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International Centre for Theoretical Sciences
Tata Institute of Fundamental Research

Vortex Ratchets in Highly Anisotropic Superconductors

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Vortex Lensing Experiments

Molecular Dynamics Simulations

BSCCO Single Crystals

OUTLINE

Introduction

- **Brownian motors & ratchets**
- **Vortex ratchets**
- **'Crossing' vortex lattices in layered superconductors**
  - *Vortex manipulation in the crossing lattices regime*
- **Experimental system**

Experimental Results; *Vortex manipulation in $Bi_2Sr_2CaCu_2O_{8+\delta}$*

- ***Vortex 'ratchet-like' experiments using time-asymmetric drives***
  - *Comparison with molecular dynamics simulations – role of vortex viscosity*
- ***'Quasi-adiabatic' vortex focusing (lensing) experiments***
  - *Comparison with molecular dynamics simulations – role of vortex-vortex interactions*

Conclusions and Prospects

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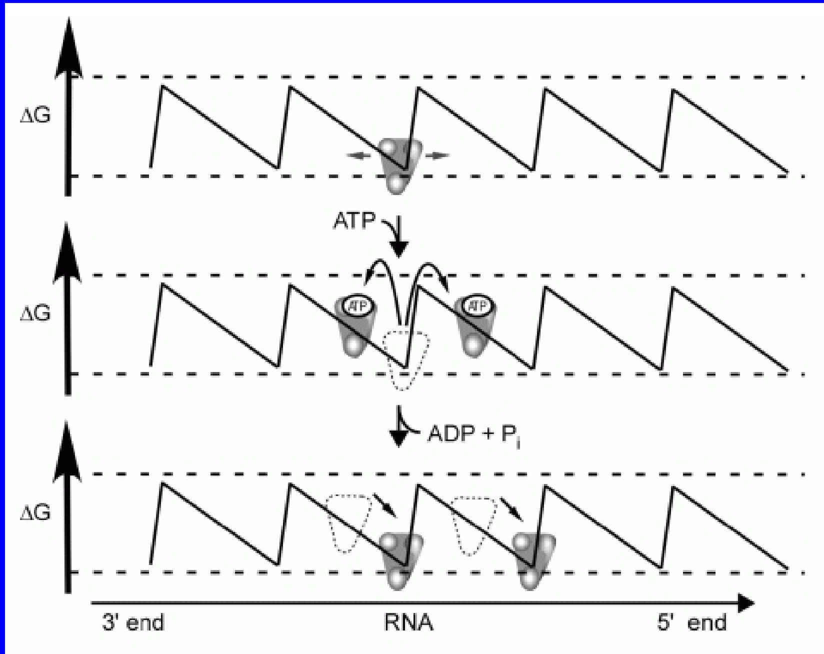
Biological Motors

A motor is a device that consumes energy in order to perform mechanical work.

- *Molecular motors are biological molecular machines that consume energy (e.g., chemical energy released by the hydrolysis of ATP) to enable movement in living organisms.*

Molecular motors are very different from the macroscopic motors we are used to – their operation depends intimately on the constant Brownian motion of the wet, viscous, nanoscale biological world.

The hepatitis C virus has a protein portion with the ability to travel along RNA, fueled by ATP hydrolysis. This allows the protein to displace complementary strands of DNA and RNA (and bound proteins). Normally the protein is 'pinned' by molecular barriers, but after binding with ATP it changes conformation and becomes free to move. Brownian fluctuations are more likely to move to the protein to the right in the asymmetric molecular potential before the protein is 'repinned' upon ATP hydrolysis.



M.K. Levin *et al.*, Nat. Struct. Mol, Biol. **12**, 429 (2005)

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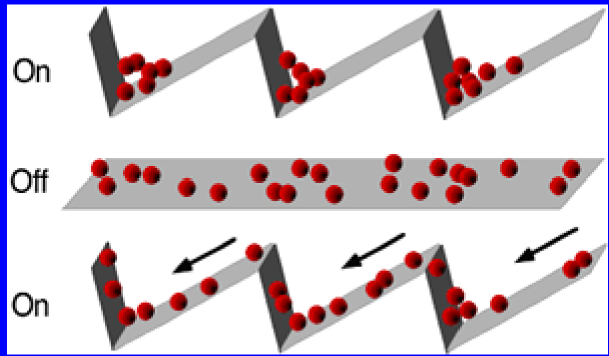
Brownian Motors & Ratchets

The hepatitis virus molecular motor is a form of Brownian motor.

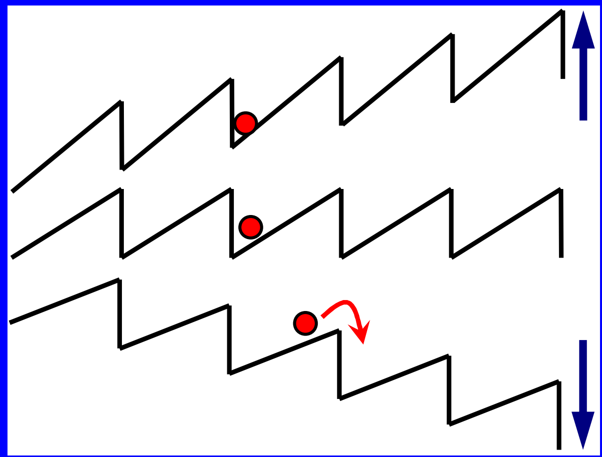
Operating far from thermal equilibrium, Brownian motors combine noise and asymmetry (e.g., via a 'ratchet' potential) to achieve directed motion.

There are two main classes of ratchet device:-

Flashing ratchets. Brownian particles are trapped in a periodic, asymmetric potential that can be turned on and off. Random diffusion when the potential is off is converted into net motion to the left when the ratchet is on.



Rocking ratchets. Brownian particles are trapped in a periodic, asymmetric potential that can be rocked (tilted) up and down. In one half of the cycle the particles become trapped against the steep potential wall on the left. In the other half of the cycle they can drift relatively freely to the right.



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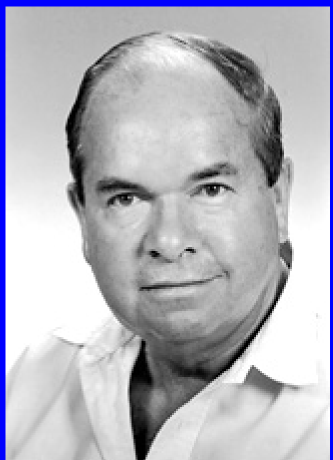
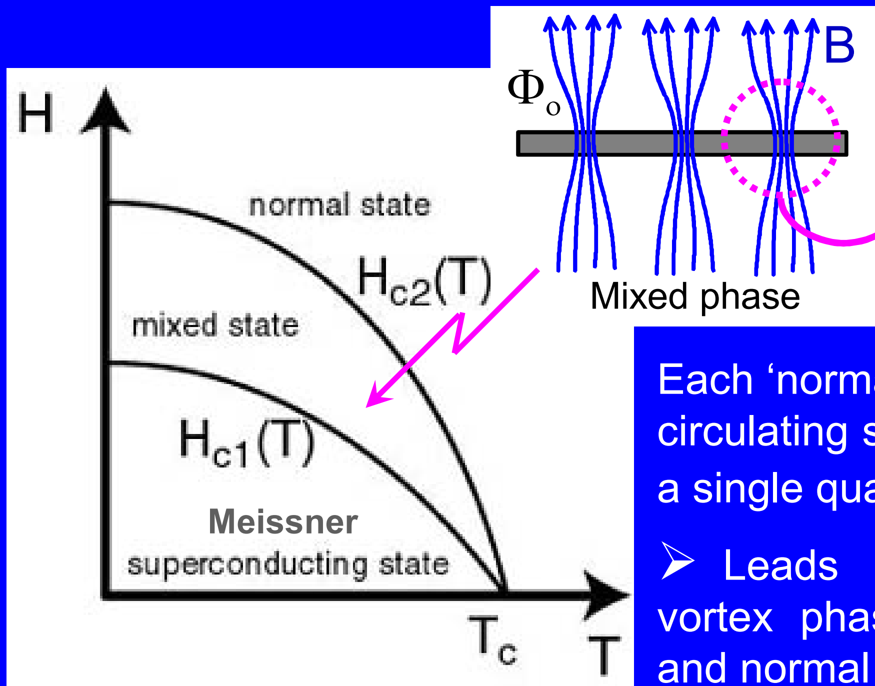
Introduction to Vortices in Type II Superconductors

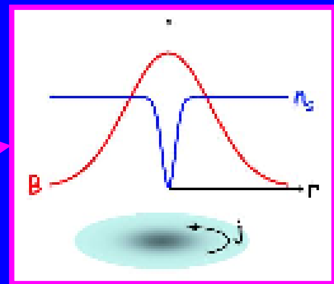
In 1954 Abrikosov solved the Ginzburg-Landau equations in an applied magnetic field for $\kappa = \frac{\lambda}{\xi} > \frac{1}{\sqrt{2}}$. He found his famous vortex solution whereby $\psi(x,y)$ contains a periodic lattice of zeroes.

$$\Psi(x,y) = 3^{1/8} \sum_{n=-\infty}^{\infty} \exp\left[-\frac{2\pi}{\sqrt{3}} \left(\frac{y}{a_0} + \frac{\sqrt{3}}{2} n \right)^2 + 2\pi i n \left(\frac{x}{a_0} + \frac{1}{4} n \right) \right]$$



Abrikosov – 2003 Physics Nobel Prize





Each ‘normal’ pole is associated with a circulating supercurrent that generates a single quantum of magnetic flux, ϕ_0.

- Leads to a new *mixed* Abrikosov vortex phase between the Meissner and normal states.

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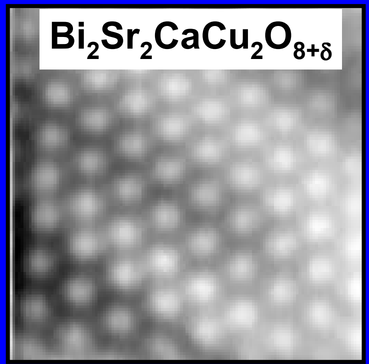
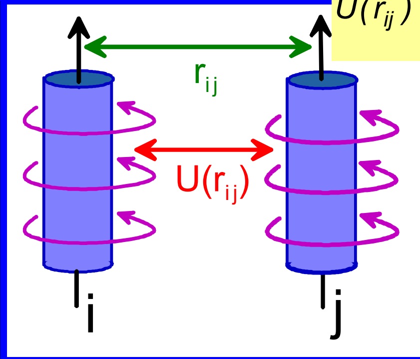
Introduction to Vortices in Type II Superconductors



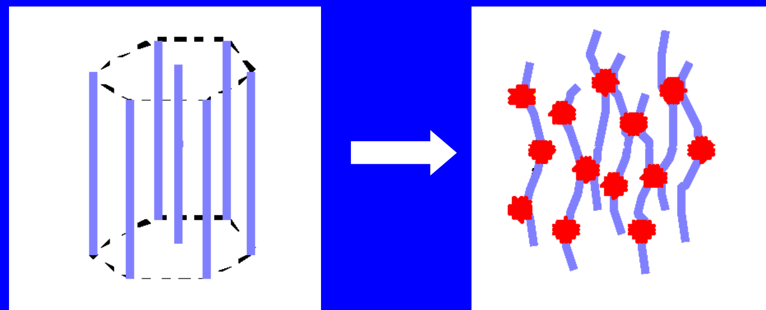


$$U(r_{ij}) \sim \frac{\phi_0^2}{2\pi\mu_0\lambda^2} exp\left(-\frac{r_{ij}}{\lambda}\right)$$

Vortices are mutually repulsive - leads to formation of an ordered triangular lattice.

Also Lorentz force on vortices due to external supercurrents.

$$\vec{F}_L = \vec{J}_s \times \vec{\Phi}_0$$



Vortices readily interact with quenched disorder, becoming *pinned* on e.g., defects and impurities in the sample.

Can also introduce artificial pinning sites; e.g., holes (antidots) or nanomagnets.

