Detection of the Rydberg states of electrons on superfluid helium confined in microchannel devices

OIST

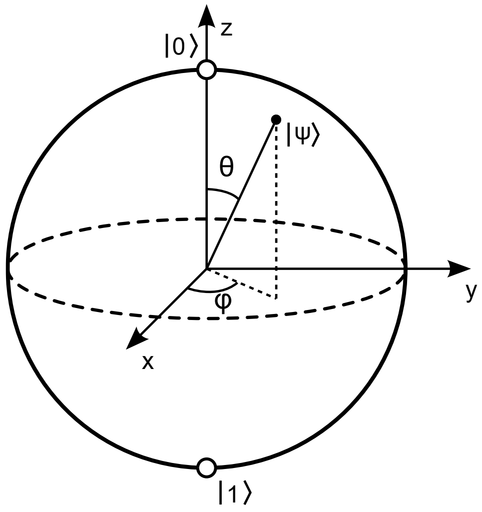
Shan Zou

Public presentation 2022/07/12

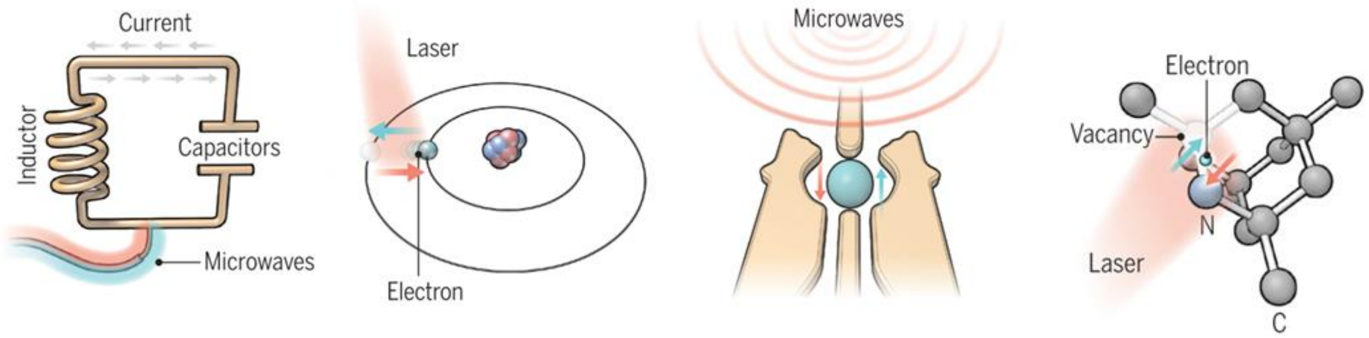
2022/7/14

Motivations

Quantum bit (qubit)



Quantum computation platform



Superconducting circuit | Trapped ions | Silicon quantum dots | Vacancies in diamond

G. Popkin, Science 354, 1090 (2016)

Electrons on liquid helium system
A new platform for quantum computing?

First proposal: P. Platzman and M. Dykman, Science 284, 1967 (1999)

Advantages:
Large scalability
Mobile qubits
Full electrical control

Goal: Realizing sensitive quantum state detection of electrons on helium for qubit implementation

Content

Introduction to electrons on helium system (for qubit implementation)

Quantum (Rydberg) states detection

--Project 1: Conductivity method

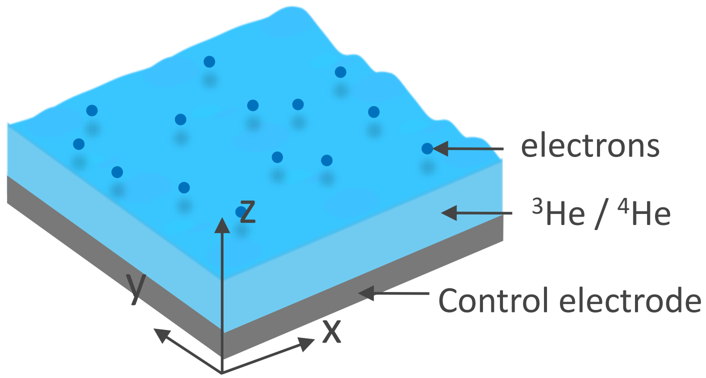
--Project 2: Image charge method

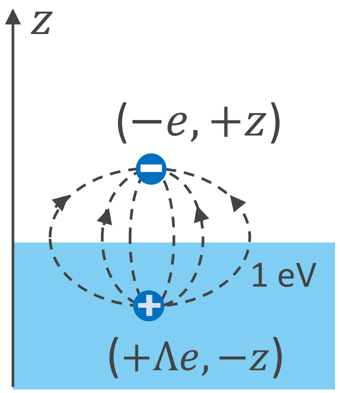
Novel transport phenomenon

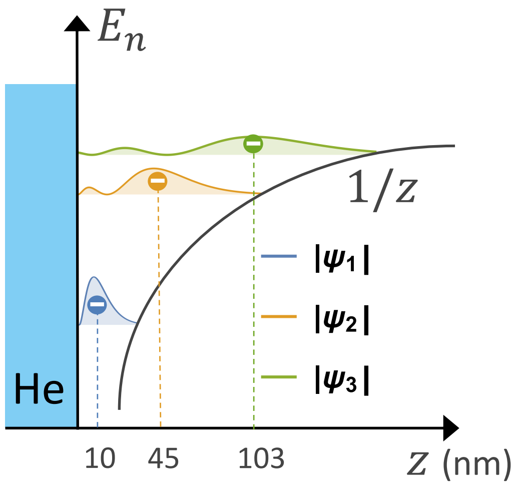
--Project 3: Repetitive stick-slip motion

Electron on helium system for qubit implementation

Basic picture



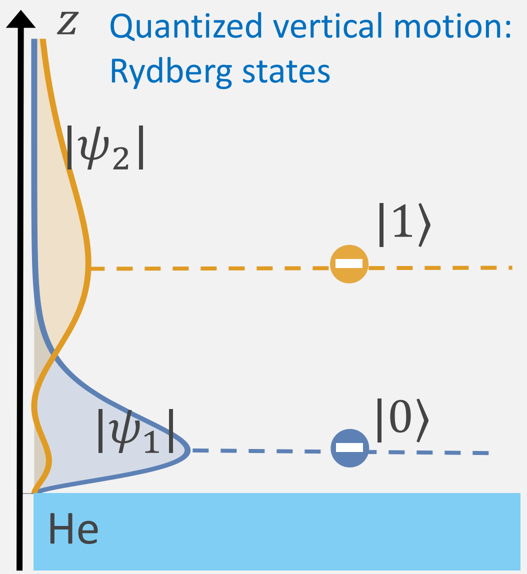


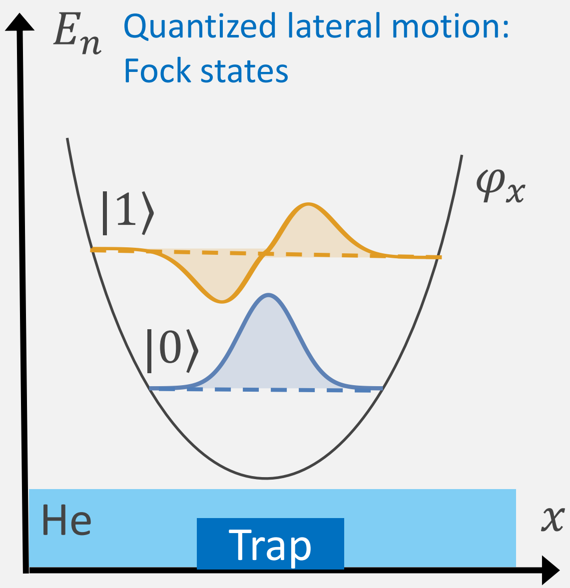


$\Lambda = 0.0068$

Qubit implementation

Charge Qubit

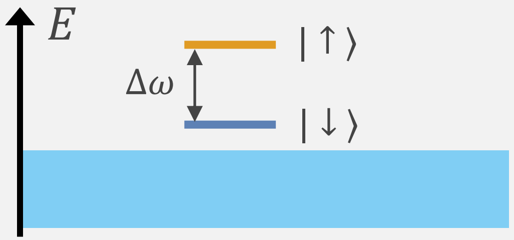




Platzman and Dykman, Science 284, 1967 (1999)

D. Schuster, et al., PRL 105, 040503 (2010)

Spin Qubit



S. Lyon, PRA 74, 052338 (2006)

Readout of spin state:
singlet-triplet splitting? No overlapping

Spin-Orbit coupling

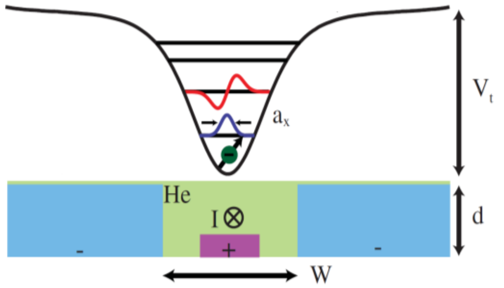
D. Schuster, et al., PRL 105, 040503 (2010)

E. Kawakami et al., PRL 123, 086801 (2019)

Quantized lateral motion of a single electron

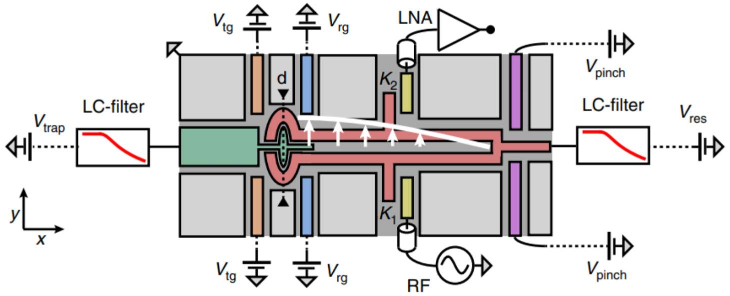
Circuit QED architecture
with electron on He/Ne surface

