Development of a Laser System for Rubidium Neutral-Atom Quantum Computers

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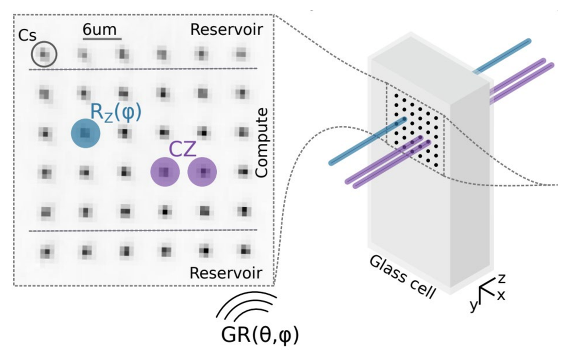
Goal 6 moonshot Cold-atom QC

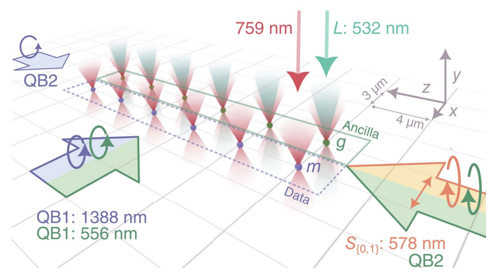
National Institutes of Natural Sciences Institute for Molecular Science

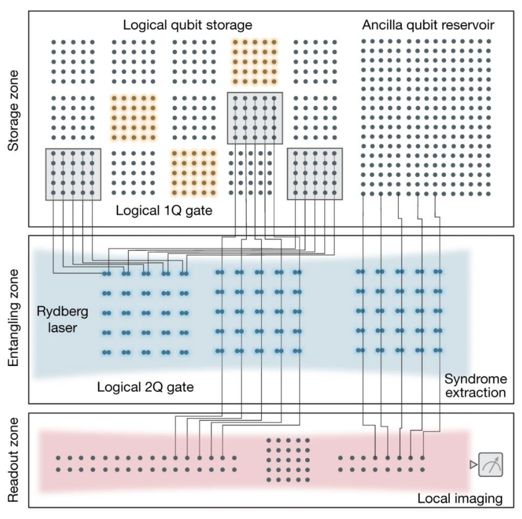
Introduction

Neutral-atom quantum computer

- Perfect and identical qubits
- Scalability up to 10k
- Long coherent time
- Controllable/reconfigurable interactions

