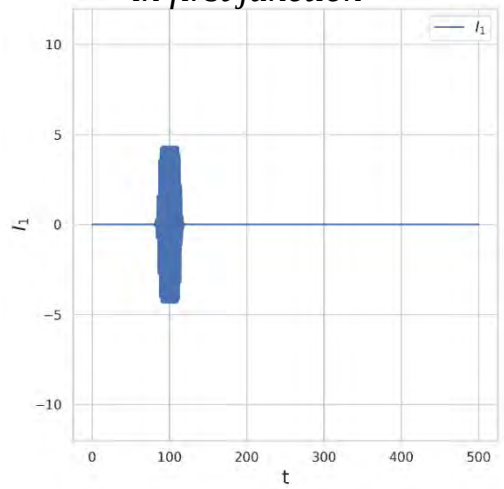
Time dependence of m_z in first junction



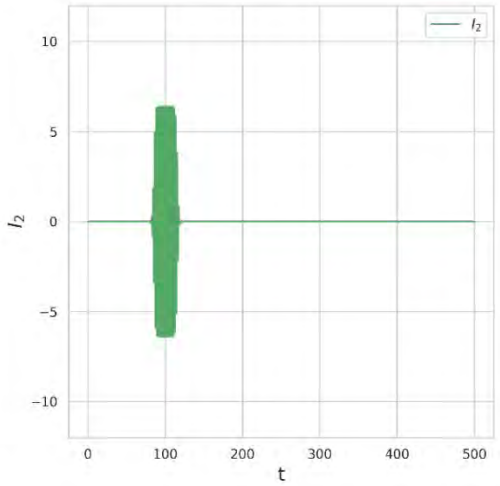
Time dependence of m_z in second junction



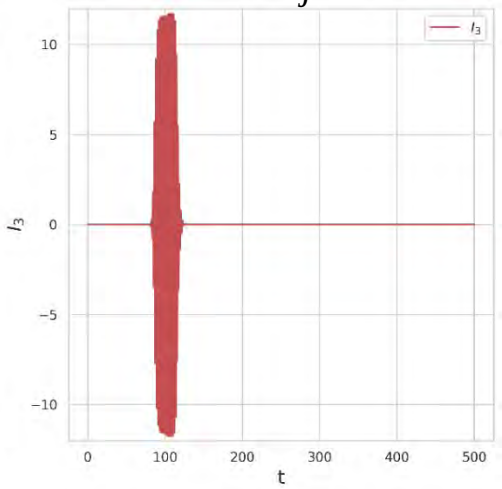
Time dependence of m_z in third junction



Time dependence of I through the first branch



Time dependence of I through the second branch



Time dependence of I through the third branch

Here we applied voltage pulse with frequency corresponding to the eigenfrequency of third LCR-circuit and obtain magnetization reversal of third φ0 junction

