Experiments with Fluxon ratchet

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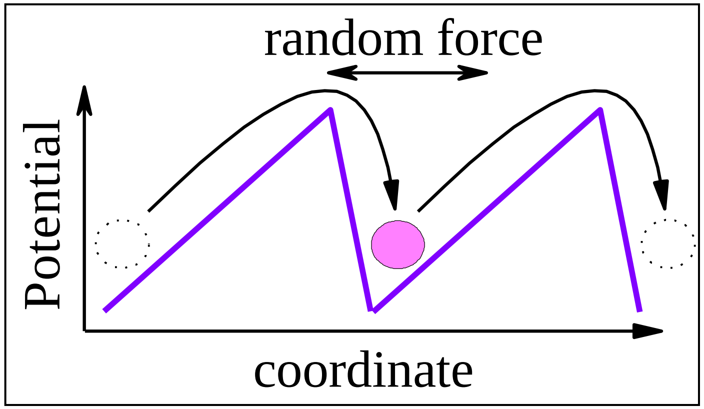
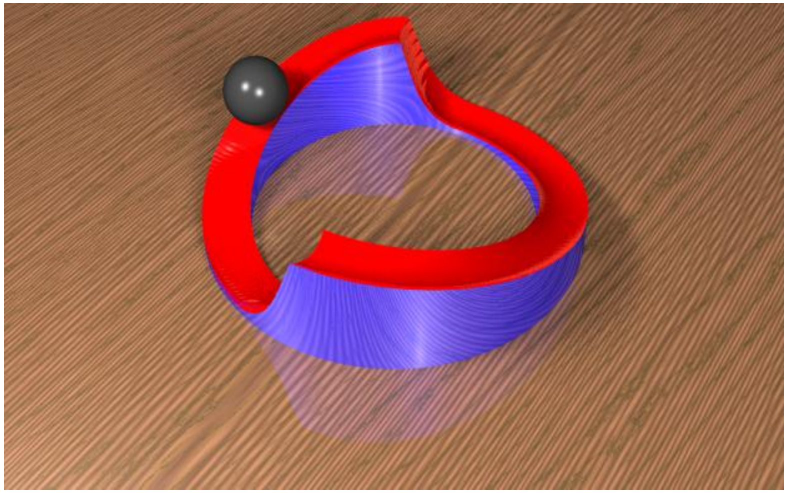
What is a Ratchet?

Point-like Brownian particle in asymmetric periodic potential





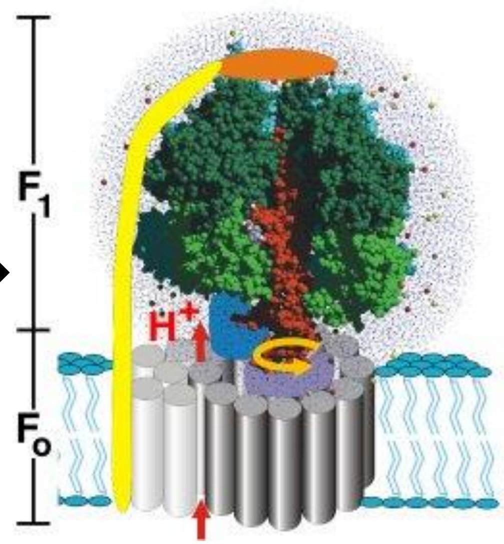
Aim: to rectify fluctuations

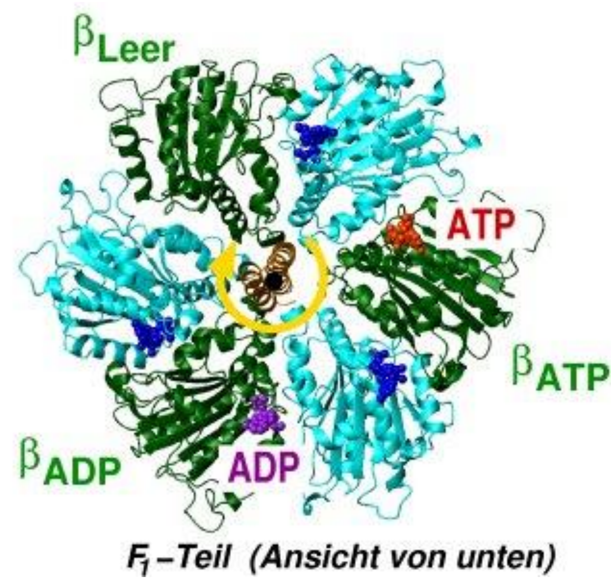
📖 Reimann, Phys. Rep. **361**, 57 (2002).
📖 P. Hänggi, F. Marchesoni, and F. Nori, Ann. Phys. (N.Y.) **14**, 51 (2005).
📖 P. Hänggi and F. Marchesoni, Rev. Mod. Phys. **81**, 387 (2009).

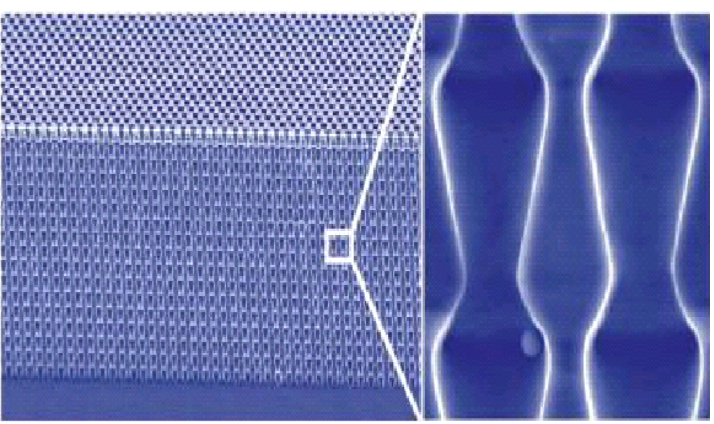
Ratchet effect

🡐Classical ratchet system

Transport
in biological
systems 🡒







🡐 Separation of macromolecules

What is a Josephson Vortex Ratchet (JVR)?

JVR Principle (Pert. theory approx.)

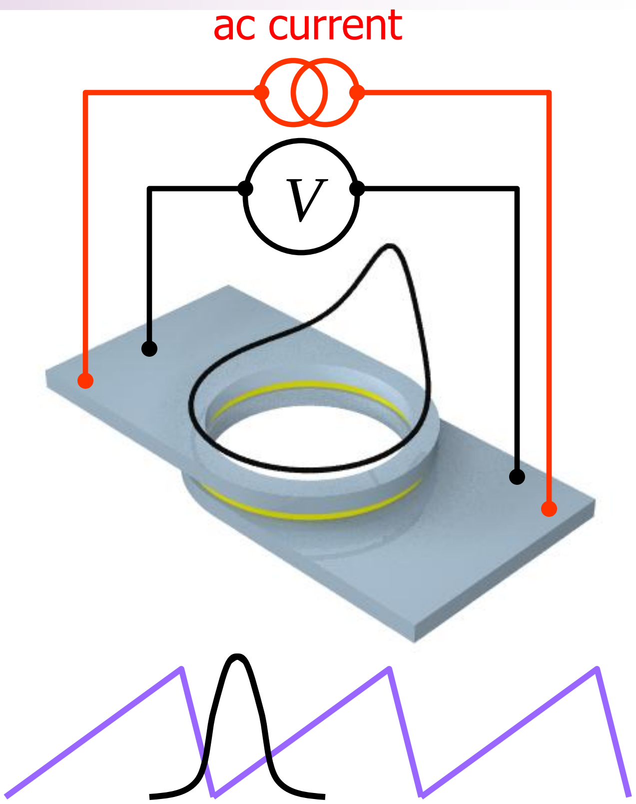
Particle → fluxon
Potential → $w(x)$, $h(x)$, $j(x)$
Periodic → annular LJJ (n periods)

Advantages of "Josephson"

Directed motion → voltage
Band → up to 100GHz
overdamped↔underdamped
quantum ratchet

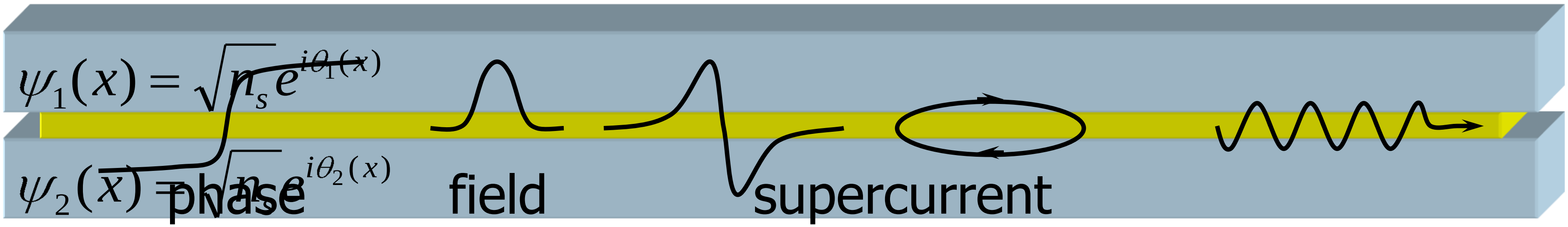
Peculiarities

Particle→relativistic soliton



📖 Carapella, PRB **63**, 54515 (2001)
📖 Carapella et al., PRL **87**, 77002 (2001)
📖 E. Goldobin, et al. Phys. Rev. E **63**, 031111 (2001)
📖 M. Beck, et al. Phys. Rev. Lett. **95**, 090603 (2005)

Long Josephson junctions

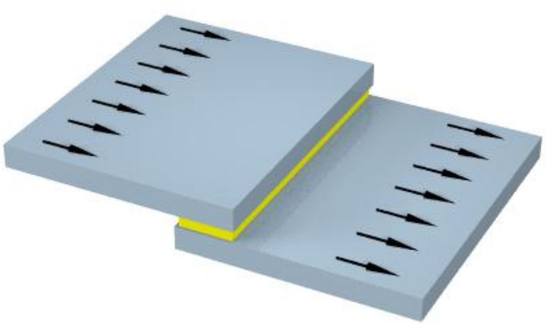


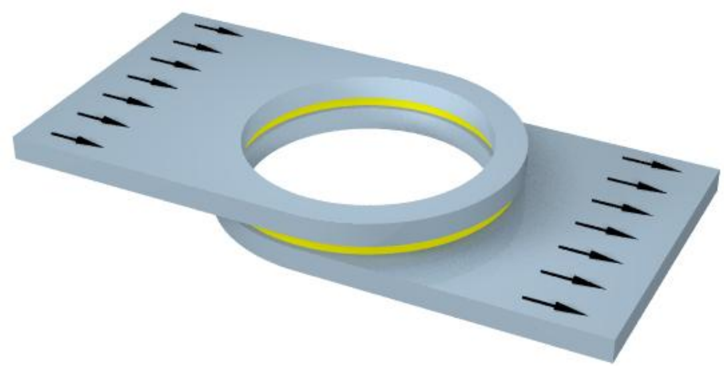
1D model: $\phi_{xx} - \phi_{tt} - \sin(\phi) = \alpha\phi_t - \gamma(x)$

$\lambda_J \sim 1 \dots 30\,\mu\mathrm{m}$

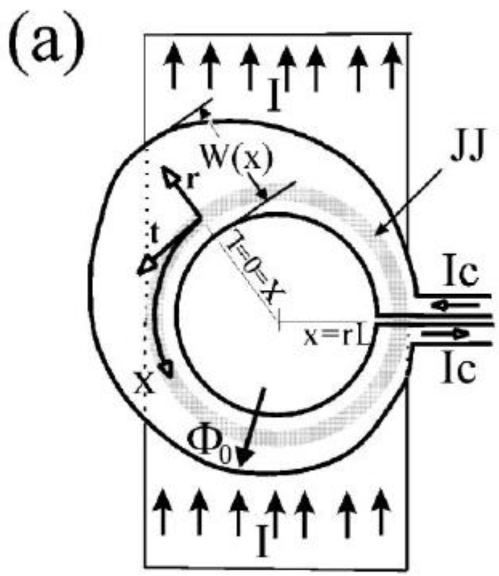
$\omega_p \sim 50 \dots 4000\,\mathrm{GHz}$

$\lambda_J \cdot \omega_p \equiv \bar{c}_0 \approx \dfrac{c_{\mathrm{light}}}{20 \dots 40}$





Different approaches to construct Asymmetric Periodic Potential



Carapella et al., PRL **87**, 77002 (2001)

Carapella, PRB **63**, 54515 (2001)

Internal modes:

$$\phi_{,tt} - \phi_{,xx} + \frac{\partial V(\phi)}{\partial \phi} = -\frac{\partial V_{\text{ext}}}{\partial \phi} - \beta\phi_{,t} + \eta(x,t)$$

Willis et al., PRE **69**, 056612 (2004)
PRE **71**, 016604 (2005)

Morales-Molina, et al., PRL **91**, 234102 (2003)

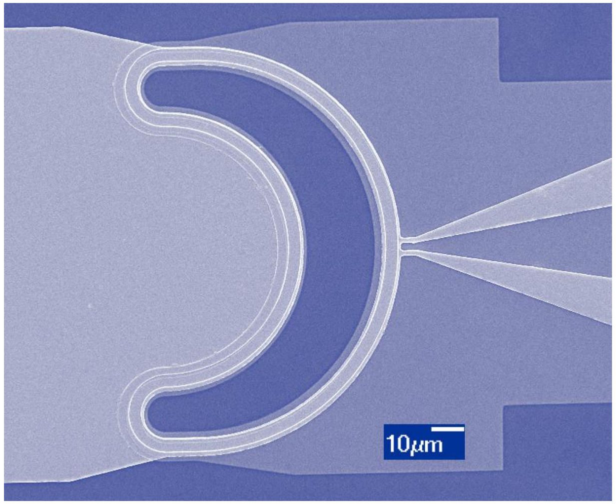
Constantini, et al., PRL **87**, 114102 (2001)

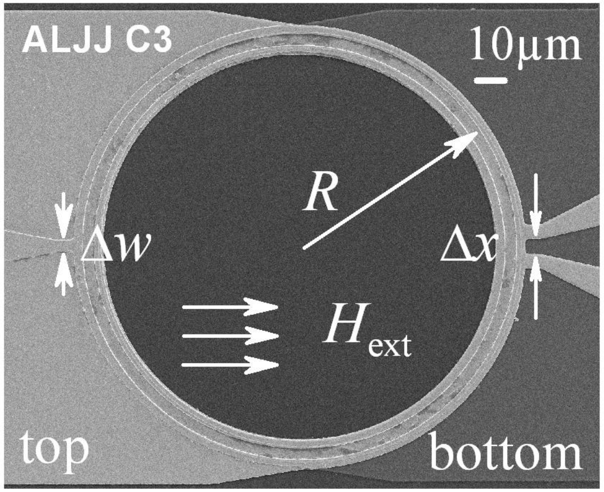
Asymmetric substrate pot.+symm. drive: move soliton in some dir.

Salerno et al., PRE **65**, 25602 (2002);
Constantini et al., PRE **65**, 51103 (2002)

Asymmetric potential

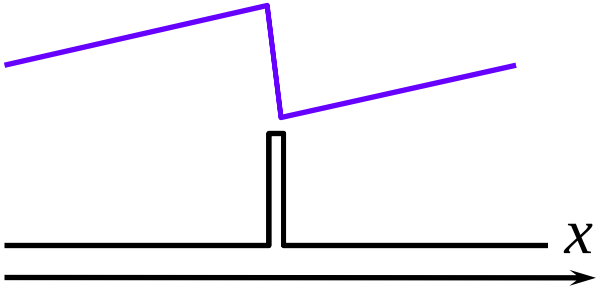
$$\phi_{xx} - \phi_{tt} - \sin(\phi) = \alpha\phi_t - \gamma(x) + h_x(x) - \frac{w_x(x)}{w(x)}\left[\phi_x - h(x)\right]$$





$U(x$ … $h(x_0)$

Potential:	*w(x)*	*h(x)*	*j(x)*
tunability?	no	yes	yes
topo. limits?	no	yes	no
I/H source?	no	yes	yes



📖 E. Goldobin, et al. PRE **63**, 031111 (2001)

JJ width modulation – potential for fluxon

$$\phi_{xx} - \phi_{tt} - \sin(\phi) = \alpha\phi_t - \gamma(t) - \frac{w_x(x)}{w(x)}\phi_x$$

