# Vortices : collective variables for turbulence in Josephson arrays

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*Abstract.* In previous work we had shown that a dc-current driven ($I_x(y)$) array of overdamped Josephson junctions, without disorder, external field ($f = 0$) or thermal excitation ($T = 0$), would exhibit chaos for sufficiently large edge injected vorticity $\partial I_x(y)/\partial y$. We now show that the chaos transition (rise in voltage noise) is associated with injected vortices moving suddenly away from the injection edge, and their (previous regular) appearance times becoming irregular. Thus vortices may be collective variables for spatially varying chaos, or 'turbulence'.

## Introduction

The dynamics of 2D Josephson arrays is governed by Total Current Conservation (TCC), as first considered in a calculation of the dynamic conductivity $\sigma(\omega, T)$ at the Kosterlitz–Thouless transition [1]. TCC dynamics was then applied to the simplest possible nonequilibrium case, to investigate the possibility of chaos in arrays and its origin [2]. The junctions were overdamped, and external drives dc, so chaos could only come from many-body couplings. Complicating factors such as thermal or field-induced vortices, or disorder, were eliminated. (These have been considered, in some further studies [3, 4]).

It was found [2] that under these conditions $f = 0$, $T = 0$, only an ac Josephson effect results from a *uniform* dc drive at the $x = 0$ edge, with external current per bond $I > 1$, (scaled in the critical current $I_J$). For *chaos* to occur, a transversely varying *nonuniform* dc drive was necessary. The simplest such drive was a linear profile (Fig. 1).

$$I_x(y) = I_{\max} - \Delta I \bar{y}; \qquad \bar{y} = y/L_y \tag{1}$$

for array dimensions $L_x \times L_y$, with $I_{\max} L_x = (N_x - 1)a_0$, where $-\partial I_x/\partial y = \Delta I$ is a local injected vorticity at the edge, $x = 0$. The $I_m$ versus $\Delta I$ phase diagram has periodic, quasiperiodic (3 frequencies), and spatially varying chaotic regimes, the last for $\Delta I > \Delta I_c$ and $I_{\max} > 2$. The critical $\Delta I_c$ is independent of the length $N_x$ for $N_x > 4$. $\Delta I_c$ decreases with the width $L_y$, but in a definite way, with total injected vorticity $\Delta I_c(N_y + 1)$ a constant, $\simeq 8$ as checked from $N_y = 3$ up to $N_y = 14$. Thus $4 \times 3$ and upward-sized arrays behave similarly.

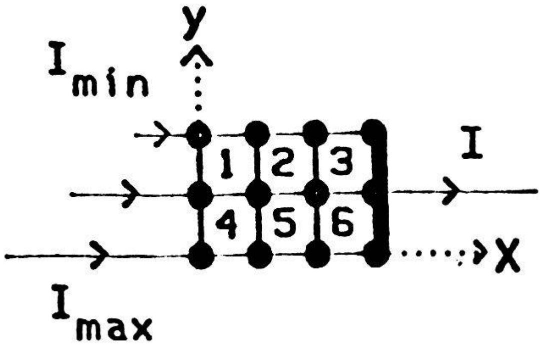


Figure 1
Junction array, with plaquettes numbered and nonuniform drive, at $x = 0$ with $x = L_x$ side shorted out.

## Vortex behaviour at chaos onset

Vortices in plaquettes can be identified by adding the phase differences along the plaquette boundary. The number $N_{\pm}(t)$ of vortices in the array $(N_- \gg N_+)$ varies, as they appear and disappear, in time, with only a few present at any instant. In the quasiperiodic regime, their appearance times, (in a particular plaquette) are regular (Fig. 2a) but go irregular for $\Delta I > \Delta I_c$, in the chaotic regime (Fig. 2b).

