Center for **Quantum Networks**

National Science Foundation Engineering Research Center

AI-Augmented Hardware Co-Designed Quantum Control for Neutral Atom Processors Using a Digital Twin of a Programmable Photonic Engine

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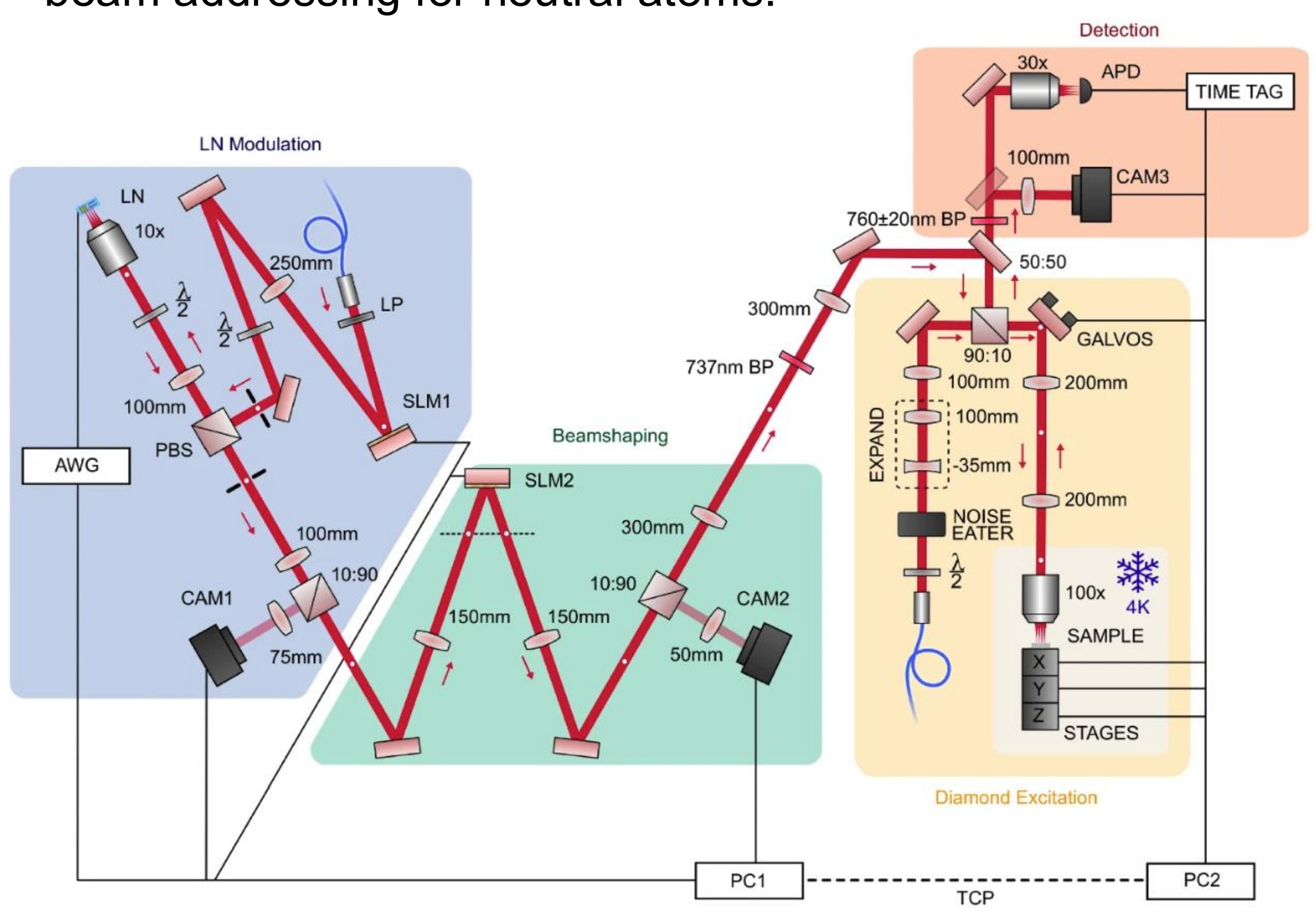
Introduction

- Background:

  Integrated photonic engines for programmable atomic control recently reported in [1] [2] enable fast and dynamic individual beam addressing for neutral atoms.



