Towards characterization of optical tweezer traps for a Rubidium Neutral Atom Quantum Computer

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moonshot Goal 6 Cold-atom QC

National Institutes of Natural Sciences Institute for Molecular Science

Neutral Atom QC

Our System

- ***Target***
  - Full-stack quantum computer
    - 500 qubits
    - Fidelity >99%
    - Stable operation
  - First neutral-atom quantum computer in Japan

System characteristics

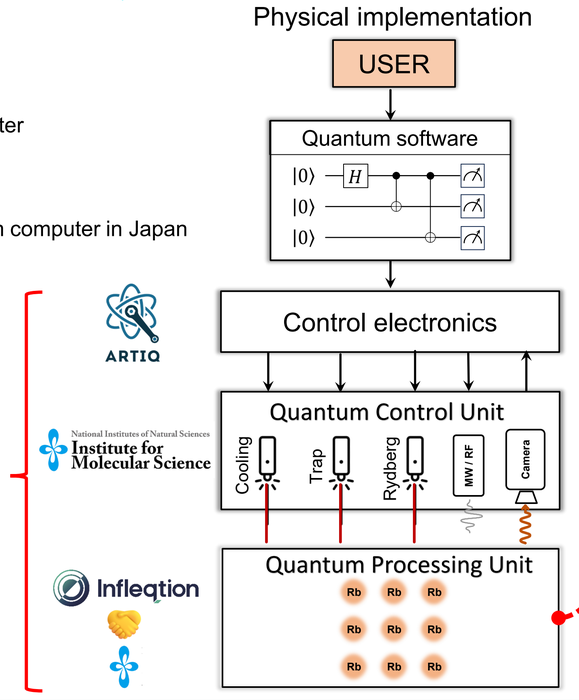
Artiq-based Control Electronics
with Infleqtion Science-Kit orchestrator

Modular Laser systems
designed by Ohmori Group (IMS)

Quantum Processing Unit
co-designed with Infleqtion (since 2023)

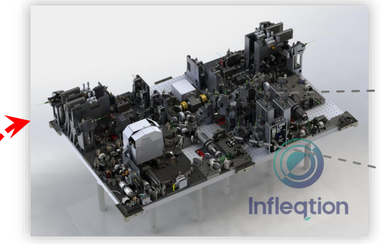
G. Radnaev *et al.*, arXiv:2408.08288 (2025)

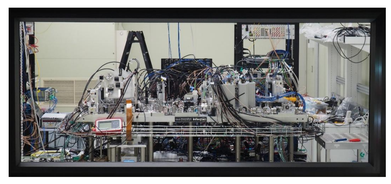
Physical implementation



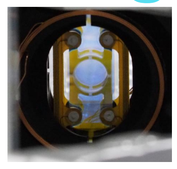
Quantum Processing Unit (QPU)

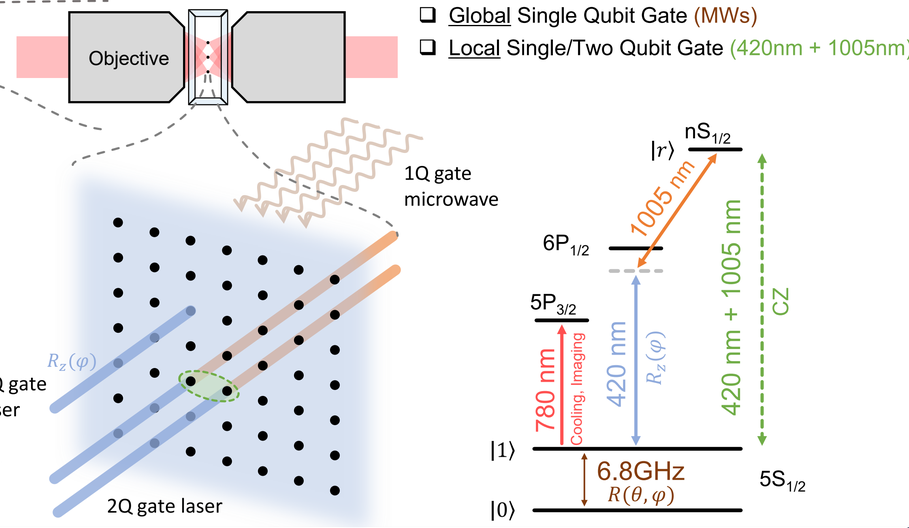
Cold Atoms: ^{87}Rb





Bluvstein, D. et al. Nature 626, 58–65 (2024).

