Surface fluctuations and high-frequency phenomena in electrons on helium

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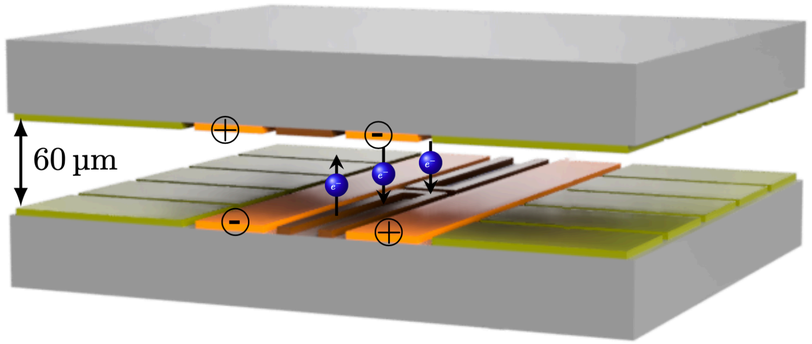
MIDWEST QUANTUM COLLABORATORY

Trapping electrons

Trapped electrons in ion traps

Paul traps / Penning traps

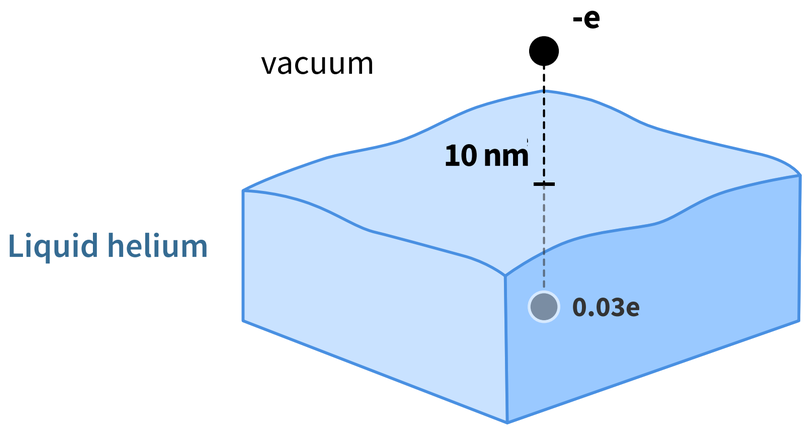


Rf-frequency ion-trap architecture

N. Daniilidis et al., *New Journal of Physics* 15.7: 073017 (2013)
Pai Peng et al., *Phys. Rev. A* **95**, 012312 (2017)
C. Matthiesen et al., *Phys. Rev. X* **11**, 011019 (2021)
Qian Yu et al., *Phys. Rev. A* **105**, 022420 (2022)

Trapped electrons on cryogenic substrates

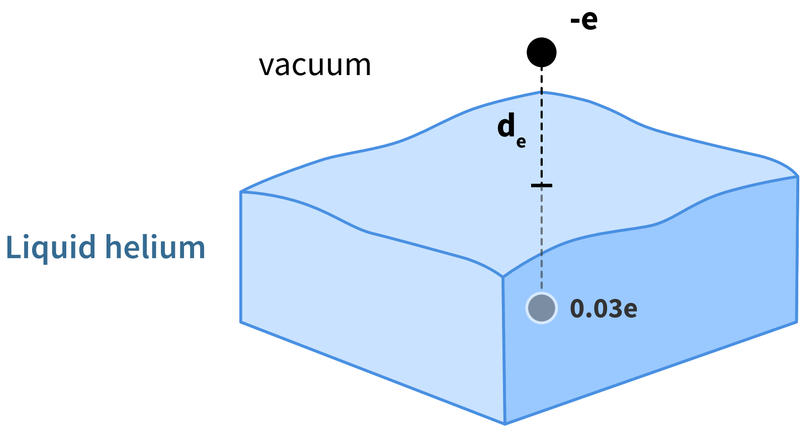
liquid helium / solid neon

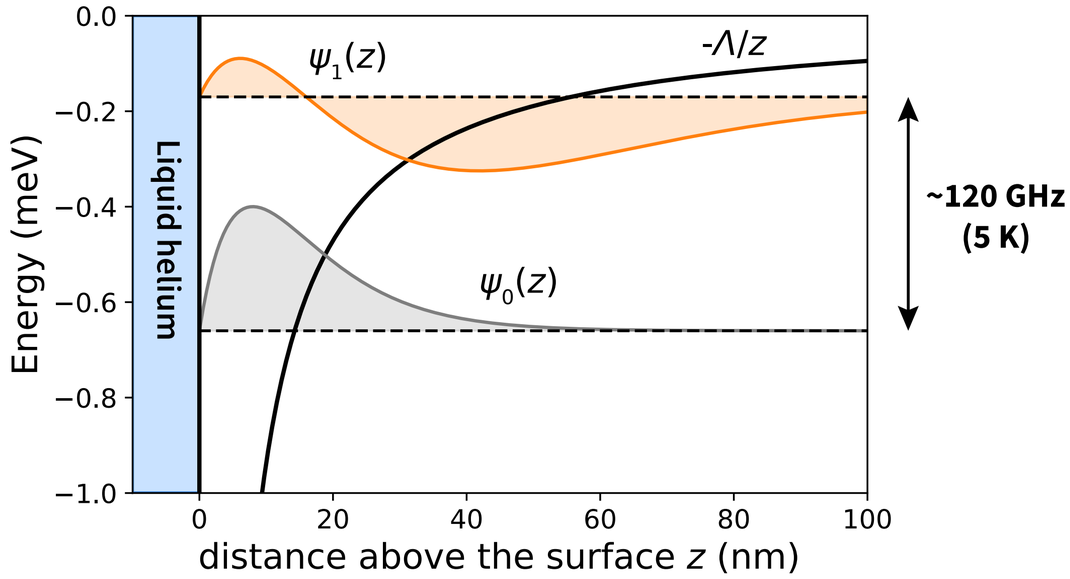


Electrons are attracted to liquid He by an image charge $Q = 0.03e$…
…but repelled by a 1 eV potential barrier at the surface

P.M. Platzman and M.I. Dykman, *Science* **284** (5422), pp.1967 (1999)
S. A. Lyon, *Phys. Rev. A* **74**, 052338 (2006)
D.I. Schuster et al., *Phys. Rev. Lett.* **105**, 040503 (2010)

Surface state electrons





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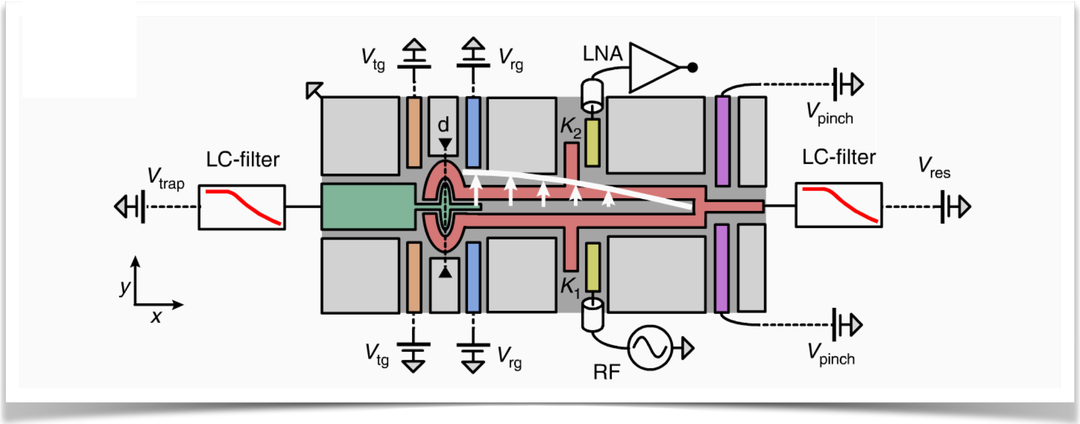
“1D Hydrogen atom” with Rydberg series of states

$$E_n = -\frac{m_e \Lambda^2}{2\hbar^2 n^2} \quad (n = 1, 2, 3\ldots)$$

Circuit QED with electrons on liquid helium and solid neon

Towards coherent control

Circuit QED with electrons on liquid helium

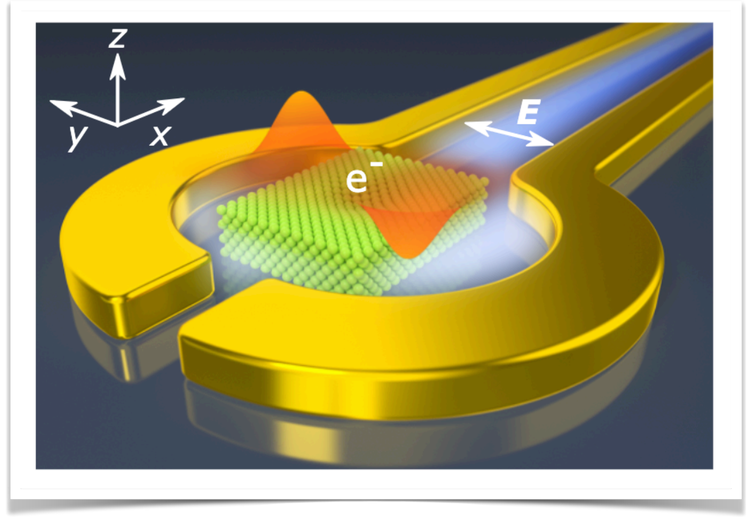


G. Koolstra et al., *Nat.Comm.* **10**, 5323 (2019)

electron-photon coupling strength $g \simeq 5$ MHz

electron linewidth $\gamma \simeq 80$ MHz

Circuit QED with electrons on solid neon



X. Zhou et al., *arXiv*:2106.10326 (2021)

relaxation time $T_1 = 15\ \mu$s

dephasing time $T_2^* = 50$ ns

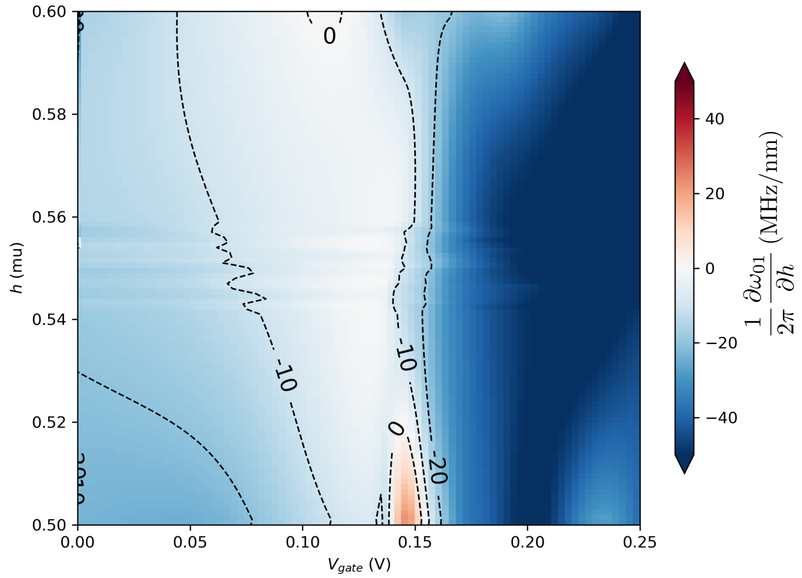
Coherence and electron control

1 improving dephasing time

Helium fluctuations change the electrostatic potential seen by electron, thus electron in-plane motional state frequency fluctuates

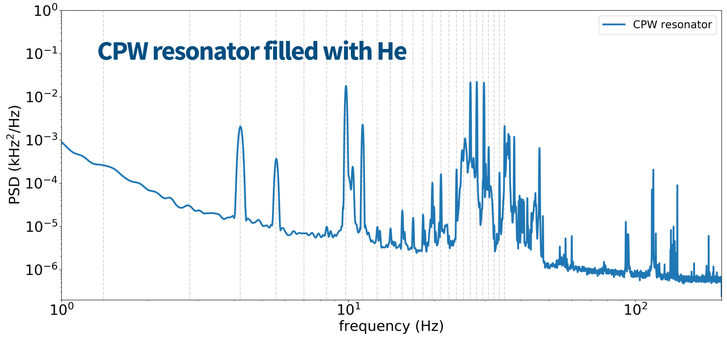
$$\frac{1}{T_\phi^h} \propto \left|\frac{\partial \omega_{01}}{\partial h}\right|^2 S_h(\omega \to 0)$$

coupling to helium fluctuations



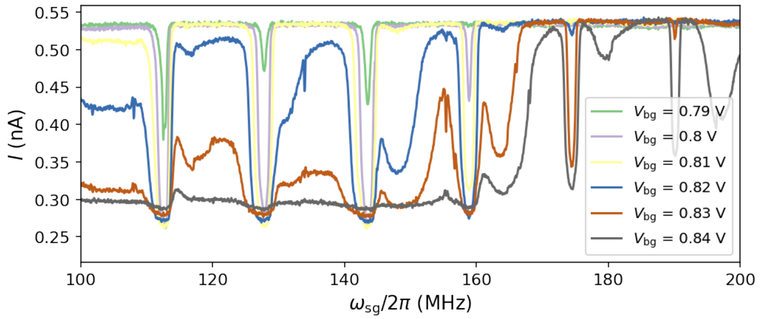
Spectral density of the helium surface fluctuations

helium/cryostat vibrations



2 controlling electrons

Microdevices covered with liquid helium
New high-frequency studies



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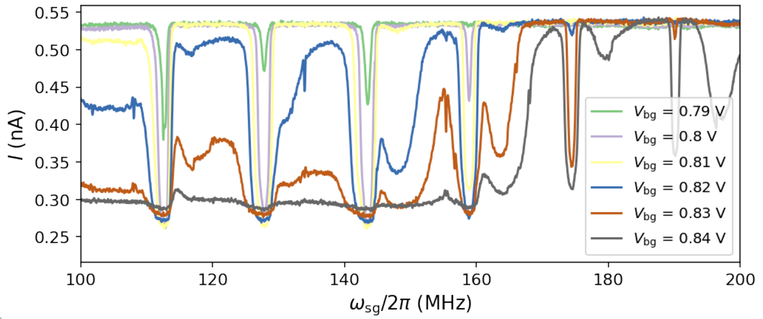

