Image-charge detection: towards realizing spin qubits using electrons on helium

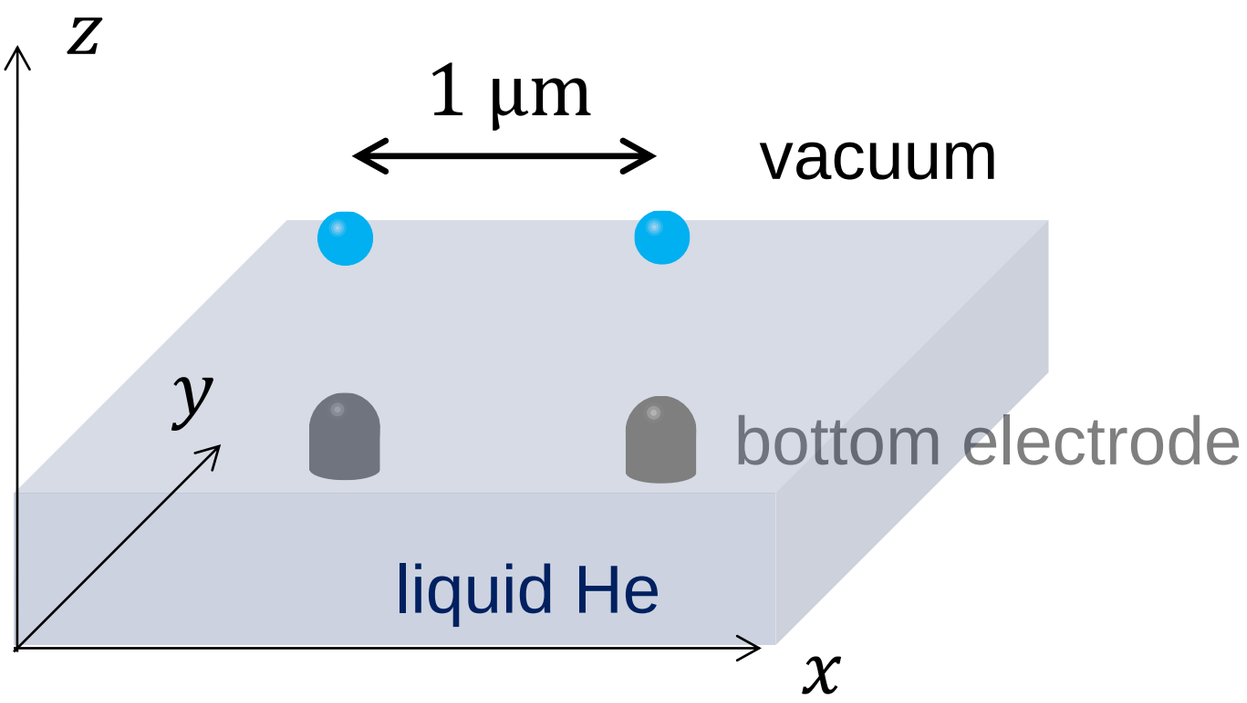
Okinawa Institute of Science and Technology,
Quantum Dynamics Unit (Denis Konstantinov Unit)

Erika Kawakami

OIST
OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY
沖縄科学技術大学院大学

He quantum computer

one electron = one quantum bit



- clean

  ⇨ high qubit gate fidelity

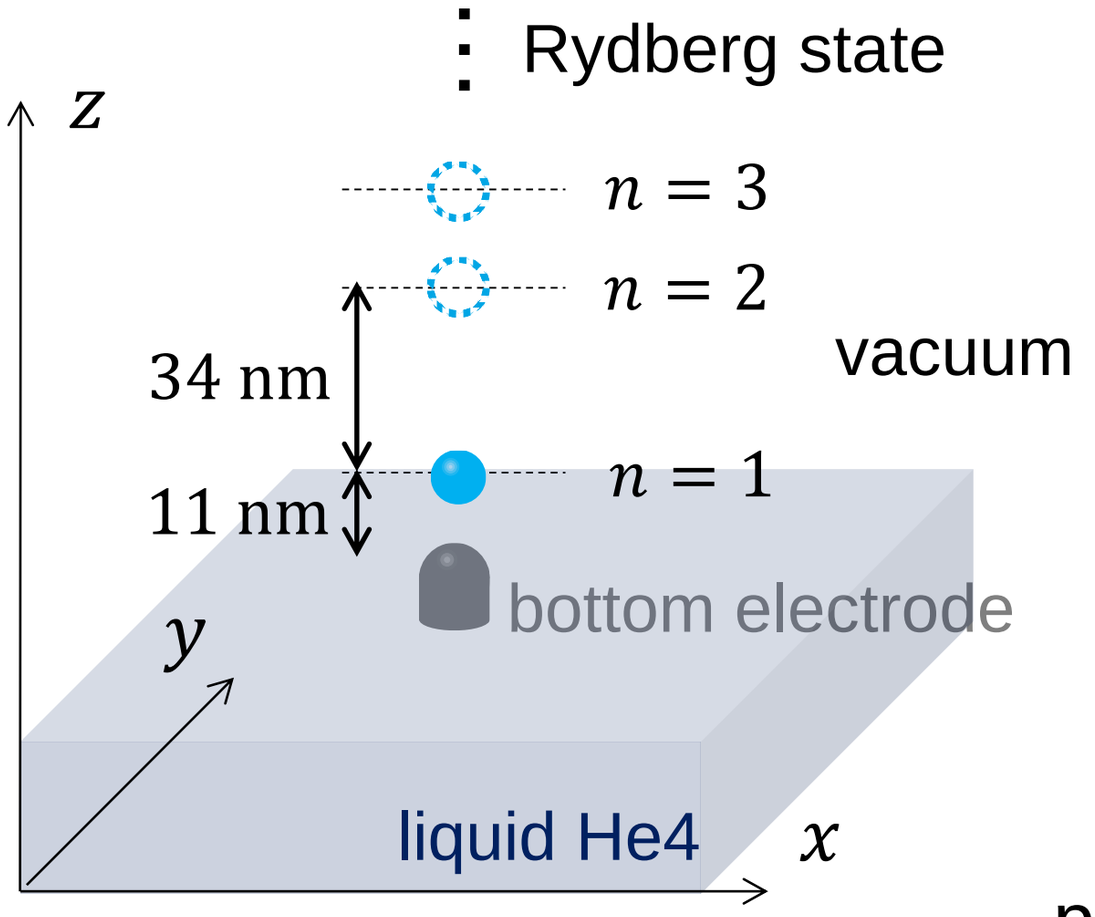
- long-range interaction

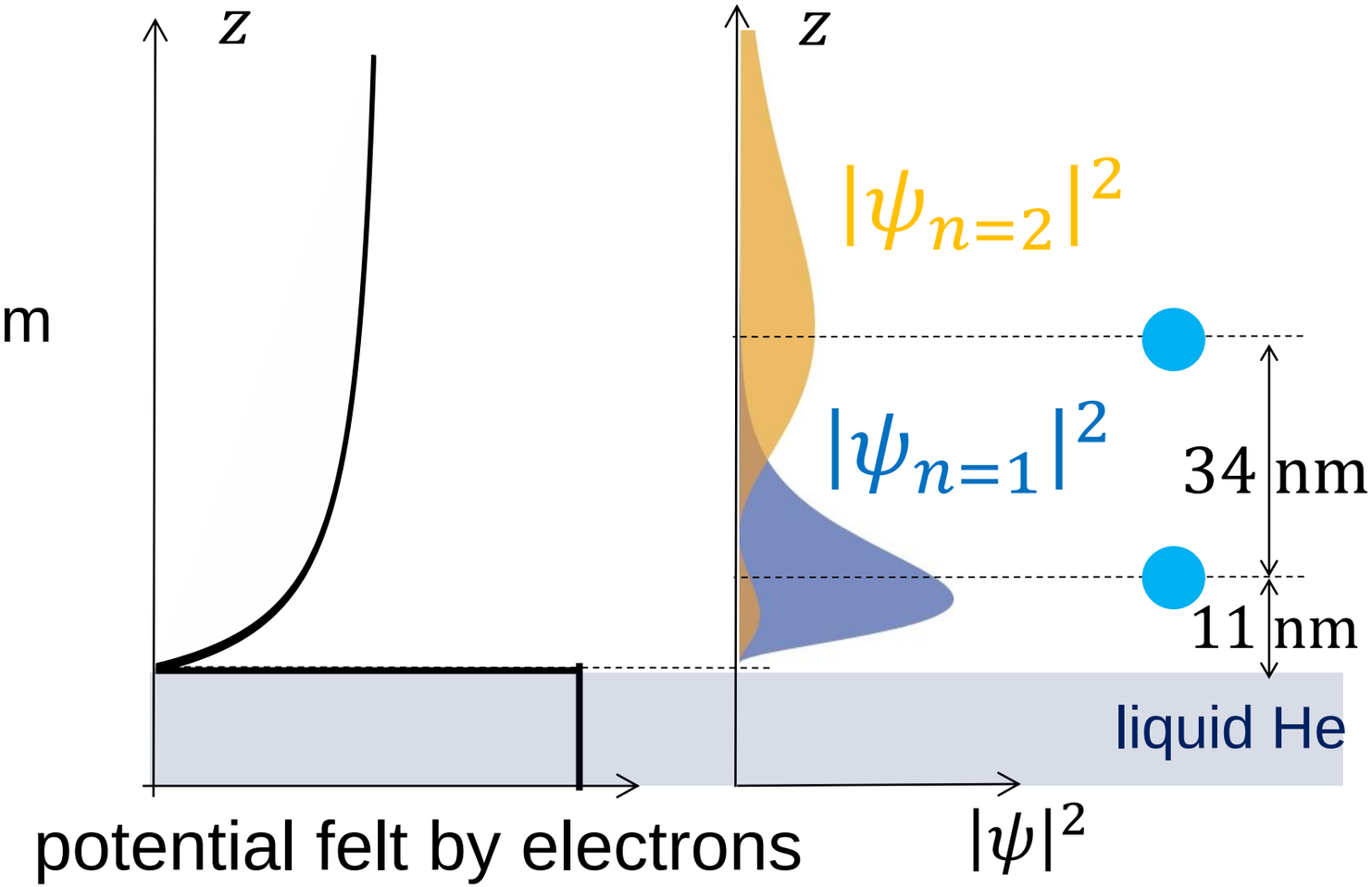
  (Coulomb interaction)

  ⇨ scalable

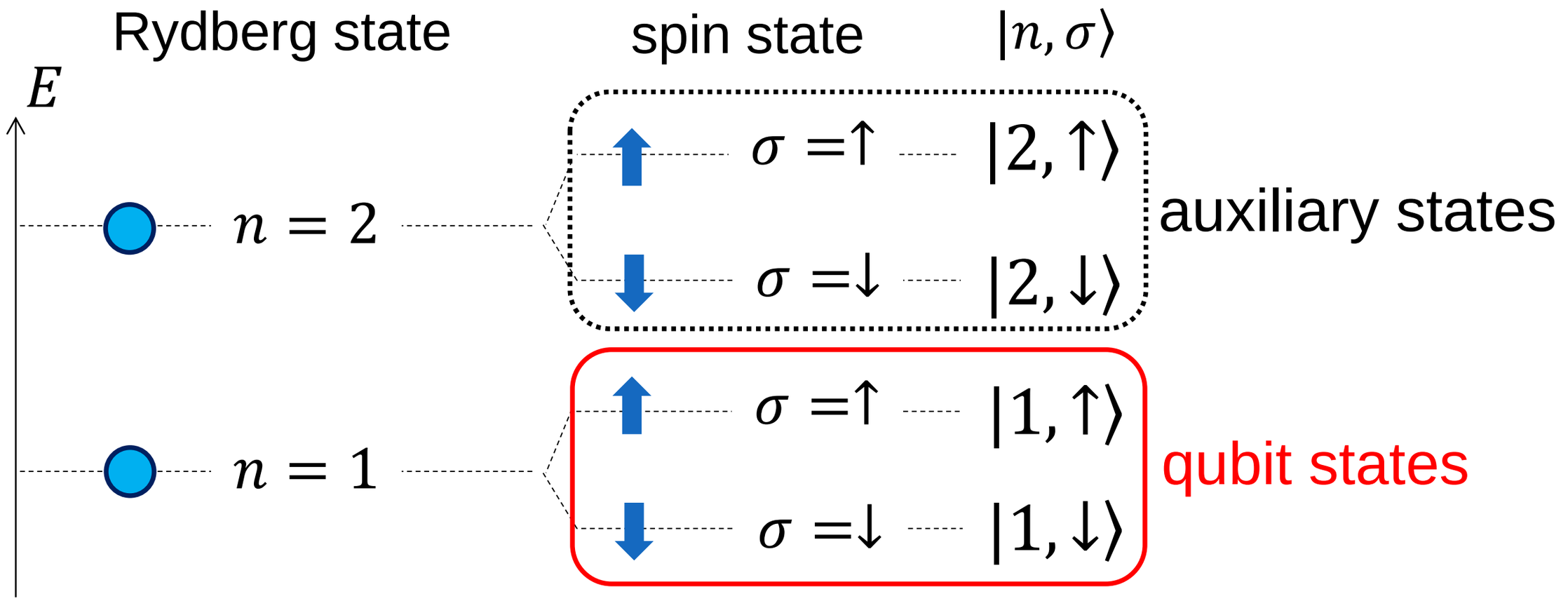
P.M. Platzman et al., Science 284, 1967 (1999).
Lyon, Phys. Rev. A 74, 052338 (2006).

