SWITCHING PHENOMENA AND PULSED OPERATION IN LONG JOSEPHSON DEVICES

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Recent findings by G.Pepe et al. (Appl.Phys.Lett.**89**, 2770, 2001) have given new insights over the dynamics of Josephson junctions subject to electronic pulse injection. These experiments can be considered important steps toward the study of non-equilibrium effects involved in junctions under very fast (e.g. laser induced) pumping signals. In the governing equations (sine-Gordon or coupled sine-Gordon depending on the system) pulse operation is entering via Josephson current distribution or via bias current distribution. By means of numerical simulations here we study the dependence of the switching to resistive state on fast local depression of Josephson current. Next using simulated electronic pulse train we show how the flip-flop operating mode found in G.Pepe et al. is a common feature of single or stacked Josephson systems without regards for the pulse waveform or the presence of the gap structure in the I-V characteristics. The effect of the length and magnetic field is also discussed.

1 Introduction

Non-equilibrium phenomena in Josephson junctions are a promising field for future applications involving fast devices designed to interact with optical signals [1,2]. This implies the need to study transistor-like devices [3] and bi-stable devices [4] to investigate what is the behavior of Josephson junction subjected to (fast) signals, both electronical and optical, which alter the equilibrium distribution of charge carriers (quasiparticles and Cooper pairs). In this paper we present some numerical results concerning the behavior of a current biased Josephson Junction (JJ) under the influence of a fast local depression of Josephson current and of an electronic current pulse injected in the junction from a second JJ forming a double tunnel junction stacked device.

2 Josephson electrodynamics under Fast Pulsed Signals

The simulations will be based on the numerical integration of model equation for the Josephson junctions (perturbed Sine-Gordon equation) in which the perturbation will be introduced via a fast time-space depending modulation of Josephson supercurrent. In general the Sine-Gordon Equations for a JJ of normalized length *l* subject to EM pulse signals can be written as:

$$\phi_{tt}-\phi_{xx}+\delta(x,t)\sin\phi+\alpha\phi_t=\gamma_B+\gamma_P(x,t)+\gamma_N(x,t) \quad (1)$$

where $\alpha=1/\beta_C$ is the loss parameter, γ_B the current bias, $\gamma_P(x,t)$ a pulse in the bias supply, γ_N is a noise current term, $\delta(x,t)$ is a time-space dependent modulation of the Josephson current. To above equation have to be added the open boundary conditions: $\phi_x(0)=\phi_x(l)=\eta$ where η is the external normalized magnetic field. A Gaussian noise $<\gamma_N(t)>=0$, $<\gamma_N(t)\gamma_N(t')>=\sigma\delta(t-t')$ was added to simulate the thermal bath effect. The perturbations $\delta(x,t)$ and $\gamma_P(x,t)$ model the interaction of the JJ with an external EM field. We assume that in the laser pulse case the main role is played by modulation of the critical current $\delta(x,t)$ which is assumed to be a simple step function in time. On the other hand electronic pulse trains pumping results in [4] are obtained with a stacked double junction. Stacked systems will be described according to the following equations (in presence of electronic pulses we suppose a constant critical current):

$$\begin{aligned}\varepsilon\partial_{xx}\varphi-\partial_{xx}\psi+\partial_{tt}\psi+\alpha\partial_t\psi+\sin\psi+\gamma_P(x,t)+\gamma_N(x,t)=0\\ \varepsilon\partial_{xx}\psi-\partial_{xx}\varphi+\partial_{tt}\varphi+\alpha\partial_t\varphi+\sin\varphi+\gamma_B+\gamma_N(x,t)=0\end{aligned} \quad (2)$$

For the pulse expression we assume the general (triangolar) form [4,5]:

$$\gamma_P(x,t)=\begin{cases}\Gamma h_1\left(\frac{x}{l}\right)\left(\frac{t}{T_1}\right) & for\ 0\le t\le T_1\\ \Gamma h_2\left(\frac{x}{l}\right)\left(1-\frac{t-T_1}{T_2}\right) & for\ T_1\le t\le T_1+T_2=T\\ 0 & for\ T\le t\le T_p\end{cases} \quad (3)$$

where $h_i(y)$ are the functions carrying the spatial dependence (it will be assumed that they take values between zero and one), T_1 is the (upward) risetime and T_2 the pulse slowing down, T is the total pulse length, l the normalized junction length, Γ the pulse peak value and T_p the time interval between pulses. For short symmetric pulses $h_1=h_2$ and $T_1=T_2$. For pulses with long decay we set $h_2=1$ whereas h_1 carry the spatial dependence. In the following we choose $h_i(y)=y$, also if similar results can be obtained also with $h_i(y)=y^n$, with n>1 integer or also by assuming $h(y)$ a simple step function, i.e., $h_i=0$ for $0<y<y^*$ and $h_i=1$ for $y^*<y<1$, where y^* is a suitable value, e.g., $y^*=0.9$. All these choices imply that pulse effect is localized mainly on one side of the stack.