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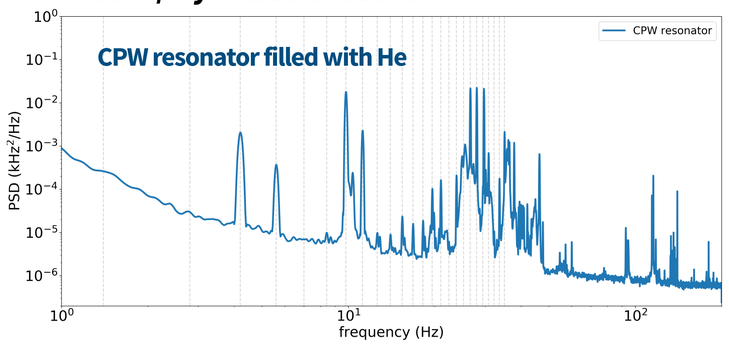
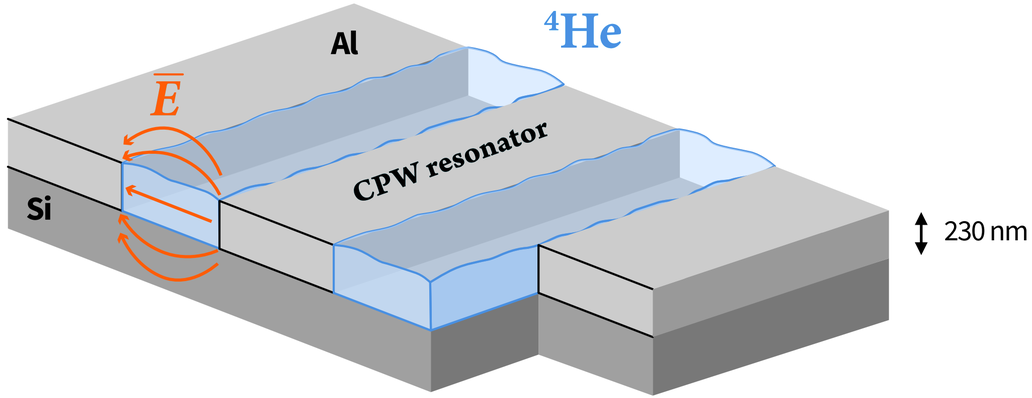
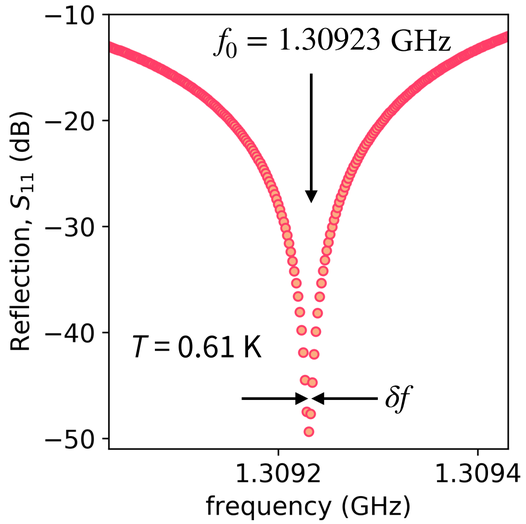


CPW resonator covered with helium



$$\varepsilon_{\mathrm{He}} = 1.057$$



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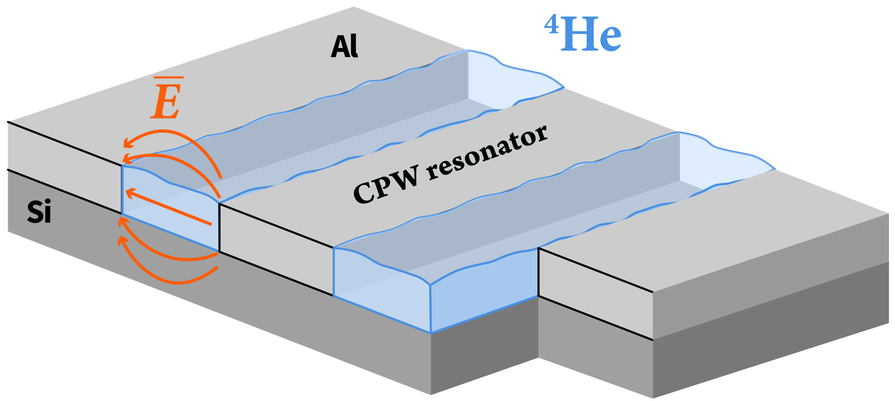
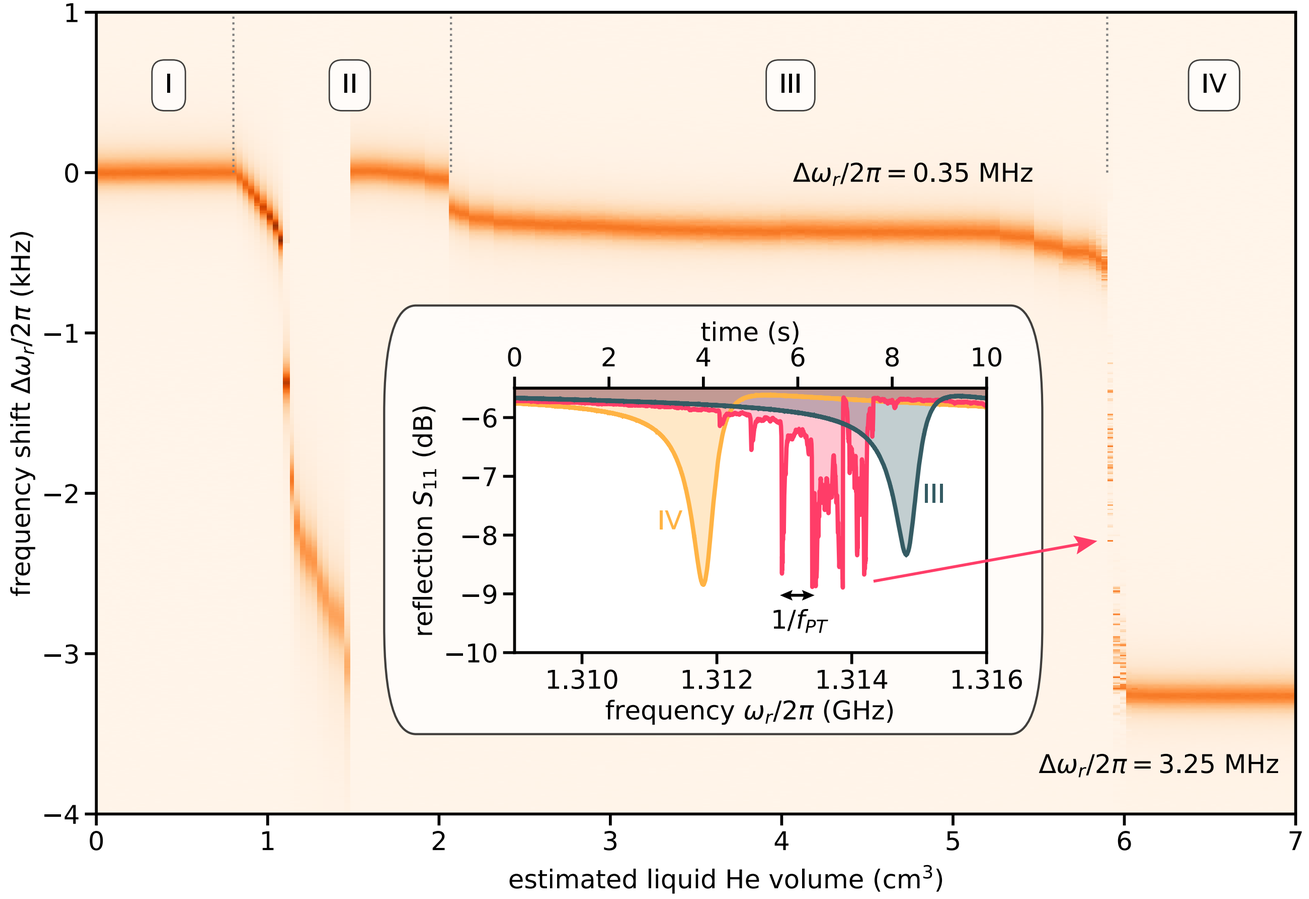


$$\varepsilon_{\mathrm{He}} = 1.057$$

I - empty cell
II - liquid helium in sample cell
III - filling the channel with superfluid He
IV - full sample cell



G. Yang et al., *Phys. Rev. X* **6**(1), 011031 (2016)
G. Koolstra et al., *Nat.Comm.* **10**, 5323 (2019)

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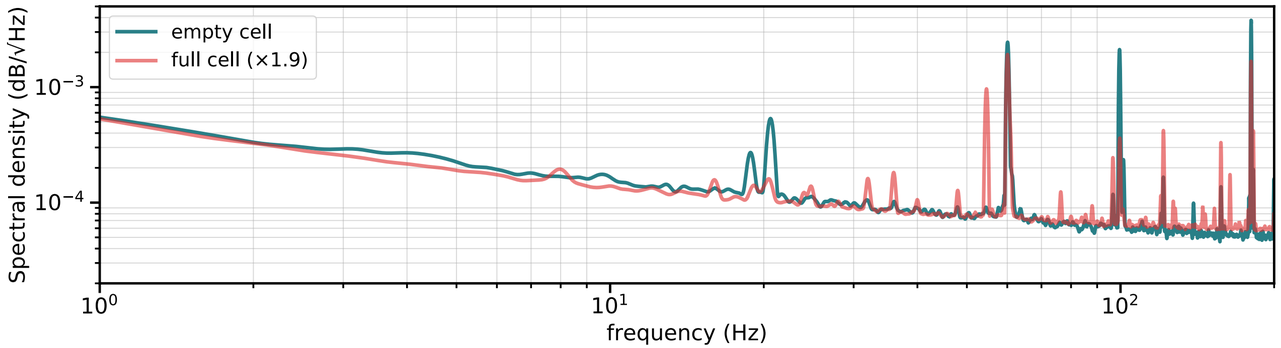
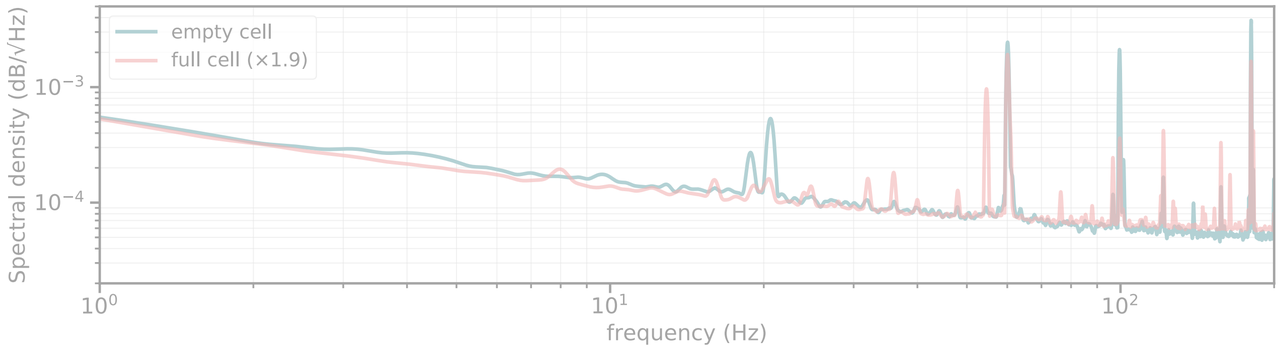
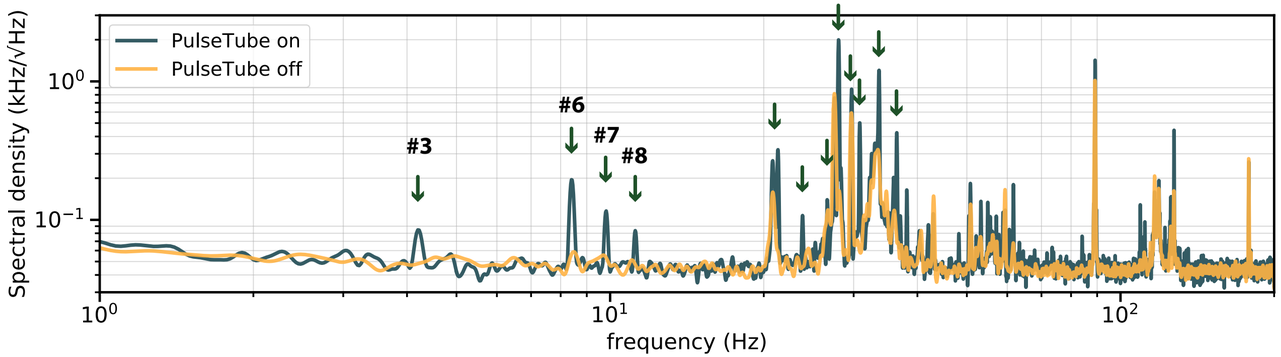
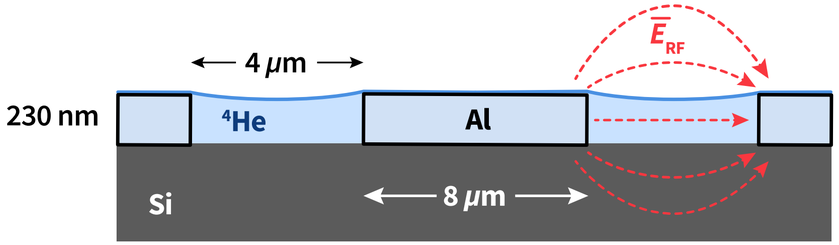