Trapped states with quantized lateral motion

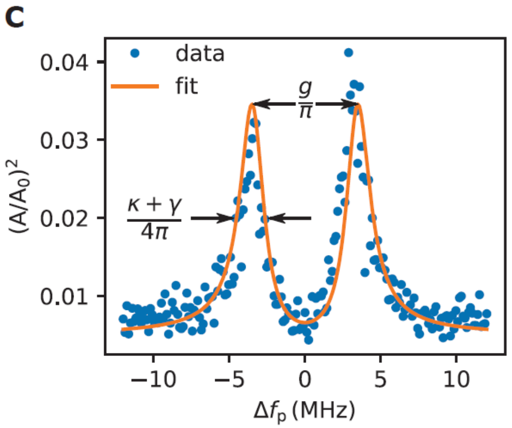


Coupled with

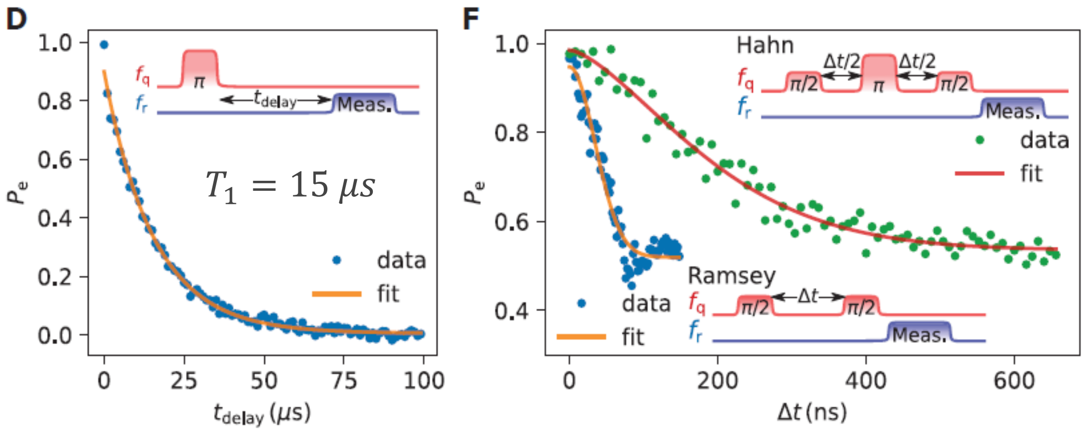
MW photons (5-10 GHz) provided by CPW



Rabi splitting



Time-domain characterization



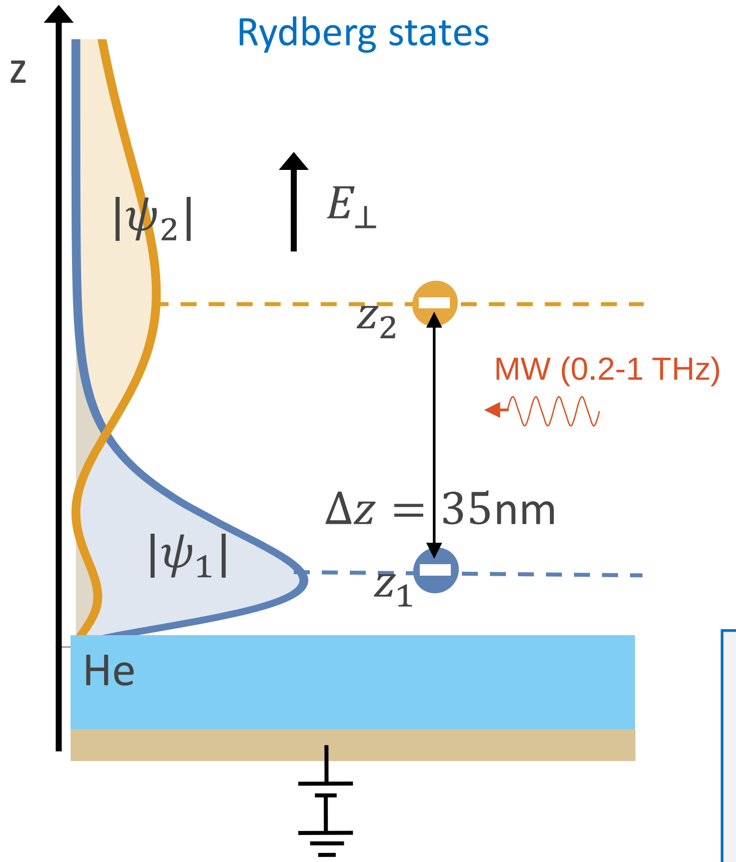
$T_2^* = 50\ ns$

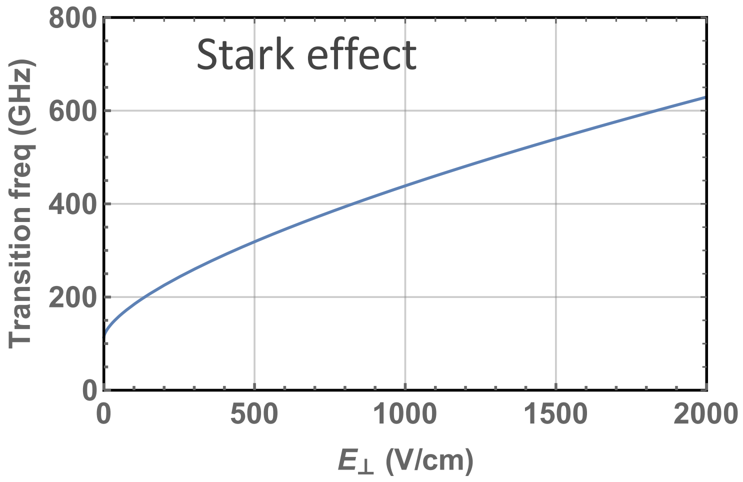
$T_2 = 220\ ns$

D. Schuster, et al., PRL 105, 040503 (2010)
G. Koolstra, et al., Nat. Comm 10, 5323 (2019)
X. Zhou, et al., Nature 605, 46 (2022)

MW: microwave CPW: coplanar waveguide circuit QED: circuit quantum electrodynamics

Quantized vertical motion of a single electron

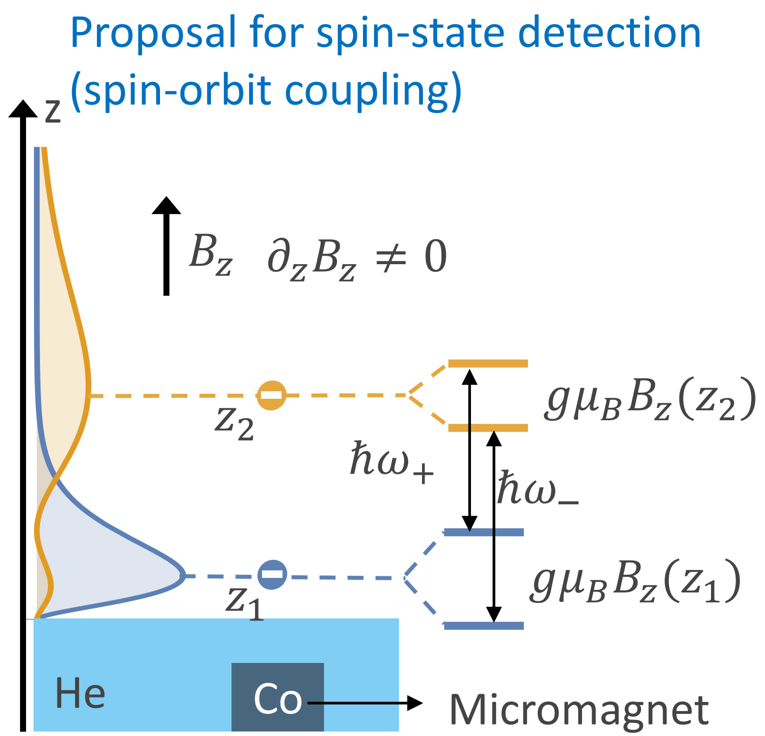




Lack of sensitive state-readout method!

Circuit QED ? MW photons > 100GHz

Substitutions:
(1) Image charge measurement
(2) Conductivity measurement



E. Kawakami et al., PRL 123, 086801 (2019)

$\omega_- - \omega_+ \simeq \frac{g\mu_B \partial_z B_z \Delta z}{\hbar} >$ linewidth of Rydberg resonance

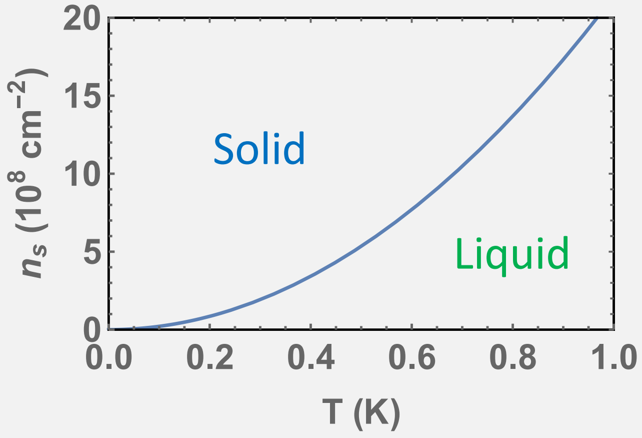
Project 1

Rydberg state detection (conductivity method)

