Commensurability-dependent transport of a Wigner crystal in a nanoconstriction

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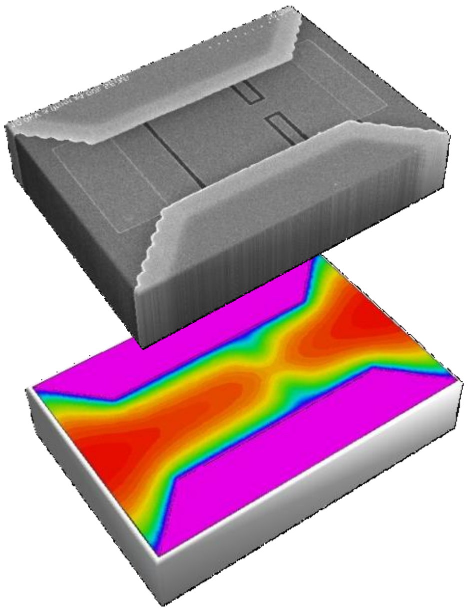
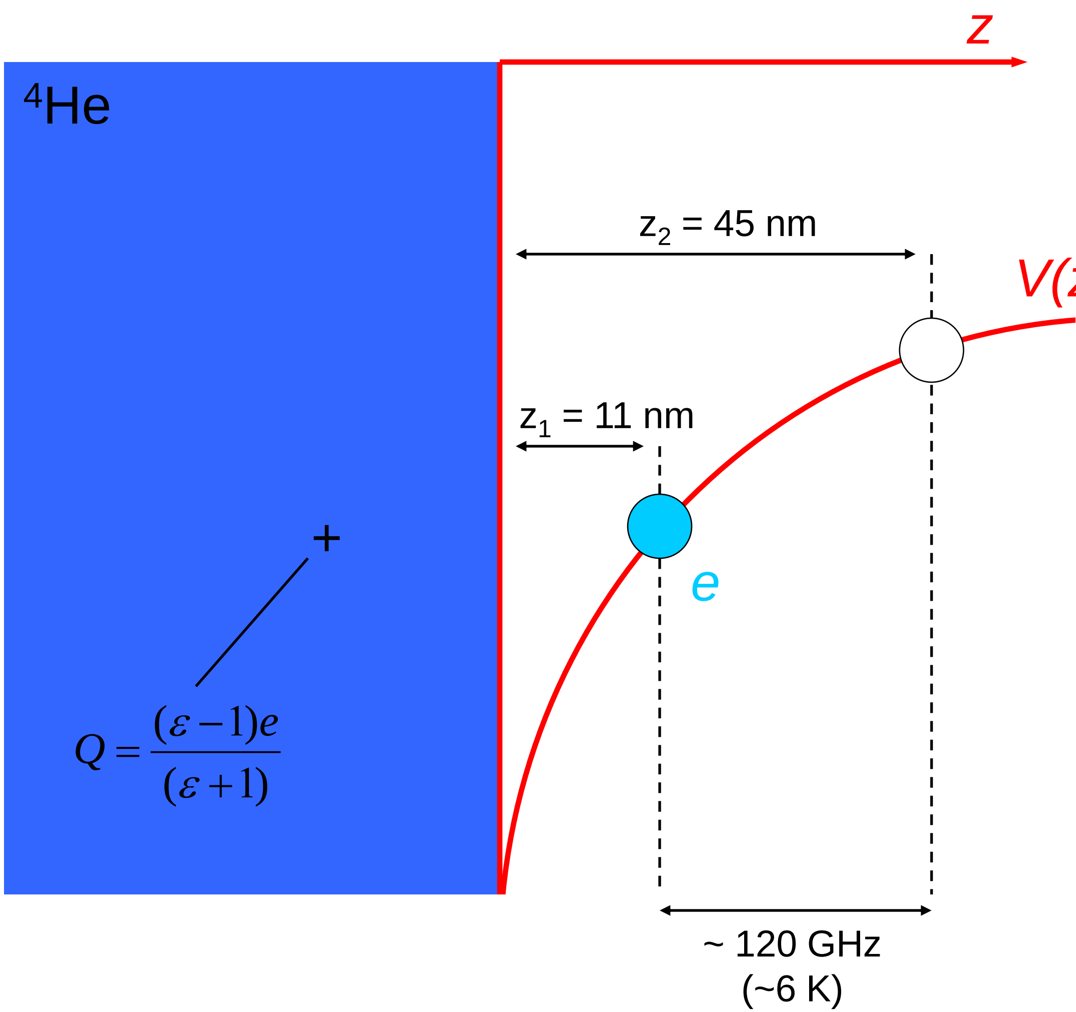
Outline

- Introduction - Electrons on helium
- Microchannel samples for mesoscopic experiments
- Point-contact transport properties of classical electron liquids
- Point-contact transport properties of Wigner crystals
- Conclusions



Electrons on Helium



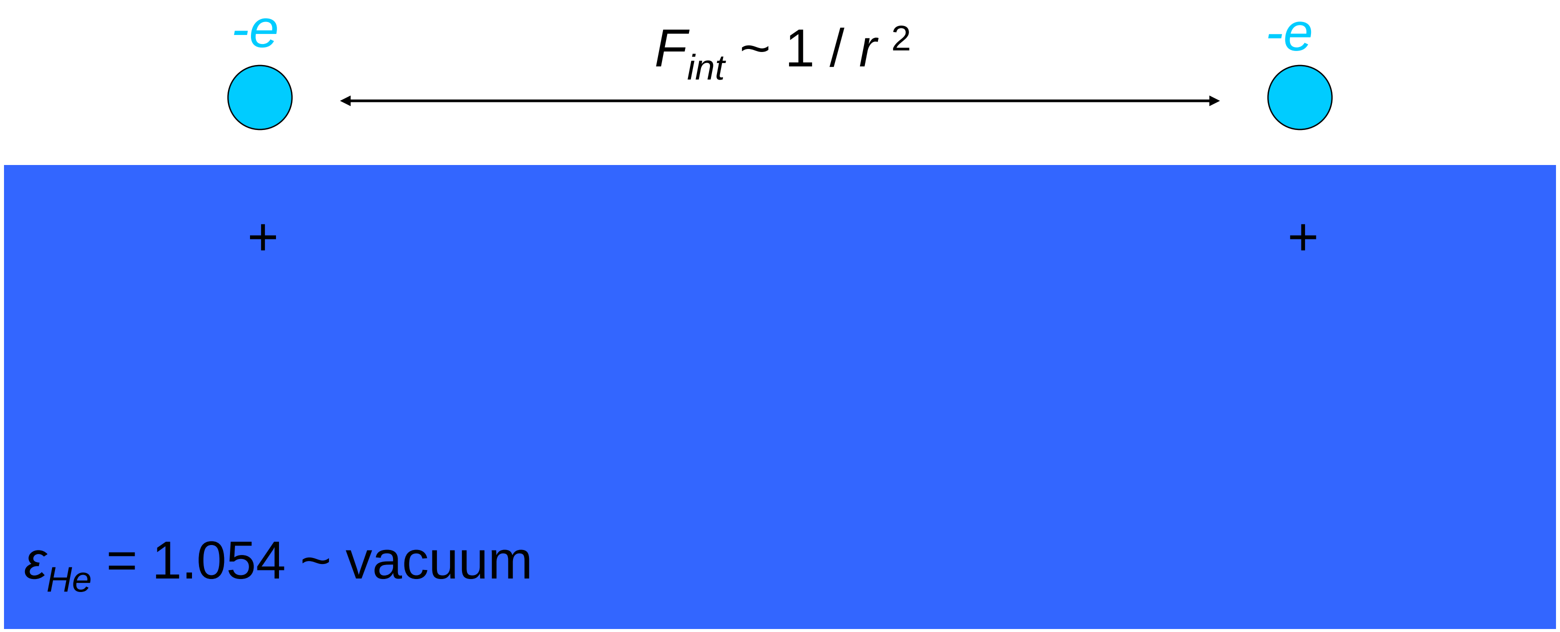
Electrons are attracted to a liquid He surface by an image charge…

…but prevented from entering the liquid by a ~ 1eV potential barrier (Pauli).

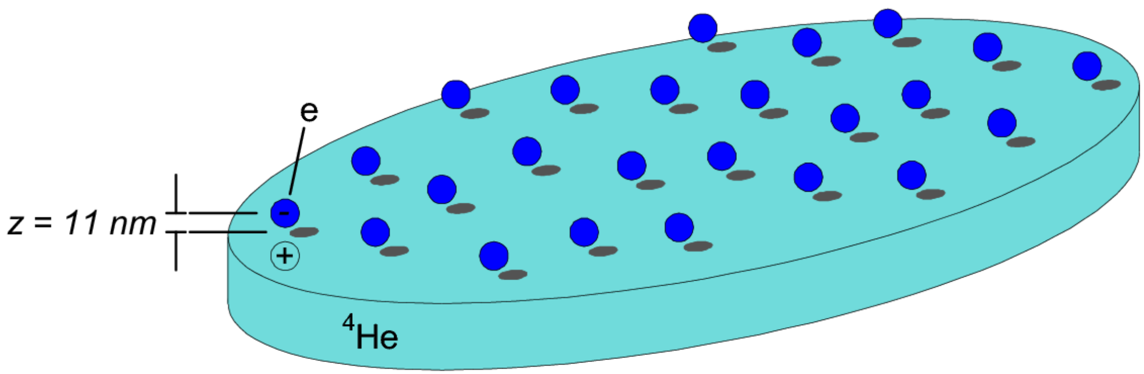
Result: a ‘1D Hydrogen atom’ with Rydberg series of states.

Y. P. Monarkha and K. Kono (Springer-Verlag, Berlin, 2004)

The Coulomb interaction between electrons is essentially unscreened:



We can (almost) consider electrons floating in free space…



'Low' surface density: $n_s \sim 10^6 - 10^9$ cm^{-2}

Liquid helium is a perfectly clean substrate: $\mu \sim 10^8$ cm^2/V•s at 10 mK

→ A nondegenerate, high mobility, 'classical' 2D electron liquid (or solid)

Electrons on helium vs. 2DEG in GaAs

	GaAs-2DEG	**electrons on helium**
n_s	$10^{10} – 10^{12}$ cm^{-2}	$10^{6} – 10^{9}$ cm^{-2}
Mass	$m_e^* \sim 0.067 m_e$	m_e
E_F	~ 10 K	~ 1 mK
Velocity	$\hbar k_F / m_e^* \sim 10^7$ cm/s	$(2k_B T / m_e)^{½} \sim 10^5$ cm/s
Mobility	~ 10^6 cm^2/Vs	~ 10^8 cm^2/Vs
Mean free path	~ 10 µm	~ 1 µm (at 1 K)
System characteristics	Fermi degenerate electron gas	Nondegenerate Coulomb liquid / crystal

New physics?

Classical many-body physics in strongly-correlated systems:

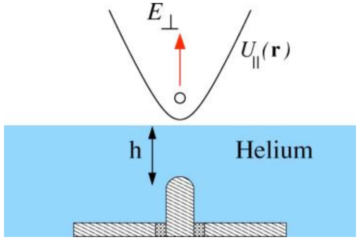
- Wigner crystallisation
- 2D melting in confined geometry
- Transport of interacting particles: Jamming, pinning etc…

What can we do with electrons on helium?