empty cell
full cell

Helium surface fluctuations





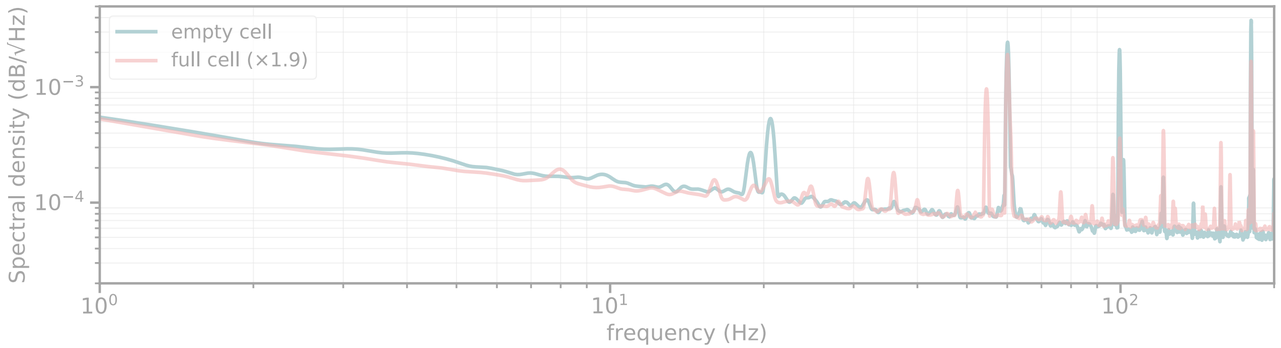


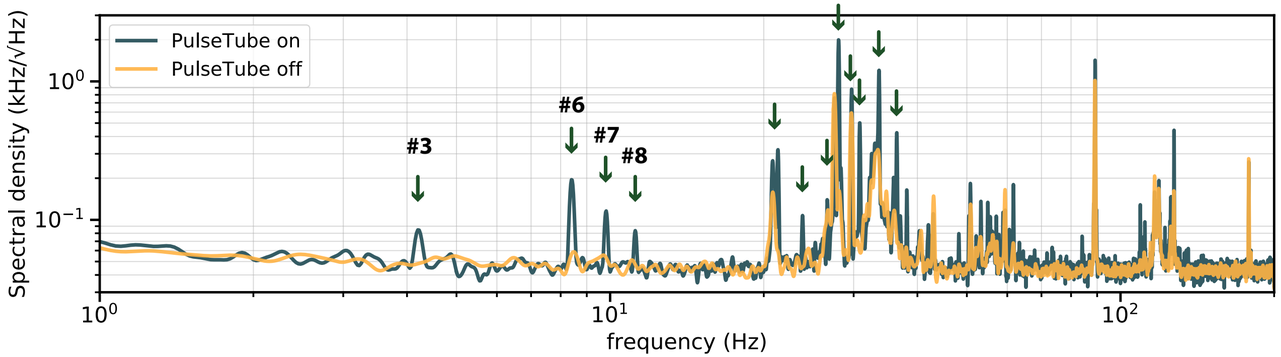
RMS vibration:

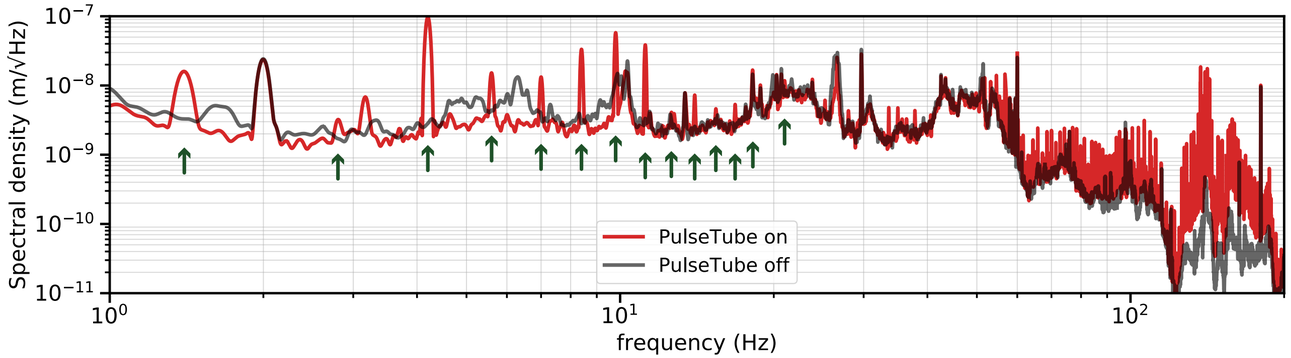
$$\Delta h = \left(\frac{df_0}{dh}\right)^{-1} \sqrt{\int_{f_1}^{f_2} S_h(f)^2 df}$$

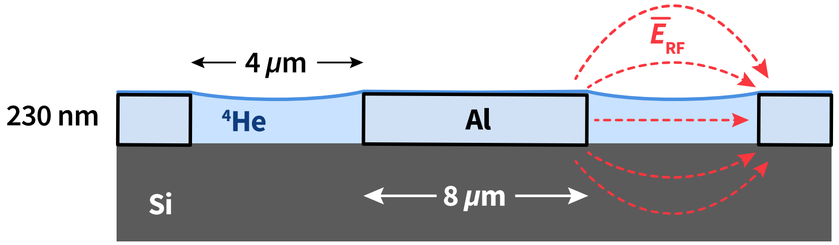
$\Delta h = 0.9$ nm	PT on
$\Delta h = 0.77$ nm	PT off

Helium surface fluctuations









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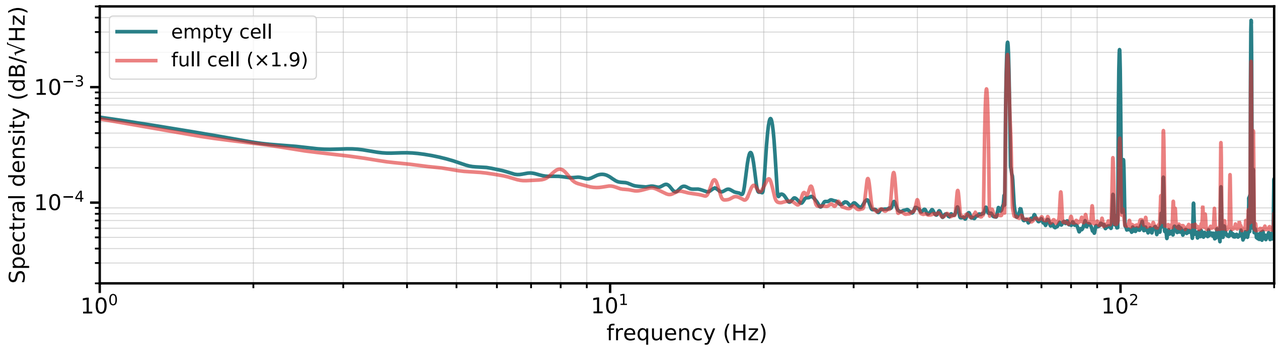
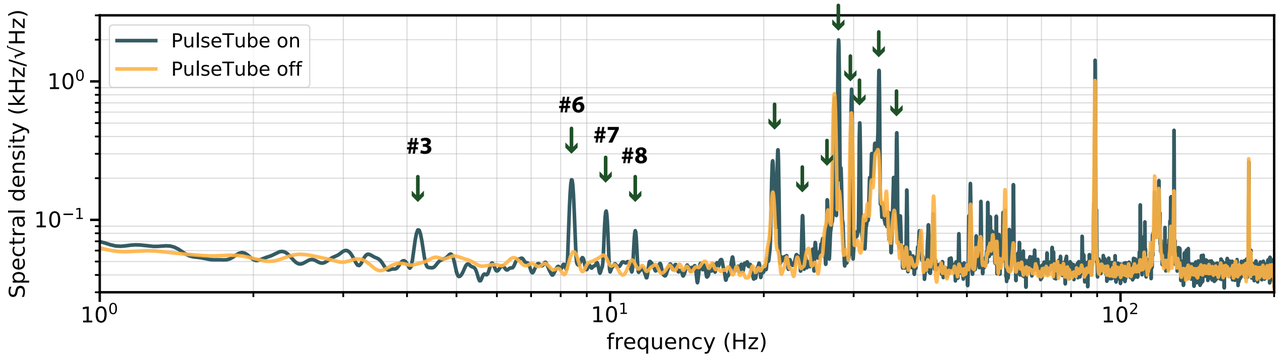
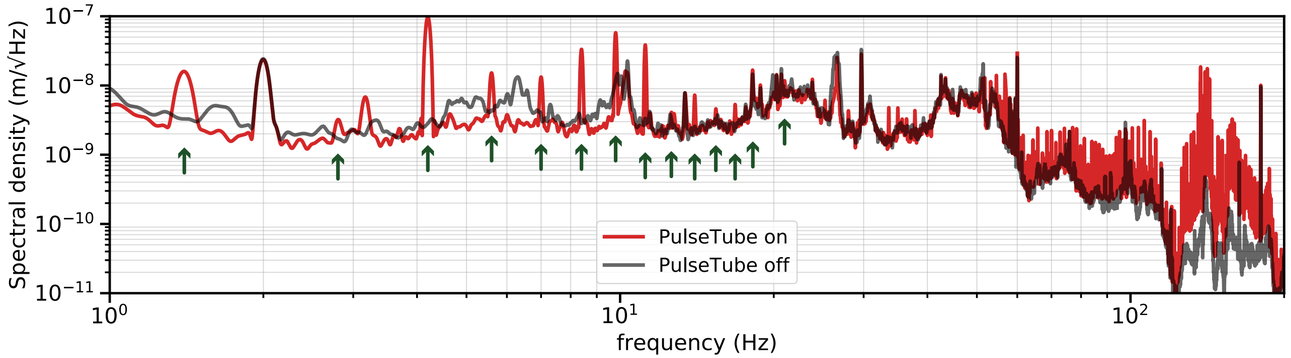
geophone measurements

Helium surface fluctuations





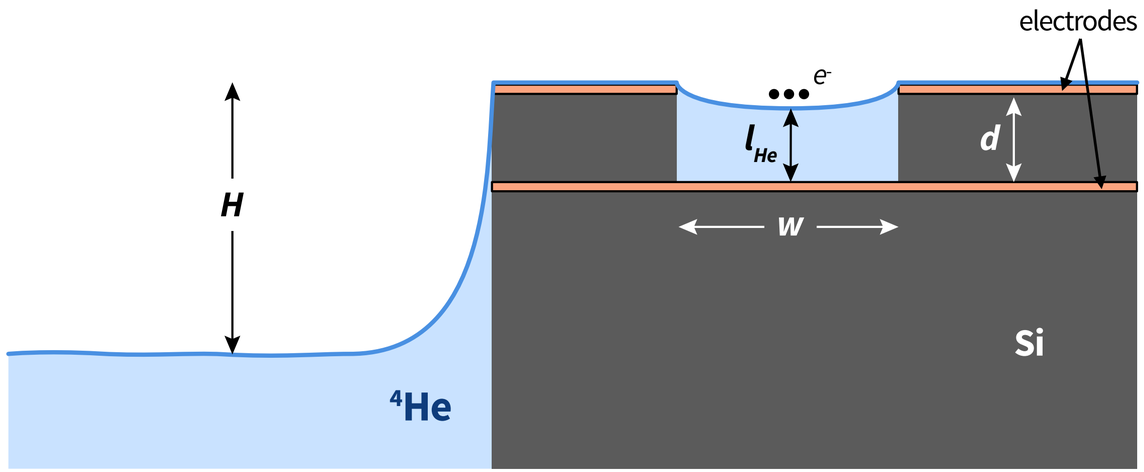


possible solutions:

- **spring suspended stage**
- **eddie current dampers**
- **“helium batteries”**
- **wet cryostats**

N.R. Beysengulov et al., *J. Low Temp. Phys.* 1-10, (2022)