Electrons are floating in vacuum



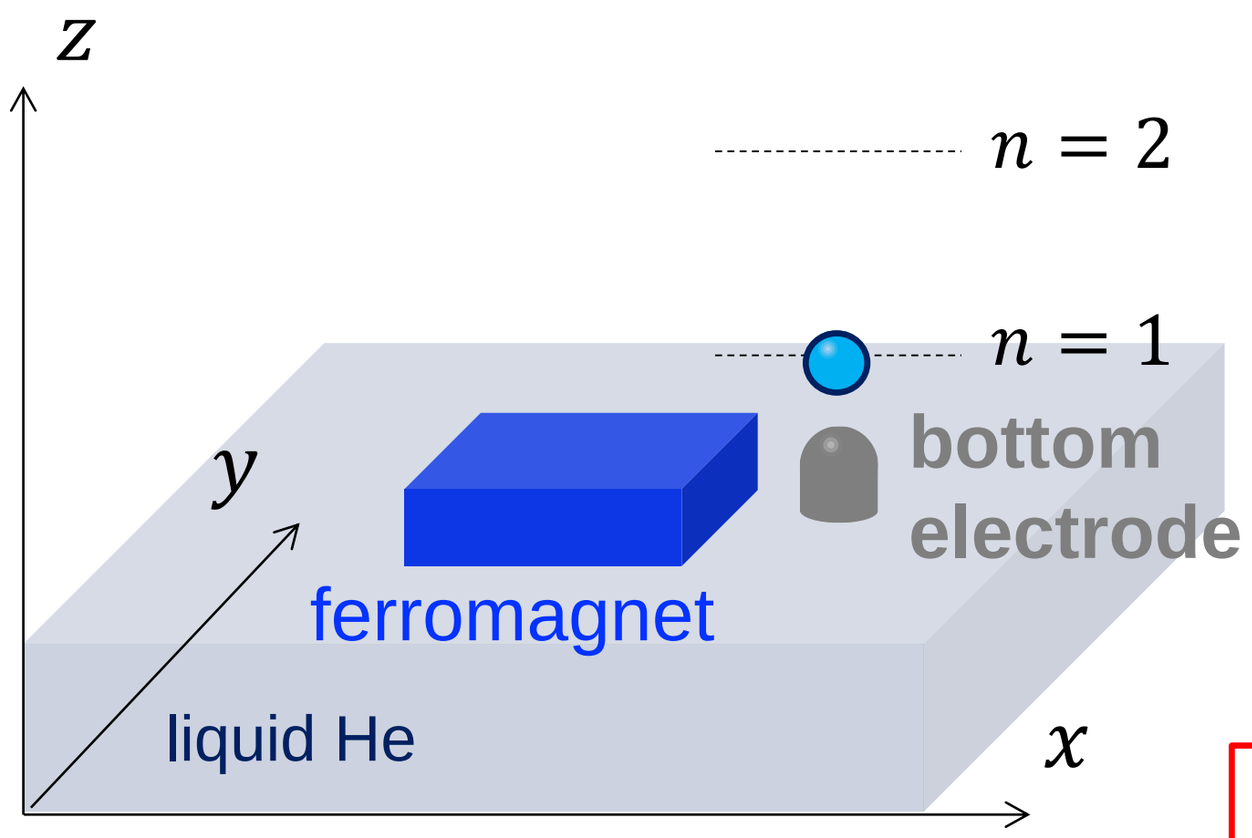


electrons on helium as qubits

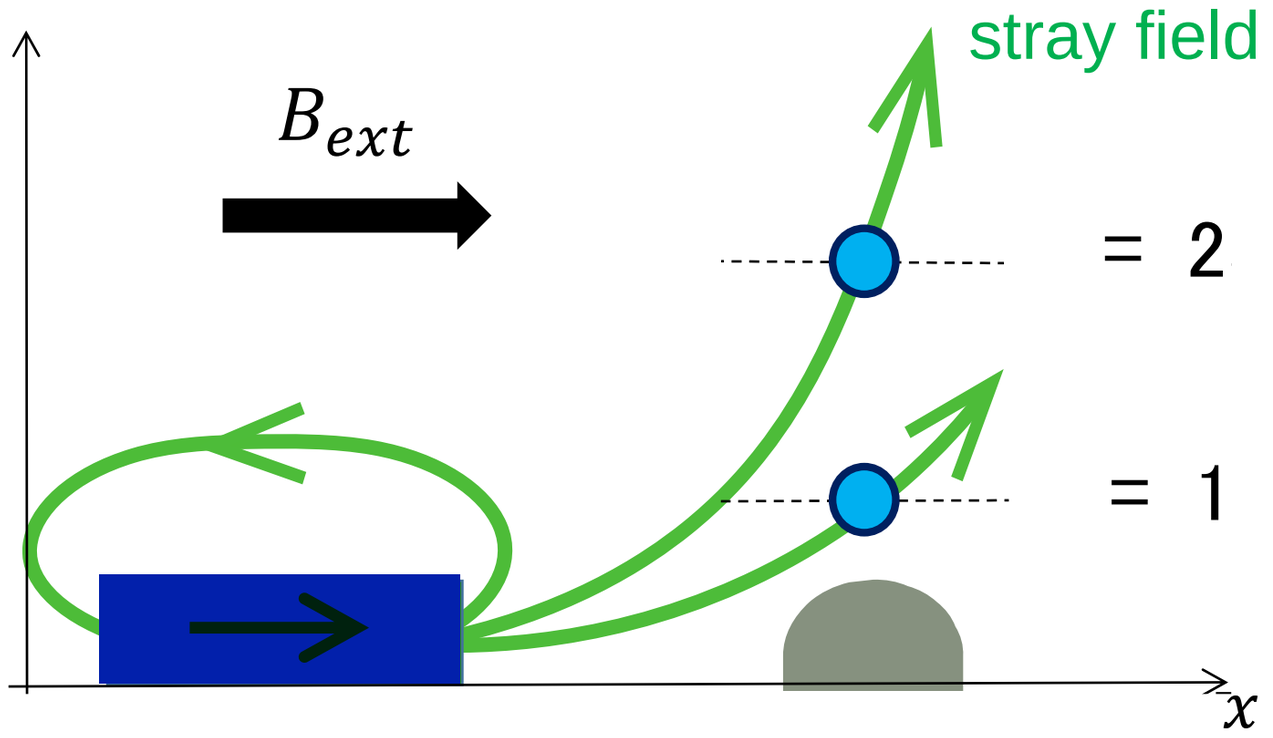


I make use of both the Rydberg state and the spin state via the interaction between the spin state and the Rydberg state.

interaction between the Rydberg state and the spin state



Magnetize the ferromagnet.



The electron feels different magnetic field depending on the Rydberg states (Rydberg-spin interaction)

Artificial spin-orbital interaction in semiconductor quantum dots: Pioro-Ladriere et al, Nature Phys **4**, 776 (2008).

Spin qubits using electrons on helium

We realize

- Universal one-qubit gate
- A two-qubit gate

} Universal quantum gate

- Read-out and initialization of qubit states

using the Rydberg-spin interaction.

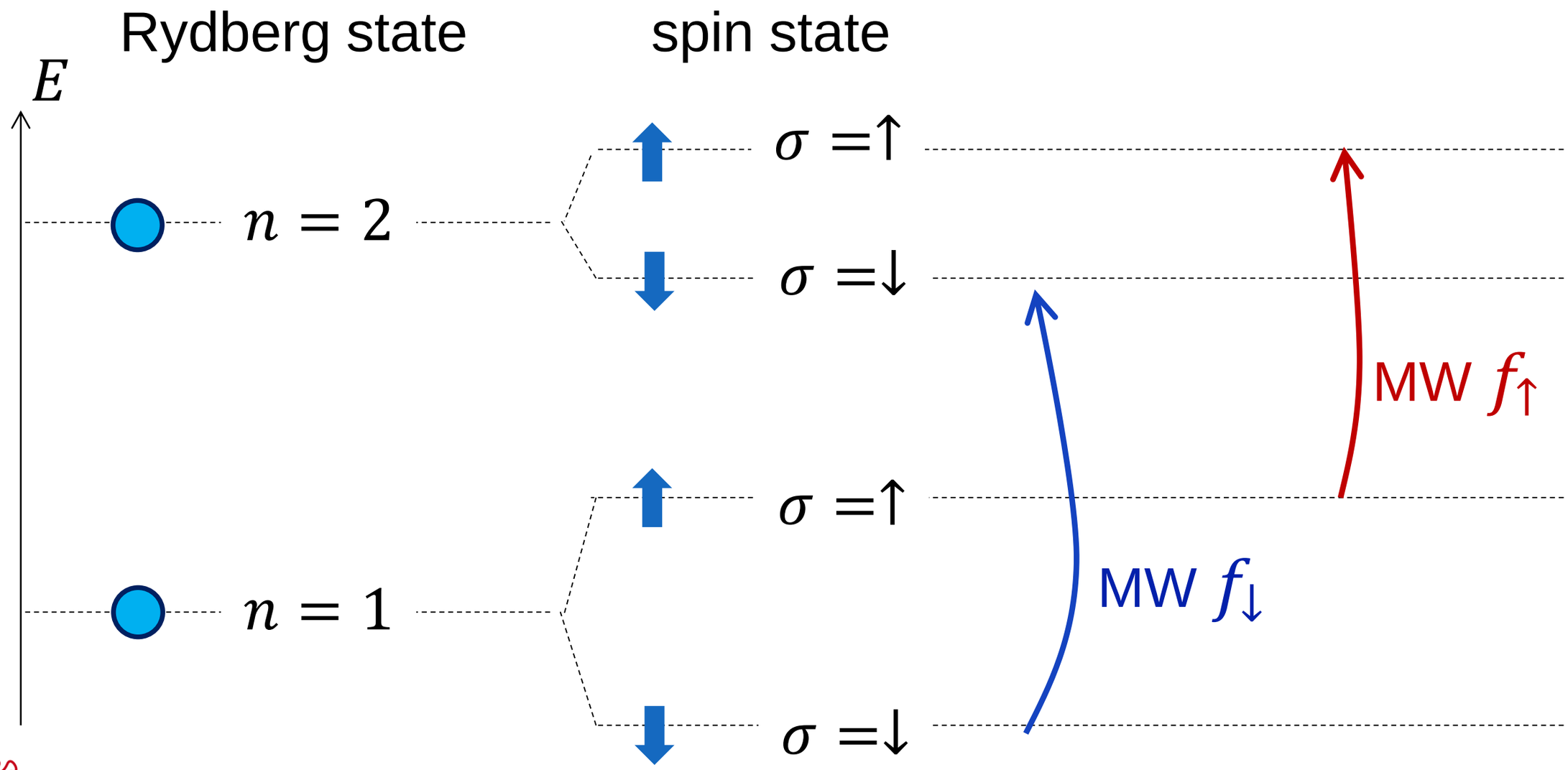
He quantum computer

We realize

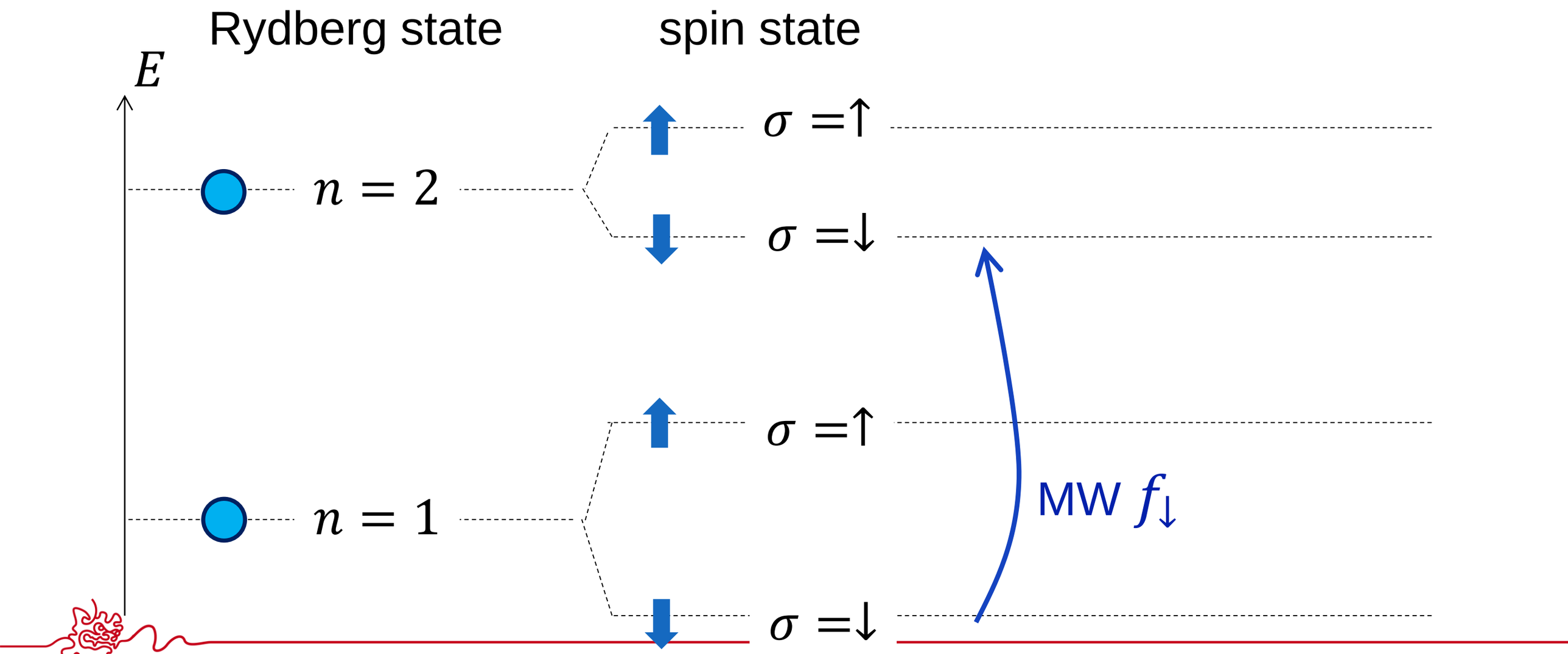
- Universal one-qubit gate → Electric Dipole Spin Resonance
- A two-qubit gate → Coulomb interaction
- Read-out and initialization of qubit states

using the Rydberg-spin interaction.