1.1 Background

In-plane motion:
Nondegenerate 2DES

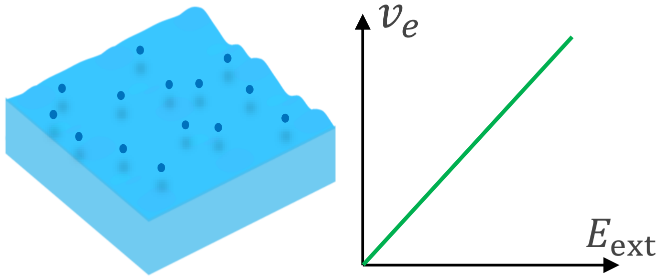
Phase diagram



Coulomb interaction: $1/\sqrt{n_s}$

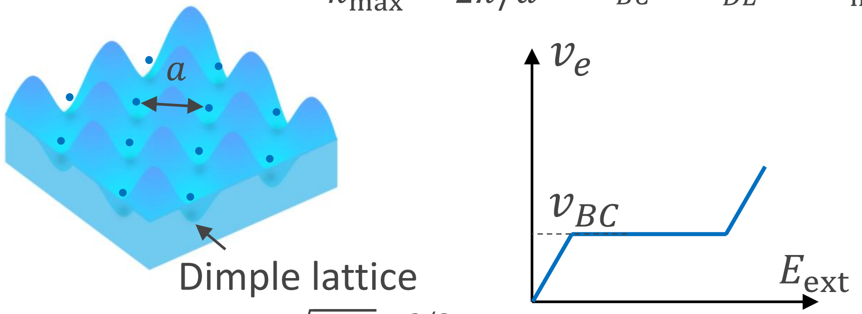
Kinetic energy: $k_B T$

Electron liquid



Electron solid

$k_{\max} = 2\pi/a$ $\quad v_{BC} \equiv v_{DL}^{\max} \propto k_{\max}^{1/2}$

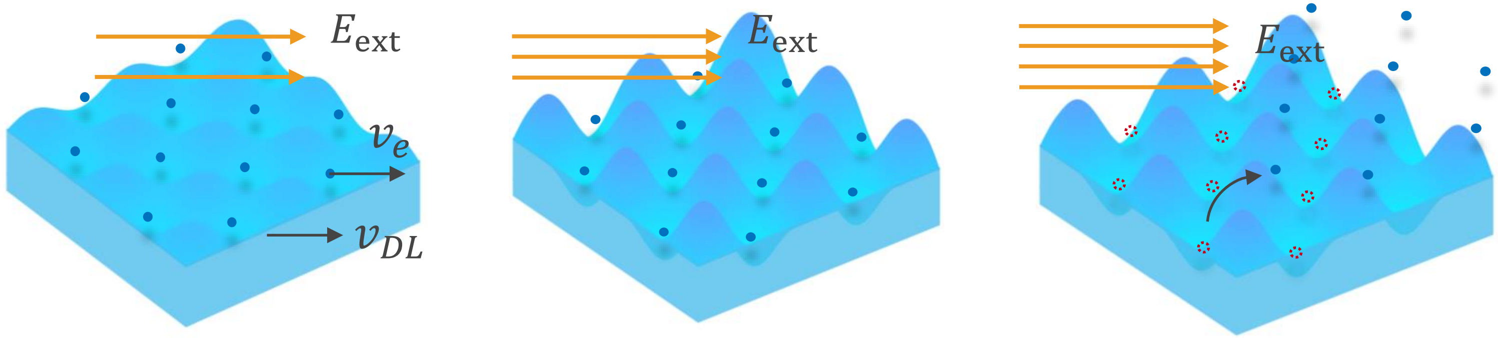


$\Omega_k = \sqrt{\alpha/\rho}\, k^{3/2}$

α: Surface tension of helium $\quad \rho$: density of liquid helium

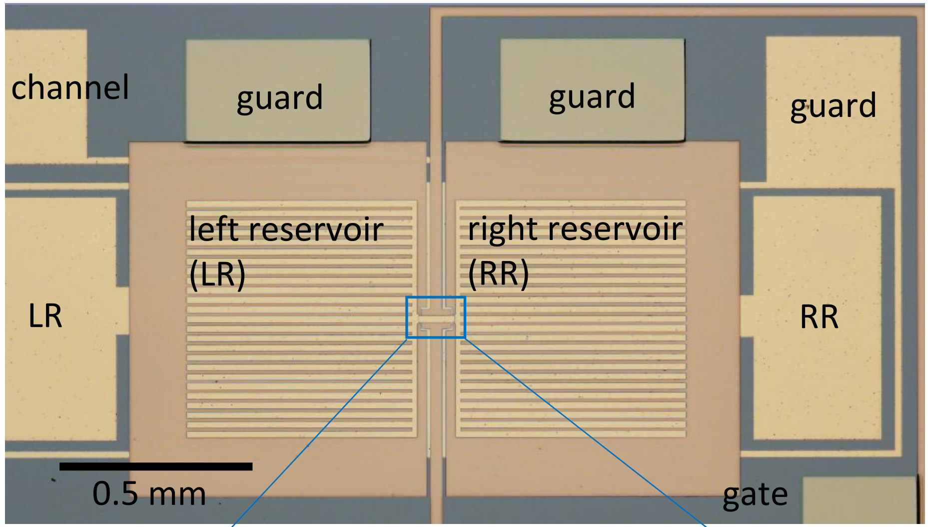
Bragg Cherenkov (BC) effect:

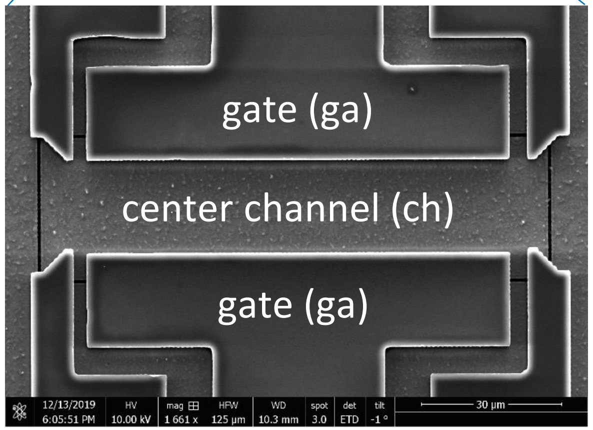
nonlinear mobility of electron solid in response to the external driving field

