

Fault tolerant control of warm ions (FALCON)

IMPERIAL

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Abstract

This project overcomes a key bottleneck of trapped-ion quantum computing: the need for frequent, time-consuming recoiling to maintain high-fidelity entangling gates. Instead of insisting on motional ground states, we develop and demonstrate a high-fidelity, thermally resilient universal gate-set based on a novel version of the light-shift (LS) gate that operates reliably on warm, multi-mode ion strings.

Our core idea is to embed robustness directly into the entangling interactions. Building on and extending optimally controlled quantum gates (including shaped pulses, composite pulses and dynamical decoupling), we design multi-tone, time-modulated, composite LS gates that (i) cancel leading-order errors from amplitude miscalibration, detuning, mode-frequency drift and cross-talk, and (ii) tolerate significantly elevated motional excitation. Analytic design rules and error bounds are combined with numerical optimisation pipelines and integrated device-level noise models. The gate families and control strategies developed by SOF and ICL will be implemented and benchmarked on state-of-the-art trapped-ion platforms at UIBK and on a commercial system from AQT, our industrial partner. We target two-qubit gate errors at or below 2×10^{-5} on ion strings of ≥ 10 ions, with at least a five-fold reduction in duty cycle and a clear path to $\sim 30\times$ speed-up in time-to-solution by eliminating repeated recoiling steps.

By delivering a validated, warm-tolerant LS gate toolbox integrated into a commercial trapped-ion stack, the project directly advances the Applied Quantum Science goals of QuantERA. It transforms trapped-ion devices from "high-fidelity but cooling-limited" prototypes into fast, reliable processors, strengthens European industrial capabilities in quantum hardware, and trains a new generation of researchers at the interface of AMO physics, quantum control and electronics.

Addressed challenges

1 Performance

high-fidelity low cross-talk entangling operations so far limited to 2-ion crystals

2 Resilience

time-to-solution in trapped-ion quantum computing limited by shuttling and re-cooling operations