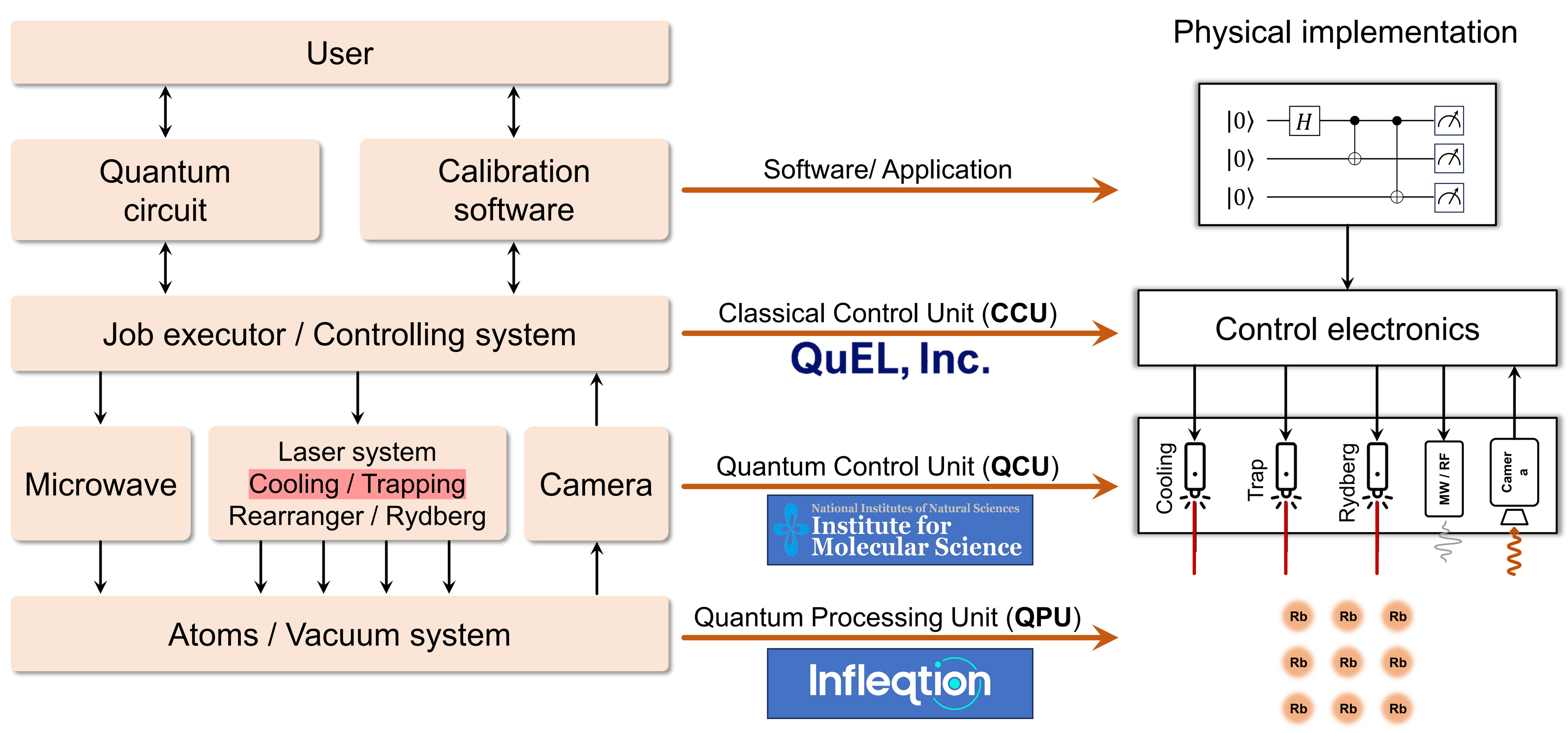






D. Bluvstein *et al.*, Nature **626**, 58 (2023)
G. Radnaev *et al.*, arXiv:2408.08288 (2025)
J. W. Lis *et al.*, Phys. Rev. X 13, 041035 (2025)

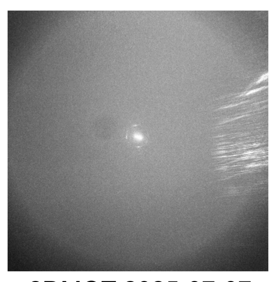
Quantum computer stack (Neutral-atom)



State Preparation & Measurement

2D/3D-Magneto Optical Trap

- Cooling and trapping of Rb atoms using counter-propagating beams and magnetic gradients (~300 μK)
- **2D-MOT** captures hot atoms and forms atomic beam
- The atomic beam delivers atoms to the **3D-MOT** in a separate vacuum chamber.
- High flux, low background, and clean trapping



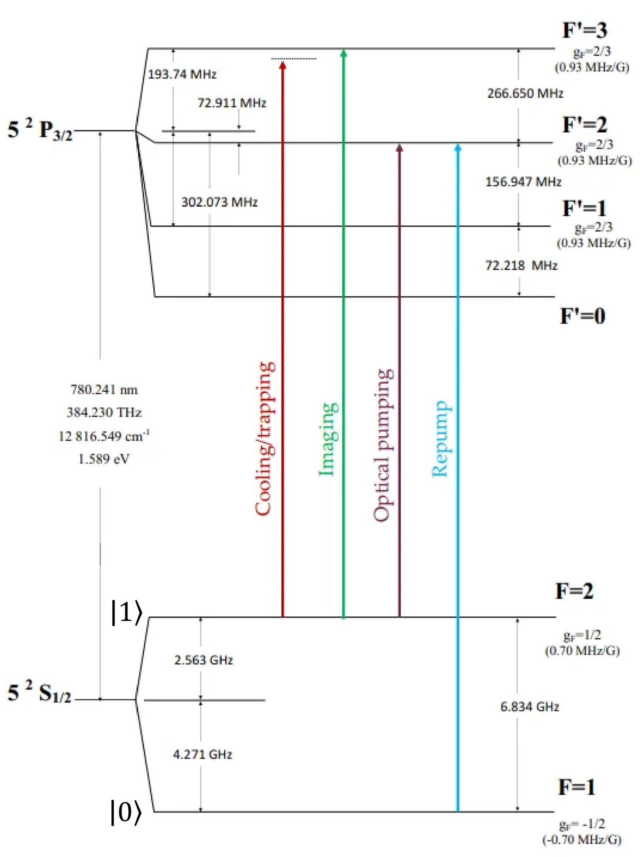
2DMOT 2025-07-07

Molasses Cooling

- Sub-Doppler cooling via polarization gradients (~10 μK)