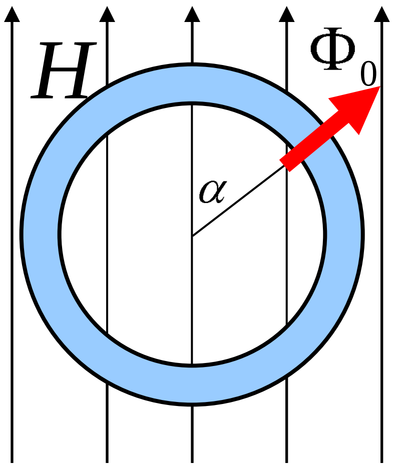
$$H = \int_0^L \left[\frac{\phi_t^2}{2} + \frac{\phi_x^2}{2} + (1 - \cos\phi)\right] w(x)\, dx$$

$$\phi(x,t) = 4 \arctan \exp\left(\frac{x - ut - x_0}{\sqrt{1-u^2}}\right)$$

$$U(x_0) = \int_0^L \frac{4w(x)}{\cosh^2(x - x_0)} \approx 8w(x_0)$$

Non-relativistic approx,
“slow” modulation

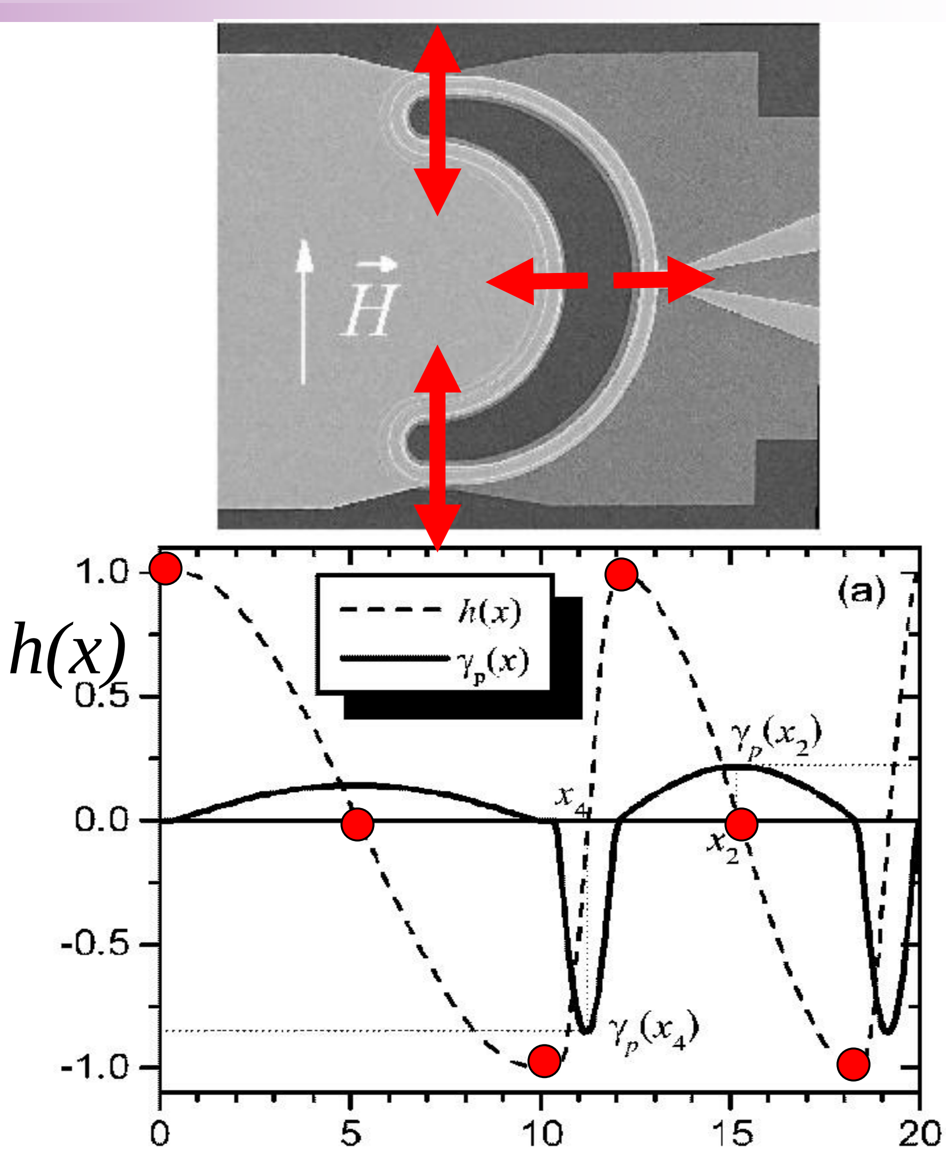
Asymmetry due to non-uniform field



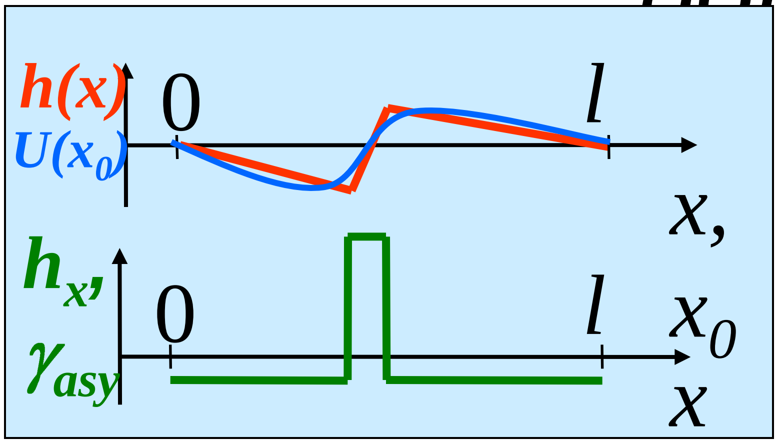
$$H(x) = H \cdot \cos\alpha$$

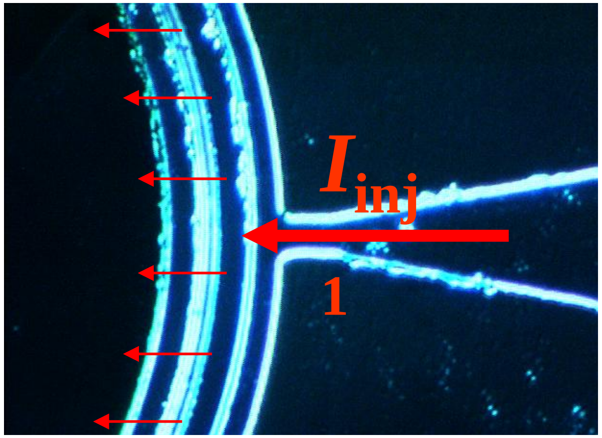
$$U(x_0) = -2\pi w h(x_0)$$

- Tunable potential
- Topological limitations

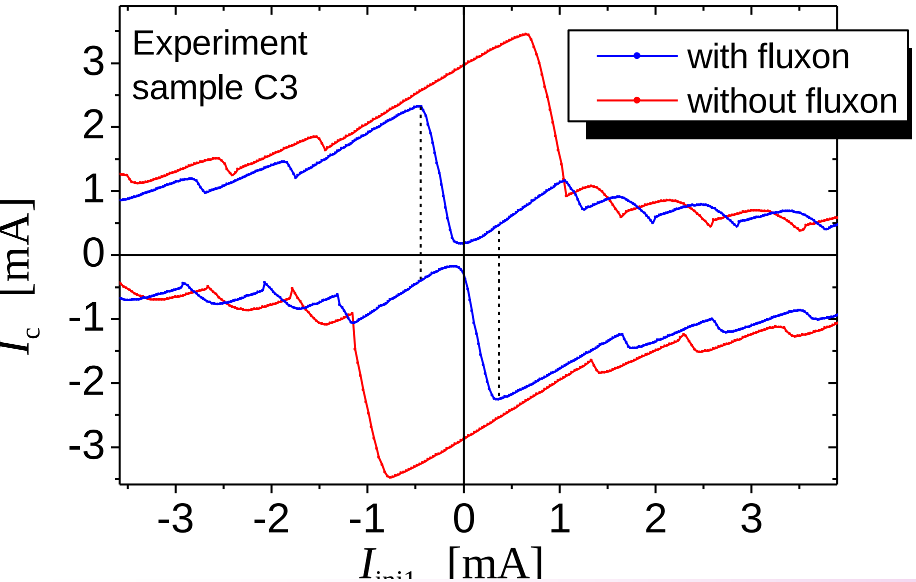


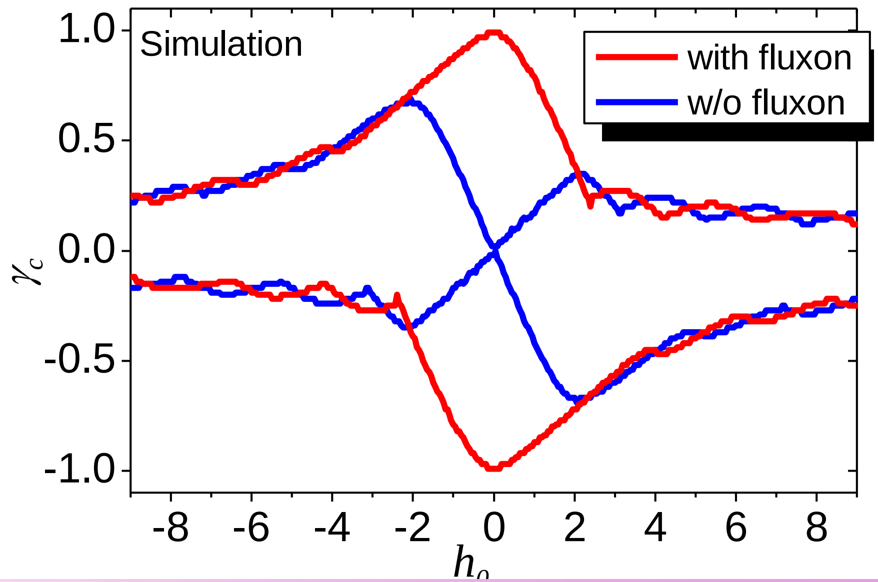
How an injector can create strongly asymmetric saw-tooth potential?





$$\frac{m_-}{m_+} = 6{,}6$$





E. Goldobin, et al. Phys. Rev. E **63**, 031111 (2001)

System under investigation: Relativistic Deterministic JVR

For theorists

$$\phi_{xx} - \phi_{tt} - \sin\phi = $$
$$= \alpha\phi_t + h_x(x) - \gamma_{\rm ac}\sin(\omega t)$$

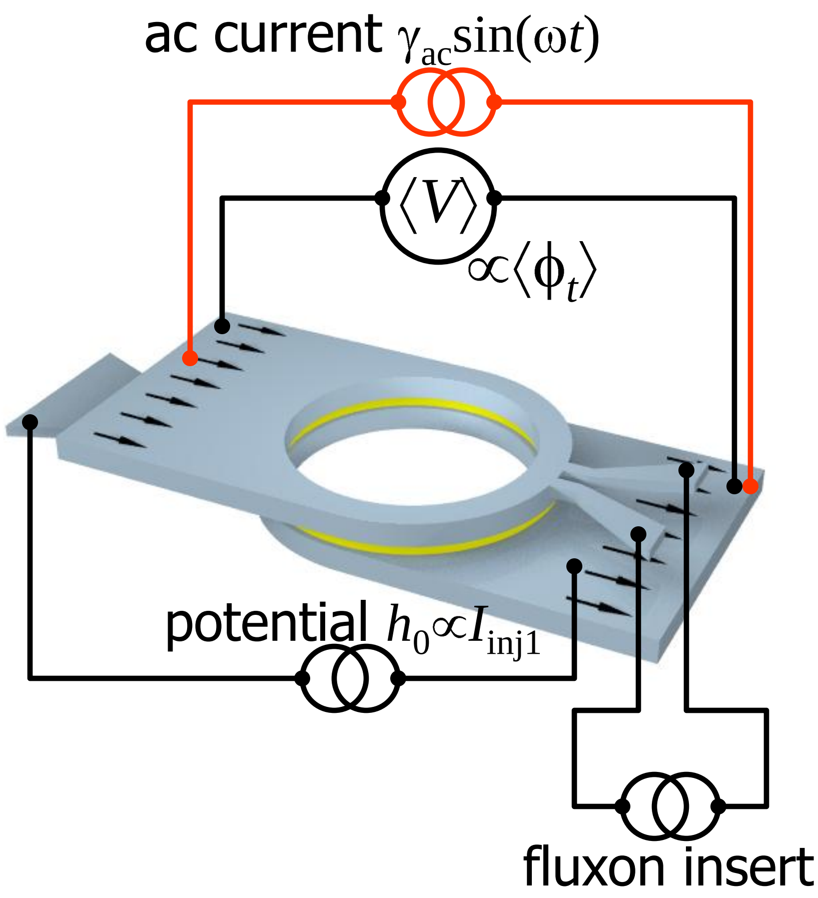
α – damping ($\alpha \ll 1$)
$h(x)$ – potential profile (saw-tooth)
γ_{ac} – amplitude of ac drive
γ_{dc} – dc force (usually =0)

$$\phi(x,t) = 4\arctan\exp\left[\frac{x - x_0(t)}{\sqrt{1-\dot{x}^2}}\right]$$

One can derive eq. for $x_0(t)$ in the PT limit, assuming rigid fluxon shape.

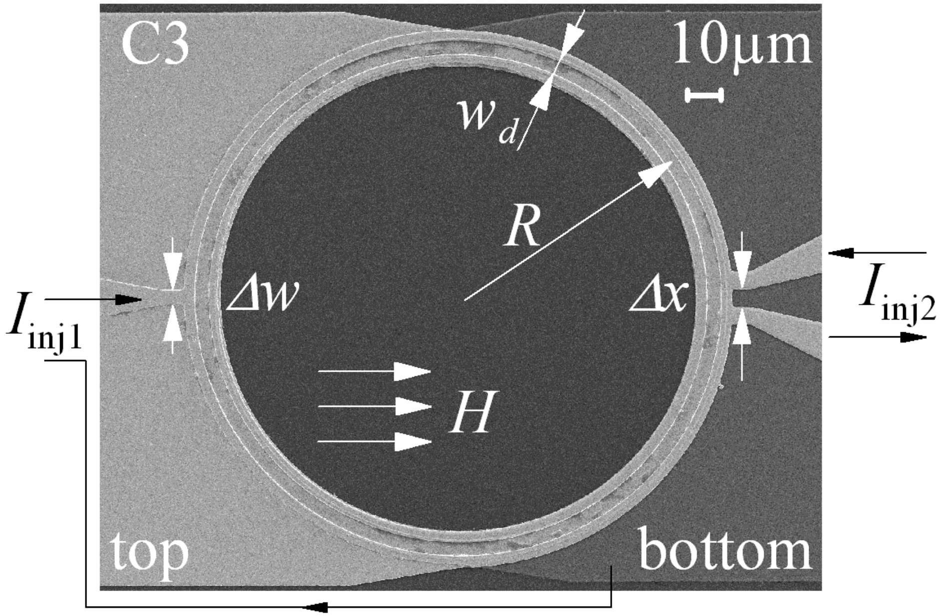
📖 E. Goldobin et al, PRE **63**, 031111 (2001)
📖 G. Carapella et al., PRB **63**, 054515 (2001).

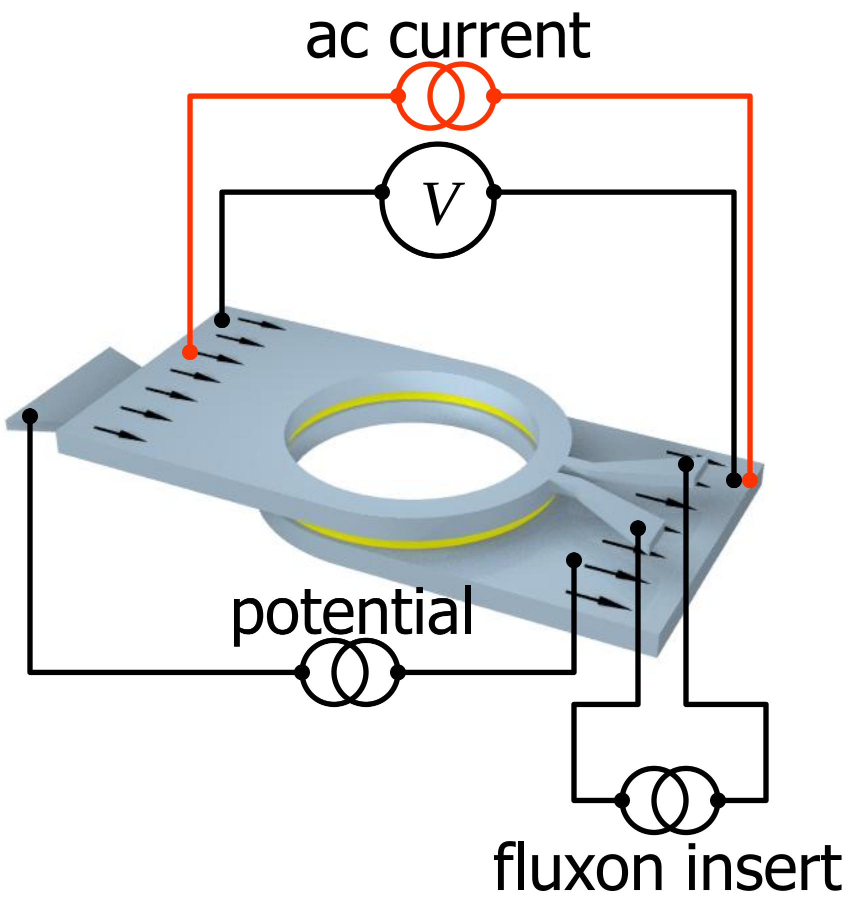
For experimentalists



📖 M. Beck, et al. PRL **95**, 090603 (2005)

Geometry

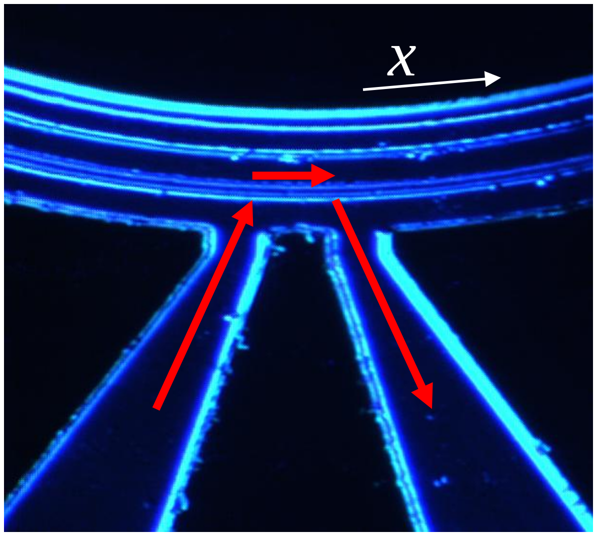


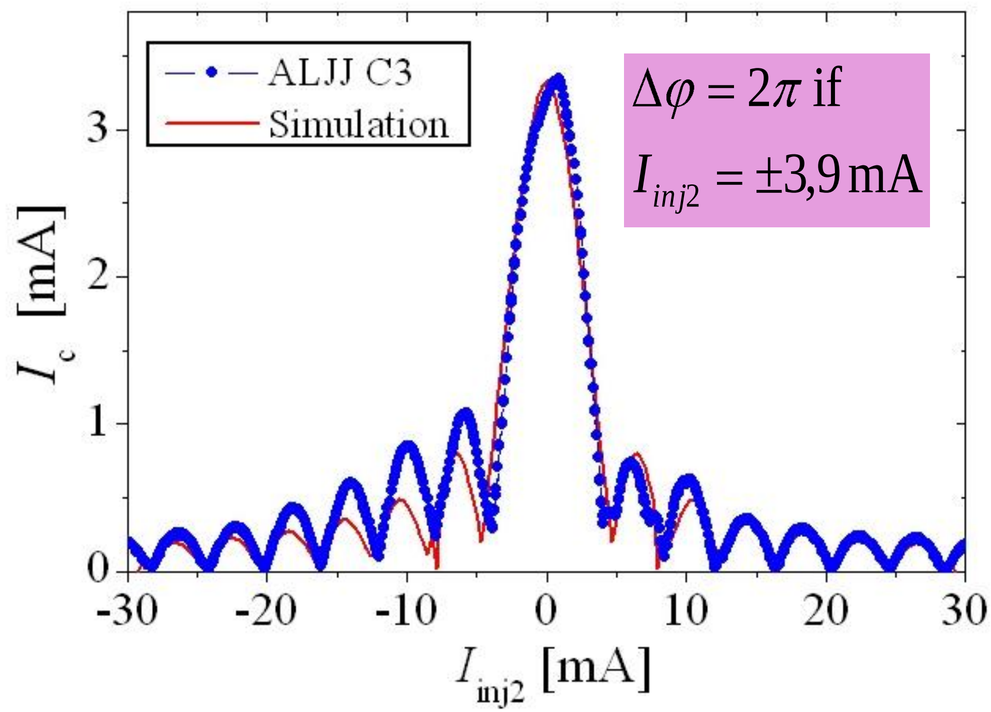


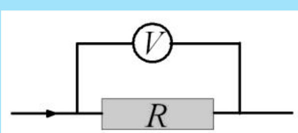
$R = 70\mu m$, $\Delta x = 5\mu m$, $\Delta w = 5\mu m$