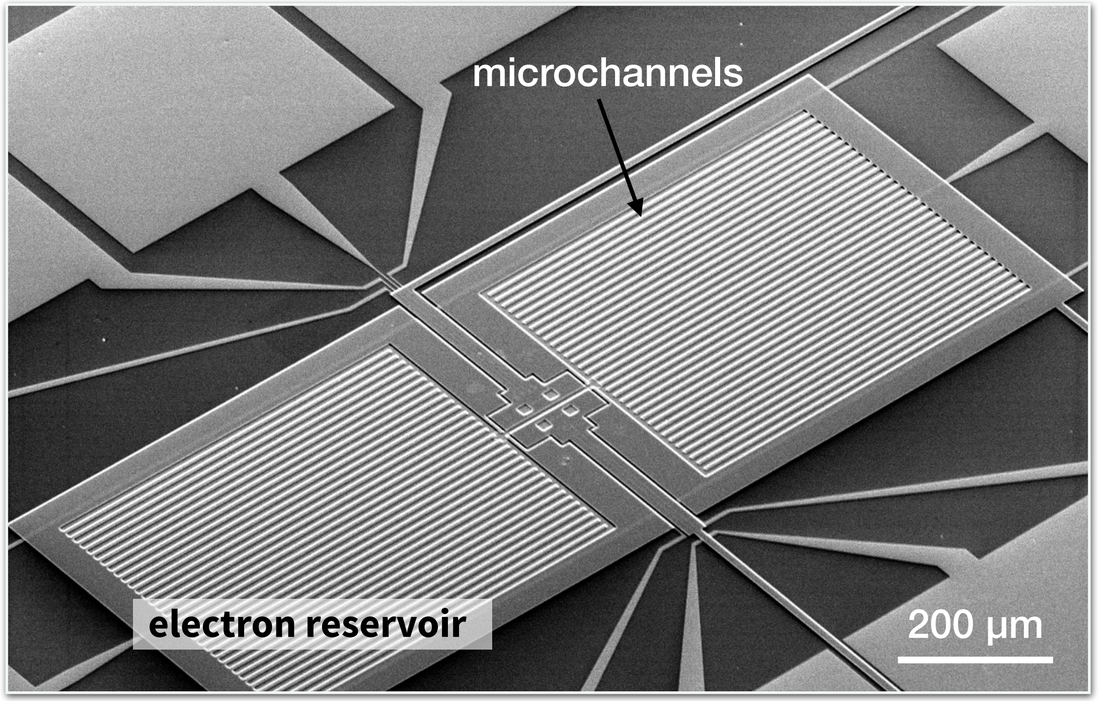
Electron Devices with superfluid helium



microstructures filled by capillary action of superfluid ^{4}He

$$l_{He} = d - \frac{w^2}{8}\frac{\rho g H}{\alpha_t}$$

α_t - surface tension of liquid helium
ρ - density liquid helium
w - width typical 1 - 20 μm
d - depth typical 0.5 - 2 μm

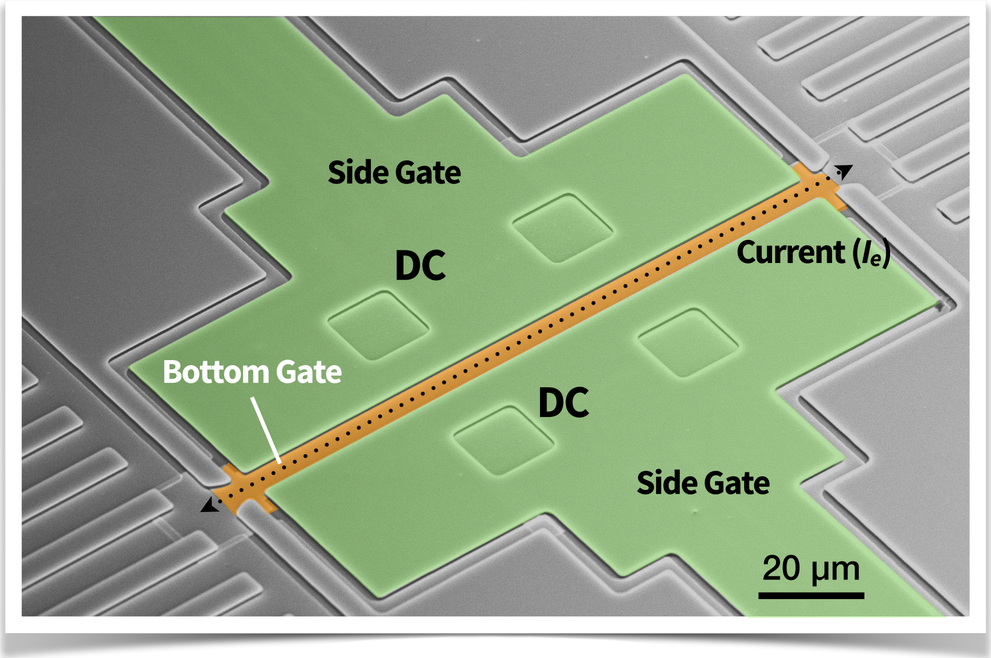


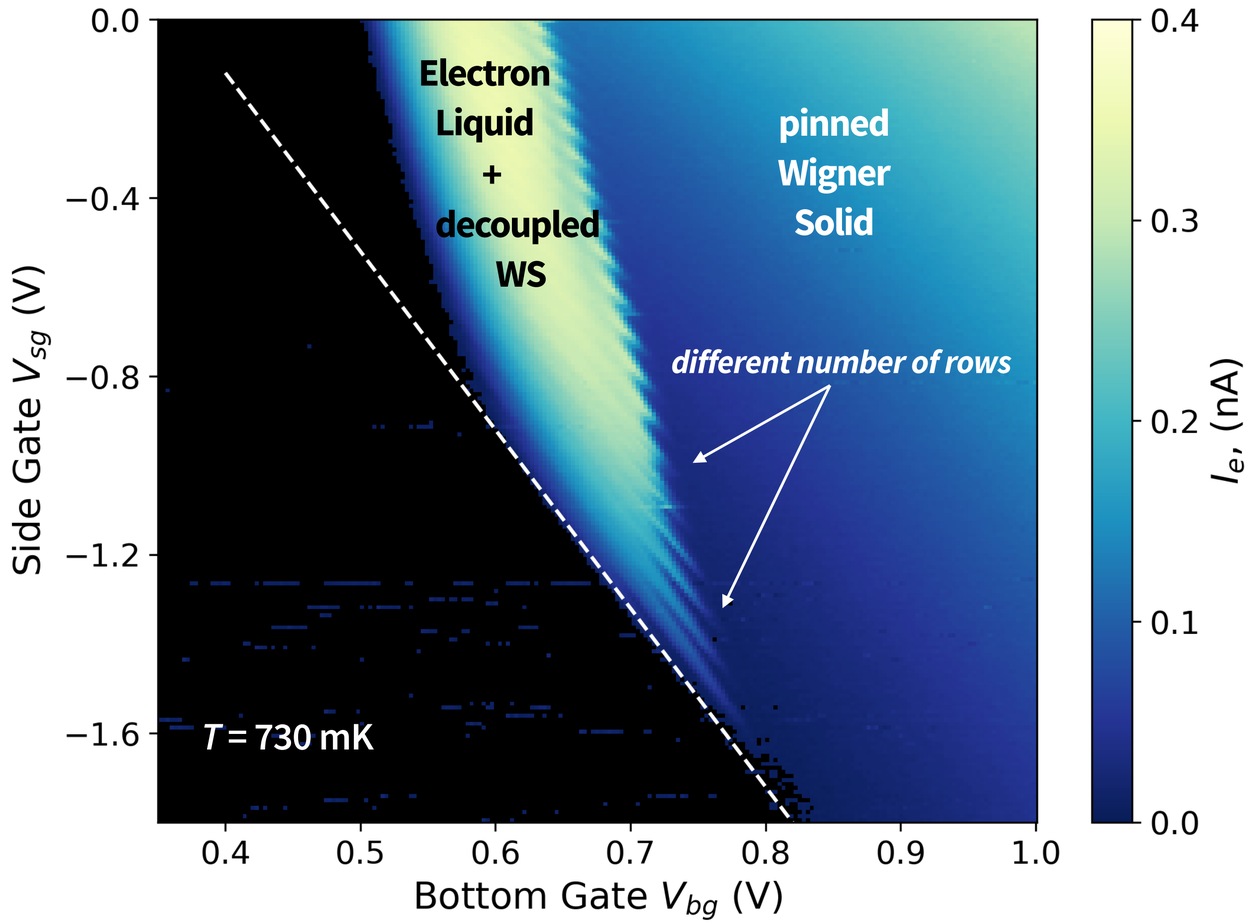
SEM image of microdevice fabricated in LHQS MSU

Electron Reservoirs:
Set of long helium microchannels is used to store electrons

D.G. Rees et al., *J. Low Temp. Phys.* 166 (2011)

Low-frequency electronic transport

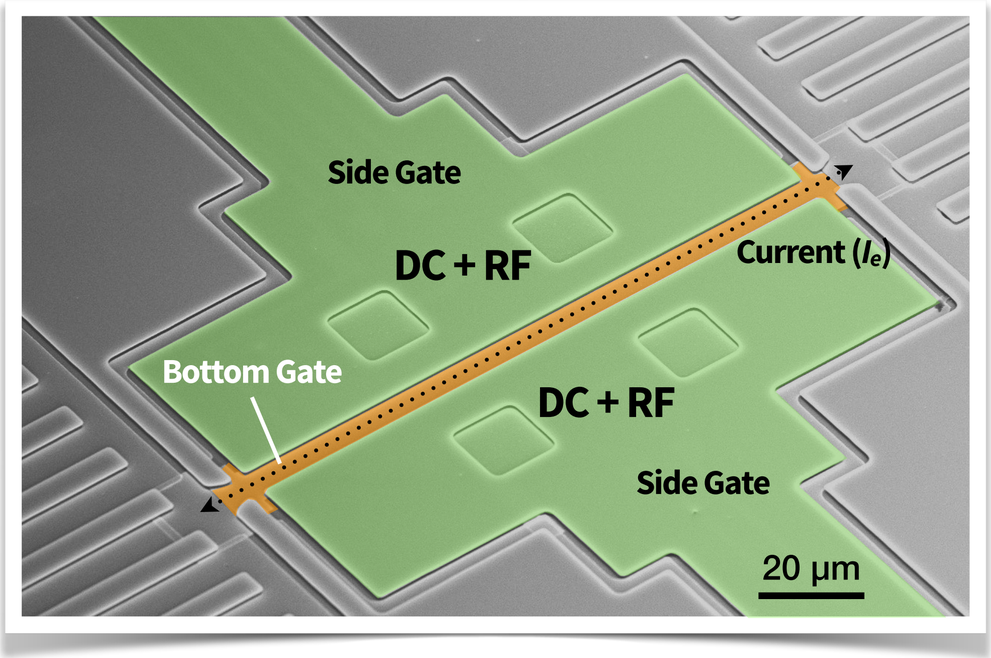




At structural transitions between adjacent N_y increased lattice defects reduce positional order. Therefore the Bragg ripplon scattering weakens and the electron mobility increases.

see more in *PRL* **116**, 20680 (2016) and *PRB* **94**, 045139 (2016)

Superimposing rf-excitations



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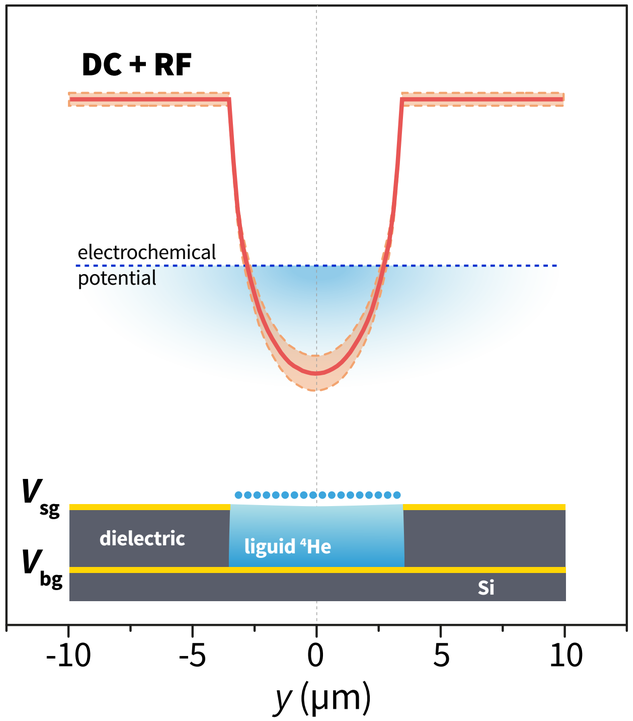

