Computer simulation of tunneling characteristics of superconducting nanostructures

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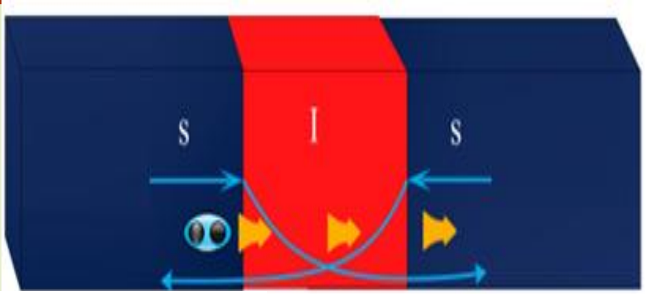
Outlines

- Josephson junction (J.J) and Josephson effect.
- Superconductor/Ferromagnet/ Superconductor (S/F/S) J.J.
- Landau-Lifshitz-Gilbert (LLG) equation.
- Resistively Shunted Junction (RSJ) Model of S/F/S J.J.
- Transformation Parameters.
- Non Linear Landau-Lifshitz-Gilbert Equation and Effective field form.
- Results and Calculations:
  - Current Voltage Characteristic (CVC) of S/F/SJ.J.
  - Amplitude dependence of Shapiro step's width at different frequencies; Ω_o =0.3,0.45,0.5.
  - Amplitude dependence of specific Shapiro steps (V=2 Ω_o and 4 Ω_o).
- Conclusion

Josephson junction and Josephson effect



$$\Psi_1 = \sqrt{n_1} e^{i\theta_1} \qquad \Psi_2 = \sqrt{n_2} e^{i\theta_2}$$

Cooper pair density

A **Josephson junction** is a quantum mechanical device, which is made of two superconducting electrodes separated by a barrier (thin insulating tunnel barrier, normal metal, semiconductor, ferromagnet)[1]

- **DC tunneling supercurrent**

$$\mathbf{I_s(\varphi) = I_c \sin\varphi}$$

Phase difference: $\varphi = \theta_2 - \theta_1$

$I < I_C,\ V = 0$

- **AC current**

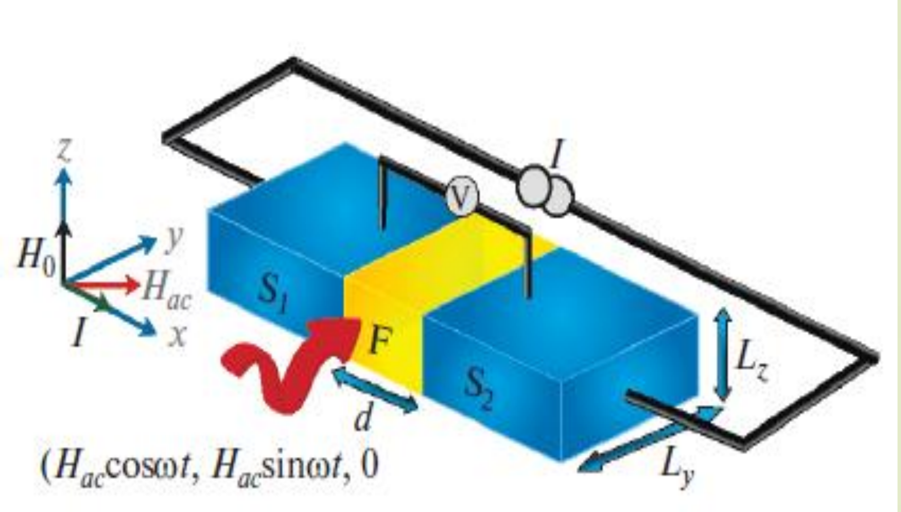
$$\frac{d\varphi}{dt} = \frac{2e}{\hbar} V$$

$I > I_C,\ V > 0$

[1]B.D.Josephson *Phys. Lett.* 1 (7): 251–253 (1962)

Superconductor/Ferromagnet/ Superconductor J.J

- **S/F/S Josephson junction under application of circularly polarized magnetic field in xy-plane with different values of amplitude h_{ac} and frequency ω.**



SC Phase Dynamics

Coupling through gauge-invariant phase difference

FM Magnetization Dynamics

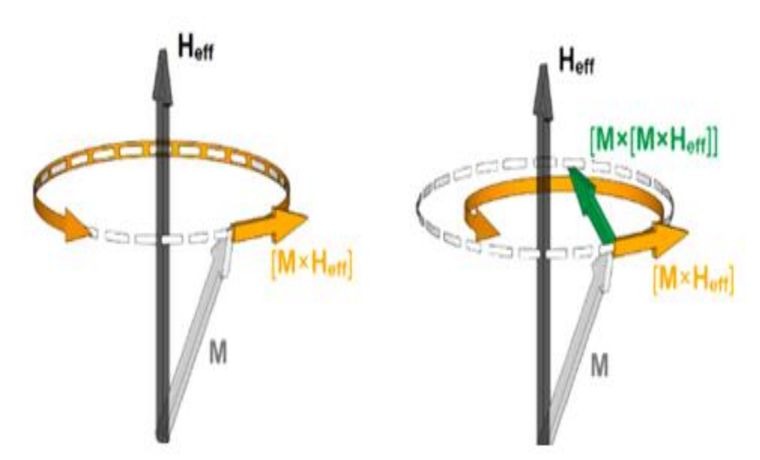
Landau-Lifshitz-Gilbert (LLG) equation

$$(1+\alpha^2)\frac{dM}{dt} = -(\gamma M \times H_{eff} + \frac{\gamma\alpha}{|M|}[M \times (M \times H_{eff})])$$