M. Beck, E. Goldobin, et al. Phys. Rev. Lett. **95**, 090603 (2005)

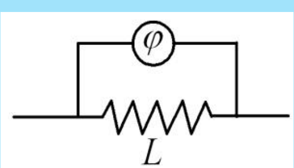
Insertion of fluxon







$$U = R \cdot I$$



$$\Phi = L \cdot I$$

$$\Delta\varphi = \frac{2\pi \cdot \Phi}{\Phi_0} \propto L \cdot I$$

Insertion of a fluxon ($\Delta\varphi=2\pi$):

📖 A. V. Ustinov, APL **80**, 3153 (2002)

📖 B. Malomed, et al. PRB **69**, 64502 (2004)

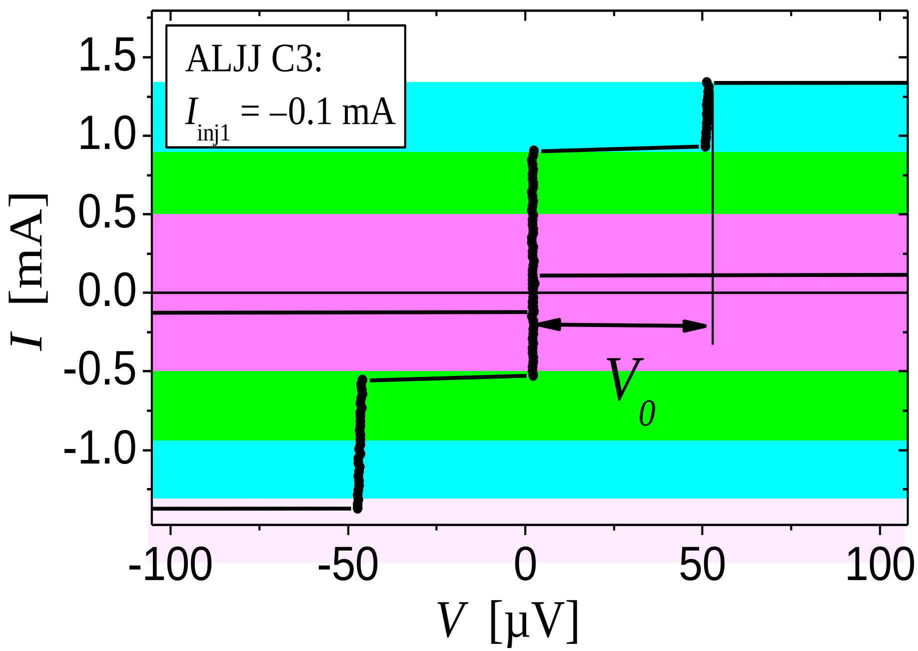
📖 E. Goldobin, et al. PRB **67**, 224515 (2003); PRL **92**, 57005(2005)

Quasi-static drive (100Hz)

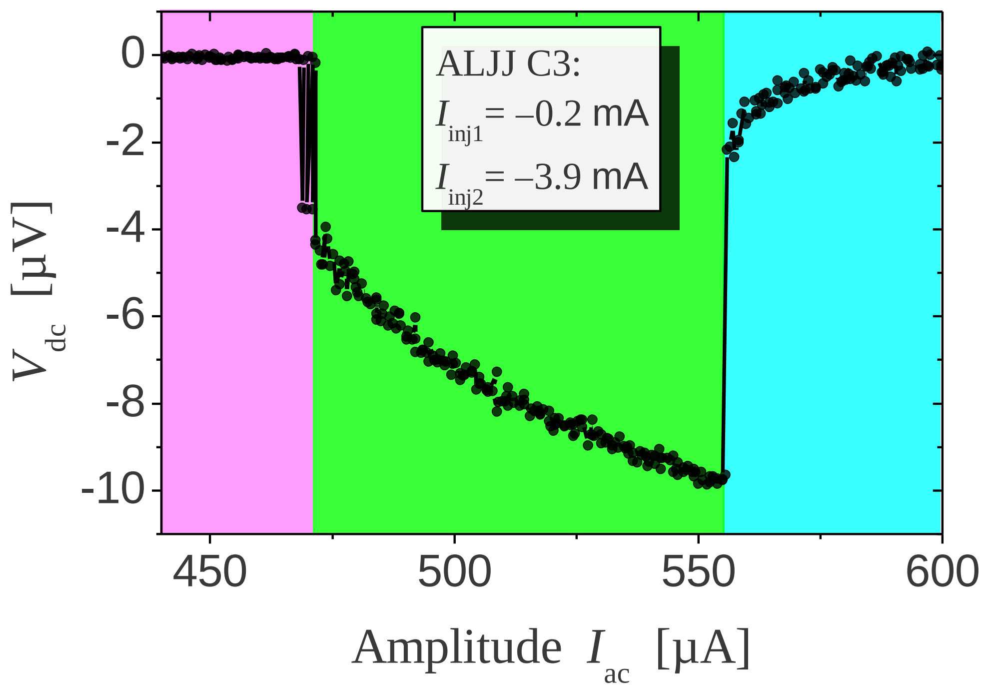
Apply : $I(t) = I_{ac} \cdot \cos(\omega t)$

Measure : $V_{dc}(I_{ac}) = \langle V \rangle (I_{ac})$

I-*V* Characteristic



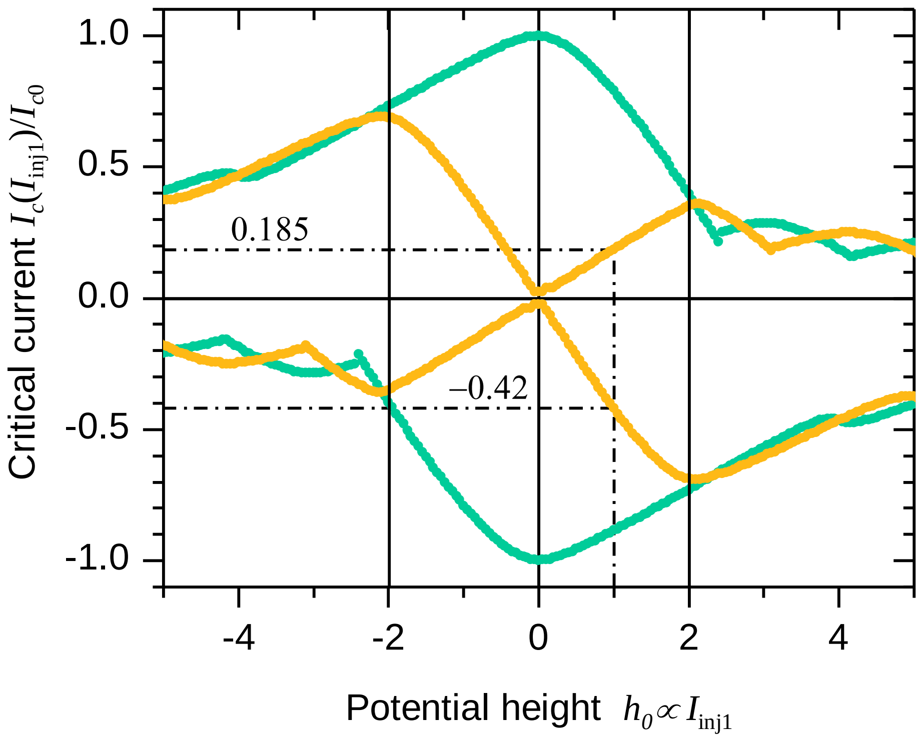
Rectification curve $V_{dc}(I_{ac})$

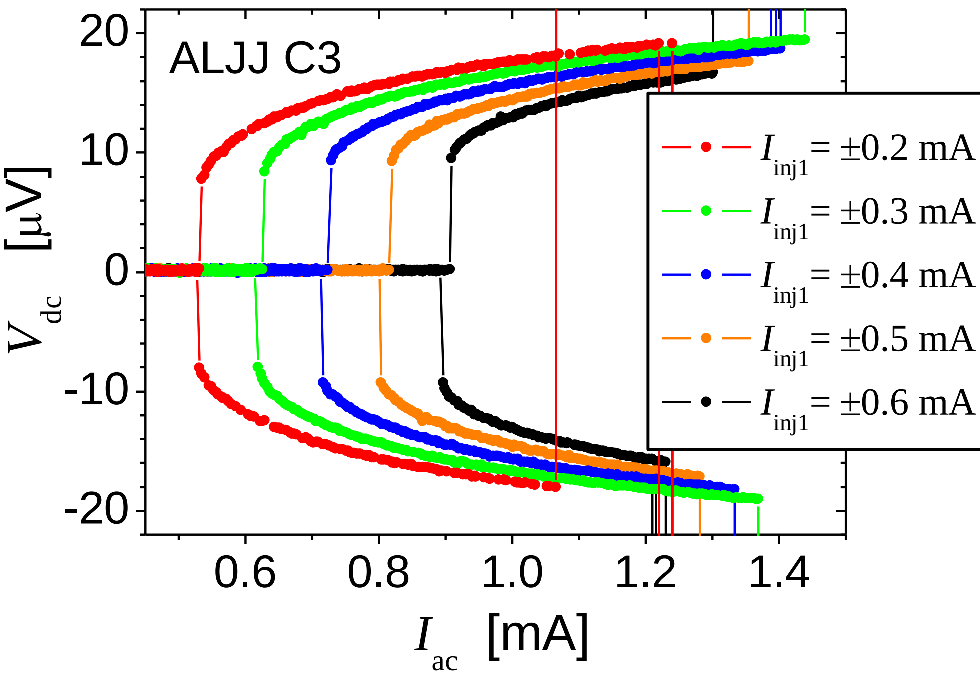


Asymmetric fluxon steps!

M. Beck, E. Goldobin, et al. Phys. Rev. Lett. **95**, 090603 (2005)

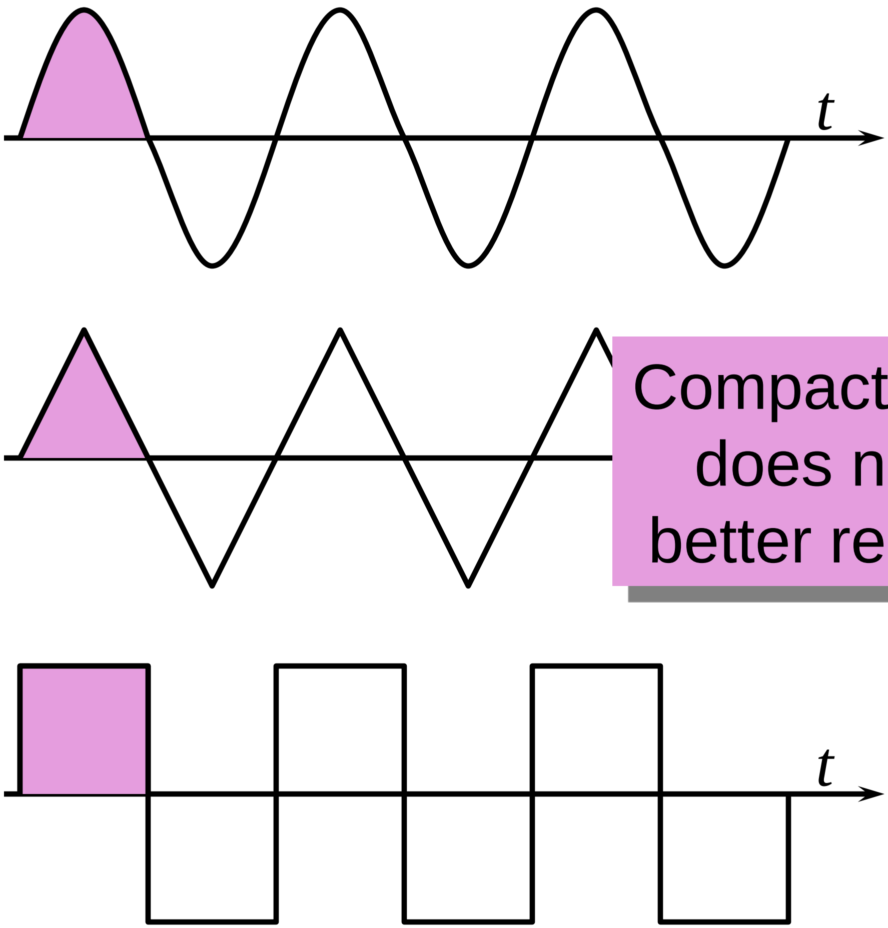
Ratchet effect vs. potential height



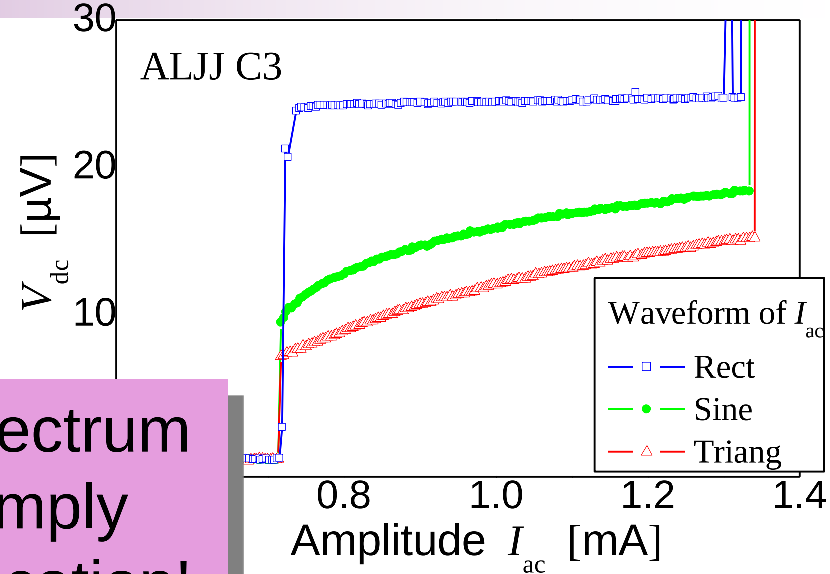


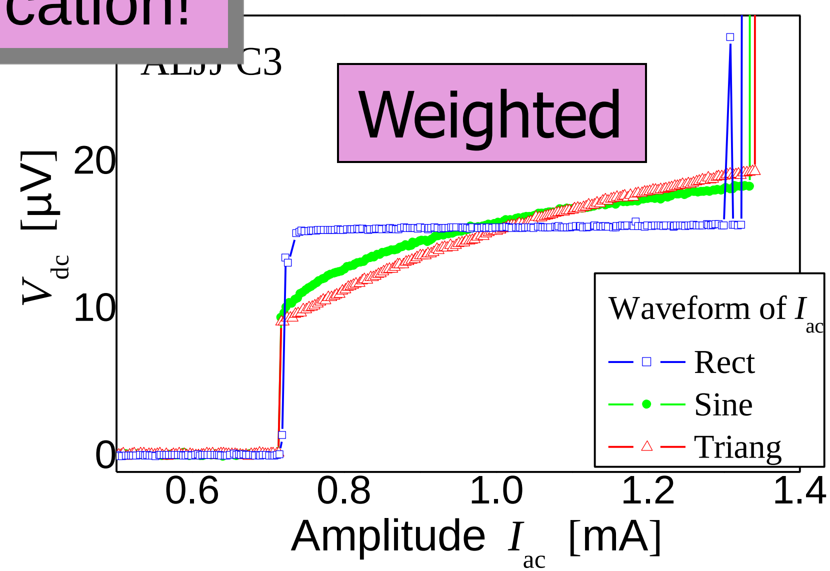
📖 M. Beck, E. Goldobin, et al. Phys. Rev. Lett. **95**, 090603 (2005)

Ratchet effect vs. driver shape

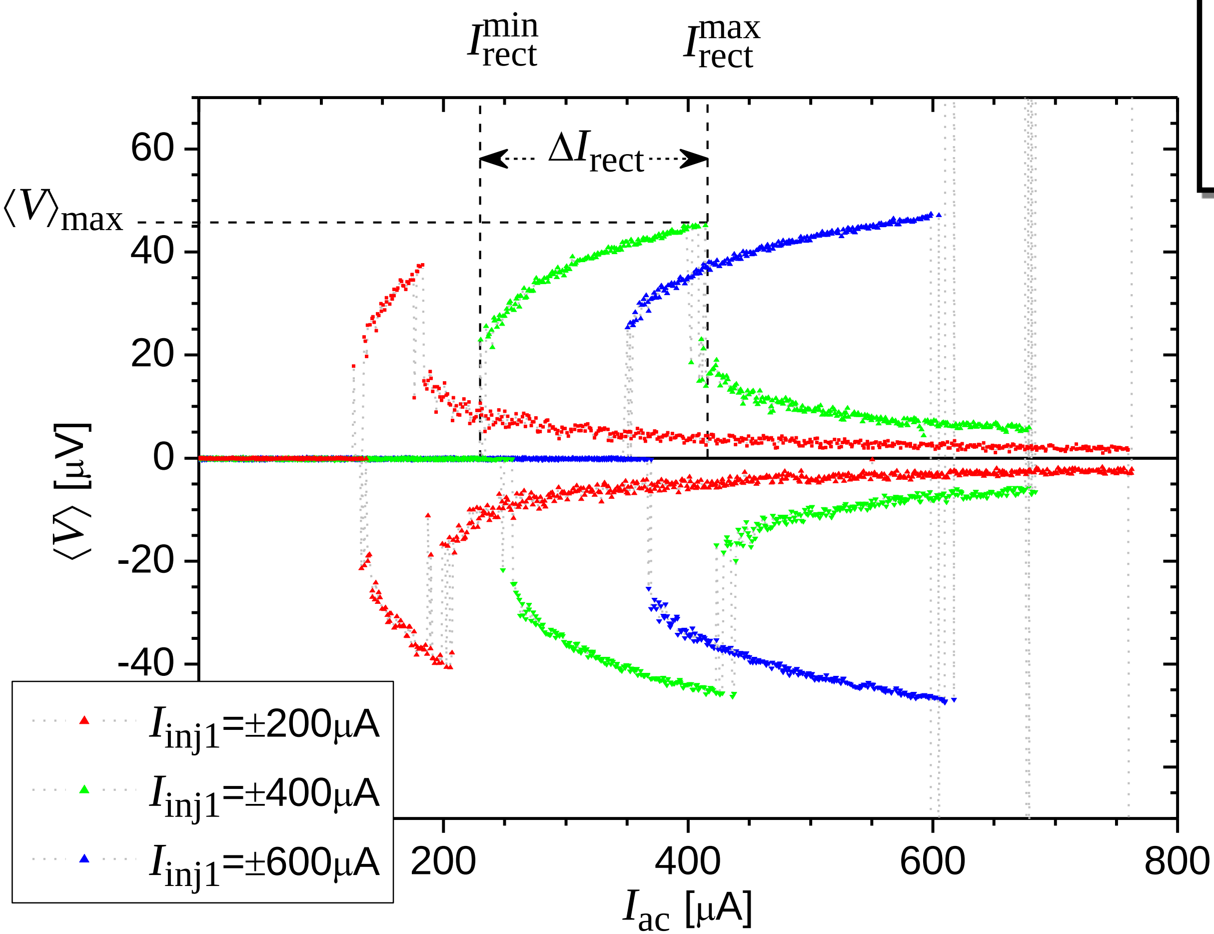


Compact spectrum does not imply better rectification!