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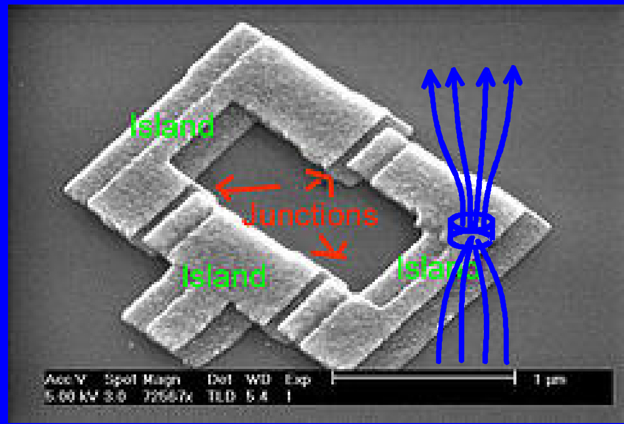
Why Ratchet Devices for Vortices?

Biological motors have inspired a range of nanoscale structures for controlling the motion of nanoparticles.

➢ Here we focus on new ways to manipulate vortices in superconductors.

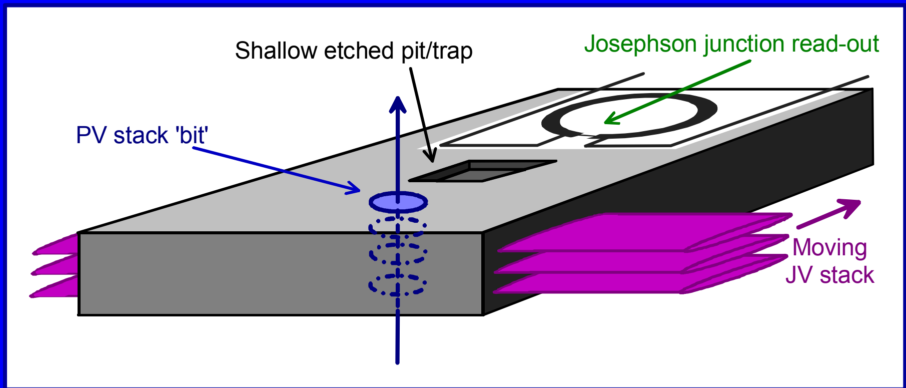
WHY?

▪ Flux trapped in active (e.g. SQUIDs) and passive (e.g. HF filters) superconducting devices generates noise and limits performance. The ability to remove or at least move vortices would be very valuable.



Lorentz force on vortices

$$\vec{F}_L = \vec{J}_s \times \vec{\Phi}_0$$



▪ Could form basis of novel logic devices designed around the manipulation of individual flux quanta (potential applications in field of quantum computation).

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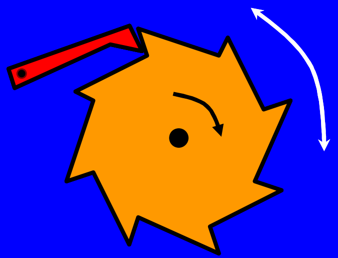
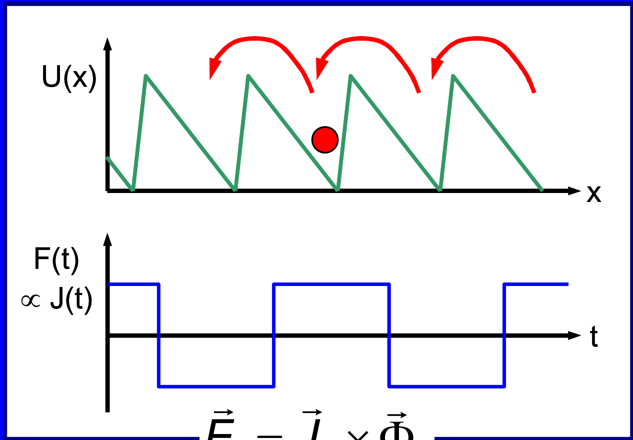
Approaches to Vortex Manipulation using *Ratchets*



$\langle F(t) \rangle = 0$

but

$\langle v(t) \rangle \neq 0$



$$\vec{F}_L = \vec{J}_s \times \vec{\Phi}_0$$

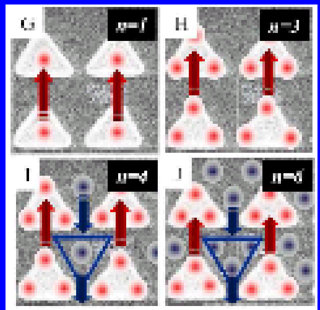
(i) *Spatial Asymmetry*

'Traditional' Rocking Ratchets

Devices rely on a *spatial asymmetry* in the potential landscape to promote particle motion in one chosen direction (low *-dU/dx*) over the other (high *–dU/dx*).

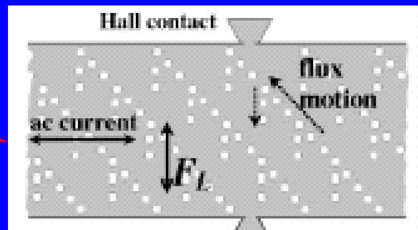
➢ **Structures with spatially *asymmetric* lithographically patterned pinning potentials**

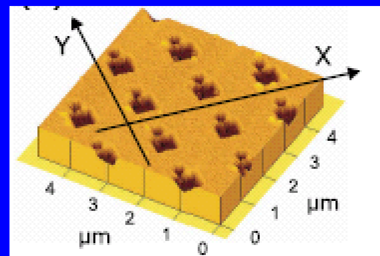
Theory; Wambaugh *et al.*, *PRL* **83**, 5106 (1999), Lee *et al.*, *Nature* **400**, 337 (1999), Zhu *et al.*, *PRL* **92**, 180602 (2004)



Asymmetric (triangular) ferromagnetic pinning arrays in a superconducting film.

Villegas *et al.*, *Science* **302**, 1188 (2003)





Spatially asymmetric arrays of lithographically patterned holes (antidots) in a superconducting film.

Wördenweber *et al.*, PRB **69**, 184504 (2004), Van de Vondel *et al.*, PRL **94**, 057003 (2005), Togawa *et al.*, PRL **95**, 087002 (2005), De Souza Silva *et al.*, Nature **440**, 651 (2006)

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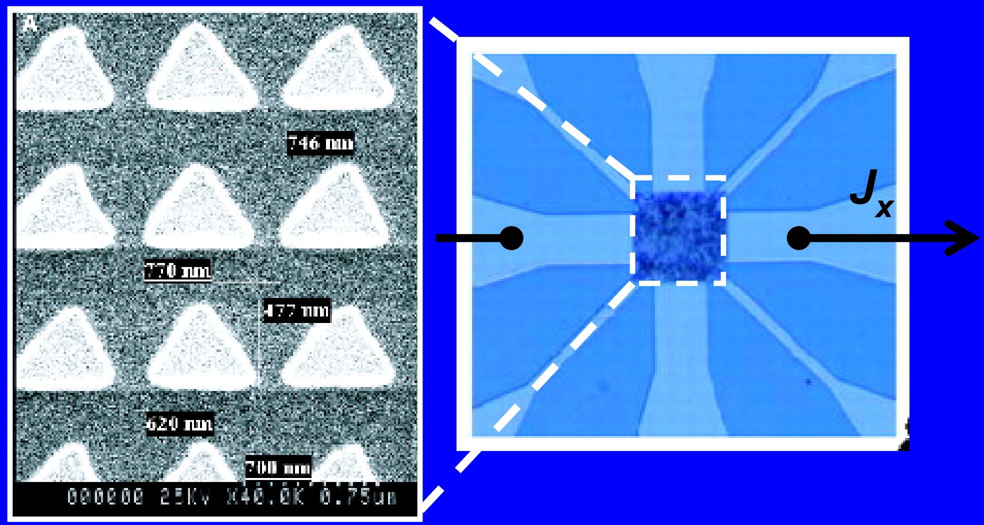
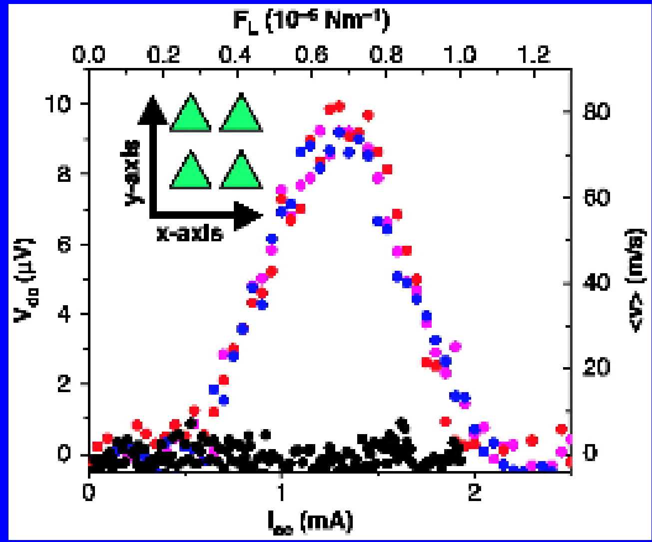
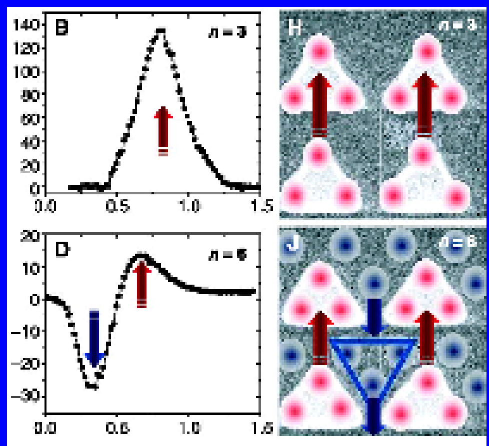
Vortex *Ratchets – Ferromagnetic Pinning Arrays*



Scanning electron microscope image of the array of Ni triangles before coating with 100nm Nb.



V_{dc} vs I_{ac} at H=32Oe and T = 0.99T_c. DC voltage only when Lorentz force is along broken symmetry direction.



Both positive & negative dc voltages are observed depending on whether ‘pinned’ or ‘interstitial’ vortices dominate.

Villegas *et al.*, *Science* **302**, 1188 (2003)