Quantum electron dynamics in a low-decoherence environment:

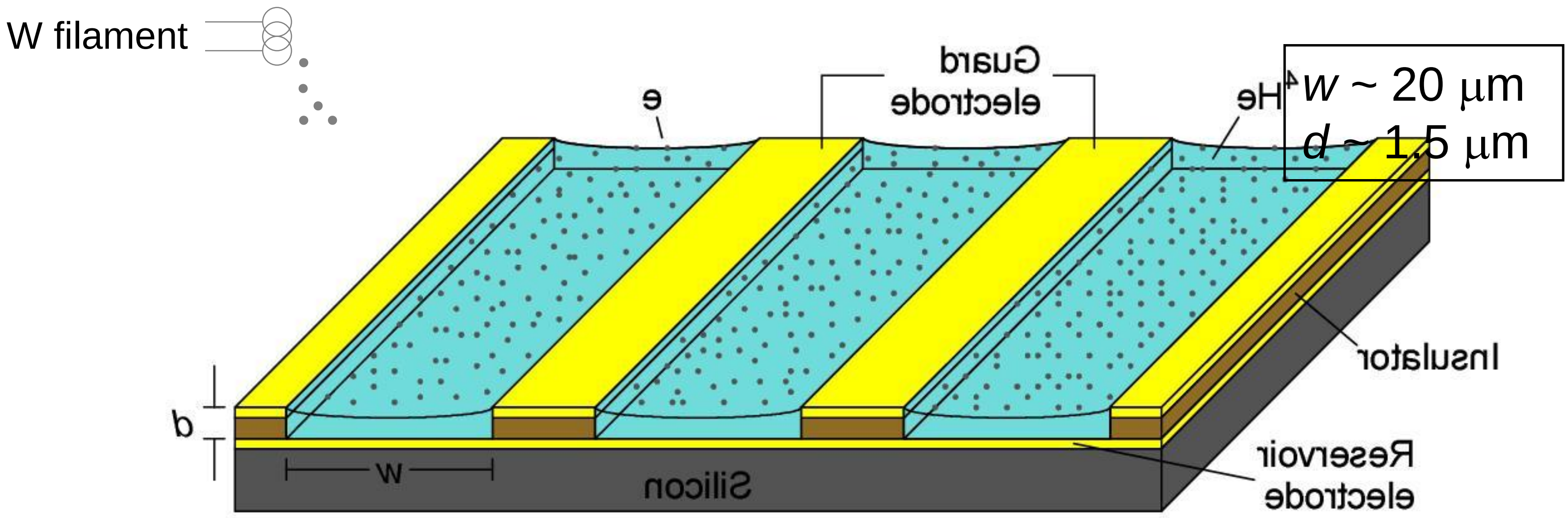
- Quantum transport (D. Konstantinov *et al*., Phys. Rev. Lett., **105** (2010))
- Qubits* with long coherence times?

*Rydberg states: P.M. Platzman and M.I. Dykman., Science **284** (1999)
*Spin states: S.A. Lyon, Phys. Rev. A **74** (2006)
*Orbital states: D. Schuster *et al*., Phys. Rev. Lett. **105** (2010)



Helium microchannels

Mesoscopics? Use microchannels filled by capillary action of superfluid ^{4}He:

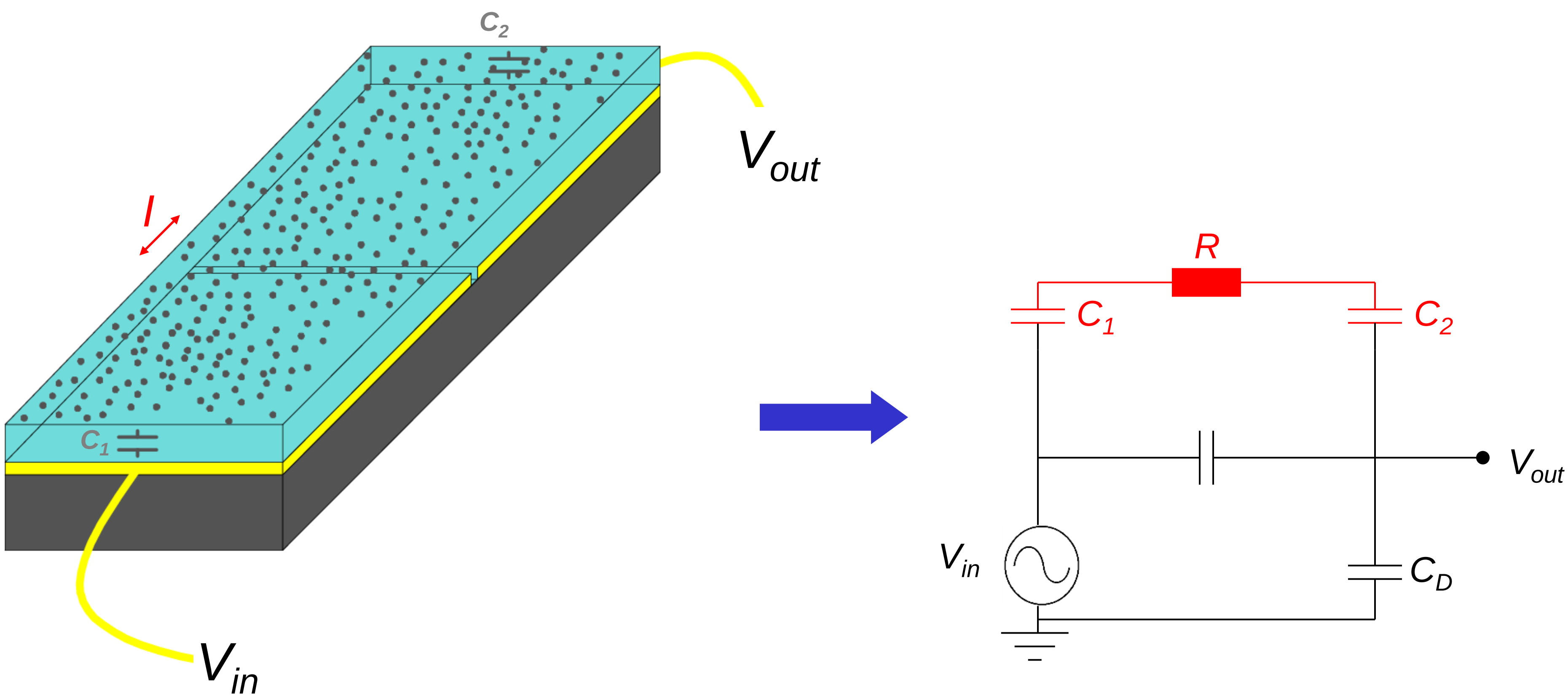


D. G. Rees *et al*., J. Low Temp. Phys. (2011)

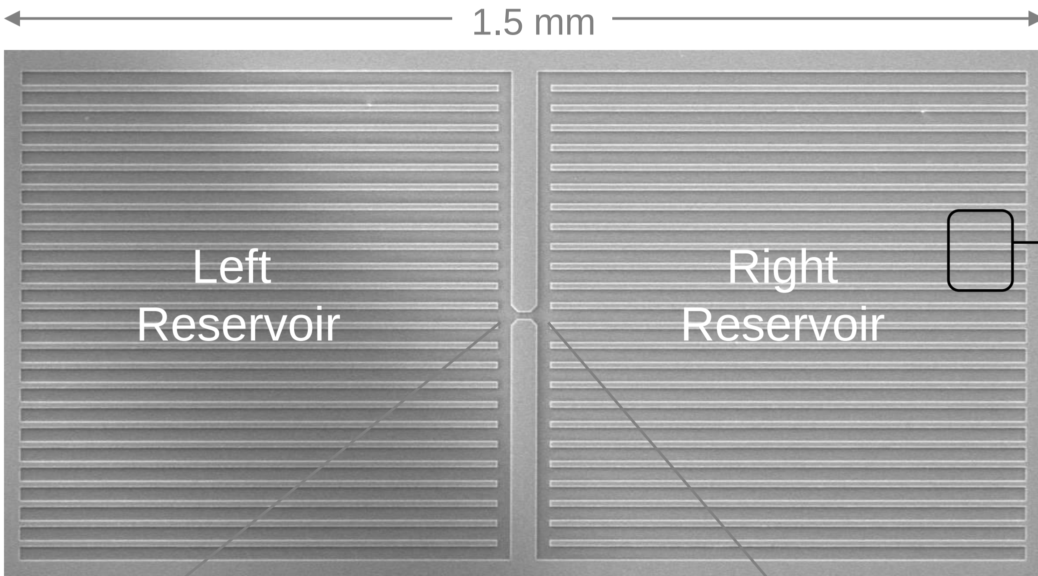
Fabrication techniques:
- UV / e-beam lithography (2 or 3 layers)
- Thermal / e-beam evaporation of metals
- Etching of hard-baked photoresist to create insulating layer

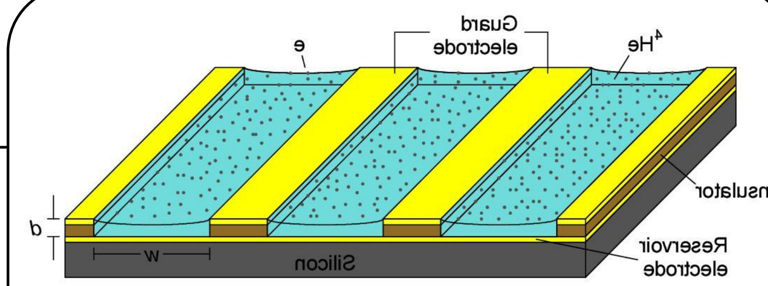
Transport measurements

We can measure the transport properties of the electron system using a lumped-circuit model:

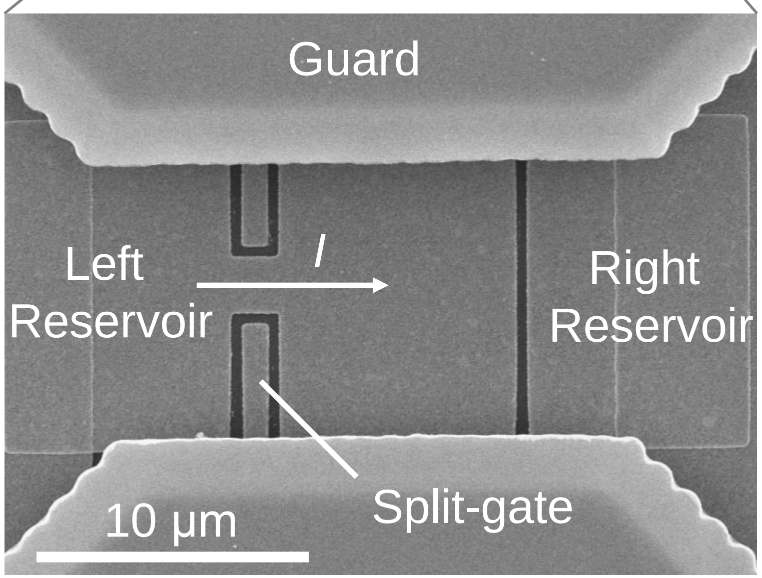


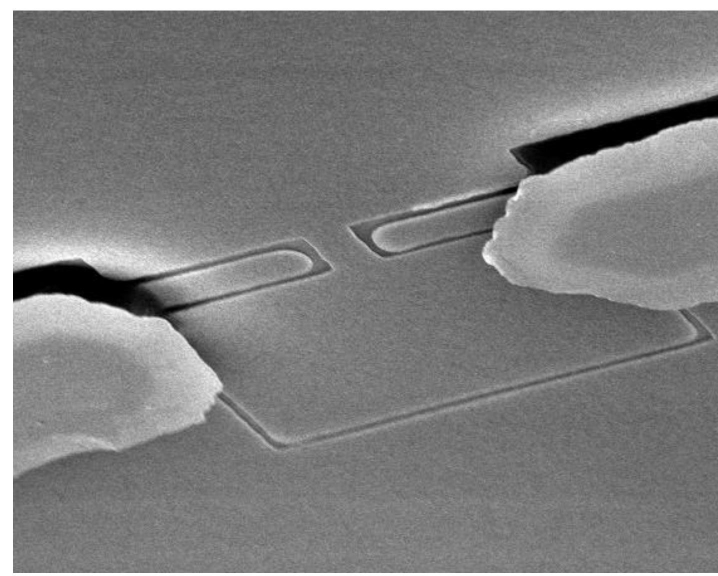
Split-gate device for e on He





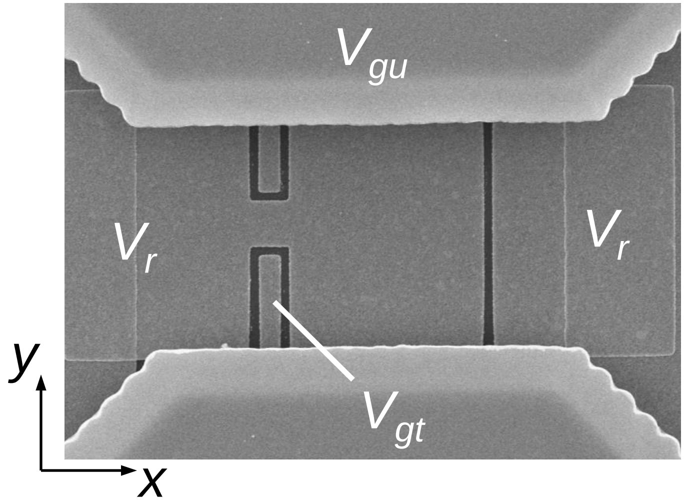
w = 20 μm, d = 1.5 μm



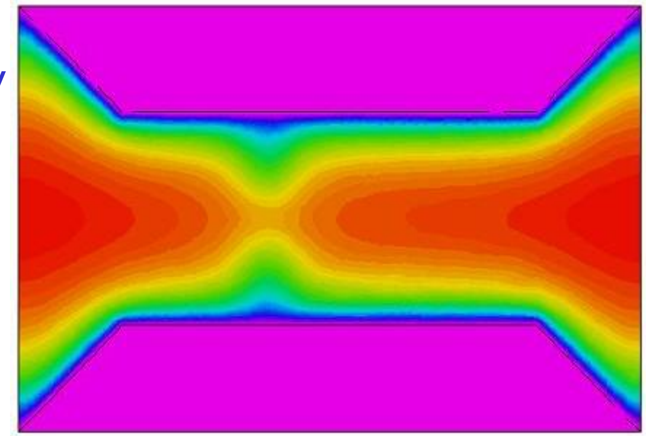


Split-gate device – potential profile

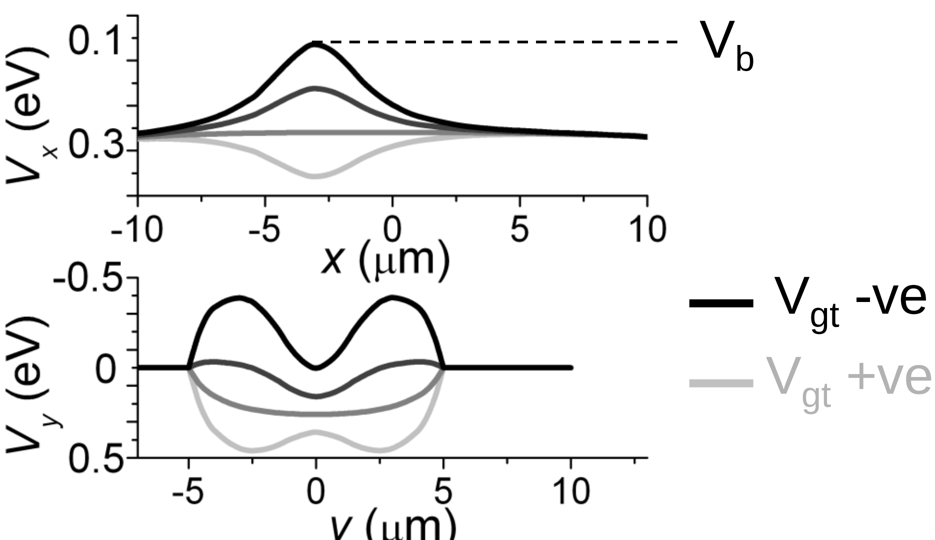
Finite-element modelling shows that a *saddle-point potential* is created at the constriction:



V_{gu} = 0 V
V_{gt} = +0.5 V
V_r = +1 V:



At negative gate voltage we may form a potential barrier between reservoirs:



From the model we find:

$V_b = \alpha V_r + \beta V_{gt} + \gamma V_{gu}$

$\alpha = 0.75,\ \beta = 0.10,\ \gamma = 0.15$

T_{Well} ~ 20 GHz ~ 1 K ~ 0.1 meV

Results - I vs V_{gt}

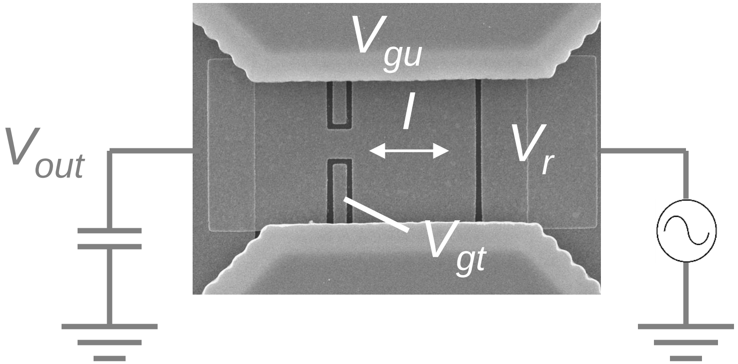
Experimental parameters:

T = 1.2 K

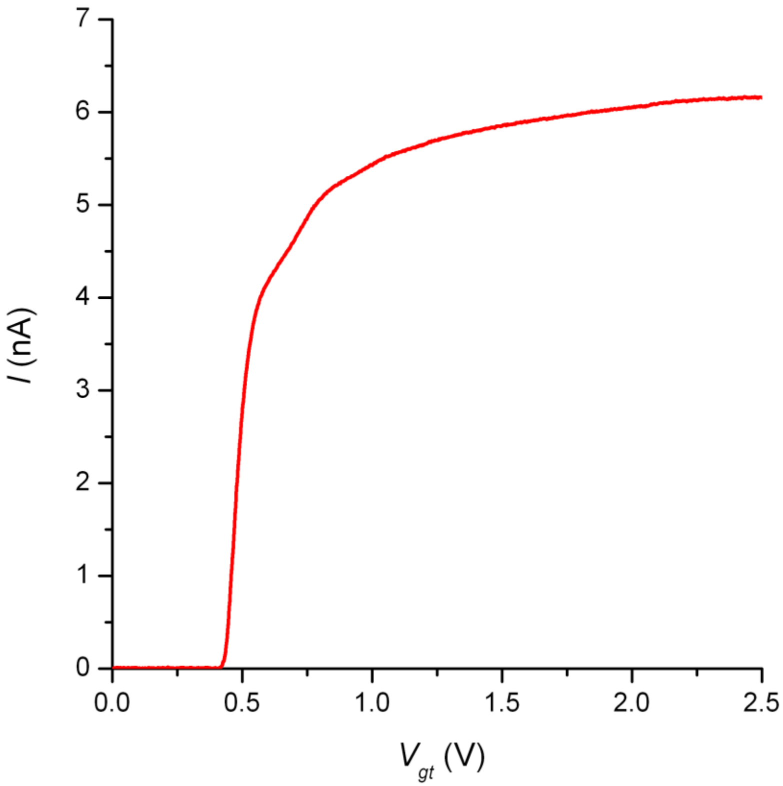
V_r = +1 V, V_{gu} = 0 V

n_s = 2 x 10^9 cm^{-2}

V_{in} ~ 5 mV_{pp}

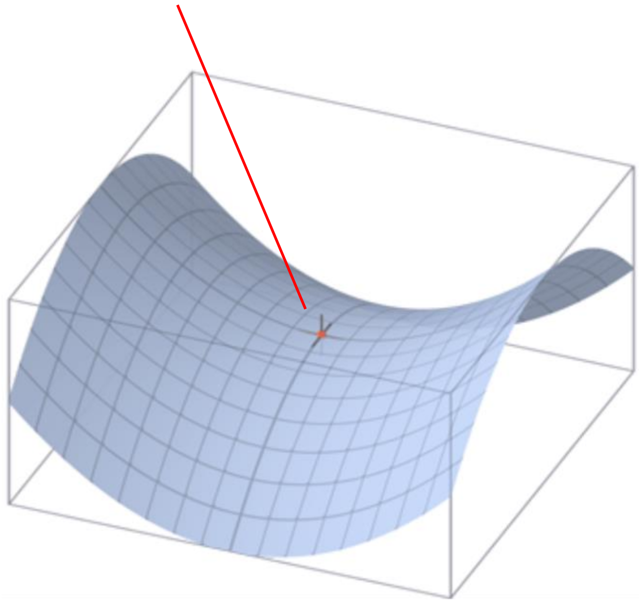


Sweep V_{gt}:



Electrode coupling to barrier

$$V_b = \alpha V_r + \beta V_{gt} + \gamma V_{gu}$$

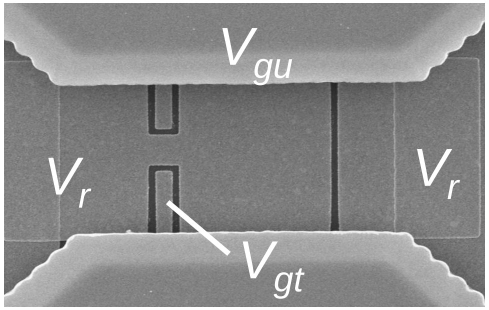


From V_{gt} threshold measurements:

Coupling Constant	Model	Measured
α	0.75	0.77
β	0.10	0.16
γ	0.15	0.07

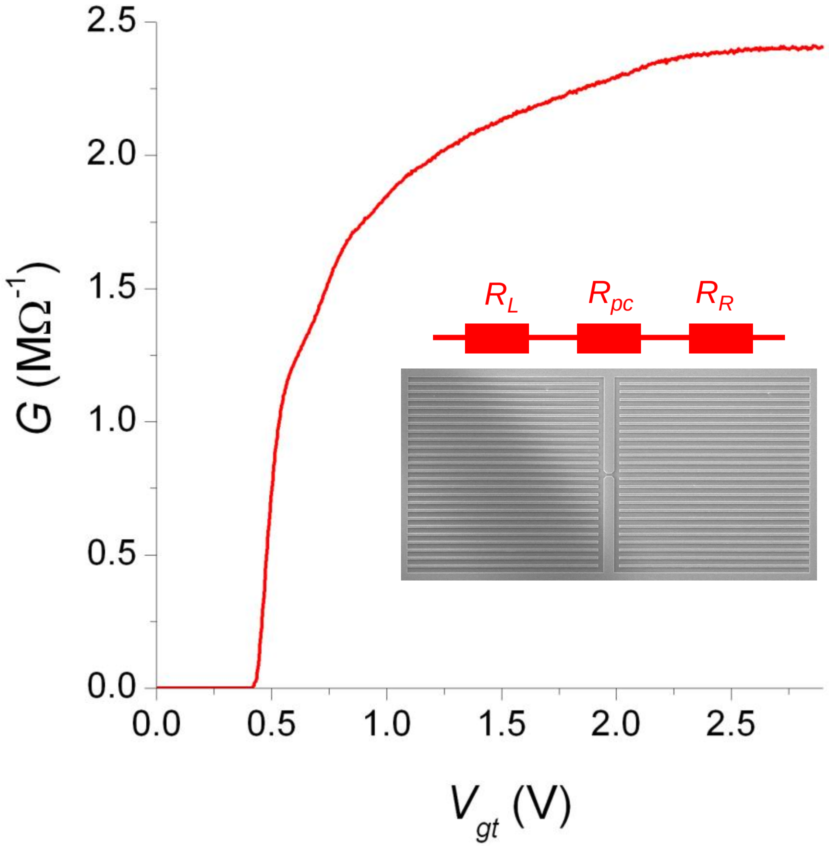
Good agreement…

Electrons are indeed above the reservoir electrode, between the split-gate:

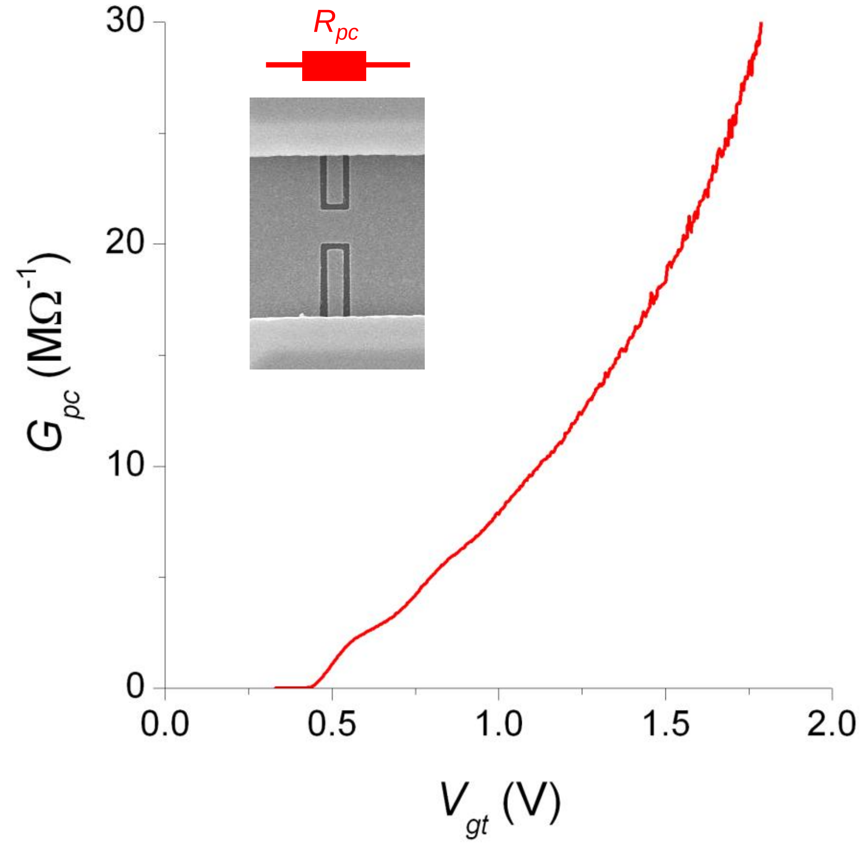


Structure in G vs V_{gt}

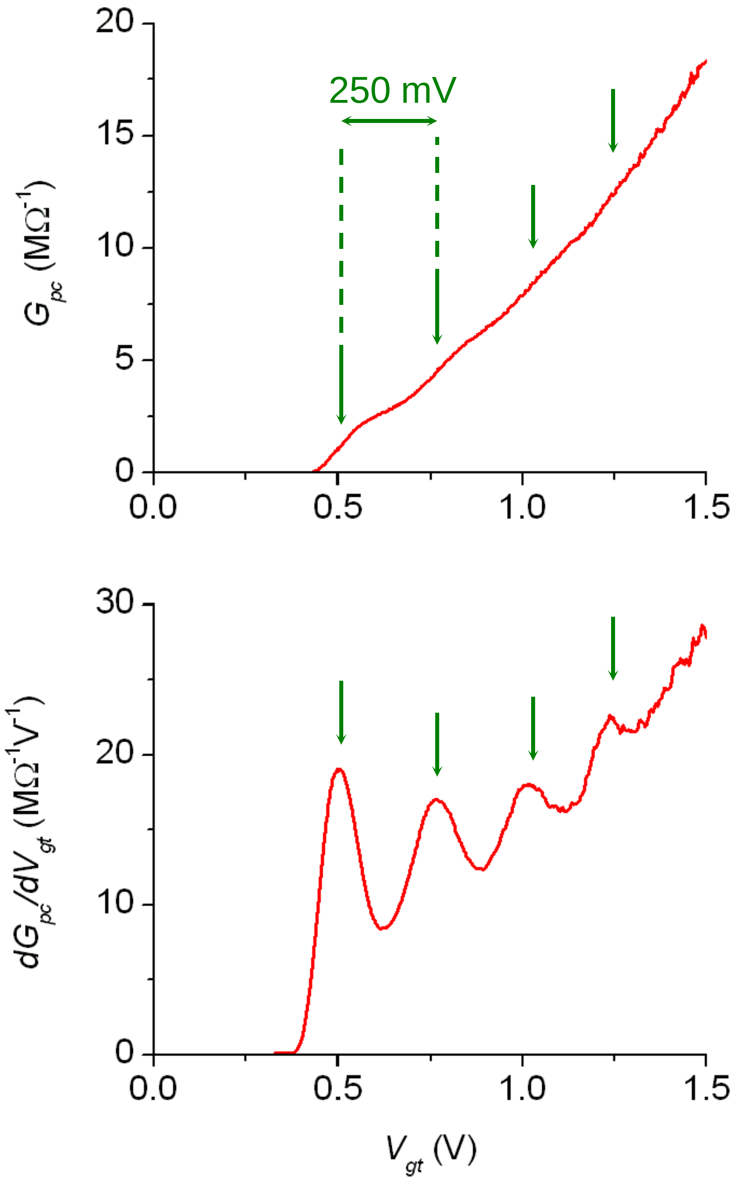
Total conductance:



Point-contact conductance:



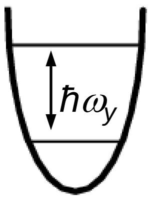
Structure in G vs V_{gt}



Here $k_B T >> E_F$

also: V_{in} ~ 5 mV_{pp}

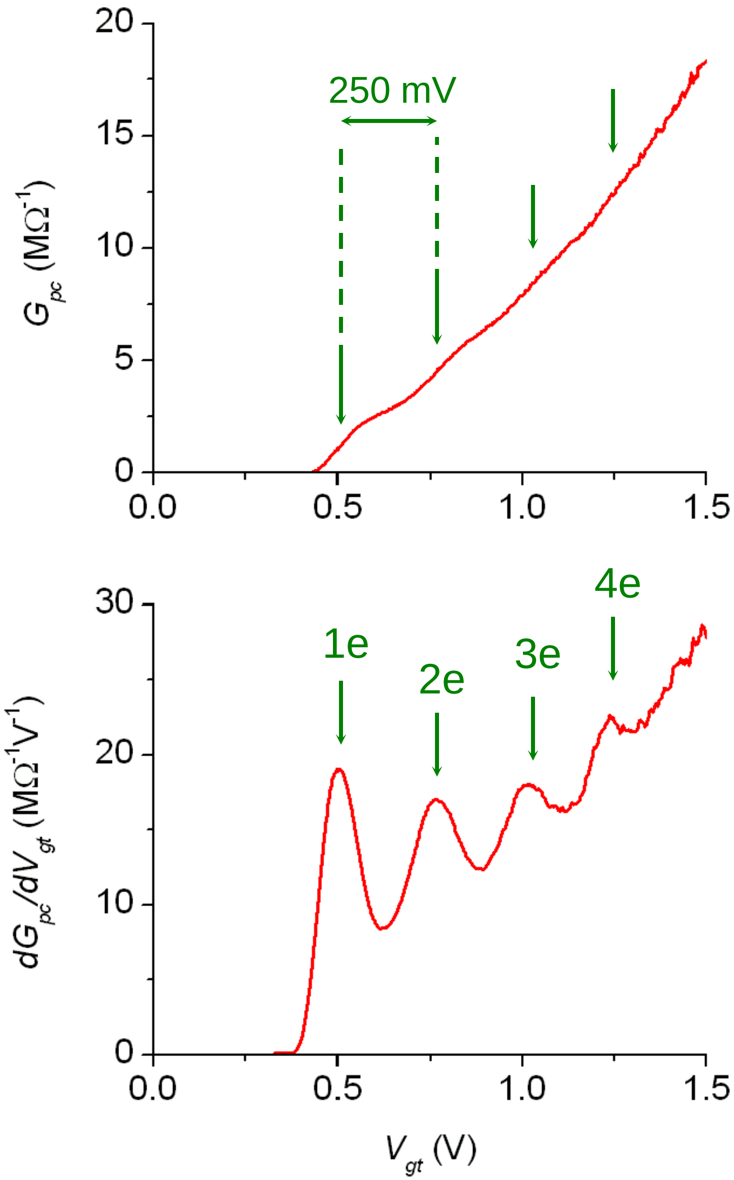
whilst: $\hbar\omega_y$ ~ 0.1 meV



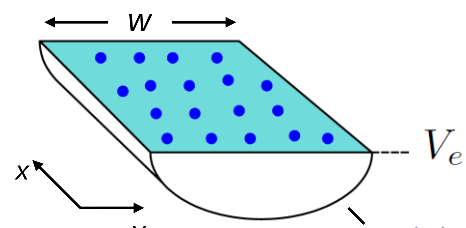
The steps are unlikely to be related to lateral subbands:

This is not a 'quantum' point contact

Structure in G vs V_{gt}



Consider the number of electrons across the constriction:



$$V(y) = V_b - \frac{1}{2}by^2$$

$$N_y = \left(\int_{\frac{-w}{2}}^{\frac{w}{2}} \int_{\frac{-w}{2}}^{\frac{w}{2}} \frac{\varepsilon\varepsilon_0}{ed} (V(y) - V_e)\, \mathrm{d}x\mathrm{d}y \right)^{\frac{1}{2}}$$

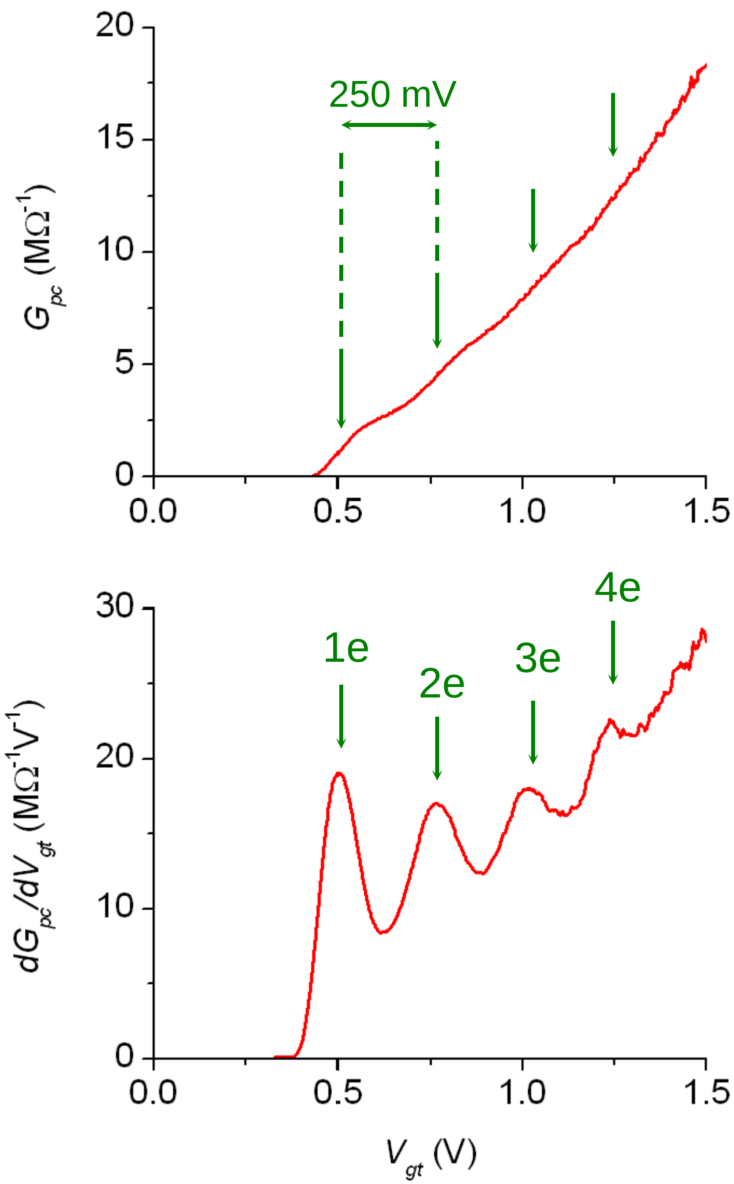
$$= \left(\frac{1}{b} \cdot \frac{16\varepsilon\varepsilon_0}{3ed} \right)^{\frac{1}{2}} \beta(V_{gt} - V_{gt}^{th})$$

ΔV_{gt} required to add 1 electron 'row':

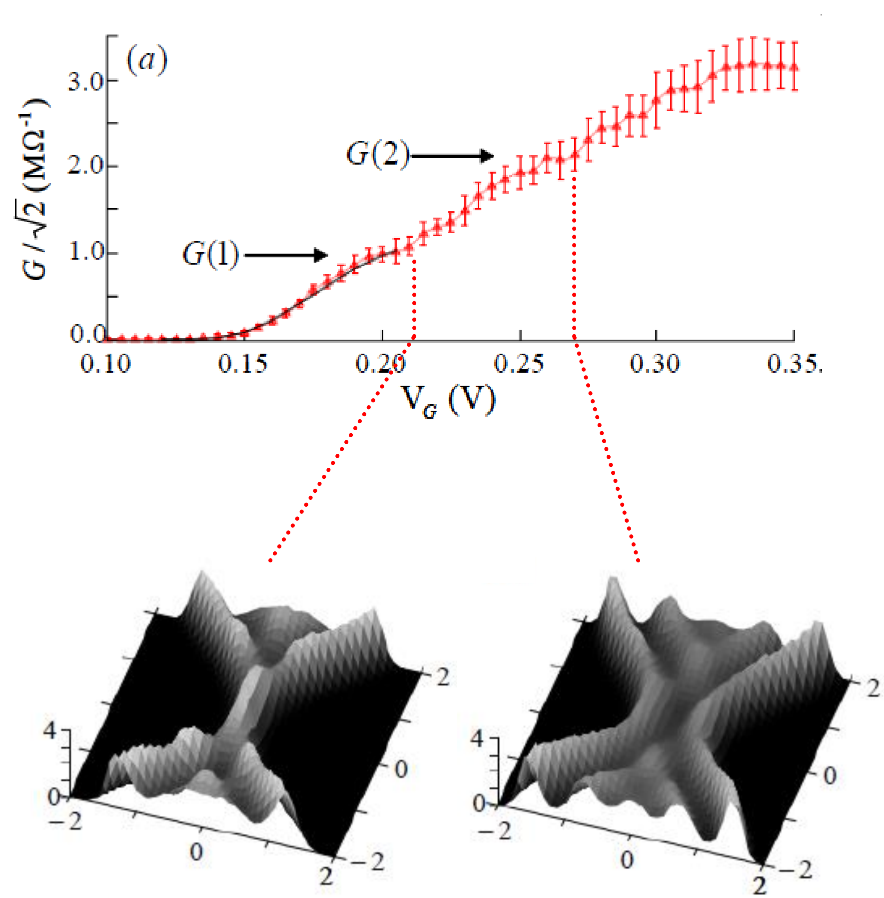
ΔV_{gt} = 225 mV

D.G. Rees *et al.*, Phys. Rev. Lett. **106**, 026803 (2011)