H_{eff} : effective field

γ :gyromagnetic ratio

α : Gilbert damping



- **Total energy of S/F/S system:**

$$E = E_M + E_{ac} + E_s$$

$$E_s = -\frac{\Phi_0}{2\pi}\left(\theta(t) - \frac{8\pi^2 d}{\Phi_0}(M_z(t)y - M_y(t)z)\right)I + E_J\left[1 - \cos\left(\theta(t) - \frac{8\pi^2 d}{\Phi_0}(M_z(t)y - M_y(t)z)\right)\right]$$

$$E_M = -v H_0 M_z(t),$$

$$E_{ac} = -v M_x(t) H_{ac}\cos(\omega t) - v M_y(t) H_{ac}\sin(\omega t)$$

E_M : Energy of dc magnetic field.

E_{ac} : Energy of ac magnetic field.

E_s: Josephson energy

- **The effective field is calculated from:**

$$H_e = -\frac{1}{v}\nabla_M E$$

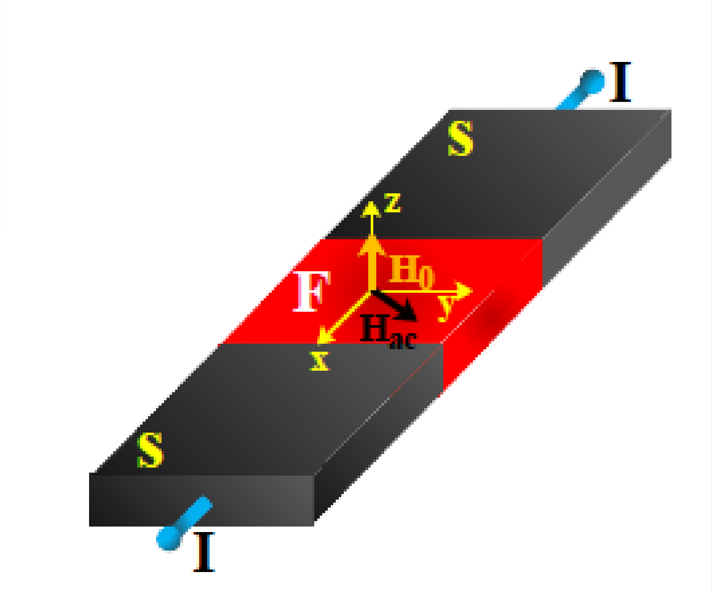
Resistively Shunted Junction (RSJ) Model[2]

- **Gauge invariant phase difference**

$$\Theta(y,z,t) = \theta(t) - \frac{8\pi^2\, dM_z(t)}{\phi_0}\, y + \frac{8\pi^2\, dM_y(t)}{\phi_0}\, z$$

- **The RSJ equation**

$$\frac{I}{I_c^0} = \sin\theta(y,z,t) + \frac{\Phi_0}{2\pi I_c^0 R}\frac{d\theta(y,z,t)}{dt}$$



$$\frac{I}{I_c^0} = \frac{\Phi_o^2 \sin(\theta(t)) \sin\left(\frac{4\pi^2 dM_z(t) L_y}{\Phi_o}\right) \sin\left(\frac{4\pi^2 dM_y(t) L_z}{\Phi_o}\right)}{16\pi^4 d^2 L_z L_y M_z(t) M_y(t)} + \frac{\Phi_0}{2\pi R I_c^0}\frac{d\theta(y,z,t)}{dt}.$$

I_c^0 : critical current
ϕ_0=h/2e,magnetic flux quantum.

[2] The gauge-invariant phase difference is given by K. K. Likharev, Dynamics of Josephson junctions and circuits , Gordon and Breach science publishers –Switzerland.

Transformation Parameters:

$m=\frac{M}{|M|}$ Normalized magnetization

$h_e=\frac{He}{Ho}$ Normalized effective magnetic field

$\varepsilon_J=\frac{E_j}{V\,|M|\,H_0}$ Normalized Josephson Energy

$h_{ac}=\frac{H_{ac}}{H_o}$ Normalized polarized magnetic field

$\Omega=\frac{\omega}{\omega_c}$ Normalized external Frequency

$t=\tau\omega_c$ Normalized Time

$\omega_c=2\pi\, I_c^0\, R/\Phi_0$ Characteristic Frequency

$H_0=\frac{\Omega_0}{\gamma}$ Applied Uniform Field in Z direction

$\Omega_0=\frac{\omega_0}{\omega_c}$ Normalized FMR Frequency

$\Phi_{sy}=\frac{4\pi^2\, L_y\, d|M|}{\phi_0}$ Phase difference in y- direction

$\Phi_{sz}=\frac{4\pi^2\, L_z\, d|M|}{\phi_0}$ Phase difference in z-direction

- **Non-Linear Landau-Lifshitz-Gilbert Equation and Effective field form for S/F/S J.J**

$$\frac{d\mathbf{m}}{dt} = -\frac{\Omega_0}{(1+\alpha^2)}\left(\mathbf{m}\times\mathbf{h}_{eff} + \alpha\left[\mathbf{m}\times(\mathbf{m}\times\mathbf{h}_{eff})\right]\right)$$

with

$$\mathbf{h}_{eff} = h_{ac}\cos(\Omega t)\hat{\mathbf{e}}_x + (h_{ac}\ sin(\Omega t) + \Gamma_{ij}\epsilon_J\cos\theta)\,\hat{\mathbf{e}}_y + (1+\Gamma_{ji}\epsilon_J\cos\theta)\,\hat{\mathbf{e}}_z,$$

$$\Gamma_{ij} = \frac{\sin(\phi_{si}m_j)}{m_i(\phi_{si}m_j)}\left[\cos(\phi_{sj}m_i) - \frac{\sin(\phi_{sj}m_i)}{(\phi_{sj}m_i)}\right]$$