Rydberg-spin interaction ⇨ $f_\downarrow \neq f_\uparrow$



We can detect the spin state by measuring if the excitation of the Rydberg state happens.



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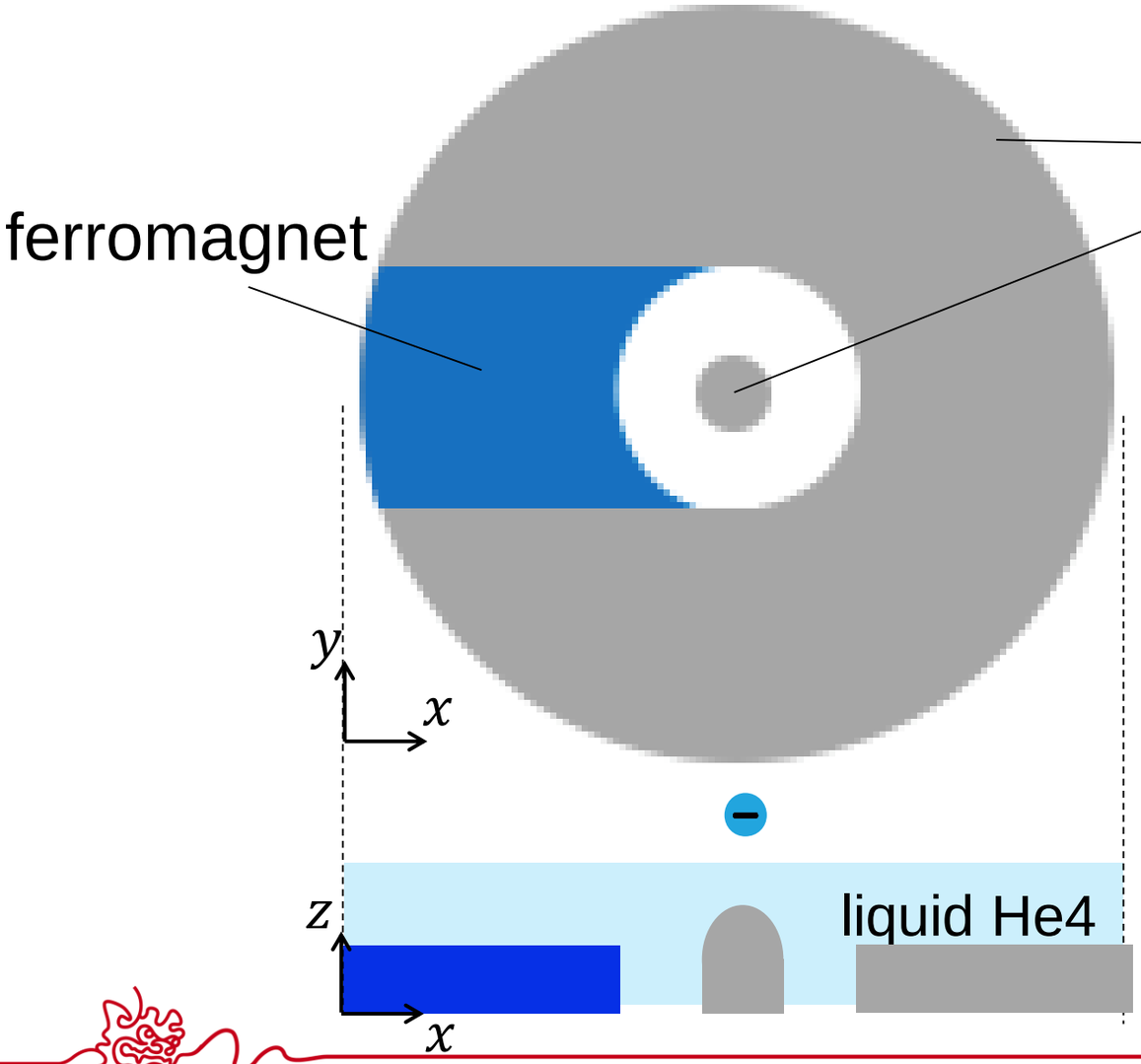
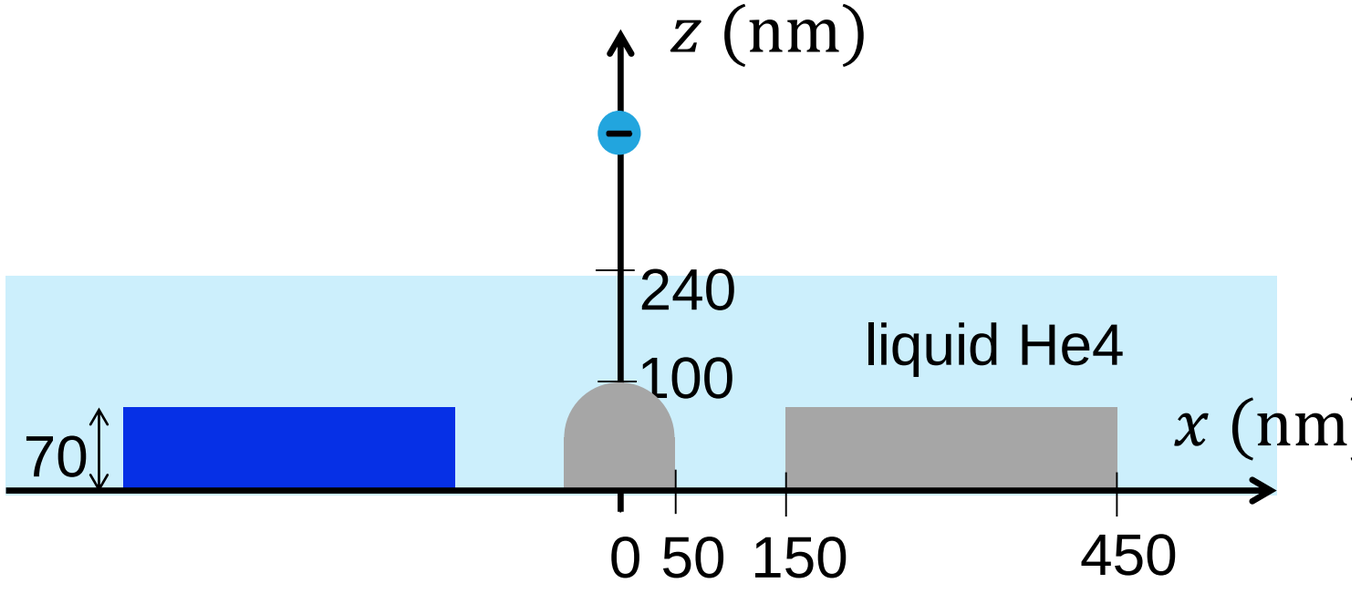
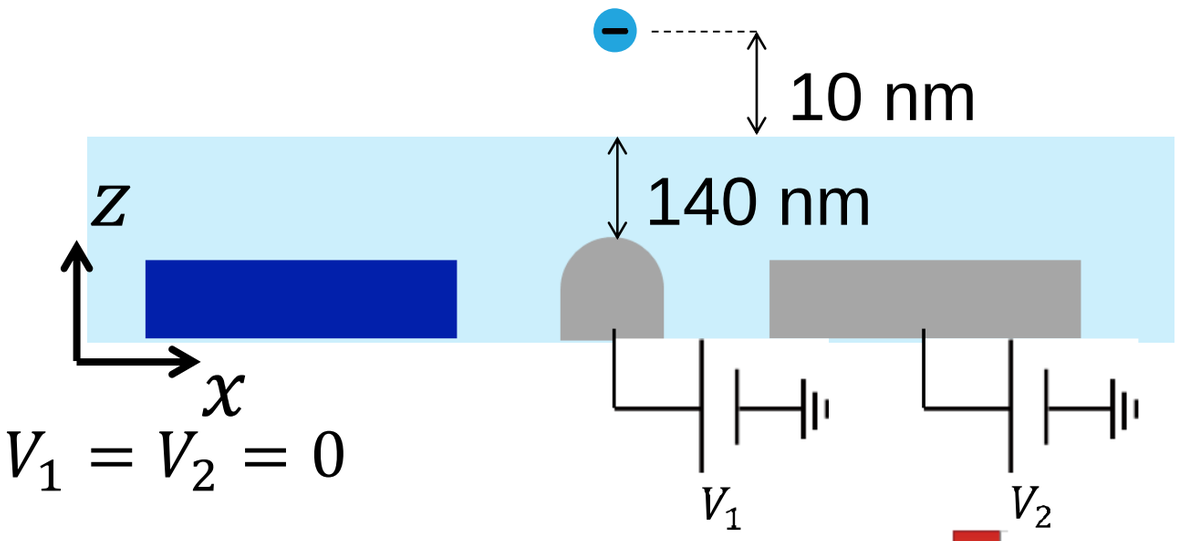
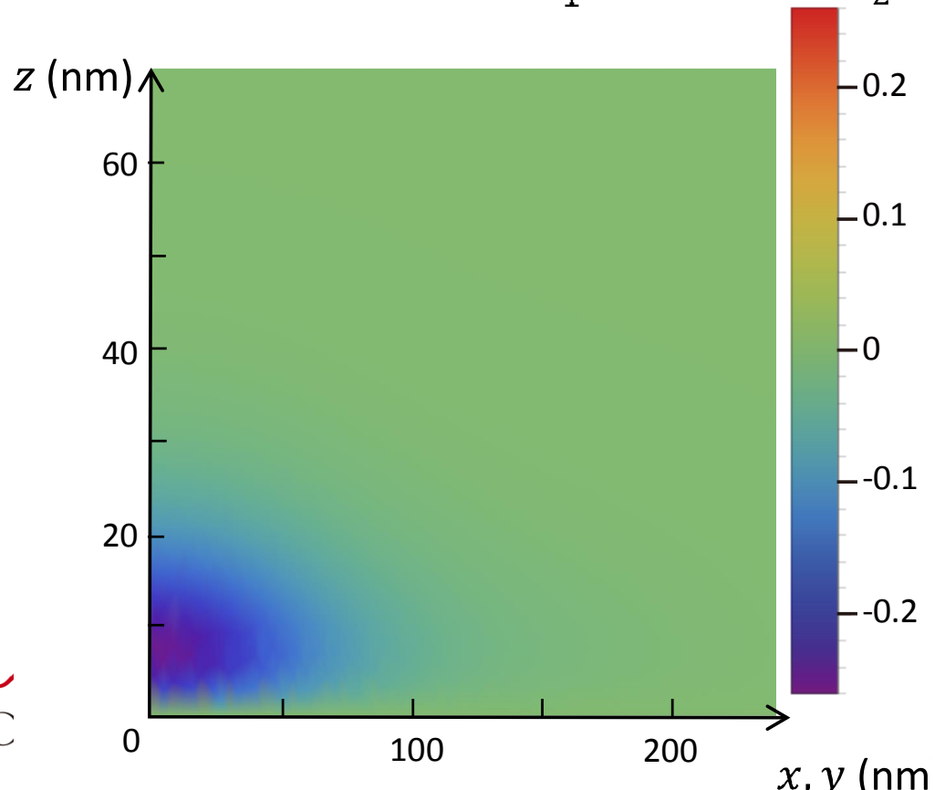
-How can we detect the excitation of the Rydberg state of one electron?