Molecular Dynamics Simulations



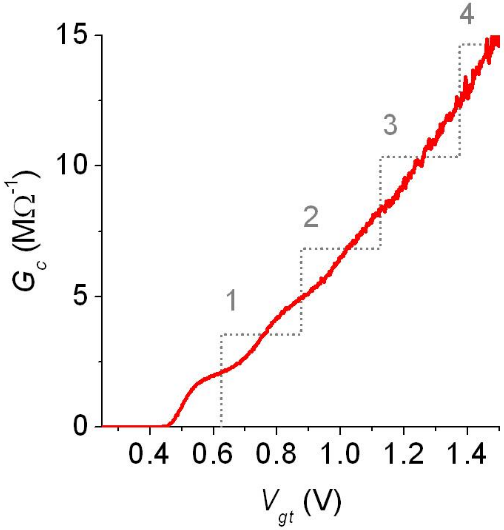
Molecular dynamics simulations by
M. Araki and H. Hayakawa, Kyoto University:



M. Araki and H. Hayakawa, arXiv:1104.4854 (2011)

Role of fluctuations

Why are the steps smoothed?



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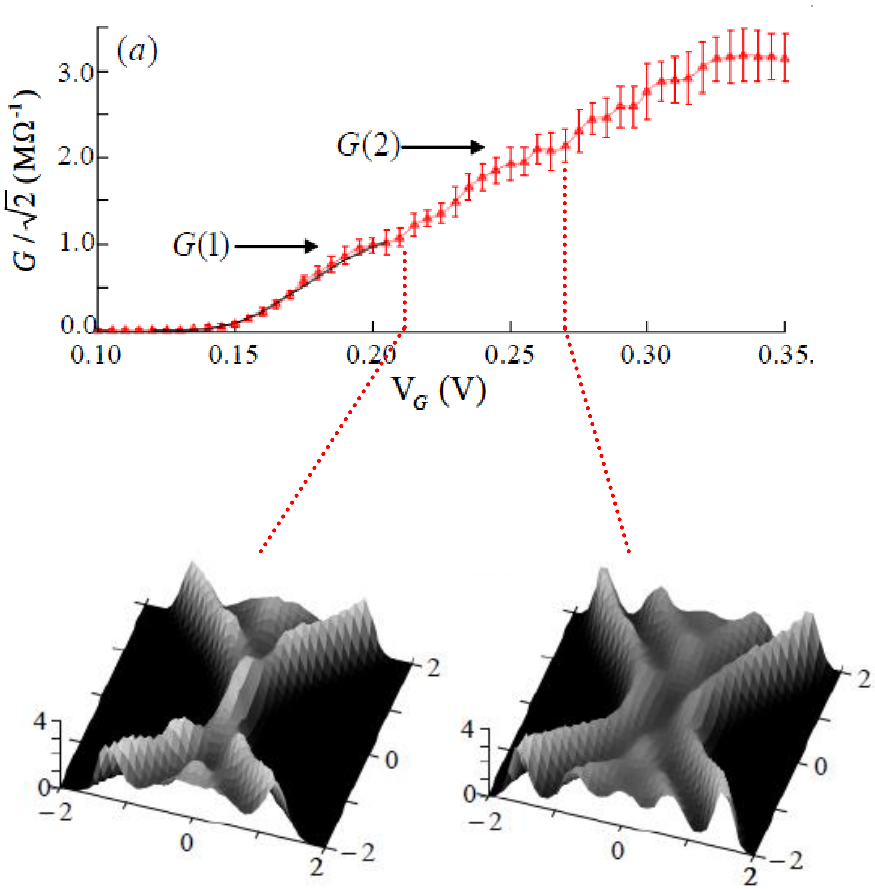


In the strongly-correlated system, electrons 'see' a strongly fluctuating electric field:

$$E_{fl} \sim T^{1/2} n^{3/4} \quad \text{(bulk 2D system)}$$

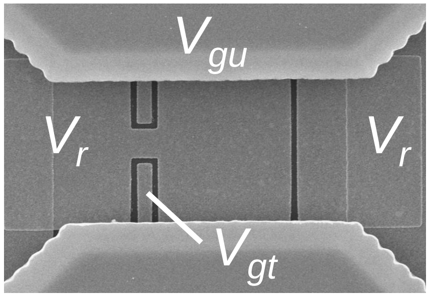
From the simulation, for electrons entering the constriction:

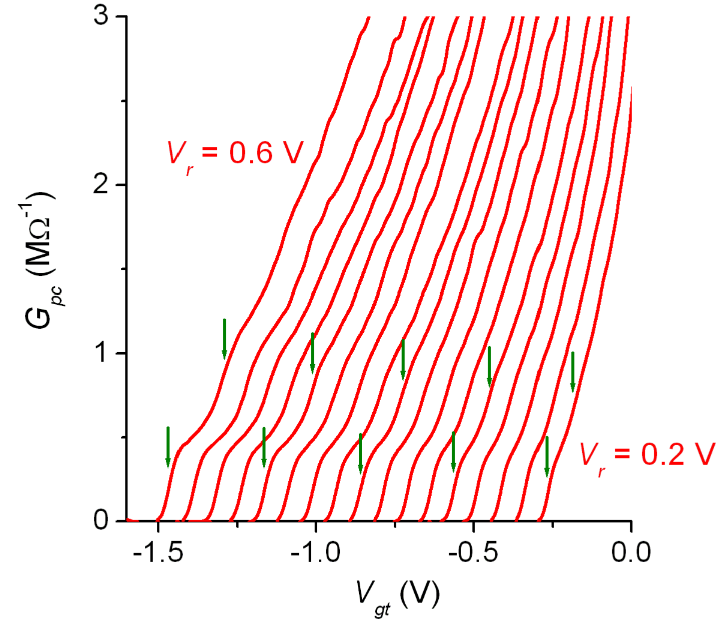
$$\sigma_\varphi \sim 1 \text{ meV} \sim V_{in}$$

M. Araki and H. Hayakawa, arXiv:1104.4854 (2011)

V_r dependence

Measure the conductance for different V_r :

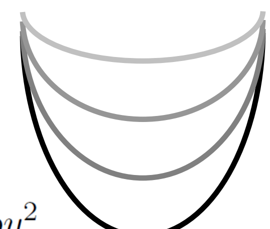




For less positive V_r :

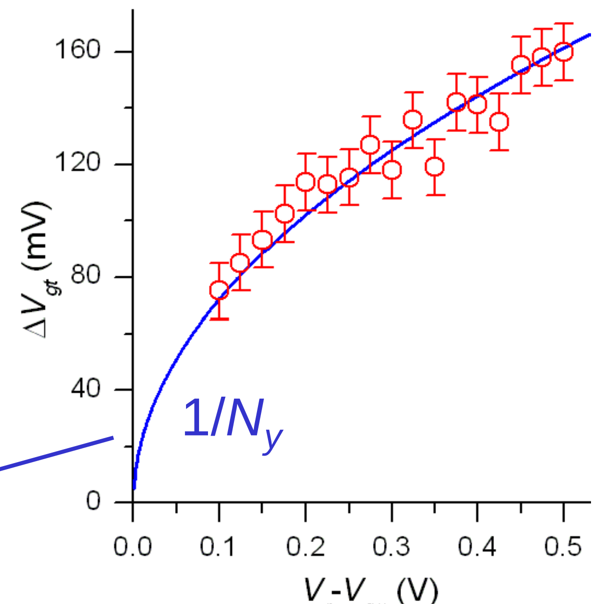
1) V_{gt} threshold is less negative
2) Step width is smaller

because the parabolic confinement becomes shallower:



$$V(y) = V_b - \frac{1}{2}by^2$$

$$N_y = \left(\frac{1}{b} \cdot \frac{16\varepsilon\varepsilon_0}{3ed}\right)^{\frac{1}{2}} \beta(V_{gt} - V_{gt}^{th})$$



Conclusions so far…

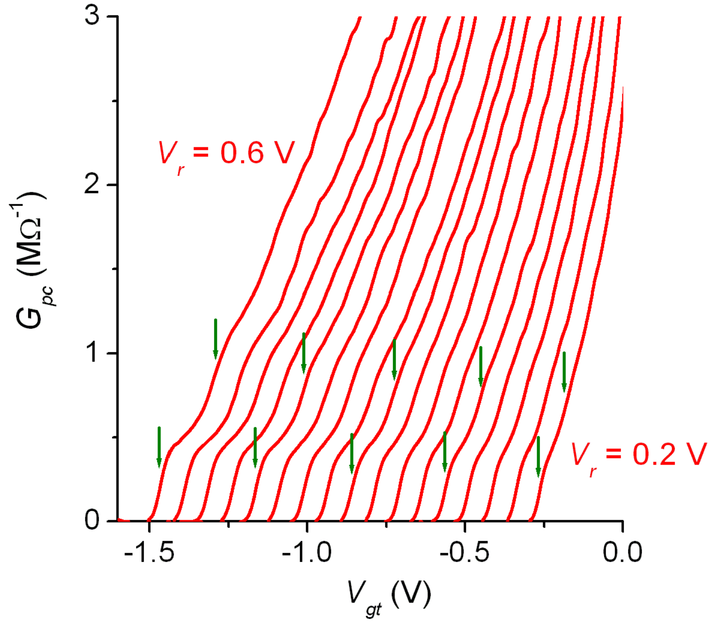
- We have observed a steplike increase in current in the PC device.

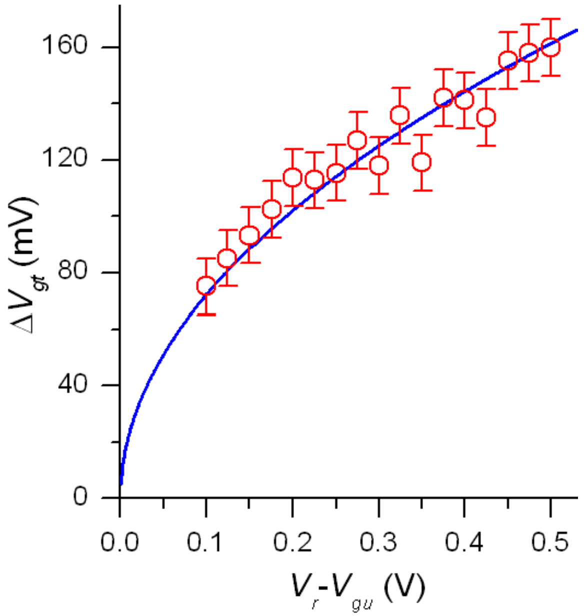
- This is due to the increase of the number of electrons able to pass side-by-side through the constriction.

- This can be considered as an effect of Coulomb blockade, at a single constriction.

- Result: A classical analogue of the QPC.