- **Current-phase Equation**

$$I/I_c^0 = \frac{\sin(\phi_{sy}m_z)\sin(\phi_{sz}m_y)}{(\phi_{sy}m_z)(\phi_{sz}m_y)}\sin\theta + \frac{d\theta}{dt}$$

Microwave induced tunable subharmonic steps in superconductor-ferromagnet-superconductor Josephson junction

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We investigate the coupling between ferromagnet and superconducting phase dynamics in superconductor-ferromagnet-superconductor Josephson junction. The current-voltage characteristics of the junction demonstrate a pattern of subharmonic current steps which forms a devil's staircase structure. We show that a width of the steps becomes maximal at ferromagnetic resonance. Moreover, we demonstrate that the structure of the steps and their widths can be tuned by changing the frequency of the external magnetic field, ratio of Josephson to magnetic energy, Gilbert damping and the junction size.

This paper is submitted to LTP Journal.

I. INTRODUCTION

Josephson junction with ferromagnet layer (F) is widely considered to be the place where spintronics and superconductivity fields interact[1]. In these junctions the supercurrent induces magnetization dynamics due to the coupling between the Josephson and magnetic subsystems. The possibility of achieving electric control over the magnetic properties of the magnet via Josephson current and its counterpart, i.e., achieving magnetic control over Josephson current, recently at- matches the spin wave frequency, this resonantly excites the magnetization dynamics $M(t)$[18]. Due to the nonlinearity of the Josephson effect, there is a rectification of current across the junction, resulting in a dip in the average dc component of the suppercurrent[18].

In Ref.[13] the authors neglect the effective field due to Josephson energy in LLG equation and the results reveal that even steps appear in the IV-characteristic of SFS junction under external magnetic field. The origin of these steps is due to the interaction of Cooper pairs with even number of magnons. Inside the ferromagnet, if the Cooper pairs scattered by odd number of magnons, no Josephson current flows due to the formation of spin triplet state[13]. However, if the Cooper pairs interact with even number of magnons, the Josephson

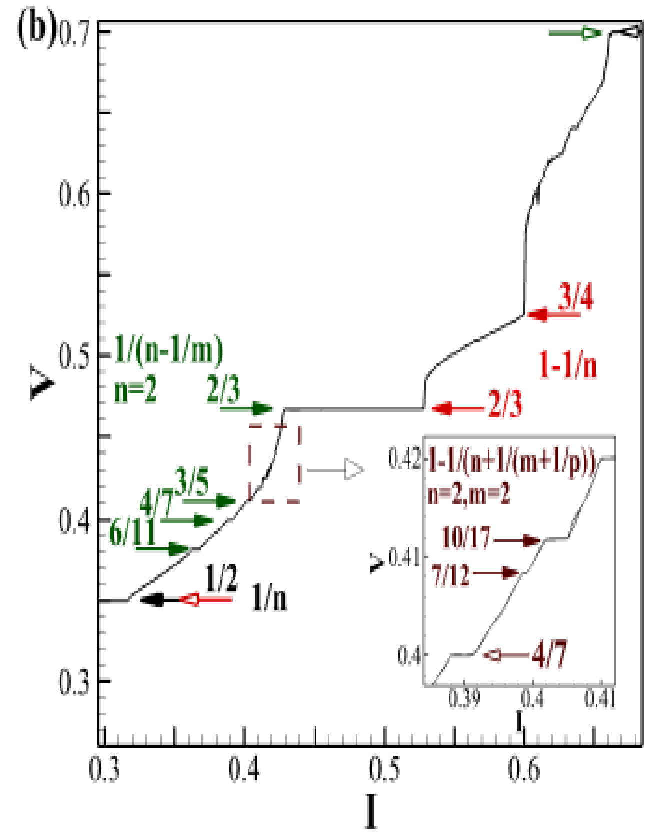


FIG. 2. (a) IV-characteristic at three different values of Ω. For clarity, the IV-characteristics for $\Omega = 0.5$ and $\Omega = 0.7$ have been shifted to the right, by $\Delta I = 0.5$ and $\Delta I = 1$, respectively with respect to $\Omega = 0.2$; (b) An enlarged part of the IV-characteristic with $\Omega = 0.7$. To get step voltage multiply the corresponding fraction with $\Omega = 0.7$.

