Physica B 280 (2000) 239–240

PHYSICA B

www.elsevier.com/locate/physb

Nonlinear resonance between a soliton and Josephson plasma waves: experiment and theory

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Abstract

Resonant interaction of a soliton (Josephson fluxon) with its self-generated Josephson plasma waves is studied experimentally, numerically, and analytically. An externally applied magnetic field H forms a cos-like potential relief for the soliton in the annular junction. Soliton motion under the influence of the bias current leads to an emission of plasma waves, which gives rise to a resonance at a certain soliton velocity. This resonance on the current–voltage characteristics shows a clear backbending accompanied by *a negative differential resistance*. Our analysis quantitatively explains the observed effect.

PACS: 03.40.Kf; 03.65.Pm; 74.50.+r

Keywords: Flux lines; Josephson effect; Long Josephson junctions; Plasma waves; Solitons

Magnetic fluxons in long Josephson junctions have many properties of ballistic relativistic particles as have been seen in large number of experiments [1]. Fluxons moving in an inhomogeneous media can generate Josephson plasma waves which are essentially small-amplitude linear oscillations of the phase difference across the junction. Interaction of fluxons with these waves leads to resonances which appear as fine structure steps on the current–voltage (I–V) characteristics [2,3]. It has been seen so far in a number of experiments that these fine structure steps have often an interesting feature which is *backbending*, i.e. the voltage of the step decreases with increasing current. In this work, based on new experiments and their theoretical analysis, we show that such a backbending of resonances is due to excitation of *large amplitude plasma waves* which have nonlinear nature and therefore modify the dispersion relation.

We have measured and analyzed the dynamics of a single fluxon trapped in an annular Josephson junction which is placed in an externally applied magnetic field H. Due to the interaction of the fluxon with the radial field component [4], the fluxon feels a periodic potential $U(\theta) \sim H \cos\theta$. The minimum of the potential is located in the region of the ring where the fluxon's magnetic field is directed along the field.

Experiments have been performed on Nb/Al-AlO_x/Nb Josephson junctions. We applied the bias current I through the junction and measured the DC voltage generated due to the fluxon motion.

The fluxon's I–V characteristics are shown in Fig. 1. As indicated on the plot, curves correspond to different values of the magnetic field. With increasing H, the critical current I_{cr} increases, and hysteresis appears on the I–V curves. At $I > I_{cr}$ the fluxon overcomes the pinning potential and starts to move in the junction, which induces DC voltage. The resonant step at 28–30 μV very clearly shows a *backbending*, i.e., negative differential resistance in a certain current range.

Based on numerical simulations and theoretical analysis [5] we explain the mechanism behind the

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0921-4526/00/$ - see front matter
PII: S0921-4526(99)01638-5

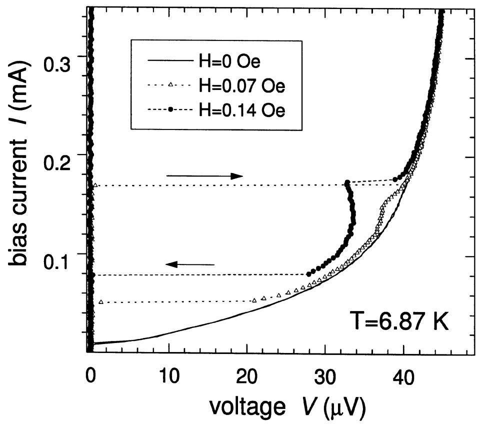

Fig. 1. Current–voltage characteristics of a single fluxon moving in the annular junction.

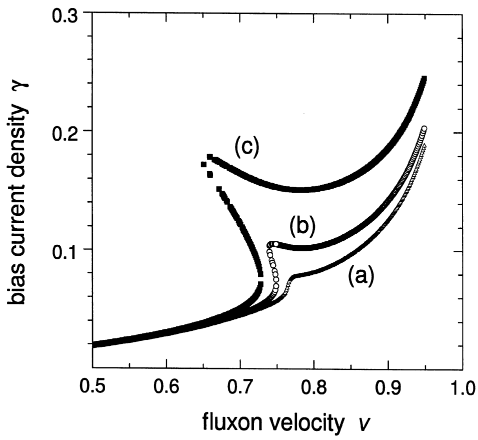

Fig. 2. Analytically derived current–voltage characteristics in the region of the backbending resonance [5]. The magnetic field increases from (a) to (c).

backbending step in Fig. 1 as nonlinear resonance between the rotating fluxon and plasma radiation field which it generates in a spatially inhomogeneous potential in the junction. A simple model for the linear case of such a resonance has been put forward in Ref. [6]. An essentially novel step to be done new analysis is to take into regard a finite amplitude of the background radiation. If the radiation's amplitude is finite but still small enough, one expands the unperturbed sine-Gordon equation in a straightforward way:

$$\varphi_{tt} - \varphi_{xx} + \varphi - \tfrac{1}{6}\varphi^3 = 0 \qquad (1)$$

which leads to the nonlinear dispersion relation for the finite-amplitude radiation,

$$\omega^2 = 1 + k^2 - \tfrac{1}{8}A^2. \qquad (2)$$

In Fig. 2, we display a set of the I–V curves obtained from our analytical approach presented in Ref. [5]. The backbending on the I–V curve for larger fields is clearly seen. We conclude that decrease of the effective plasma-frequency gap produced by the finite-amplitude radiation background is indeed a crucial fact that consistently explains the backbending of the I–V curves observed in many previous experiments with fluxons in long Josephson junctions and parallel 1D Josephson arrays.

Acknowledgements

This work was partly supported by a Grant G0464-247.07/95 from the German–Israeli Foundation.

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