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An Elementary Trapped-Ion Quantum Network

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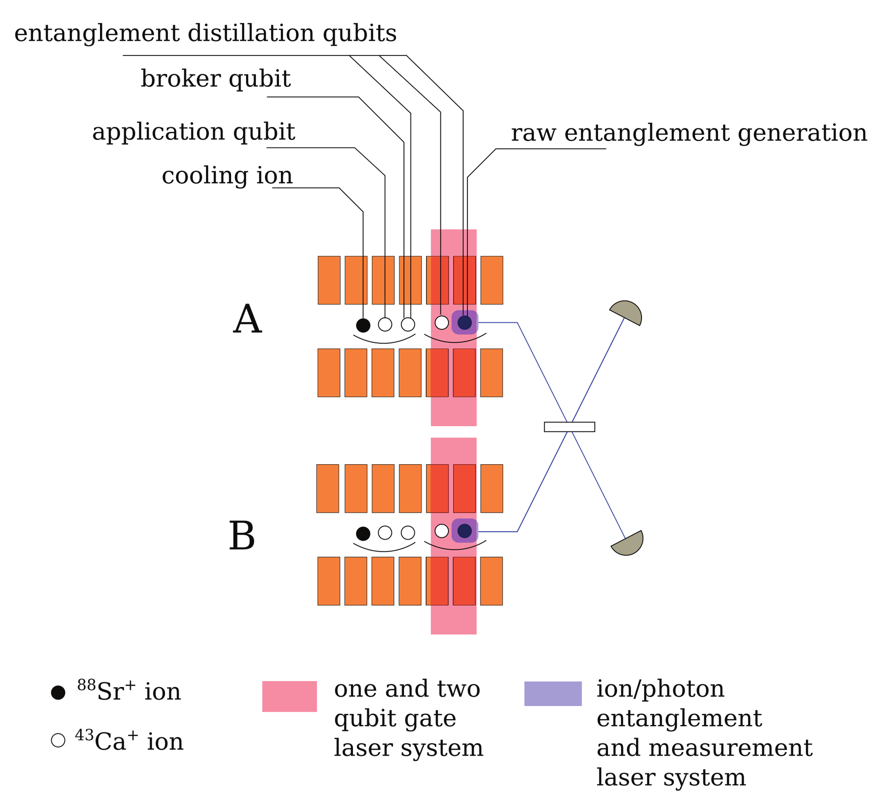
Trapped ions are a promising candidate for quantum information processing. Hybrid quantum networks based on photonic interfaces have been proposed as a modular architecture for trapped ion processors. In this work, two $^{88}Sr^{+}$ ions in separate traps are entangled via the polarisation degree of freedom of spontaneously emitted 422 nm photons. We are able to generate Bell states with a fidelity of 94%, at a rate of 182 s^{-1} [1]. Using mixed species gate techniques developed by Hughes et al. [2], we aim to incorporate $^{43}Ca^{+}$ qubits, which have excellent coherence properties, to create a hybrid quantum network.

The Goal

We aim to generate high fidelity entanglement distributed over a quantum network. To generate raw entanglement states, ions in separate traps emit single photons whose interference is measured [1]. This fidelity of this entanglement can be improved using entanglement distillation [3].

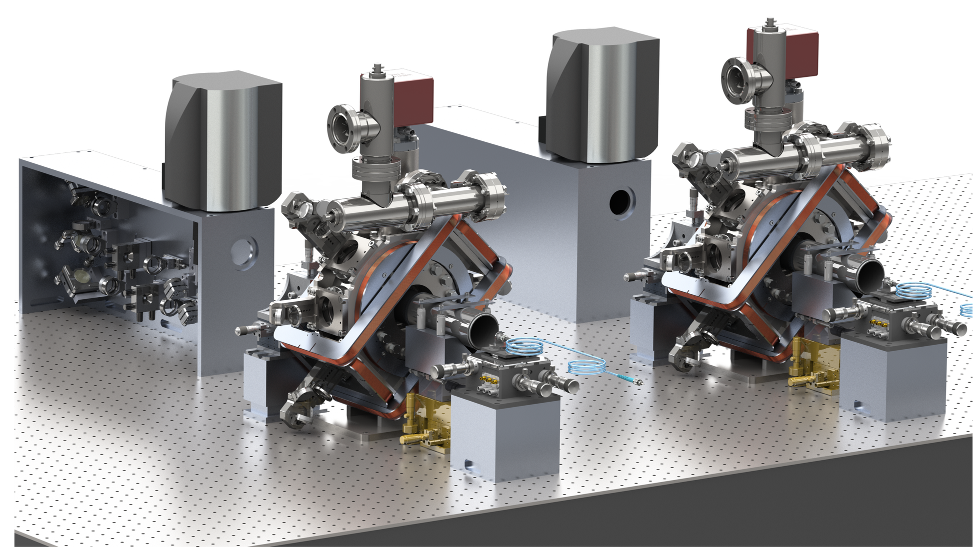
This optimised distillation scheme improves the remote entanglement fidelity using only nearest neighbour operations in two trap zones. We require two species in each trap but not requiring individual addressing.



