Easily-Controllable Collective Stepmotor of Magnetic Flux Quanta

B. Y. Zhu [a], F. Marchesoni [a,b], V. V. Moshchalkov [c], and Franco Nori [a,d]

[a] *Frontier Research System, The Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama 351-0198, Japan*
[b] *Istituto Nazionale di Fisica della Materia, Universitá di Camerino, I-62032 Camerino, Italy*
[c] *Laboratorium voor Vaste-Stoffysica en Magnetisme, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium*
[d] *Center for Theoretical Physics, Physics Department, CSCS, University of Michigan, Ann Arbor, MI 48109-1120, USA*

Abstract

We study the transport of vortices in superconductors with regular arrays of asymmetric pinning wells when applying an alternating electrical current. We show that this system can induce a net rectifying or diode effect for the vortex motion, including collective stepmotor-type dynamics, where many vortices move forward a controlled and exact number of pin-lattice-spacings at each cycle of the AC driving force. This results in a remarkable net DC response with striking sawtooth-type oscillations. This system provides an experimentally realizable stepmotor of quanta and a precise control of the motion of vortices.

Key words: Superconducting Vortex Dynamics, Flux Pinning, Vortex-Motion Control Devices.

Vortex dynamics in superconductors under the influence of an asymmetric periodic potential have attracted considerable interest in recent years [1–4]. The control of the motion of vortices using asymmetric pinning can be useful for applications in superconducting devices, including the removal of unwanted trapped flux in devices. Here, we produce asymmetric pinning sites by superimposing two interpenetrating arrays of weak and strong pinning centers [3] and numerically study the stochastic rectification of AC-driven vortices due to the 'ratchet effect" of asymmetric pinning sites.

Figure 1 shows only three periods of the vortex pinning potential $U_p(y)$ and its corresponding pinning force $F_p = -dU_p/dy$, which are AC-driven along the y-axis. All pinning centers are modelled here by Gaussian potential wells [3] with decay length R_p. We use a near optimal separation $d = 0.2a_0$ between the two sublattices of strong and weak pinning traps. The square pin-lattice spacing a_0 is set equal to 1. The applied AC Lorentz driving force acting on the vortices is parallel to the y-axis, i.e., $\mathbf{F}_L = F_L(t)\mathbf{y}$. The repulsive vortex-vortex interaction is modelled [3] by a logarithmic potential. Thus, the overdamped equation of motion for each vortex is given by $\eta\mathbf{v} = \mathbf{F}_L + \mathbf{F}_{vv} + \mathbf{F}_p$. A more

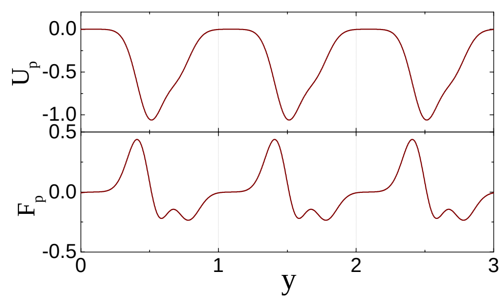

Fig. 1. Pinning potential (top) and pinning force (bottom) for a small subset of the square asymmetric pinning system.

detailed description of this asymmetric model and simulation can be found in Ref. [3,4].

Net DC Voltage versus AC Drive Period.— Figure 2 shows the net DC voltage (or velocity) V_{DC} of the vortices for different amplitudes, $F_L = 0.3$ and 0.6, of the driving force at the first matching field $H/H_1 = 1$. Each curve has 400 plotted points, and each non-zero point is obtained by averaging over 200 periods, each with about 10^4 to 10^6 MD steps. A sharp jump and a striking *sawtooth-type rectified voltage* $V_{DC}(P)$ curve appear when the amplitude of the AC drive is smaller

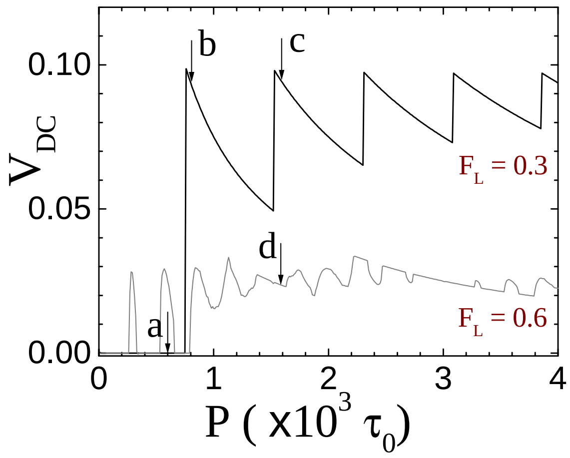

Fig. 2. Net average DC velocity V_{DC} versus the half period P of the AC driving force for different amplitudes, $F_L = 0.3$, 0.6 at the first matching field, $H/H_1 = 1$.

than the largest critical depinning force $F_M \sim 0.44$ (for $\mathbf{F}_L \parallel -\mathbf{y}$), and larger than the smallest depinning force $F_m \sim 0.23$ (when $\mathbf{F}_L \parallel +\mathbf{y}$). As seen in Fig. 2, when $F_L = 0.6 > F_M$ the V_{DC} response changes drastically: becoming non-periodic and typically lower than $V_{DC}(F_L = 0.3 > F_m)$.