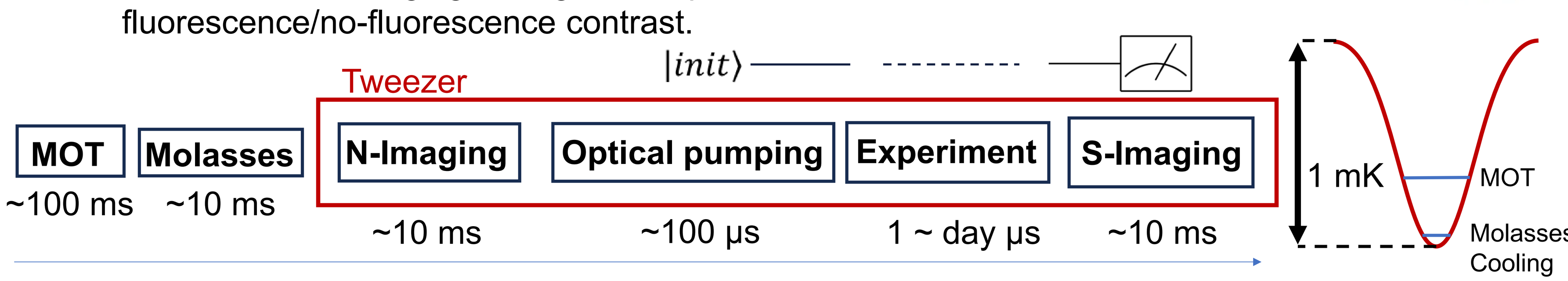
Optical Pumping

- Atoms are polarized into a specific Zeeman sublevel using circular or linear polarized light.
- Crucial for state preparation, qubit initialization, and selective detection.



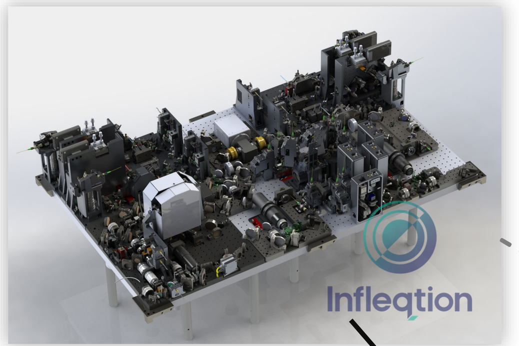
Imaging

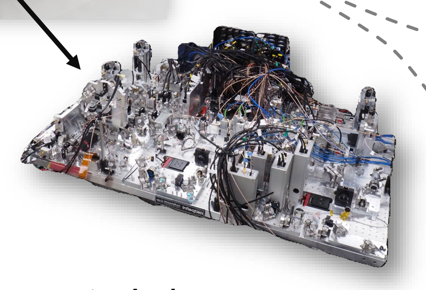
- Non-State-selective imaging: Resonant fluorescence imaging confirms whether an atom is trapped.
- State-selective imaging: State-selective imaging distinguishes qubit states via fluorescence/no-fluorescence contrast.



