Computer Simulation studies of superconductivity of Nanostructured: Using Josephson Junction

Student: D.M. Tshwane

Supervisor: Prof Yu. Shukrinov

Cons.: M. Nashaat

National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

Outline

- Superconductivity
- Josephson Junction
- Model and Simulations
- Results
- Conclusions

Superconductivity

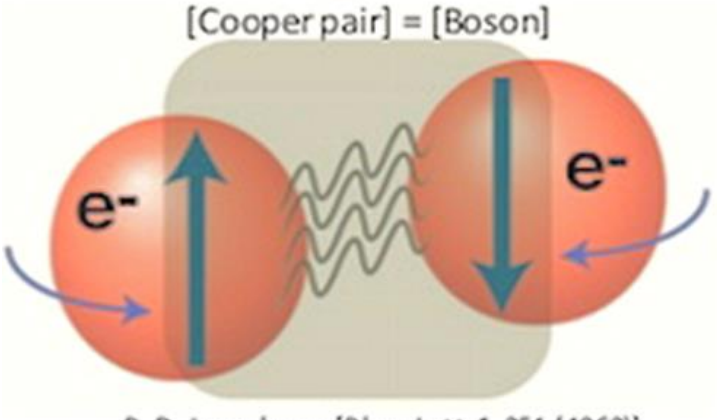
- According to F. London (**1935**), Superconductivity is a quantum phenomena, which is characterized by perfect conduction and completed diamagnetism where resistor R become zero below a critical temperature and magnetic field M are expelled.

1962~

✓ **Superconductors (SC)**

(1973)

[Cooper pair] = [Boson]



B. D. Josephson, [Phys. Lett. 1, 251 (1962)]

Fig by [Fa Wang and Dung-Hai Lee, Science, 332 (2011) 200]

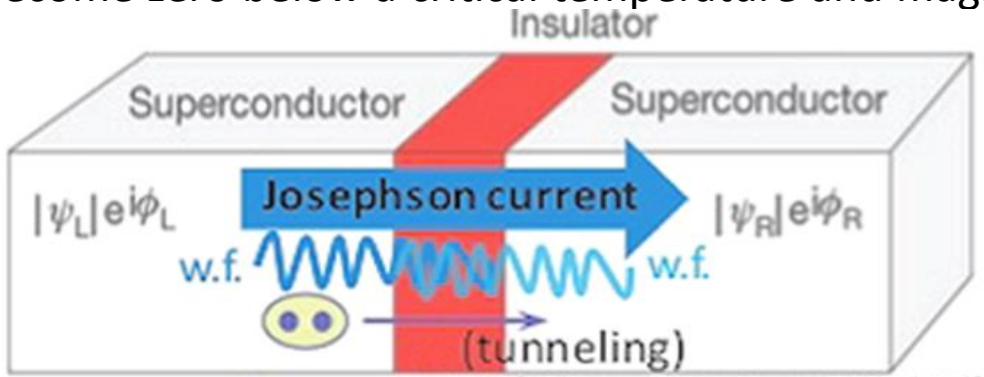


Fig by [J. Q. You and F. Nori, Nature, 474, 589 (2011)]

Textbook by Leggett

Josephson equations in SC

$$\begin{cases} I = I_c \sin\phi & \text{; Josephson current} \\ & \rightarrow \text{"charge current"} \\ \frac{d}{dt}\phi(t) = \frac{2eV(t)}{\hbar} = \frac{2\pi V}{\Phi_0}, \ \Phi_0 = h/2e & \text{(quantized magnetic flux)} \end{cases}$$

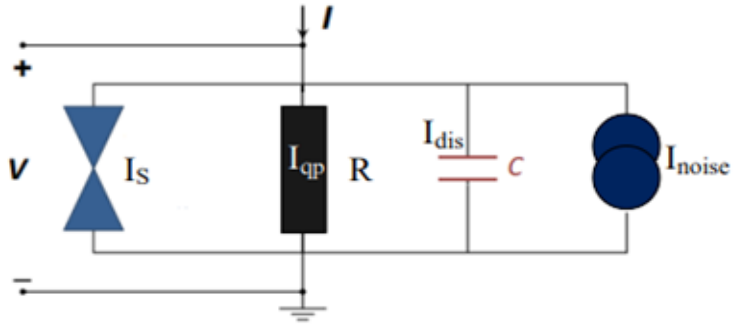
✓ **dc Josephson effect;** $\frac{d}{dt}\phi(t) \propto V(t) = 0$

→ **Relative phase is time-independent;** $\frac{d}{dt}\phi(t) = 0$

- Josephson Junctions are regarded as the most excellent model system for studying variety of nonlinear phenomena in different field of science, such as frequency locking and transport in superconductivity, especially properties of Shapiro steps.

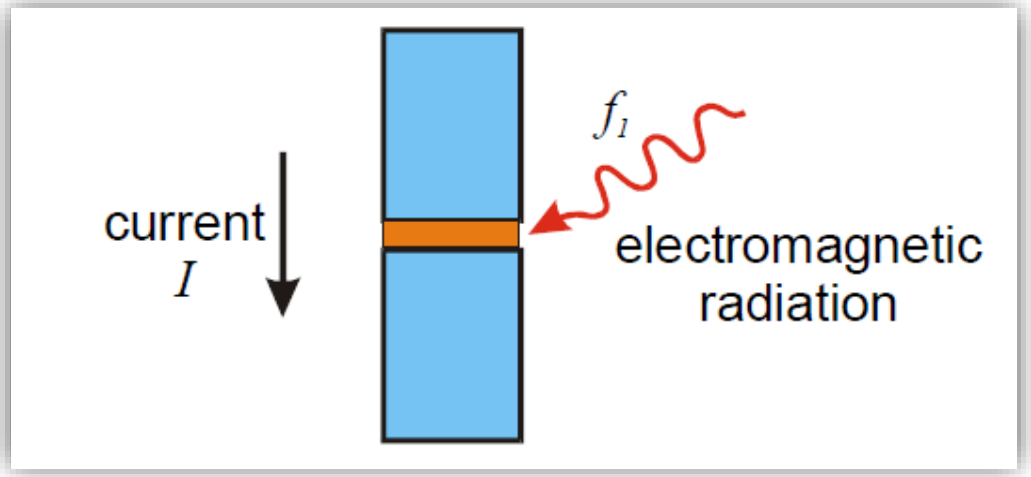
C.A. Hamilton: Phys. Lett. 50, 1637 (1972) **J. Tekic: Phys. Rev E83, (2011)**