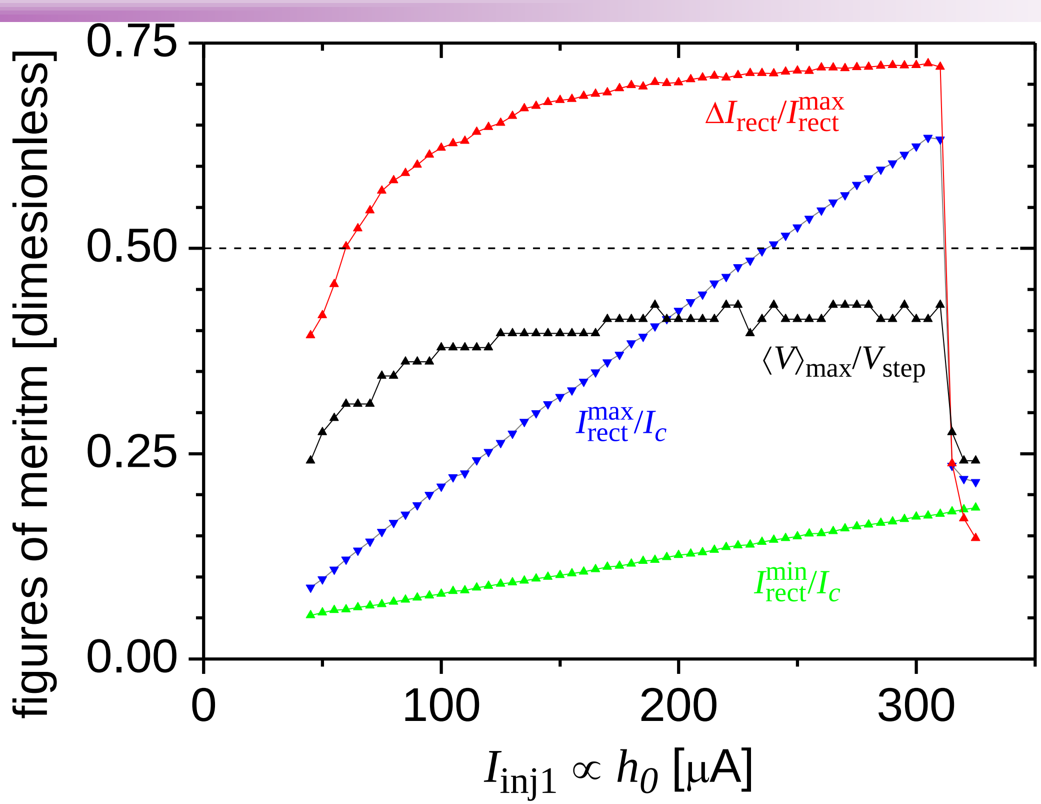
Figures of merit



Figures of merit

- ➔ min. I_{rect} (aim: ↓, h_0 ↓)
- ➔ max. I_{rect} (aim: ↑, h_0 ↑)
- ➔ ΔI_{rect} (aim: ↑, h_0 ↑)
- ➔ $\langle V \rangle_{max}$ (aim: ↑, h_0 ↑)

Adiabatic JVR: optimazation



Figures of merit

- ➔ min. I_{rect} (aim: ↓, h_0 ↓)
- ➔ max. I_{rect} (aim: ↑, h_0 ↑)
- ➔ ΔI_{rect} (aim: ↑, h_0 ↑)
- ➔ $\langle V\rangle_{max}$(aim: ↑, h_0 ↑)

Result

- ➔ One cannot optimize all figures at ones.
- ➔ Increasing h_0 we optimize 3 out of 4: most importantly ΔI_{rect} and $\langle V\rangle_{max}$.

Loaded quasi-static JVR

How large should be the dc counter force to stop the ratchet?

In adiabatic regime the result can be obtained from the IVC: $V(I) = V(I_{ac}\sin(\omega t) + I_{dc})$

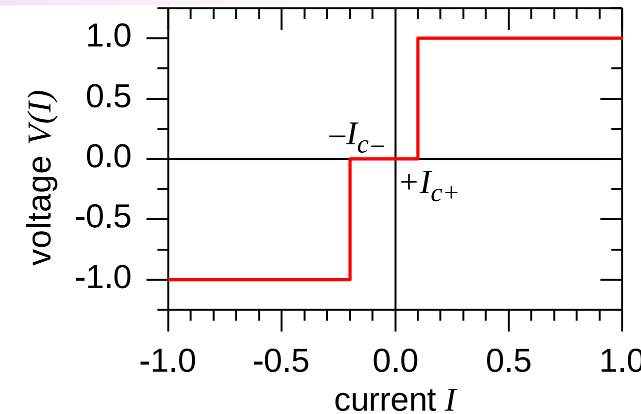
Averaging over one period we get

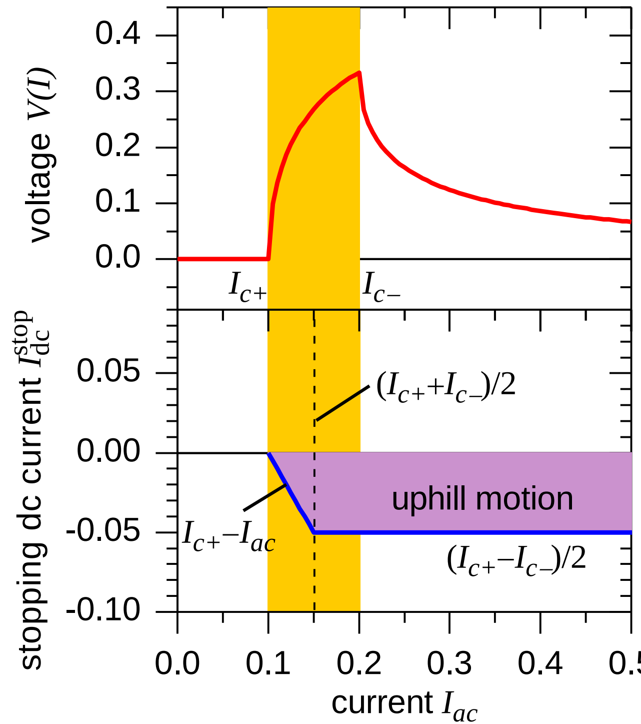
$$\langle V\rangle(I_{ac}, I_{dc})$$

Solving $\langle V\rangle(I_{ac}, I_{dc}) = 0$ for I_{dc} we get $I_{dc}^{\mathrm{stop}}(I_{ac})$

Results for a simple step-like IVC model (I_{c+},I_{c-})

- ➔ stopping force grows linearly
- ➔ it saturates in the middle of rect. window
- ➔ saturation value is equal to rect. window size
- ➔ make window as large as possible (large h_0)
- ➔ operate ratchet in the 2nd half of rect. window!

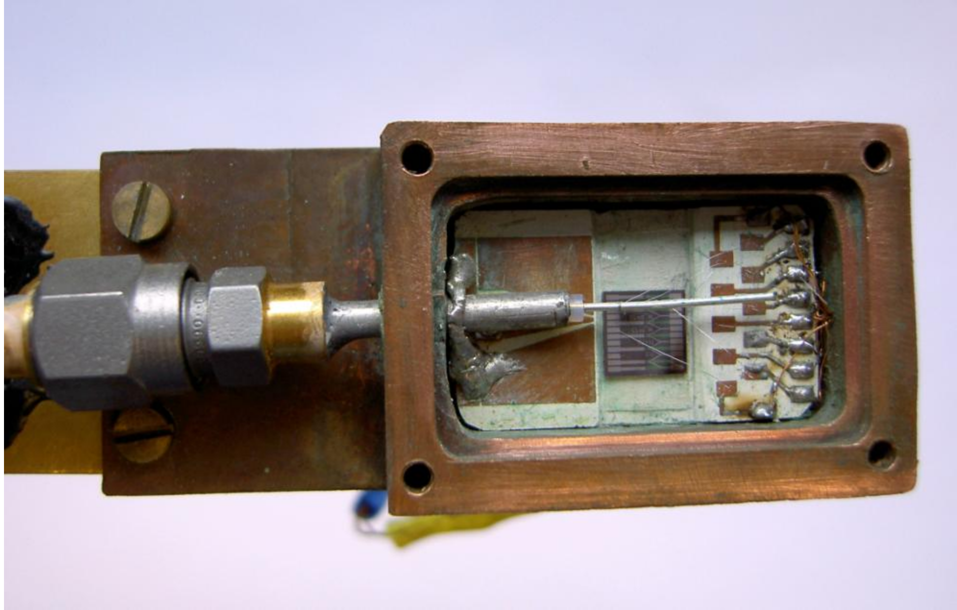




High frequency drive – non Adiabatic JVR (nA-JVR)

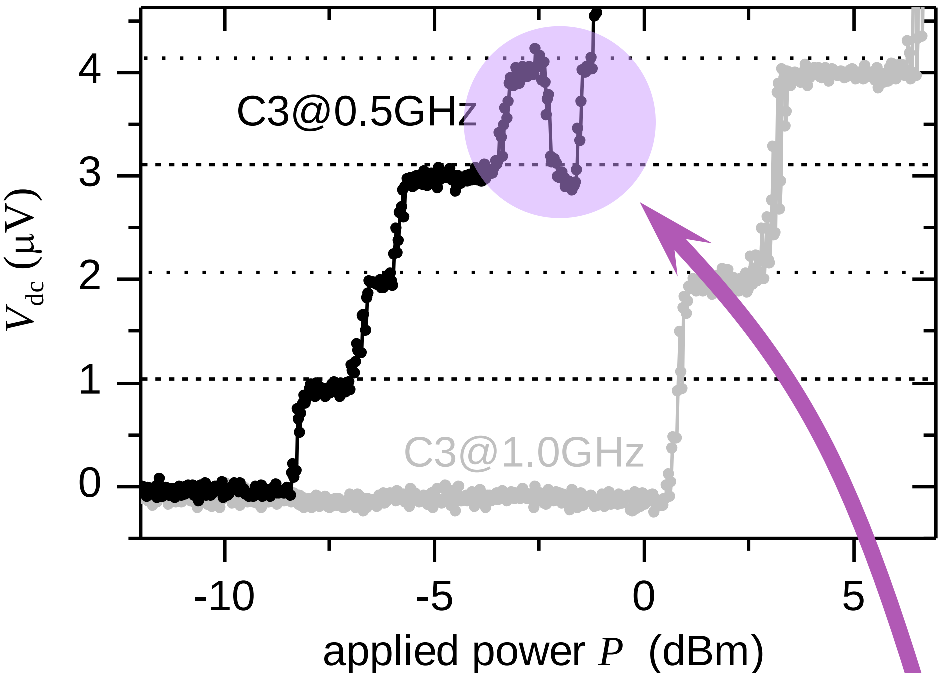
- What means **high** frequency?
  - Period of the drive is comparable with the time it takes for fluxon to move around the annulus
  - periodic dynamics → integer number of turns
  - discrete average velocity=desctere average voltage steps
- Underdamped system: inertial effects, chaos

Setup:
- Resonator cupper box, the first mode @ 6.0 GHz
- Sender: rf-antenna
- Receiver: JJ-Electrodes
- $I_{ac} \leftrightarrow$ power P

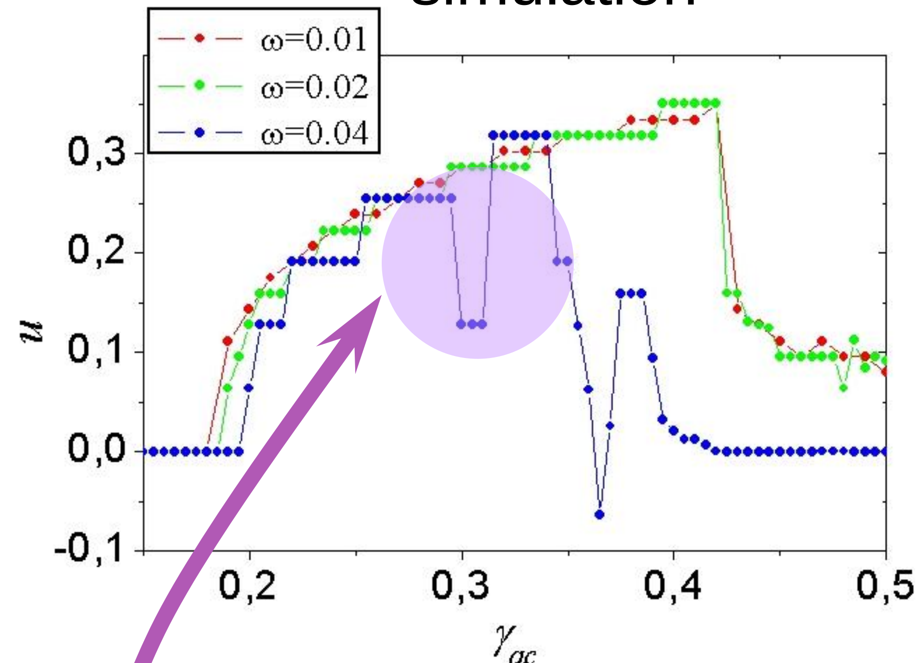


nA-JVR: Quantized rectification

experiment



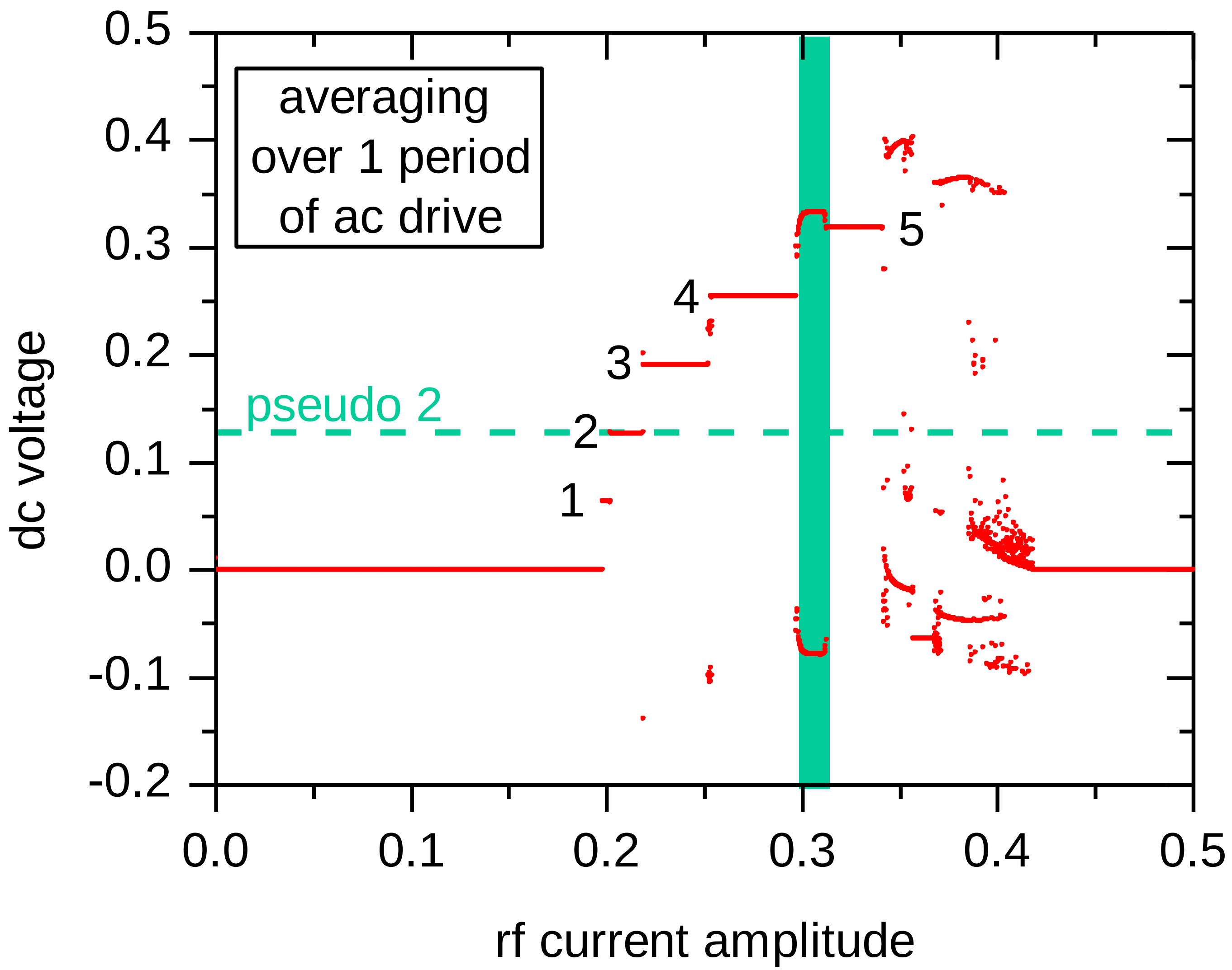
simulation



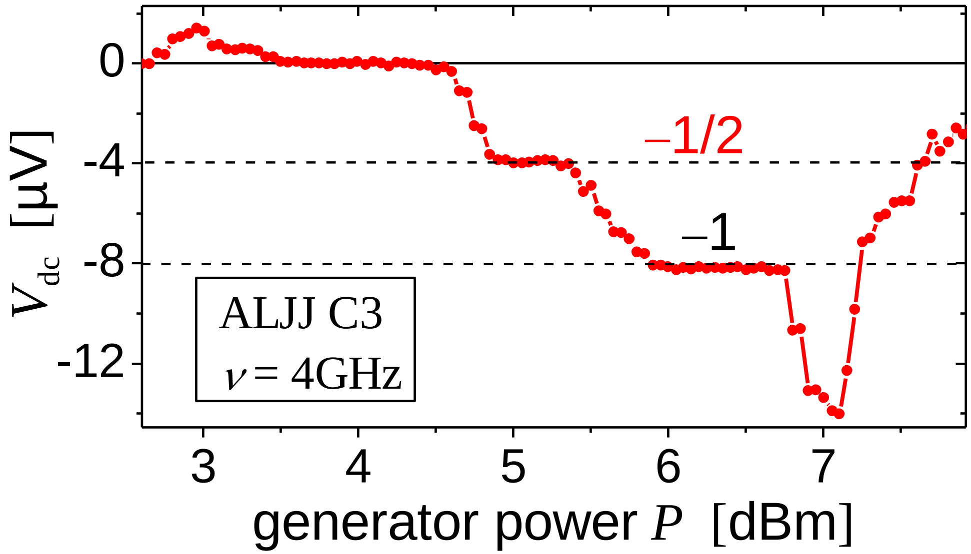
$$V_{dc}^{n} = n\Phi_0 \frac{\omega}{2\pi} \approx n\left[2\mu V / GHz\right]$$

Non-monotonous steps!