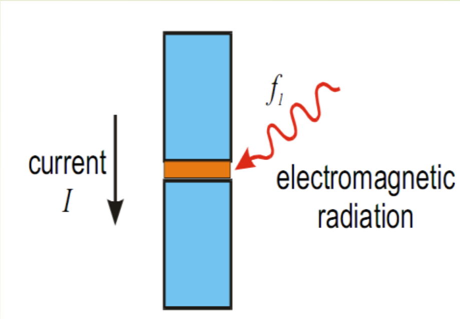
Results and Calculations

CVC of S/F/S J.J

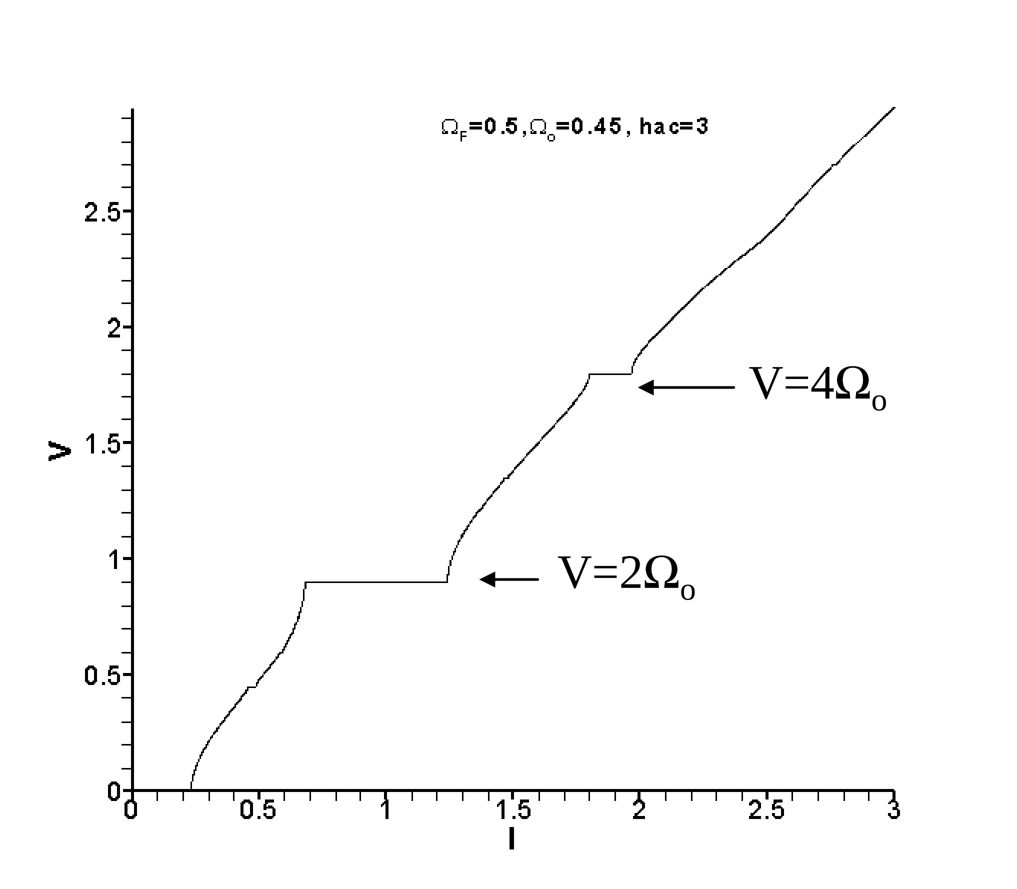
CVC at h_{ac} =3, Ω_o = 0.45, Ω_F =0.5.

h_{ac}: magnitude of circularly polarized magnetic field.