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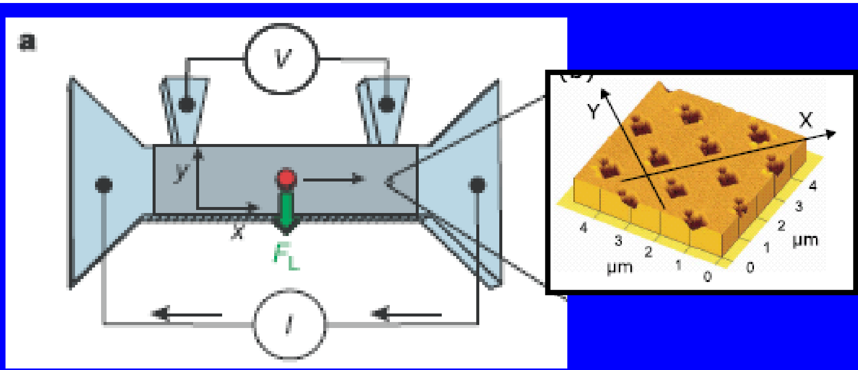
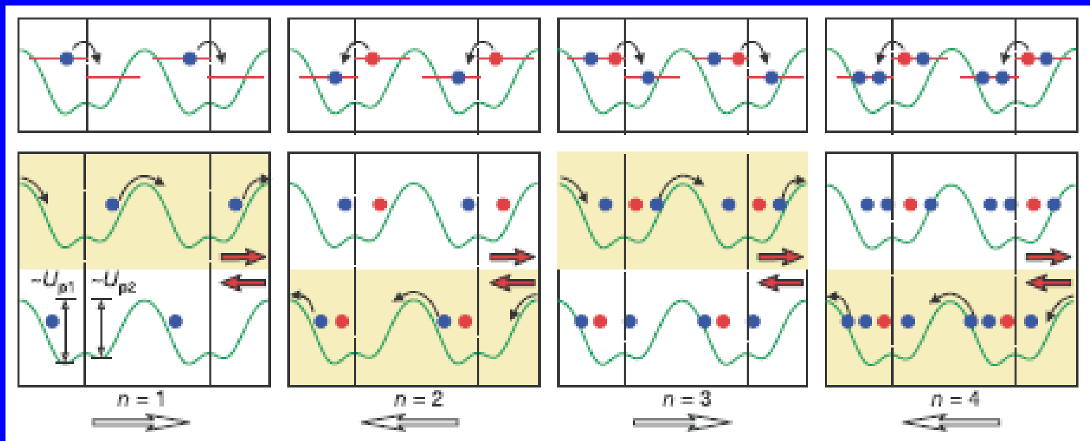
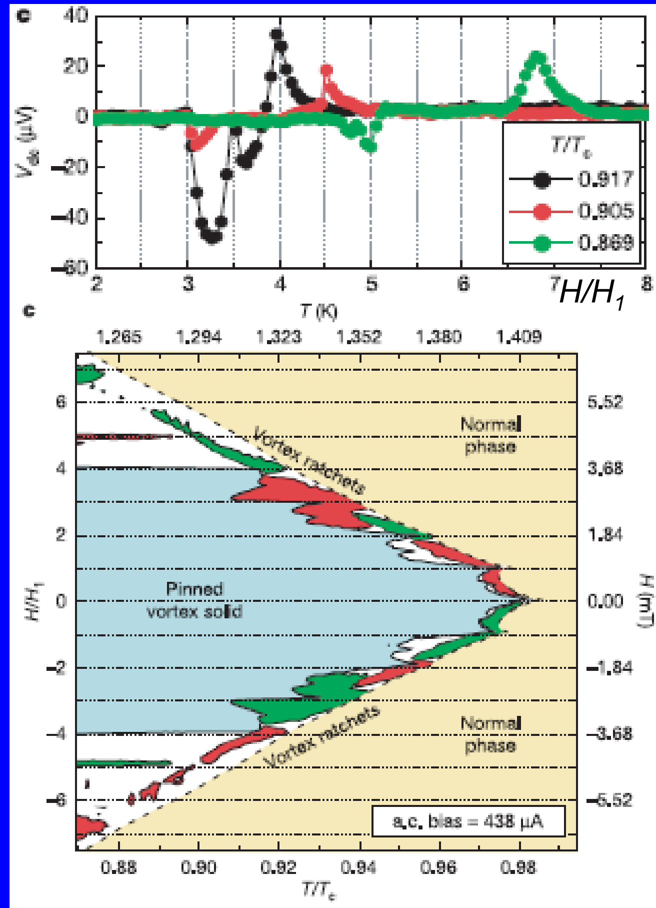
Vortex Ratchets – Asymmetric Antidot Pairs



Sketch of the experimental system composed of a double-antidot array (pairs of 300nm & 600nm antidots with 1.5µm period) in a 90nm Al film.



Explained in terms of vortex interactions. Vortex drift is initiated by most weakly pinned vortex (red) jumping to the next available pinning site.



Multiple reversals (green/brown) of V_{dc} observed as a function of T and H. White regions depict V_{dc}=0.

de Souza Silva *et al.*, Nature **440**, 651 (2006)

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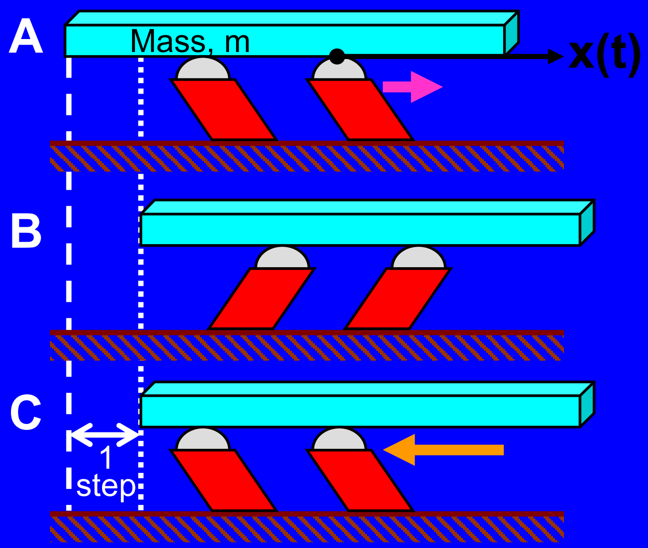
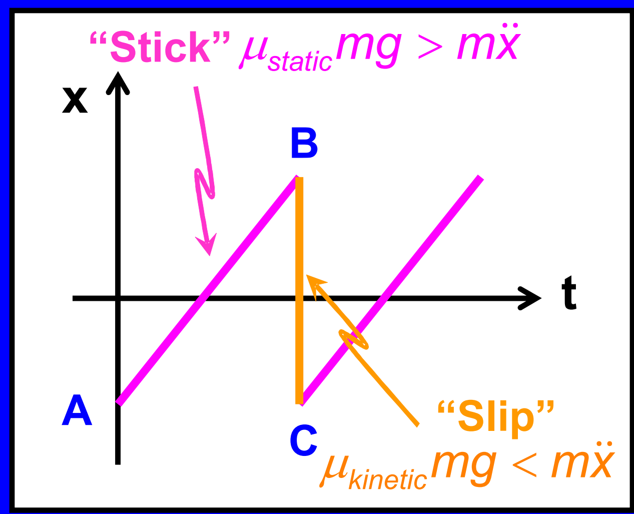
Alternative Approach to Realising Vortex Ratchets



A Stick-Slip Motor

(ii) *Time Asymmetry*

(needs no sample nanofabrication)



In our experiment we have the following mapping:-

- ***Static friction force ⇒ 'pinning force' for pancake vortices at Josephson vortices***
- ***Inertial force ⇒ pancake vortex viscous drag force***

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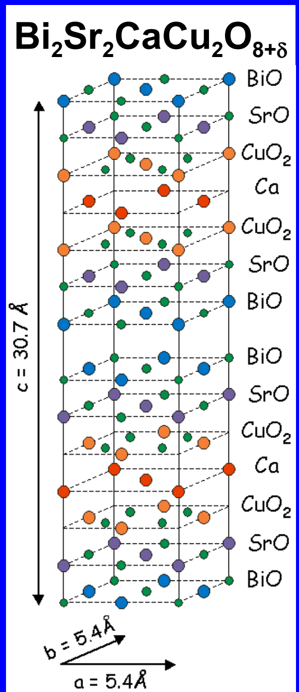
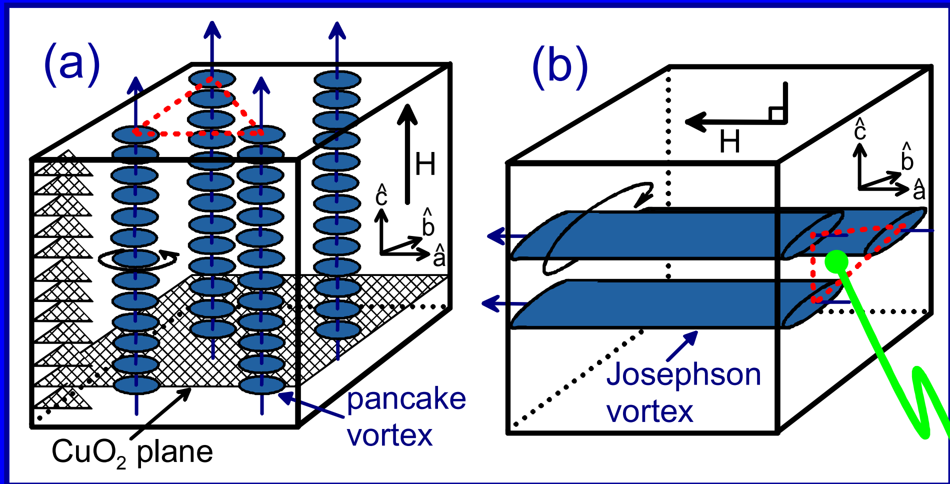
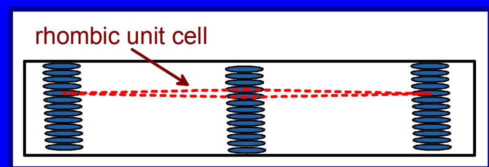
Anisotropic Vortex Structures in $Bi_2Sr_2CaCu_2O_{8+\delta}$





Very strong crystalline anisotropy in the cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) is also reflected in the vortex (and vortex lattice) structure as a function of direction of applied field.



Realistic side view of Josephson vortex lattice.

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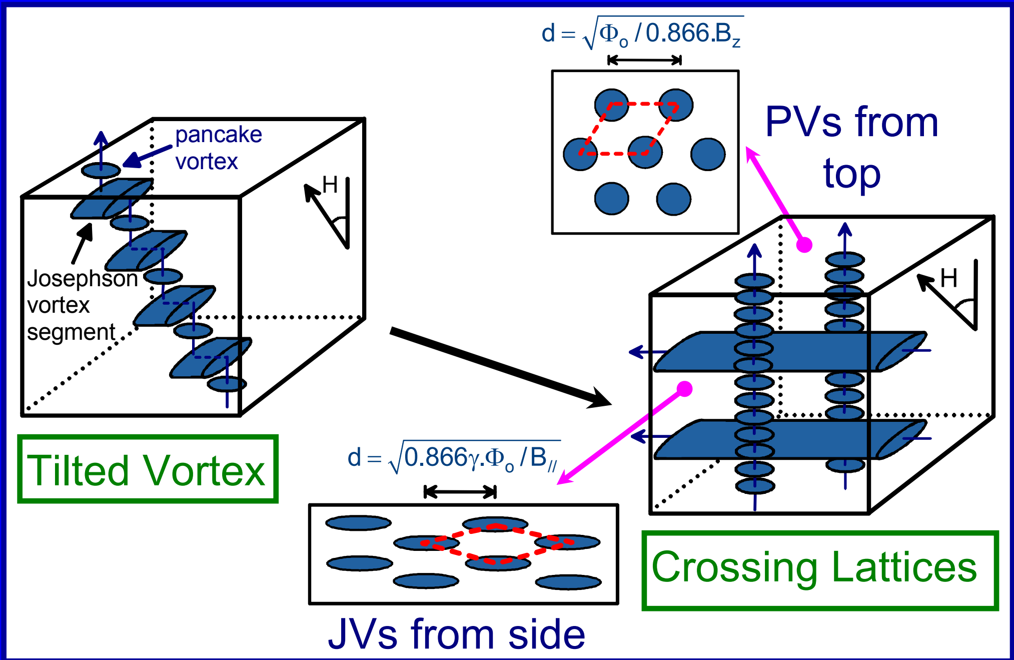
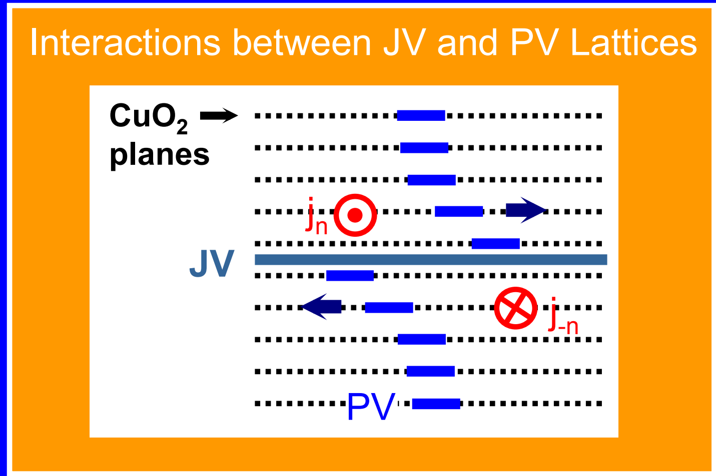
Tilted Vortex Instability in $Bi_2Sr_2CaCu_2O_{8+\delta}$ Single Crystals



A homogeneous tilt of the PV stacks costs magnetic energy and for a wide range of applied field angles the ground state consists of coexisting, perpendicular JV and PV 'crossing lattices'.

L.N.Bulaevskii *et al.*, PRB **46**, 366 (1992)



PVs lying on stacks of JVs become displaced (u_n) due to interactions with the JV supercurrents.

$$E_n = A.C_{44}u_n^2 - B.j_n u_n$$

Although this costs the stack tilt energy it results in a net reduction of energy, and leads to an attractive interaction between JVs and PVs.

