Ion Coulomb Crystals in Storage Rings for Quantum Information Science

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Abstract:

Quantum information science is a growing field that promises to take computing into a new age of higher performance and larger scale computing as well as being capable of solving problems classical computers are incapable of solving. The outstanding issue in practical quantum computing today is scaling up the system while maintaining interconnectivity of the qubits and low error rates in qubit operations to be able to implement error correction and fault-tolerant operations. Trapped ion qubits offer long coherence times that allow error correction. However, error correction algorithms require large numbers of qubits to work properly. We can potentially create many thousands (or more) of qubits with long coherence states in a storage ring. For example, a circular radio-frequency quadrupole, which acts as a large circular ion trap and could enable larger scale quantum computing. Such a Storage Ring Quantum Computer (SRQC) would be a scalable and fault tolerant quantum information system, composed of qubits with very long coherence lifetimes. With computing demands potentially outpacing the supply of high-performance systems, quantum computing could bring innovation and scientific advances to particle physics and other DOE supported programs. Increased support of R&D in large scale ion trap quantum computers will allow the timely exploration of this exciting new scalable quantum computer. The R&D would include the design and construction of a prototype SRQC. We invite feedback from and collaboration with the particle physics and quantum information science communities.

SnowMass 2021 Frontiers of Interest
Accelerator Frontier, Advanced Accelerator Concepts (AF6) and Accelerator Technology R&D (AF7)
Computational Frontier, Quantum Computing (CF6)
Theory Frontier, Astro-particle physics & cosmology (TF9) and Quantum Information Science (TF10)

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We call the attention of the particle physics and accelerator communities to the opportunity to advance and bring the scientific and technological expertise of accelerator science and technology to support advances in quantum information sciences (QIS). We believe a discussion and increased collaboration between the communities of particle physics, accelerator science, and quantum information science on methods to advance quantum computing to problems in particle physics and other disciplines will greatly advance the science and technology in these communities.

We are already investigating two areas of accelerator technology for quantum computing systems, **storage rings for quantum information science and superconducting devices**. At BNL, efforts began in 2019 to study the use of crystalline beams in storage rings as platforms for quantum computing [1,2]. At Fermilab, efforts have also begun to study the use of crystalline beams in storage rings [3]. At BNL and Fermilab there are programs for research in quantum information superconducting systems, materials for quantum information systems, and on quantum devices and sensors. At LANL, there is research on materials for quantum information, quantum devices and sensor and superconducting cavities.

Many accelerator laboratories around the world are forming groups to focus on exploring quantum computing as applied to particle physics, nuclear physics, applied sciences, and more. CERN Openlab has been partnering with corporations, other laboratories, and universities to advance in several computing topics, including quantum technologies [4]. In 2018 they held the Quantum Computing for High Energy Physics workshop, to focus on how to overcome significant challenges related to information and communications technologies in the next decade and beyond for the LHC and detector systems [5].

The needs of particle physics for quantum computing systems are well documented and beyond the scope of this letter. We will cite, however, the DOE HEP QuantiSED initiative to develop technology for quantum information science and quantum computing approaches for particle physics experiments [6]. A number of workshops were held to define the scientific needs and opportunities, including the HEP-ASCR Study Group Report, *Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing* from 2015 [7], the BES-HEP roundtable report, *Common Problems in Condensed Matter and High Energy Physics* from 2015 [8], the ASCR Report on *Quantum Computing for Science* from 2015 [9], and the HEP-ASCR QIS roundtable report, *Quantum Sensors at the Intersections of Fundamental Science, QIS and Computing* from 2016 [10].