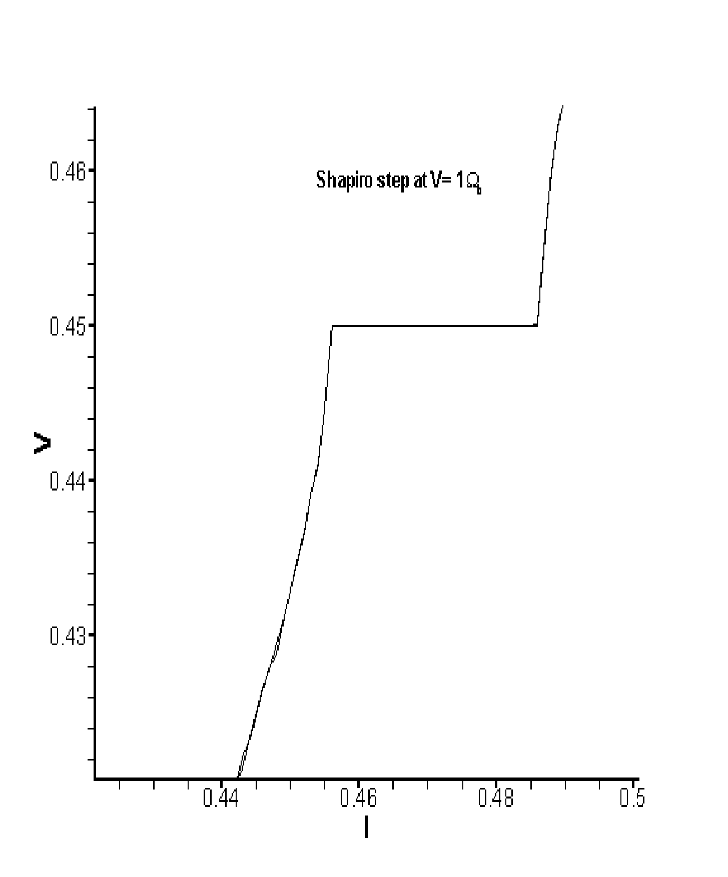
$V = n\Omega_o$



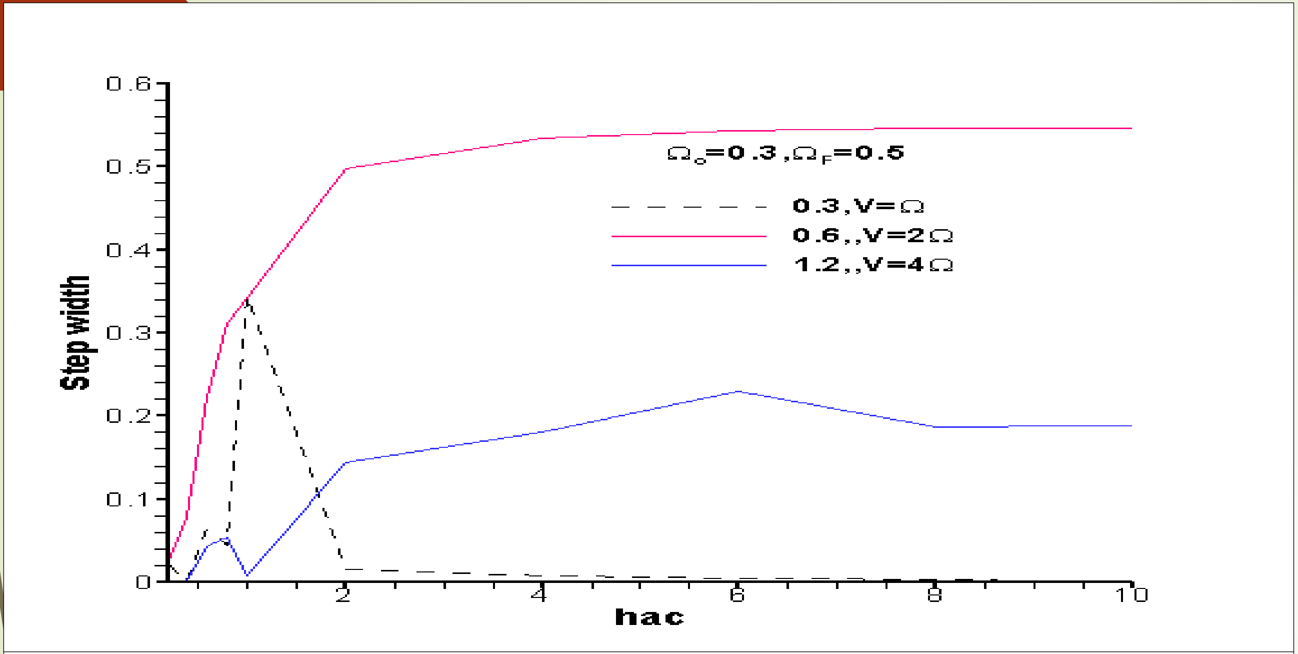
Shapiro step at $V=2\Omega_o$ & $4\Omega_o$