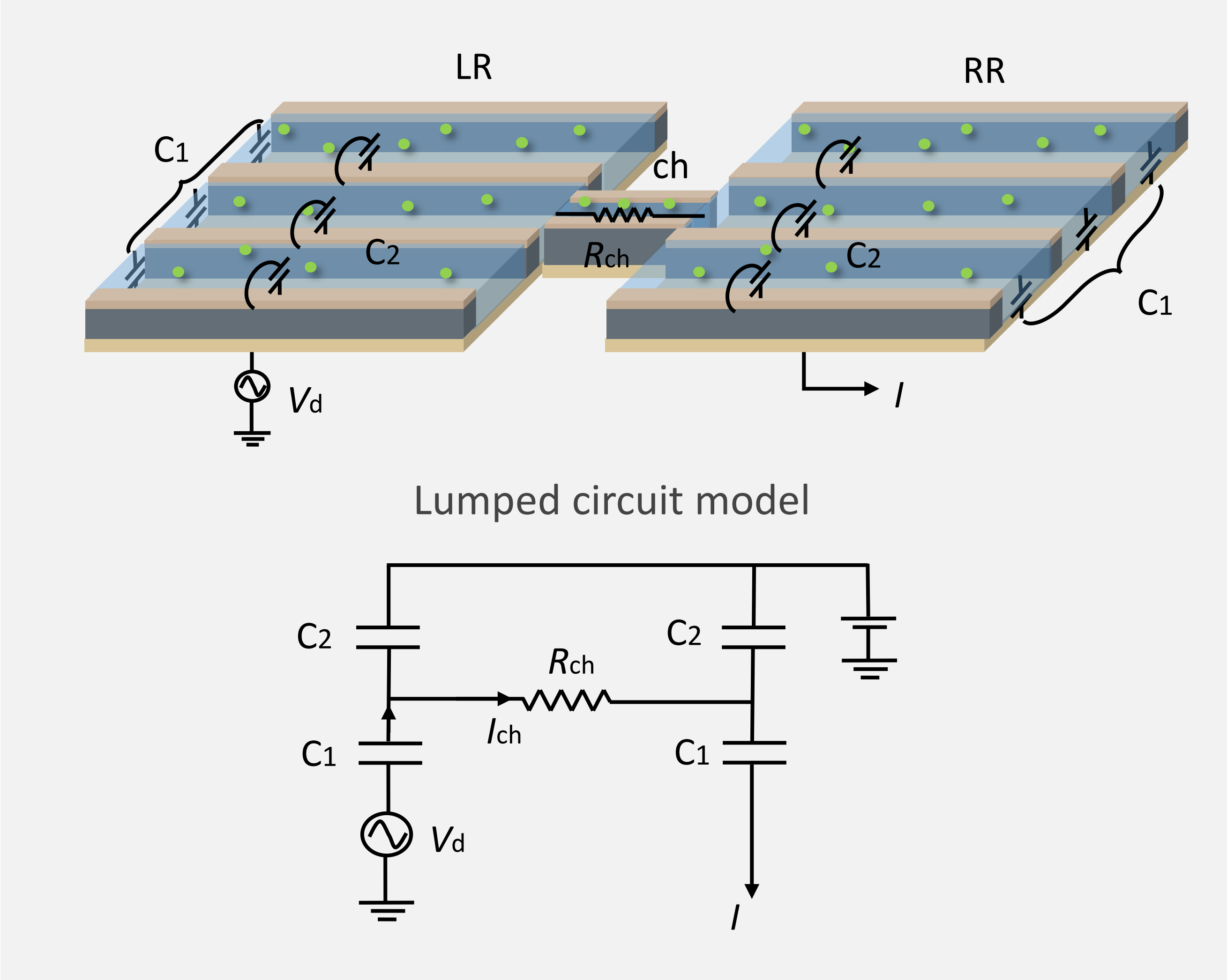


$v_{DL} = v_e < v_{BC}$ $\quad v_{DL} = v_e = v_{BC}$ $\quad v_e > v_{BC}$

1.2 Microchannel devices

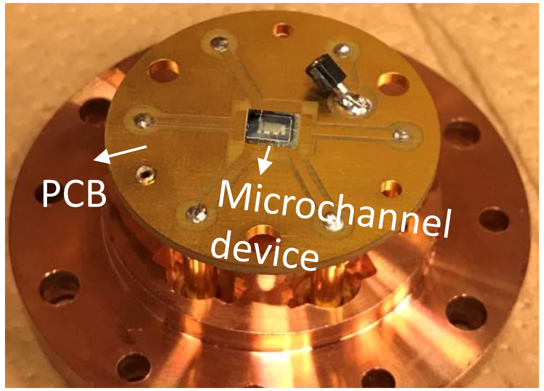


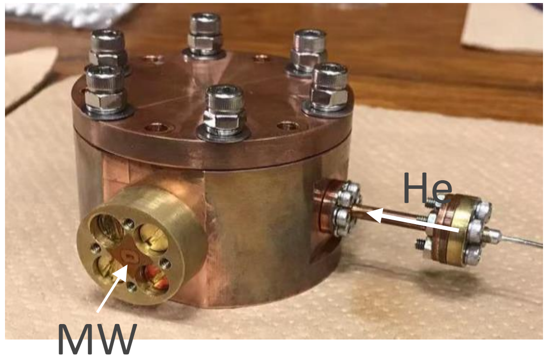


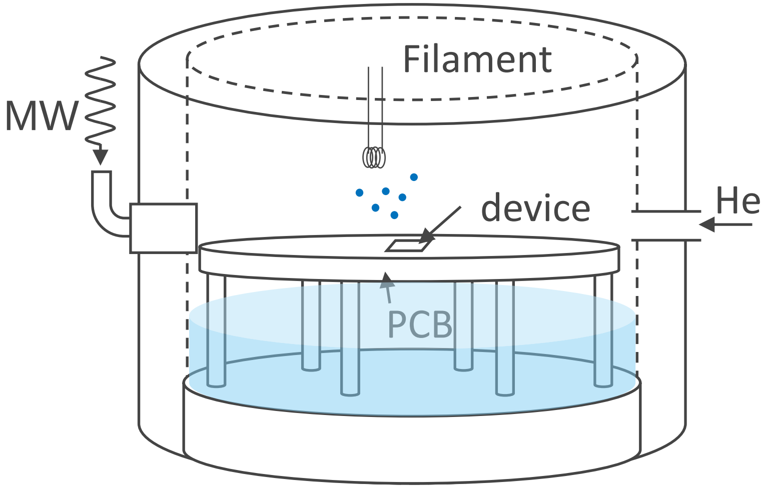


1.2 Cryogenic setup

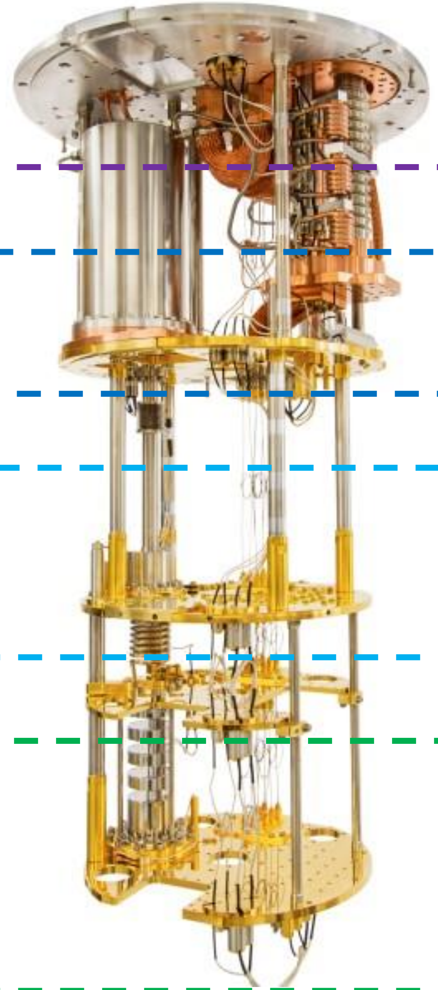
Experimental cell







Dilution refrigerator (BlueFors DL 400)



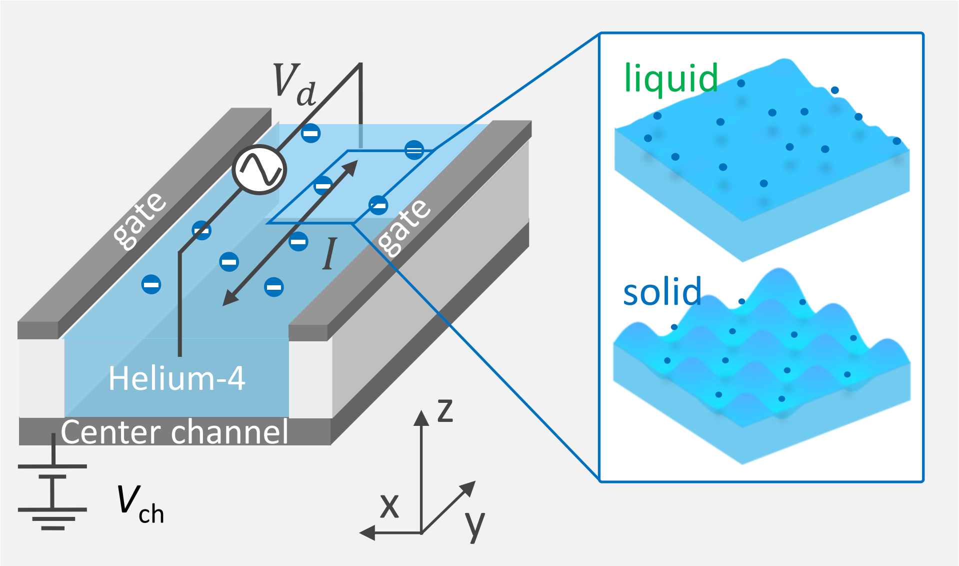
50K Plate

4K Plate
~0.4 W

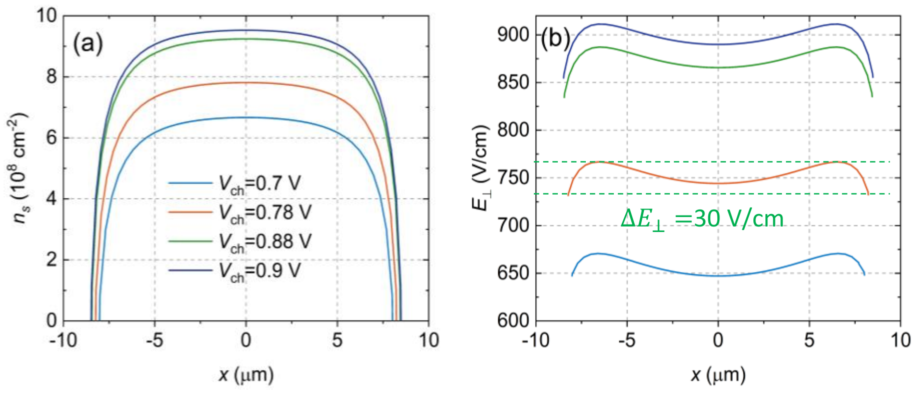
Still
0.5 / 1 K
~ 50mW

Mixing Chamber
30 / 150 mK
15 / 500 μW

1.3 Rydberg states detection (conductivity change)

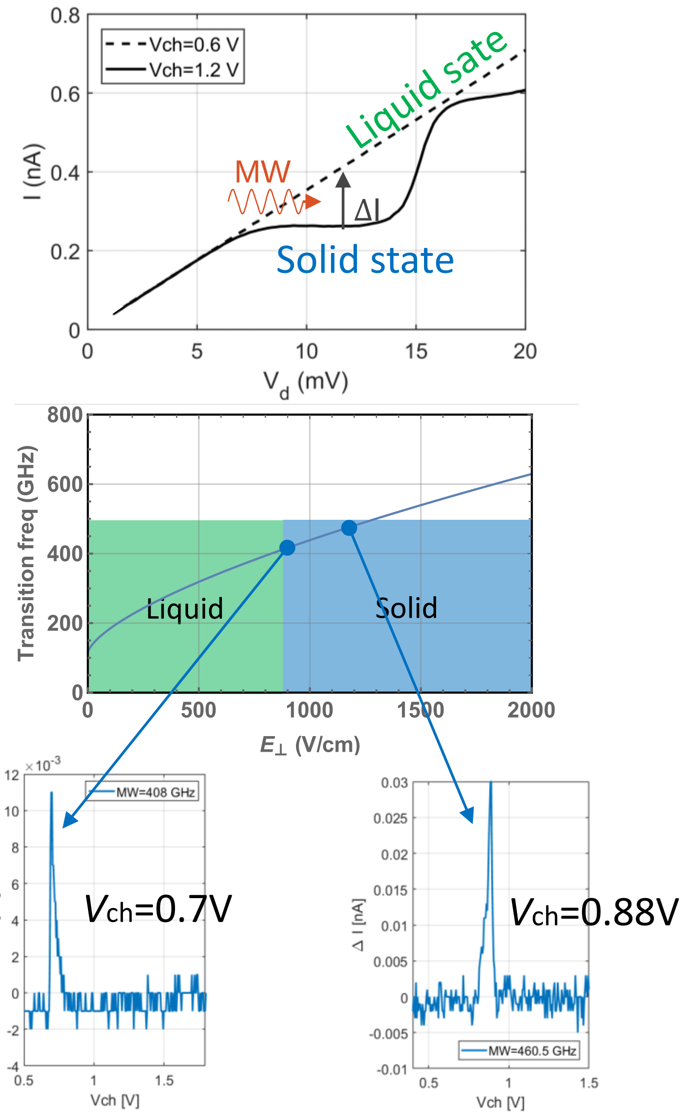


Cross-sectional profile of electron density and holding field



Inhomogeneous broadening approx. 10 GHz

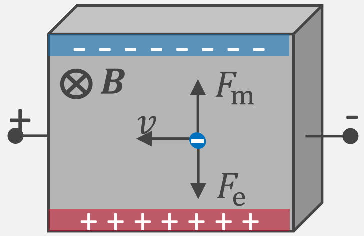
Excitation induced conductivity change



limitations:

(1) Sensitive to the B field

Hall effect



(2) Many-electron effect

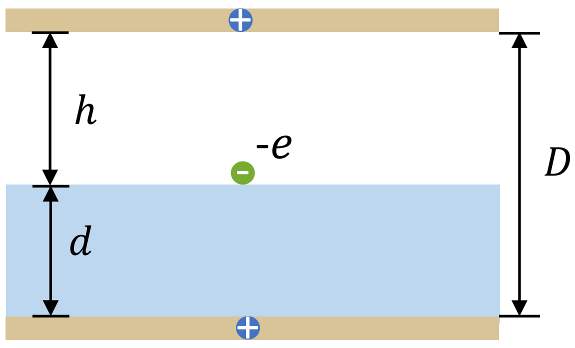
cannot scale down to single electron

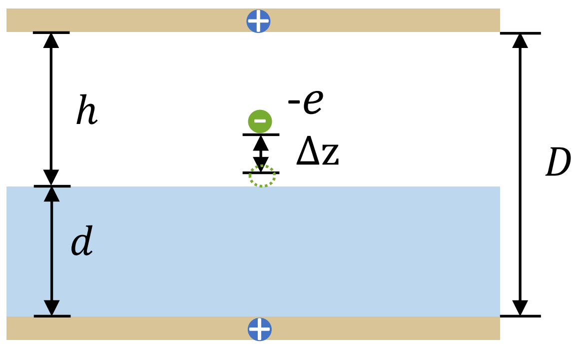
S. Zou et al. JLTP (2022)

Project 2

Rydberg state detection (Image-charge method)