- The same dynamics should be observed in a variety of other systems…



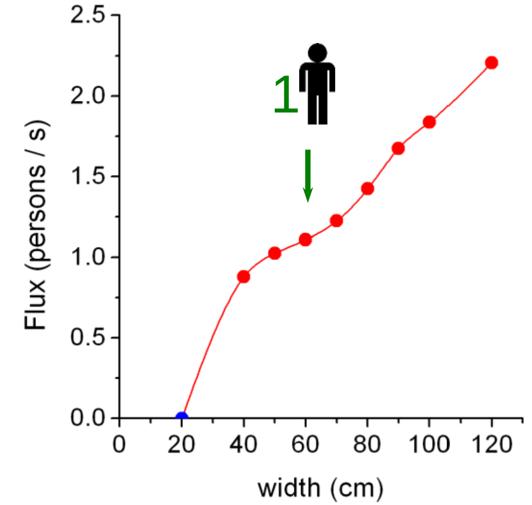


Pedestrians at bottlenecks

Humans also exhibit long-range interactions:

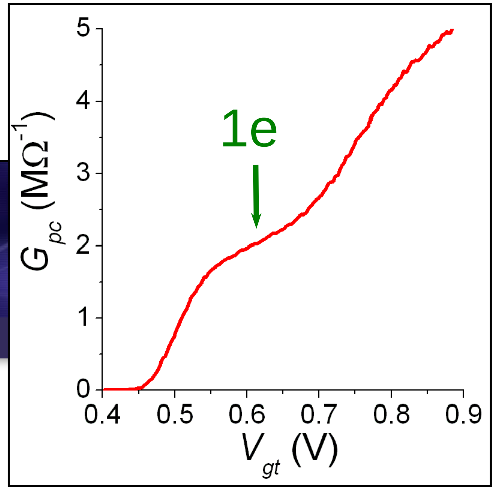
$$F_{int} \sim e^{-r}$$

Kretz *et al*, J. Stat. Mech. (2006):



Coulomb systems:

$$F_{int} \sim 1 / r^2$$



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Focus: Electrons Take Turns Like Pedestrians

Published January 21, 2011 | *Phys. Rev. Focus* **27**, 3 (2011) | DOI: 10.1103/PhysRevFocus.27.3

Electrons confined to a layer floating above liquid helium move in an orderly way through a constriction because their repulsion forces them to keep their distance from one another.

When electrons are put onto liquid helium, they skate like air-hockey pucks above the surface. In the 14 January *Physical Review Letters*, experimentalists report that, when they force a sheet of such electrons through a narrow constriction, the particles' mutual repulsion causes them to take turns passing through, like a crowd of commuters going through a turnstile. The results show how a two-dimensional layer of electrons acts when their quantum nature is not important.

Point-Contact Transport Properties of Strongly Correlated Electrons on Liquid Helium
D. G. Rees, I. Kuroda, C. A. Marrache-Kikuchi, M. Höfer, P. Leiderer, and K. Kono
Phys. Rev. Lett. **106**, 026803 (2011)
Published January 14, 2011

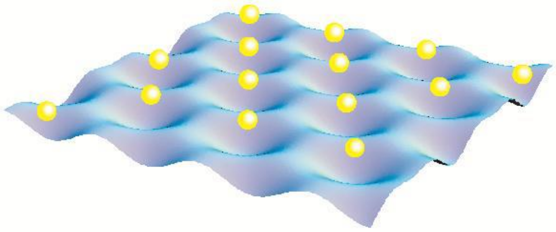
Wigner crystal transport

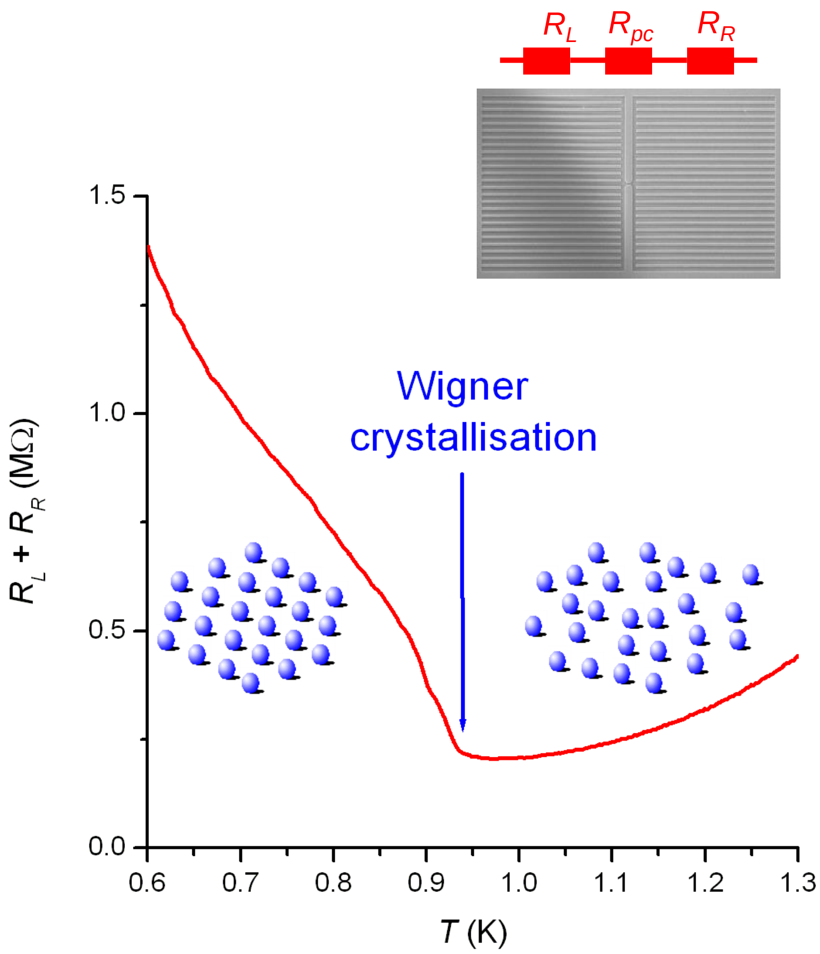
The electron system 'freezes' for $\Gamma > 130$:

$$\Gamma = \frac{E_{Coulomb}}{E_{kinetic}} \sim \frac{n_s^{1/2}}{k_B T}$$

For $n_s \sim 10^9$ cm^{-2}, $T_m \sim 1$ K

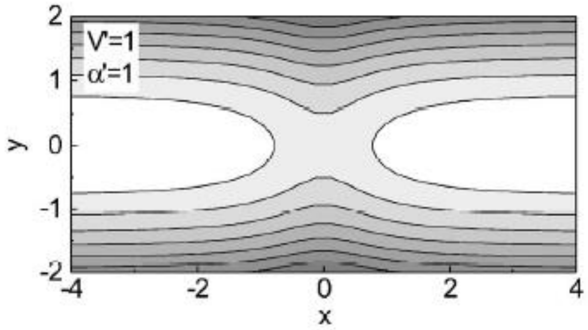
'Dimples' formed beneath each electron increase resistivity:

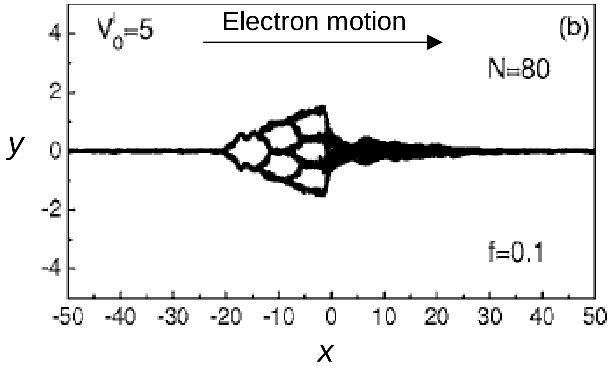




Simulations of Wigner crystal transport through constrictions:

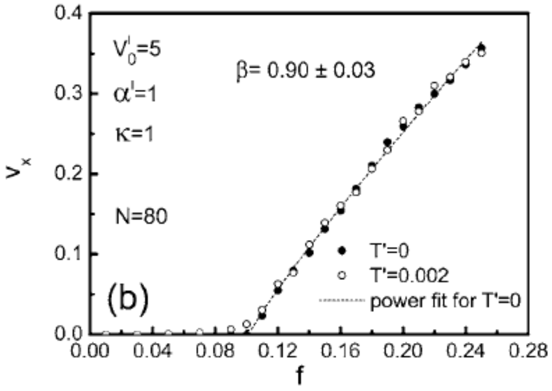
- Piacente and Peeters, PRB **72** (2005):





At low temperatures we expect the system to become pinned at the constriction.

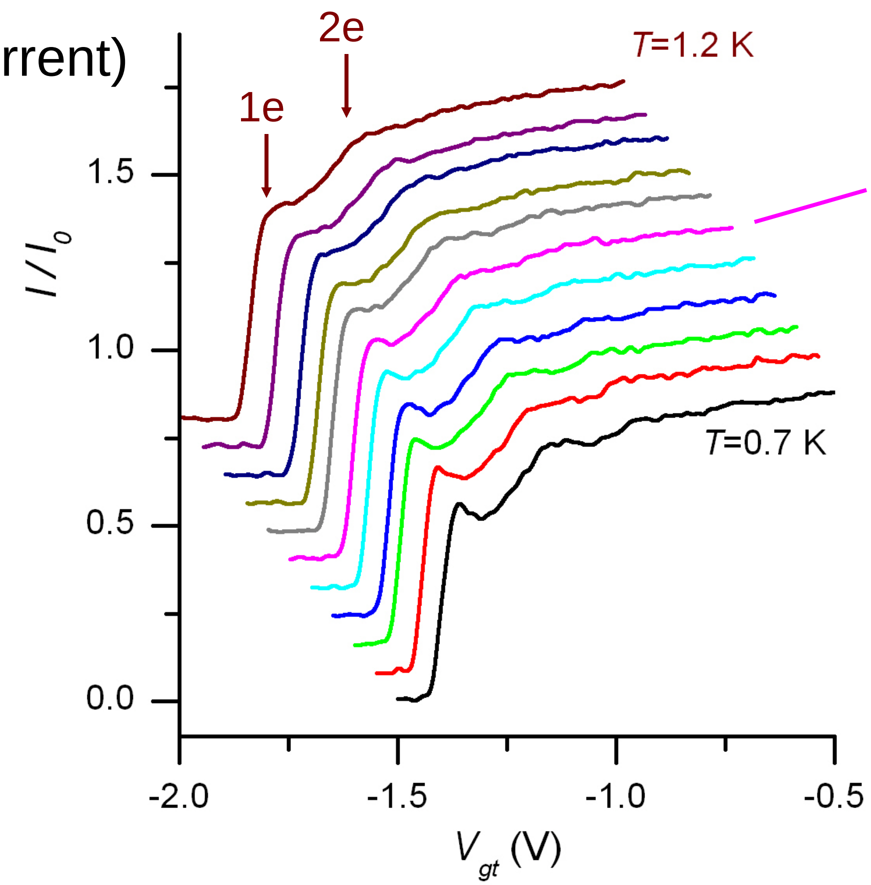
Motion can be induced by increasing the force applied to the system (depinning):



Wigner crystal transport

Change temperature (here T_m = 1.19 K):