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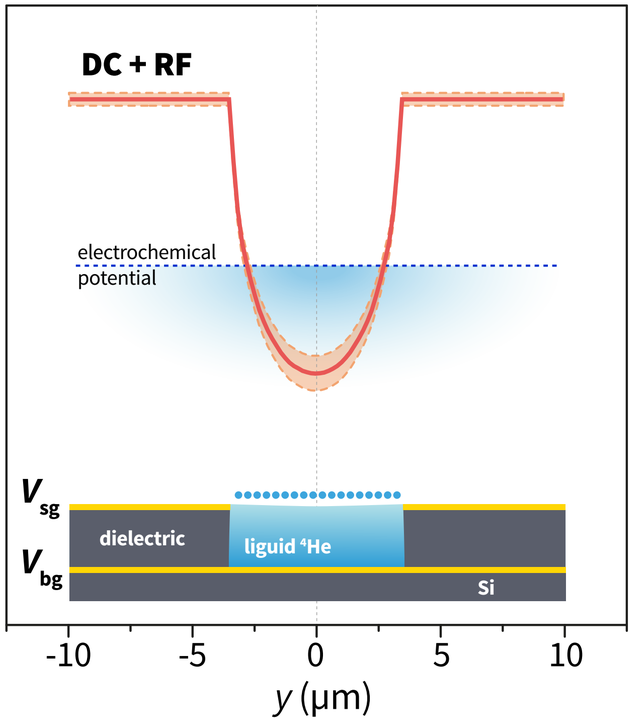
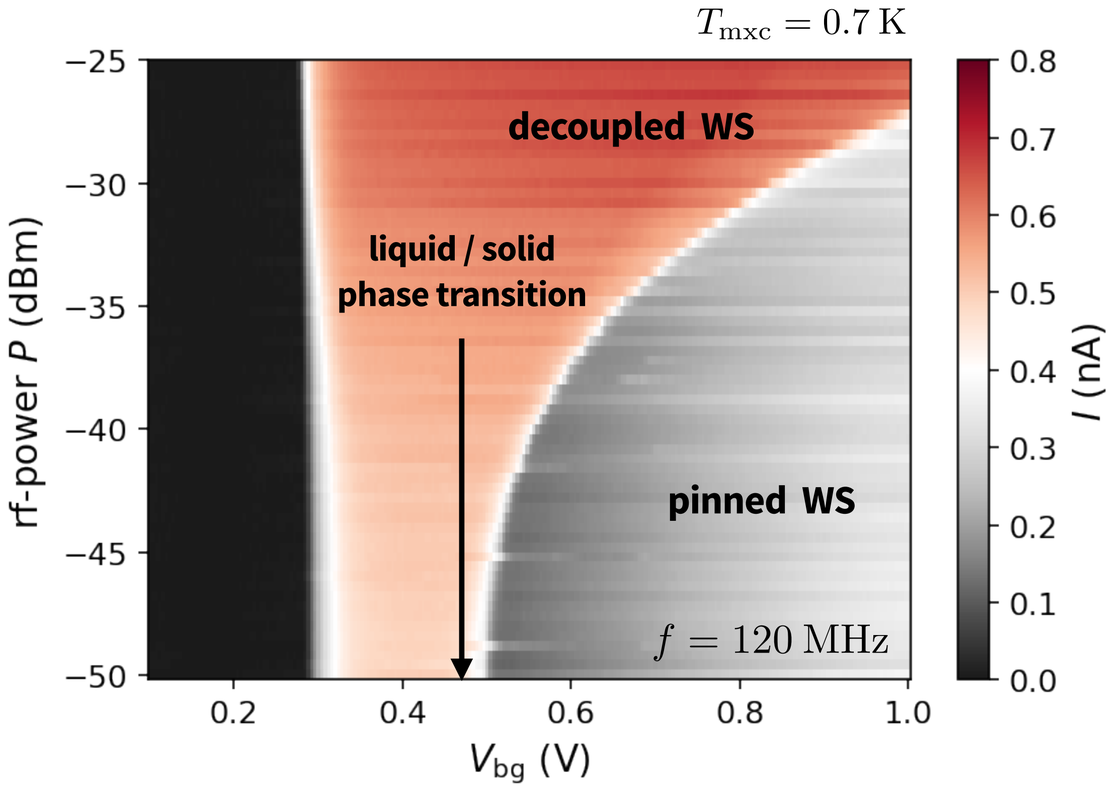
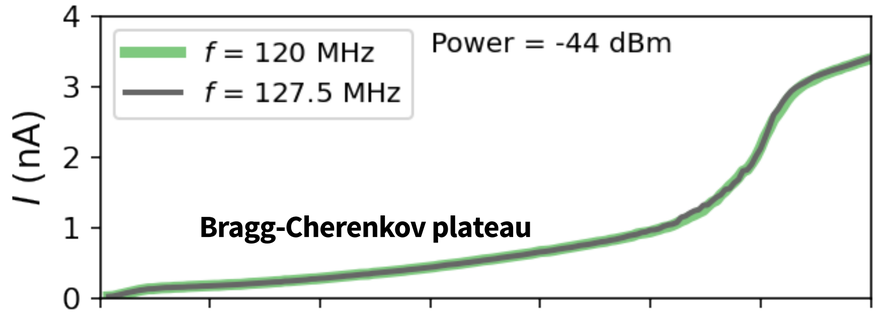
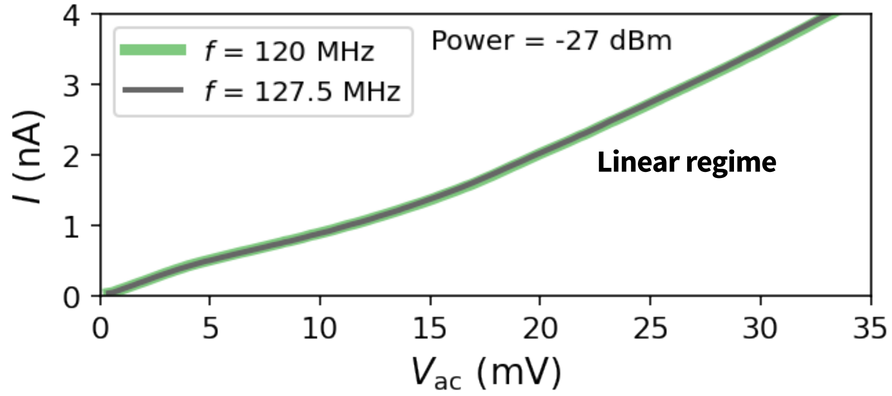




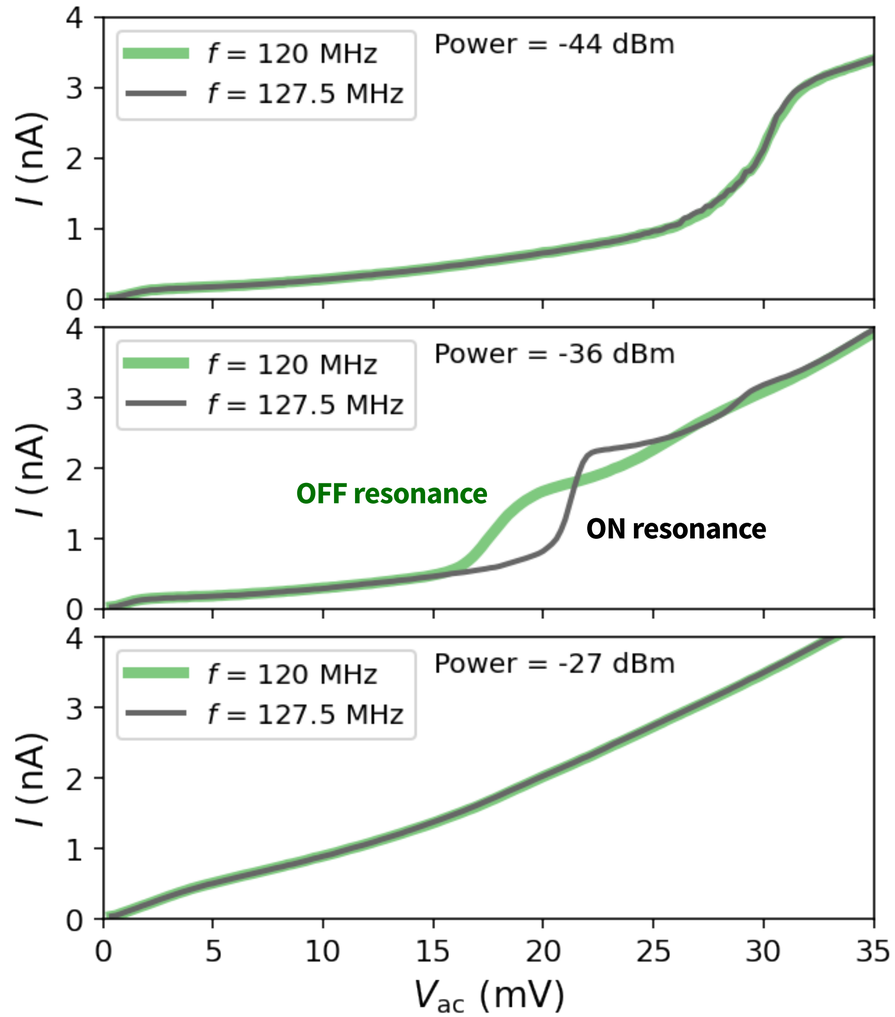
- Modification of the phase diagram
- Hot electron effects

Evidence of “hot” electron effects





New resonance-like features



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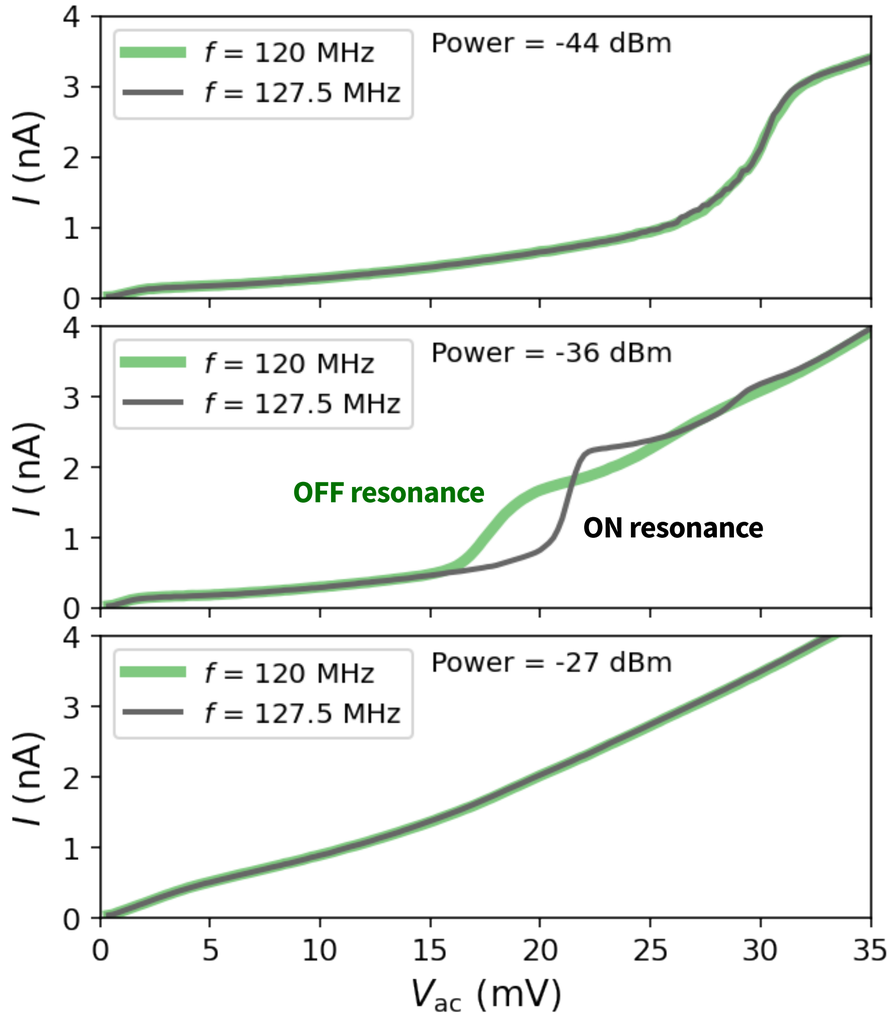
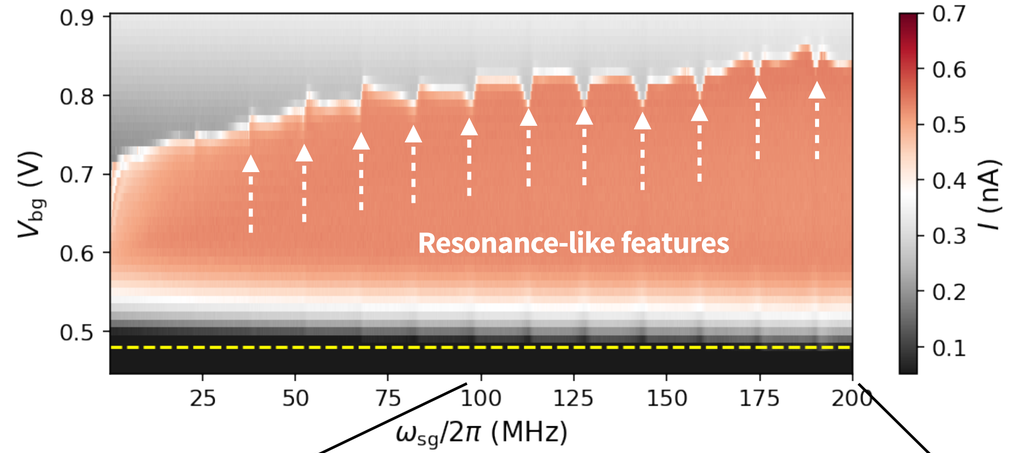
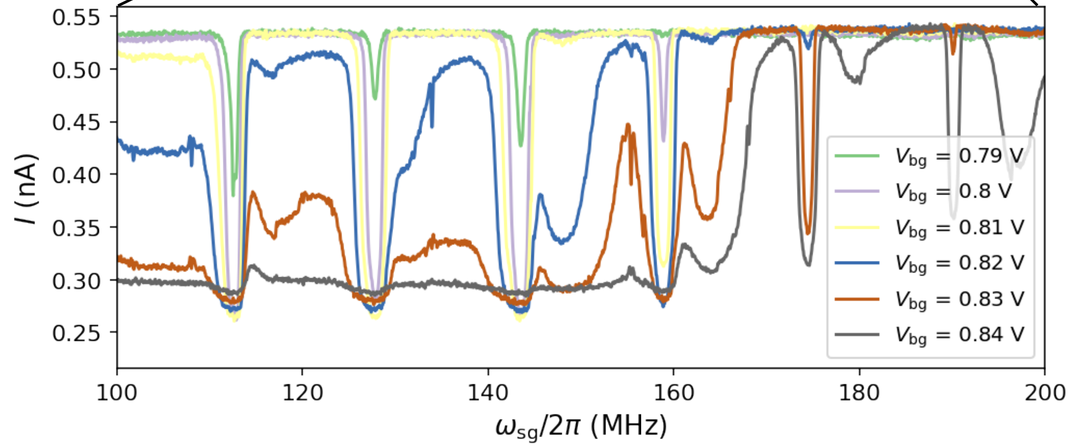




spacing between features $\Delta\omega_{\mathrm{sg}} = 15\ \mathrm{MHz}$



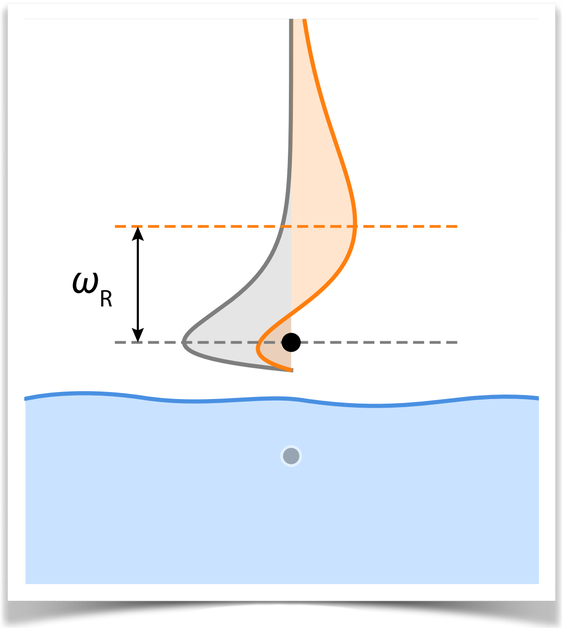
Conclusion

1. CPW resonator with superfluid helium
   - identified contributions from PT
   - possible routes to reduce vibrations

2. Microdevices with electrons on helium: high-frequency excitations
   - hot electron effects
   - new resonant phenomena?