Simulation and Equation



Type of Current	Equation
Super Current	$I_s = I_c \sin\varphi \qquad \frac{d\varphi}{dt} = \frac{2e}{h}V(t)$
Normal(Ohmic) Current	$I_n = \frac{V}{R}$
Displacement Current	$I_d = C\frac{dV}{dt}$
Bias Current	$I = I_c \sin\varphi + I_n(V) + C\frac{d(V)}{dt}$
For Stack of Josephson Junction	$\frac{h\,d\varphi}{2e\,dt} = V_i - \alpha(V_{i-1} + V_{i-i} - 2V_i)$

$$V_0 = \frac{\hbar\omega_p}{2e};\quad \omega_p = \sqrt{\frac{2eI_c}{C\hbar}};\quad \beta = \frac{1}{R}\sqrt{\frac{\hbar}{2eI_cC}};$$



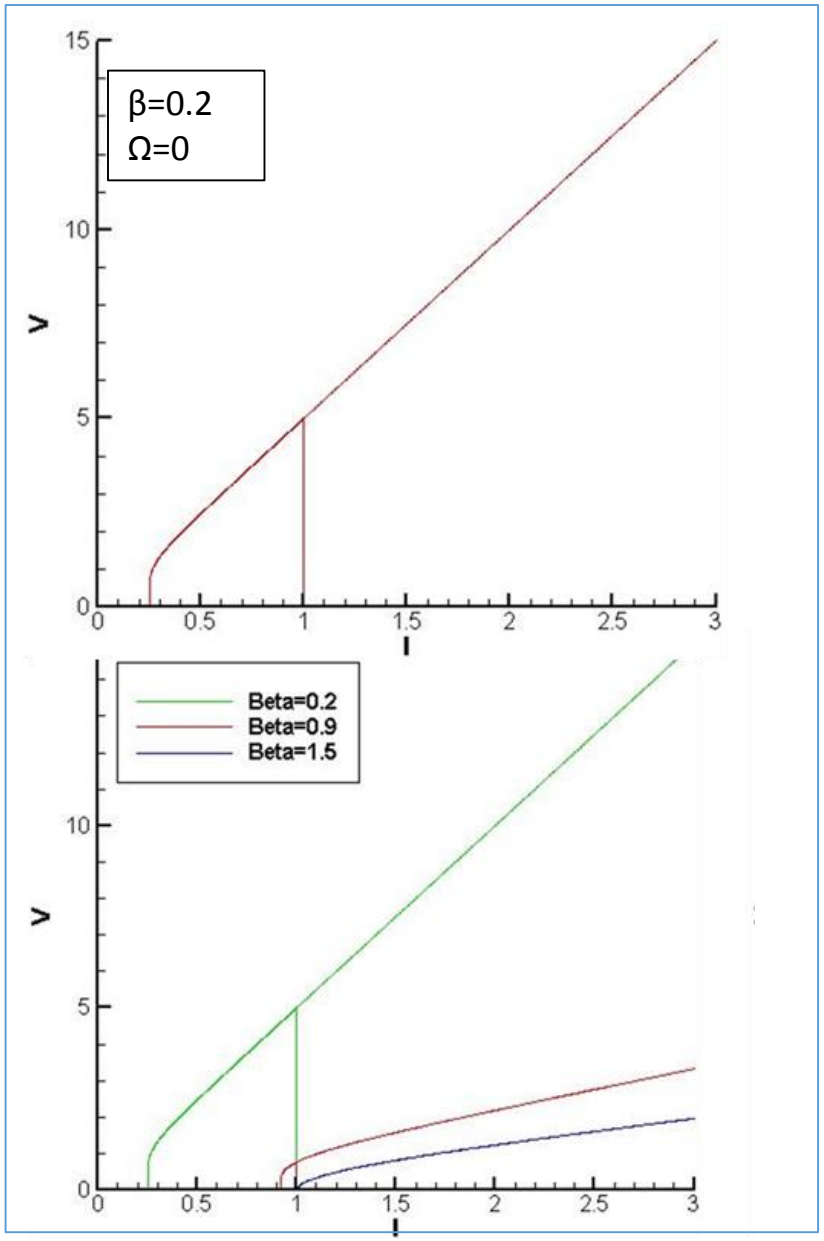
$V = V_0 + V_1 \cos wt$

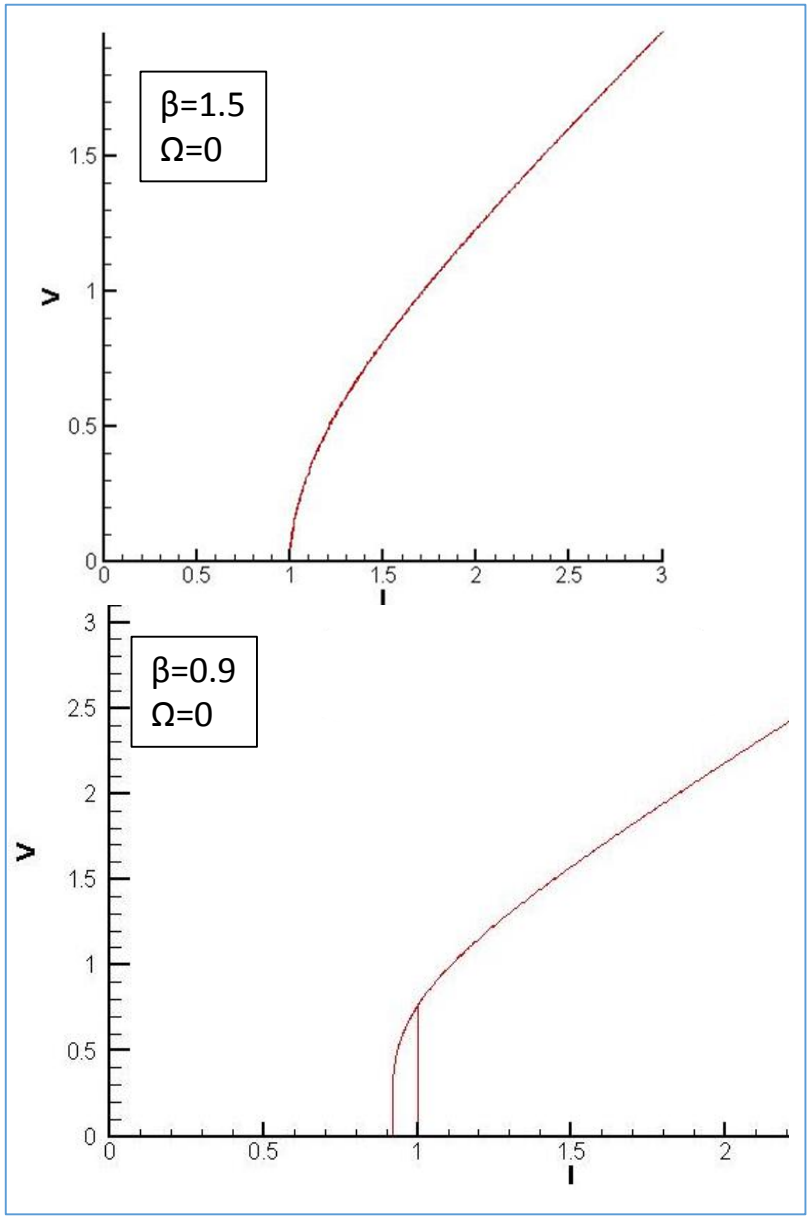
$$I_s = I_c \sum_{n=-\infty}^{\infty} (-1)^n J_n\left(\frac{V_1}{w}\right)\sin(\varphi_0 + V_0 t - nwt)$$