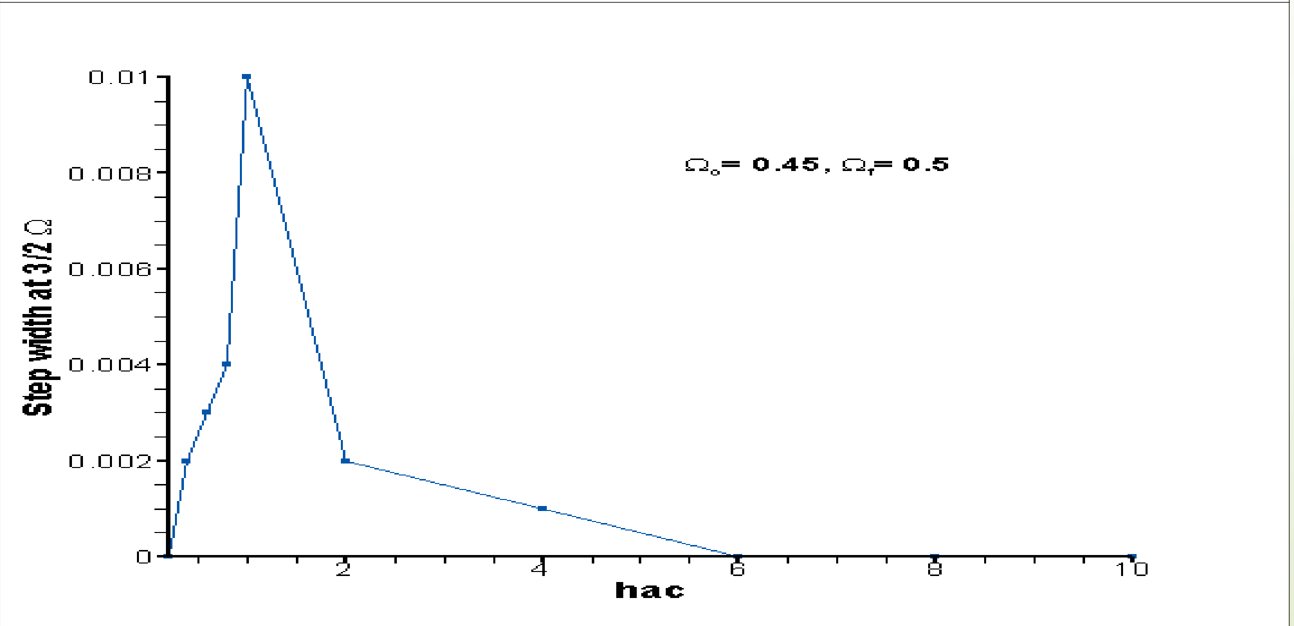
Shapiro step at $V=1\ \Omega_o$



- **Amplitude dependence of Shapiro steps' width at Ω_o = 0.3.**

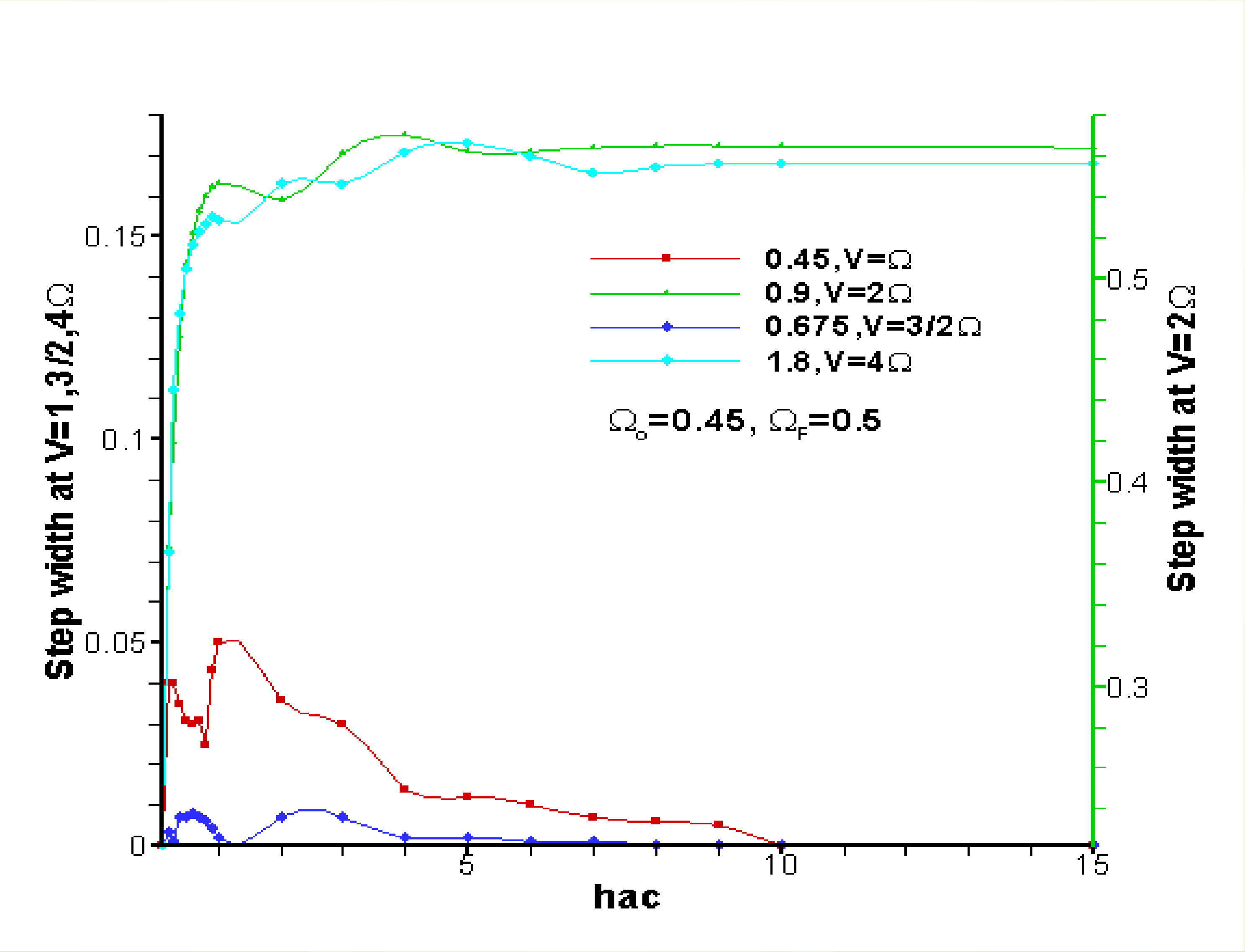


Step width at
$V = \Omega, 2\Omega \& 4\Omega$ **where**