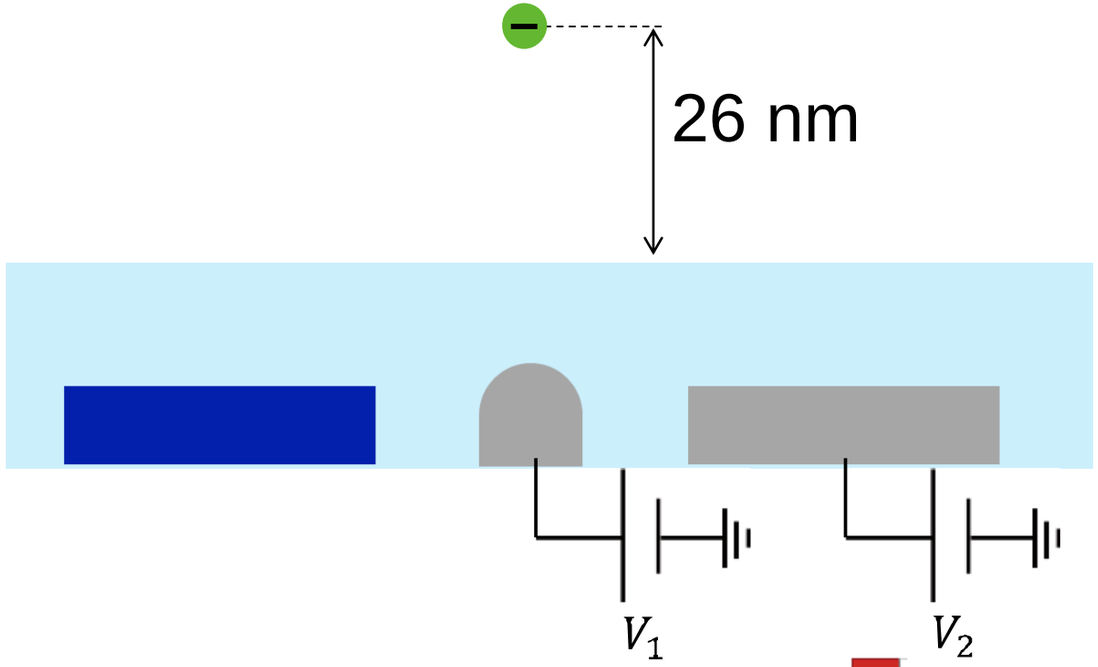


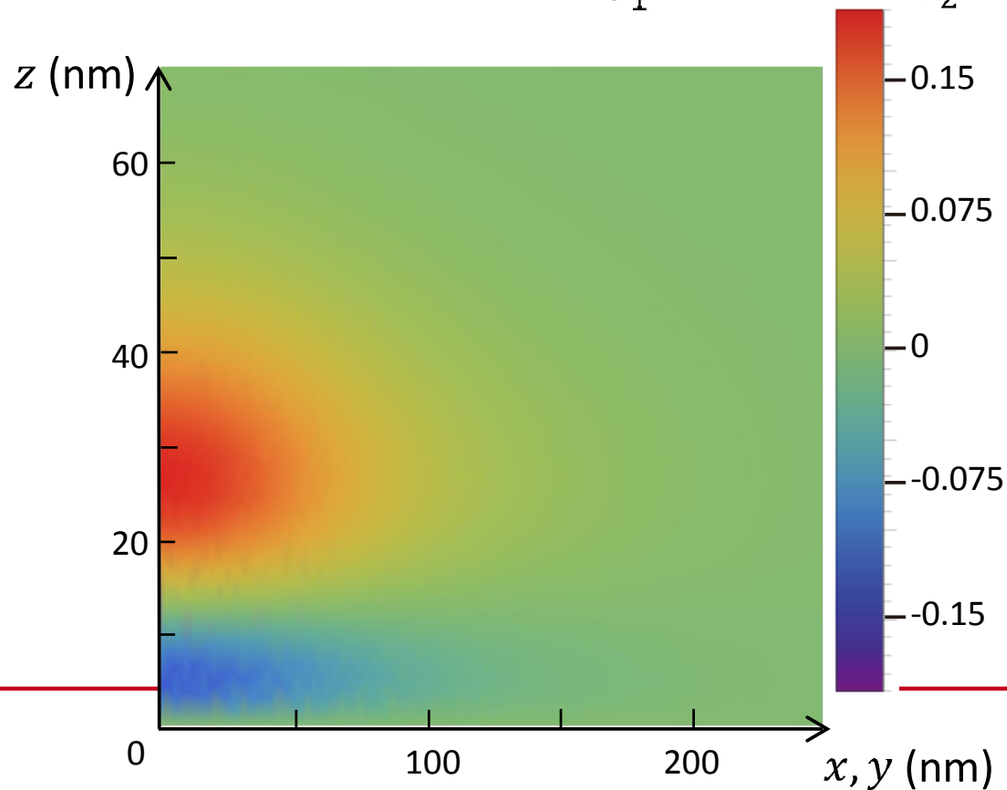


COMSOL + Mathematica simulation

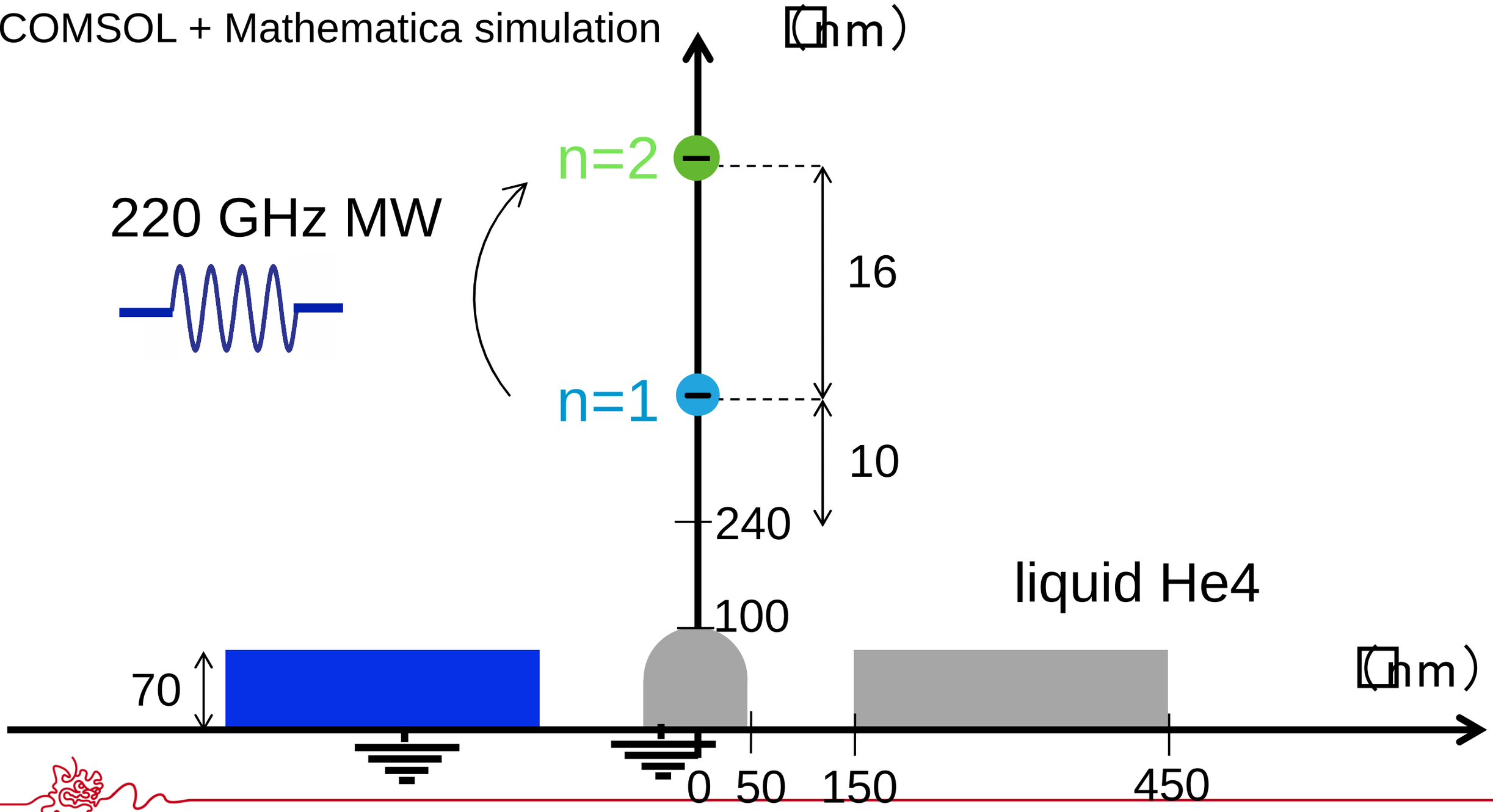








COMSOL + Mathematica simulation



-How can we detect the excitation of the Rydberg state of one electron?

-By measuring the change in the image charge on the electrode (image charge detection).

$$\Delta Q_0 = -0.01e$$

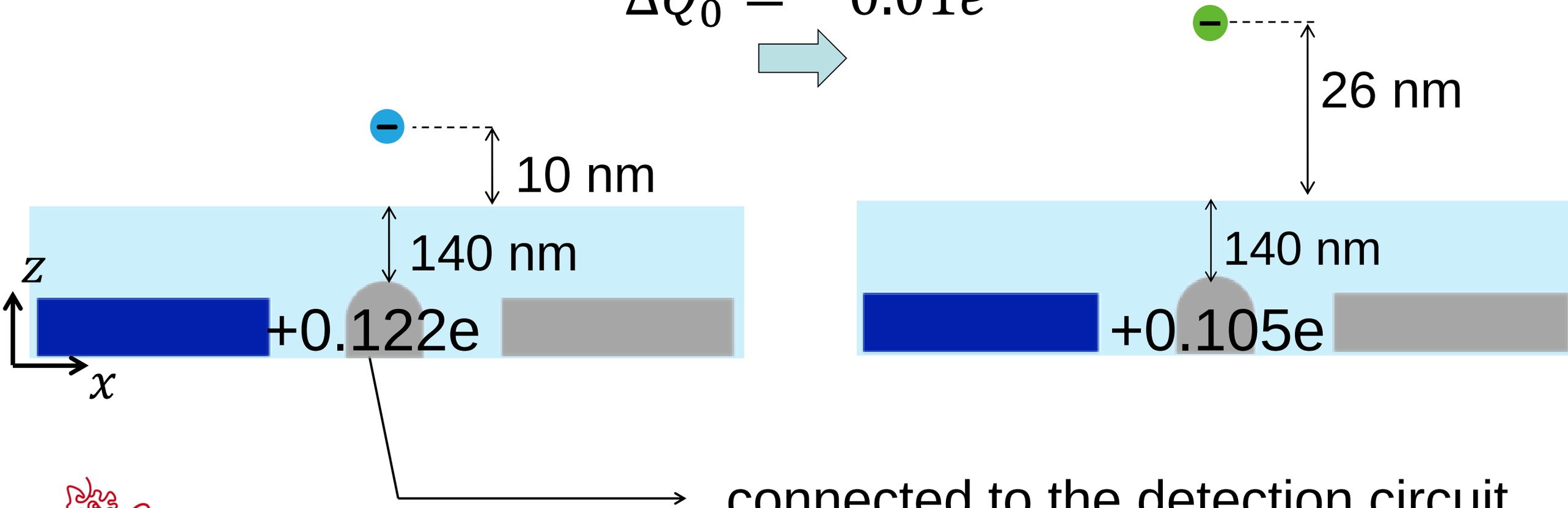


image-charge detection (with many electrons)

