

Preparation and Control of Deterministic 3D Cold-Atom Arrays for Fault-Tolerant Logical Qubits

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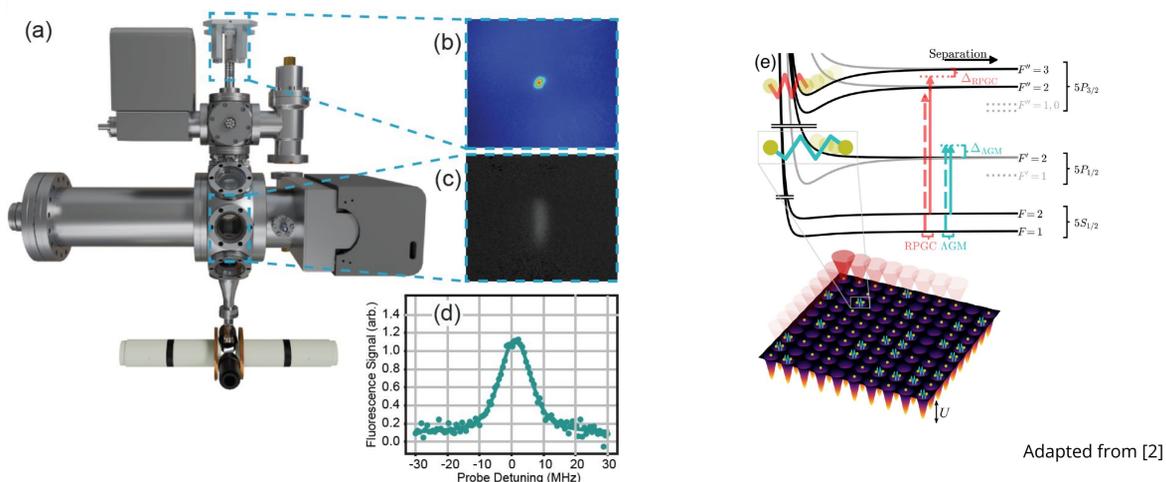
Introduction

A 3D neutral-atom array offers a path out. Here we report our progress toward building a 3D neutral-atom platform for quantum computation, including a quantum error-correction co-design study tailored to 3D geometries to improve time efficiency.

MOT(Magneto - Optical Trap) / Control system

• 2D+ MOT / 3D MOT

- To reduce background collisions in the science region, our MOT is implemented in a two-stage configuration: a 2D+ MOT for high-flux atomic-beam generation and a 3D MOT for capture and further cooling.
- From these measurements, we estimate the atomic-beam transverse velocity to be 15.4–24.8 m/s.
- We plan to implement Λ -enhanced gray molasses cooling, which will reduce the atom temperature from the Doppler limit to $\sim 0.1 \mu\text{K}$ [1] and increase the initial tweezer loading rate to up to 85% [2].



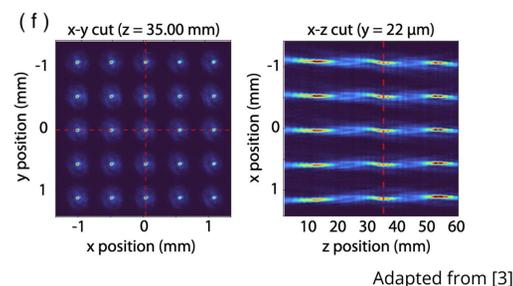
[Figure] (a) Vacuum chamber system (b) 2D MOT fluorescent imaging (c) Atomic beam flux fluorescent imaging (d) Beam flux spectroscopy (horizontal) (e) Enhanced loading efficiency through a grey molasses cooling [2]

• FPGA Control system

- We use ARTIQ as our FPGA-based experiment control system for timing-critical sequencing and hardware synchronization.
- A graphical user interface is also under development to enable real-time parameter tuning.

• 3D reconfigurable tweezer

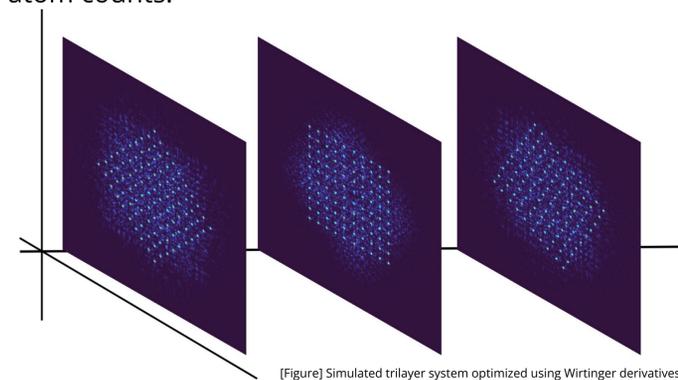
- We are building a 3D reconfigurable optical tweezer system using three AODs to steer traps in three dimensions [3].



