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Ratchet without spatial asymmetry: Controlling the motion of magnetic flux quanta using time-asymmetric drives

S.J. Bending [a,*], D. Cole [a], S. Savel'ev [b,c], F. Nori [b,d], T. Tamegai [e]

[a] Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK
[b] Frontier Research System, RIKEN, Saitama 351-0198, Japan
[c] Department of Physics, Loughborough University, Loughborough LE11 3TU, UK
[d] Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109-1040, USA
[e] Department of Applied Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

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Abstract

We report on vortex manipulation experiments which exploit the attractive interaction between 'crossing' pancake vortex (PV) and Josephson vortex (JV) lattices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystals under tilted magnetic fields. Deformations of the JV lattice allow us to *indirectly* move mutually interacting PVs. In *dc-driven* mode the in-plane field is varied slowly (adiabatically) while the PV density is monitored at different points in our single crystal BSCCO sample using a micro-Hall probe array. Variations in PV density as large as 40% have been demonstrated in this way and both enhancement and depletion are observed, depending on the location in the crystal, temperature and PV density. In *ac-driven* experiments, manipulation is achieved by applying trains of time-asymmetric (saw-tooth) in-plane field pulses. We show how both flux focusing and defocussing can be readily achieved merely by varying the time-asymmetry of the drive. Our experimental results are well described by molecular dynamics simulations which consider the dragging of PVs by JVs.

Keywords: Type II superconductors; Crossing vortex lattices; Vortex pumps

1. Introduction

In recent years dramatic progress has been made in the control of *static* flux structures in type II superconductors by the introduction of artificial vortex pinning sites. The next major challenge is to find ways to control the *dynamic* properties of vortices so that different flux profiles can be realised in the same superconducting sample. Rectification of the ac motion of nanoscale particles has been demonstrated in so-called 'ratchet devices' incorporating a spatially-asymmetric pinning potential [1,2]. However, a spatially-asymmetric 'ratchet substrate' is not a fundamental requirement for vortex manipulation, and recent proposals [3,4] have described novel methods to control the motion of tiny particles in a binary mixture by the dragging of one component by the other one. Here we describe the first such experimental implementation of a ratchet device using *time-asymmetric* drives in the binary vortex system present in highly anisotropic layered superconductors under tilted magnetic fields [5].

2. Experiments and molecular dynamics simulations

Direct visualization has revealed that a tilted magnetic field penetrates the highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) superconductor in two interpenetrating vortex arrays, known as 'crossing' vortex lattices [6]. One vortex sublattice consists of stacks of pancake vortices (PVs) aligned along the *c*-axis, while the other sublattice is formed by Josephson vortices (JVs) confined between CuO_2 layers. Superconducting currents generated by JVs

* Corresponding author. Tel.: +44 1225 385173; fax: +44 1225 386110.
E-mail address: pyssb@bath.ac.uk (S.J. Bending).

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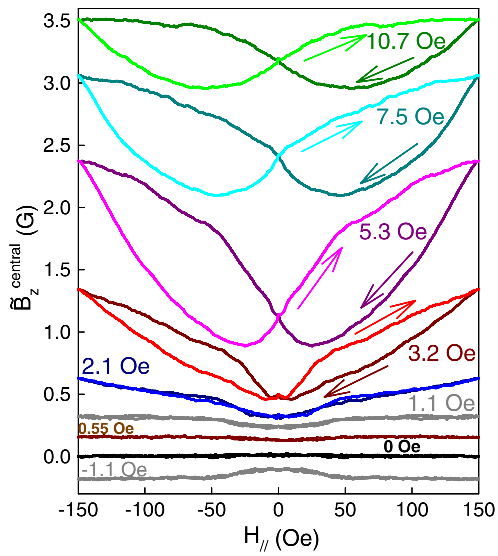

Fig. 1. *DC-driven*: Changes (vertically offset for clarity) in the local out-of-plane magnetic induction, B_z, versus $H_{\parallel}$ near the center of the BSCCO sample at 77 K and the indicated values of H_z.