Dc current step appears at $V_0 = nw$

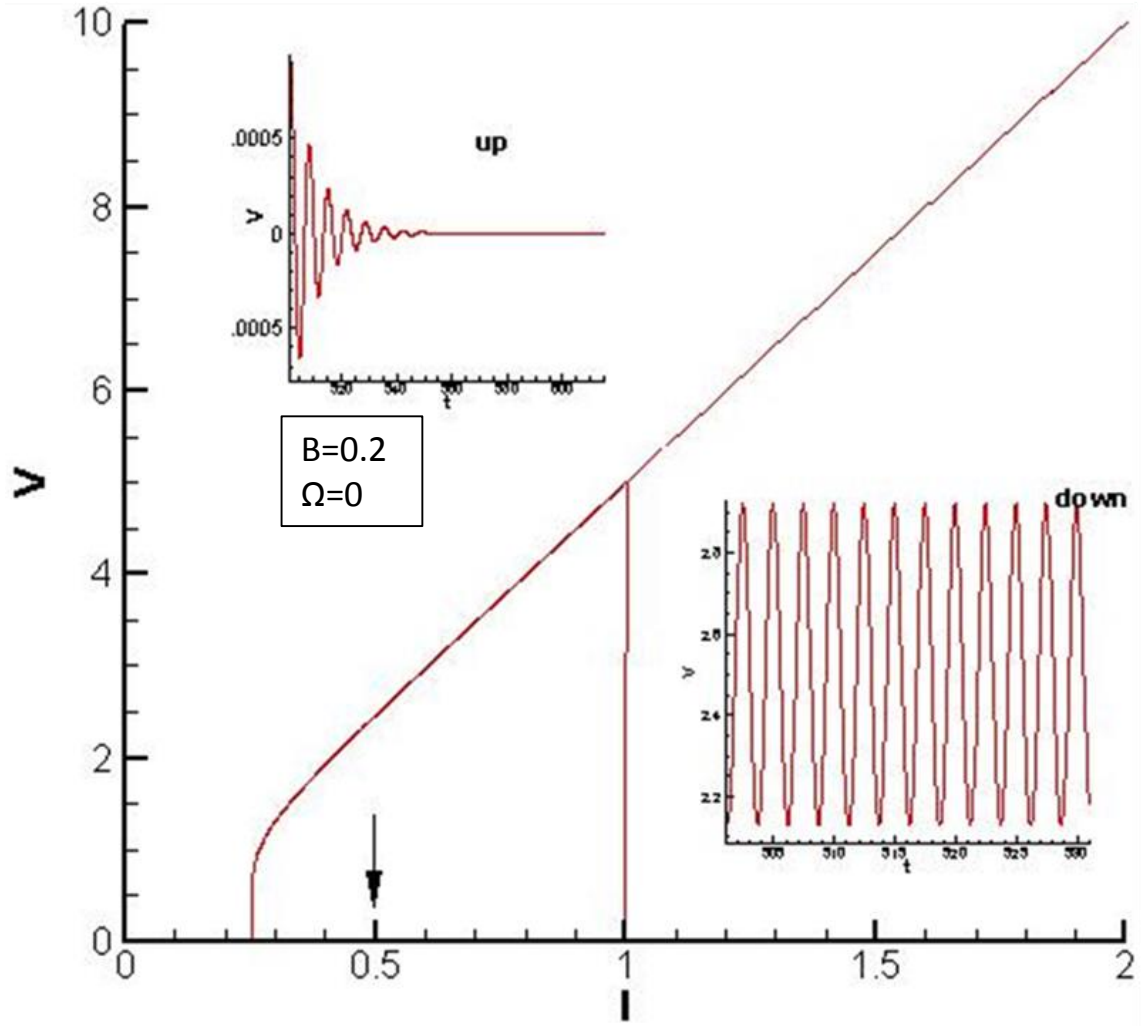
W.C. Stewart, Appl. Phys. Lett. 12, 277 (1968);
D.E. McCumber, J. Appl. Phys. 39, 3113 (1968)