Kawakami, Elarabi, and Konstantinov, arXiv:1904.01238

$$|\Delta Q_0| = \frac{Ne\Delta z}{D} \sim 100e$$

N: number of electrons

$N \sim 10^7$

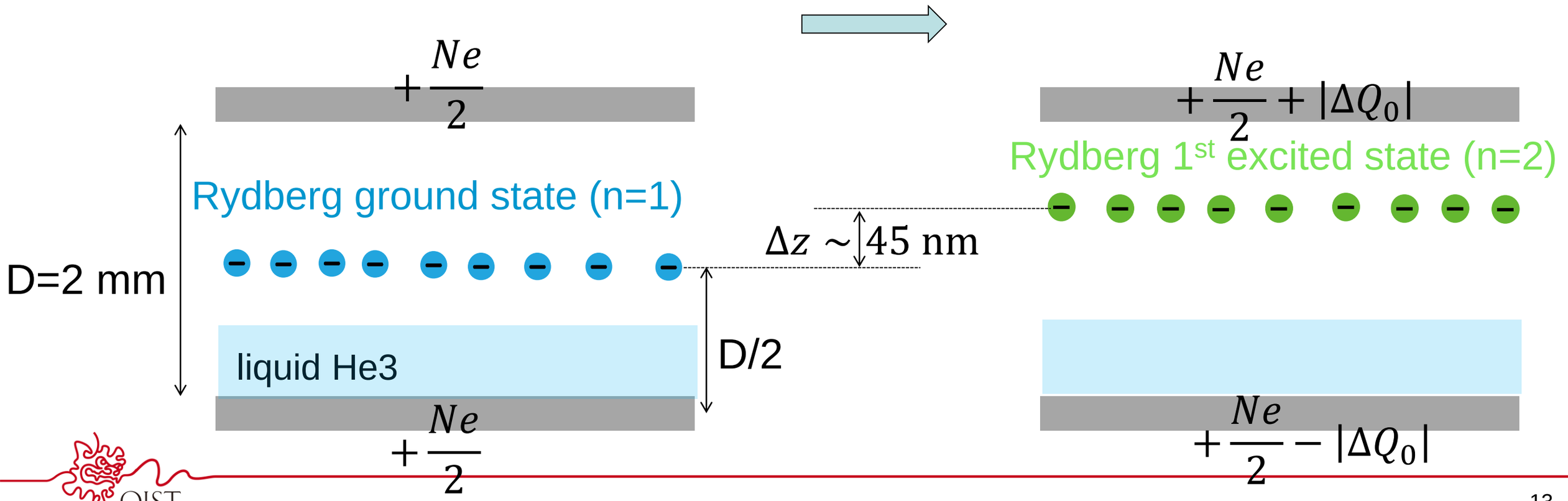
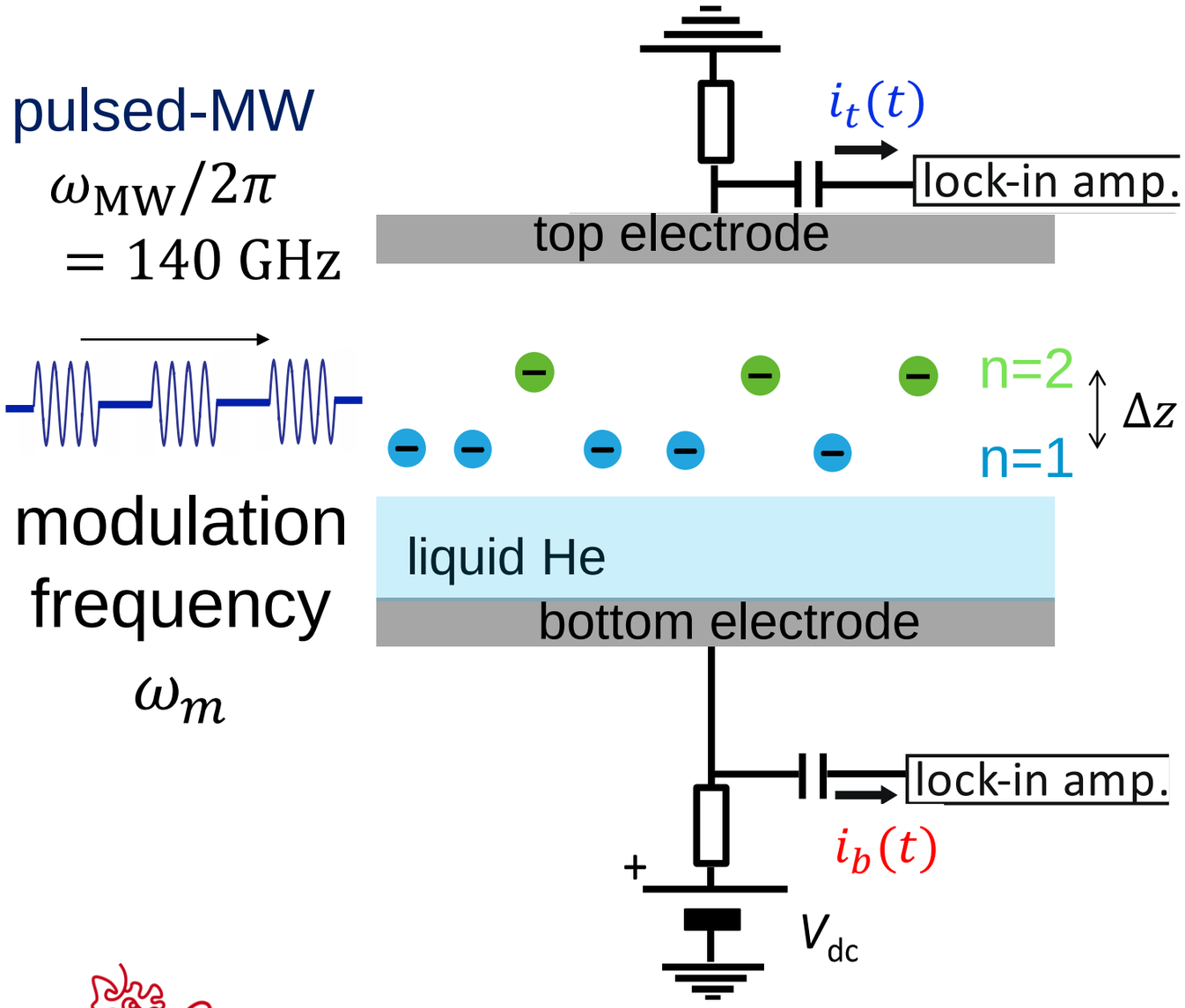
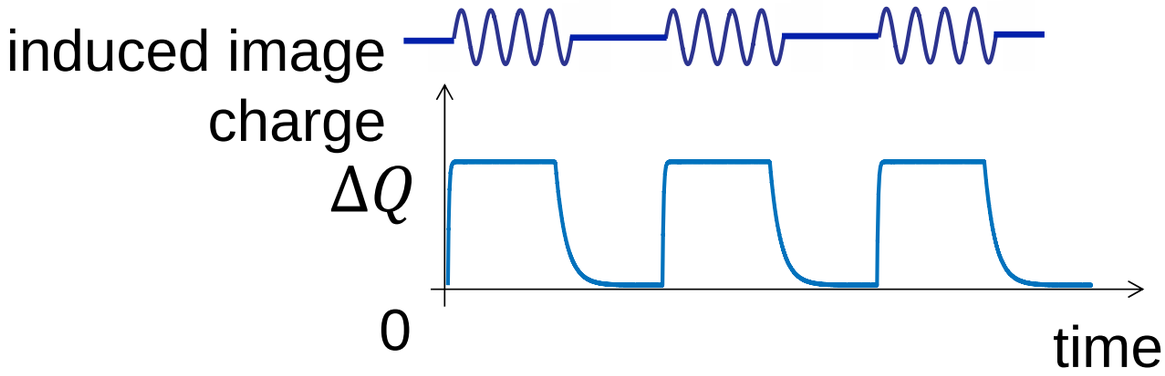


Image-charge detection of the Rydberg state of the electrons on helium





$$|\Delta Q| = |\Delta Q_0|\rho \sim 10e$$

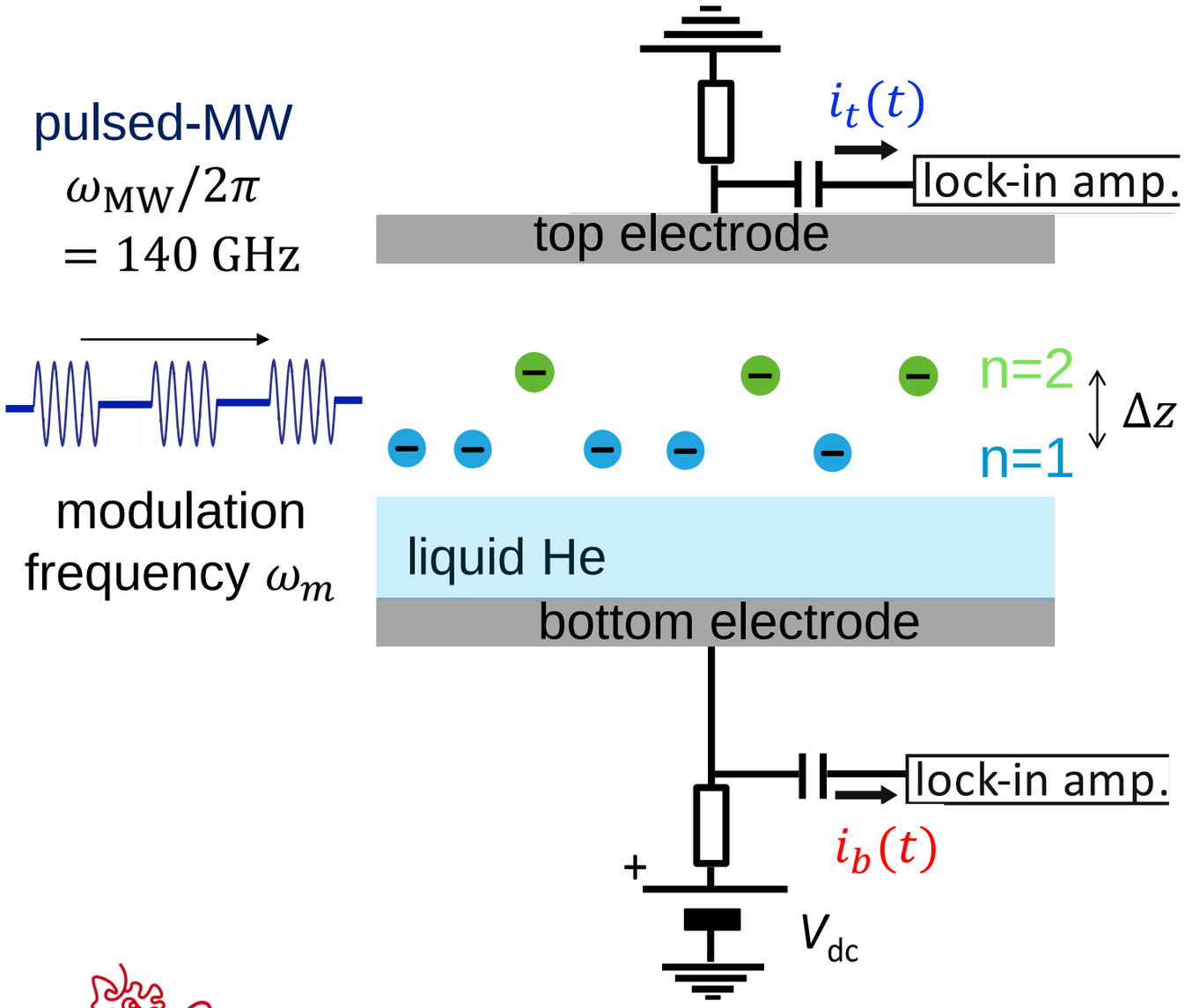
ρ: fraction of the electrons in the excited state

$(\rho \sim 10\%)$

$$|I| = \left|\frac{dQ}{dt}\right| = |\Delta Q_0|\rho\omega_m \sim 10\mathrm{pA}$$