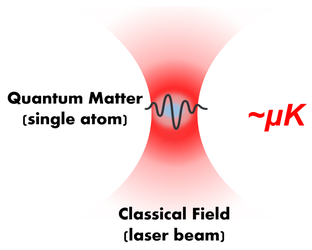




- Modular Operations
  - ***Trap Array Generation Module*** (850nm)
  - ***The ReArranger*** (850nm)
  - Cooling & Imaging Module (780nm)
  - Global Single Qubit Gate (MWs)
  - Local Single/Two Qubit Gate (420nm + 1005nm)

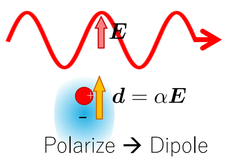
Optical Tweezer Traps

Atom-Light Interaction



Semiclassical approximation

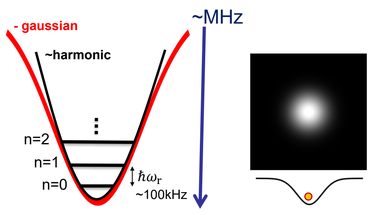
Dipole approximation



Energy

$$U = -\boldsymbol{d}\cdot\boldsymbol{E} \propto -\text{Intensity}$$

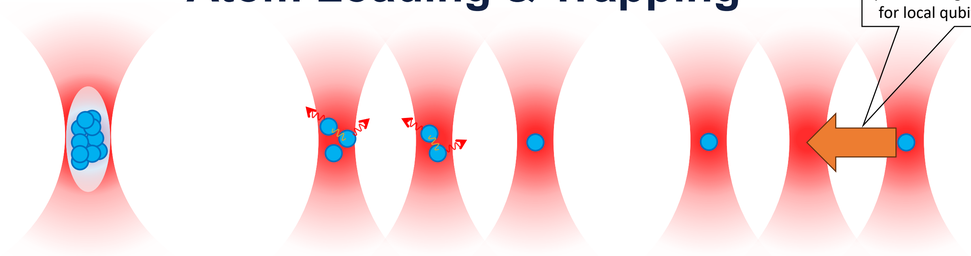
Grimm, Weidemüller & Ovchinnikov, Adv. At. Mol. Opt. Phys. 42, 95 (2000)



Gaussian-Harmonic approximation

Atom Loading & Trapping

We need post-loading rearrangement for local qubit addressing!!

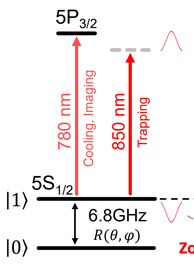


Laser Cooling
2D MOT, 3D MOT, Molasses
$300\ K \rightarrow \sim 50\ \mu K$

Light Assisted Collision
Tweezer Trap Phenomena

Single Atom Traps
Further cooling to ground state
$\sim 50\ \mu K \rightarrow \sim 3\mu K$

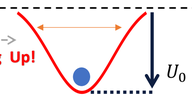
SYSTEM REQUIREMENTS	1mK ~ 3mW per tweezer 1024 tweezers ➡ 512 atoms ➡ 6W per array rearrangement need arises!



Trap characterization

Zooming Up!

Trap Depth

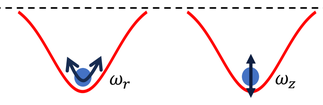


$$U_0 \sim \frac{Power}{\pi w_0^2/2}$$

$\sim 1\ mK$
$\sim h \times 20\ MHz$

Controlled at laser source!