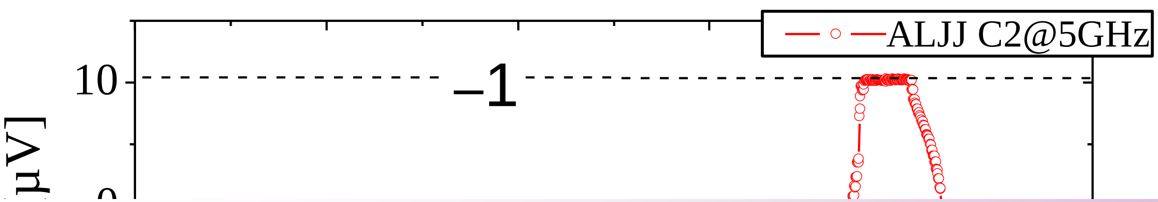
nA-JVR: Period-2 dynamics



nA-JVR: half integer steps & current reversal



One turn takes **two** driving periods!



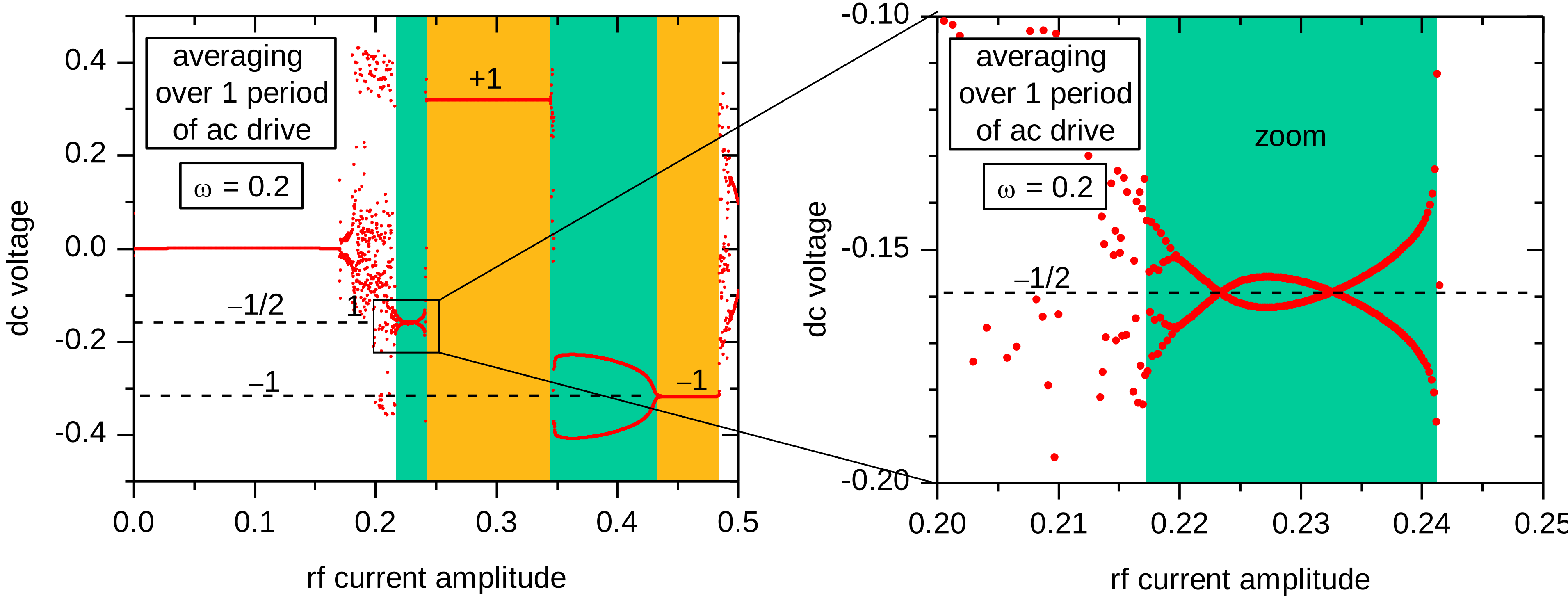
Particle's (fluxon's) **current reversal**

📖 J. Mateos, et al. PRL **84**, 258 (2000)
Physica A **325**, 92 (2003)

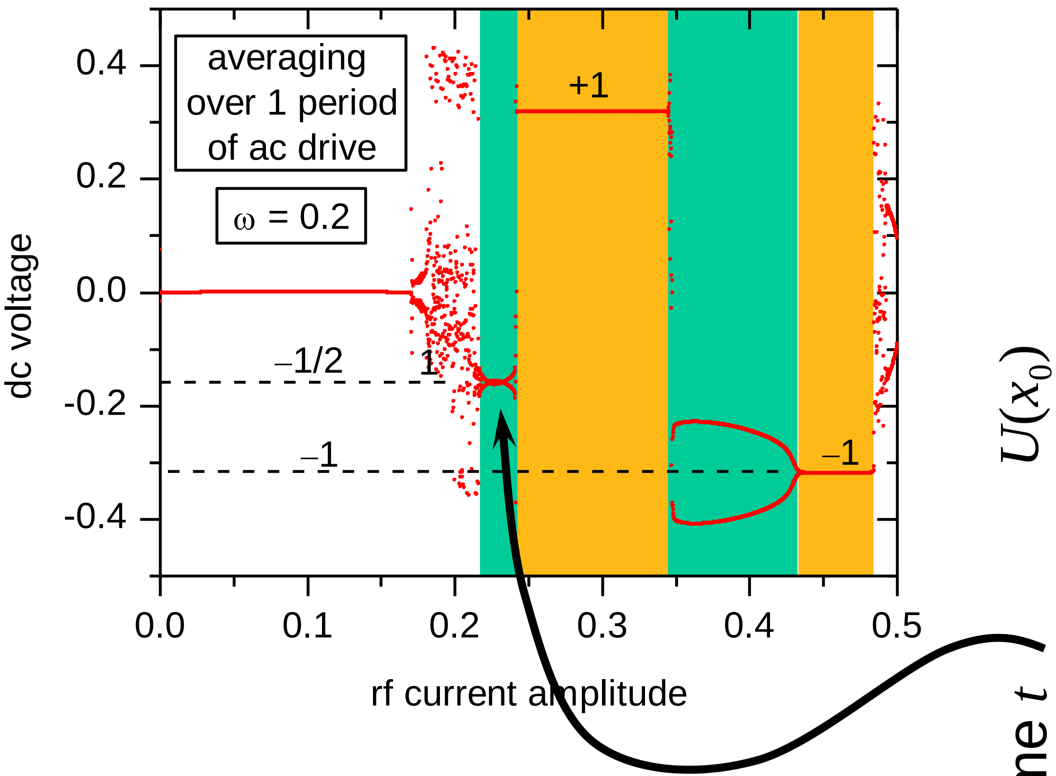
📖 M. Barbi, et al. Phys. Rev. E **62**, 1988 (2000)

📖 P. Jung, et al. Phys. Rev. Lett. **76**, 3436 (1996)

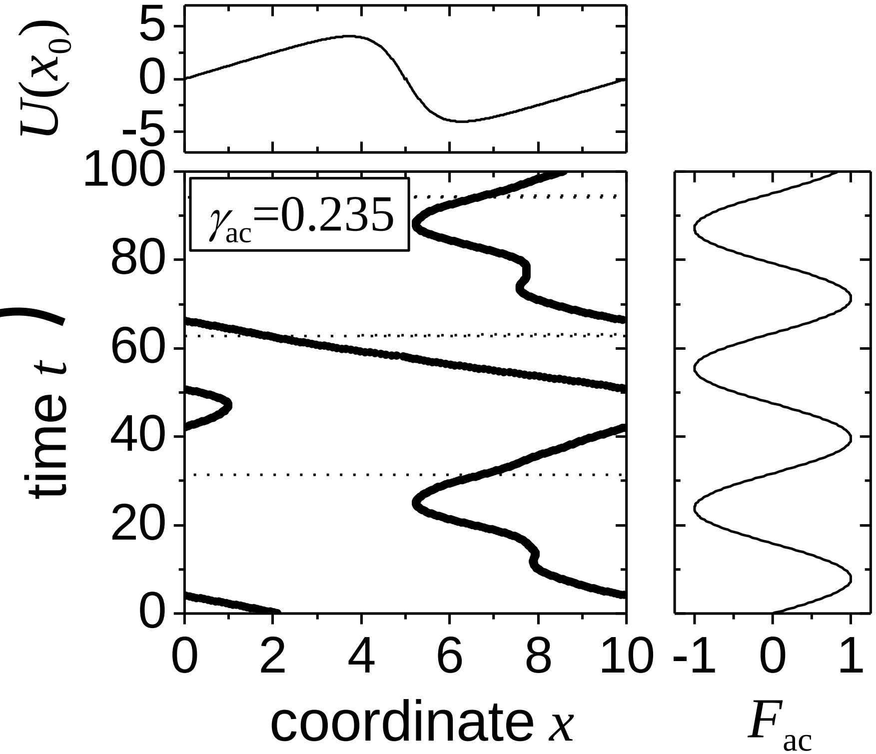
nA-JVR: Half integer steps & current reversal