$(\omega_m \sim 100\ \mathrm{kHz})$

Image-charge detection of the Rydberg state of the electrons on helium



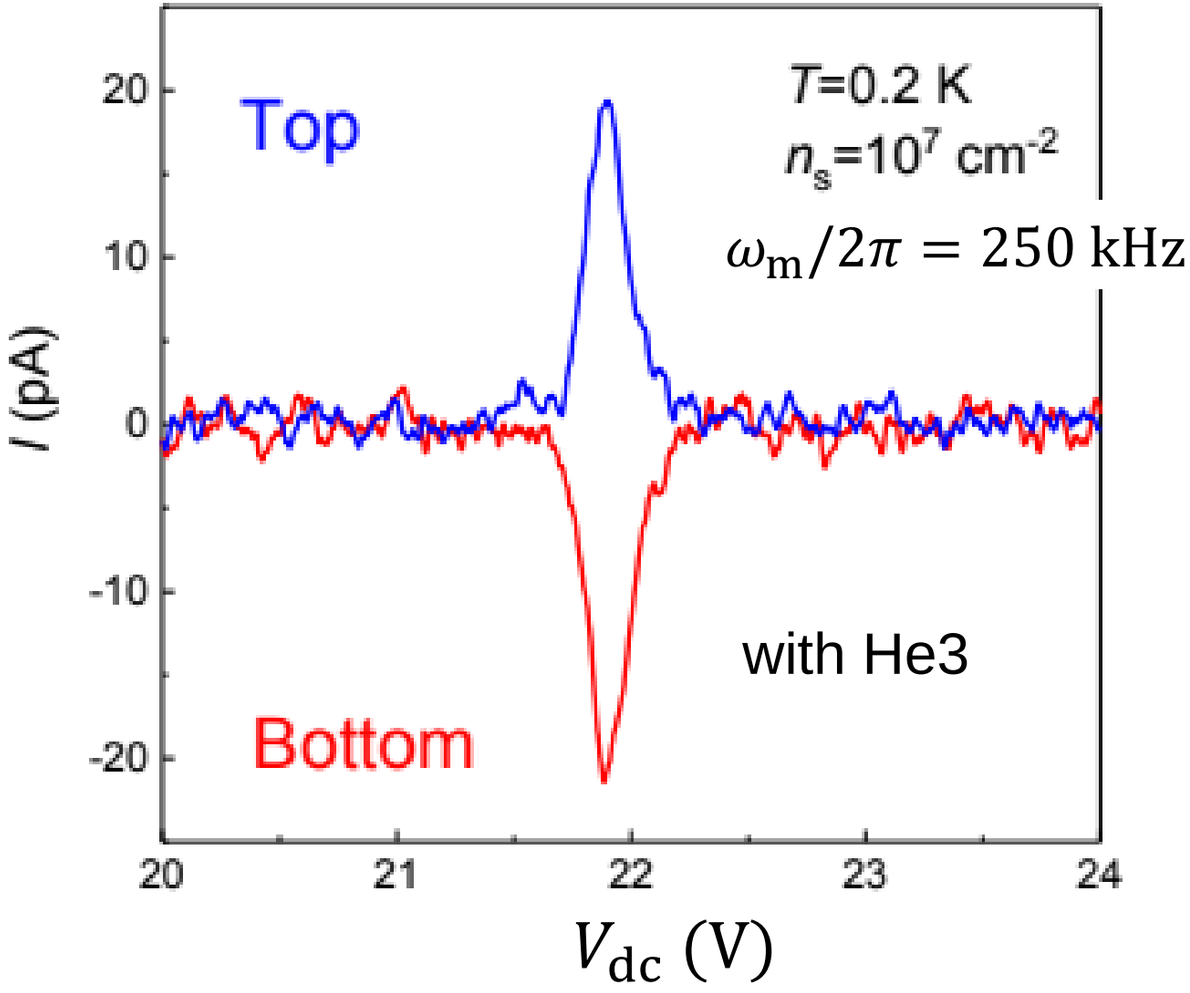
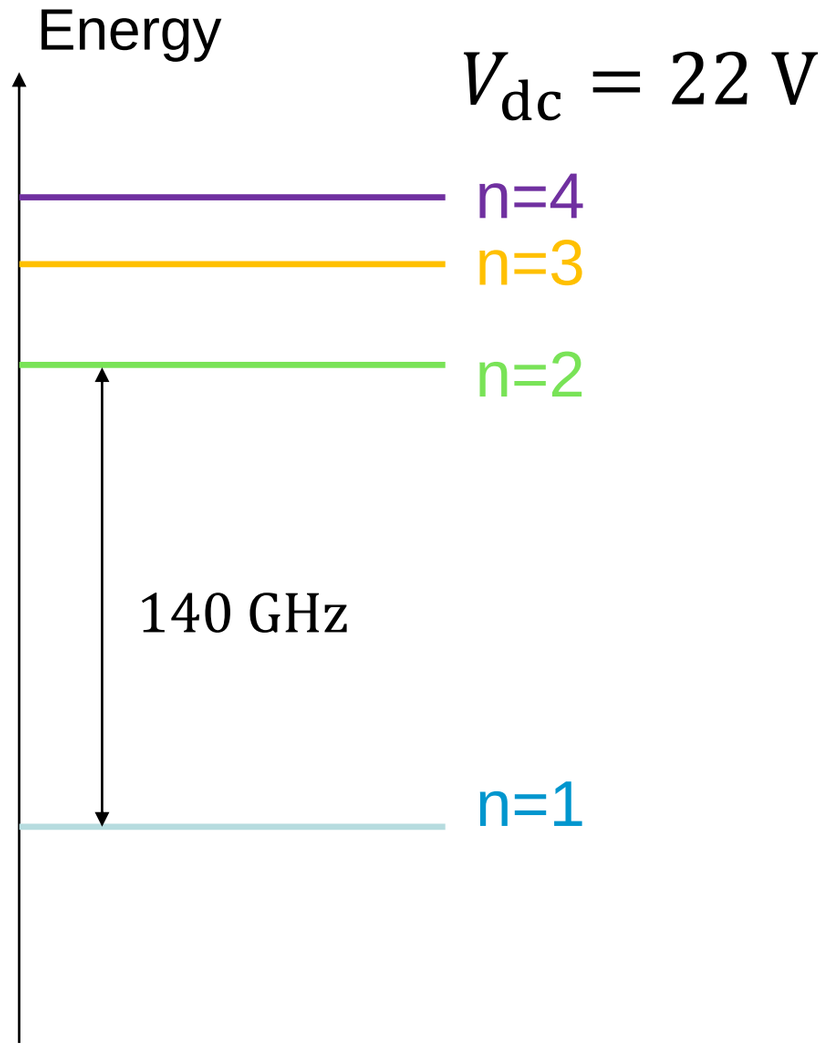


Image-charge detection of the Rydberg state of the electrons on helium



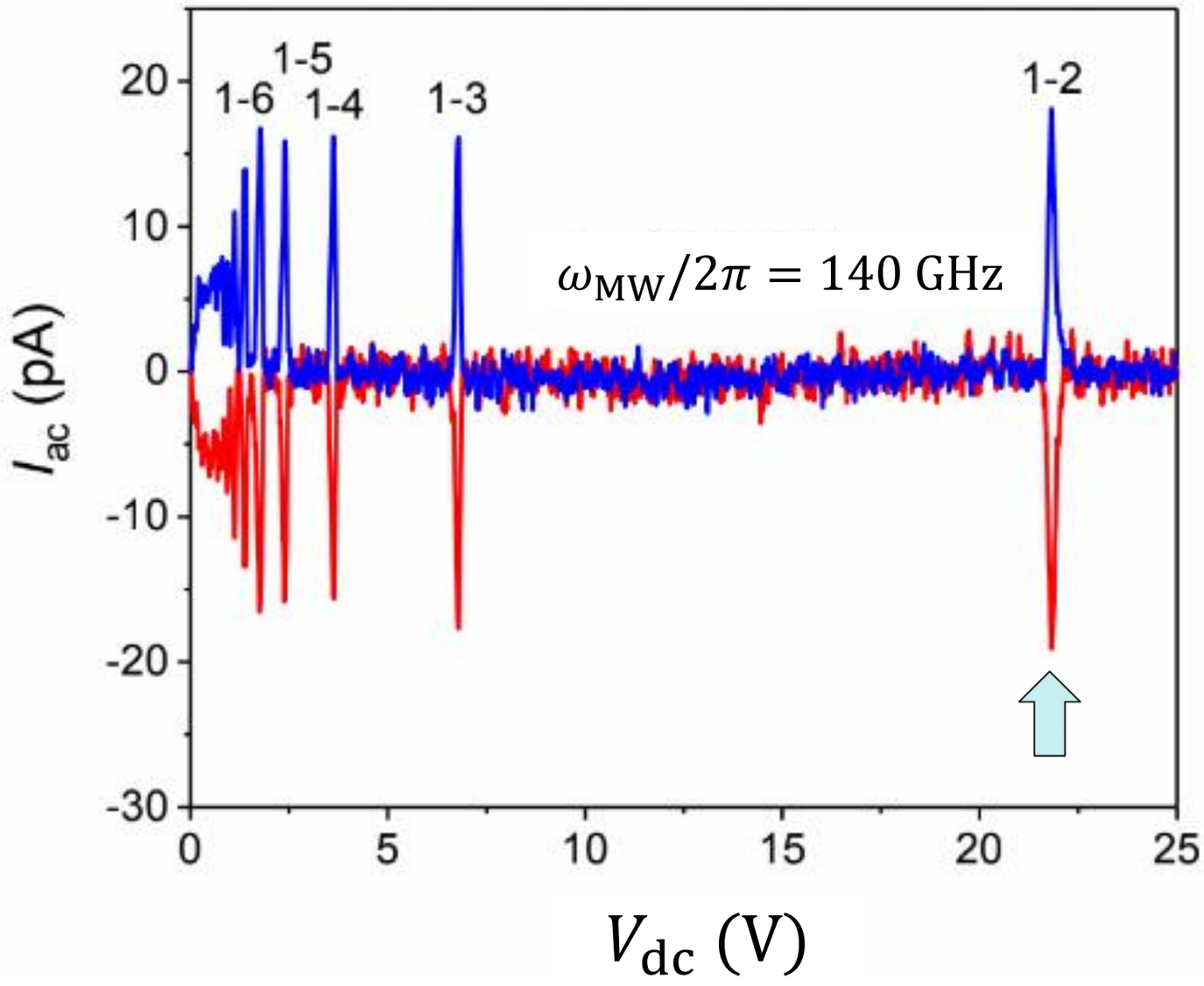
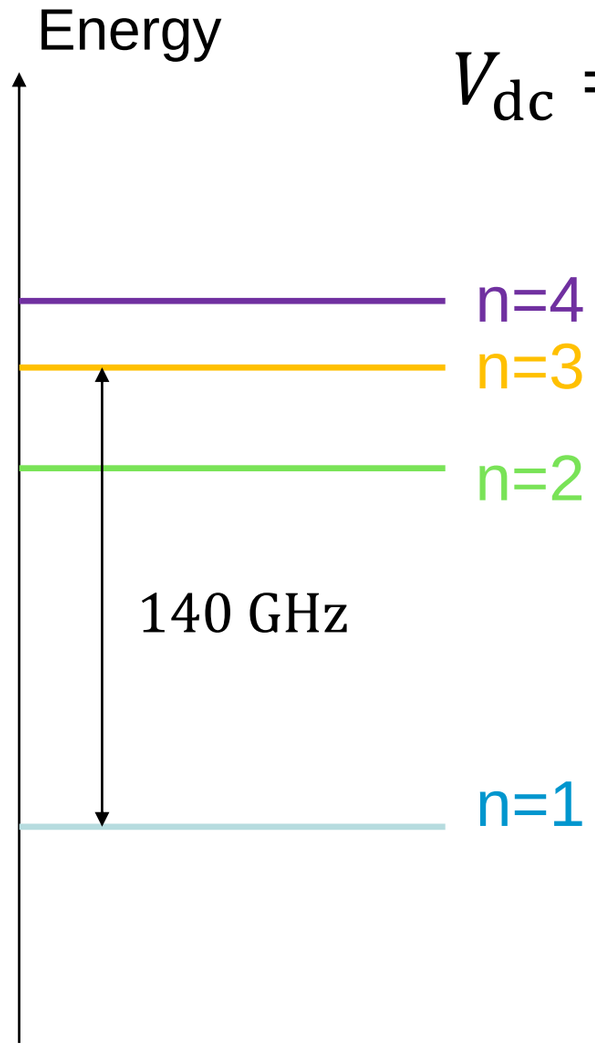