A.E.Koshelev, PRL **83**, 187 (1999).

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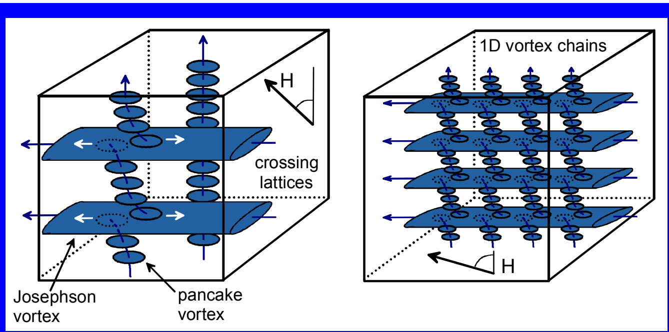
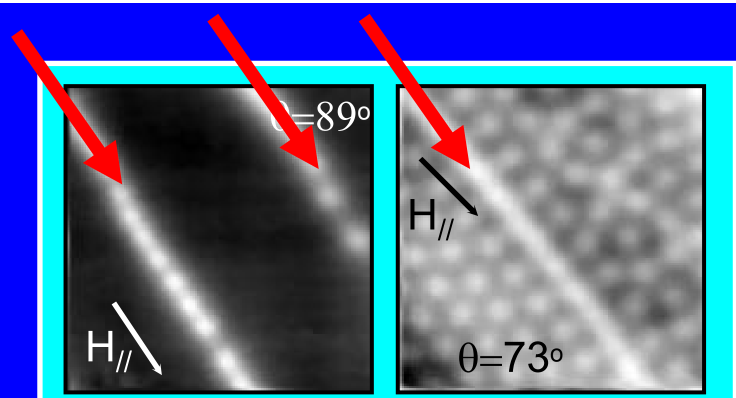
Vortex Manipulation using Interacting Crossing Lattices

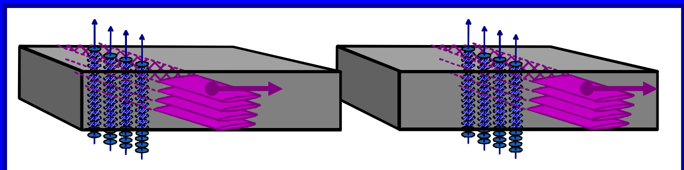


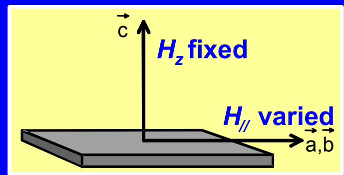
There is a residual attractive interaction between PVs and JVs, which results in PVs lining up along chains where there are underlying JV stacks.

A.E.Koshelev, PRL **83**, 187 (1999)



Images of pancake vortices in tilted fields at low and high PV densities

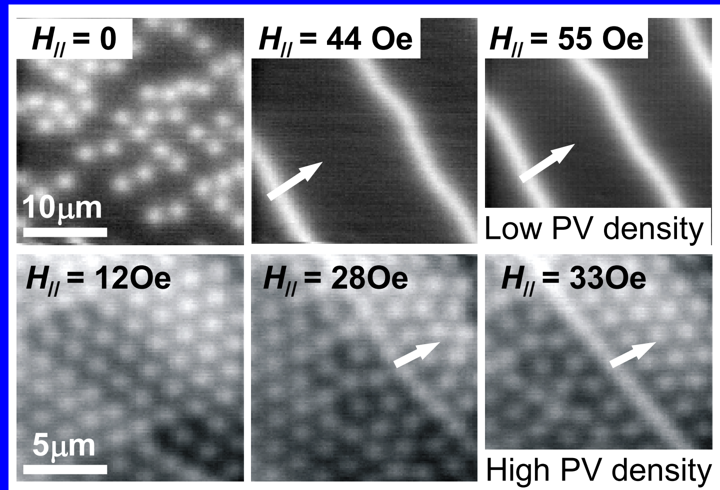




Moving JVs (e.g. by varying $H_{//}$ to deform JV lattice) leads to parallel motion of coupled PVs (or *vice versa*).

Vortex pumps, diodes & lenses based on crossing lattices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ have been proposed:-

Theory: S.Savel'ev & F.Nori, Nature Materials **1**, 179 (2002).
Experiment: G.J.Perkins *et al*., SuST **18**, 1290 (2005).



Moving JV stacks "drag" or "brush" pancake vortices as $H_{//}$ is increased.

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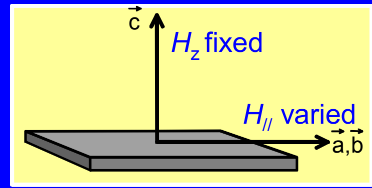
Two Distinct Types of Manipulation Experiment

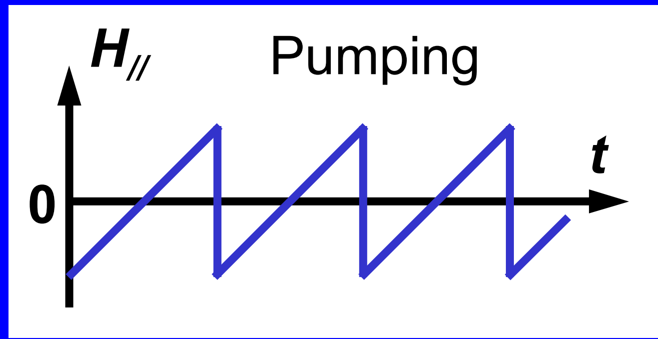


(1) AC - driven Vortex 'Ratchet'

- broken *time-symmetry*

Exploits response of coupled JV-PV system to time-asymmetric (saw-tooth) trains of $H_{//}$ field pulses.

Operates far from equilibrium.

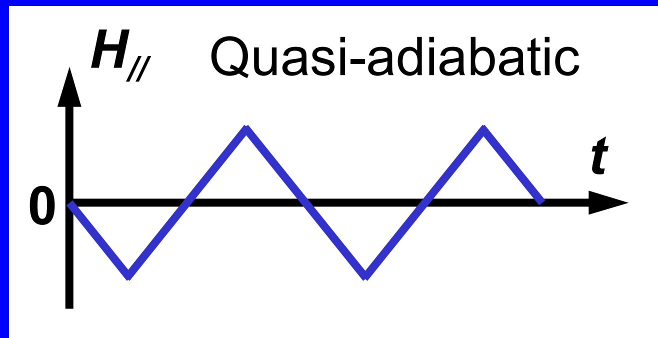


(2) DC - driven Vortex 'Lens'

- quasi-adiabatic

Exploits response of coupled JV-PV system to **slowly** varying $H_{//}$ sweeps.

PVs largely remain bound to the JVs and are dragged/pushed along with them towards/away from the sample center.



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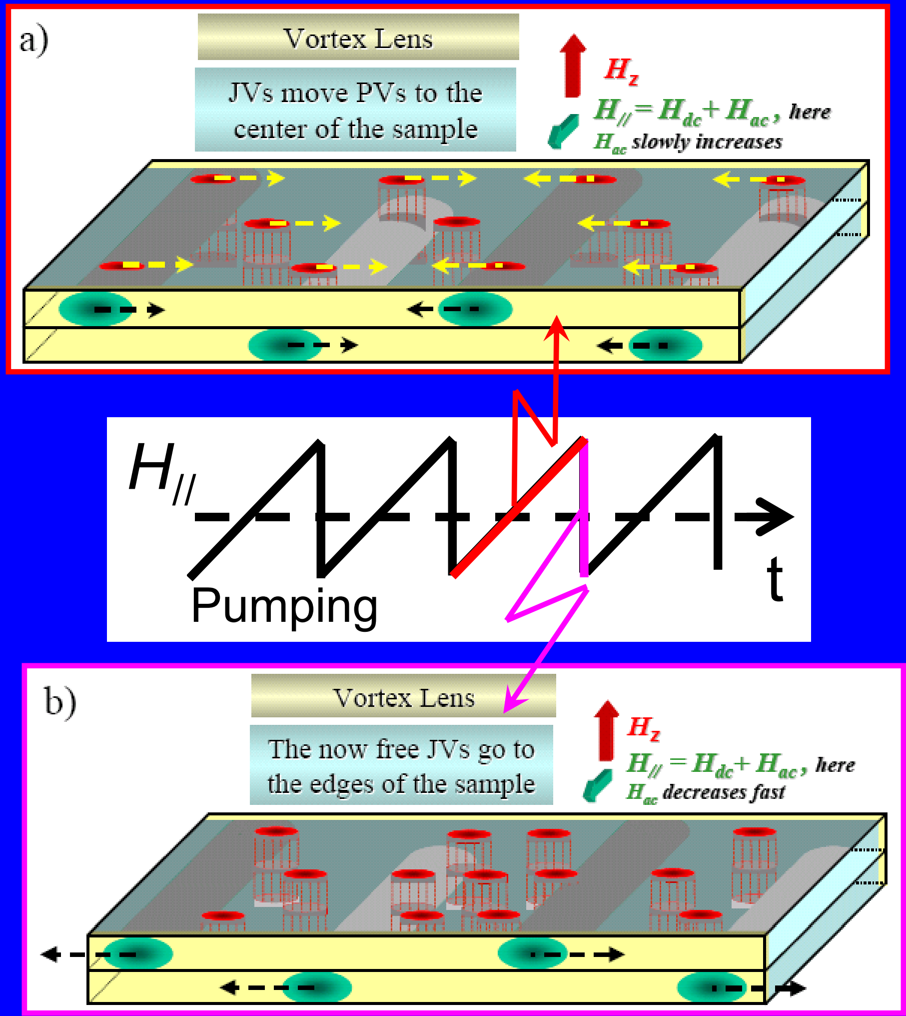
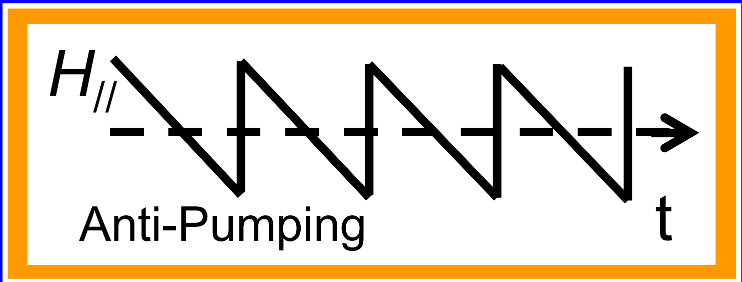
(1) AC - driven Vortex Ratchet

Our vortex 'ratchet' does not use asymmetric pinning potentials, but relies on the JV-PV response to time-asymmetric trains of field pulses

- **If $H_{//}$ is *increased* slowly, the PVs remain bound to the JVs and are dragged along with them towards the sample center**

- **If $H_{//}$ is *decreased* rapidly, the PVs are dragged off the JVs and remain stationary as the JVs move towards the sample edges.**





To reverse the ratchet we simply use a time-reversed sawtooth waveform.