Ω_o **=0.3**

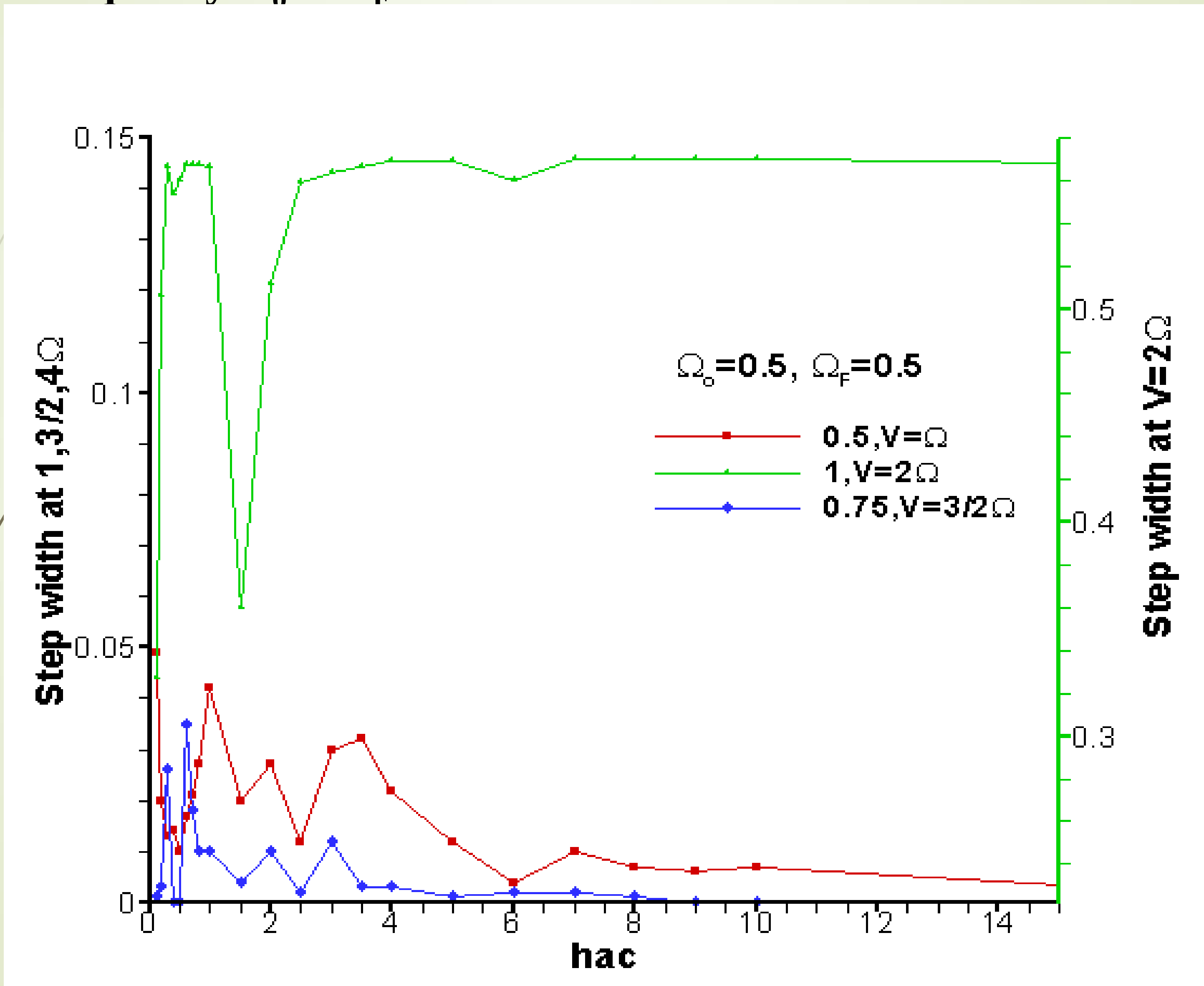


$\textit{Step width at} V = \frac{3}{2}\Omega$
where Ω=0.3

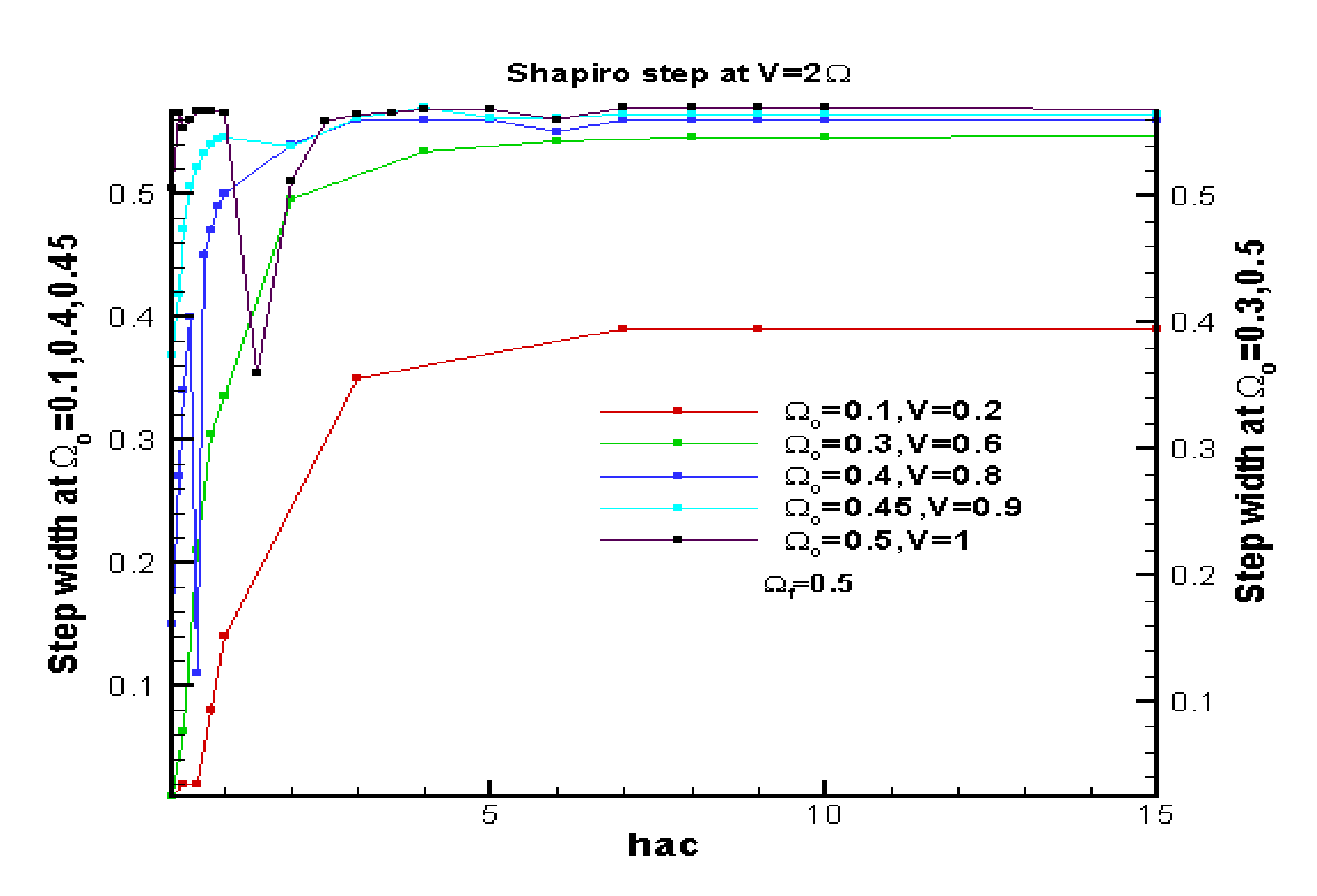
- **Amplitude dependence of Shapiro steps' width at Ω_o =0.45.**