Image-charge detection of the Rydberg state of the electrons on helium



$V_{\mathrm{dc}} = 6.5\ \mathrm{V}$

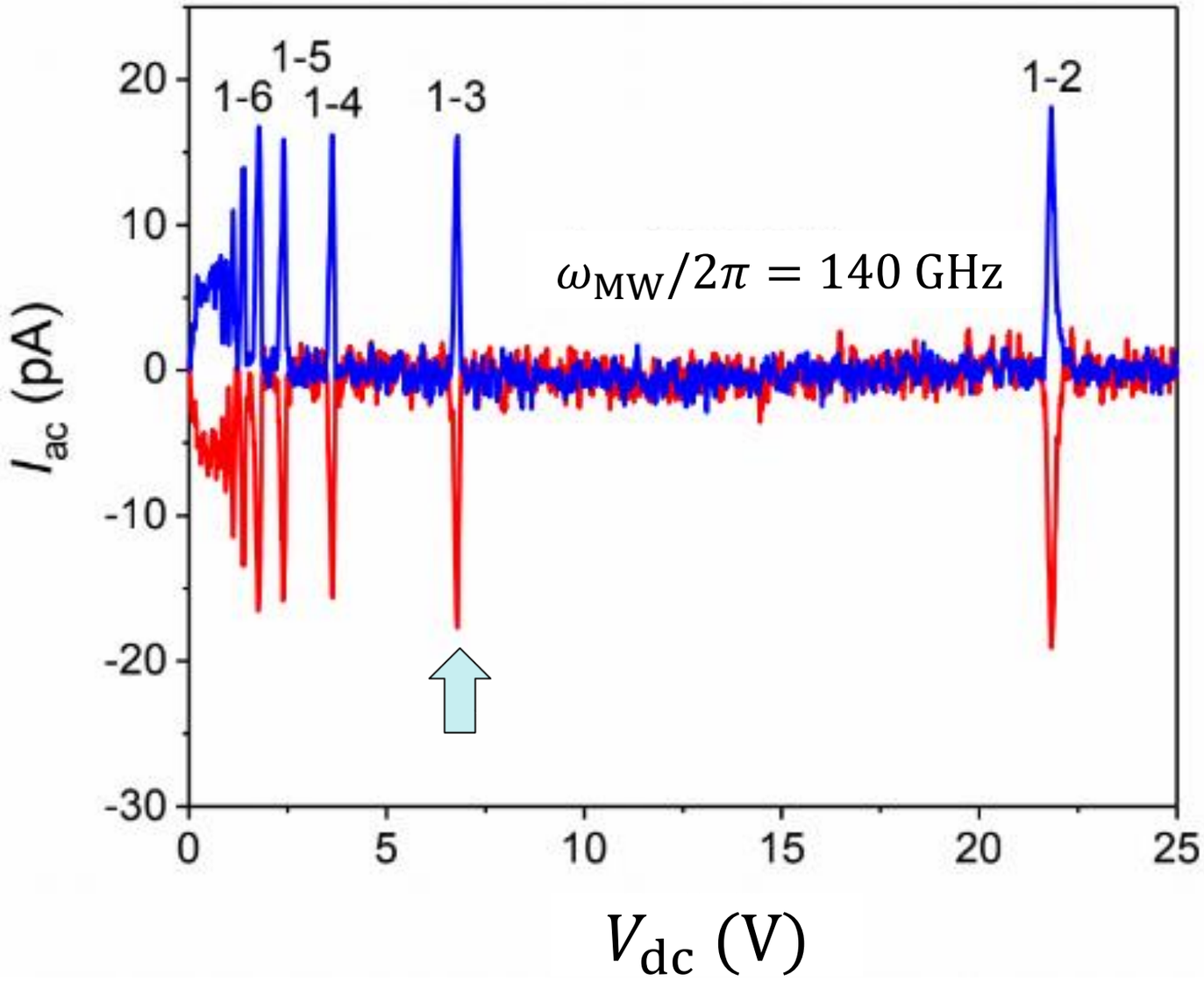
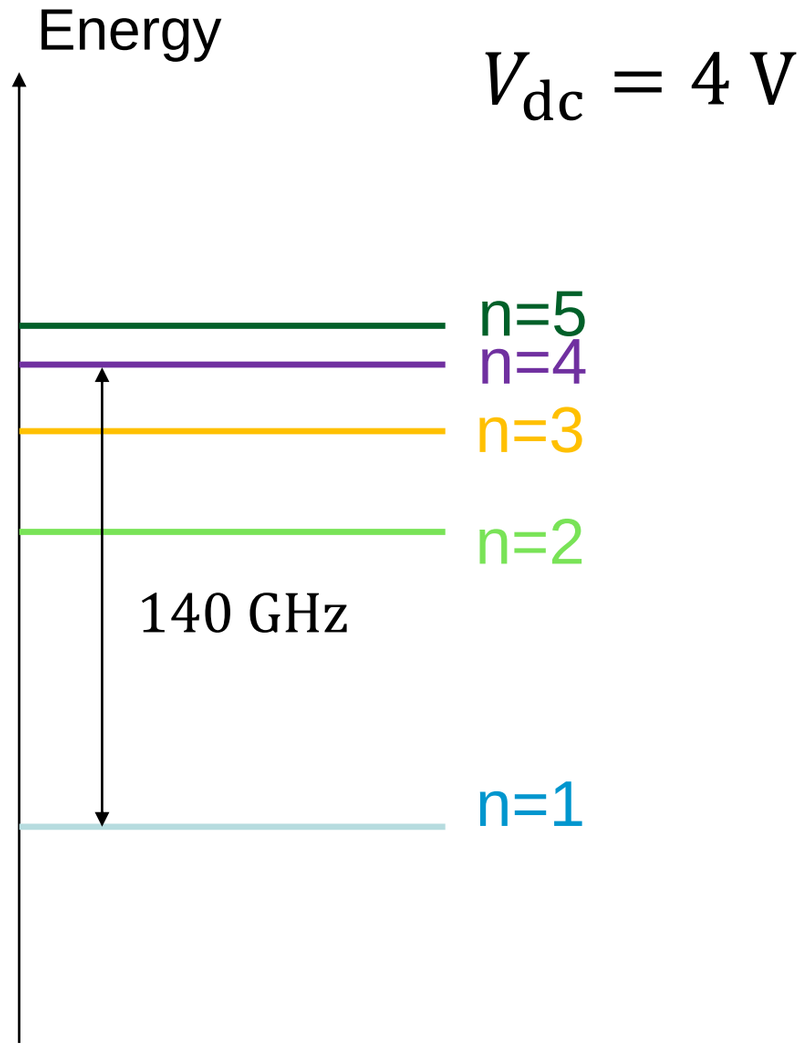
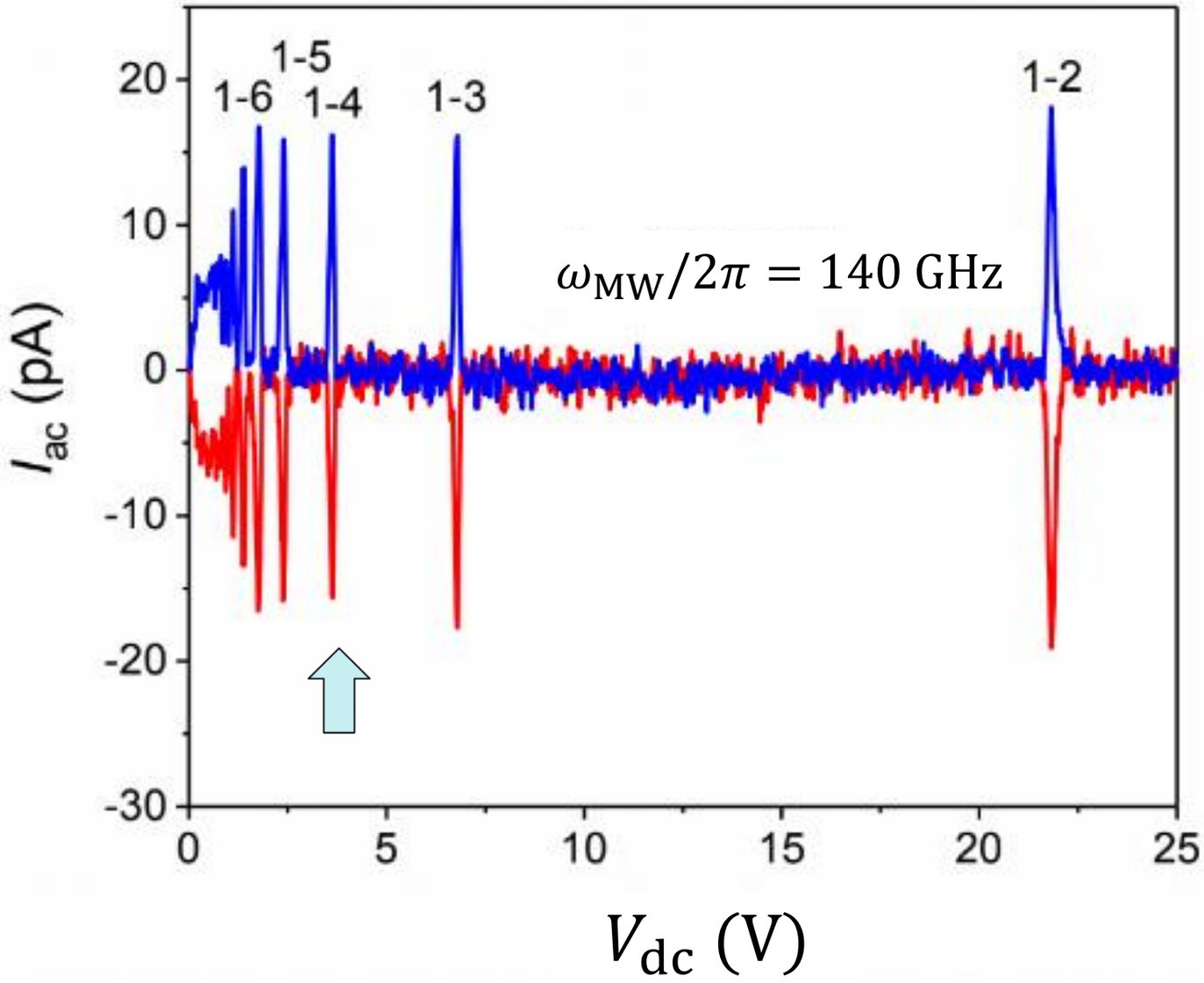


Image-charge detection of the Rydberg state of the electrons on helium





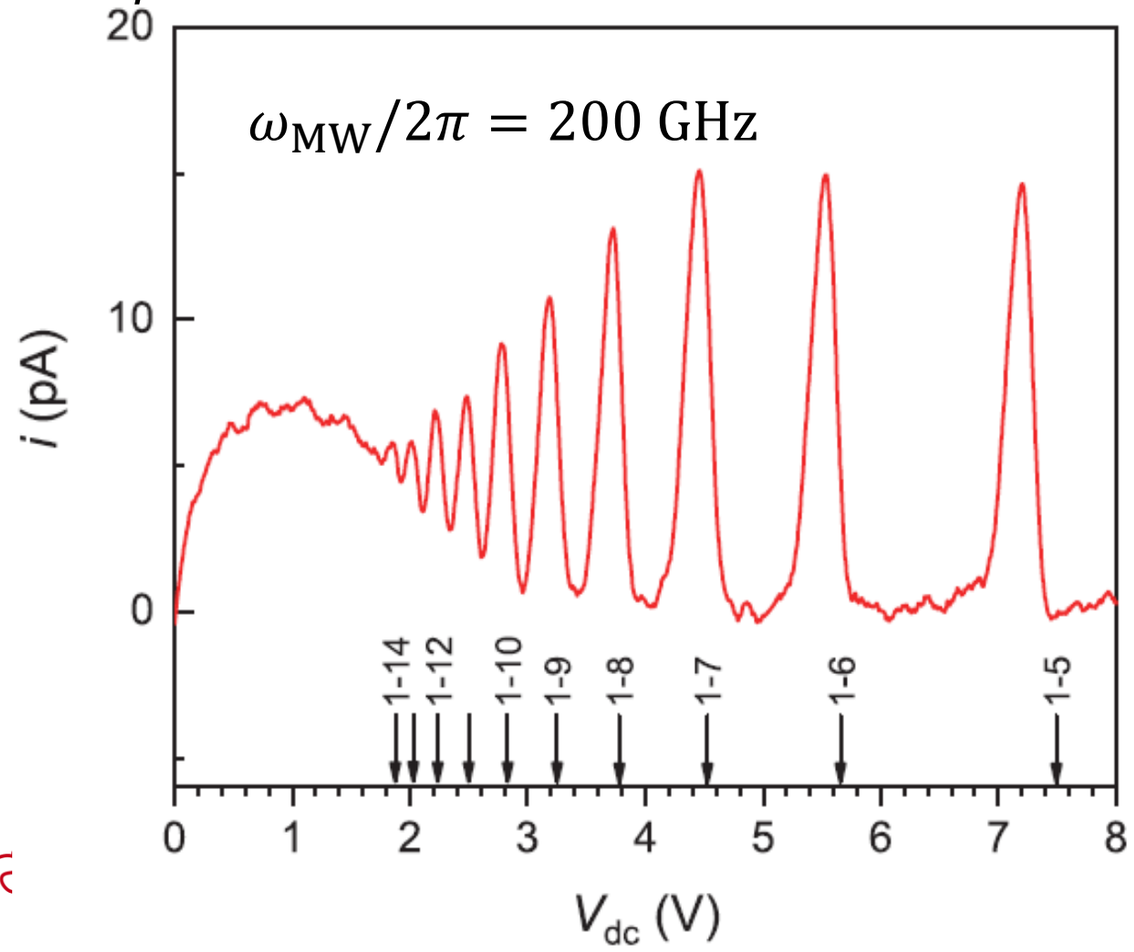
Spectroscopy of the Rydberg state of the electrons on helium

image-charge detection

Kawakami, Elarabi, and Konstantinov, arXiv:1904.01238

$$|I| = Ne\Delta z \rho \omega_m / D$$

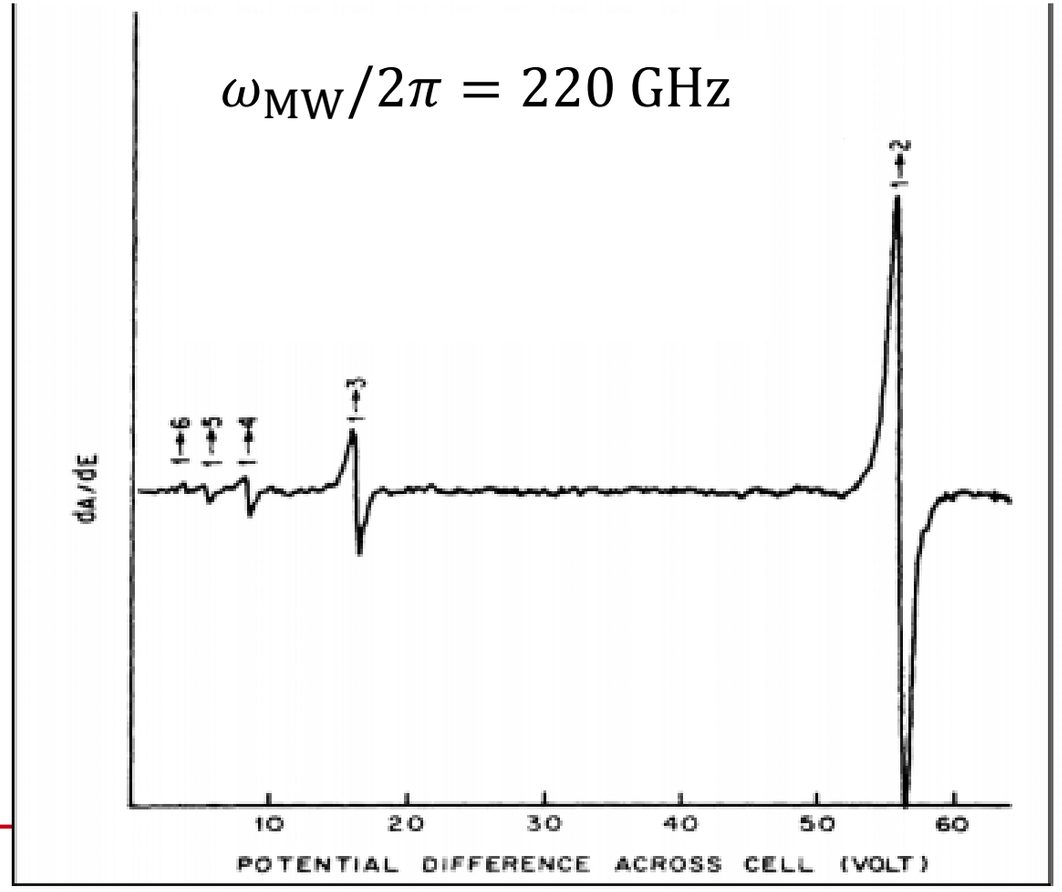
ρ: fraction of the electrons in the excited state