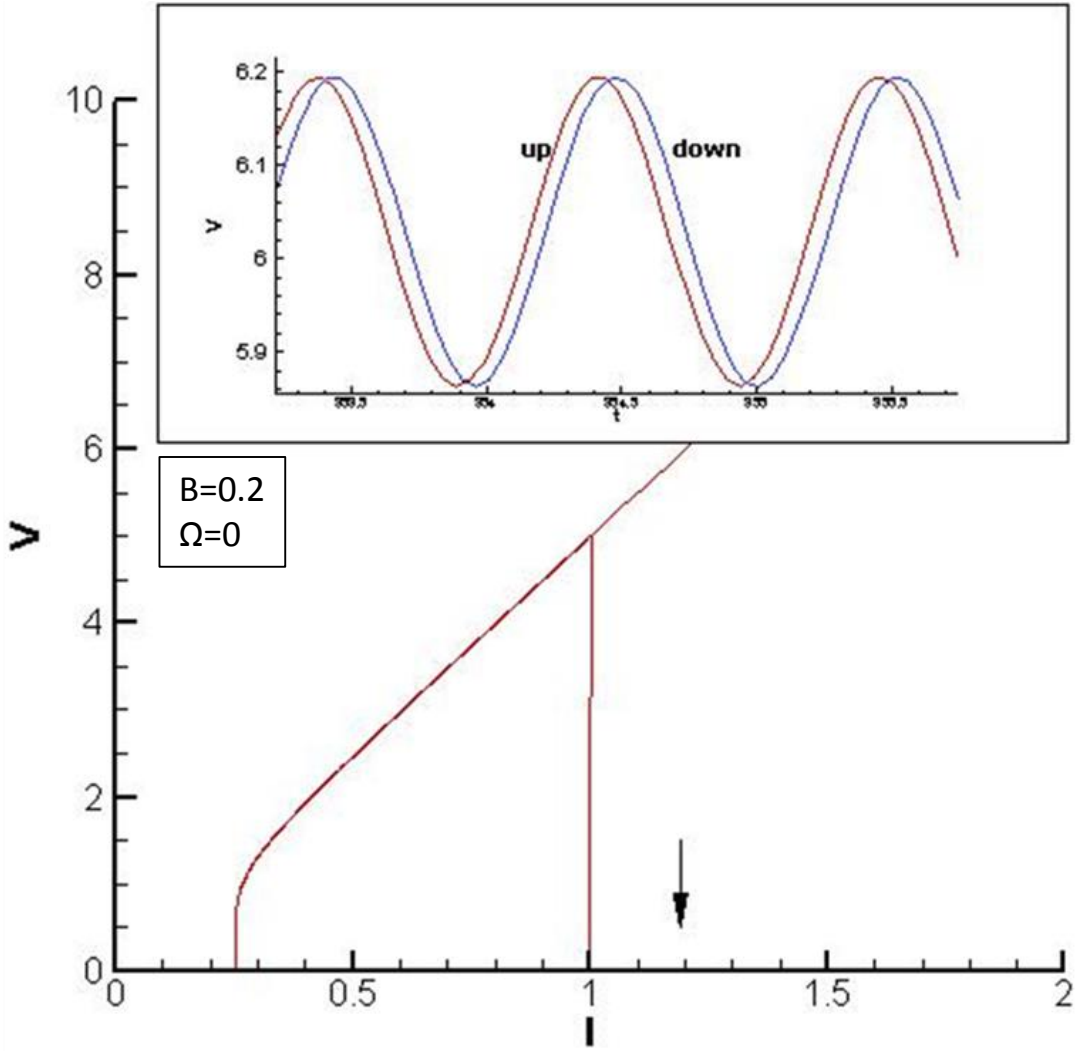
Single-JJ: IV-Characteristics without Radiation



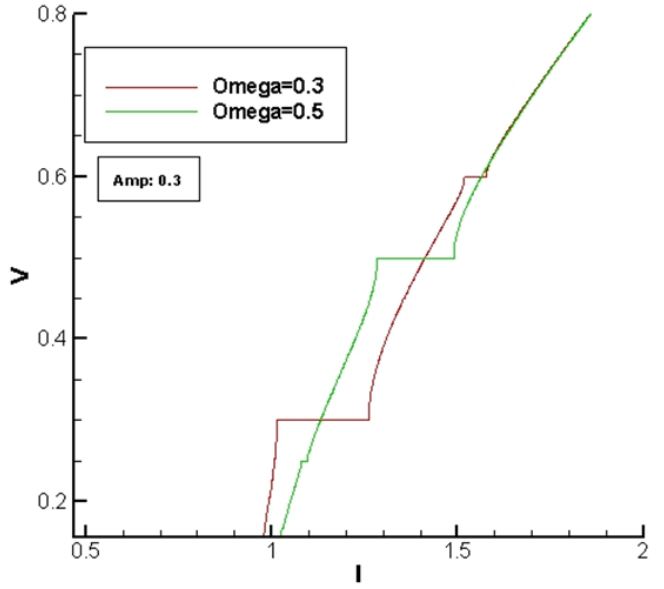


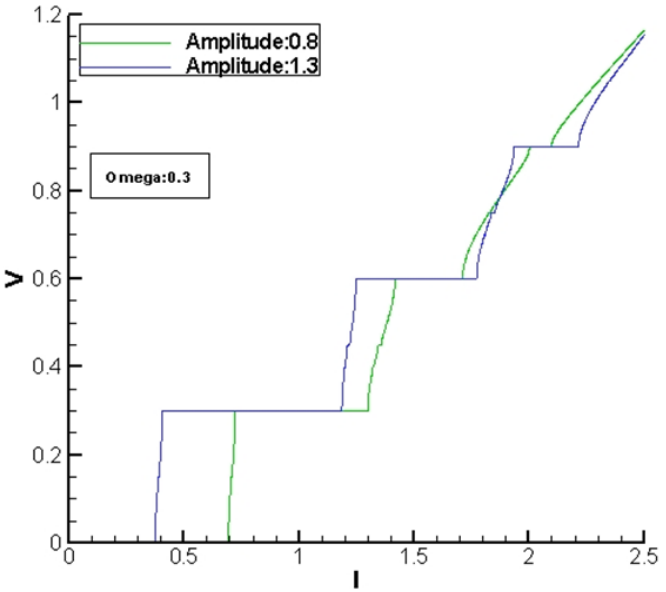
Single JJ- IV-Curves





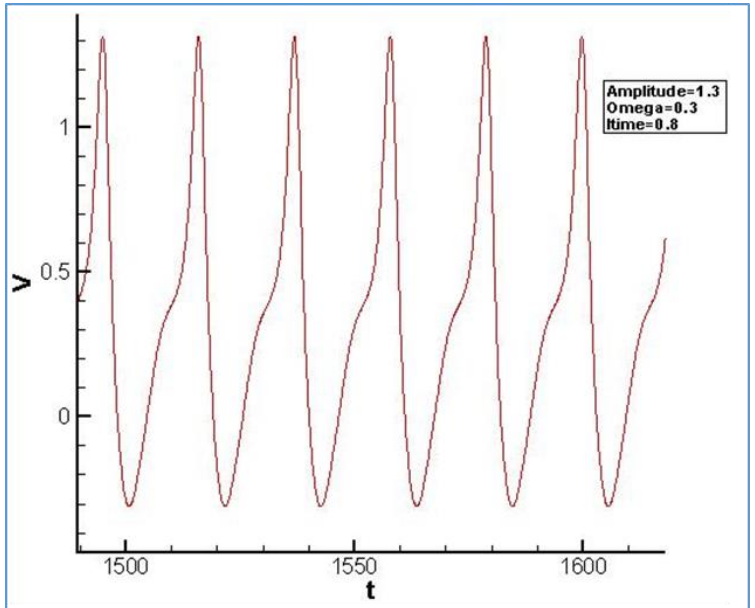
Single JJ: IV-Curves with External Radiation (over-damped)