The $x$-component of the 'centre-of-charge', or first moment of the (time averaged) $\pm$ vortex charge density, $X^{(\pm)} = \sum_{\vec{r}} n^{(\pm)}(\vec{r}, t)x$, shows a sharp change at $\Delta I_c$, with $-1$ vortices 'de-adsorbed' from the injection edges, and $+1$ vortices moving to $x = 0$ and 'mixing' (Fig. 3). Thus vortices, central to the equilibrium KT transition, may also drive the chaos transition.

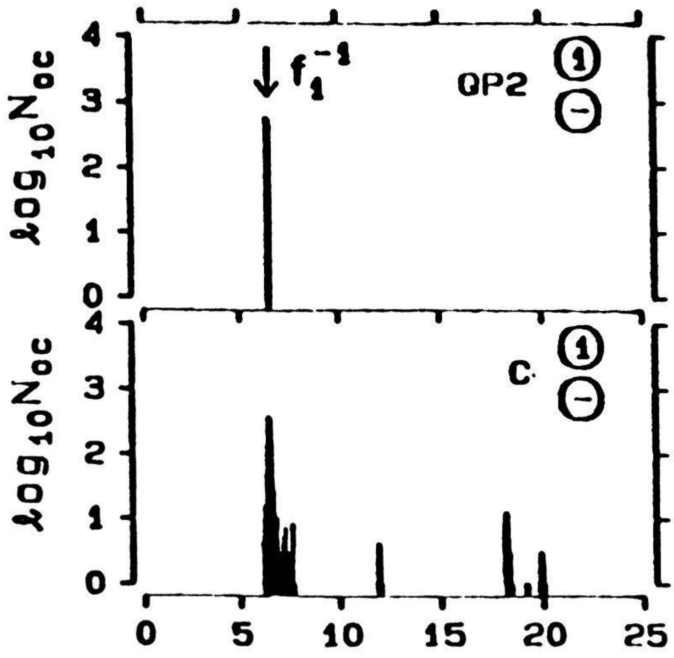


Figure 2
Distribution $N_{0C}$ of intervals of occurrence $t$ of $-1$ vortices appearing in plaquette 1, in a quasi periodic (QP) and chaotic (C) regimes.

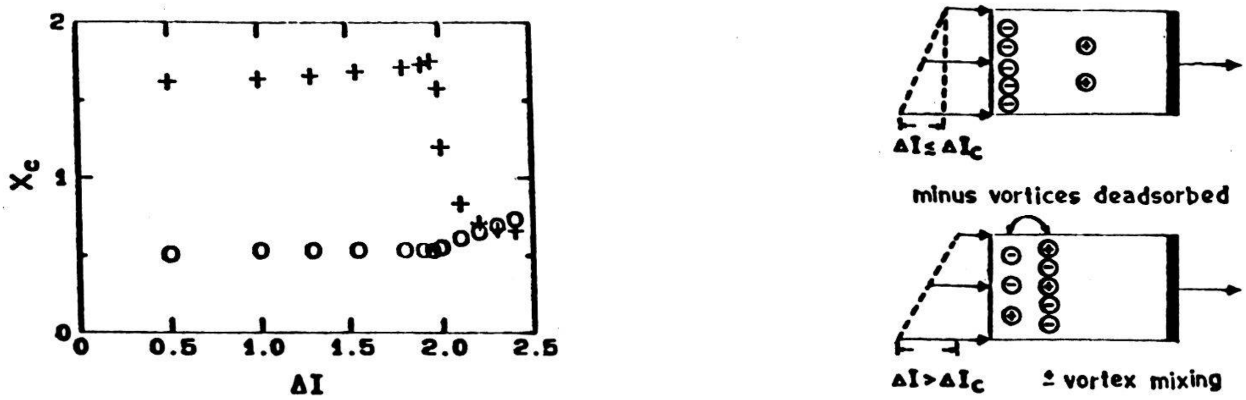


Figure 3
(a) $X$-component of centre of charge versus $\Delta I$ for negative (0) and positive (+) vortices. Injection edge is $x = 0$. (b) schematic of physical picture.

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