2.1 Image charge method





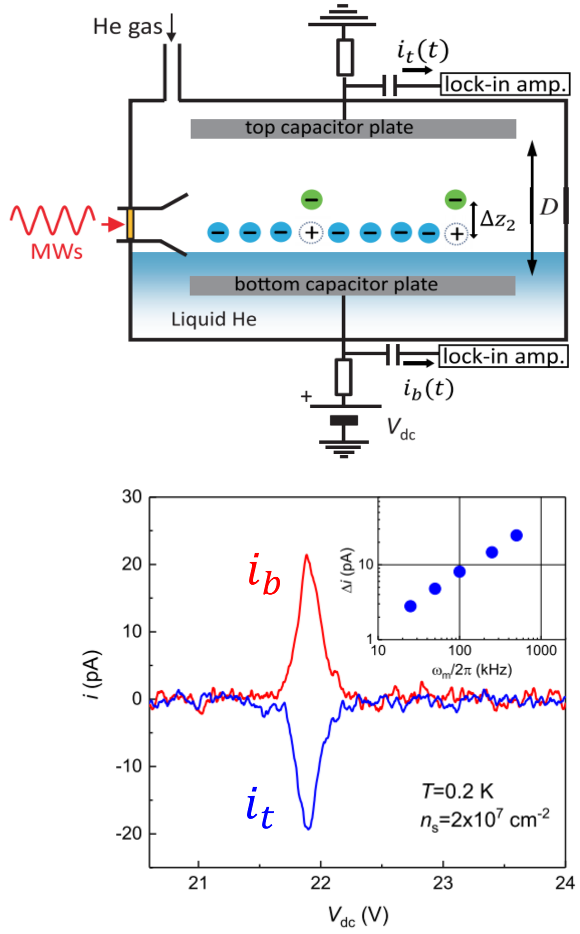
Change of image charge

$$\Delta q_t = q'_t - q_t = \frac{\Delta z}{D}e \simeq 10^{-5}e \quad \Delta q_b = q'_b - q_b = -\frac{\Delta z}{D}e \simeq -10^{-5}e$$

Parallel-plate capacitor		microchannel device
$D = 2\text{mm}\ (\Delta q \simeq 10^{-5}e)$	➡	$D = 4\ \mu\text{m}\ (\Delta q \simeq 10^{-2}e)$

e : Elementary charge

Experimental results

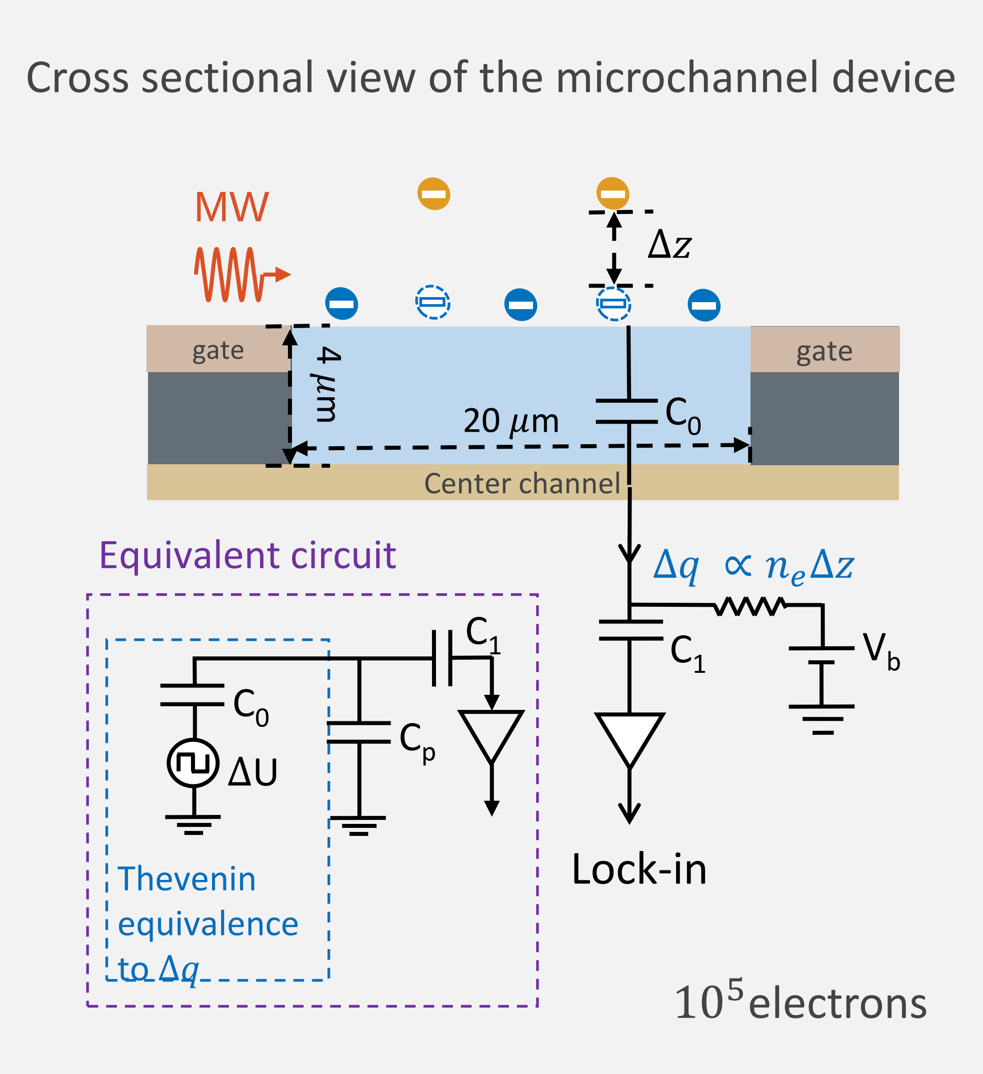


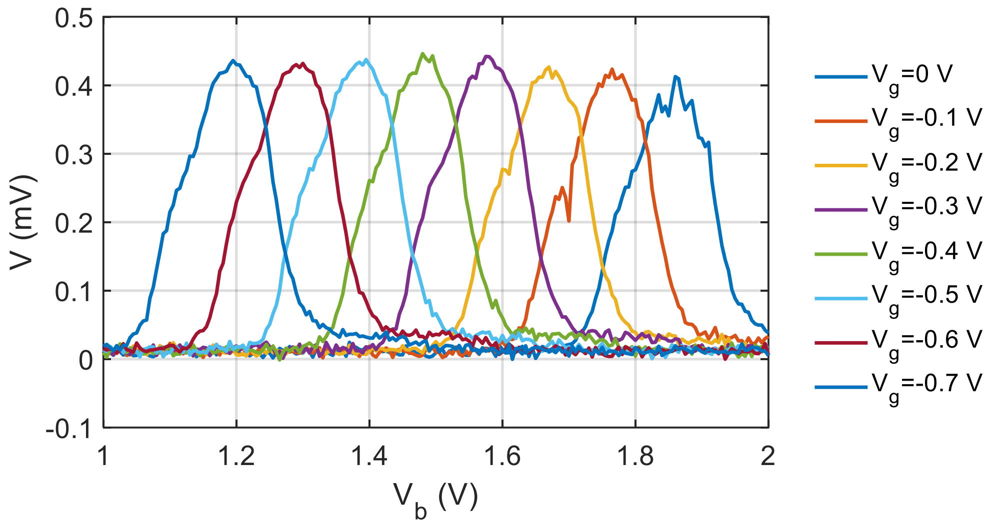
$D = 2\text{mm}$

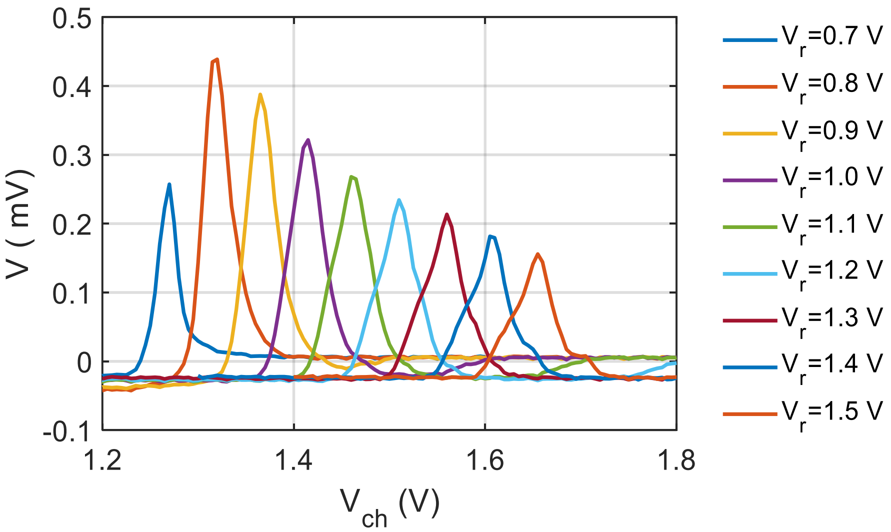
10^8electrons

E. Kawakami et al Phys. Rev.Lett.123.086801 (2019)

2.2 Image charge detection using microchannel device



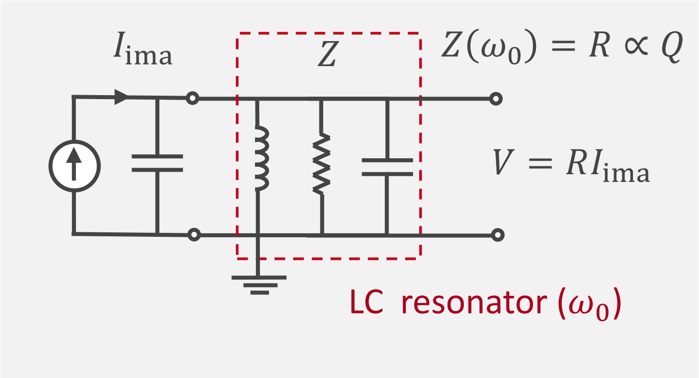


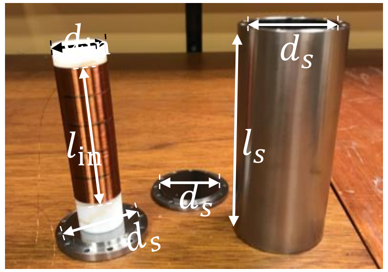


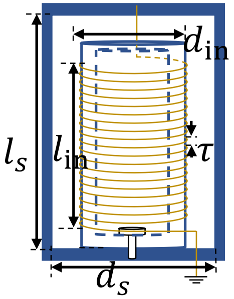
S. Zou and D. Konstantinov, arXiv 2207, 03737 (2022)