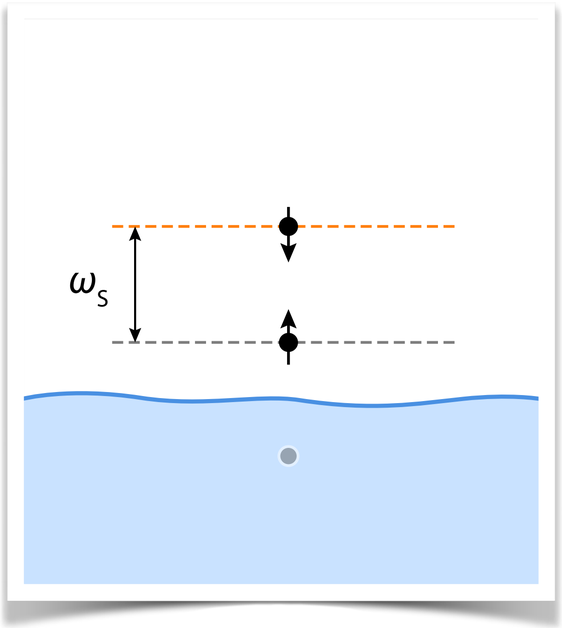
stay tuned…

Qubit states



Rydberg states

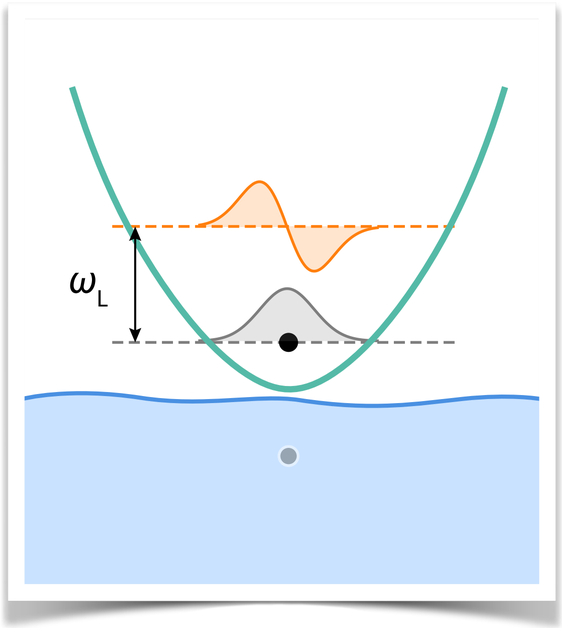
$\omega_R/2\pi = 120$ GHz



Spin states

$\omega_s/2\pi = 5$ GHz at $B = 0.2$ T

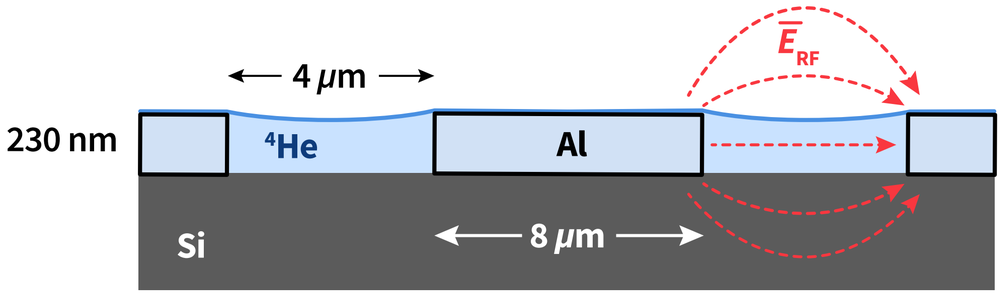
($T_2 \approx 1.5$ s)



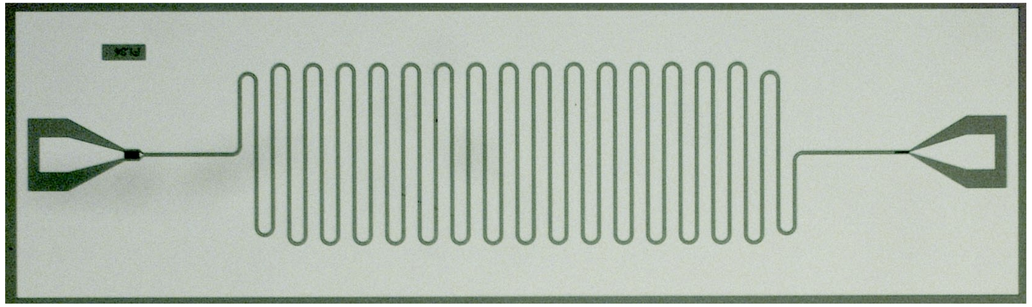
Lateral motional states

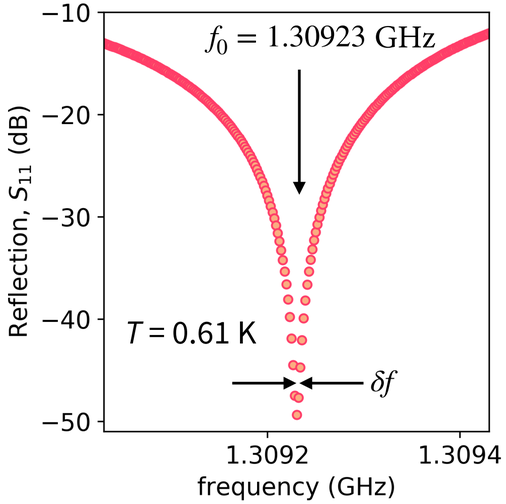
$\omega_s/2\pi = 5$ GHz

Coplanar waveguide resonator

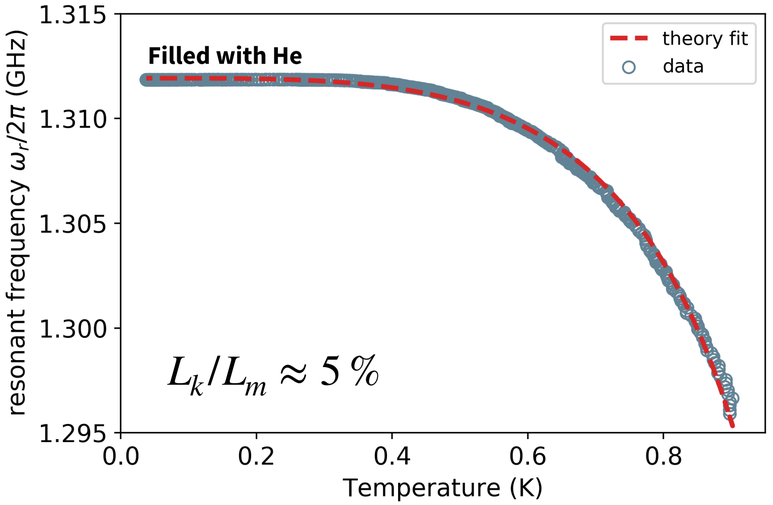


reflection S_{11} is measured using VNA

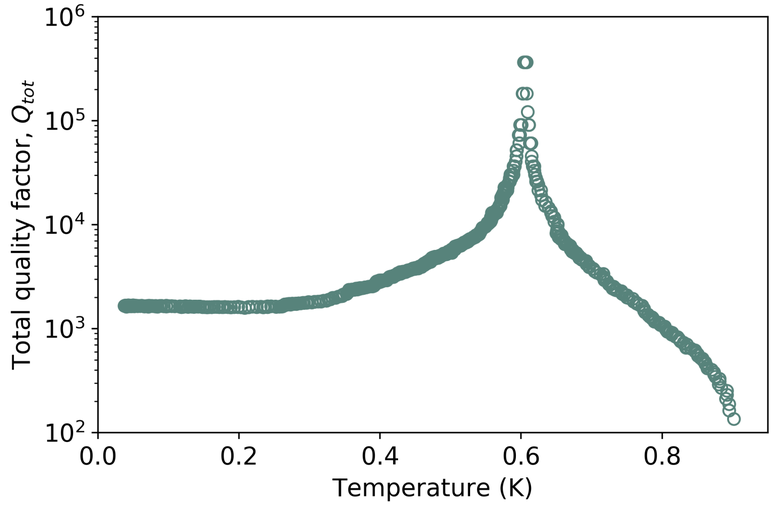




Resonance frequency



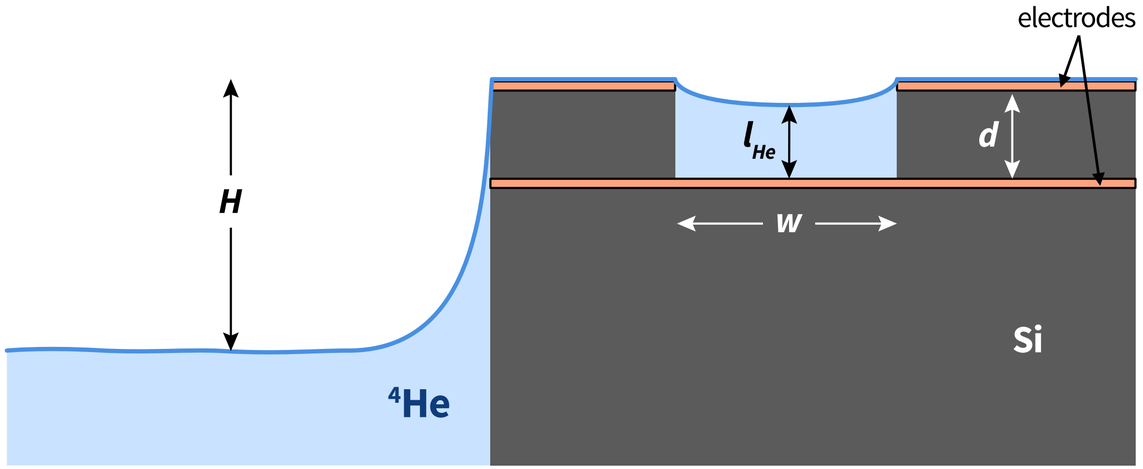
Quality factor



$\omega_r \propto 1/\sqrt{L_k + L_m}$ $\quad L_k \propto \lambda_L(T)^2$

Anomaly around 0.6 K ?