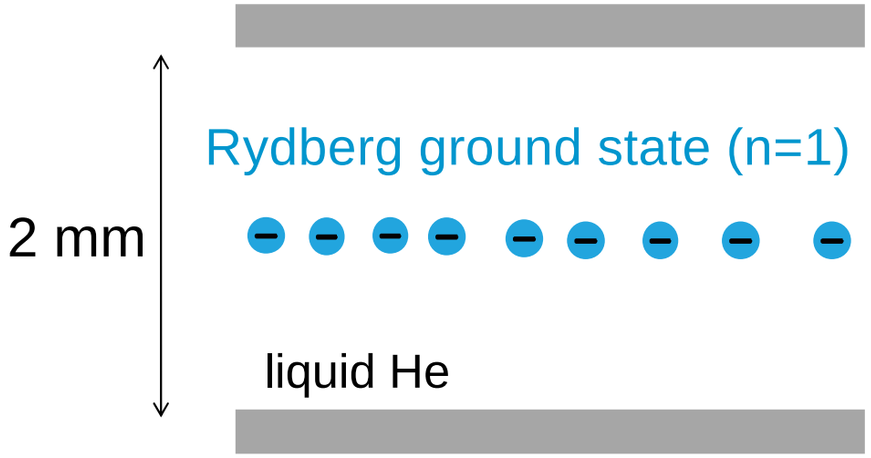
microwave absorption measurement

Grimes and Brown, Phys. Rev. Lett. 32, 280, (1974)

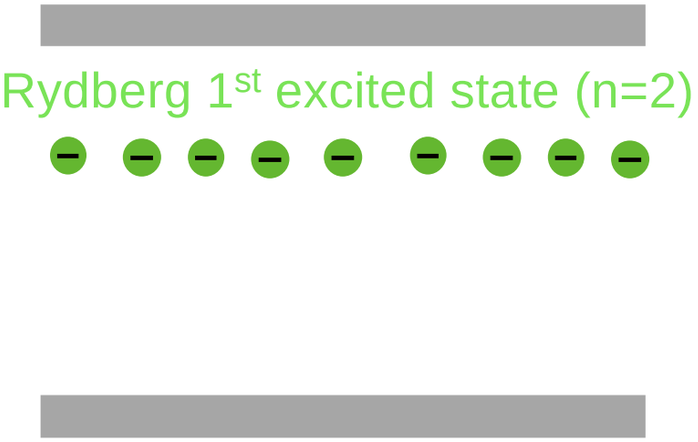
$$\Delta P \propto \hbar\omega_{MW} |\langle 1|z|n\rangle|^2$$



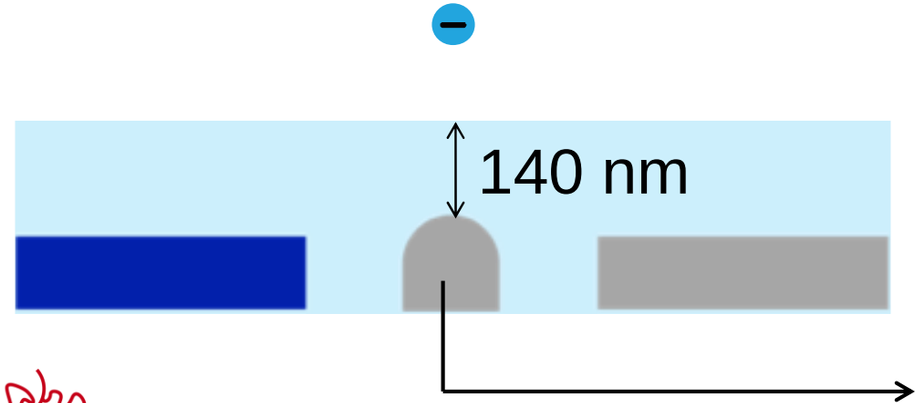
How can we detect a single electron?

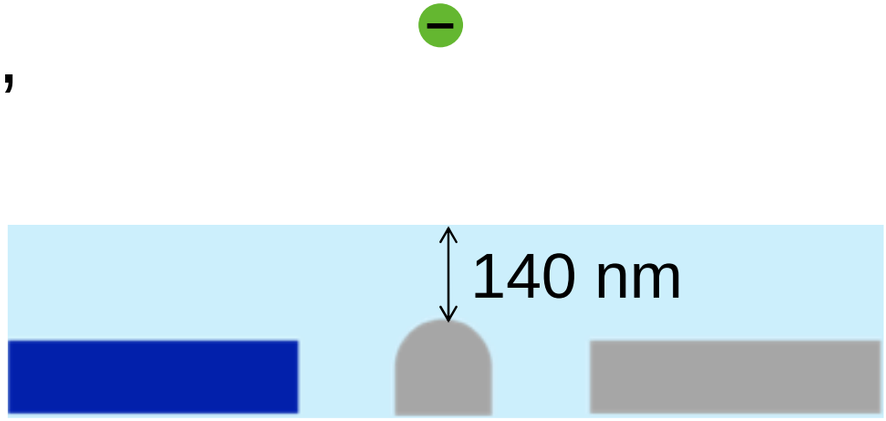


with 10^7 electrons,
$|\Delta Q_0| \sim 100e$



with one electron,
$|\Delta Q_0| \sim 0.01e$





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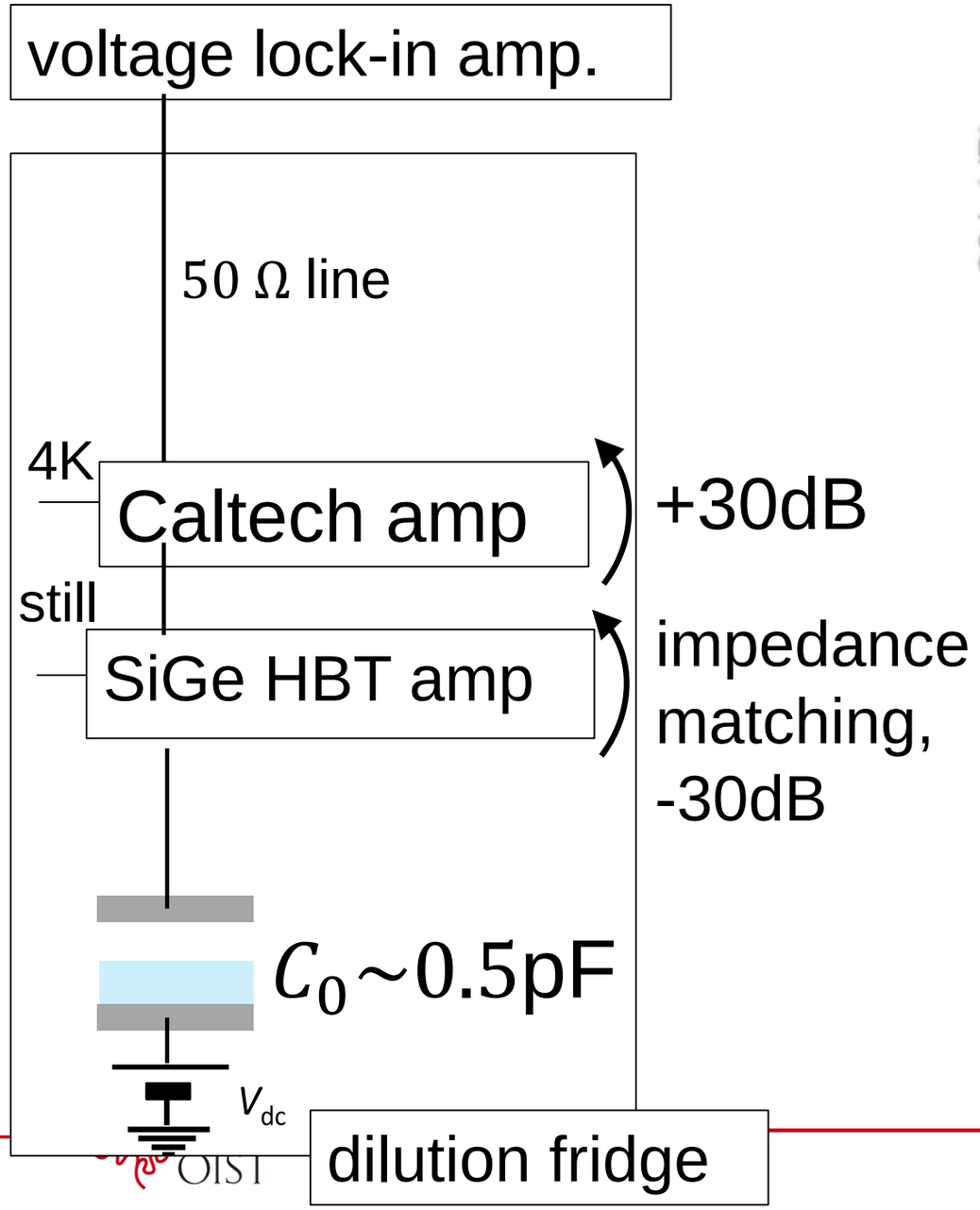
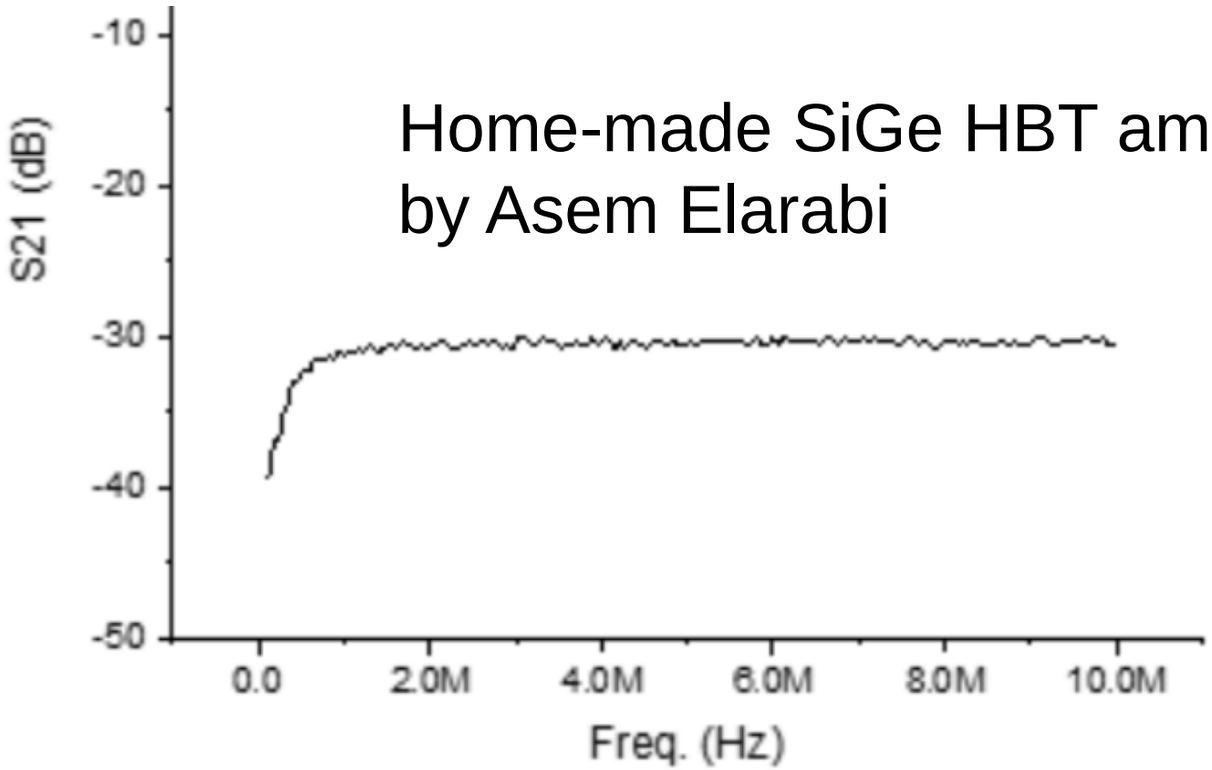




Home-made SiGe HBT amp
by Asem Elarabi

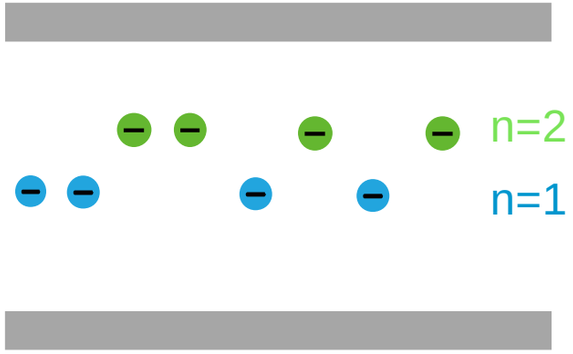
voltage drop due to the electron(s): $V_d = \frac{\Delta Q}{C_0}$

$\Delta Q = 0.01e \rightarrow V_d \sim 3\ \mathrm{nV}$

Summary

Motivation: realize spin qubits with electrons on helium using Rydberg-spin interaction

Progress achieved so far:
Image-charge detection with many electrons



Future: trap and detect a single electron