Experimental Apparatus

Our apparatus comprises two identical Paul traps, separated by approximately 2 metres. We have designed rack-mounted laser systems for addressing both $^{88}Sr^{+}$ and $^{43}Ca^{+}$ ions to greatly reduce the footprint as well as improve experimental stability.

We are using the High Optical Access traps fabricated by Sandia. For each trap, we have two imaging systems, one for independent readout of strontium and calcium ions, and another with a high-numerical aperture to couple 422 nm photon emission into a fibre.



The ARTIQ system is used for real-time experimental control [4]. Multiple crates of Sinara open-source hardware are deployed throughout the lab, synchronised via optical fibres. ARTIQ also features a Python-based language for simple and fast development of complex experimental sequences. We have recently made many of our projects open source [5].

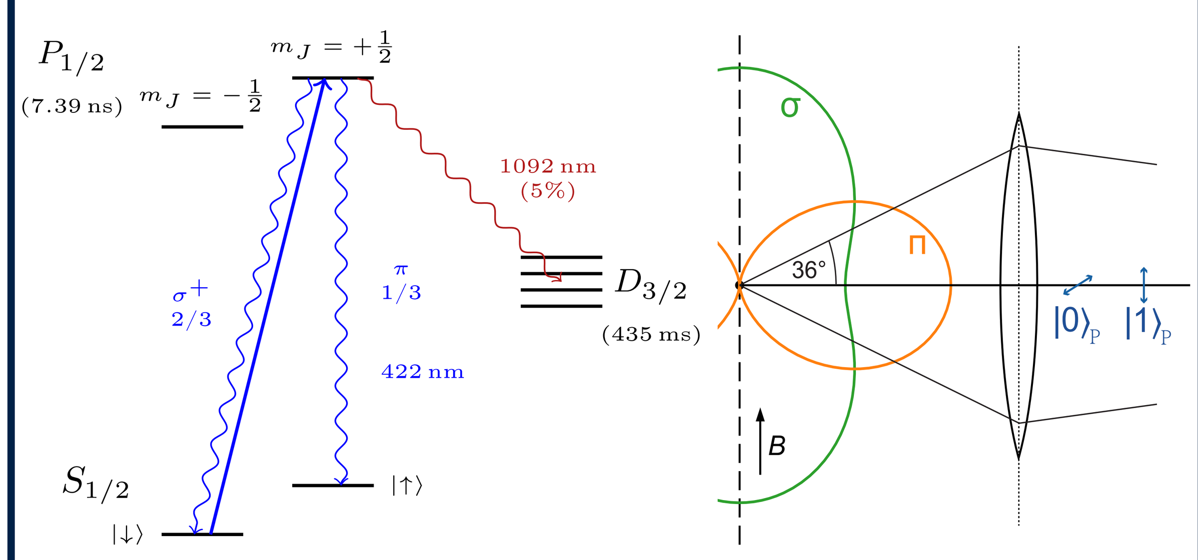
We have automated regular calibrations and diagnostics, enhancing the stability and reliability of the experiment.