nA-JVR: fluxon trajectories & period 2 dynamics

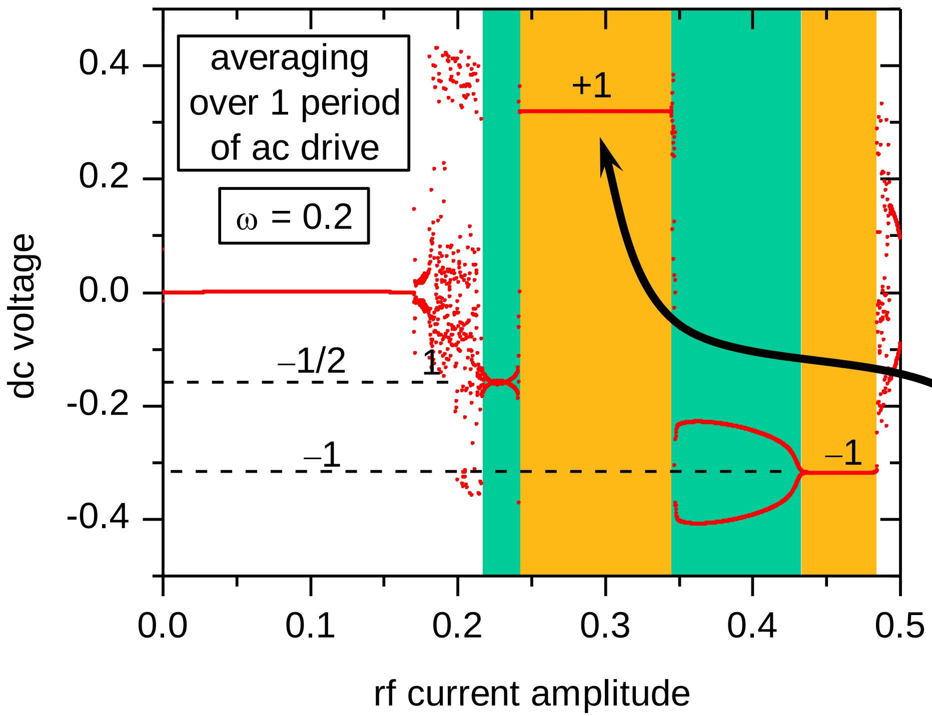


l = 10, h_0 = 1.0, ω = 0.2

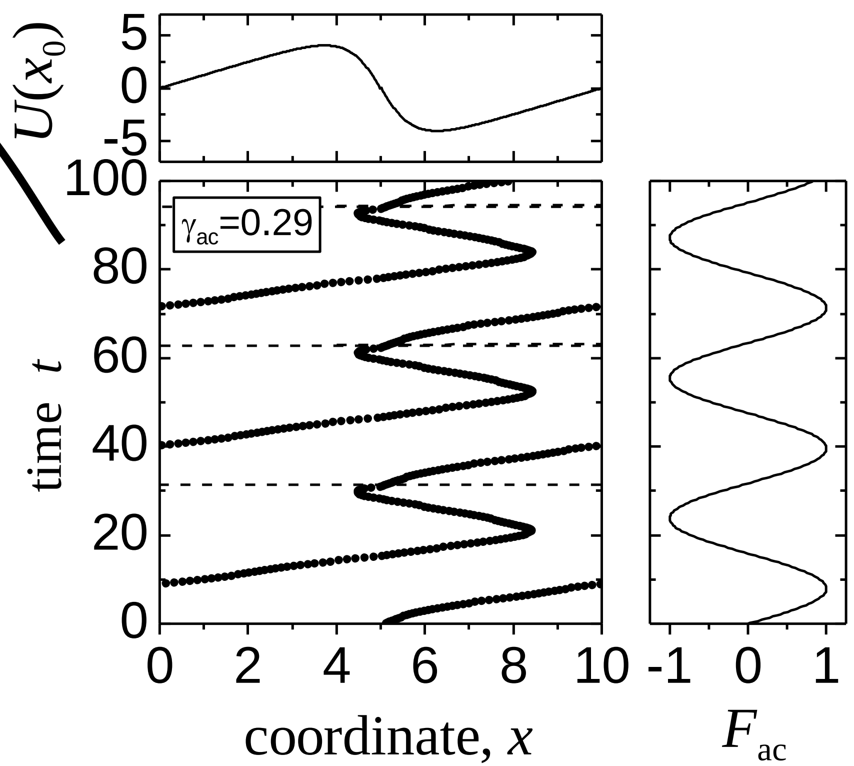


subharmonic

nA-JVR: Period-1 dynamics: forward step

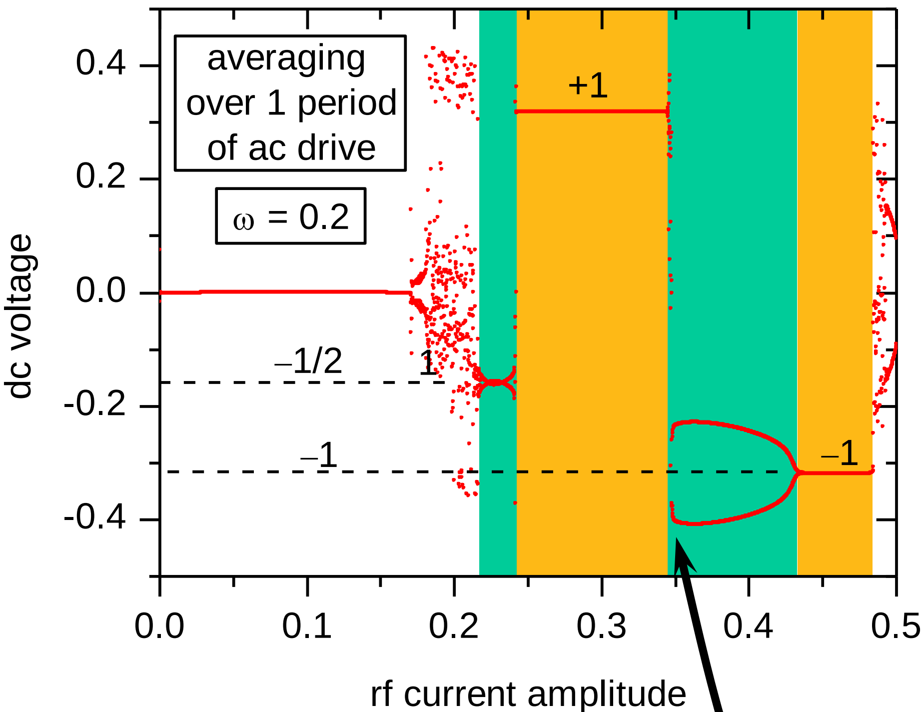


$l = 10,\ h_0 = 1.0,\ \omega = 0.2$

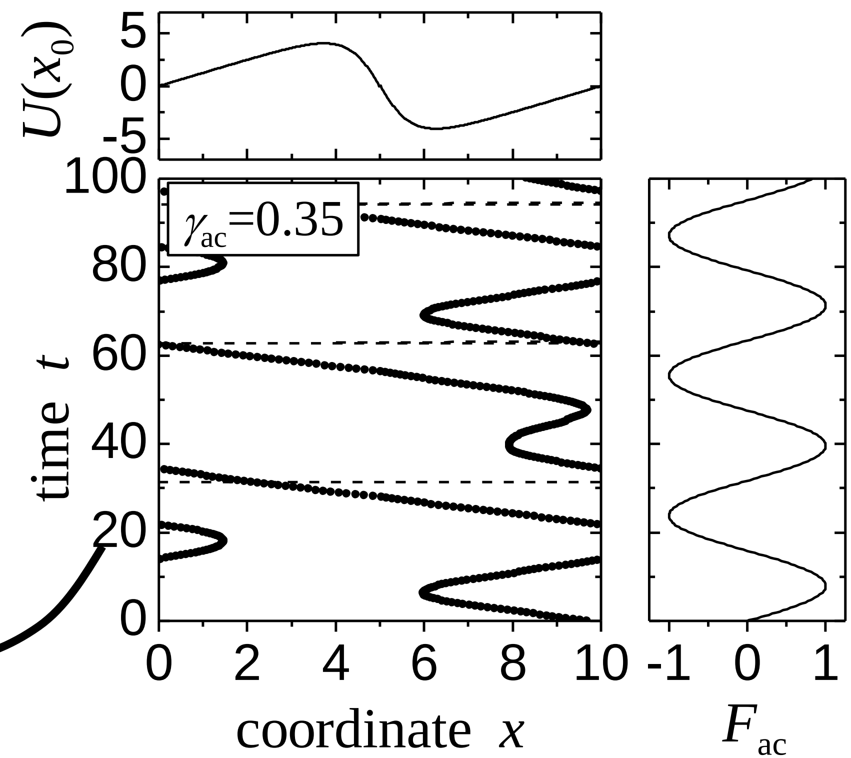


harmonic

nA-JVR: Period 1&2 dynamics, current (voltage) reversal



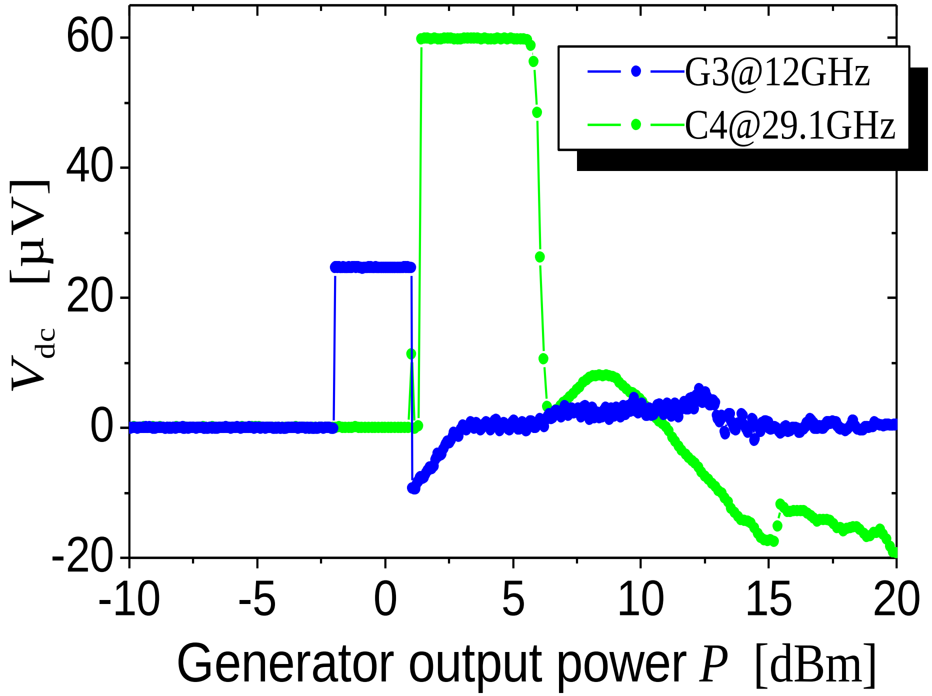
$l = 10,\ h_0 = 1.0,\ \omega = 0.2$



Subharmonic

current reversal: period 1&2

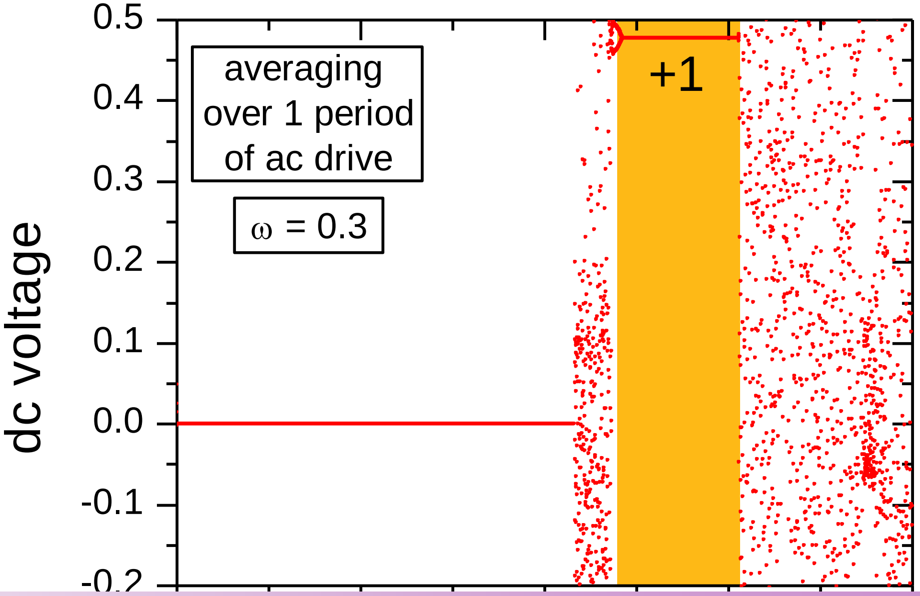
nA-JVR: Peak velocities



Average velocity :

G3 : $\langle u \rangle = 0.91\bar{c}_0$

Simulation
Max. Average velocity
0.47 (?)



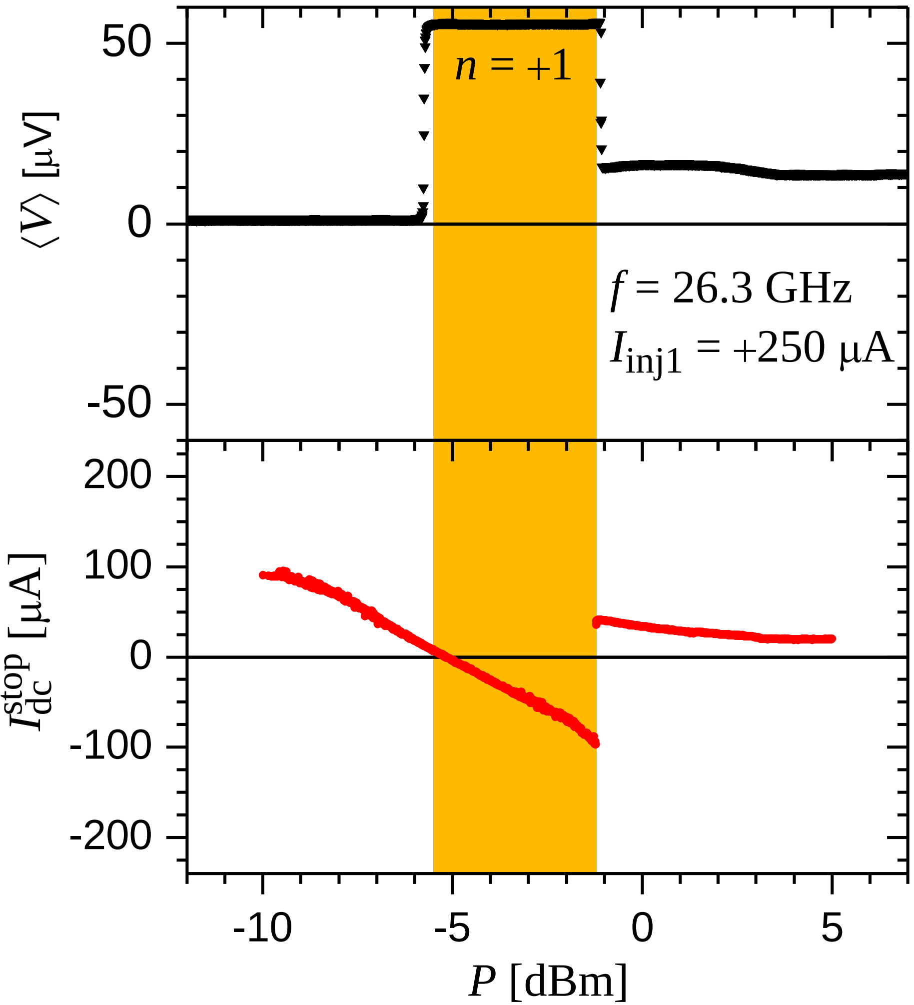
$\langle u \rangle$=0.22 : 📖 A. Ustinov, et al. PRL **93**, 87001 (2004)

$\langle u \rangle$=0.33: 📖 G. Carapella, et al. Physica C **382**, 337 (2002)

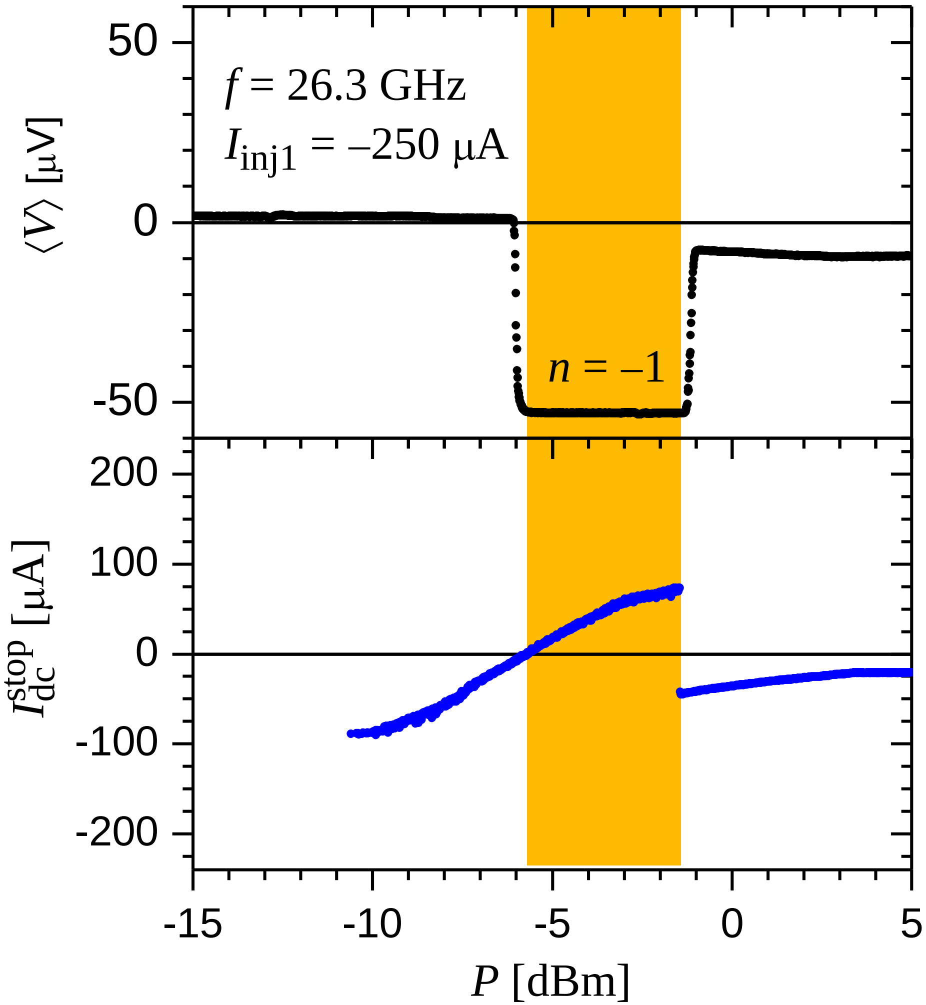
$\langle u \rangle$=0.17 @ α=1: 📖 F. Mertens, et al. PRE **74**, 66602 (2006)

nA-JVR loaded by dc current

Positive potential

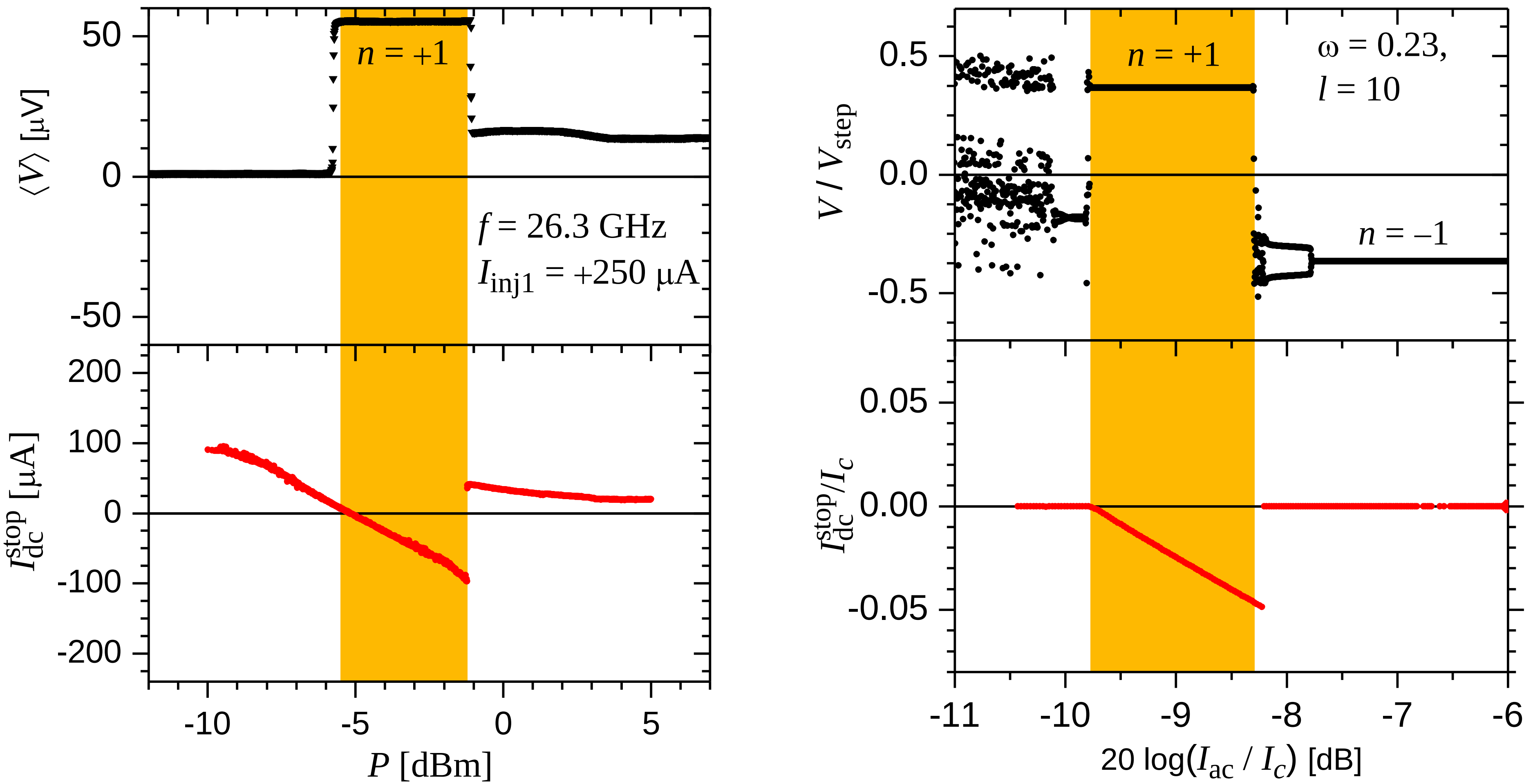


Negative potential



nA-JVR: stopping force (current) experiment vs. simulation

Experiment	Simulation

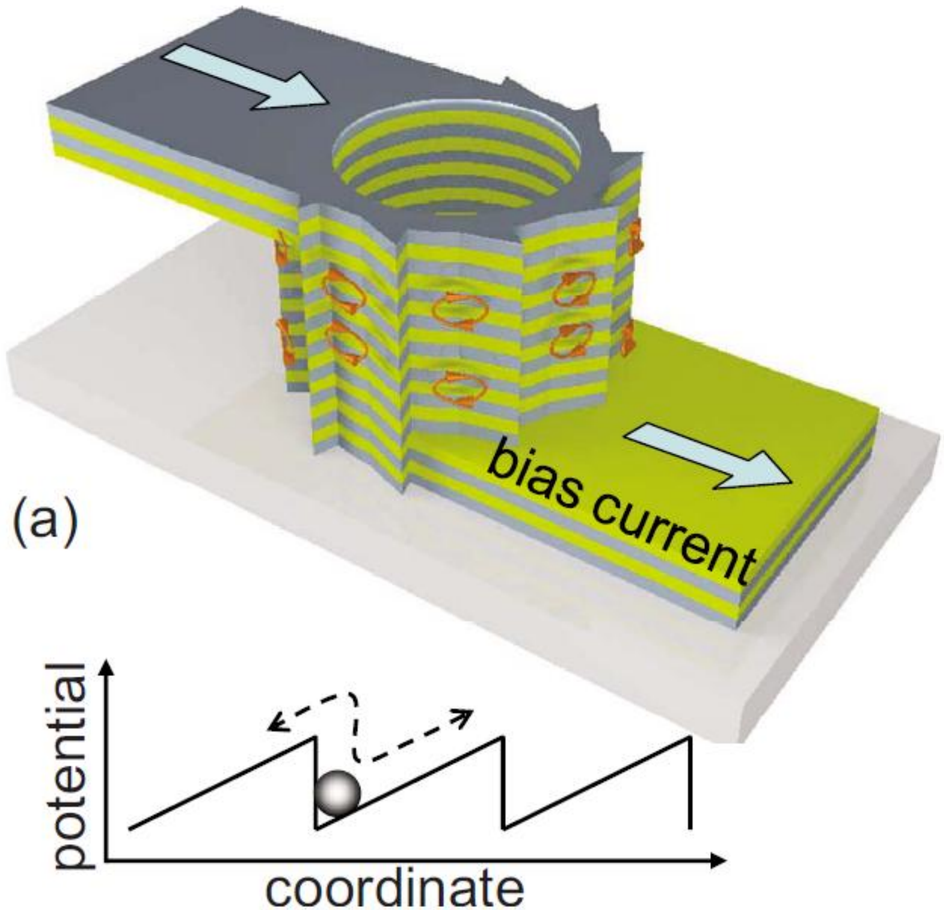


JVR made of Intrinsic JJ stack

- To increase both $f_{\max}$ and $V_{\max}$ we need to increase $v_{\max}$
- To increase $V_{\max}$ one can connect several ratchets in series
- Idea: use **intrinsic Josephson junctions** (IJJ)
- $f_{\rm pl} \sim 150\,\mathrm{GHz}$
- However, IJJ are not independent (coupled).

$$c_q = \frac{c_s}{\sqrt{1 - 2s\cos(\pi q/(N-1))}}, \quad q = 1 \ldots N.$$

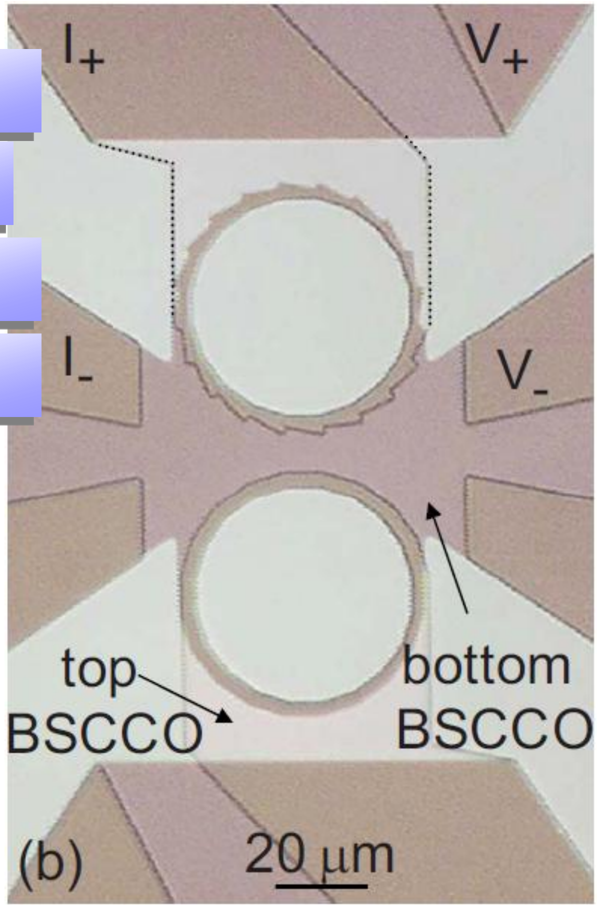
In-phase mode: $c_1 \to c_0/\sqrt{\epsilon} \gg c_s$.