Time dependence of the displacement of the AC driven vortices.— In Fig. 3, we show the *periodic* displacement y versus time for *any* vortex in the sample. In a, b, and c, $F_L = 0.3$ and satisfies $F_m < F_L < F_M$, corresponding to the sawtooth-type V_{DC} shown in Fig.2. In d, $F_L = 0.6$, satisfying $F_M < F_L$, with a non-periodic V_{DC}. For these four cases, during the half-period of the driving force parallel to the positive y-direction (namely, when $\mathbf{F}_L$ points from the strong to the weak pins in each composite pinning unit), the initially-trapped vortices can depin and move out of the composite pinning centers. During the next half-period, different cases can respond differently. Let us first consider $P = 600\tau_0$, indicated by the arrow “a” in Fig. 2, shown in panel (a) of Fig. 3. After depinning, the vortices first travel a distance smaller than the pin-spacing unit a_0, and afterwards are all driven back to their original traps.

When $P = 800\tau_0$, Fig. 3(b), after depinning the vortices can travel a distance equal or larger than the spacing unit a_0, when F_L is directed along the $+y$-axis. Thus, these vortices will be now trapped in a nearby pinning center during the second half-period of the driving force, when $\mathbf{F}_L$ points in the negative y-direction. Now the vortices cannot be driven back to their original pinning centers, because F_L is lower than the stopping force F_M for the strong pinning centers. Therefore, all vortices move forward along the $+y$-axis exactly one period a_0 for each driving cycle. Thus, the system behaves as an easily controllable *“collective vortex stepmotor”, cooperatively shifting all pinned vortices by one step for each cycle.* This collective vortex stepmotor produces the *very unusual sawtooth-shaped net DC response* for the applied AC driving force in such an asymmetric pinning system.

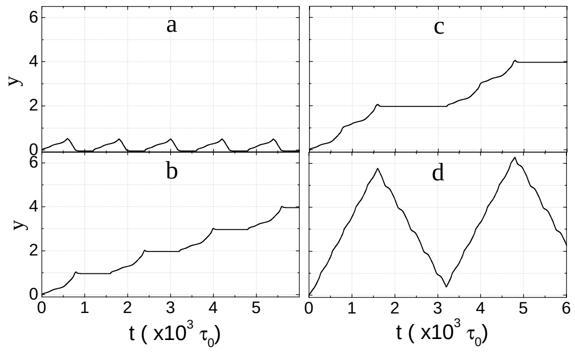

Fig. 3. Displacement $y(t)$ of any vortex as a function of time for different half periods P and amplitudes F_L of the AC drives (a) $P = 600\tau_0$, (b) $P = 800\tau_0$, (c) $P = 1600\tau_0$ at $F_L = 0.3$; and (d) $P = 1600\tau_0$ at $F_L = 0.6$.

In Fig. 3(c) and (d), we show $y(t)$ when $P = 1600\tau_0$ for $F_L = 0.3$ and 0.6, respectively. When $F_L = 0.3 < F_M$, the driven vortices can travel $2a_0$ along the $+\mathbf{y}$ during each period of the AC drive. When $F_L = 0.6 > F_M = 0.44$, the driven vortices can travel about $5.8a_0$ along the $+\mathbf{y}$ during the first half-cycle, and then about $5.3a_0$ along the $-\mathbf{y}$ during the second half-cycle of the AC drive. Thus, the net displacement of any vortex, after each cycle, is approximately equal to $0.5a_0$. Thus, even though the vortices can depin in both directions when the driving amplitude of the vortices is sufficiently large, Fig. 3(d) clearly shows the different vortex displacements along the two opposite driving directions. Thus, the asymmetric pinning sites in our system produce “anisotropic effective vortex viscosities”, that “slow down” the vortex motion in an anisotropic manner.

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References

[1] J. F. Wambaugh, *et al.*, Phys. Rev. Lett. **83**, 5106 (1999).
[2] C. J. Olson, *et al.*, Phys. Rev. Lett. **87**, 17700 (2001).
[3] B. Y. Zhu, *et al.*, Phys. Rev. B **64**, 012504 (2001).
[4] B. Y. Zhu, *et al.*, unpublished.