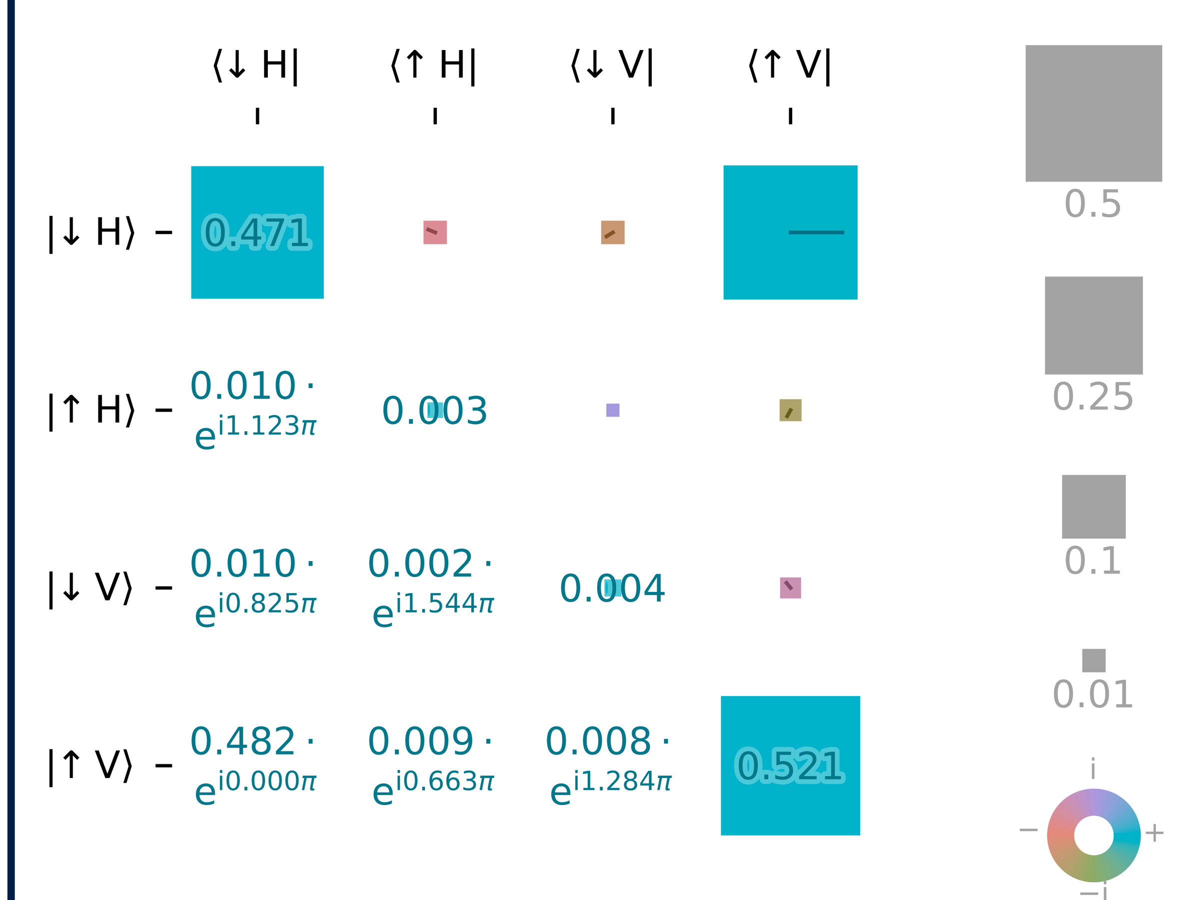
Ion-Photon Entanglement

Using a picosecond laser, we excite $^{88}Sr^{+}$ ions to the short-lived $P_{1/2}$ state. Upon decay to one of the ground Zeeman levels, the polarisation and frequency of the spontaneously emitted photon will be entangled with the spin-state of the ion.

The spontaneously emitted photons are collected perpendicular to the quantisation axis using a high numerical aperture lens. The photons are then coupled into a single-mode fibre to avoid polarisation mixing.

Using this technique, we have demonstrated the production of ion-photon Bell pairs with fidelity exceeding 97.9% at a rate 4.0 x 10^{3} s^{-1}.