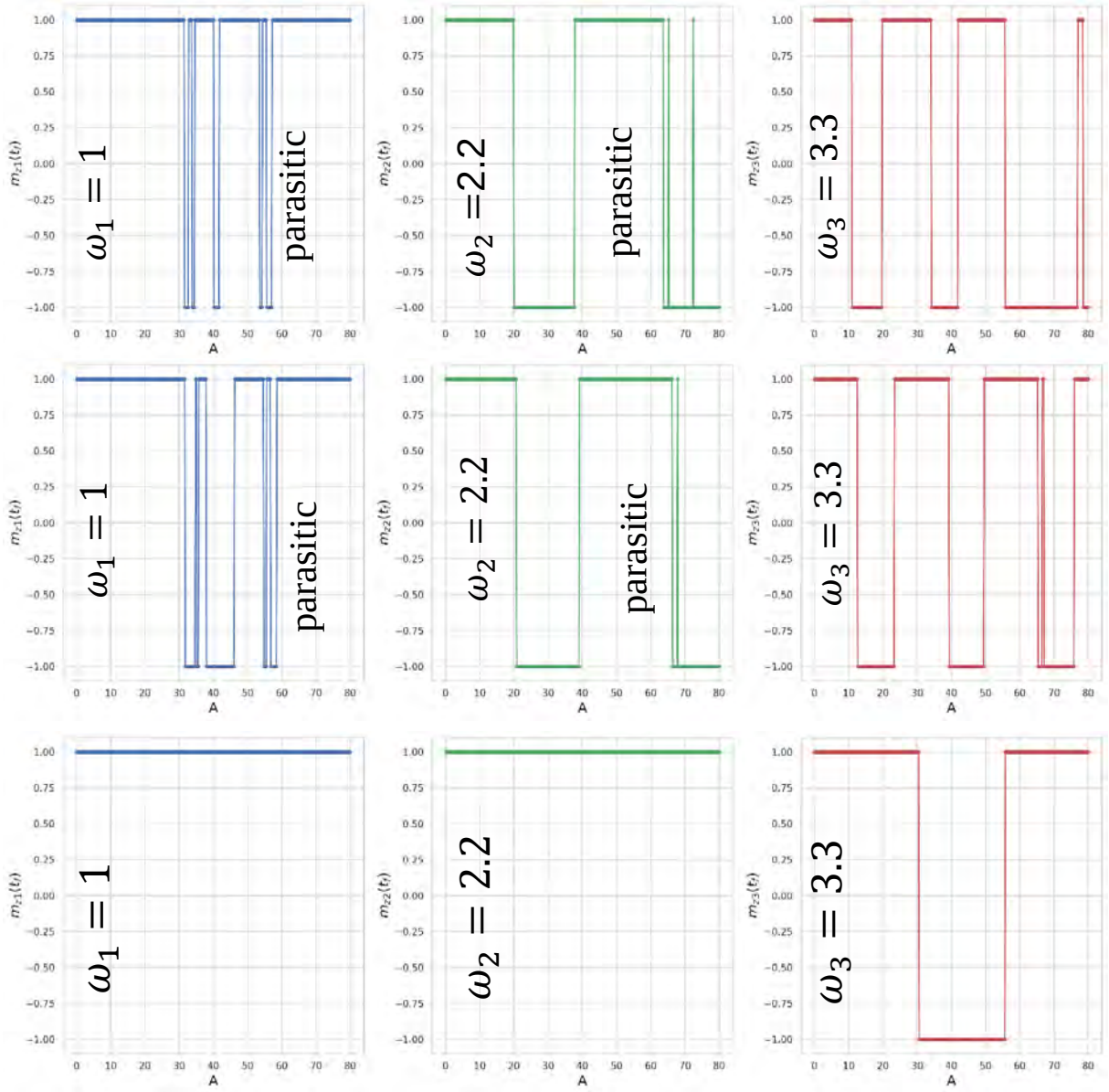
$A = 15$, $L_i = 1$, $R_i = 0.1$, $\omega_F = 1$, $G = 15$, $r = 0.1$, $\alpha = 0.1$.

Influence of pulse amplitude on magnetization reversal

Without filters

With filters Rp=0.1

With filters Rp=10



First junction *Second junction* *Third junction*

$\omega_p = 3.3$

Without filters 1st and 2nd φ0 -junctions demonstrate parasitic reversal.

Still 1st and 2nd φ0 -junctions demonstrate parasitic reversal. Optimal A interval for 3rd φ0 junction is [12.6, 20.8]

The increasing of R_p leads to the elimination of the parasitic reversal.