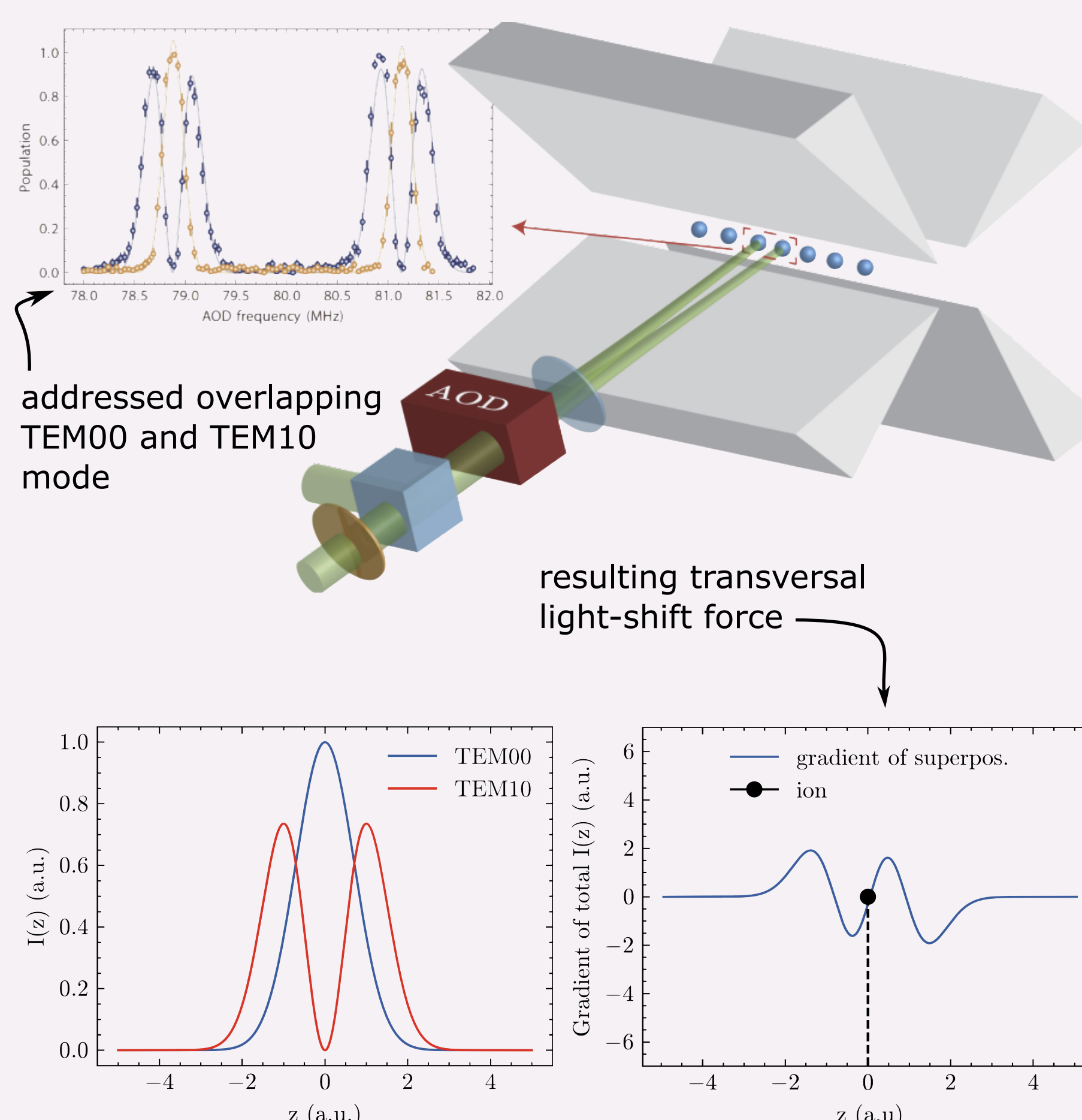
3 Reliability

higher gate fidelities require higher calibration parameter stability and increase the number of imperfections the operation is sensitive to

Performance

- new type of light-shift gate [1]
 - radially addressed
 - co-propagating TEM00 and TEM10 mode
 - coupling to well-spaced axial motional modes
- allows for high-fidelity entangling gates in larger (10-20 ions) crystals
- relaxed parameter dependences
 - frequency
 - phase
 - motion