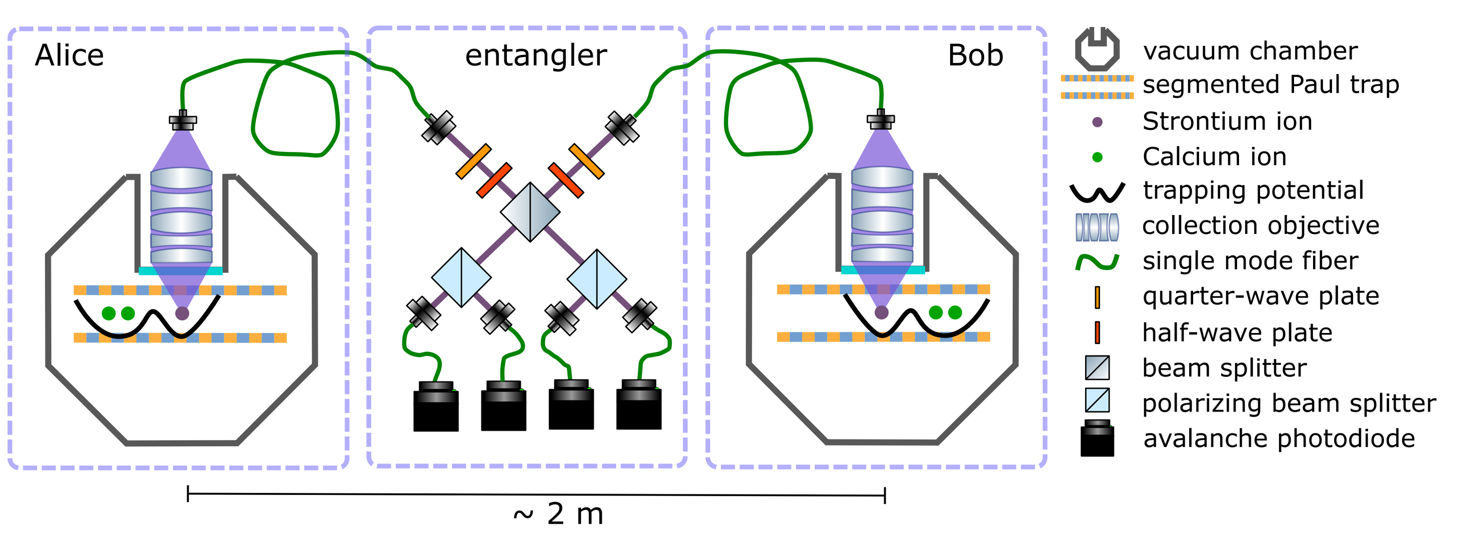


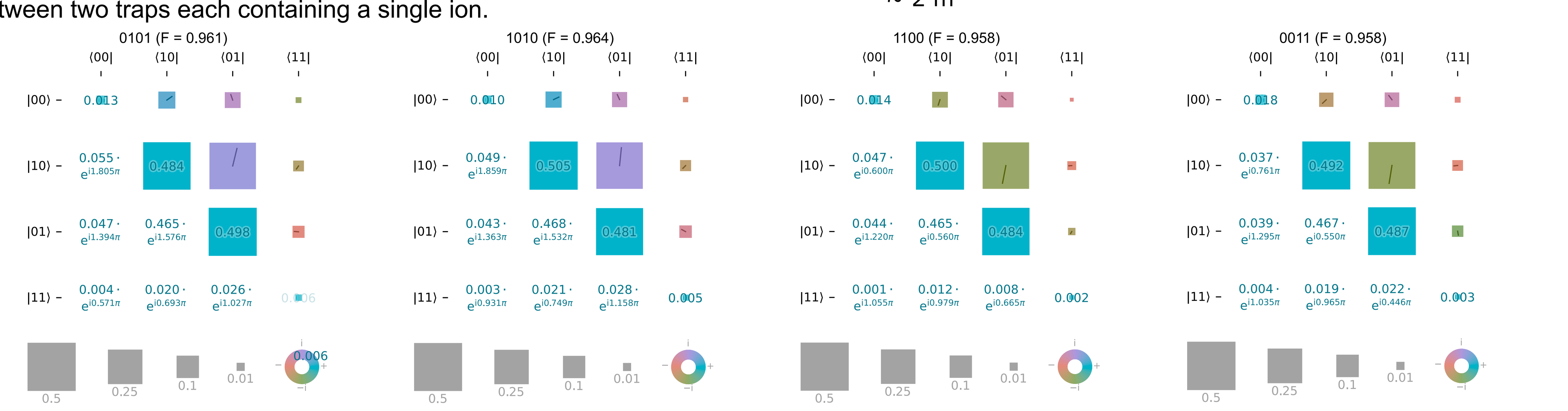


Ion-Ion Entanglement

We create ion-ion entanglement by generating ion-photon entanglement in each trap and interfering the photons at a 50:50 beam-splitter. The resulting two photon state is then measured using a four detector scheme, swapping the entanglement from the photons onto the ions and producing a maximally entangled ion-ion state.