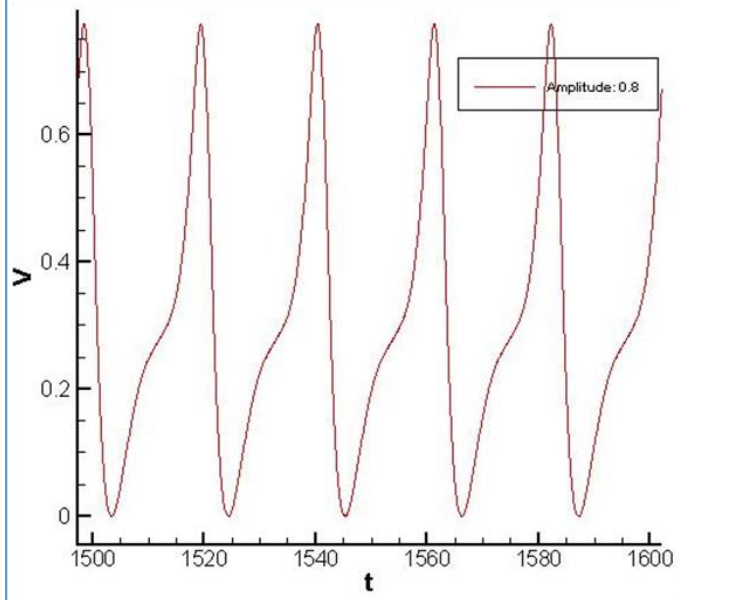




$$I_{dc} + A\ sin\ \omega t = I_c \sin\varphi + I_n(V) + C\frac{d(V)}{dt}$$

Dc current step appears at $V_0 = nw$



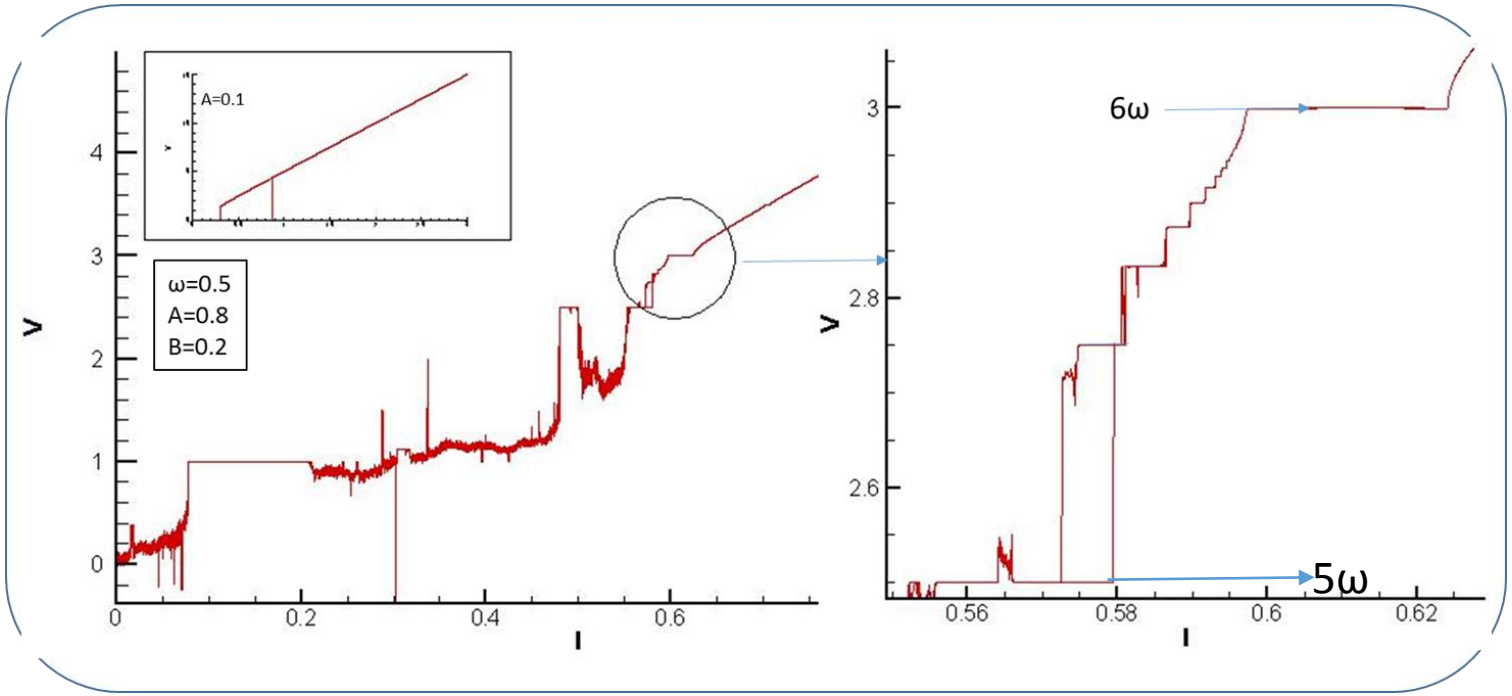


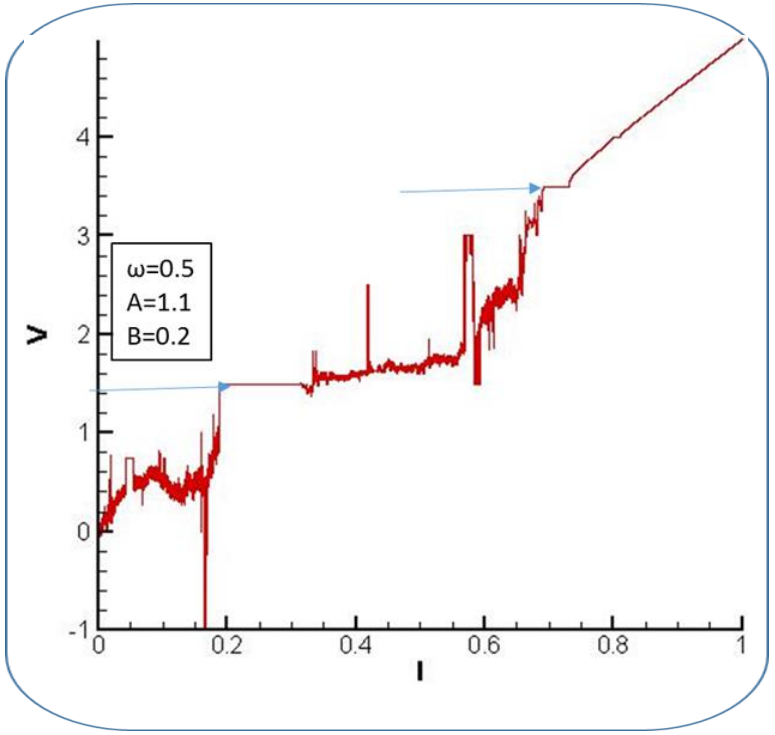
Devil's Staircase

$$I_{dc} + A\,sin\,\omega t = I_c \sin\varphi + \frac{V}{R} + C\frac{dV}{dt}$$

$$\frac{h\,d\varphi}{2e\,dt} = V$$

$$I_{dc} + A\,sin\,\omega t = \sin\varphi + \beta V + \frac{dV}{dt}$$



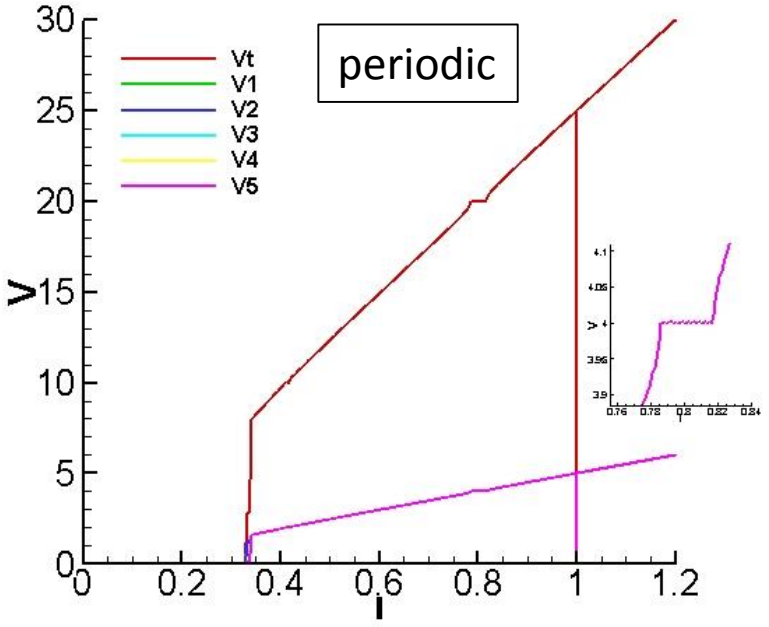


A series of step in the form of $\left(\mathrm{N} - \frac{1}{n}\right)\omega$,