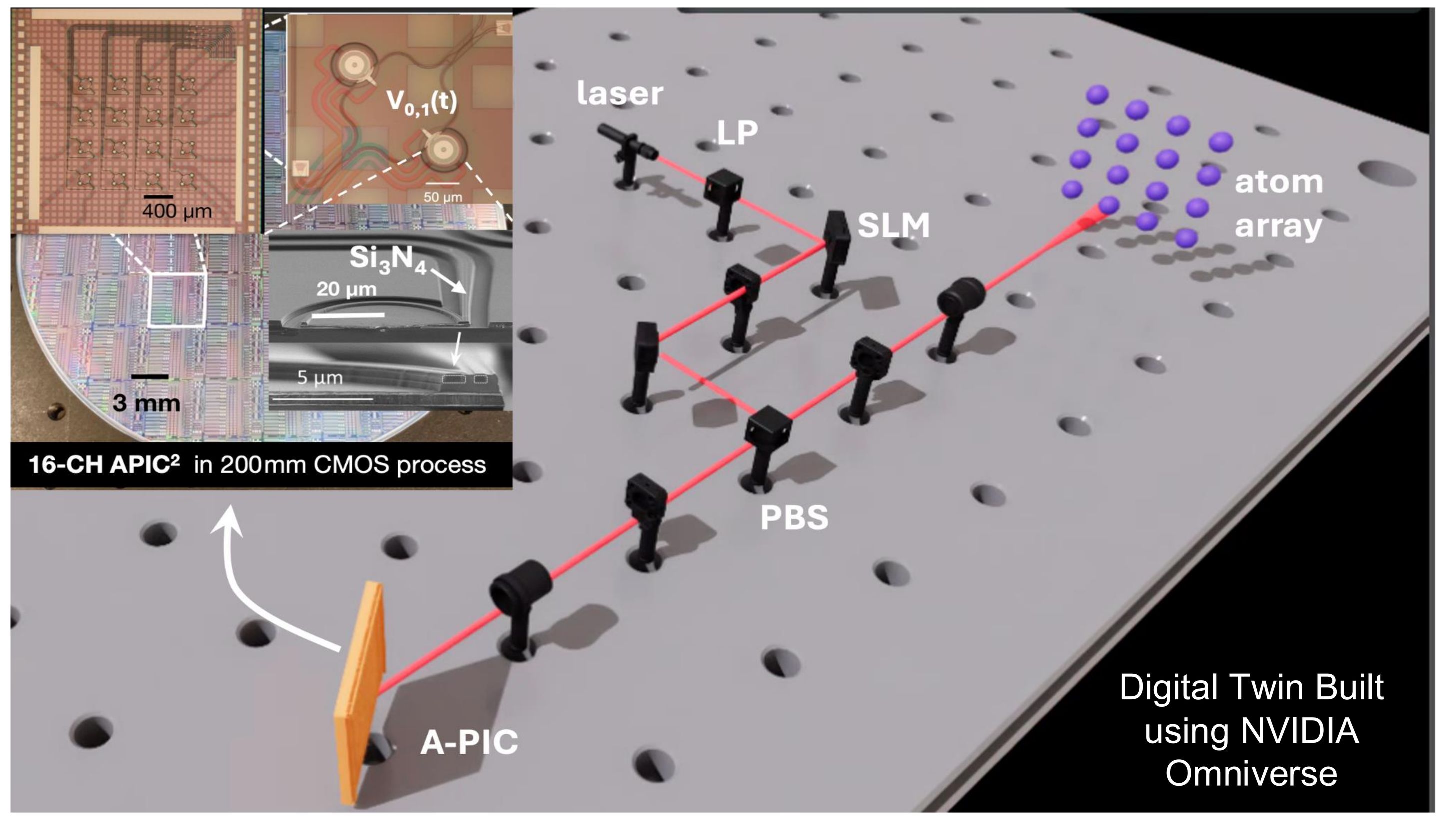
- Challenges:

  The hardware system is highly complex, comprising multiple free-space optical components, spatial light modulators (SLM) and a multi-channel programmable photonic integrated circuit (PIC). Achieving fast, real-time precise control of individual addressing beams remains a key technical hurdle.