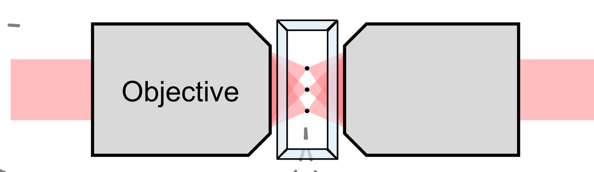
Quantum Processing Unit (QPU)

Rubidium optical tweezer array

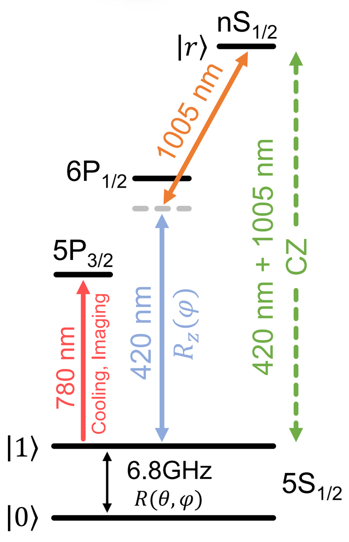


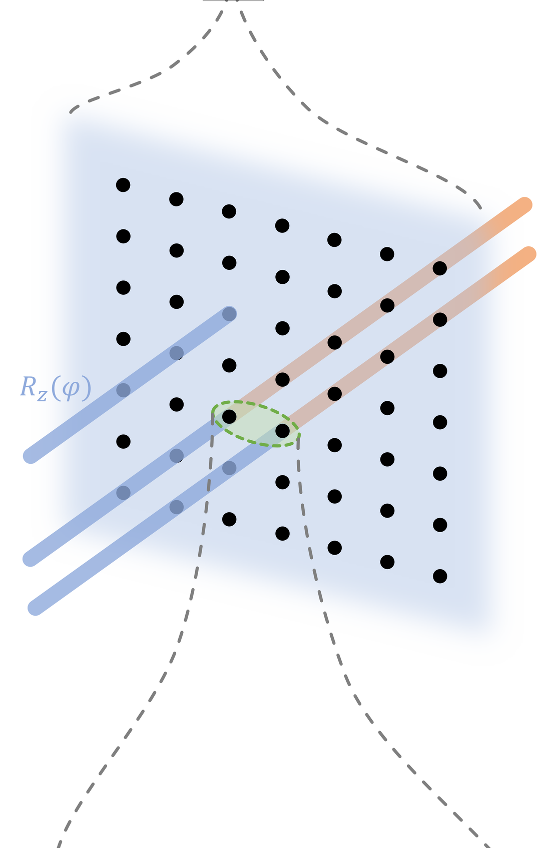


- Designed with Infleqtion (since 2023)
- Ultralow vacuum
- ^{87}Rb atoms act as qubits
- High-resolution objective (1000 traps)
- 500 reassembled qubits



- Global qubits control via microwave $R(\theta,\varphi)$
- Cooling/imaging with 780 nm D2 line
- Ground state Raman sideband cooling with 795 nm D1 line
- CZ gate with two-photon (420+1005 nm) excitation to a Rydberg state
- Parallel local addressing of $R_z(\varphi)$, CZ gate

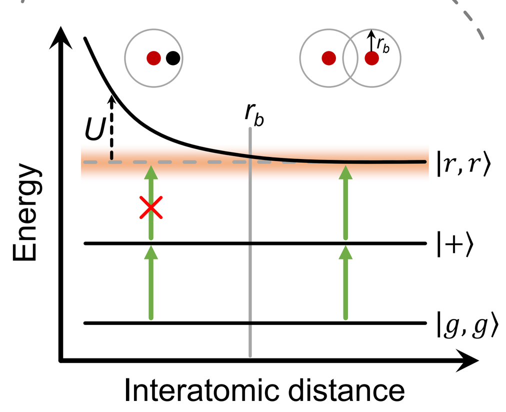




A. G. Radnaev *et al.*, arXiv:2408.08288 (2025)

Rydberg CZ gate

- Strong Rydberg interaction (*U*) causes Rydberg blockade
- High-fidelity CZ gate can be achieved with a time-optimal gate
- Flexible connectivity with swap gates or shutling