Using this technique we have demontrated ion-ion entanglement with Bell states of fidelity exceeding 94% generated at a rate of 182 s^{-1} between two traps each containing a single ion.

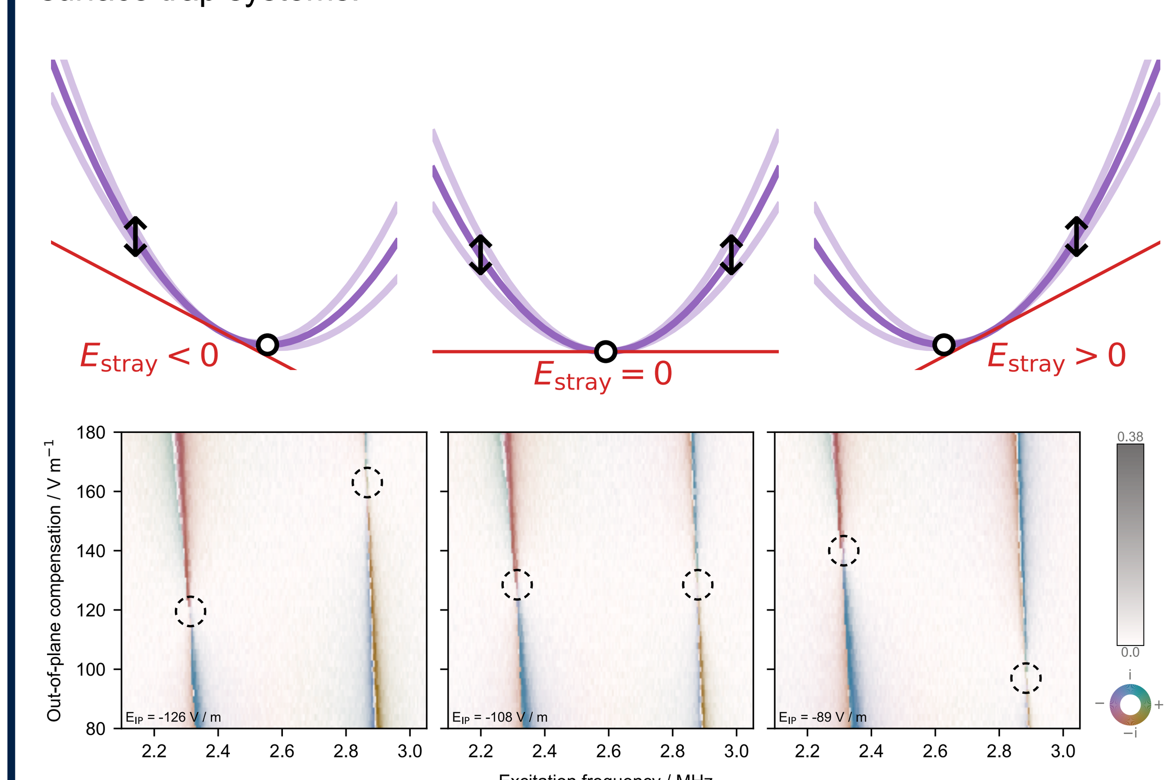




Micromotion Compensation

We have demonstrated a new technique for micromotion compensation based on parametric excitation of the ion motion by amplitude modulation of the RF potential. By time-stamping the detection of scattered cooling photons, we are able to detect and compensate for stray fields that result in the unwanted micromotion. We are able to achieve a sensitivity of 0.1 V/m/√Hz and minimal uncertainty of 0.0015 V/m.