entangling infidelity $\rightarrow 10^{-4}$

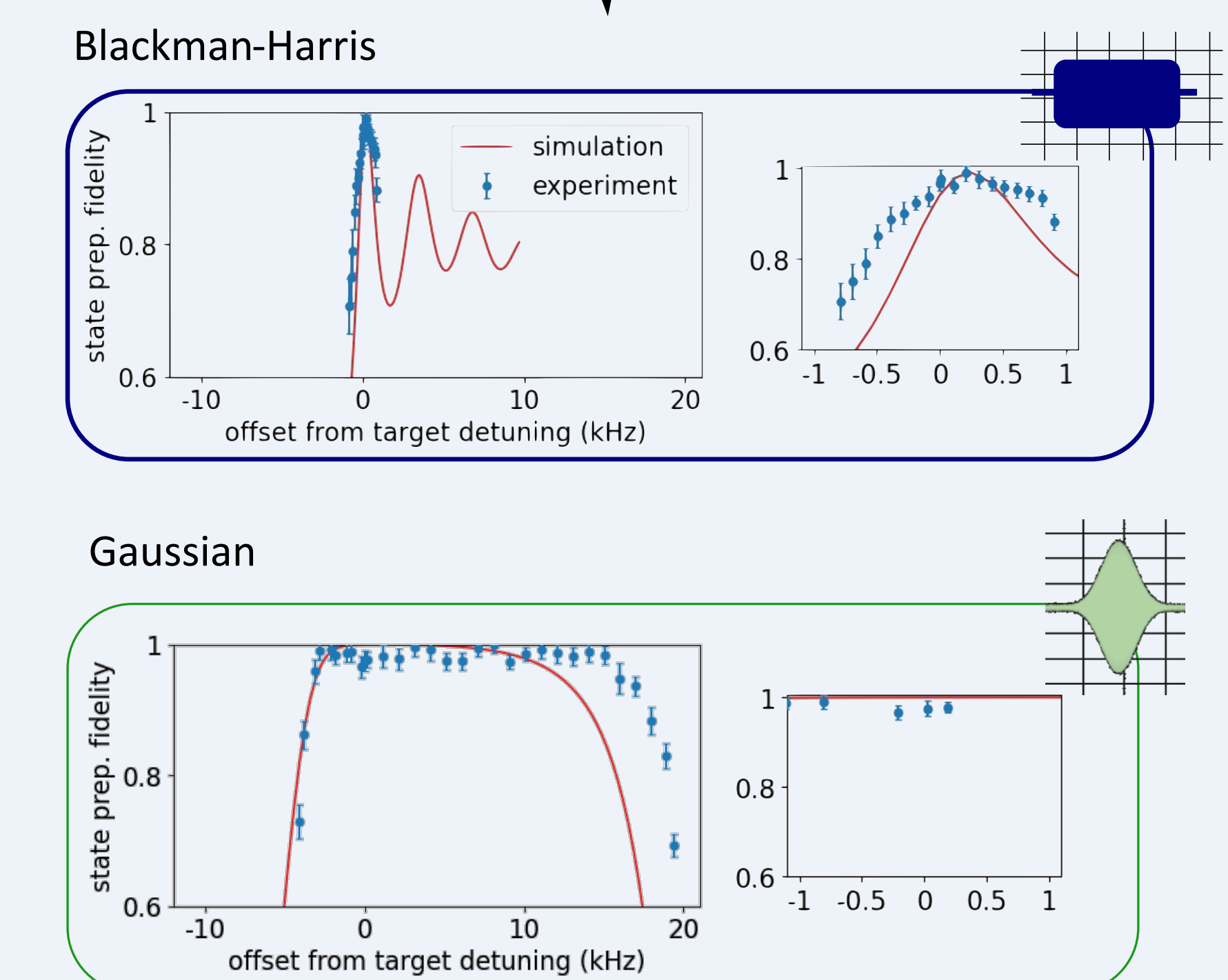


Resilience

- modulated multi-tone quantum gates
 - amplitude modulation
 - phase modulation
- tailored for temperature resilience
 - going beyond Lamb-Dicke approximation
 - high-fidelity entangling gates in Doppler-cooled ion-crystal
 - avoids time-intensive ground state cooling
 - expected time-saving of up to one order of magnitude
- further resilience against e.g. residual spin-motion entanglement or detuning offsets

detuning-robust MS gate through amplitude modulation [2]