N=6 and n is +ve integer, observed between 6ω and 5ω

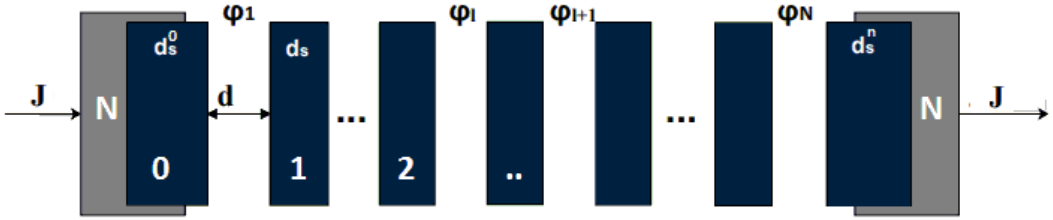
$$V = \left(N \pm \frac{1}{n \pm \frac{1}{m \pm \frac{1}{\frac{1}{\ldots}}}}\right)\omega$$

Yu. Shukrinov et al. PRB 88,214515 (2013)

Stack of JJ: External Radiation (underdamping β=0.2, ω=4 and A=0.5)



Non-periodic



$$\frac{d\varphi_1}{dt} = V_1 - \alpha(V_2 - (1+\gamma)V_1)$$
$$\frac{d\varphi_i}{dt} = (1+2\alpha)V_i - \alpha(V_{i-1} - V_{i+1})$$
$$\frac{d\varphi_N}{dt} = V_N - \alpha(V_{N-1} - (1+\gamma)V_N)$$