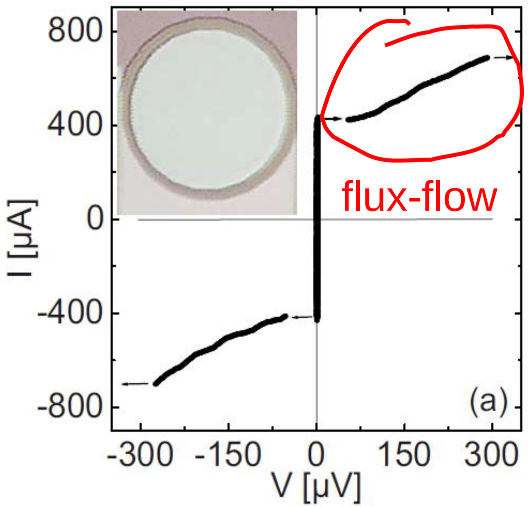
Samples, I-V characteristic

Top view

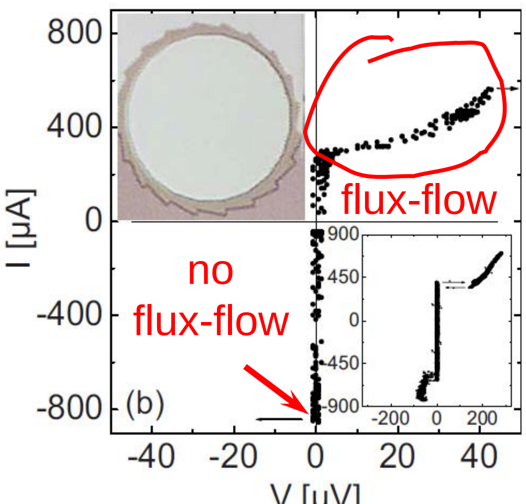
- N = 30 JJs
- n = 20 teeth
- L = 157 μm
- λ_J = 0.4 μm



$$V_{\max}^{\mathrm{FF}} = \bar{m}\Phi_0 v_{\max}/L$$



- T = 4.2 K
- V_{max} = 300 μV
- mv_{max} = 2.3×10^7 m/s
- m_{max} = 100 fluxons

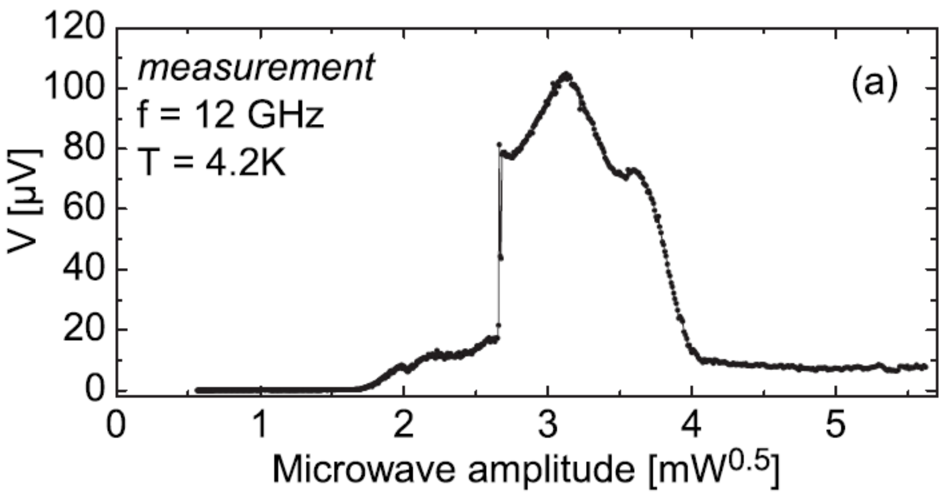


- T = 8.0 K
- V_{max} = 40 μV
- mv_{max} = 1.5×10^7 m/s
- m_{max} = 15

📖 H. B. Wang et al., PRB **80**, 224507 (2009)

Rectification

Experiment



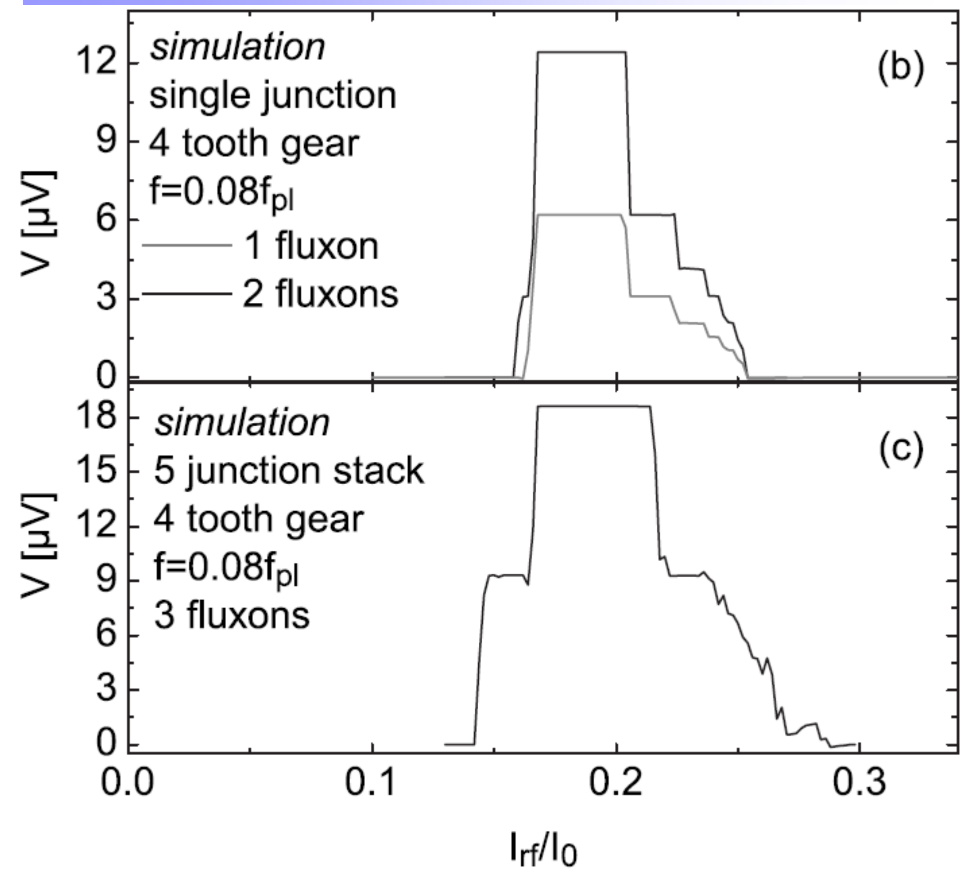
$\langle V \rangle_{max}$= 100 μV (record!)

m ~ 40 fluxons

random fluxon lattice

Why no (Shapiro) steps?

Simulation

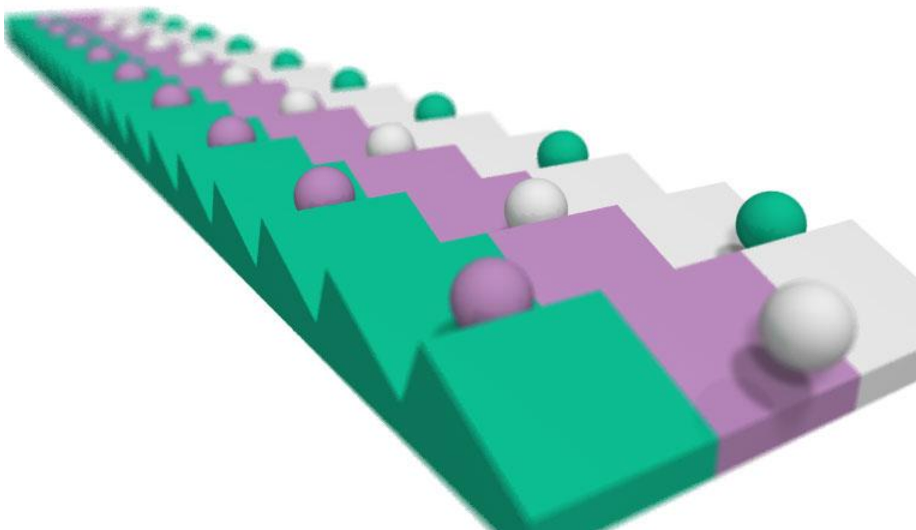


For large m and N the steps are smeared!

📖 H. B. Wang et al., PRB **80**, 224507 (2009)

Summary & Outlook

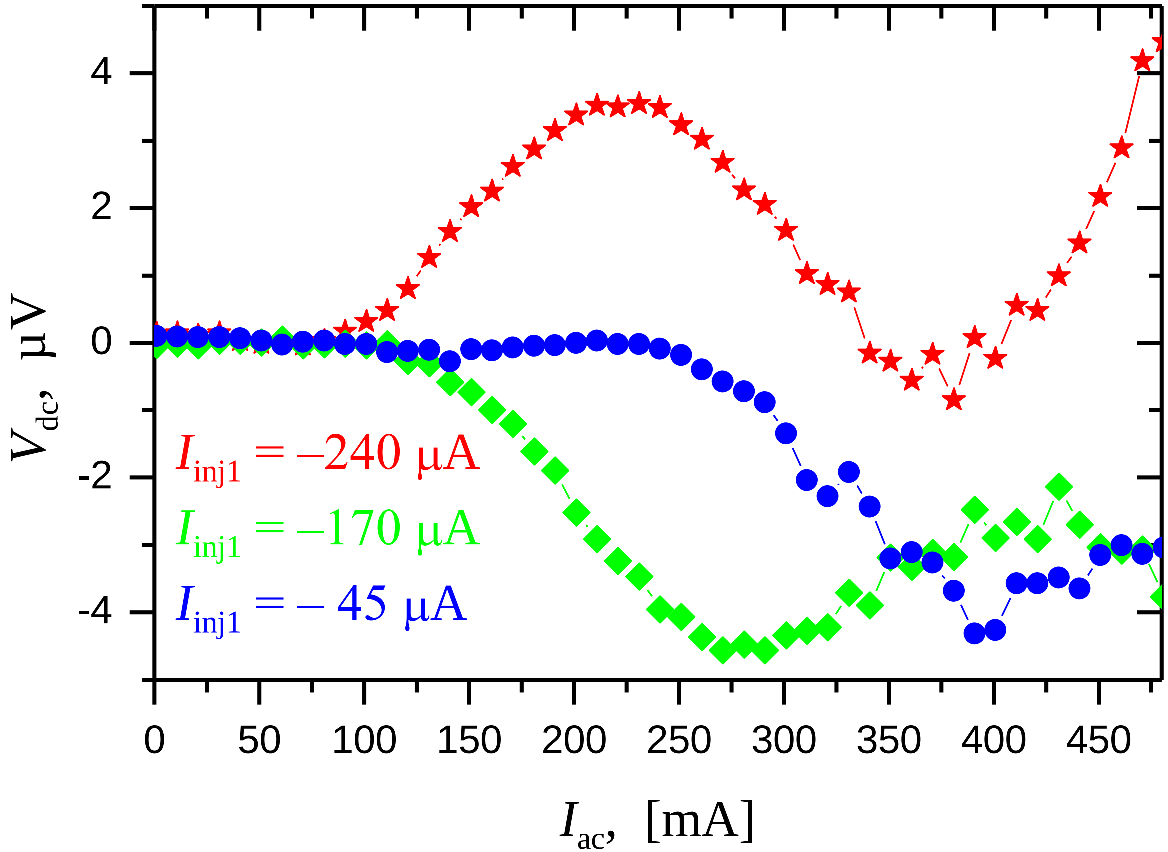
- Fluxon (Josephson Vortex) ratchet
  - principles of operation (asymmetric periodic potential, particle=fluxon)
  - advantages
- Quasi-static (adiabatic) drive:
  - rectification curves vs. potential height, driver shape
  - figures of merit
  - stopping force
- Non-adiabatic drive:
  - quantized rectification
  - period 2 dynamics:
    - subharmonic steps,
    - pseudo-integer steps
  - current (voltage) reversal
  - loaded ratchet, stopping force
- Intrinsic Josephson vortex ratchet



Thanks for your attention!

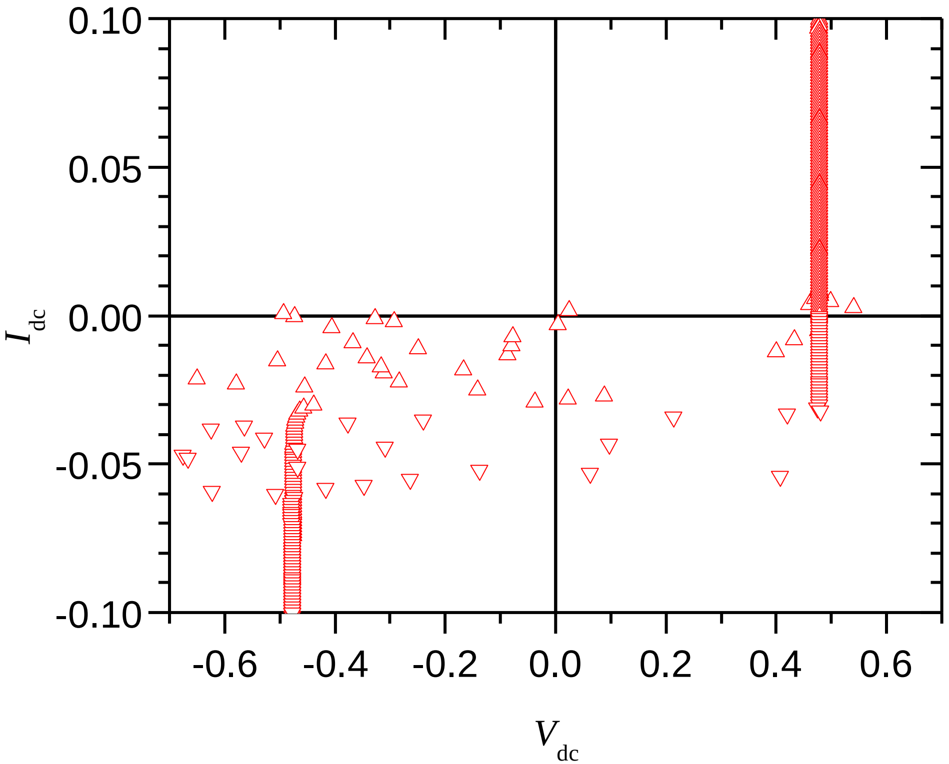
Questions?

Can I rectify a white noise?