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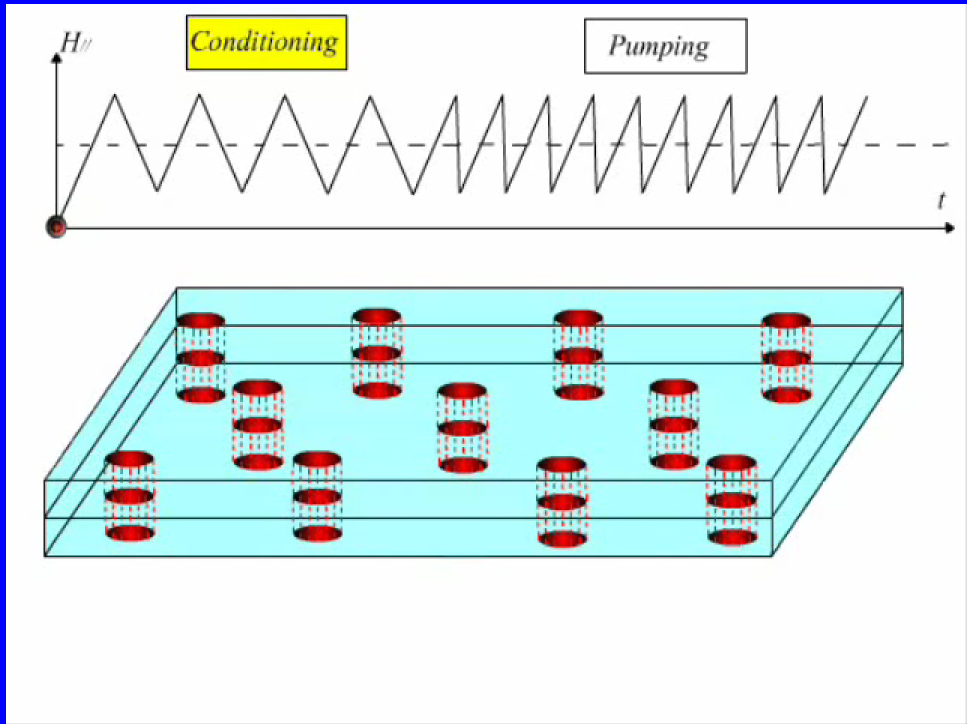
AC - driven Vortex Ratchet



Animation illustrating ac-driven 'pumping as $H_{//}$ is periodically cycled.

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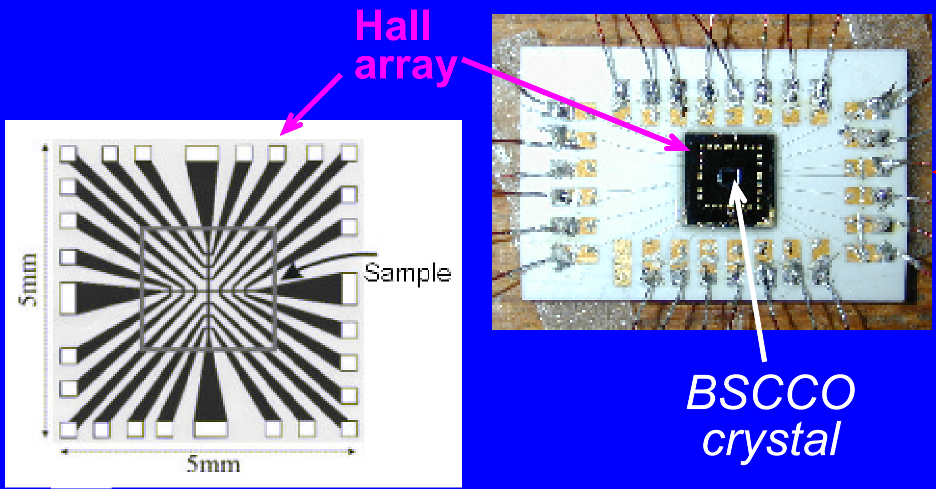
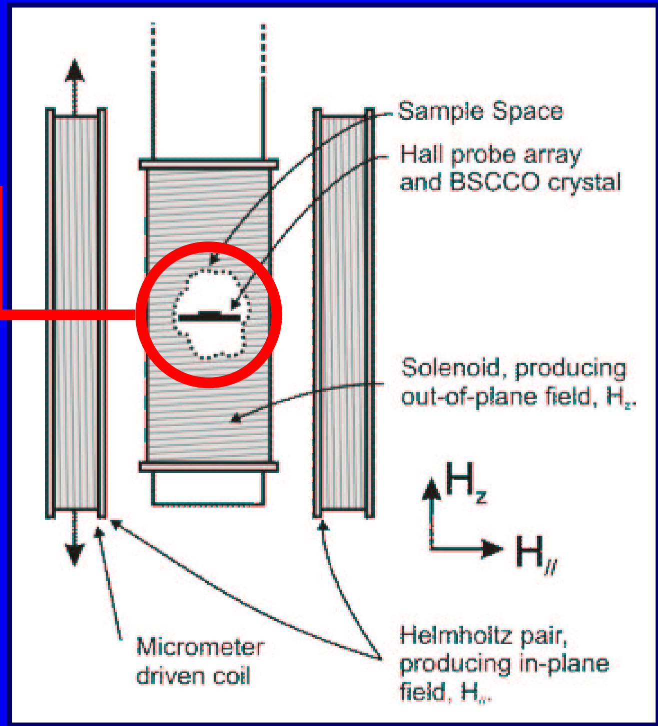
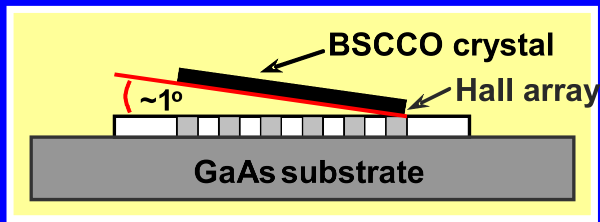
Experimental System



GaAs/AlGaAs Hall sensor array detects the 'local' B_z (≡ PV density).





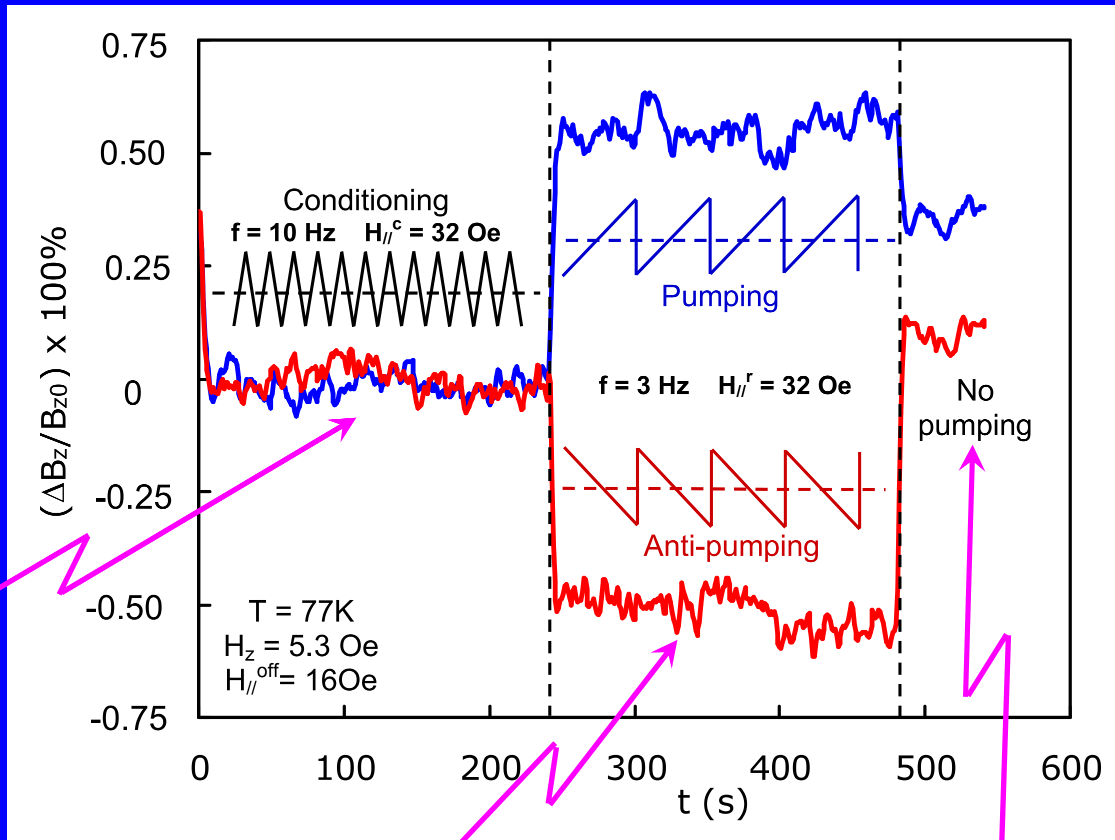
Precise alignment of $H_{//}$ with the *a-b* crystallographic planes is vital. We exploit in-plane magnetic 'lock-in' † to achieve this with a misalignment less than $\delta\theta \sim \pm 0.006°$.

† A.E.Koshelev, PRB **48**, 1180 (1993).

Simon J. Bending, *University of Bath, UK*

Results: AC - driven Vortex Ratchet

- **Sample cooled in H_z=5.3 Oe to *T*=77K**
- **A fixed 'bias' of $H_{//}^{off}$=16 Oe was then applied**
- **Different shaped triangular $H_{//}$ waveforms then superposed with $< H_{//}^{x} > = 0$**



(1) A symmetric triangular 'conditioning' wave equilibrates the PV system.

(2) PV density at center of sample increases(decreases) to a fairly constant level after a few cycles of the pump(anti-pump) sawtooth waveform.

(3) PV density relaxes to something close to equilibrium value after pump switched off.

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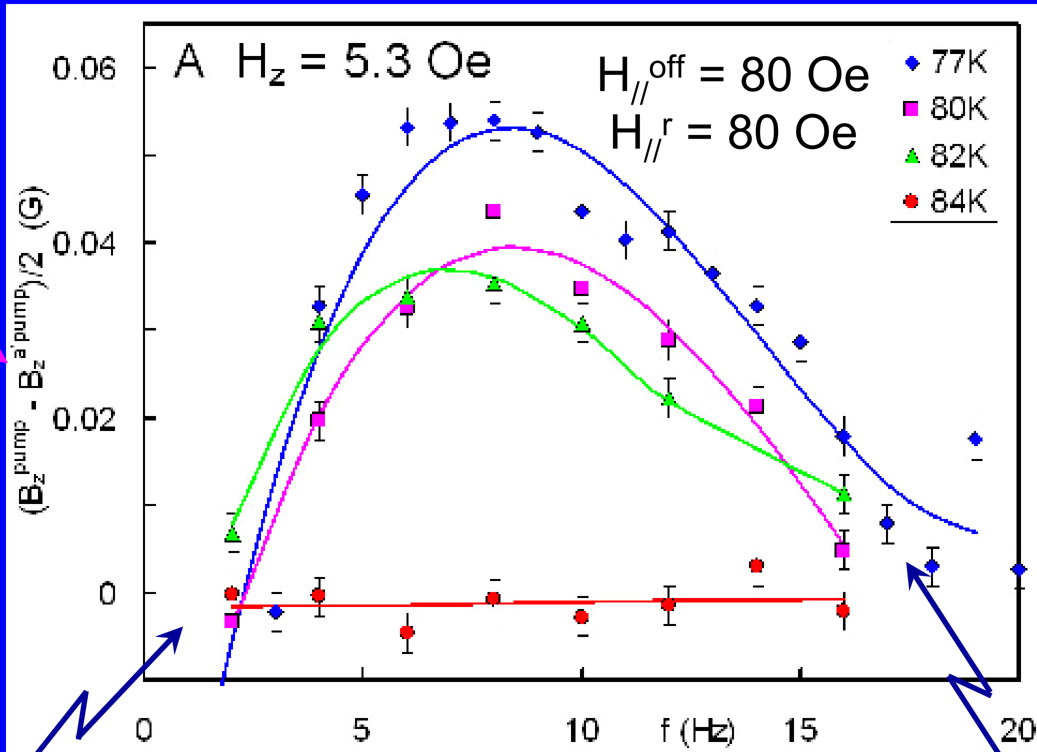
D.Cole *et al*., Nature Materials **5**, 305 (2006)

Frequency Dependence of Ratchet Effect

Half the mean difference between *pumping* and *anti-pumping* PV density.