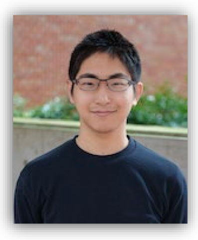


D. P. DiVincenzo *et al.*, Science **270**, 255 (1995)
D. Bluvstein *et al.*, Nature **626**, 58-65 (2024)

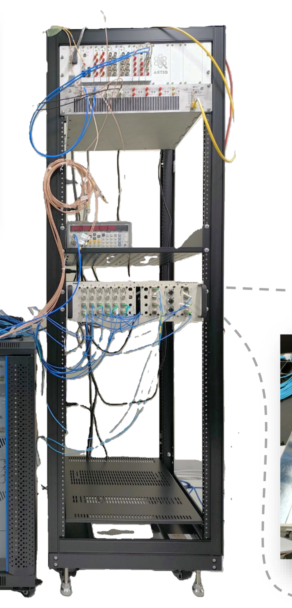
780 nm Laser System

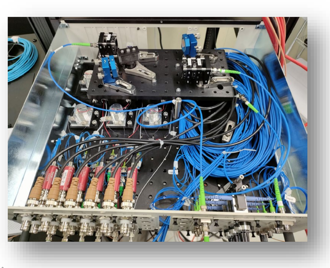
Integrated Laser

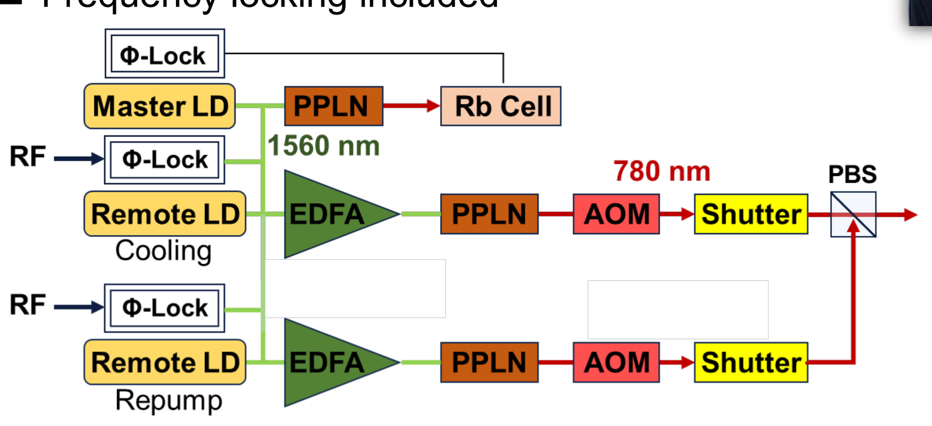
- Narrow-linewidth laser matched to Rb D2 line
- Frequency locking included



Tanaka

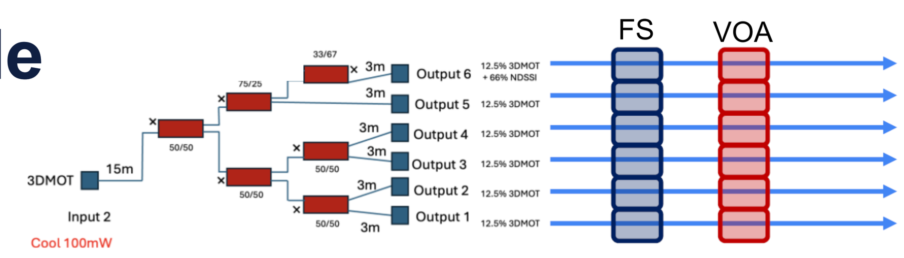






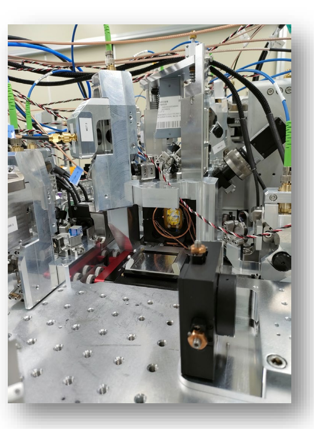
Laser Distribution Module

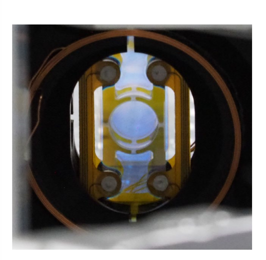
- Cooling and repump lasers combined via polarization optics
- Split into 6 MOT beams using **fiber splitter**
- **Fiber stretcher** reduces MOT interference fringes
- **VOA** adjusts MOT laser power to prevent saturation



Modules inside QPU

- Aligned optics to deliver clean MOT beams
- Laser power monitoring
- Ultra-high vacuum glass cell (~10^{-12} Torr)





Timeline/Teams