3 Switch induction by fast local depression of Josephson current

The first results have been obtained supposing $\delta(x,t)$ to be simply a local suppression of the Josephson current for a given time T over a fraction of the Josephson length (typically

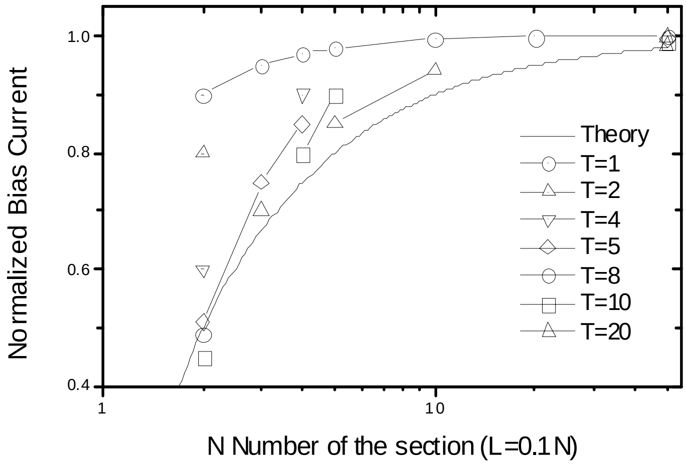

Fig.1 successful switches to resistive state *vs* the junction length (here measured in section each long 0.1, going from l=0.2 to 5) of a JJ (overlap geometry) in which the Josephson current of an end section of length 0.1 was suppressed by a variable time T (measured in normalized units). The theoretical curve represents the critical current of the reduced length junction γ_c=(N-1)/N. For T>20 there is no substantial change to this picture. For l=5 (the last series of points on the right) the difference becomes very small hindering the effect in very small fractions of critical current (1% - 2%). Where lines occur are just guides for eye. Note that is these units T=2π represents a plasma period.

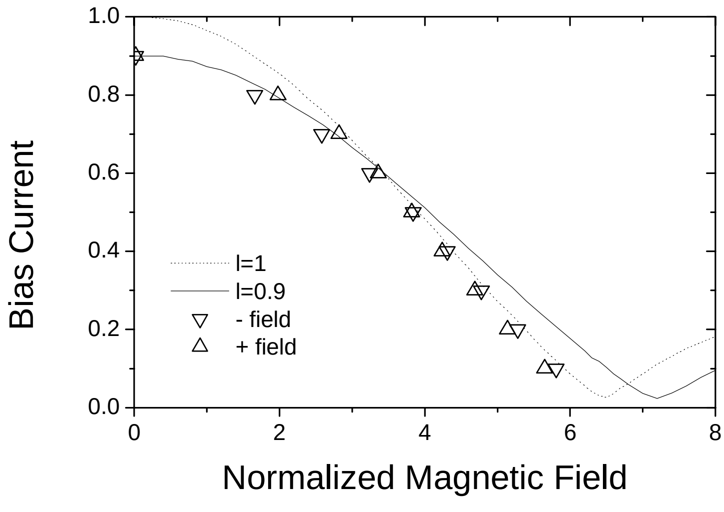

Fig.2: the effect of magnetic field over a JJ (overlap geometry) of normalized length l=1 in which the Josephson current of an end section of length 0.1 was suppressed for a time of T=10 u.t.. Each point represents the first successful switch over the resistive state when the junction is swept in field. For comparison are shown also the l=1 lobe (dotted) and the l=0.9 lobe (full). Field behavior shows also a difference in sign according to the fact that symmetry of the field pattern is broken because only one end of the junction is subject to the Josephson current suppression.

$\Delta x=0.1$ in normalized units). The status of the junction was monitored before and after the modulation "pulse", starting from Josephson state at a given bias current and ending both again in Josephson state or in the resistive state. The resistive state transition was recognized to be the system "answer to the perturbing pulse" so they have been collected as "positive" answer in Fig.s 1 and 2. Tests have been made on junction of different length from l=0.2 to l=5 (the discrete cell was chosen to be $\Delta x=0.1$, so the shorter length corresponds to a simple DC Squid). The junction is hysteretical with $\alpha=0.1$.