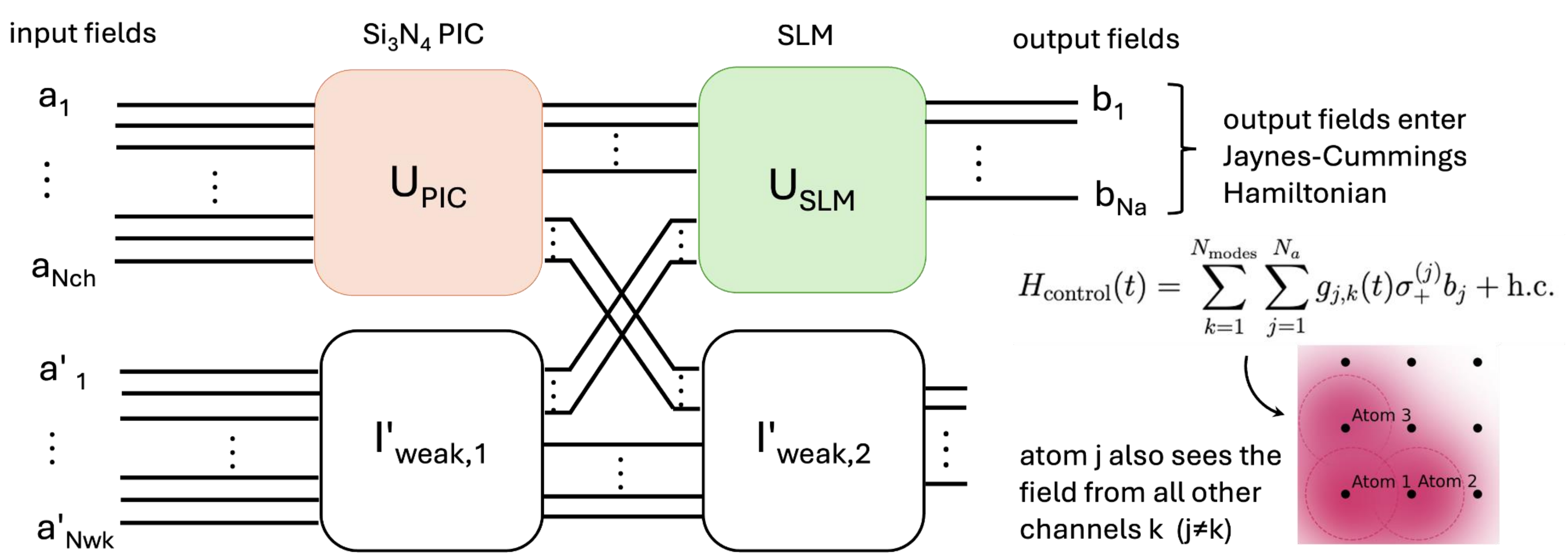
Methods

- A Proposed Solution:

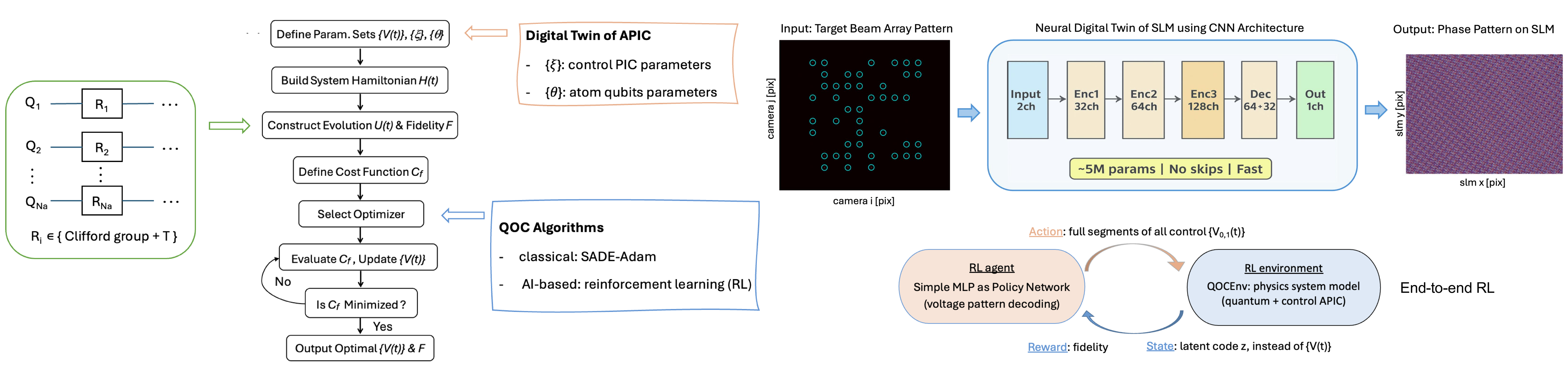
1) Build a digital twin model of control hardware (currently only the modulation stage involving SLM and PIC is implemented)



2) Formulate mathematical representations of the hardware [3]



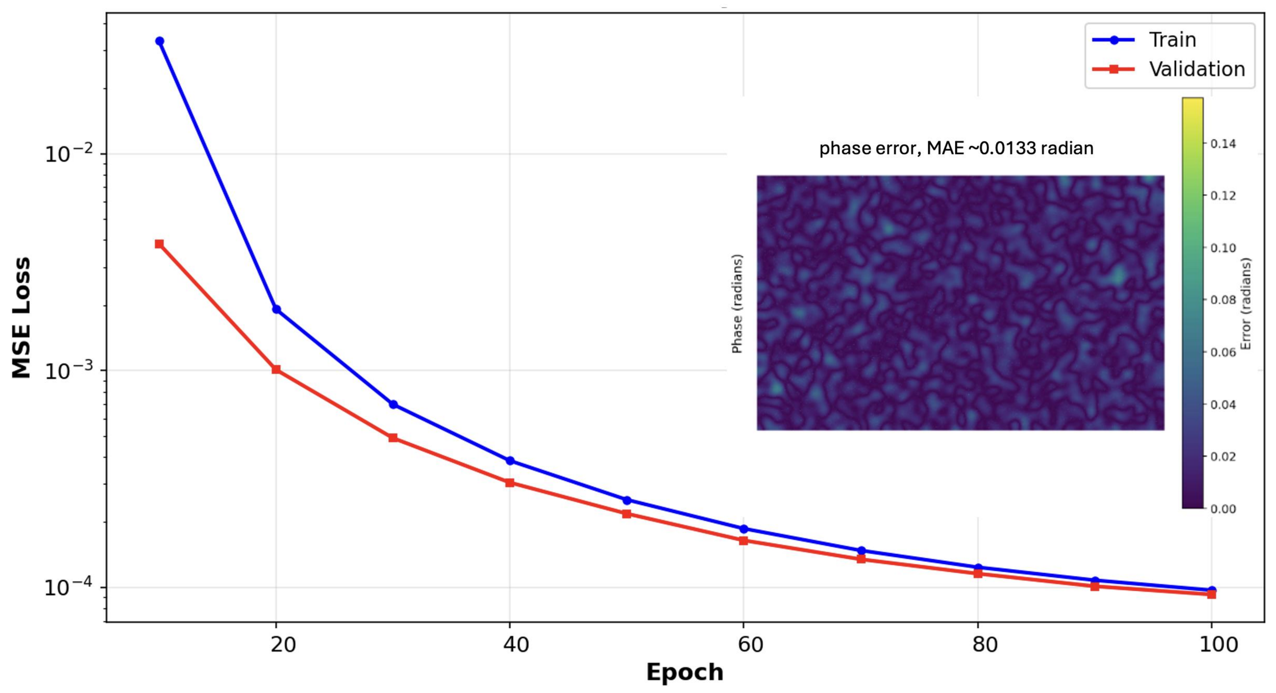
3) Integrate the hardware digital twin model into the quantum optimal control (QOC) workflow