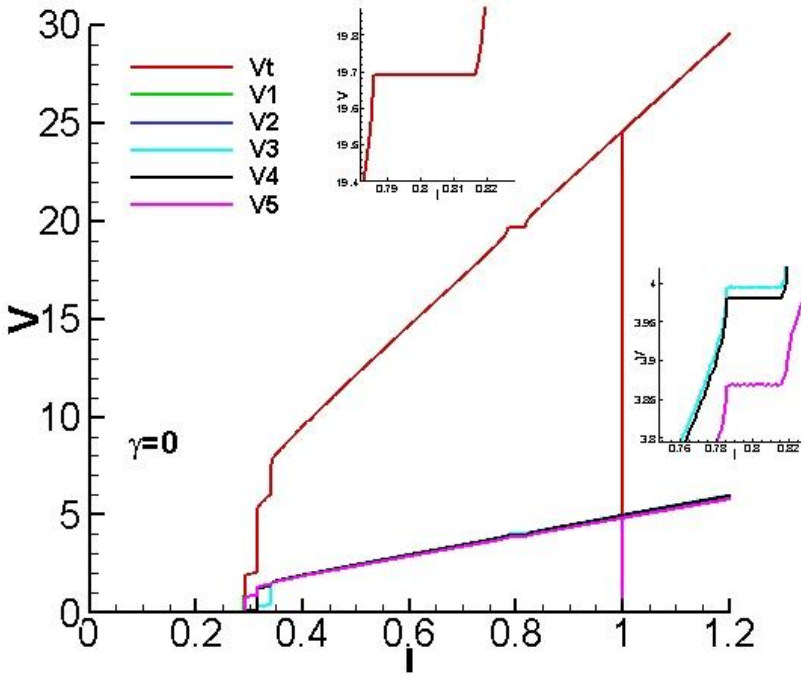
$$\gamma = \frac{d_s^l}{d_s^{0,N}}$$

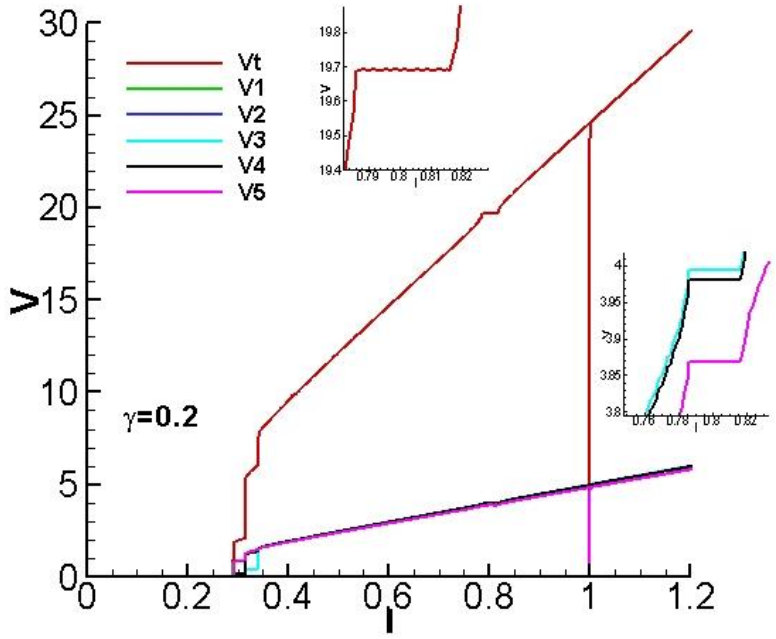
i=2,…, N-1

$$\frac{d\varphi_i}{dt} = V_i - \alpha(V_{i+1} + V_{i-i} - 2V_i)$$

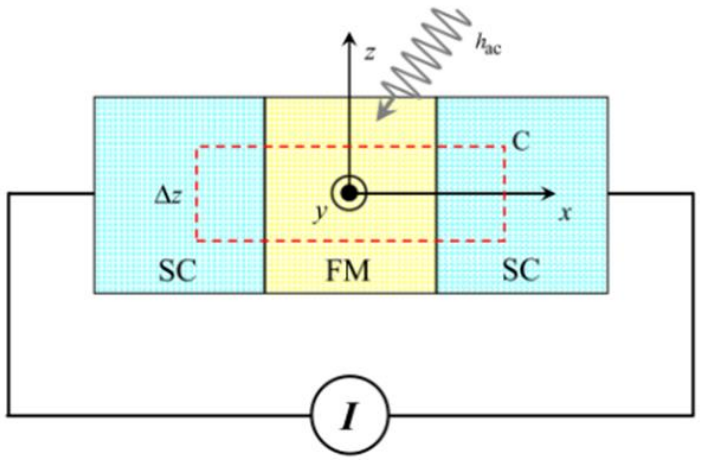
$$V_0 = V_N$$
$$V_{i+1} = V_1$$

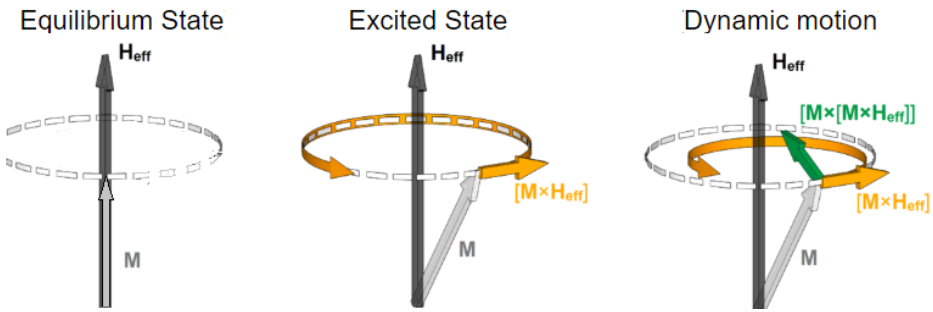
i=1,2,… N

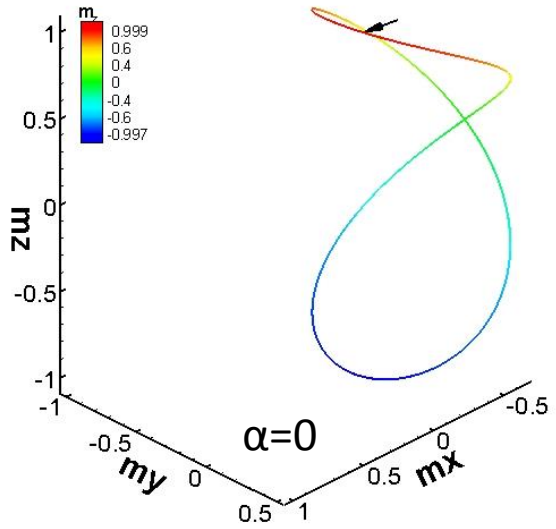




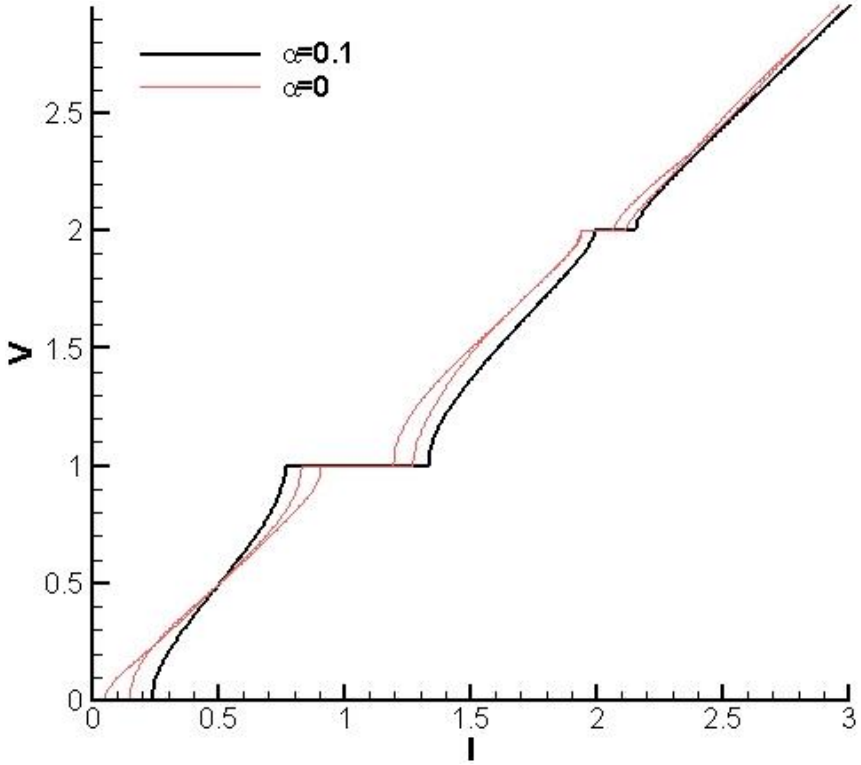
SFS Under Magnetic Field

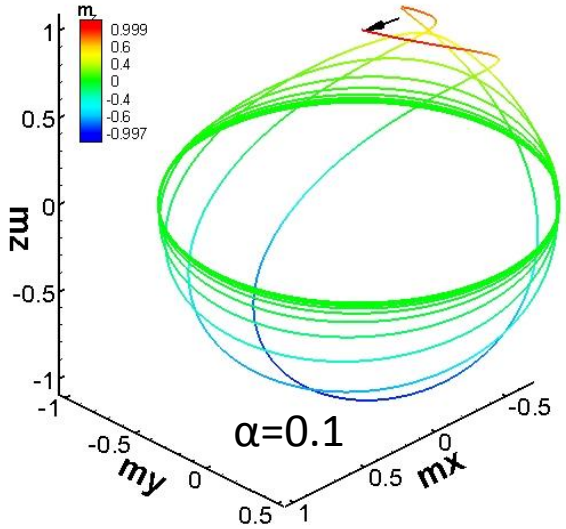


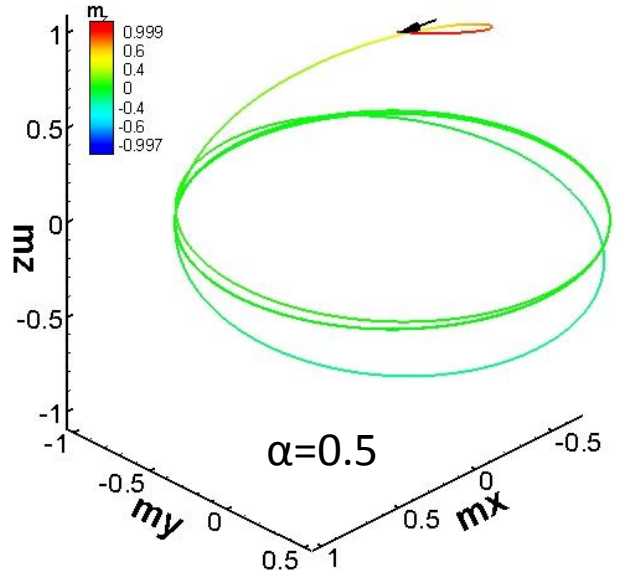




$$I/I_c^0 = \frac{\sin(\phi_{sy} m_z)\sin(\phi_{sz} m_y)}{(\phi_{sy} m_z)(\phi_{sz} m_y)}\sin\theta + \frac{d\theta}{dt} \qquad \frac{d\mathbf{m}}{dt} = -\frac{\Omega_0}{(1+\alpha^2)}\Big(\mathbf{m}\times\mathbf{h}_e + \alpha\left[\mathbf{m}\times(\mathbf{m}\times\mathbf{h}_e)\right]\Big),$$







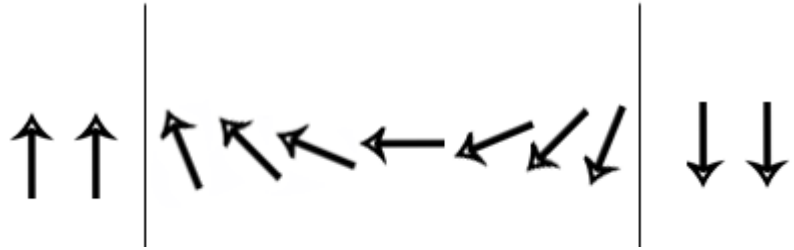
S. Hikino, et al., SUST, 24(2):024008, 2011

Conclusion

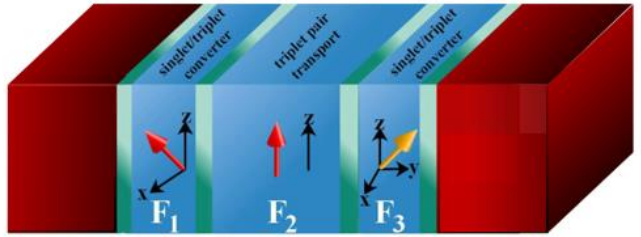
- **In Single JJ (RCSJ)**
- Using RCSJ model, we manage to get some physical properties at different junctions: IV-characteristics of single and stack JJ, Shapiro step and Devil's staircase.