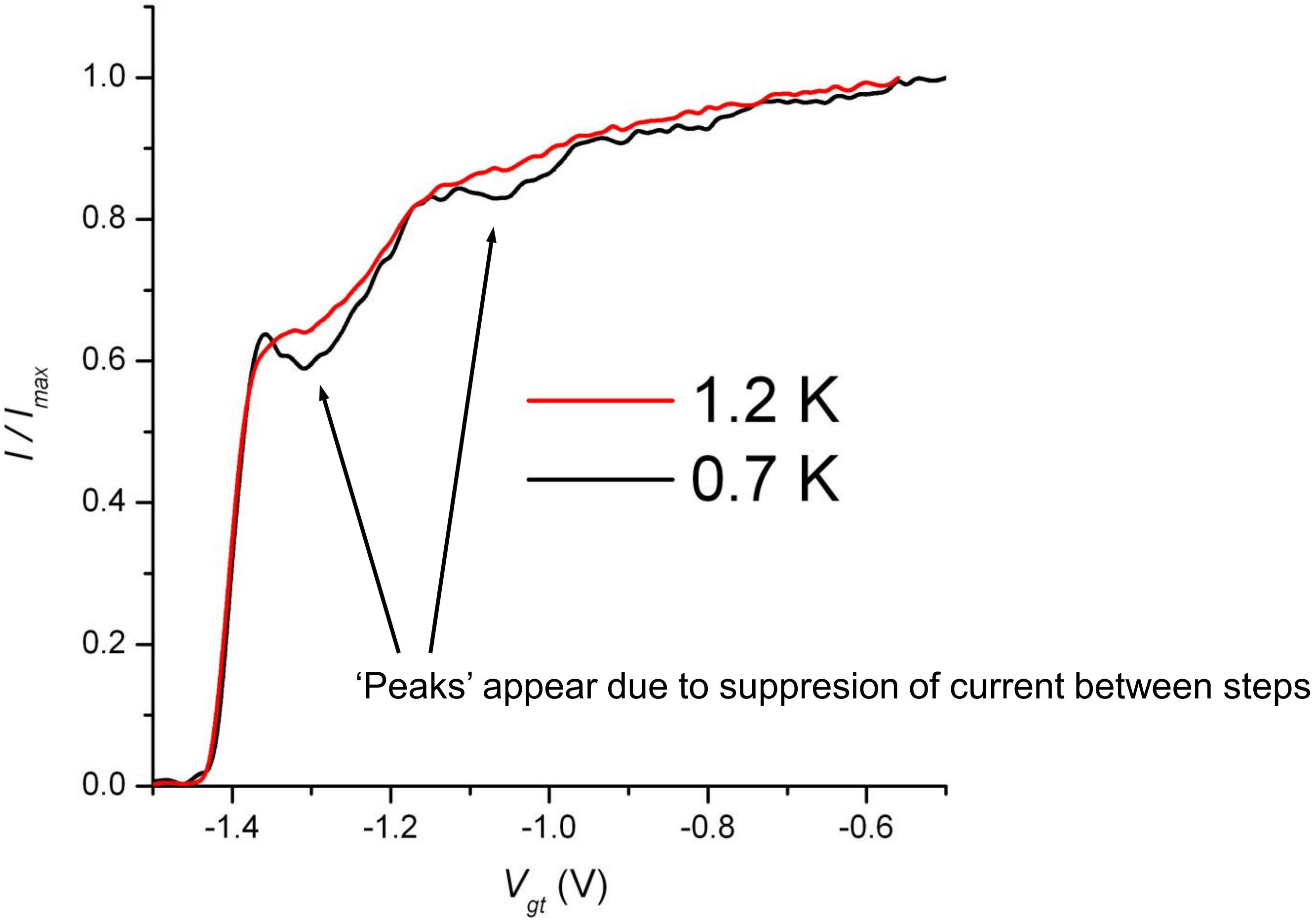
(Normalised current)



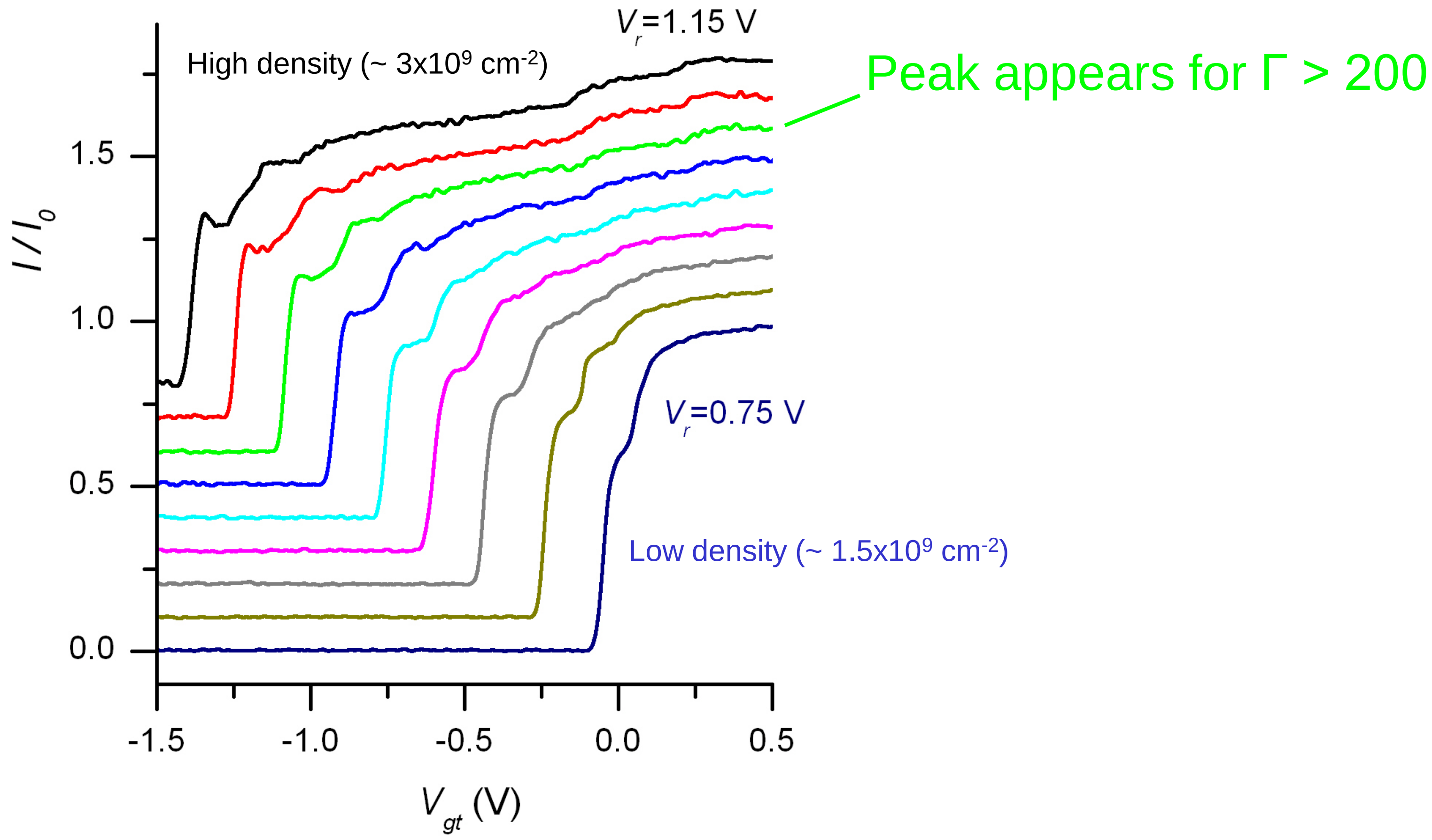
Peak appears for Γ > 159

Wigner crystal transport

Compare high and low T sweeps directly:

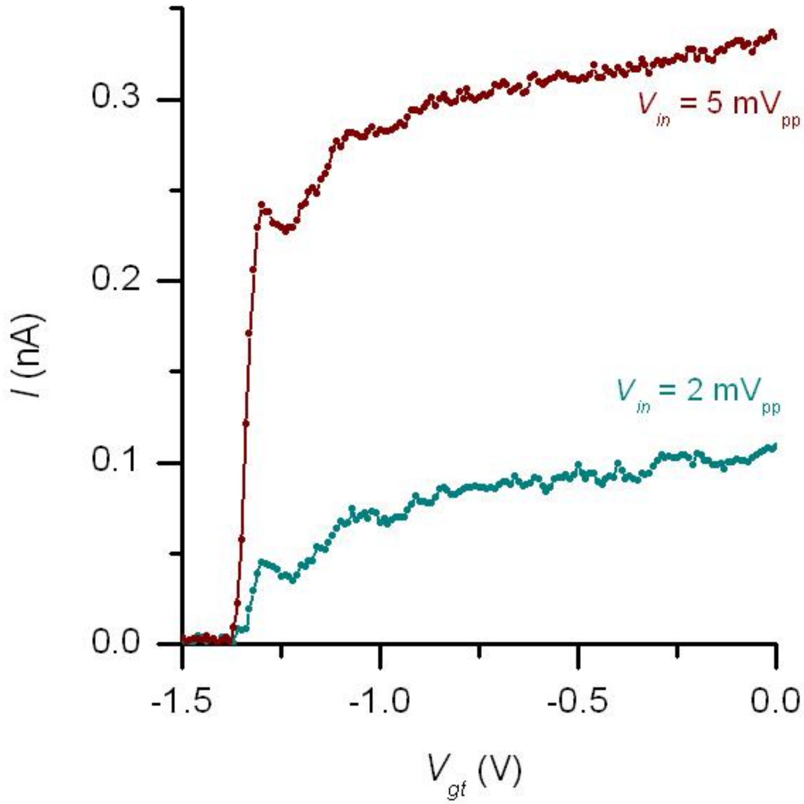


Change density (T = 0.7 K):



Change driving voltage (T = 0.5 K):

I_0 ~ 325 pA



For 5 mV$_{pp}$, I_0 is similar to that at 1.2 K, 2 mV$_{pp}$… but the peak is still visible:

The peaks do not appear simply by changing the current.

Molecular Dynamics Simulations

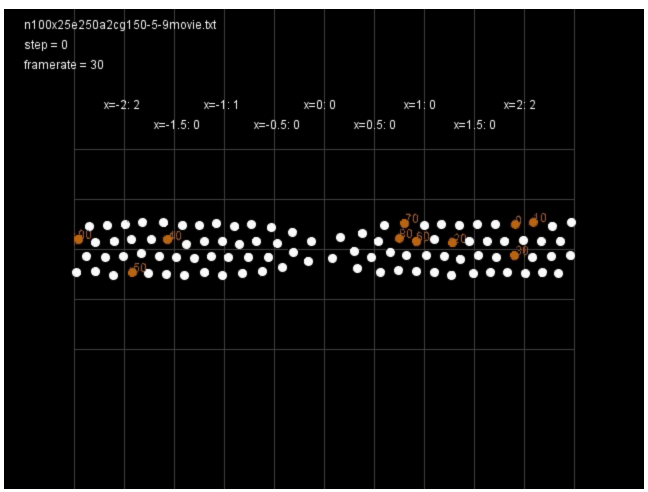
Molecular dynamics simulations (H. Totsuji):

$$H = \sum_i \frac{1}{2} m \left(\frac{dR_i}{dt} \right)^2 + \sum_{i>j} \frac{e^2}{|R_i - R_j|} + \sum_i V_{ext}(R_i)$$

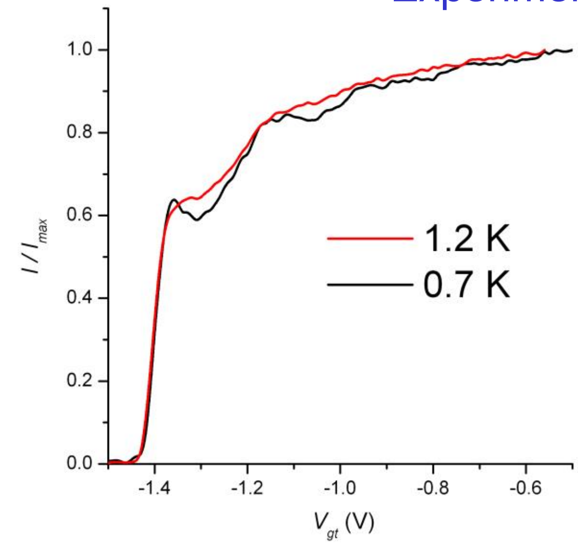
where

$$V_{ext} = V_{gu} \tanh\left(\frac{y^2}{l_0^2} \right) + V_{gt} \frac{1}{1 + (\alpha x / l_0)^2} \quad .$$

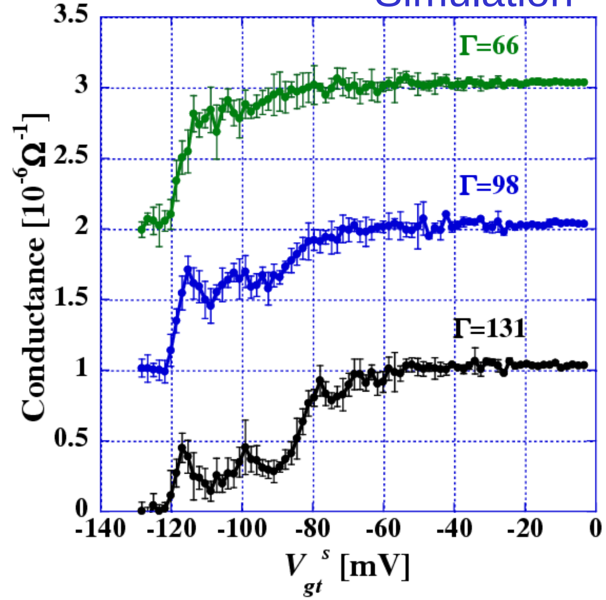
$n_s = 3 \times 10^9$ cm^{-2} :