Devices with superfluid helium

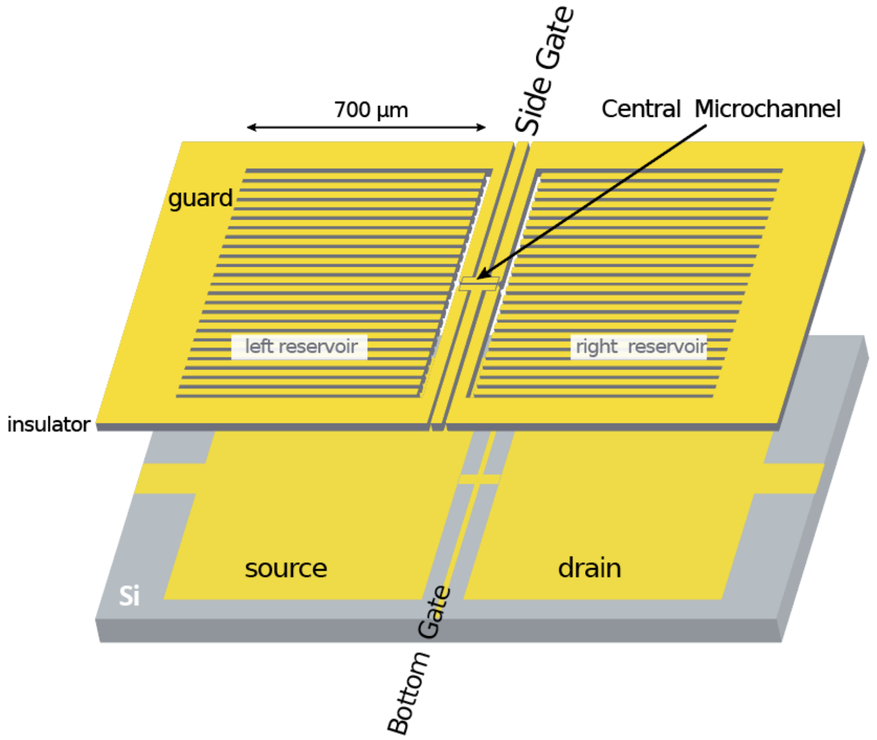


microstructures filled by capillary action of superfluid ^{4}He

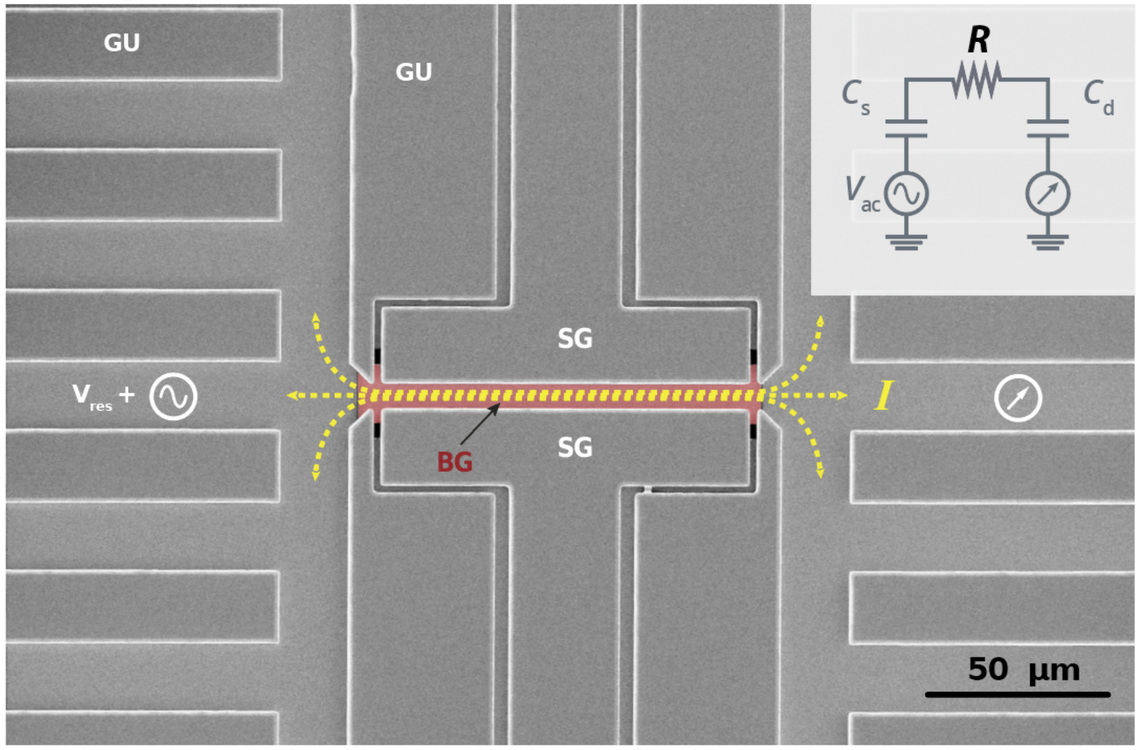
$$l_{He} = d - \frac{w^2}{8}\frac{\rho g H}{\alpha_t}$$

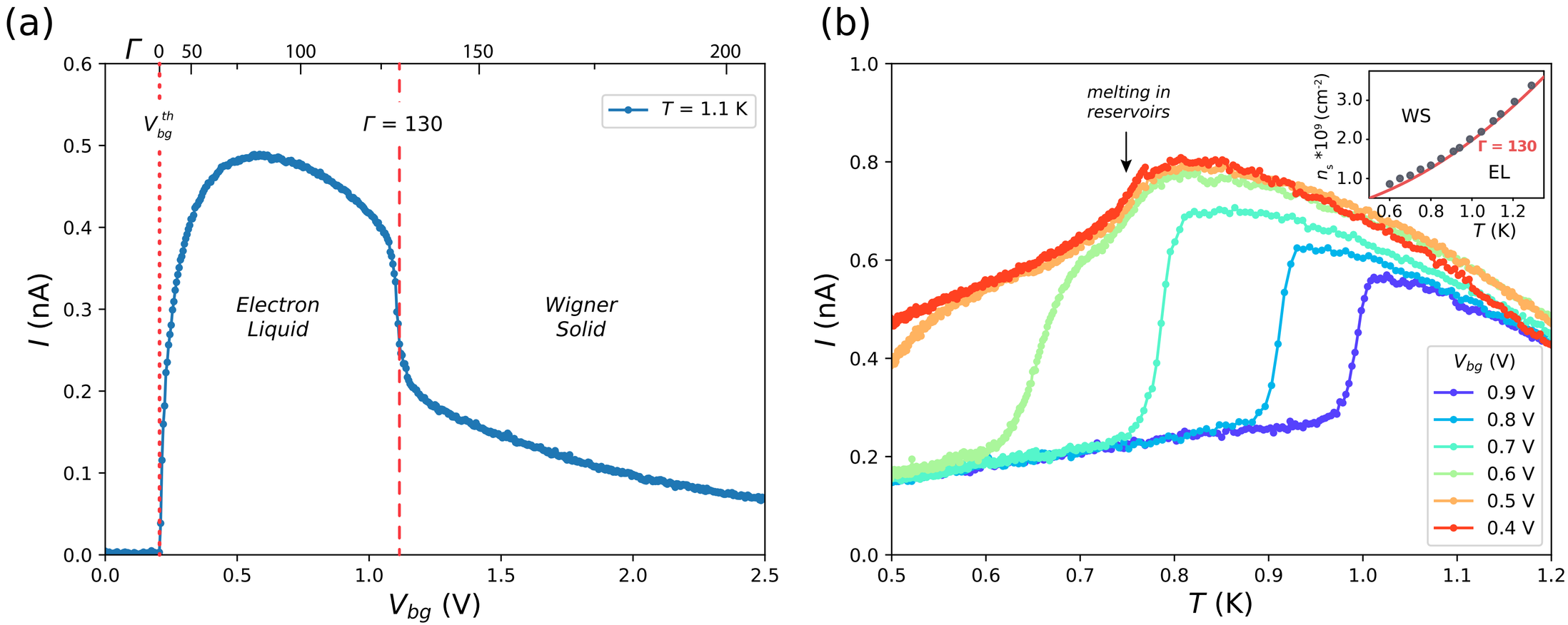
α_t - surface tension of liquid helium
ρ - density liquid helium
w - width typical 1 - 20 µm
d - depth typical 0.5 - 2 µm

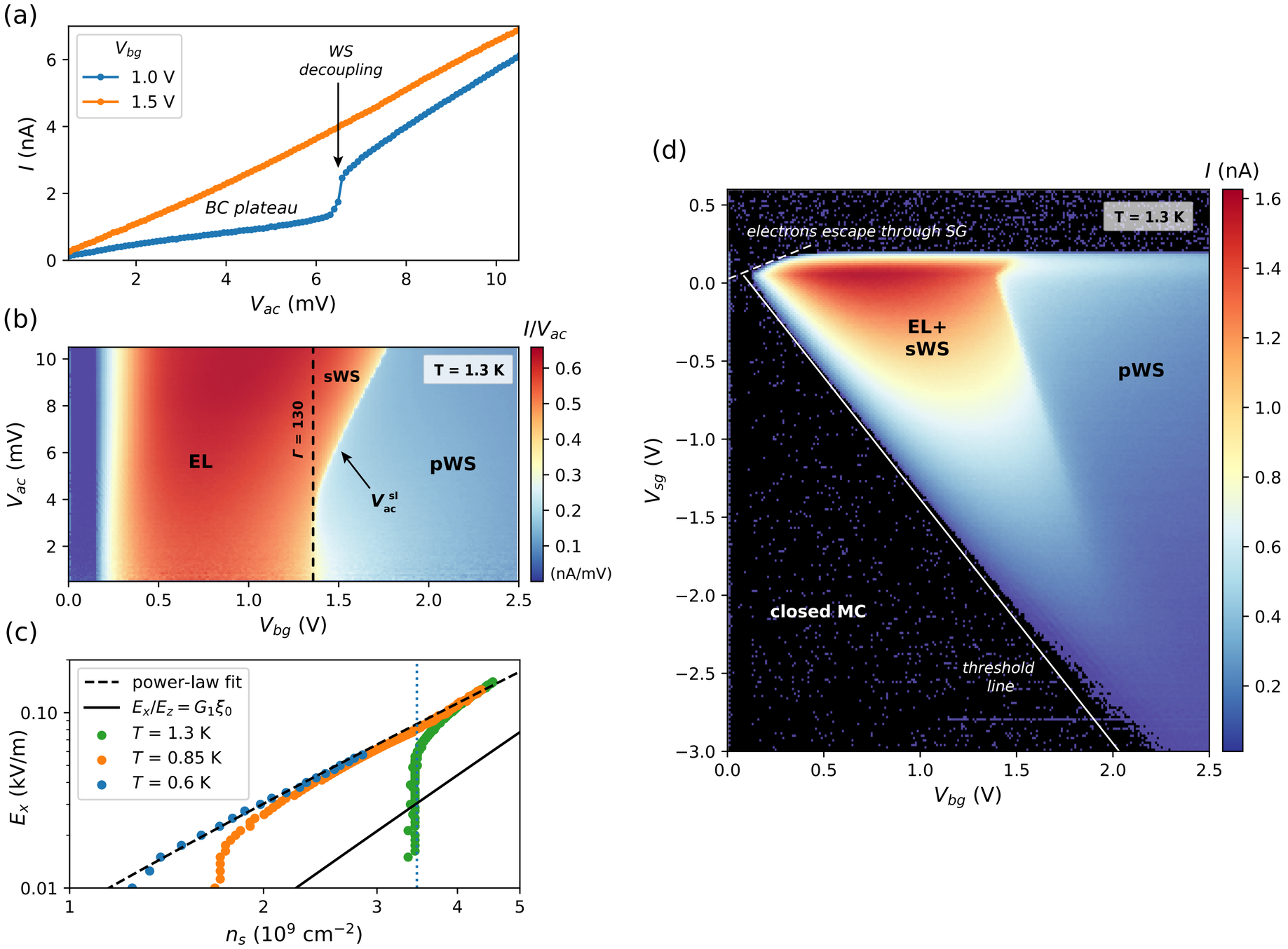
(a)


700 µm
Side Gate
Central Microchannel
guard
left reservoir
right reservoir
insulator
source
drain
Si
Bottom Gate

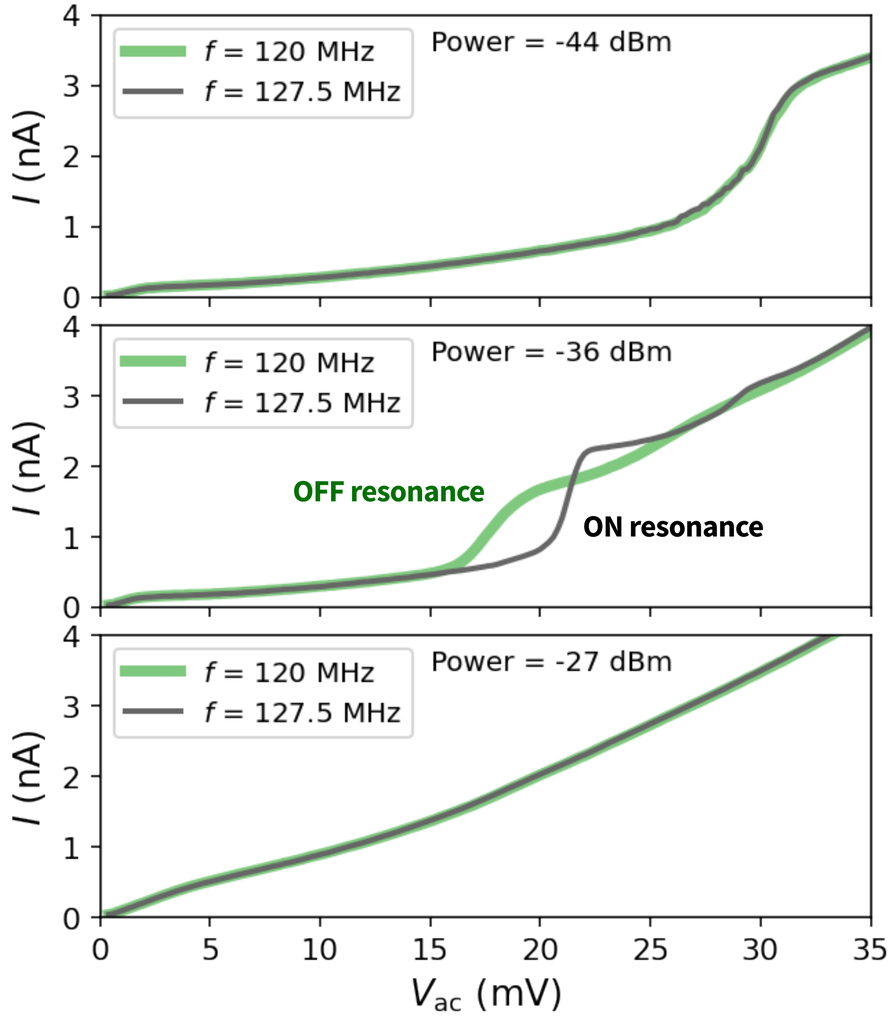
(b)

