Trapped Ion Qubits

Qubits can be encoded in clock states of trapped ions. These states are well isolated from the environment resulting in long coherence times [1] while enabling efficient high-fidelity qubit interactions mediated by the Coulomb coupled motion of the ions in the trap. Quantum states can be prepared with high fidelity and measured efficiently using fluorescence detection. State preparation and detection with 99.93% fidelity have been realized in multiple systems [1,2]. Single qubit gates have been demonstrated below rigorous fault-tolerance thresholds [1,3]. Two qubit gates have been realized with more than 99.9% fidelity [4,5]. Quantum algorithms have been demonstrated on systems of 5 to 15 qubits [6–8].

A hierarchy of approaches can be used to scale trapped ion quantum processors [9]. First, ions can be trapped and manipulated in chains of moderate length. Even though these are 1-dimensional chains, interactions between any pair of ions can be realized leading to a fully connected graph [6]. Second, on a single trap chip, larger systems can be realized by shuttling ions, and thus qubits, in microfabricated trap structures [10]. Shuttling does not only enable larger systems, but allows one to realize dynamically reconfigurable systems that can be adapted to the requirements of different quantum algorithms. Finally, using the optically active ion qubits and remote entanglement, trapped ion systems can be scaled beyond a single chip [11]. This approach enables the assembly of a large quantum information processor from identical elementary logic units.

Technical challenges to be addressed to realize scaling are the anomalous heating of ions in close proximity to trap electrodes [12], realizing an excellent vacuum to achieve long lifetime of ion chains, mastering the control complexity in shuttling ions between different sites with minimal heating of their motion and directing the necessary control laser beams on individual ions, and realizing a sufficiently strong atom light interaction for efficient generation of remote entanglement.

Realizing ion traps capable of trapping ions in many trapping locations and shuttling ions between different locations relies on microfabrication. Current fabrication technologies enable one to build almost any surface ion trap [13]. Important next steps will be the integration of light delivery [14] and detection systems with the traps. While this is a challenging task, a good balance between monolithic and hybrid integration techniques will make these integrated devices possible. Finally, integration of voltage generation and optical modulations systems would enable one to reduce the number of necessary control lines per qubit and thus be of great value to increase system size while keeping control complexity manageable.

Systems engineering will be an important aspect in balancing monolithic and hybrid integration and achieving best system performance. Overall, the realization of trapped ion processors with 20 to 50 qubits are considered realistically realizable.

Trapped ion systems are flexible and reconfigurable. In small systems, fully connected interaction graphs can be realized with important advantages for algorithm performance [15], while shuttling of ions provides a means of dynamically reconfiguring the system for optimal performance of a quantum algorithm. With the same system, analog quantum simulation as well as fault tolerant digital quantum computation can be achieved.

While trapped ion systems offer large coherence time to gate time ratios and high fidelity operations, the currently achieved clock speeds are considerably slower than in superconducting qubit systems. While the clock speeds might be sufficient to realize algorithms, the statistics necessary to calibrate and characterize a trapped ion quantum processor will take much longer due to these slow clock speeds.

First insights from a trapped ion testbed system are expected to be better characteristics of the nature of the noise that is limiting system size. At what size and how does the system break? Noise correlations and scaling of noise correlations with distance are crucial metrics that will determine the feasibility of fault tolerant quantum computing, but could also encourage and

enable the development of quantum codes specifically adapted to the noise properties of a testbed system.

The attendees agreed that trapped ion systems offer a well-established qubit technology that can be engineered to a testbed system of 20 to 50 qubits and can be scaled to much larger systems. A first testbed system will have the capability to address small-scale scientific problems and will allow us to establish noise properties and performance properties to develop a larger system, capable of solving interesting scientific problems.

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