Experiment

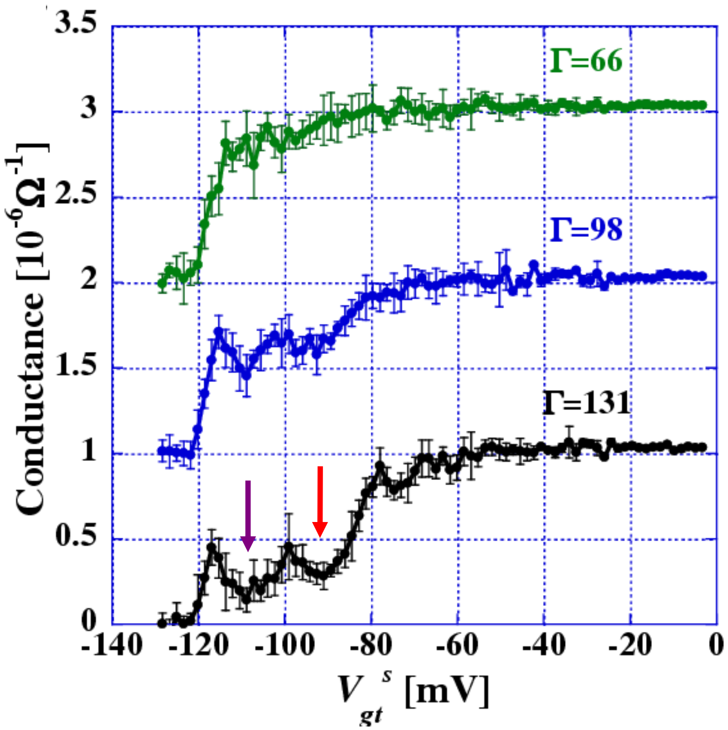


Simulation

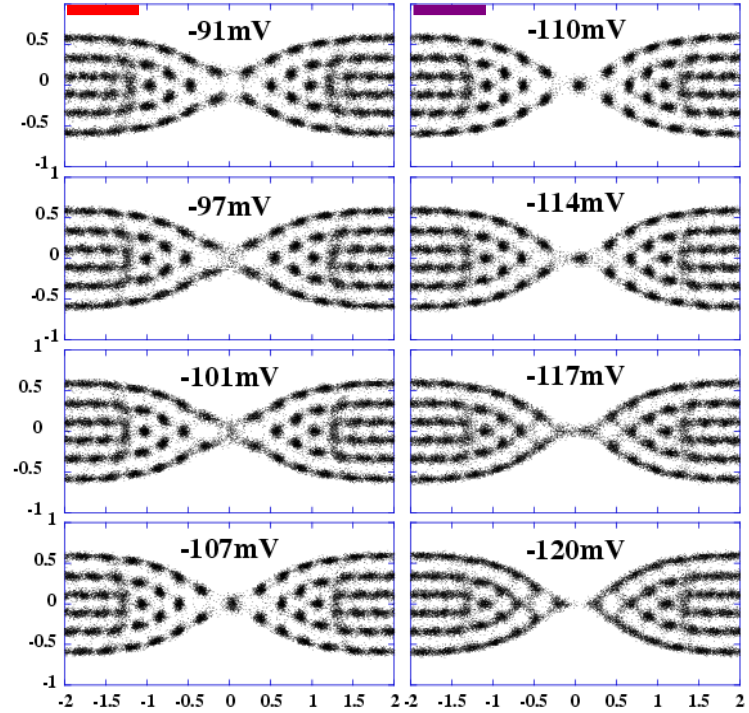


Commensurability-dependent transport

Current is suppressed for symmetric, stable configurations:



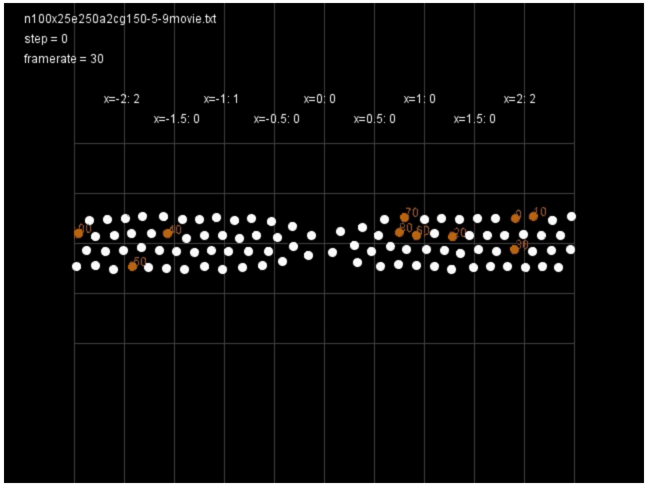
Overlap electron positions over time:



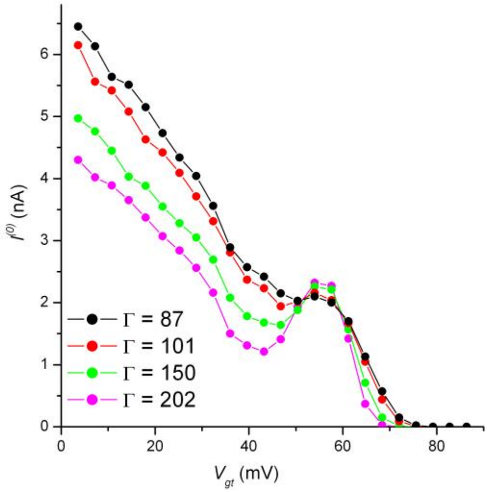
Current suppression
↓
Current grows
↓
Current peak
↓
Current suppression

Note: These pictures are also valid without the applied driving voltage…

Fluctuation current



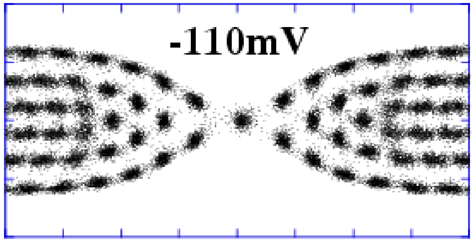
Fluctuation current $I^{(0)}$:



There is a link between the thermal fluctuations in electron positions and the conductance through the constriction…

So…

So: When particles are arranged in a commensurate way at the constriction we observe a suppression of electron thermal motion:



For this case, the fluctuation current is suppressed.

Fluctuation dissipation theorem:

> ‘The response of a system in thermodynamic equilibrium to a small applied force is the same as its response to a spontaneous fluctuation.’
>
> *eg* R. Kubo, *Rep. Prog. Phys.* **29** (1966)

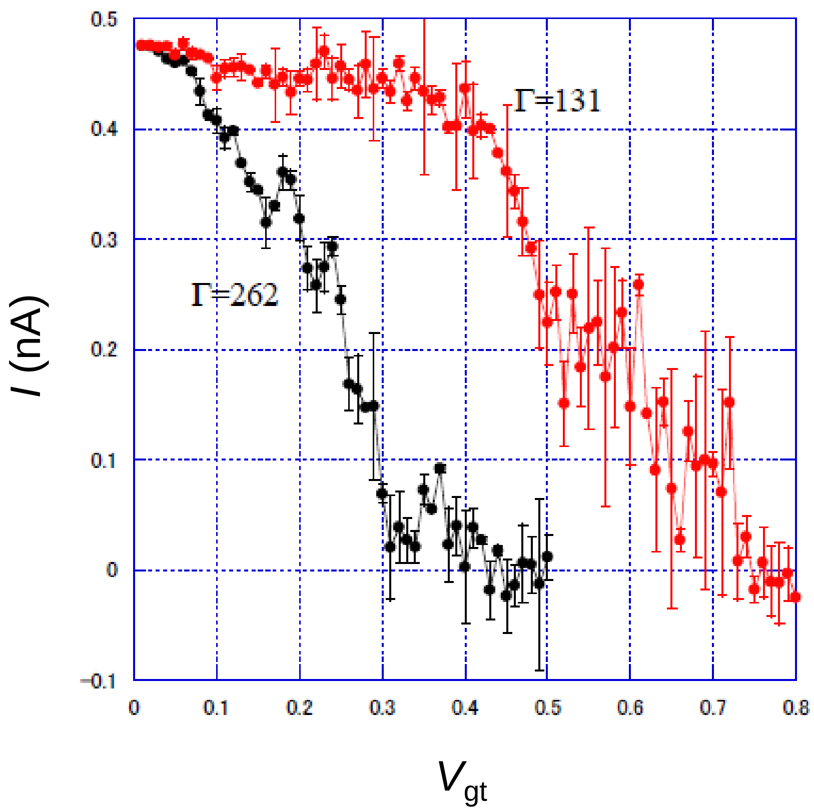
So our current is suppressed due to Coulomb interactions…

> The suppression of current can be regarded as the onset of pinning, which depends on the commensurability of the electron lattice.

D.G. Rees, H. Totsuji and K. Kono, *Phys. Rev. Lett. (accepted for PRL)*

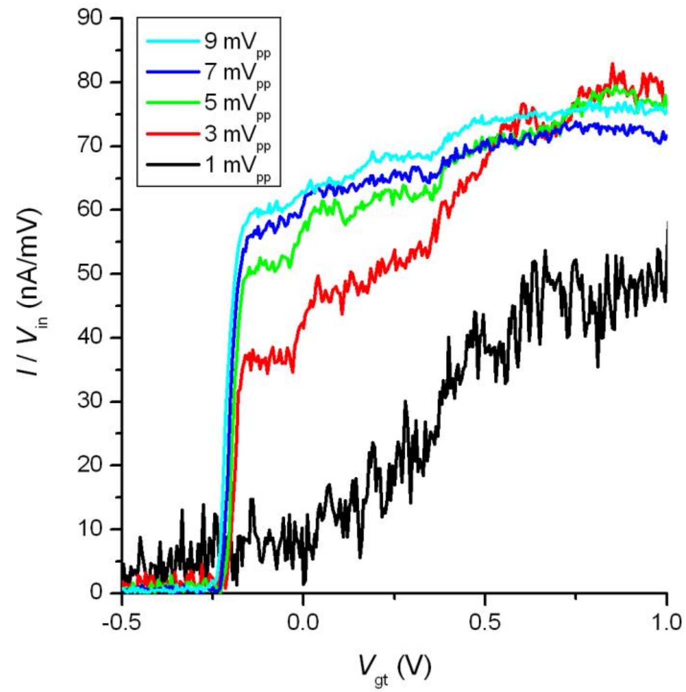
Complete pinning at low temperatures?

Preliminary simulation data:



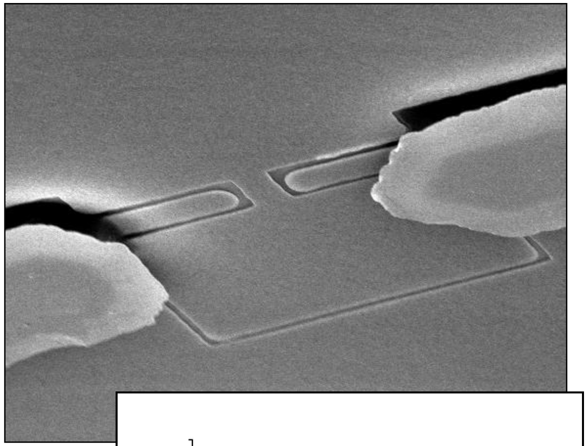
Preliminary experimental data:

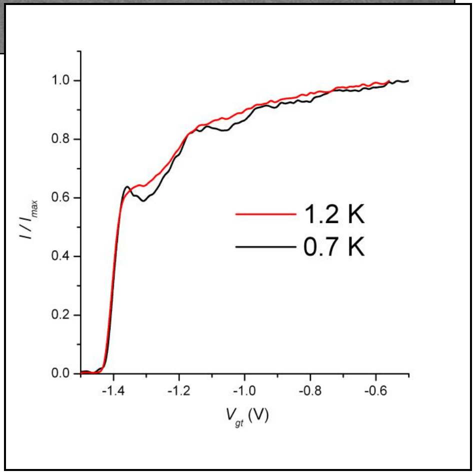
T = 440 mK:



Signs of strong suppression at low T, but further measurements required…

Conclusions





- We have measured the transport properties of classical electron liquids and solids in a point-contact device.
- In the liquid phase:

  - We observe conductance steps due to lane formation.
- In the solid phase:

  - We observe conductance peaks due to the onset of pinning for commensurate electron lattice arrangements.
- In the next talk we will see related conductance oscillations in a long microchannel, but due to ripplon scattering.
- The dynamics revealed here could be observable in many other classical many-body systems (colloids, grains, pedestrians etc…)
- Good agreement with simulations shows that e on He are a useful model system for the study of many-body systems in confined geometry.

Thankyou