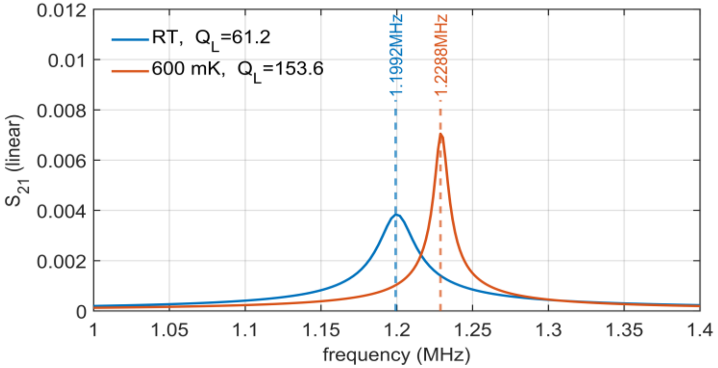
2.3 Improving Signal to Noise Ratio (SNR)

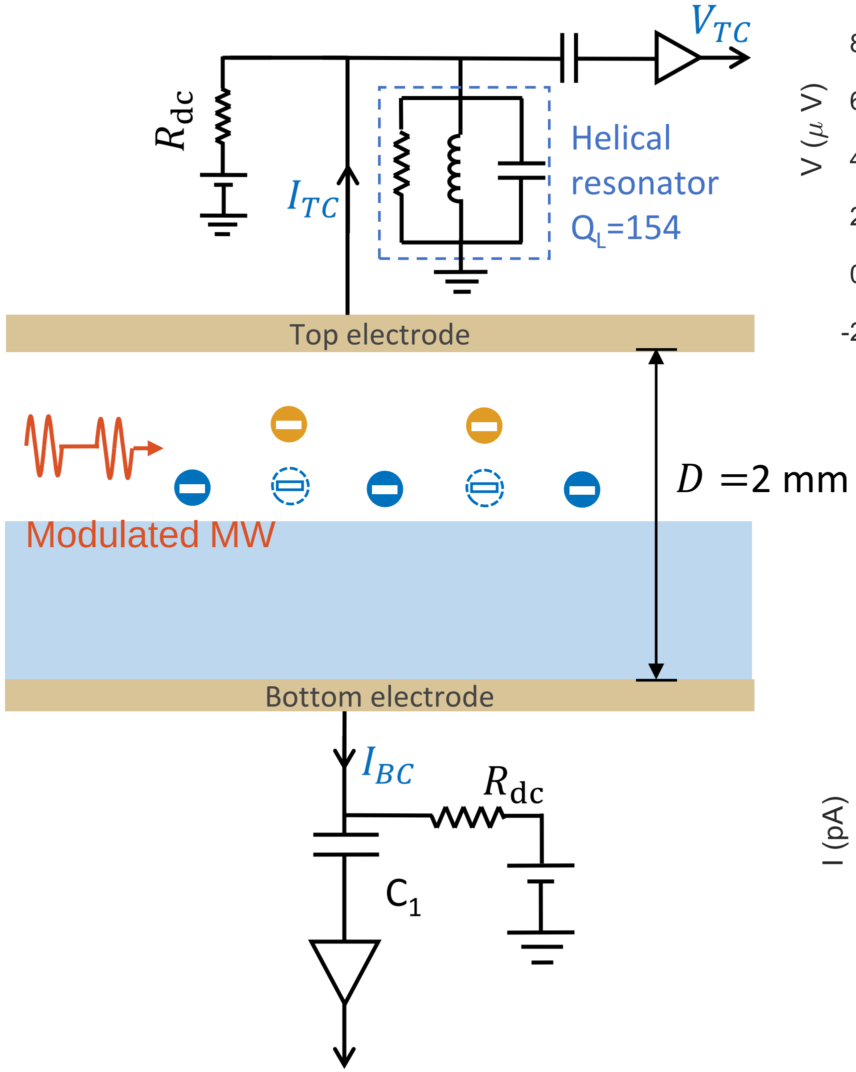
LC tank circuit

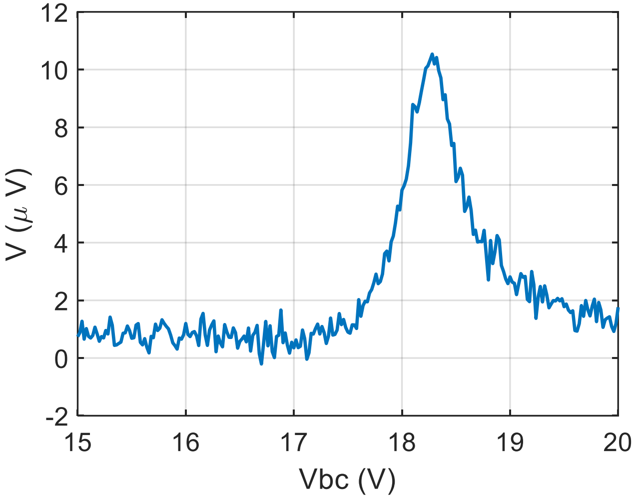


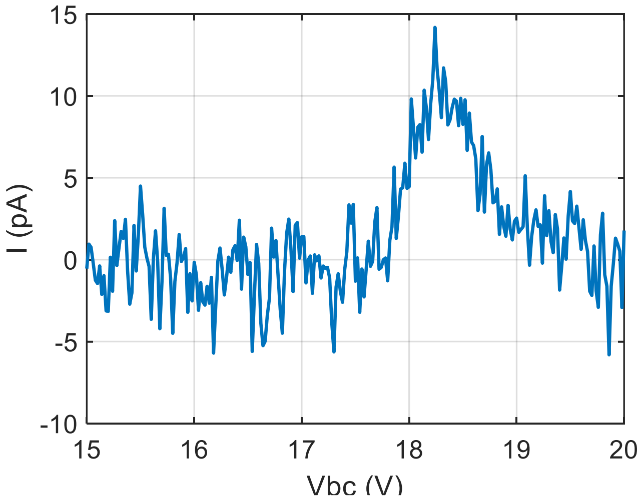








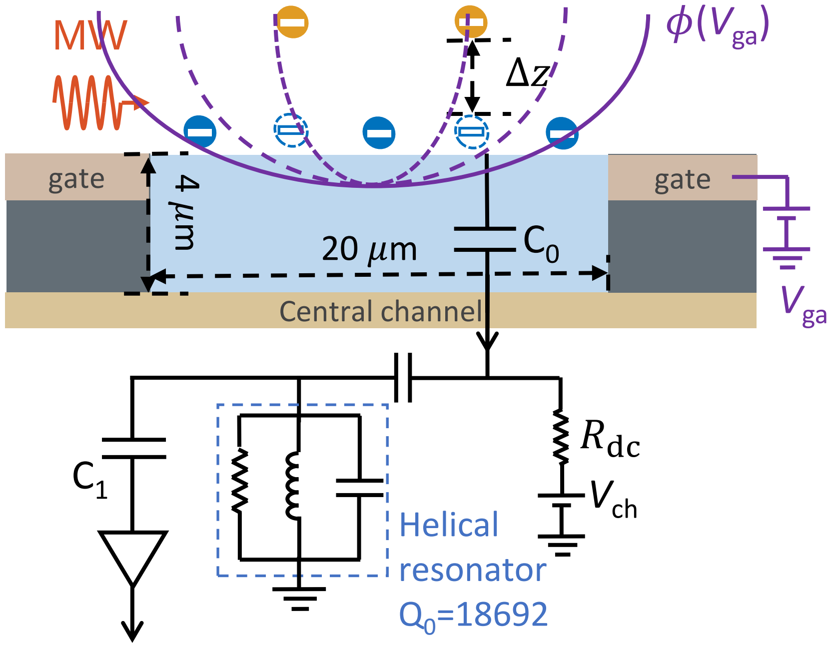




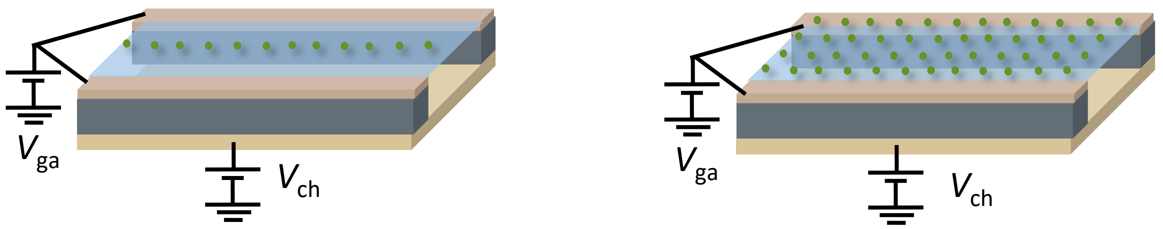
2.3 Improving SNR

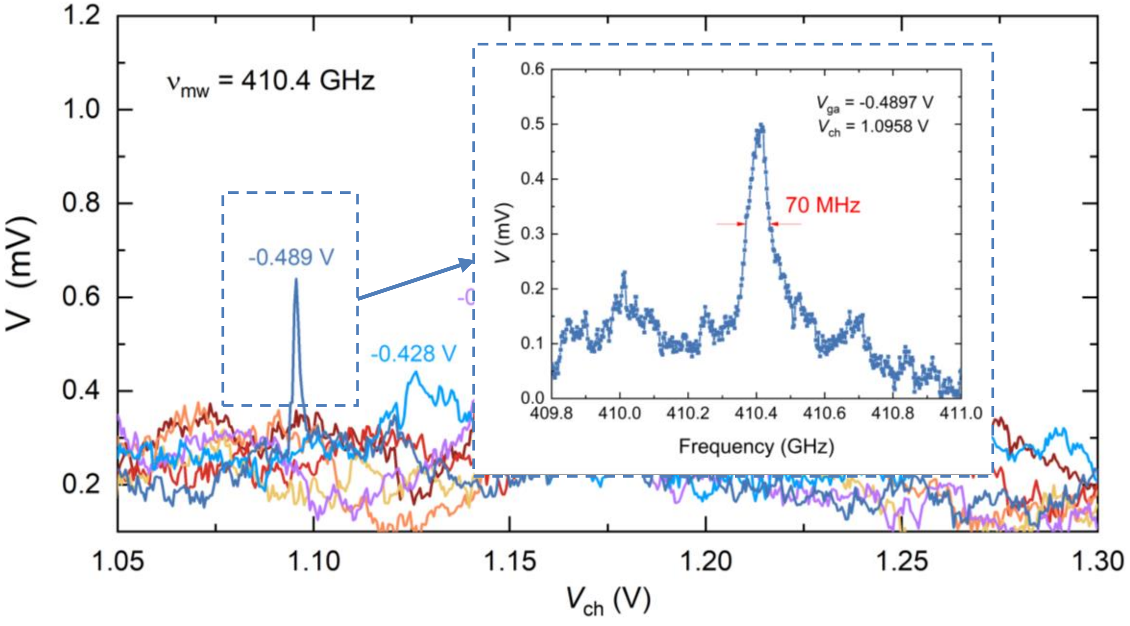
Optimization of the helical resonator

Optimization step	1	2	3
Q_0 at 4K	800	1441	18692



Reduce # of rows of electrons in central channel





Figures provided by Dr. M. Belianchikov in OIST

Summary