Low *f* - efficiency falls:-

- Repetition rate lower
- PVs start to follow JVs during 'rapid' $H_{//}$ changes

Hi *f* - efficiency falls:-

- PVs can no longer follow JVs during 'slow' $H_{//}$ changes

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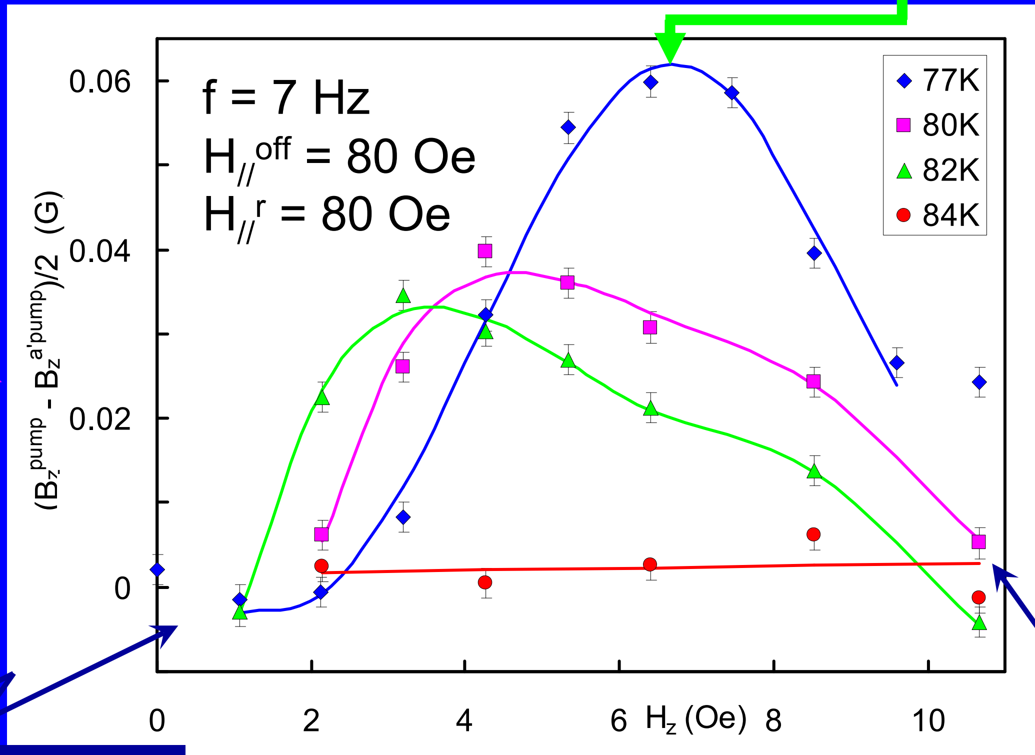
D.Cole *et al*., Nature Materials **5**, 305 (2006)

H_z Dependence of Ratchet Effect

Peak agrees quite well with predicted maximum JV pinning strength at $B_z \sim 0.26\Phi_0/(\gamma s)^2 \sim 6G$ for dilute PV limit ($\lambda < a_0 < \gamma s$).

A.E.Koshelev, PRB **68**, 094520 (2003).

Half the average difference between the pumping and anti-pumping PV density.



Low H_z - amplitude falls:-

- Lower mean PV density.
- A few strong pinning centers start to dominate PV dynamics.

Hi H_z - efficiency falls:-

- PV-PV repulsion starts to dominate PV-JV dynamics

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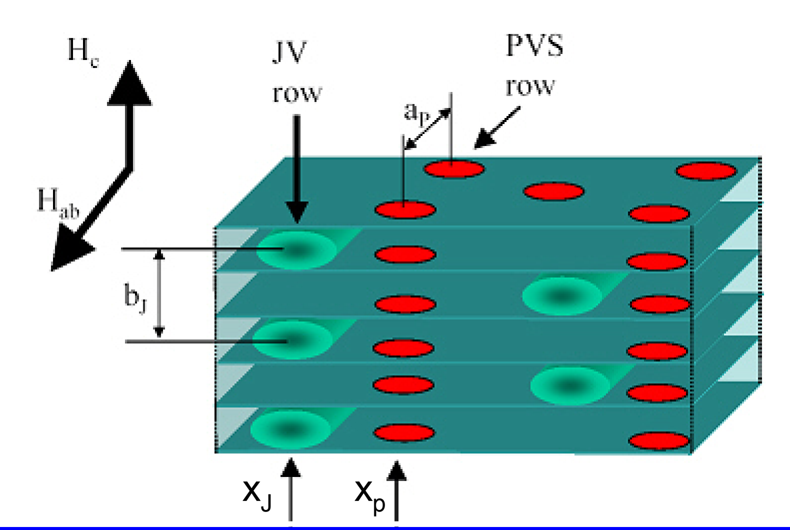
Molecular Dynamics Simulations

Sergey Savel'ev & Franco Nori, RIKEN

Minimal 1D model of interacting JV and PVS rows.



JV-JV repulsion | PV-PV repulsion | JV-PV attraction

$$F[\{x_i^J\},\{x_k^P\}] = U_{\mathrm{JJ}} + U_{\mathrm{JH}} + U_{PP} + U_{\mathrm{PJ}} + U_{\mathrm{PH}}$$

Interaction with external field

$$\eta_J \dot{x}_{i_0}^J = -b_J^{(i_0)} \frac{\partial F}{\partial x_{i_0}^J}$$

$$\eta_P \dot{x}_{k_0}^P - f_{\mathrm{pin}} \frac{\partial F/\partial x_{k_0}^P}{|\partial F/\partial x_{k_0}^P|} = -a_p \frac{\partial F}{\partial x_{k_0}^P}, \quad \text{if} \quad a_p \left|\frac{\partial F}{\partial x_{k_0}^P}\right| > f_{\mathrm{pin}}$$

$$\dot{x}_{k_0}^P = 0 \quad \text{if} \quad a_p \left|\frac{\partial F}{\partial x_{k_0}^P}\right| < f_{\mathrm{pin}}.$$

Viscous drag forces

Set of MD equations

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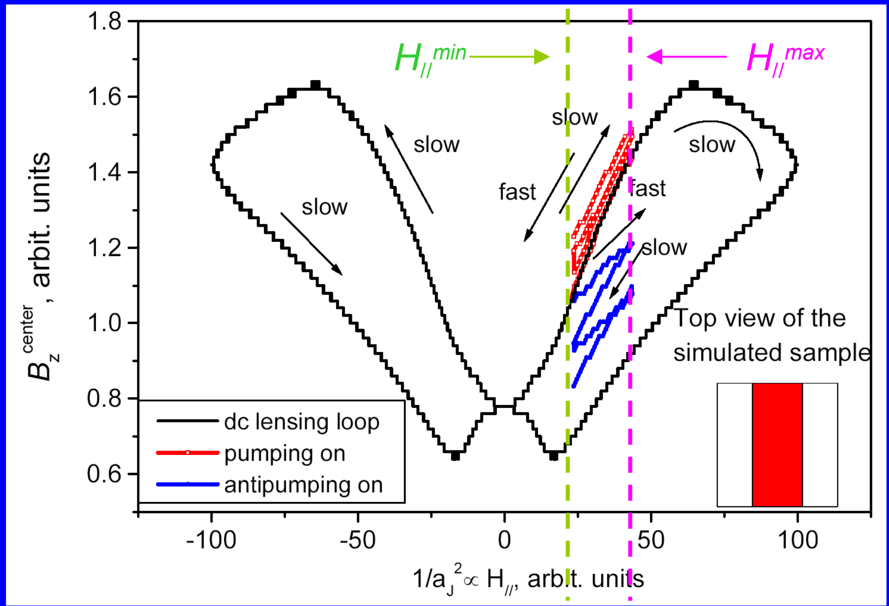
Vortex Ratchet Simulations

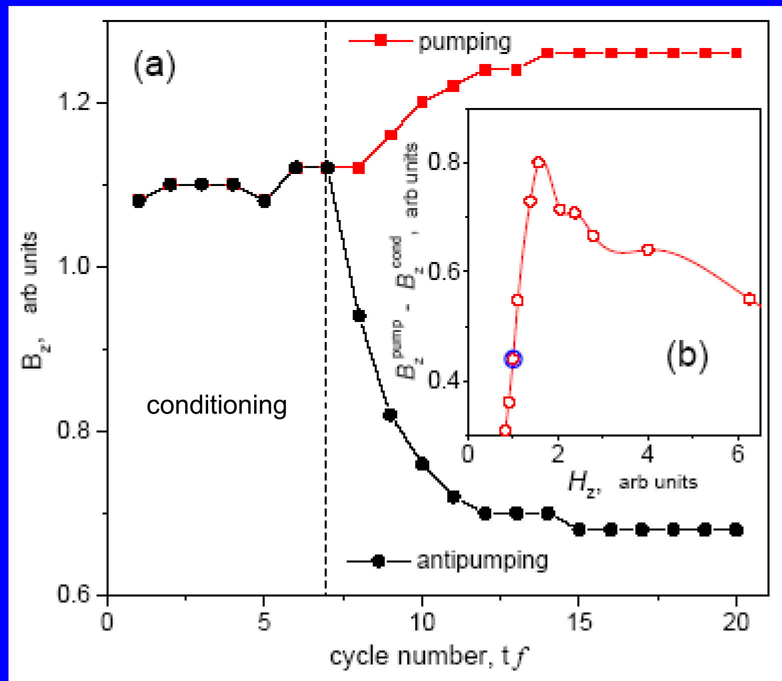


***H*$_{//}$ slowly increased to *H*$_{//}^{min}$ at which point *H*$_{//}$ *cycled* between *H*$_{//}^{min}$ and *H*$_{//}^{max}$; either**

(1) (*pumping*) slowly increasing *H*$_{//}$ up to *H*$_{//}^{max}$ followed by a fast decrease, or

(2) (*anti-pumping*) a fast increase followed by a slow decrease.

Pumping/anti-pumping behaviour is qualitatively reproduced, as well as the peaked dependence of 'ratchet' amplitude on drive frequency and H$_z$ (inset).



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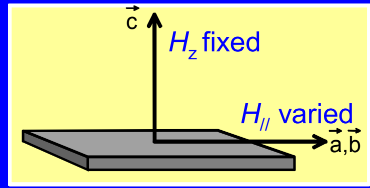
(2) DC – driven Vortex Lens

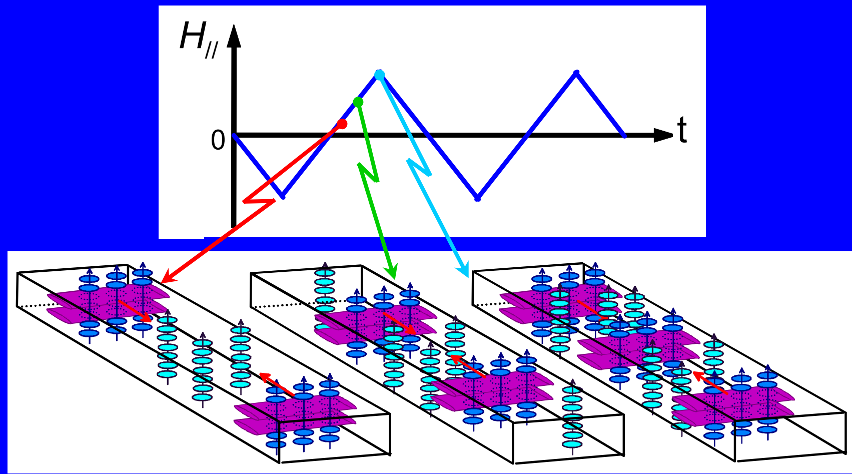


(2) DC - driven Vortex 'Lens'

- quasi-adiabatic

Exploits response of coupled JV-PV system to **slowly** varying $H_{//}$ sweeps.

PVs largely remain bound to the JVs and are dragged/pushed along with them towards/away from the sample center.