Ecosystem ML/DL/HPC of HybriLIT platform



Component for educational purposes

JupyterLab Server [**https://studhub1.jinr.ru**]
[**https://studhub2.jinr.ru**]

- 2x Intel Xeon E5-2680 v3 (12 Cores @ 2.5 GHz)
- 256 GB RAM

Component for computational tasks

Server with NVIDIA Volta [**https://jhub1.jinr.ru**]
[**https://jhub2.jinr.ru**]

- 2x Intel Xeon Gold 6148 (20 Cores @ 2.4 GHz)
- 4x NVIDIA Volta V100 SXM2 32 GB HBM2
- 512 GB RAM

Component for scientific projects

Server with NVIDIA Ampere [**https://ampere03.jinr.ru**]
[**https://ampere05.jinr.ru**]

- 2x AMD EPYC 7763 (64 Cores @ 2.4 GHz)
- 8x NVIDIA Ampere A100 SXM4 80 GB HBM2
- 2 TB RAM

Heterogeneous platform “HybriLIT”
https://hlit.jinr.ru

Various possibilities of Jupyter Book

jupyter {book}

Welcome to HLIT Jupyter Book

Python-инструментарий для моделирования динамики джозефоновского перехода под воздействием внешнего излучения

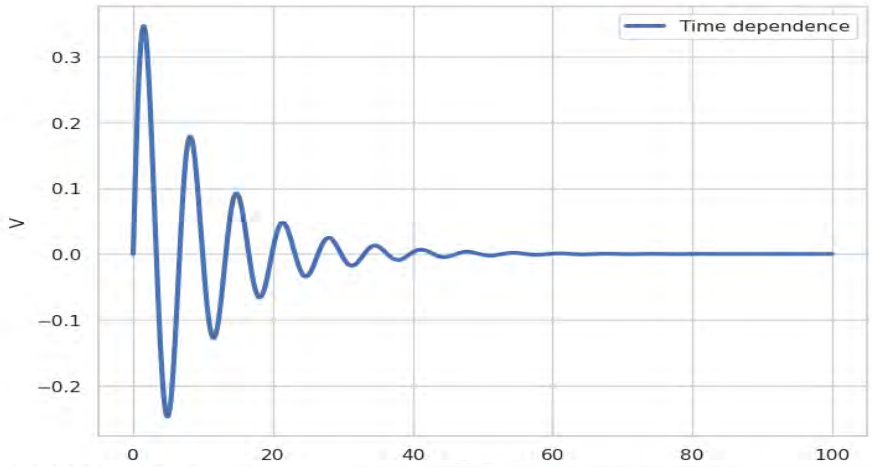
Python toolkit for simulation of the Josephson junction dynamics under the influence of external electromagnetic

jupyterhub

We draw a time dependence $V(t)$

.ipynb
.pdf

```
fig = plt.figure(figsize=(8, 6))
plt.plot(time_array, Vtime, label='Time dependence', linewidth=3.0)
plt.xlabel('Time', size=12)
plt.ylabel('V', size=12)
plt.legend(loc='upper right')
plt.show()
```



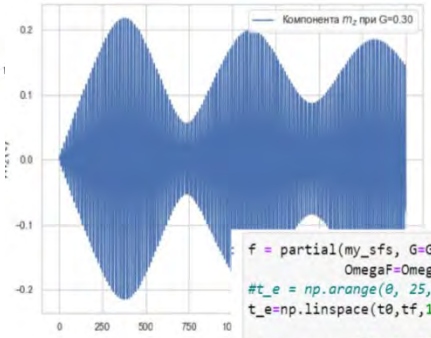
Stationary Josephson effect. When a current passes below the critical value ($I < I_c$), there is no voltage in the junction and a superconducting current flows through the junction. This current is proportional to the sine of the phase difference of the order parameters of the superconductor layers:

$$I_s = I_c \sin\varphi. \quad (1)$$

Non-stationary Josephson effect. When the current increases above the critical value ($I > I_c$), an AC voltage appears in the JJ, which is proportional to the time derivative of the phase difference

$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}. \quad (2)$$

plot




```
f = partial(my_sfs, G=G, alpha=alpha, k=k,  \
            OmegaF=OmegaF, V=V)
#t_e = np.arange(0, 25, 0.0001)
t_e=np.linspace(t0,tf,100000)

s0 = np.array([0, 1, 0])
sol_1=solve_ivp(f,[t0,tf],s0, t_eval=t_e, method='RK45')
```

KEY FEATURES

Jupyter Book is an **open-source** project for creating interactive and publishable online books, documentation, and blogs based on computational materials.