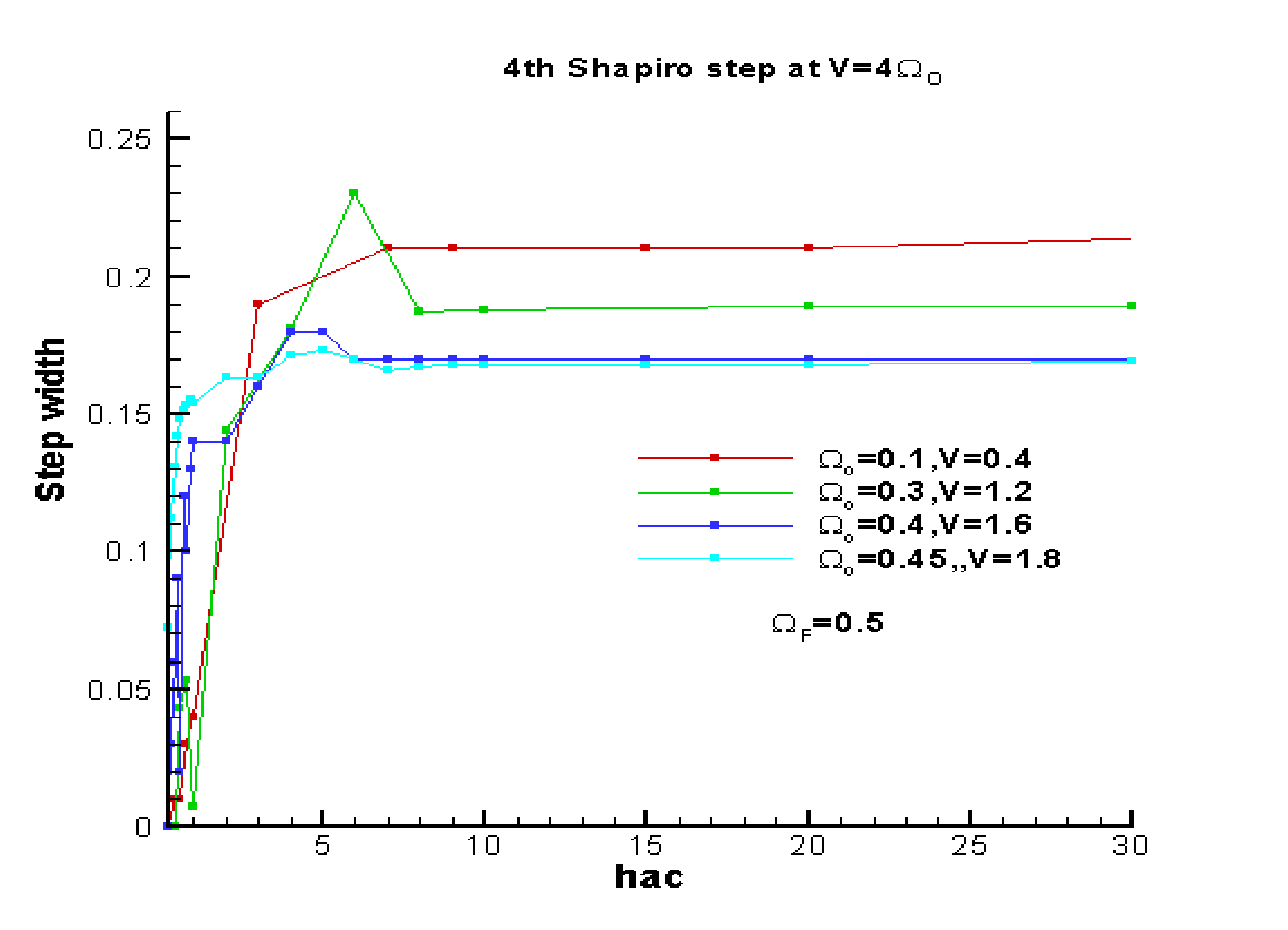
- **Amplitude dependence of Shapiro step's width at FMR frequency $\Omega_o = \Omega_F = 0.5$.**



- **Shapiro step width at V=2 Ω_o at different frequencies of circularly polarized magnetic field**



- **Shapiro step width at V= 4Ω_o at different frequencies of circularly polarized magnetic field**



Conclusions

- Investigation of Amplitude dependence of Shapiro step width for S/F/S J.J at different values of frequency and amplitude.
- Study of the anomalous behavior for width with Amplitude at even and half integer Shapiro steps.
- Our choice to study S/F/S J.J as it is the field where spintronics and superconductivity interact together and contribute in many potential applications as quantum computing.


Thank you