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DC – driven Vortex Lensing - Centre of Crystal

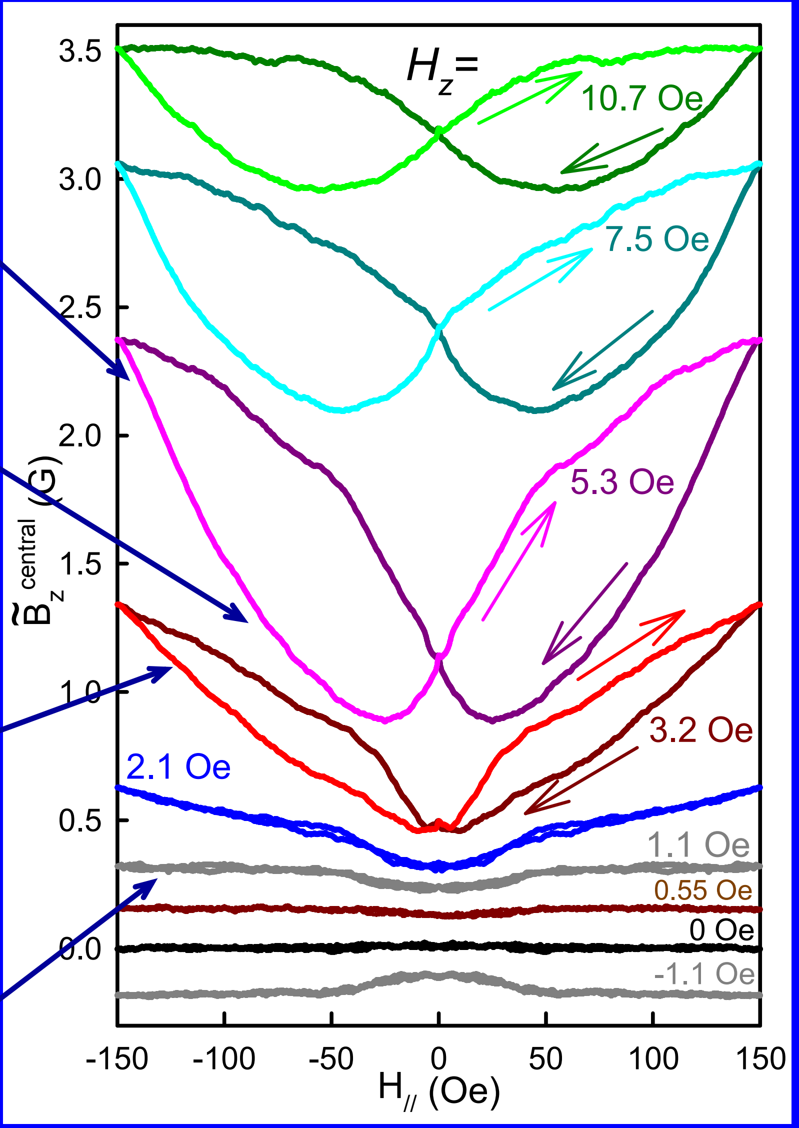
H_z dependence of dc-lensing at T=77K

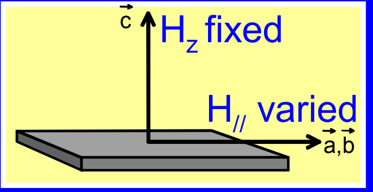
Strongest % lensing effect (~40%) around H_z~5Oe.

Small amount of 'antilensing' becomes observable on downward leg of loop H_z>3Oe.
Linked to JVs cutting through PV stacks at large $H_{//}$.

Lensing starts to become irreversible for H_z>2Oe.
Mixed chains/lattice state.

Weak reversible signal at low H_z (|H_z|<2Oe) which inverts when H_z is reversed.
Coherent "dragging" of PVs trapped on JV chains.





Hall element under ***center*** of crystal

Simon J. Bending, *University of Bath, UK*

H_z Dependence of Lensing Efficiency

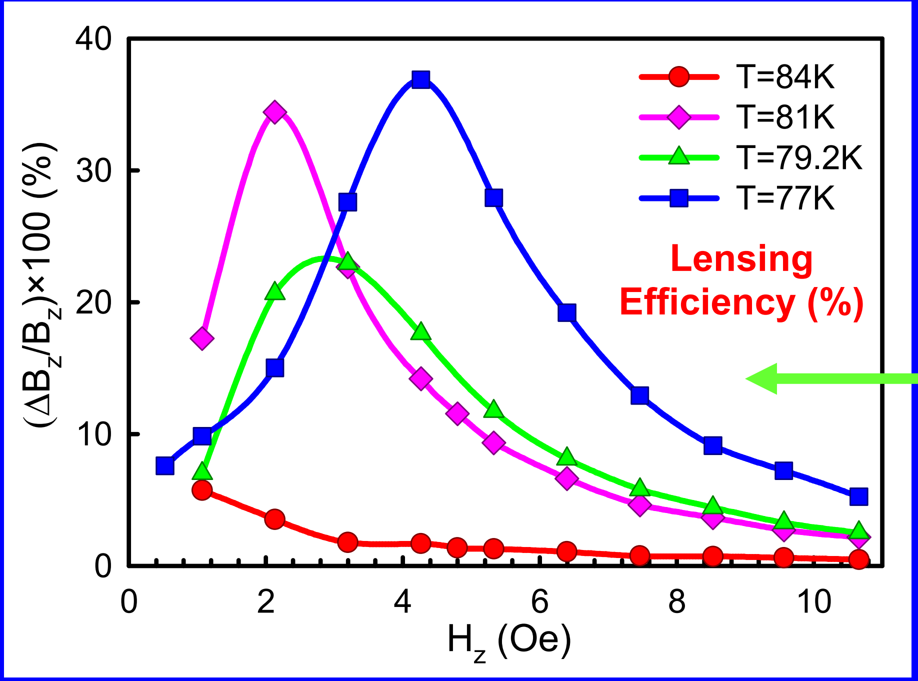
Peak agrees quite well with predicted maximum JV pinning strength (by PVs) at $B_z \sim 0.26\Phi_0/(\gamma s)^2 \sim$ 6G for dilute PV limit ($\lambda < a_0 < \gamma s$).

A.E.Koshelev, PRB **68**, 094520 (2003).

For large H_z exponential decay is also predicted.

- Lensing efficiency strongly peaked as function of H_z.
- Peak efficiency approaches 40% at low temperatures where it exhibits rather weak temperature dependence.

Hall element under ***center*** of crystal



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DC – driven Vortex Lensing - Edge of Crystal

H_z dependence of dc-lensing at T=77K

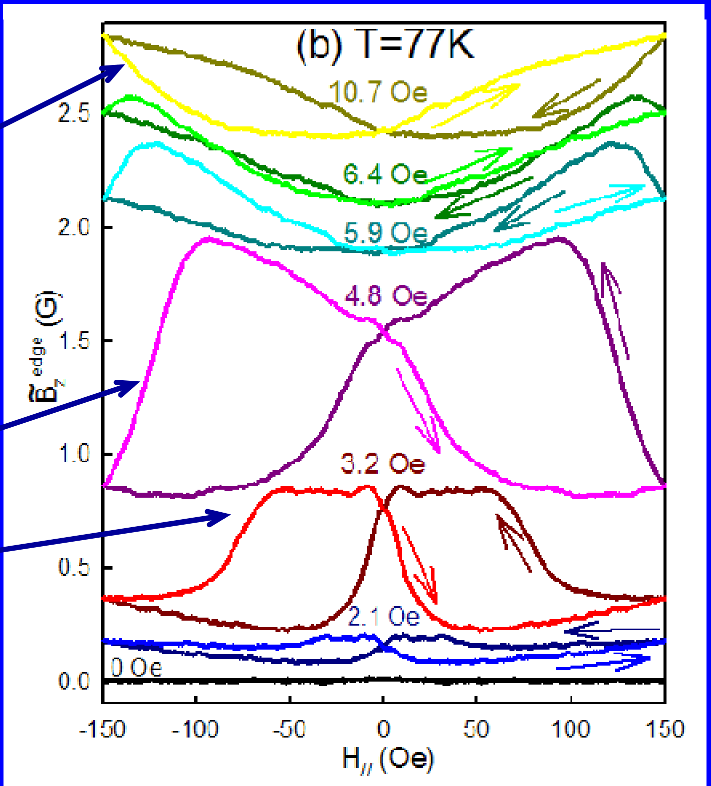
Hall element 225 μm from edge of crystal

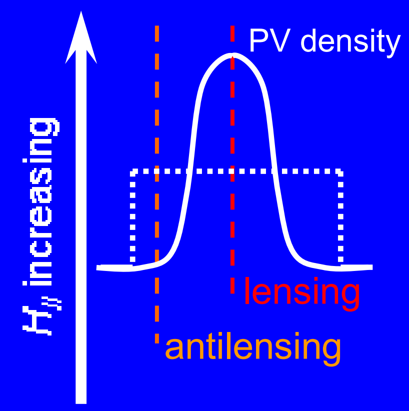
Lensing **response similar to sensor at *center* of crystal returns for H_z>7Oe.**

Strongest % *anti-lensing* effect (~30%) around H_z~5Oe.

Strong '*anti-lensing*' observed for H_z<6Oe.

Related to spatial profile of PV stack distribution





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DC – driven Vortex Lensing - Edge of Crystal

H_z dependence of dc-lensing at T=81K

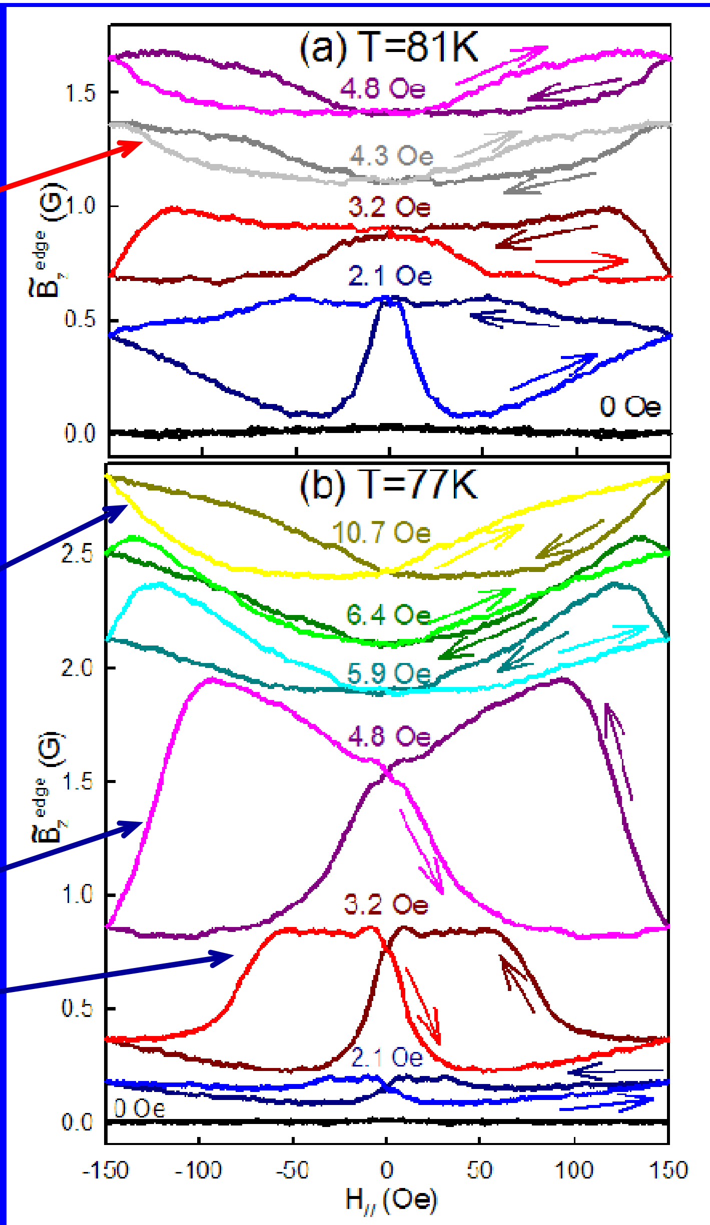
At higher temperatures cross-over from anti-lensing to lensing occurs at *lower* H_z.

Lensing response similar to sensor at *center* of crystal returns for H_z>7Oe.

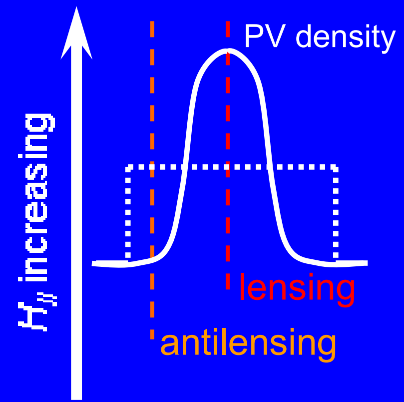
Strongest % *anti-lensing* effect (~30%) around H_z~5Oe.

Strong '*anti-lensing*' observed for H_z<6Oe.