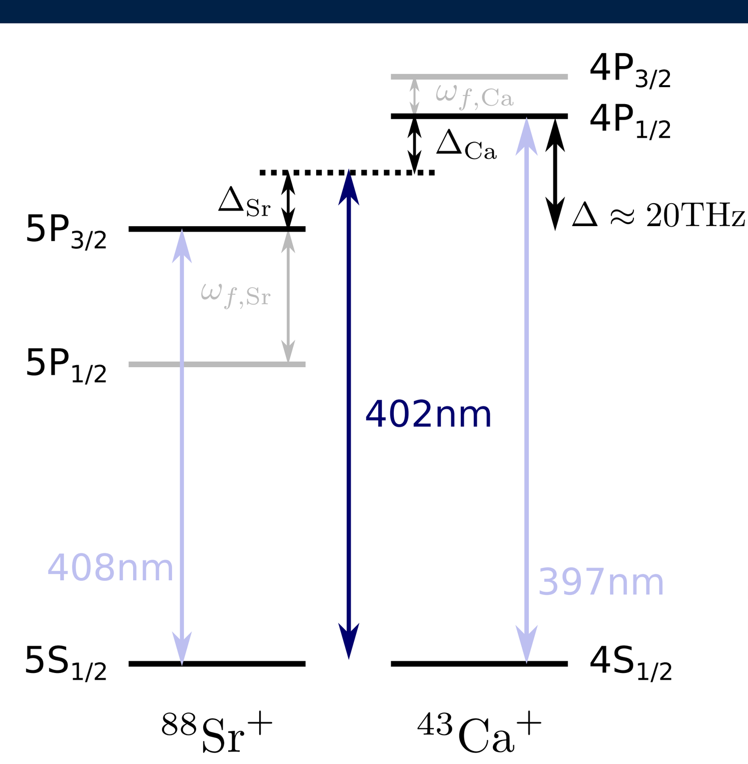
Our technique requires only one laser to sufficiently compensate for both in- and out-of-plane micromotion, minimising experimental complexity and making it well-suited for integration into mixed-species microfabricated surface trap systems.



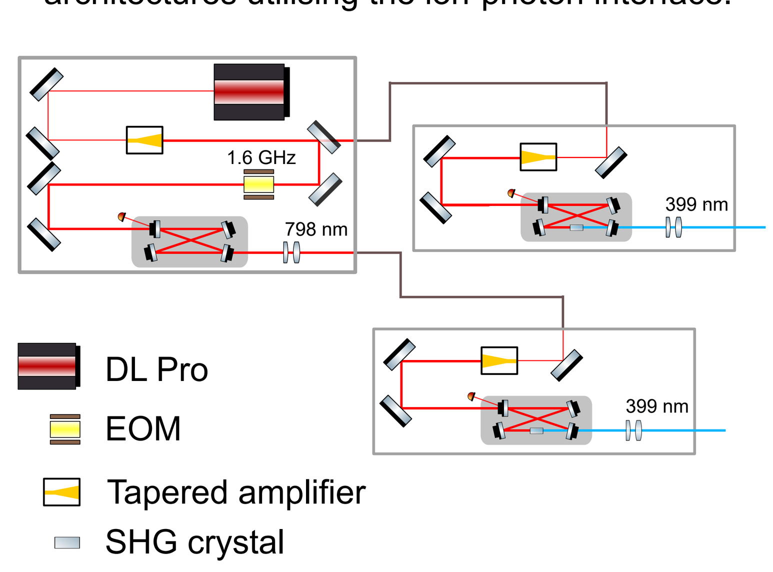
Future Work

With a view towards demonstrating entanglement distillation, we are currently setting up optics for addressing $^{43}Ca^{+}$ ions in each trap. Mixed species techniques developed by Hughes *et al.* [2] will allow us to combine the long coherence properties of calcium with the ion-photon interface provided by strontium, creating a powerful hybrid quantum network.

To perform the mixed species operations, we have purchased a Raman laser system with Raman beams from the same seeding laser diode. This configuration reduces the phase noise, enabling high-fidelity operations required by the entanglement distillation scheme.



Applications of this quantum network include quantum sensing based on remotely entangled harmonic oscillators, a variety of quantum key distribution protocols, and prover-verifier architectures utilising the ion-photon interface.



[1] L. J. Stephenson *et al.*, PRL 124, 110501 (2020)
[2] A. C. Hughes et al., PRL 125, 080504 (2020)
[3] R.Nigmatullin *et al.*, New J. Phys. 18 103028 (2016)
[4] https://m-labs.hk/experiment-control/sinara-core/
[5] https://oxfordiontrapgroup.github.io/

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