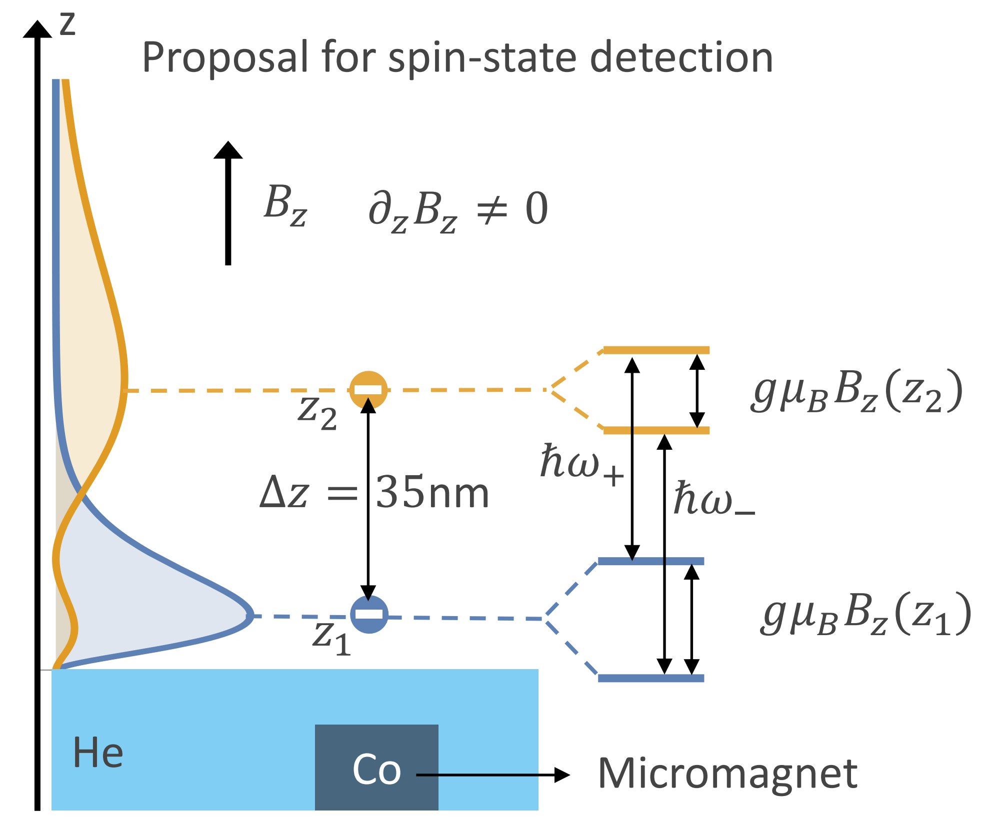
(1) Two simple methods to measure the Rydberg excitation of electrons the microchannel device

(2) Increased sensitivity using the helical resonator (approx. 100 electrons)

Outlook

(1) Scale down to single electron to be used in quantum computing

(2) Spin-state detection mediated by Rydberg excitation



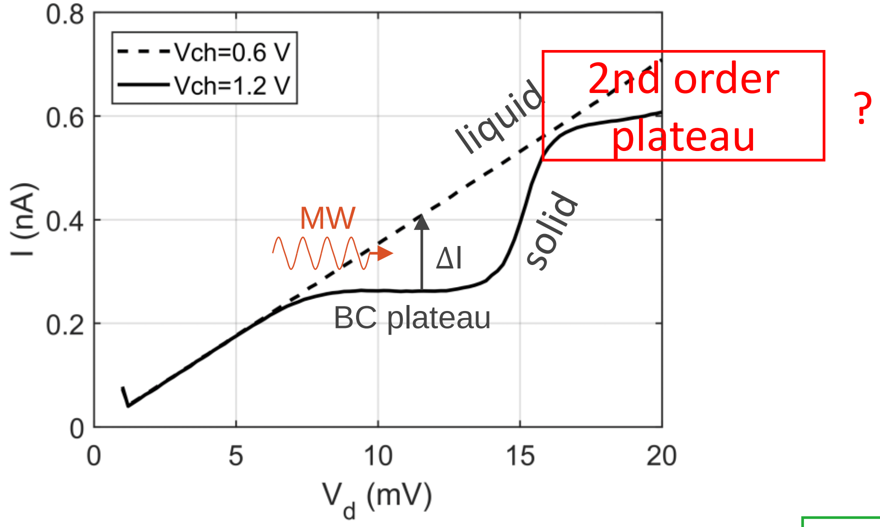
$$\omega_- - \omega_+ \simeq g\mu_B \partial_z B_z \Delta z/\hbar \simeq 2\pi \times 300\text{MHz}$$

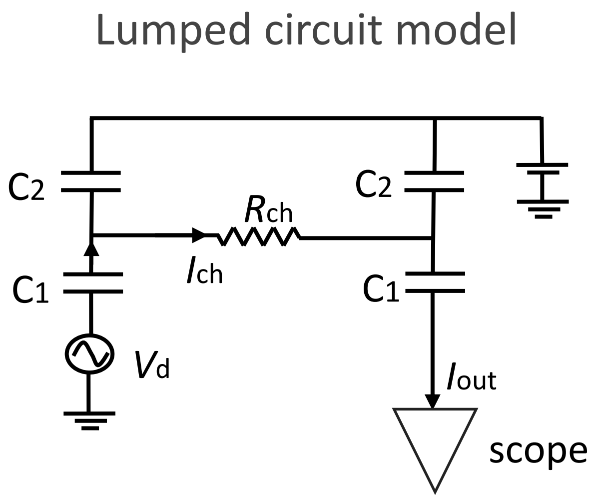
E. Kawakami et al., PRL 123, 086801 (2019)