Trap Frequencies

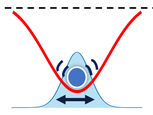


$$\omega_r = \sqrt{\frac{4U_0}{mw_0}} \qquad \omega_z = \sqrt{\frac{2U_0}{mz_R}}$$

$\sim 120\ kHz$ $\sim 30kHz$

Observables!

Atom Uncertainty



$$\Delta x = \sqrt{\frac{\hbar}{2m\omega_r}} \qquad \Delta p = \sqrt{\frac{\hbar m\omega_r}{2}}$$

$x_{rms} \sim 25nm\ \ v_{rms} \sim 1.7cm/s$

Derived!

At ground state, system behaves as a Quantum Harmonic Oscillator !

See Odagawa's poster to see why we can go to ground state ! !

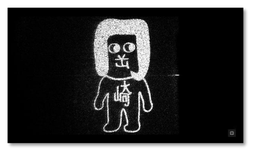
Large Array Generation

Trap Array Generation (TAG)

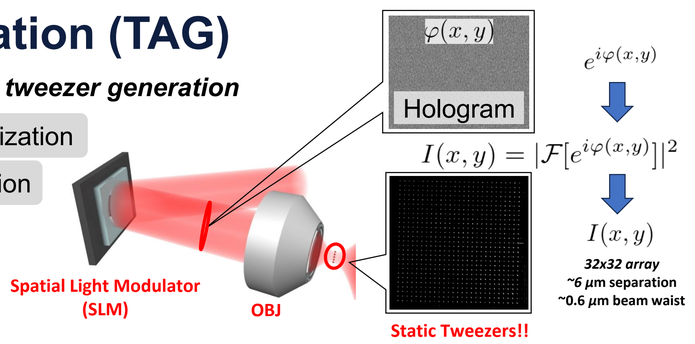
- ***GOAL: 32x32 ~ 1024 static tweezer generation***

SLM-driven tweezer homogenization

Arbitrary pattern array generation



Y. Chew *et al.*, arXiv:2407.20699 (2024)

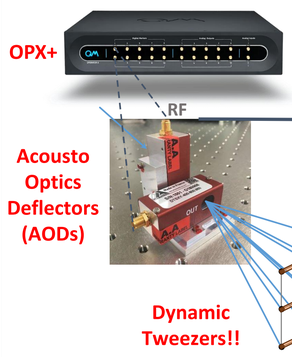


The ReArranger (ReA)

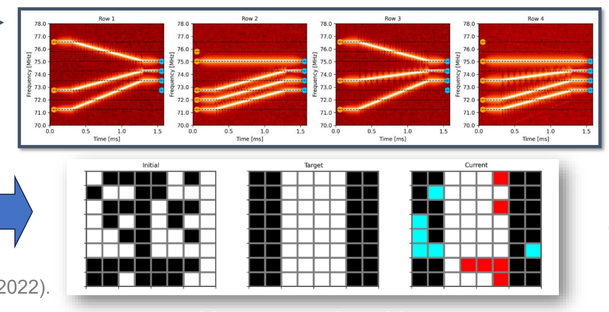
- ***GOAL: Line-by-line rearrangement of 512 atoms***

Up to 18 multitones at single channel!

Up to 16 dynamic tweezers!



Bluvstein D. et al. Nature 604, 451–456 (2022).

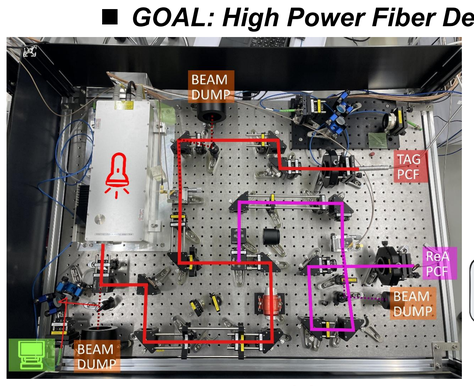


Multitone Generation with OPX+

Giorgio Micaglio @Trento, Italy

852 nm Laser Source

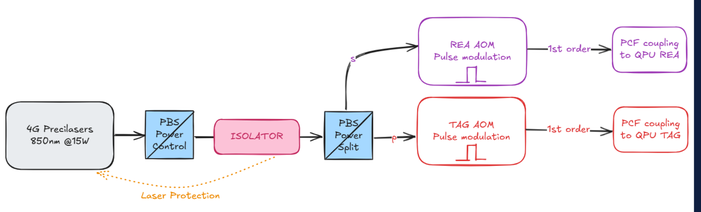
- ***GOAL: High Power Fiber Delivery at switch speed limit!***