Jupyter Book supports .ipynb, Markdown, and reStructuredText files, allowing you to combine text with **code, equations, images, and interactive elements**.

Code in Jupyter Notebook can be executed while building the book, and the results (output, plots) will be embedded in the book.

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Rahmonova A.R., Streltsova O.I., Rahmonov I.R., Zuev M.I., Kokaev D.A.
Development of an electronic recourse Jupyter Book for conducting research in Python https://studhub.jinr.ru/jjbook/intro.html

The development is carried out on the basis of the ecosystem ML/DL/HPC heterogeneous platform HybriLIT

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Python-инструментарий для моделирования динамики джозефсоновского перехода под воздействием внешнего излучения

Python toolkit for simulation of the Josephson junction dynamics under the influence of external electromagnetic

Python-реализация алгоритмов и инструментарий для моделирования динамики сверхпроводникого квантового интерферометра с двумя джозефсоновскими переходами (СКВИД постоянного тока)

Python-реализация алгоритмов и инструментарий для моделирования динамики сверхпроводникого квантового интерферометра с двумя джозефсоновскими переходами (СКВИД постоянного тока)

Моделирование динамики

Welcome to HLIT Jupyter Book

Инструментарий для моделирования гибридных наноструктур сверхпроводник/магнетик

Задача 1. Инструментарий для моделирования ступеньки Шапиро на вольт-амперной характеристике джозефсоновского перехода

В работе рассмотрена задача о моделировании динамики джозефсоновского перехода под воздействием внешнего излучения. С использованием Python в среде Jupyter book разработаны алгоритмы для вычисления вольтамперной характеристики джозефсоновского перехода под воздействием внешнего излучения и вычисления зависимости ширины ступеньки Шапиро от амплитуды. Реализован параллельный алгоритм для рассматриваемой задачи с использованием библиотеки Joblib и проанализирована эффективность параллельных вычислений.

Работа поддержана грантом РНФ № 22-71-10022.

Проект *«Математическое моделирование сверхпроводящих наноструктур с магнетиком для исследования возможностей контроля намагниченности и магнитных возбуждений с использованием высокопроизводительных вычислительных систем»*

Toolkit for modeling superconductor/magnetic hybrid nanostructures

Task 1. Toolkit for modeling of the Shapiro step on the current-voltage characteristic of a Josephson junction

The problem of modeling of the Josephson junction dynamics under the influence of external radiation is considered. Using Python in the Jupyter book environment, algorithms of calculation of the Josephson junction current-voltage characteristic under the influence of external radiation and calculation of the amplitude

Conclusions

We have investigated chain of φ0 -junctions with coupled serial and parallel LCR circuits.

We have demonstrated the controllable magnetization reversal by the pulse of alternating voltage.

We demonstrate the way how to find intervals of parameters where occurs parasitic magnetization reversal.

We demonstrate the way how to eliminate the parasitic magnetization reversal.

We expect that performed investigations and obtained results can be useful for development of cryogenic memory, based on φ0 junction.

The developed toolkit allows users to perform complex data analysis, numerical calculations and visualization tasks with minimal effort on the HybriLIT platform.

Links to the developed electronic resources
http://studhub.jinr.ru:8080/books/intro.html

http://studhub.jinr.ru:8080/jjbook/intro.html



Thank you for your attention!

A toolkit based on Python libraries and the Jupyter ecosystem for solving of scientific and applied problems

jupyter {book}

http://studhub.jinr.ru:8080/books

http://studhub.jinr.ru:8080/jjbook/intro.html