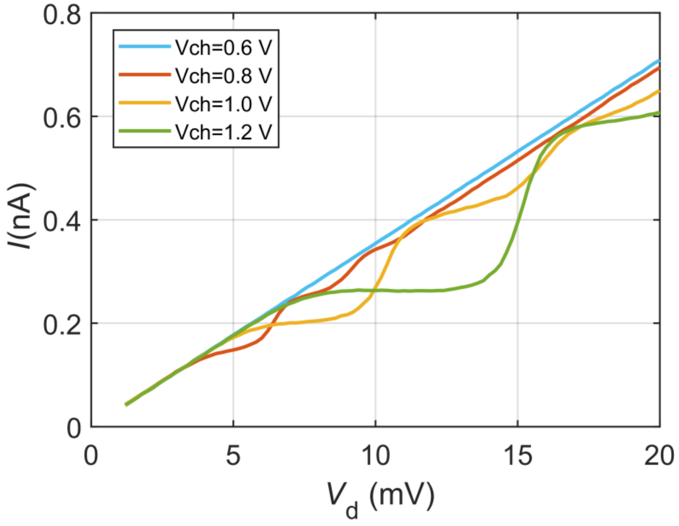
Project 3

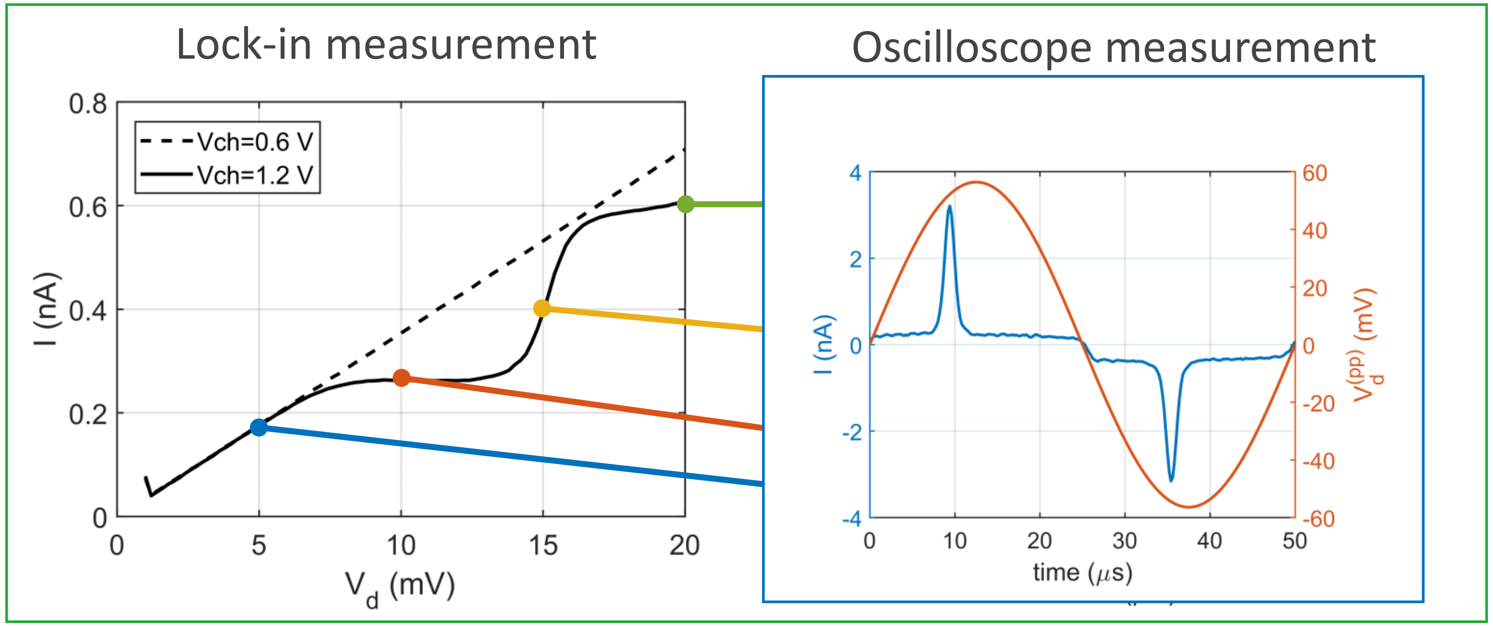
Novel transport phenomenon

Novel transport properties



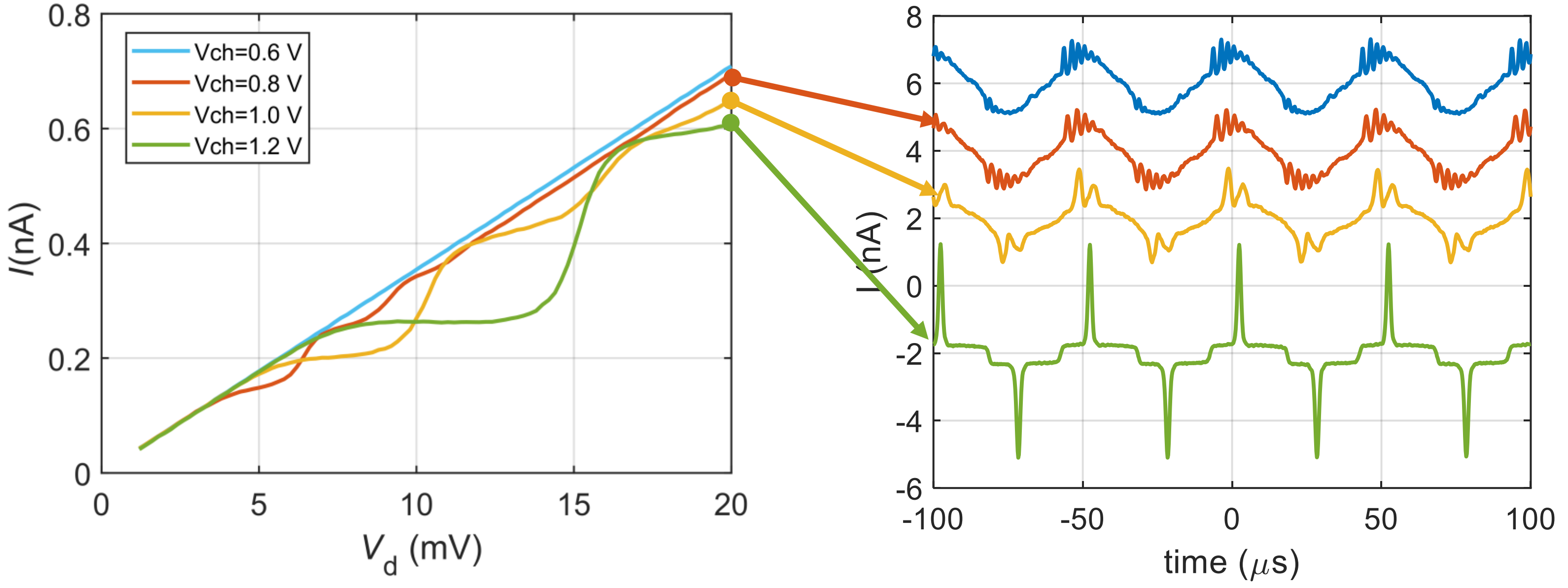






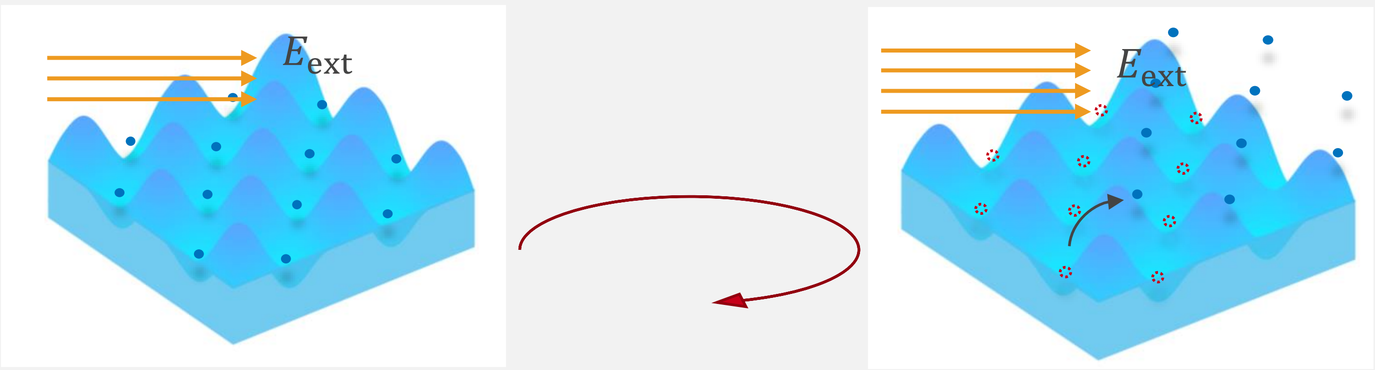
S. Zou et al. PRB, 104 045427 (2021)

Novel transport properties



Electrons stick to DL

Electrons depinned from DL



Repetitive stick-slip motion

S. Zou et al. PRB, 104 045427 (2021)

Conclusion

PhD projects:

- Rydberg state detection: Conductivity measurement

  [1] **S. Zou**, S. Grossenbach and D. Konstantinov, *Observation of the Rydberg Resonance in Surface Electrons on Superfluid Helium Confined in a 4-μm Deep Channel*, Journal of Low Temperature Physics, Online publication (2022)

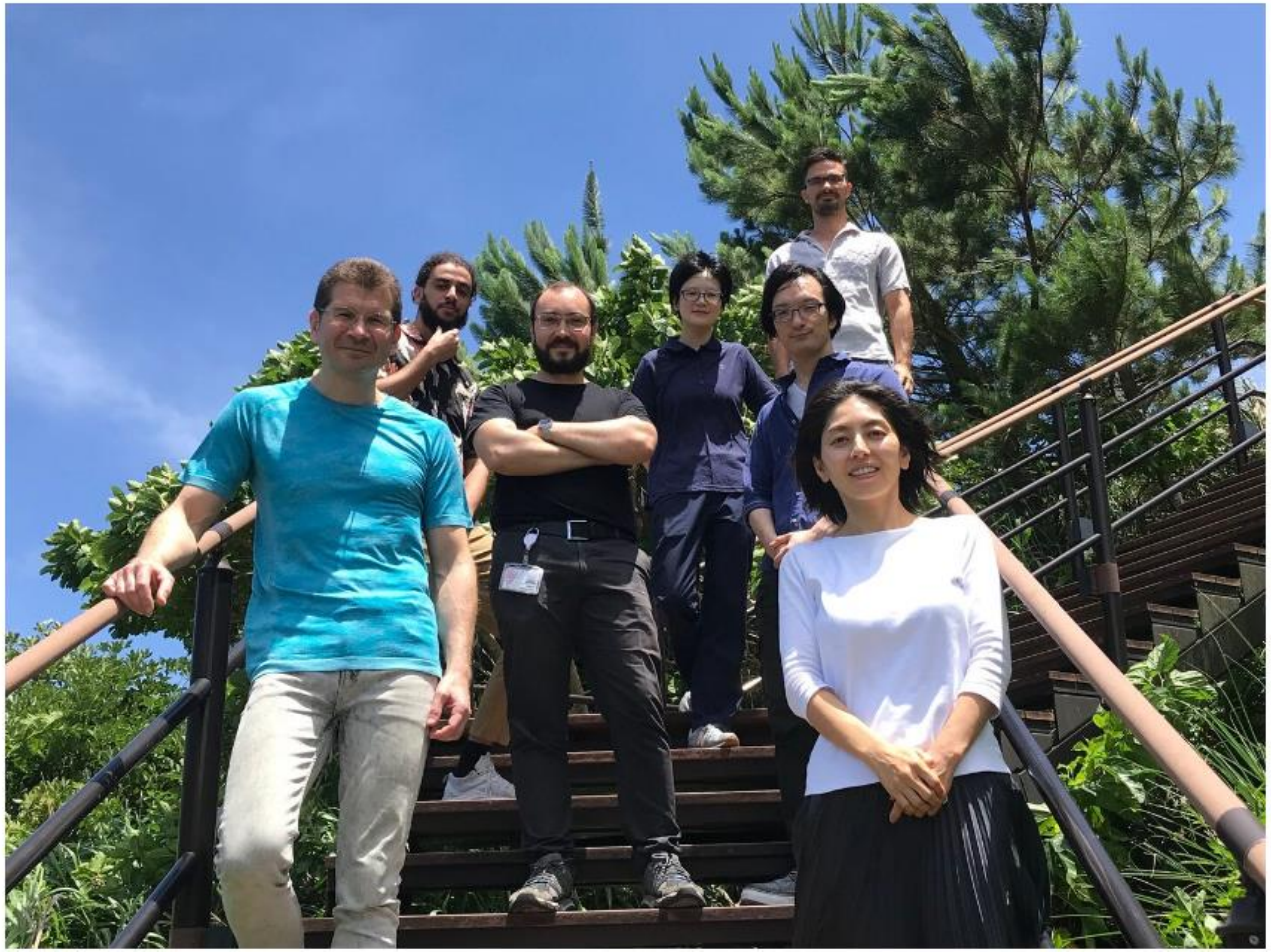
- Rydberg state detection: Image-charge measurement

  [2] **S. Zou** and D. Konstantinov, *Image-charge detection of the Rydberg transition of electrons on superfluid helium confined in a microchannel structure*, arXiv. 2207, 03737 (2022)

- Norvel transport properties: repetitive stick-slip motion

  [3] **S. Zou**, D. Konstantinov and D. Rees, *Dynamical ordering in a 2D electron crystal confined in a narrow channel geometry*, Phys. Rev. B 104, 045427 (2021)

Acknowledgment



prof. Denis Konstantinov

Group members:
Dr. Ivan Kostylev
Dr. Mohamed Hatifi
Dr. Kirill Shulga
Dr. Mikhail Belianchikov
Dr. Tomoyuki Tani
Ms. Taki Tazuke

Past members:
Dr. Oleksiy Zadorozhko
Dr. Erika Kawakami
Dr. Jui-Yin Lin
Dr. Asem Elarabi
Dr. Alexander Badrutdinov

Collaborators:
Dr. David Rees
Mr. Sebastian Grossenbach

Thank you for listening!