entangling infidelity $\rightarrow 10^{-5}$

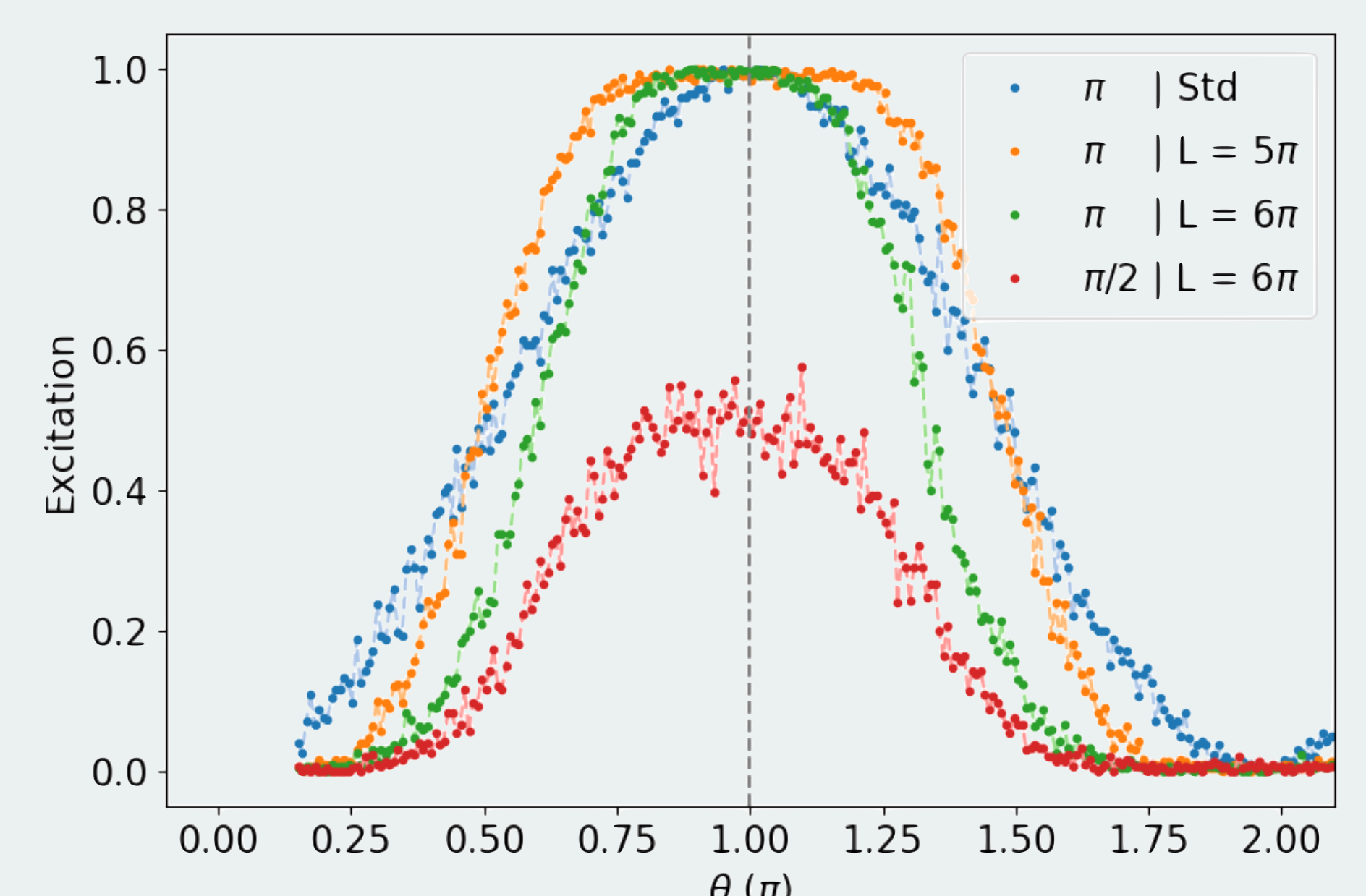


Reliability

- replace single light-shift gate by multiple tailored light-shift segments [3]
 - varying in amplitude, phase, and frequency
 - similar to composite pulses for single qubit gates
- design for resilience against small parameter drifts and imperfections
 - intensity and frequency drifts
 - cross-talk
 - timing jitter
- go beyond the stability of calibrated control parameters

high performance $\rightarrow$ hours/days

robustness of composite single qubit rotations against cross-talk and intensity fluctuations [4]



Outlook, impact and synergies

1 high-fidelity low-cross-talk entangling operations in registers of 10-20 ions

- new RF/microwave-optical hybrid quantum gate set
- reduce the control complexity
- lowering the resource overhead for logical qubits
- leverage low error rates for fault tolerance
- e.g. could enable quantum error correction with distance 7 at logical error of 10^{-10}

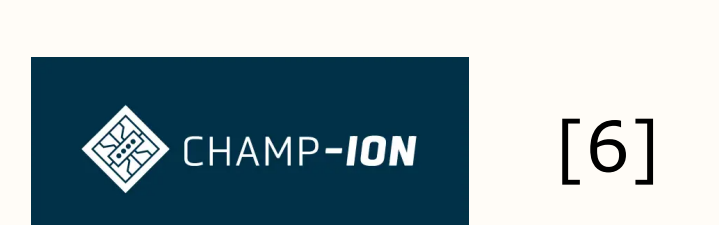
2 hot ion quantum gate set and up to factor 30 reduction in time-to-solution

- further application areas in the trapped-ion field
 - quantum communication
 - quantum sensing
 - quantum simulations
- beyond trapped-ions
 - quantum modalities coupled to bosonic modes
 - e.g. superconducting qubits coupled to resonator

3 improved stability of entangling gates beyond the stability of individual control parameters

- FALCON's control solutions will complement:
 - scaling to 100 qubits
 - trapped-ion chip pilot-line

FALCON's partner projects:



[1] Faorlin, T. et al. (2026) arXiv:2603.07548

[2] Ruzic, B. P. et al. (2024) Physical Review Applied, 22(1), 014007

[3] Ivanov, S. S. et al. (2015) Physical Review A, 92(2), 022333

[4] Torosov, B. T. et al. (2020) Physical Review A, 102(1), 013105

[5] <https://www.millennium.eu/>

[6] <https://champ-ion.eu/>