A distinction between two regimes it is evident just from this very simplified model:

1) "Heating" regime: for T>20 u.t. the behavior of the junction is practically independent of T, and dynamics take the aspect of a local "heating" of the junction. The junction typical behavior is that of a junction of reduced length $l-\Delta x$ so giving rise to a resistive transition where the bias current of the complete junction was higher than the critical current of the reduced junction (cf. Fig.1).

2) "Fast pulse" regime for T<20 u.t. the behavior is more complex because it depends on T: very short pulses are unable to set out the junction of the Josephson state, but for all explored T a bias current exists for which junction switch on the resistive state (see again Fig.1) though this can be for the longest junction very near to the critical current.

If a magnetic field is added (for T roughly 10 u.t.) the behavior follows the reduced length junction lobe until a given value of the field, and then following again the original junction lobe for higher fields (cf.Fig.2). It is evident also a different behavior in term of the sign of the magnetic field.

4 Flip-flop operation under electronic current pulses in a stacked device

A summary of results for pulse train pumping of Eq.s (2) is reported in Fig.3. Best flip-flop sequences have been obtained in simulations for small junctions in a strongly coupled stack. This is evident from Fig.3a where a detector junction with *l*=1 is pumped via the stack with a ε=-.085 using a short triangular pulse train (in the figure reported not in scale as single spikes) applied to an identical injector junction. Such deterministic behavior is difficult to obtain in experimental stacks where the typical behavior is much more similar to situation reported in Fig.3b where a longer detector junction is pumped by via the stack with low coupling ε=-.0.2 (not far from experimental values [5]) by a triangular asymmetric long pulse train. The transition occurs not at every pulse reaching the stack giving a Statistical Flip-Flop (SFF) state. We have changed the dissipation and the pulse waveform to show how stack system has a large set of parameters in which SFF exists. We note that SFF is sensible to thermal noise, here set to T=4.2 K, which can influence especially the escape from zero voltage state. Thermal noise was analyzed in Ref.s [5,8]. Triangular short pulse trains was applied again in the case of low stack coupling in Ref.[5] showing a similar behavior. The effect of an increase in the junction length is reported in Fig.3c,d for two different bias points. Subgap resonances as Zero Field Steps (ZFS) appears in the dynamical switches. For lower bias only lowest ZFS are excited (cf. Fig.3c), whereas for higher bias transition to zero voltage state are scarce and higher resonances appears (cf. Fig.3d). The effect of magnetic field is viewed in Fig.3e, a lower resonance appears corresponding to a Fiske Step (FS). Such FS excitations have been observed also in the experiments with pulse train operation. In the simulations the general effect of magnetic field is to reduce the number of resonances visited in the SFF process. Finally in Fig.3f we report the effect of having changed the