- **In Stack of JJ (Using CCJJ+Dc)**
- In periodic condition, IV-characteristics shows the step appear at the product of number of junction and the value of ω and the voltage at each junction coinciding.
- In non-periodic condition, IV characteristics shows the shifting of step from 20V to 19.7V and the voltage of the single junction overlapping.
- **SFS Junction (Using RSJ + LLG)**
- We manage to study the effect of coupling between supercurrent and magnetization in SFS-JJ under different polarized field, It was found that the IV-characteristic shows even steps in IV curve as a result of interaction with even number of magnons.

Future Work

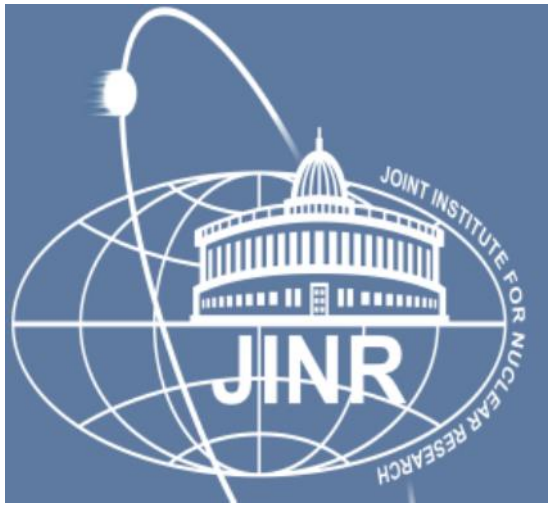
- Phase dynamics for SFS junction in the presence of domain wall motion in F-layer



- Magnetization reversal in $SF_1F_2F_3S$ with fixed spin direction in F_1 and F_2 and a free one in F_3

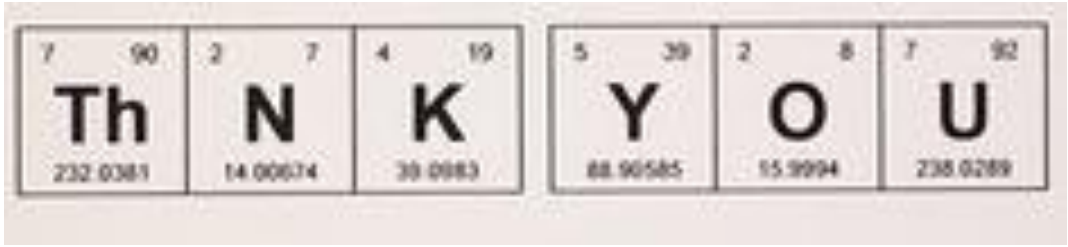


Acknowledgement



Prof Yu. Shukrinov

Mr M. Nashaat



감사합니다 Natick

Grazie Danke Ευχαριστίες Dalu Obrigado

Thank You Köszönöm

Tack

Спасибо Dank Gracias

谢谢 Merci Seé

ありがとう

Kgotso e beng le lena!!!