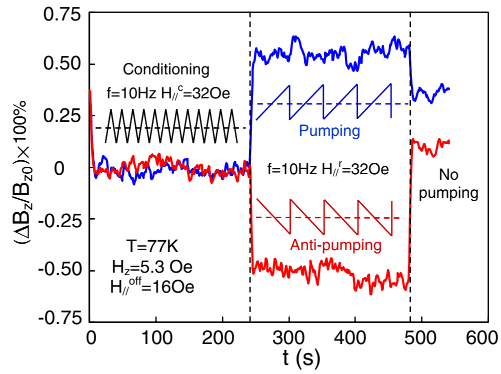

Fig. 2. *AC-driven*: Measured percentage change of the magnetic induction at the sample center as a function of time for applied pumping and anti-pumping time-asymmetric drives (see indicated $H_{\parallel}$ waveforms).

deform stacks of PVs, resulting in a mutual attraction between PVs and JVs [7,8]. This allows one to *indirectly* manipulate the PV distribution by deforming the JV lattice and *vice versa*, and vortex pumps, diodes and lenses based on this principle have recently been proposed [3,8]. We report results on two distinct types of manipulation experiments which exploit this phenomenon in BSCCO single crystals.

In *dc-driven* 'lensing' the in-plane field is varied slowly (quasi-adiabatically) while the PV density is monitored at different points in our single crystal BSCCO sample using a micro-Hall probe array. PVs remain trapped on the moving JVs and are carried towards the sample center, where their density is amplified. Variations in PV density as high as 40% (cf. Fig. 1 at $H_z = 5.3$ Oe) have been demonstrated in this way, and both enhancement and depletion are observed, depending on the location in the crystal, temperature and PV density.

In *ac-driven* experiments vortex manipulation is achieved by applying trains of time-asymmetric (sawtooth) in-plane field pulses. PVs remain trapped on JVs on the slowly varying section of the sawtooth, but are dragged off them on the rapidly varying section. In this way we can achieve the net motion of pancake vortices in a desired direction; i.e., we realise a form of ratchet device which, in contrast to other recent vortex ratchet experiments [2], does not require a spatially-asymmetric pinning potential to function. Flux 'focusing' and 'defocusing' can be readily achieved merely by varying the time-asymmetry of the drive (cf. Fig. 2), and the efficiency is a peaked function of the drive frequency, f, and H_z.

Our results have been compared with one-dimensional simulations which describe the overdamped dynamics of JV and PV rows within a set of coupled equations of motion. Both dc-driven and ac-driven experiments are well described by these molecular dynamics simulations, which directly incorporate the various time-dependent drives that are used in our experiments [5]. We find that the efficiency of flux focusing is dominated by the interplay between the attractive JV–PV crossing lattices interaction and PV–PV repulsion, and the systematic experimental trends as a function of H_z and temperature are well explained in these terms.

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References

[1] J.F. Wambaugh et al., Phys. Rev. Lett. 83 (1999) 5106;
C.J. Olson et al., Phys. Rev. Lett. 87 (2001) 177002;
B.Y. Zhu et al., Phys. Rev. Lett. 92 (2004) 180602;
C.-S. Lee et al., Nature 400 (1999) 337.
[2] J.E. Villegas et al., Science 302 (2003) 1188;
R. Wördenweber et al., Phys. Rev. B 69 (2004) 184504;
J. Van de Vondel et al., Phys. Rev. Lett. 94 (2005) 057003;
Y. Togawa et al., Phys. Rev. Lett. 95 (2005) 087002.
[3] S. Savel'ev, F. Nori, Nature Materials 1 (2002) 179.
[4] S. Savel'ev, F. Marchesoni, F. Nori, Phys. Rev. Lett. 92 (2004) 160602.
[5] David Cole et al., Nature Materials 5 (2006) 305.
[6] L.N. Bulaevskii et al., Phys. Rev. B 46 (1992) 366.
[7] A.E. Koshelev, Phys. Rev. Lett. 83 (1999) 187.
[8] A.N. Grigorenko et al., Nature 414 (2001) 728.