TAGReA Laser Module

High-power fiber delivery | Fast Optical Switch (100ns)

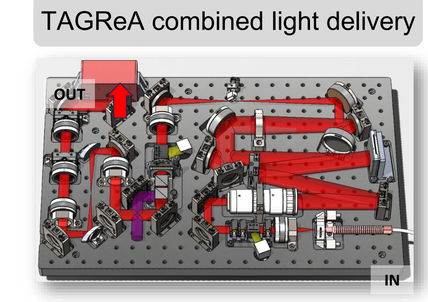
Damage threshold management



TAGReA QPU Module

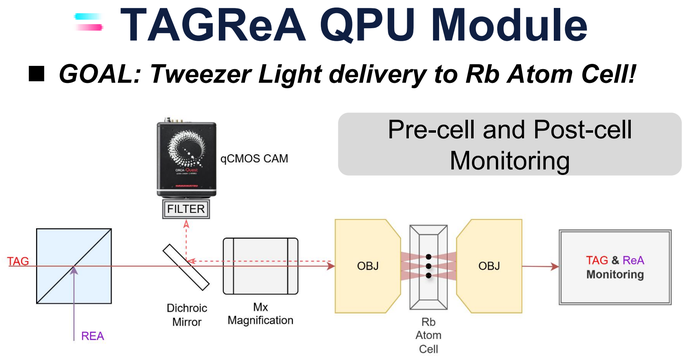
- ***GOAL: Tweezer Light delivery to Rb Atom Cell!***

TAGReA combined light delivery



TAGReA QPU Module

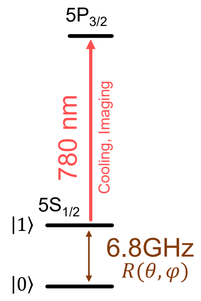
Pre-cell and Post-cell Monitoring



Neutral Atom Qubits

Qubit Detection

- Measurement of qubit state via atom fluorescence
- **Limiter**: Imaging time (~10ms)
- **Methods**: Destructive/Non-Destructive
- **Fundamental Limit**: Shot Noise (state readout fidelity)



Trap Lifetime

- Physical atom trapping time
- **Limiter**: Heating Mechanisms
  - 30 THz detuning
    - ➡ detuning-induced scattering
  - ~10^{-12} mbar of Vacuum
    - ➡ atom collision
- **Mitigation**: deeper traps, improved vacuum

Qubit Lifetime

- Qubit population and coherence preservation time
- **Limiters**: T_1 and T_2 lifetime
  - T_1 ~10 seconds to several minutes
    - ➡ Off-resonant scattering sensitive
  - $T_2 \leq 2T_1$ ~10ms
    - ➡ EM noise sensitive
- **Mitigation**: dynamical decoupling

Toward Larger Arrays

A 10 000-qubit array

- ***GOAL: Increase atomic qubits number to support future QEC architectures!***

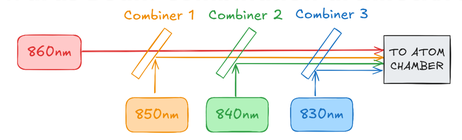
Current State

1000 traps → ~10W@852nm

10000 traps → **~100W@852nm**
(Difficult with single CW laser)

H. Manetsch *et al.*, arXiv:2403.12021 (2024)

Towards Beam Combination architectures



Future research paths...
- ✓ Coherent Beam combination
- ✓ Incoherent Beam combination