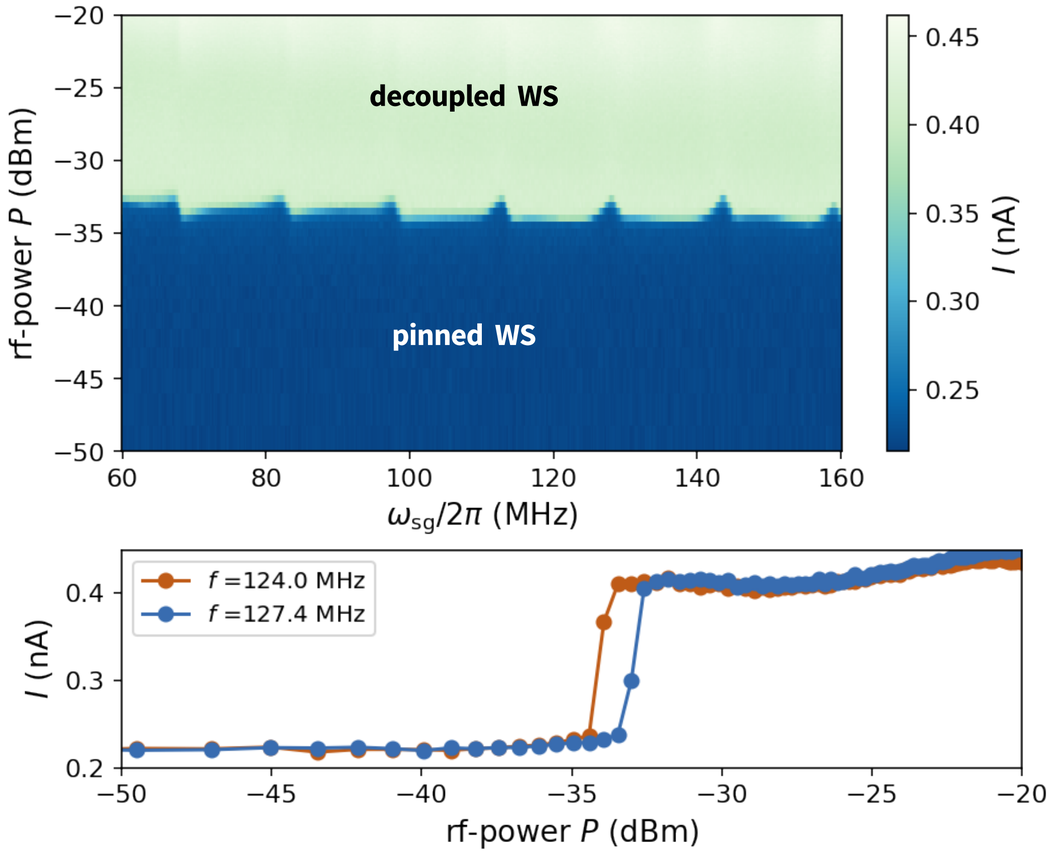

GU
GU
R
C_s
C_d
V_{ac}
SG
SG
V_{res} +
BG
I
50 µm


(a)
Γ
0
50
100
150
200
V_{bg}^{th}
Γ = 130
T = 1.1 K
Electron Liquid
Wigner Solid
I (nA)
V_{bg} (V)
(b)
melting in reservoirs
n_s *10^9 (cm^{-2})
WS
Γ = 130
EL
T (K)
V_{bg} (V)
0.9 V
0.8 V
0.7 V
0.6 V
0.5 V
0.4 V
I (nA)
T (K)

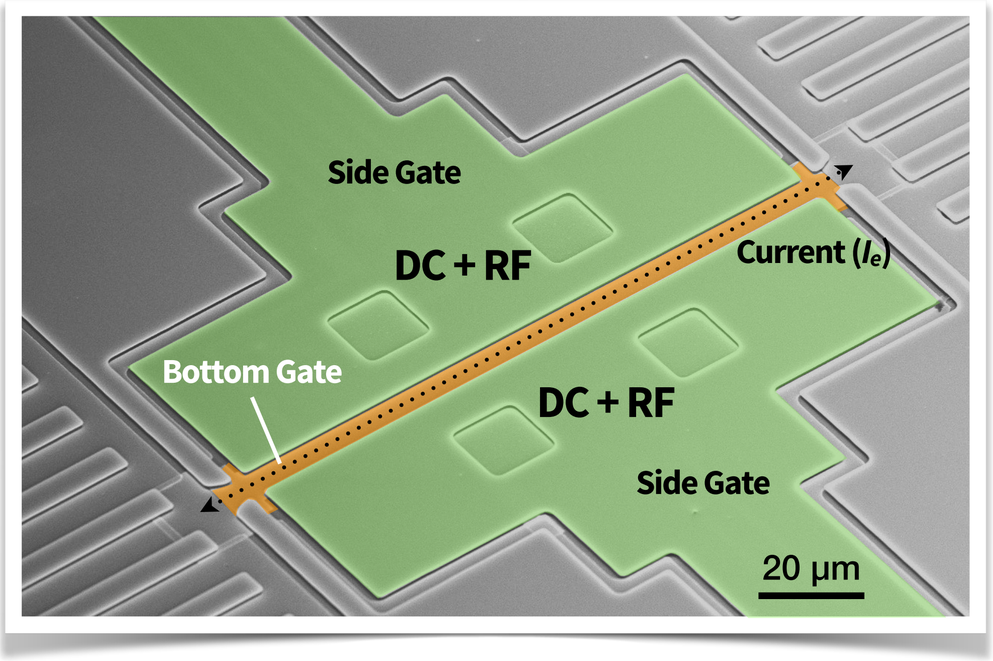

(a)
V_{bg}
1.0 V
1.5 V
WS
decoupling
BC plateau
I (nA)
V_{ac} (mV)
(b)
I/V_{ac}
T = 1.3 K
sWS
EL
pWS
r = 130
V_{ac}^{sl}
V_{ac} (mV)
V_{bg} (V)
(nA/mV)
(c)
power-law fit
$E_x/E_z = G_1\xi_0$
T = 1.3 K
T = 0.85 K
T = 0.6 K
E_x (kV/m)
n_s (10^9 cm^{-2})
(d)
I (nA)
T = 1.3 K
electrons escape through SG
EL+
sWS
pWS
closed MC
threshold
line
V_{sg} (V)
V_{bg} (V)

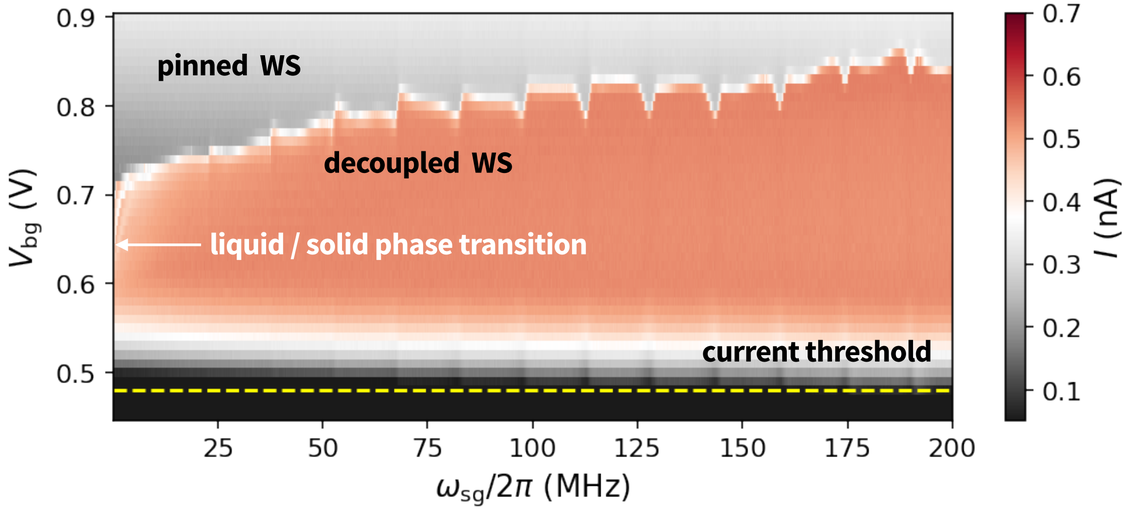
Modulation of Bragg-Cherenkov plateau





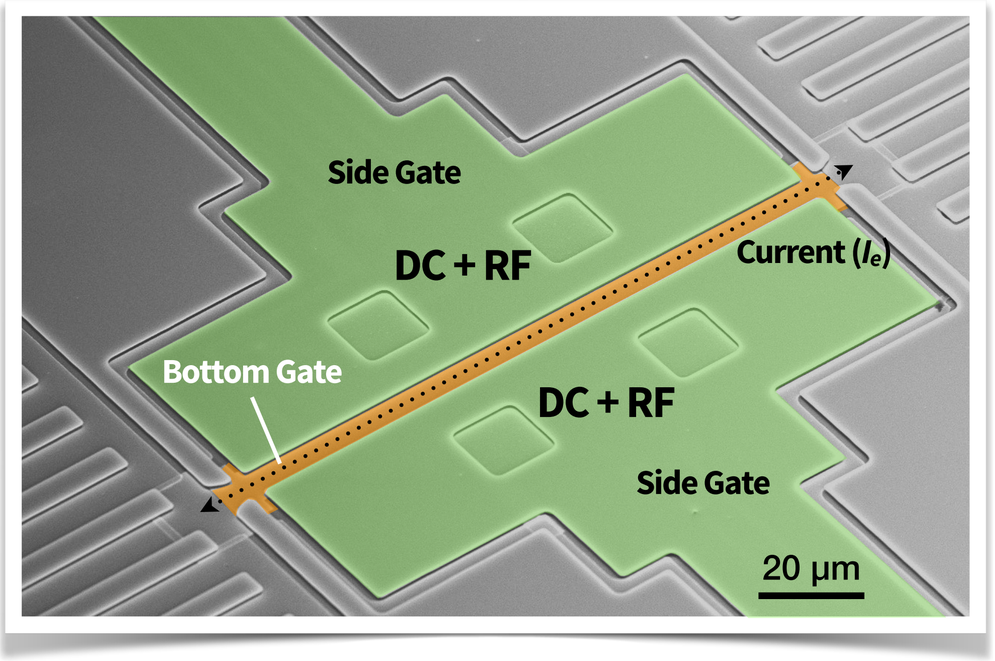
Superimposing rf-excitations

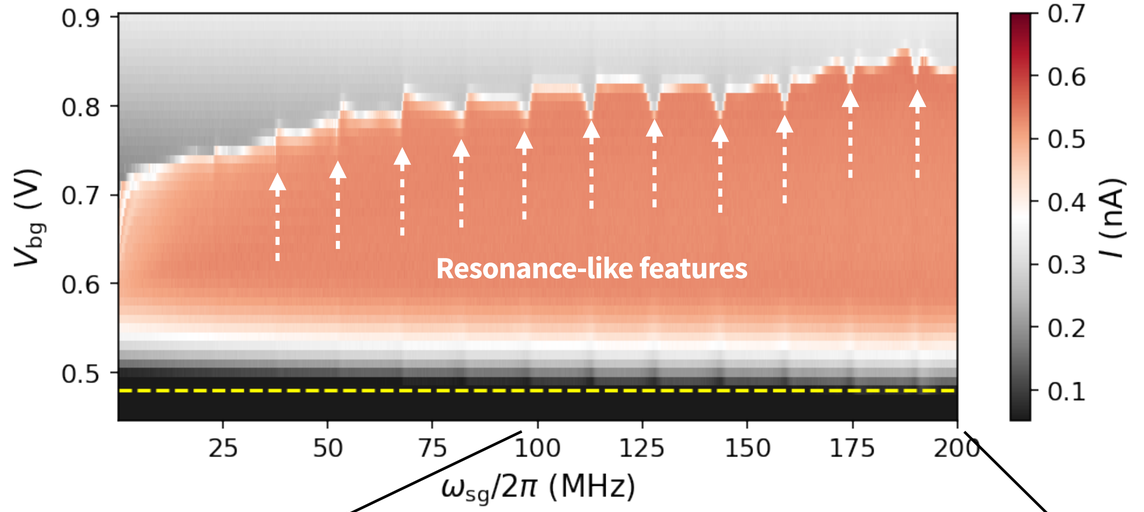


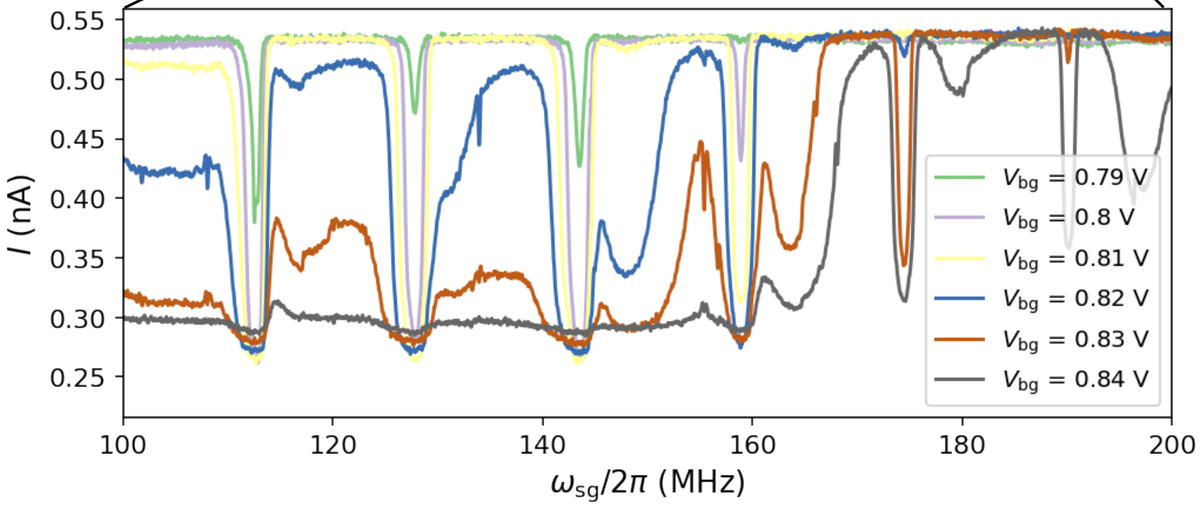


- Modification of the phase diagram

Superimposing rf-excitations







- Modification of the phase diagram
- Resonance-like features
- Spacing between features $\Delta\omega_{\mathrm{sg}} = 15\ \mathrm{MHz}$