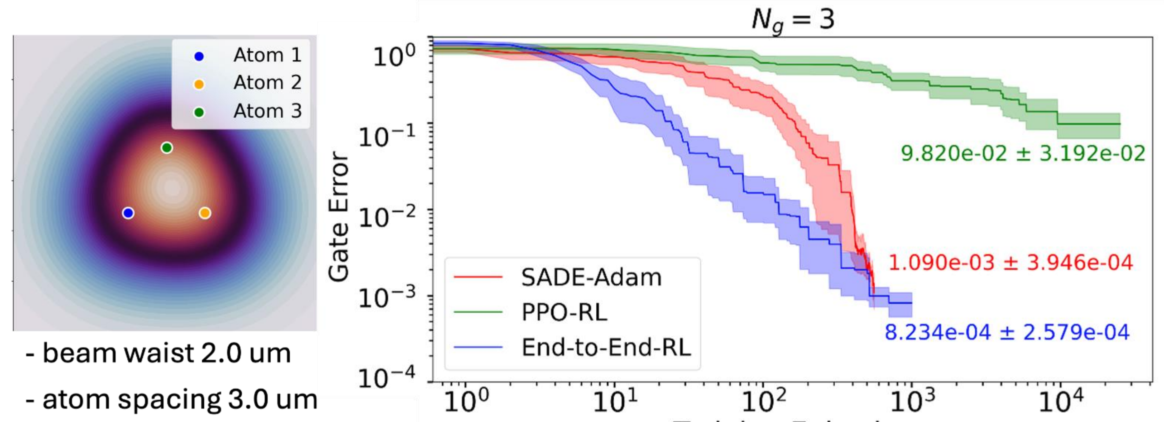
- [note] three QOC algorithms have been implemented: one classical hybrid local and global solver, Self-Adaptive Differentiable Evolution (SADE)-Adam, and two AI-based optimizers - Proximal Policy Optimization (PPO)-RL and End-to-End RL.

Results

1) Training of neural digital twin for SLM
   - 10,000 training samples generated using *slmsuite* [4]
   - Fast inference with digital twin model: 10 ms vs. 3 s for classical Gerchberg–Saxton (GS) algorithm



2) Hardware co-designed QOC optimizer performance



- beam waist 2.0 um
- atom spacing 3.0 um
- $T_{1q\text{-gate}}$ set to 100 ns

- DT model serves as env. for RL
- $U_{target} = R_1 \otimes R_2 \otimes R_3$
- R_i: single-qubit gate, random Clifford
- each curve shows the average over 5 random sets (shaded region shows std. deviation)

References

[1] I. Christen, T. Propson, M. Sutula, *et al.* An integrated photonic engine for programmable atomic control. *Nat Commun* 16, 82 (2025).

[2] A. Menssen, A. Hermans, I. Christen, *et al.* Scalable photonic integrated circuits for high-fidelity light control. *Optica* 10, 1366-1372 (2023).

[3] Q. Ding and D. Englund, Hardware Co-Designed Optimal Control for Programmable Atomic Quantum Processors via Reinforcement Learning. *arXiv*:2504.11737 (2025)

[4] I. Christen, C. Panuski, T. Propson and D. Englund, Full-volume aberration-space holography. *arXiv*:2505.08777 (2025)

Acknowledgements

- NSF Center for Quantum Networks (CQN)
- Swiss National Science Foundation (SNSF) Postdoc Mobility Fellowship
- Computational resources provided by NVIDIA Academic Grant and subMIT at MIT Physics