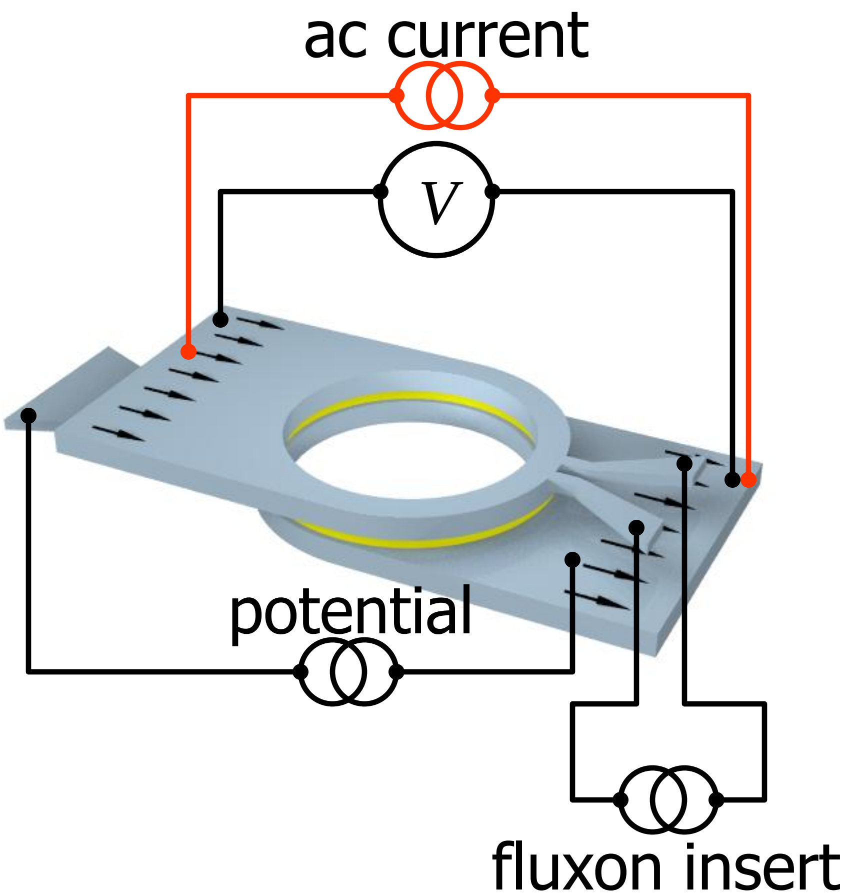


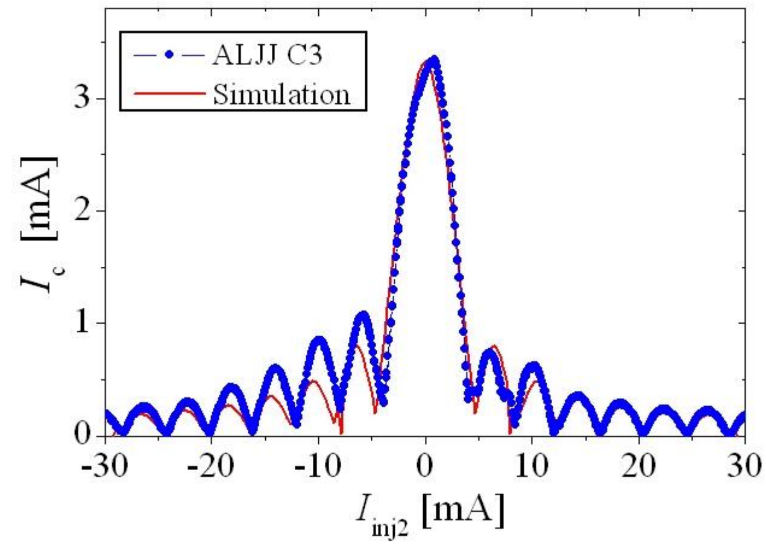
“white” noise cut off at 50MHz

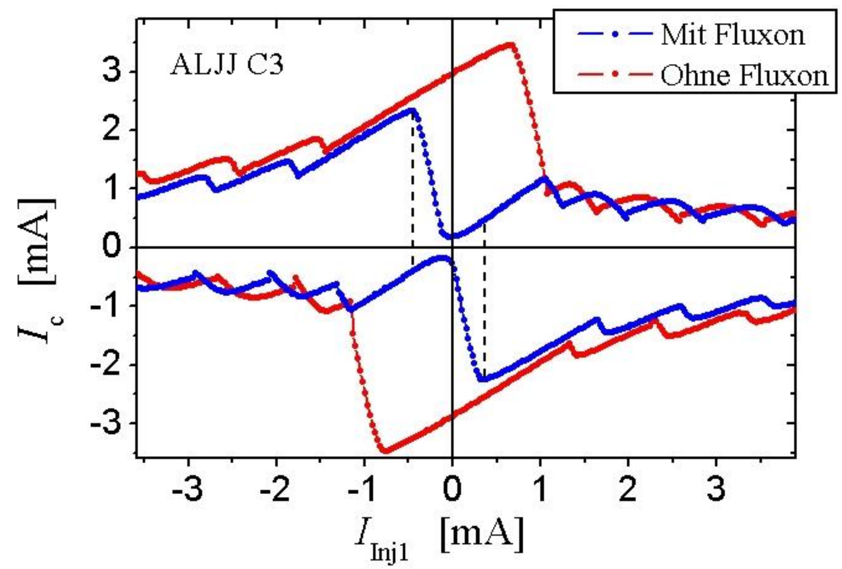
Ratchet or just synchronization?



How do we measure?



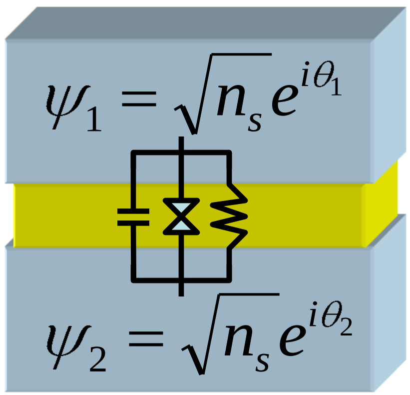


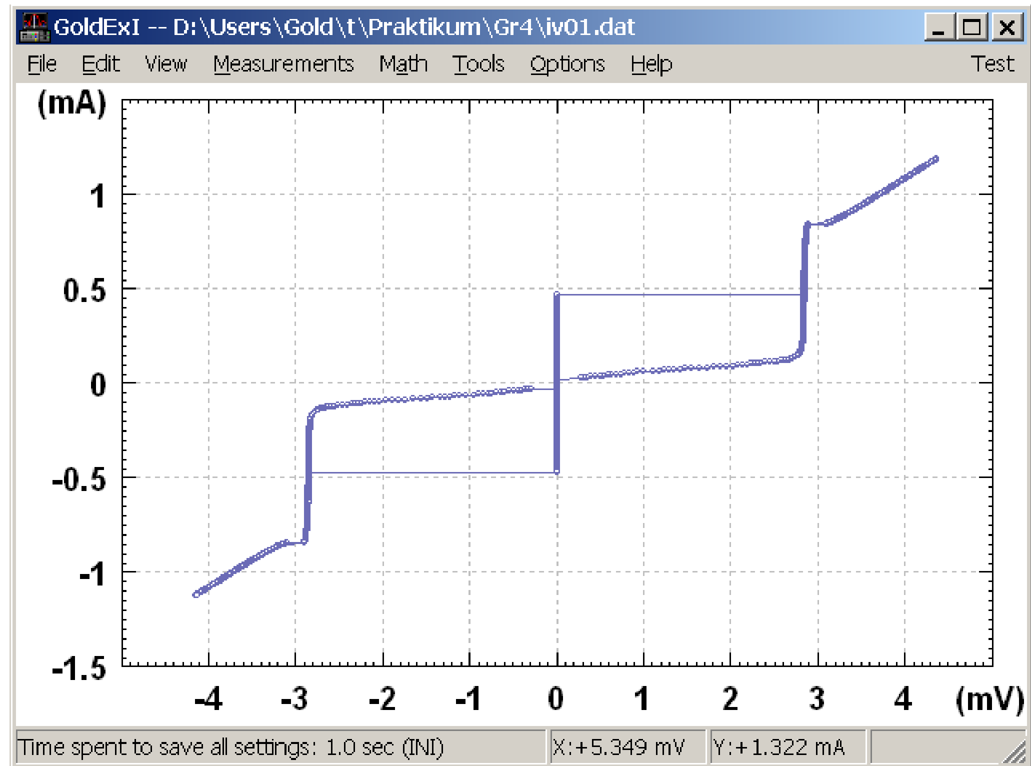


$$\text{Apply}: I(t) = I_{ac} \cdot \cos(\omega t)$$

$$\text{Measure}: V_{dc}(I_{ac}) = \langle V \rangle (I_{ac})$$

Josephson junction



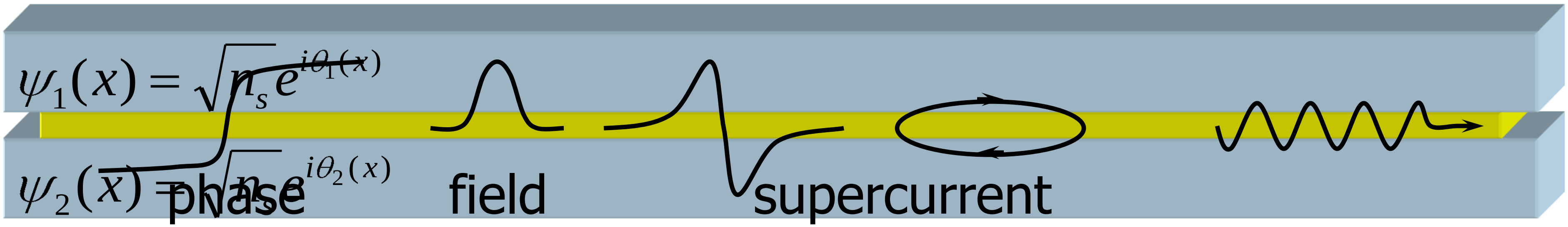


$$I_s = I_c \sin(\theta_2 - \theta_1) = I_c \sin(\phi)$$

$$I_c \propto \text{overlap of } \psi$$

📖 B. D. Josephson, Phys. Lett. **1**, 251 (1962).

Long Josephson junctions

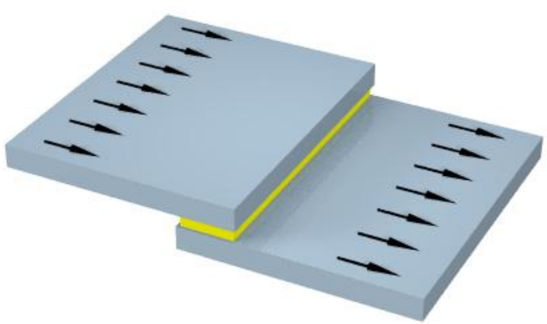


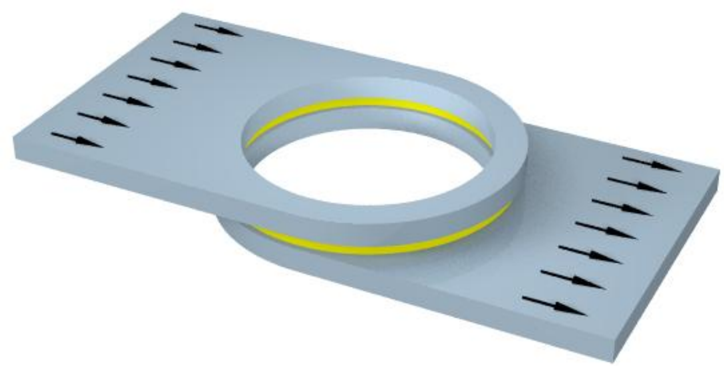
1D model: $\phi_{xx} - \phi_{tt} - \sin(\phi) = \alpha\phi_t - \gamma(x)$

$\lambda_J \sim 1 \ldots 30\,\mu\text{m}$

$\omega_p \sim 50 \ldots 4000\,\text{GHz}$

$\lambda_J \cdot \omega_p \equiv \bar{c}_0 \approx \dfrac{c_{\text{light}}}{20 \ldots 40}$

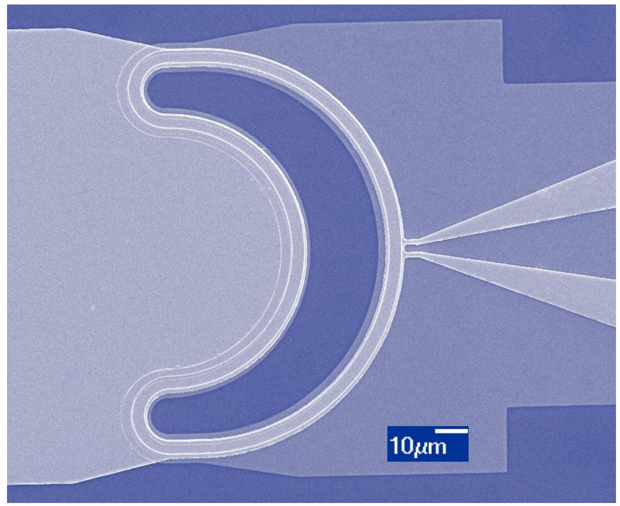


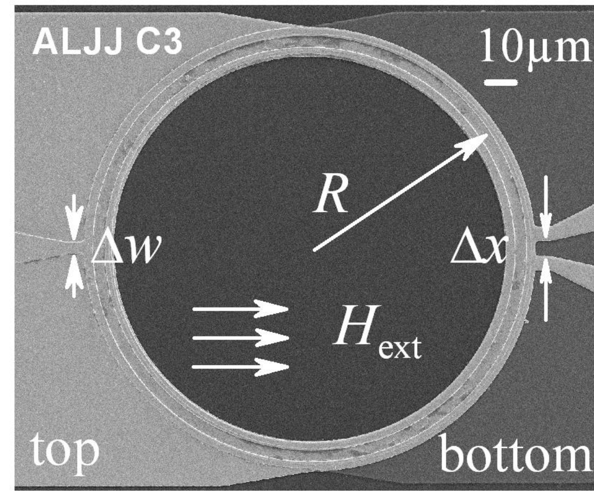


Content

- Introduction
  - What is (long) Josephson junction?
  - What is a ratchet?
  - Why to build ratchets using long Josephson junctions?
- How to create an efficient asymmetric periodic potential?
- Results (experiment and simulations)
  - Everything under control: 1 injector, 2 injectors..(calibration)
  - Quasi-statically (adiabatically) driven ratchet
  - Non-adiabatic effects
- Conclusions & outlook

Asymmetric potential

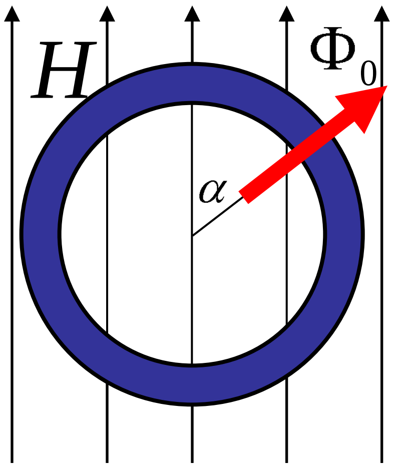




Potential:	*w(x)*	*h(x)*	*j(x)*
tunability?	no	yes	yes
topological. limits?	no	yes	no
current/field source?	no	yes	yes

📖 E. Goldobin, et al. PRE **63**, 031111 (2001)

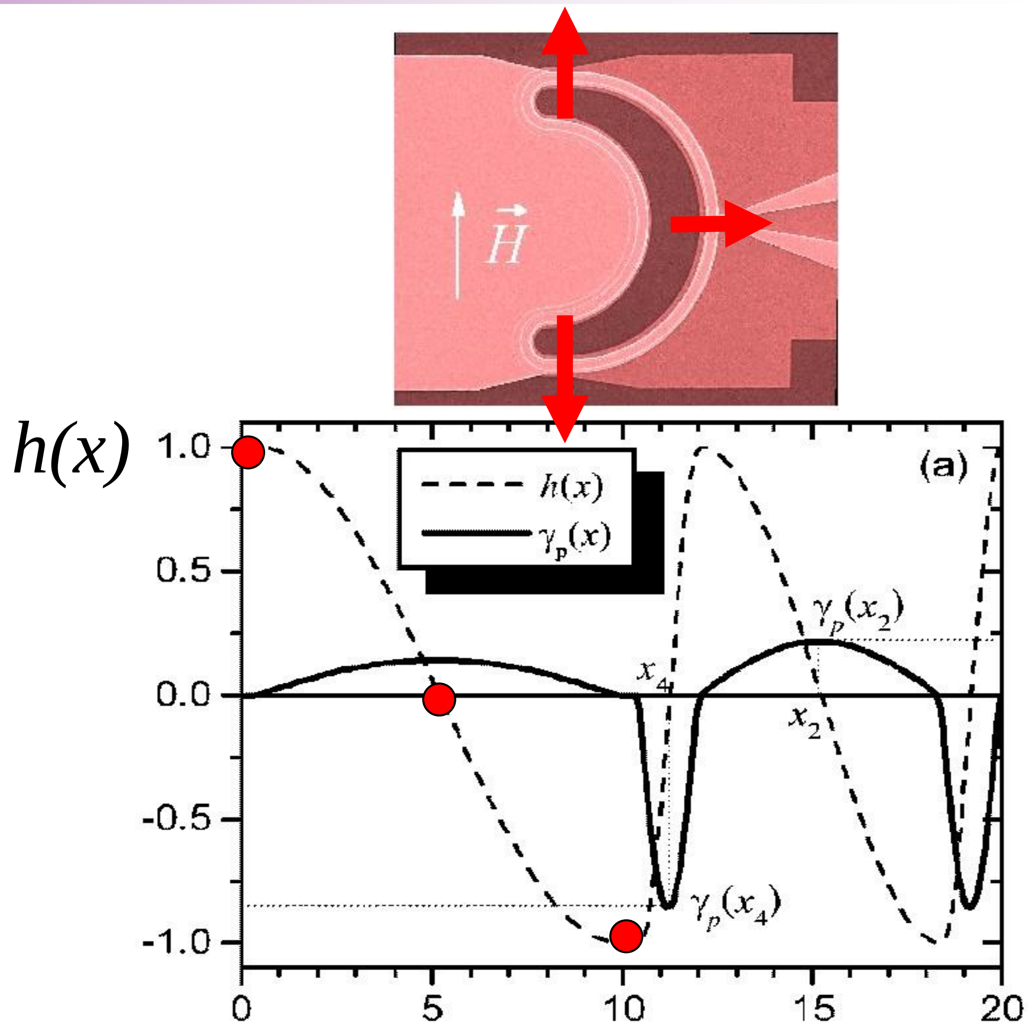
Asymmetry due to non-uniform field



$$H(x) = H \cdot \cos\alpha$$

$$U(x_0) = -2\pi w h(x_0)$$

- Tunable potential
- Topological limitations



📖 E. Goldobin, et al. PRE **63**, 031111 (2001)

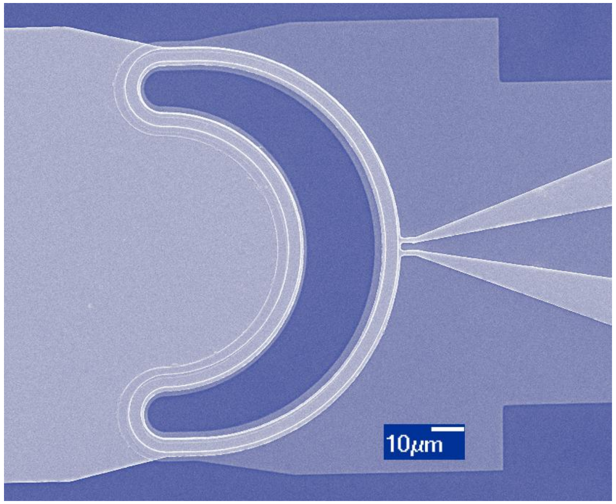
Asymmetric potential

$$\phi_{xx} - \phi_{tt} - \sin(\phi) = \alpha\phi_t - \gamma(x) + h_x(x) - \frac{w_x(x)}{w(x)}\left[\phi_x - h(x)\right]$$

$$H = \int_0^L w(x)\left[\frac{\phi_t^2}{2} + \frac{(\phi_x - h)^2}{2} + (1+\cos\phi)\right]dx$$

$$U(x_0) = \int_{-\infty}^{+\infty} \frac{4w(x)}{\cosh^2(x-x_0)} - \frac{2w(x)h(x)}{\cosh(x-x_0)}\,dx$$

$U(x_0) \approx 8w(x_0)$



$U(x_0) = -2\pi w h(x_0)$