[Figure] (f) Reported 3D optical tweezer using three AODs [3]

3D holography / Imaging system / QEC codesign

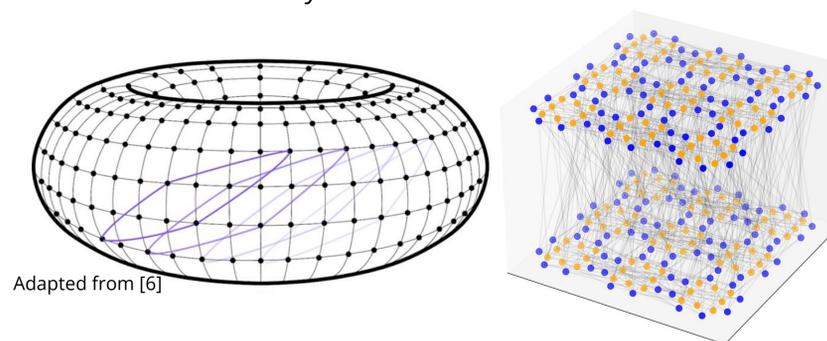
- Trap atoms in reconfigurable holographic trap arrays, shaped by a spatial light modulator (SLM).
- Goal: extend trap arrays to three dimensions (3D) to overcome laser power limitations and enable record atom counts.



[Figure] Simulated trilayer system optimized using Wirtinger derivatives

• Quantum Error Correction (Bivariate Bicyclic Code)

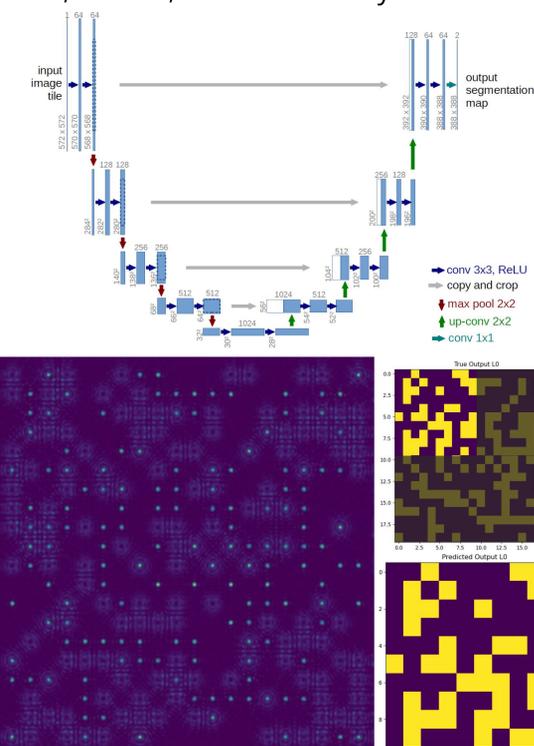
- 2D \rightarrow 3D trades entangling concurrency for increased locality, cutting geometric footprint in half.
- Additional atom density accelerates syndrome measurement cycle.



[Figure] (left) Visualization of the bivariate bicyclic code [6] (right) Embedding of $[[144, 12, 12]]$ bivariate bicyclic code in a hybrid 3D architecture (below) Syndrome measurement cycle time for the $[[144, 12, 12]]$ bivariate bicyclic code.

• Atom Detection

- Train U-Net to decipher readout image of atoms in simulated noisy bi/trilayer system.
- (bilayer) 99.99%, 99.91% accuracy, (trilayer) 99.9%, 99.56%, 95.99% accuracy



[Figure] (top) U-net architecture (bottom) Simulated bilayer system and predicted outputs of neural network.

Acknowledgements & References

Parsons for his continued support, insightful feedback, and mentorship.

- DOI:10.1038/s41598-018-19814-z
- 10.1103/PhysRevX.9.011057
- arXiv:2510.07633
- 10.1145/3779066
- 10.1103/PhysRevA.111.022433
- 10.1038/s41586-024-07107-7

Lattice Spacing	Our Work	SoTA
$\sim 5 \mu\text{m}$	1.83 ms (hybrid 3D)	2.97 _[4] ms (dynamic 2D)
$\sim 1.7 \mu\text{m}$	1.05 ms (hybrid 3D)	1.27 _[5] ms (static 2D)