Related to spatial profile of PV stack distribution



Hall element 225μm from edge of crystal



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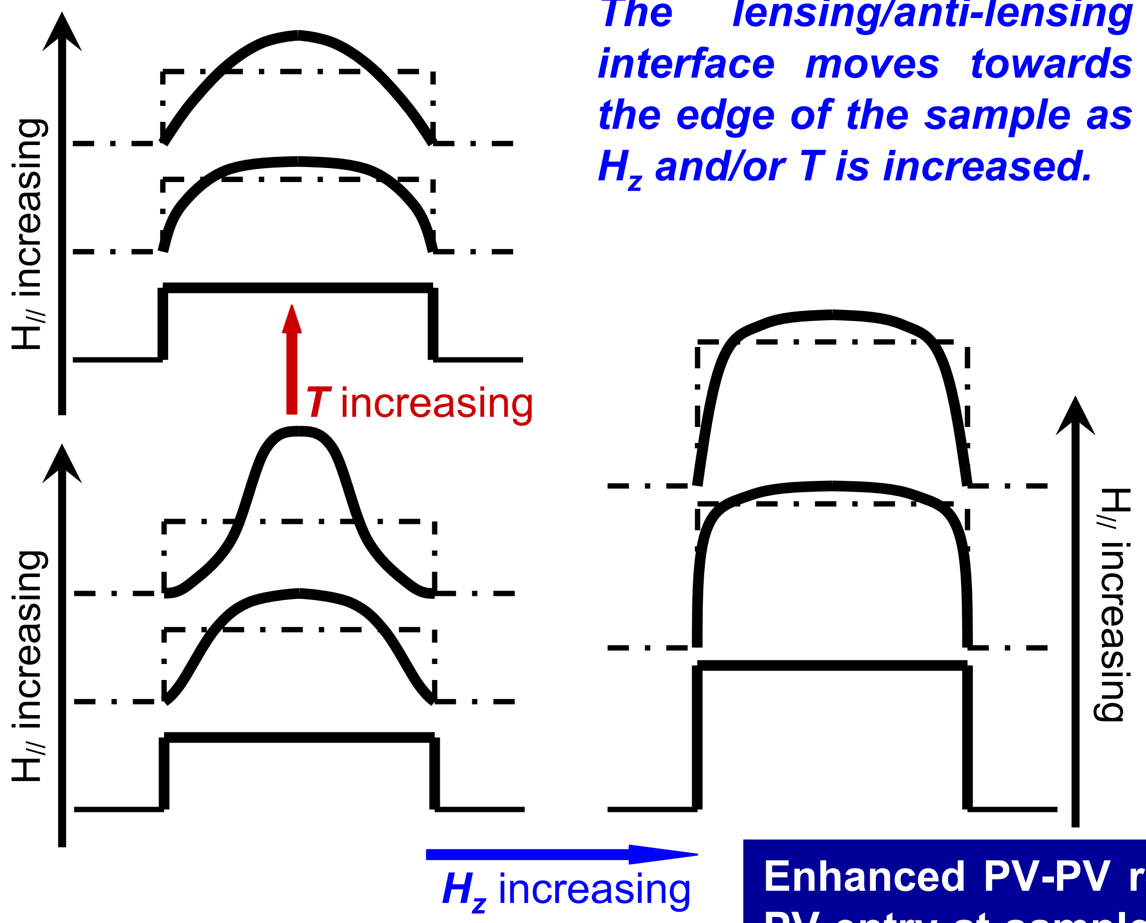
A Qualitative Understanding of Lensing Behaviour

Increased λ(T) leads to enhanced (relative to JV/PV attraction) PV-PV repulsion and broadened 'focus' regions.

The lensing/anti-lensing interface moves towards the edge of the sample as H_z and/or T is increased.



Enhanced PV-PV repulsion and PV entry at sample edges leads to broadened 'focus' regions.

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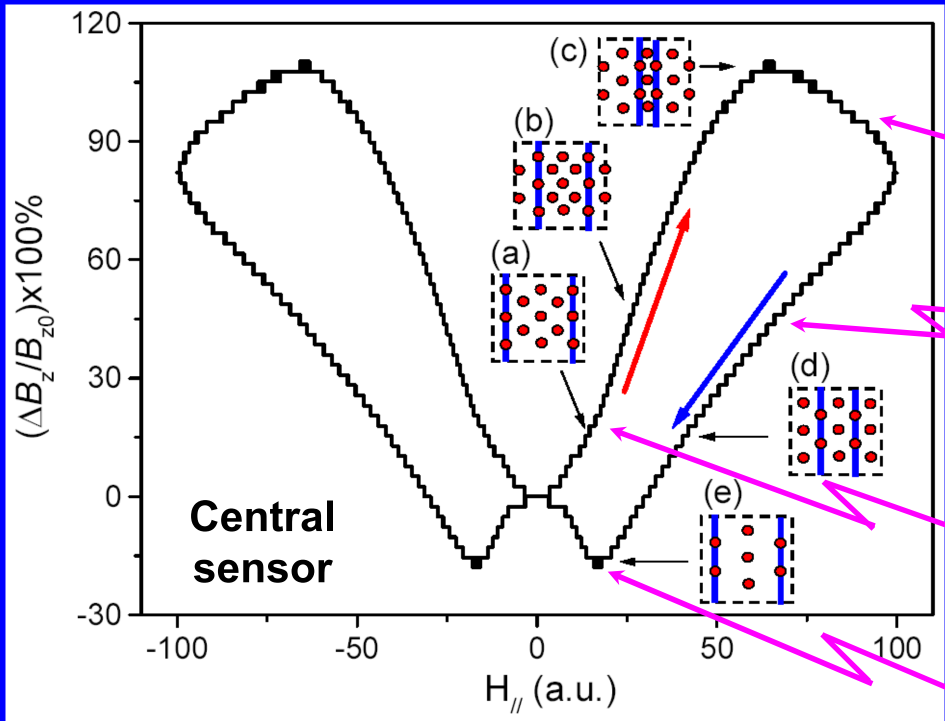
Molecular Dynamics Simulations – Centre of Sample

Simulation for Hall element under ***center*** of crystal



(c) PV-PV repulsion increases faster than JV-PV attraction and JVs start to cut through PV stacks.

(d) PV-PV repulsion ***aids*** rapid 'decompression' of PV system.

(a, b) JVs move to sample center and drag PVs with them.

(e) System 'undershoots' equilibrium PV density as a result of PV stack cutting at high $H_{//}$.

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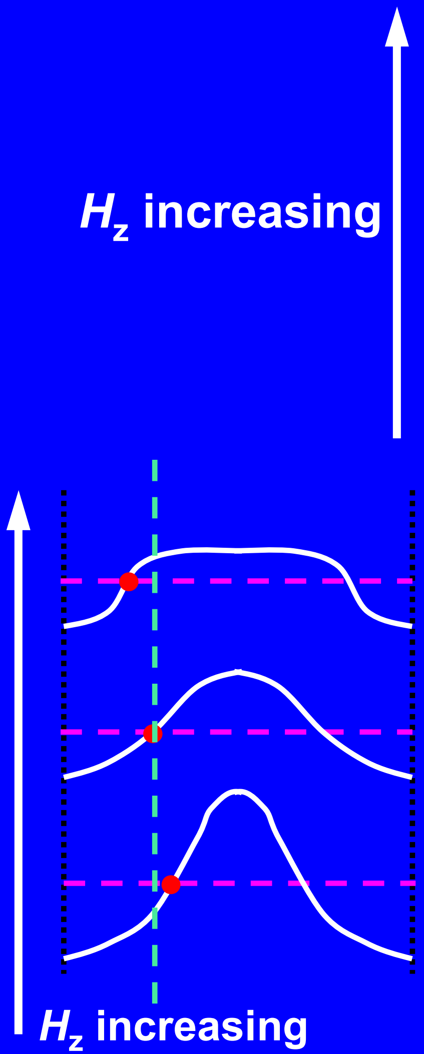
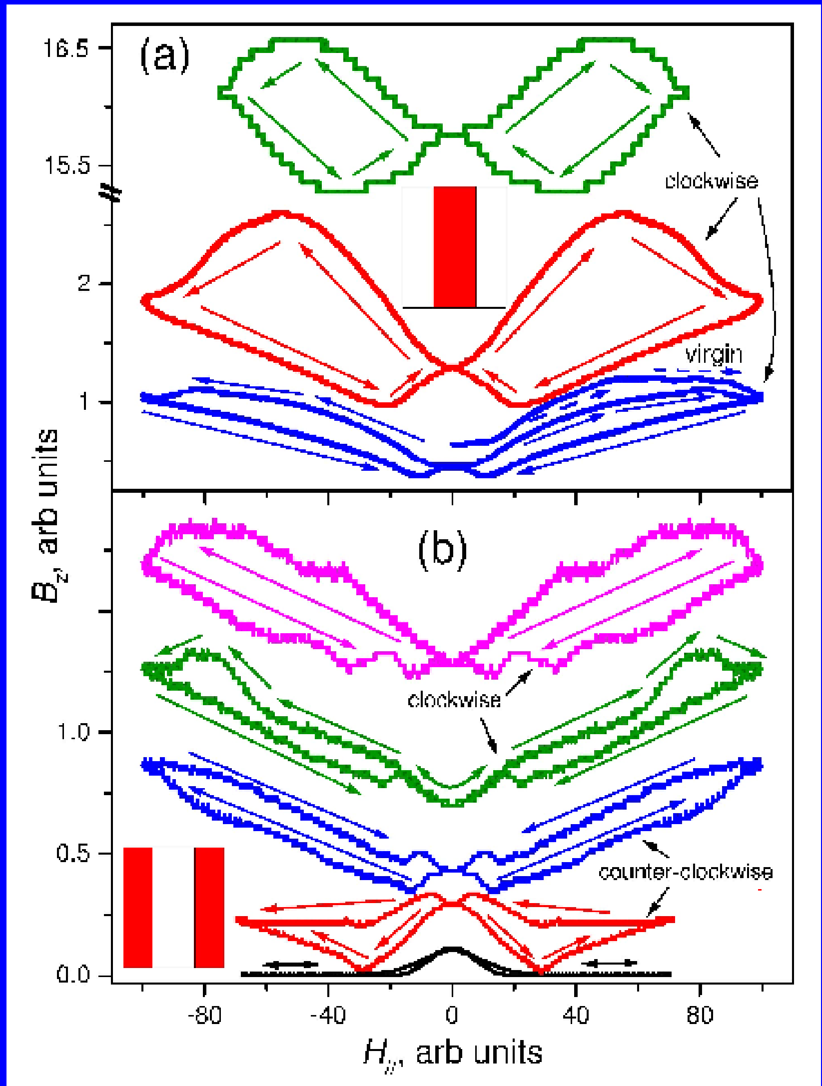
Molecular Dynamics Simulations – Edge of Sample





Lensing near the sample center

As in experiments $\Delta B_z(H_{//})$ loops are all ***clockwise,*** and exhibit a peak in amplitude as H_z is increased.

Lensing near the sample edge

As in experiments a transition from ***counter-clockwise*** to ***clockwise*** $\Delta B_z(H_{//})$ loops occurs at a given point near the edge as H_z is increased.

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Conclusions & Prospects

We have demonstrated how one can control the motion of pancake vortices, in the crossing vortex lattices regime of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal, by varying the in-plane magnetic field component, $H_{//}$ (≡ Josephson vortex density).

– Non-equilibrium PV pumping/anti-pumping has been observed with a vortex ratchet–like device based on the application of a periodic sawtooth in-plane field.

– Pump efficiency is a peaked function of drive frequency and H_z.

– Focusing (lensing) efficiencies as high as 40% have been obtained with slow (‘quasi-adiabatic’) $H_{//}$ sweeps for optimal H_z at 77K. Changes in PV density are a subtle function of position, H_z and *T*, and reflect the interplay between JV-PV attraction and PV-PV repulsion.

– 1D molecular dynamics simulations in good agreement with our observations.

Future Work

– Improve pump efficiency by ‘guiding’ PV stacks in direction of motion (e.g. by milling surface tracks) and different approaches to driving JV system (e.g. with an applied current).

– Gain a better understanding of the dynamics of Josephson vortices (e.g. equilibrium distortions of the JV lattice require JVs to cut through CuO_2 planes).

– Molecular dynamics simulations with bulk pinning – must generalise to 2D?

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