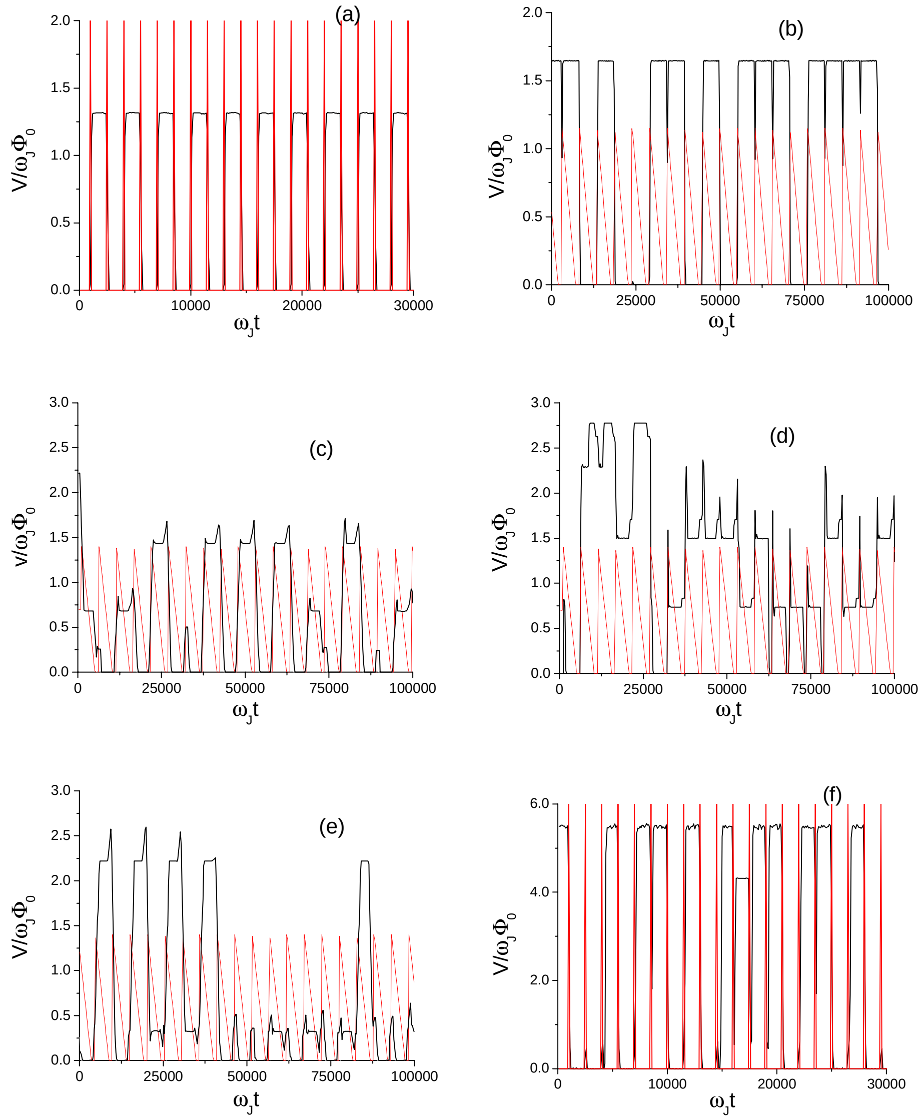

Fig.3: simulated SFF transitions in different stacked systems described by Eq.s (2): a) l=1, α=0.15, ε=-0.85, γ_B=0.23, Γ=21, triangular short pulses with T=100 u.t.; b) l=2.5, α=0.05, ε=-0.2, γ_B=0.0875, Γ=46, triangular asymmetric pulses with T_1=50 u.t. and T_2=2000; c) l=5, α=0.1, ε=-0.55, γ_B=0.23, Γ=56, triangular asymmetric pulses with T_1=50 u.t. and T_2=2000; d) l=5, α=0.1, ε=-0.55, γ_B=0.28, Γ=56, triangular asymmetric pulses with T_1=50 u.t. and T_2=2000; e) l=5, α=0.1, ε=-0.55, γ_B=0.28, Γ=56, triangular asymmetric pulses with T_1=50 u.t. and T_2=2000, with magnetic field at boundary η=1.0; f) l=2, ω_g=8ω_J, ε=-0.55, γ_B=0.18, Γ=60, triangular short pulses with T=100 u.t. some instability and also an intermediate state occurs due to low dissipation under the gap. In all figures pulses are not in scale and have been reported just as guide for eyes.

linear conductance part in Eq.(2) via a patchwork gap model similar to that described in Ref.[9] with a ratio of ω_g/ω_J=8. Surprisingly the much higher voltage and the change in dissipative properties is not a limitation for the existence of SFF also with this different dissipation model. So we belief that SFF is a very general characteristic of Eq.s (2) or of the single Josephson junction (cf. Ref.[6,8]) independently from dissipation model, pulse waveform and pulse spatial dependence.

5 Conclusion

In the last year several experiments have been devised to show the presence of SFF in different devices (cf.Ref.[4,5,6,8,9]). There are evidences that pulsed assisted escape from zero voltage is very similar to standard thermal escape (cf. Ref.[5]), on the other hand the reset pulse (back switch to zero voltage from resistive state) appears related to the non-linear dynamics effects involved in Eq.s (2). We note that the possibility of having long deterministic flip-flop series is again to be proved. Moreover the study of length effect and magnetic field control is again at the beginning. Progress in obtain a deterministic FF have been made using a magnetic control line as reported in Ref.[6]. More promising appears the possibilities of use ultrafast (20 ps to 100 fs) laser pulses to pump detector junctions away from zero voltage state for the developing of a fast opto-superconducting electronics. Studies on SFF are in some sense preliminary to laser dynamics that involve a more complex physics due to its influence, behind the phase dynamics, on the equilibrium distribution of both Cooper pairs and quasi-particles.

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