The particle physics quantum information science challenges include a need for greater computational power for simulations and reconstructing events. For example, researchers are working on a quadratic unconstrained binary optimization (QUBO) [11] for track reconstructing [12]. In a quantum implementation they treat a ground state of a Hamiltonian as a quantum machine instruction that is equivalent to a QUBO, easily transformed into an Ising model or Hopfield network. The same group is researching quantum associative memory, used with quantum algorithms for finding track candidates with a constant-time lookup. This is a commonly used real-time pattern recognition technique used in particle physics. We discuss these examples because they highlight the demanding computing needs for particle physics data analysis. The parallelism required and the ability to use quantum memory fit well with a storage ring quantum computer that potentially can contain 10's of thousands of qubits that can act as computational elements or as memory elements. To obtain such a scaling they are currently using D-Wave systems, which perform quantum computations based on quantum annealing. A storage ring ion trap system would be a gate-model quantum computer with a large number of qubits; it should be pursued as an alternative to the quantum annealing approach.

A storage ring quantum computer will make use of a unique and proven particle accelerator device called a circular radiofrequency quadrupole (CRFQ). We can think of a CRFQ as an unbounded Paul trap, where ions circulate at some fixed velocity (and thus fixed frequency). Although the words 'storage ring' may evoke thoughts of a large device kilometers in circumference, a single CRFQ in our preliminary design is only one meter in circumference and can contain 10's of thousands of ions that, when cooled sufficiently using laser cooling techniques, will form ion Coulomb crystals. Given that a single quantum computation involving a handful of logical error-corrected qubits makes use of thousands of physical qubits to implement an error-correcting code with fault tolerance, such a particle accelerator-based architecture enables high throughput, full quantum computations including the error correction overhead.

We can form two basic states of matter by cooling ion beams down to very low temperatures. The first is a classical crystalline beam, defined, to be "a cluster of circulating, charged particles in its classical lower-energy state subject to circumferentially varying guiding and focusing electro-magnetic forces and Coulomb interacting forces". The second state of matter is an ultracold crystalline beam, or what we refer to as an **ion Coulomb crystal**, cooled well below the Doppler cooling limit to the resolved sideband limit, but not to the point of the Lamb-Dicke limit. This is something of a 'Goldilocks' regime, where couplings between internal and external quantum states are not strongly suppressed. In this regime, thermal vibrations are small enough to distinguish the external quantum modes of the crystalline structure and to minimize any micromotion from the rf confining the ions in the center of the trap [The laser cooling systems can reduce the motional degrees of freedom of the ions but cannot diminish kinetic energy from the induced micromotion.]

Ion trap systems **exploit two quantum properties of the ions** in the trap, external eigenstates, such as the axial center-of-mass motion of the string of ions in the trap, and the internal eigenstates of each ion in the string. When sufficiently cooled, the string of ions in the trap has properties that we can use to define a set of computational basis states operated on using laser excitations.

The primary method of establishing a qubit involves excitation and measurement of stable or metastable internal states of individual ions, such as the hyperfine states. The basic method, as described by Wineland et al., using $^9Be^+$ and then using the $^2S_{1/2}(F = 2, m_F = 2)$ and $^2S_{1/2}(F = 1, m_F = 1)$ hyperfine ground states (denoted $|\downarrow\rangle$ and $|\uparrow\rangle$, respectively), we can construct a practical qubit. Tuning a polarized laser beam to the $|\downarrow\rangle \rightarrow {}^2P_{3/2}$ transition and by observing the scattered photons we can resolve two distinct spin states. With this technique, per Wineland et al., the quantum states can be determined with almost 100% efficiency. Using Raman transitions and polarized light scattering we can 'write' and measure the hyperfine states.

A significant challenge in quantum computing is controlling quantum decoherence. However, research in ion traps has shown that **quantum states in trapped ions can persist for very long times**, even on the scale of minutes. In a storage ring environment, we will have to be sure to eliminate any sources of noise and other forms of energy that may disrupt the trapped ion quantum states. There is a good discussion of this topic by Wineland, et al. [13]. The scaling of the number of qubits (N), while limited mostly to internal interactions, is related to the problem of decoherence. It has a unique temporal component we must consider, since we cannot operate on all ions in the crystalline beam simultaneously.

Inside the storage ring system, we can isolate groups of smaller numbers of ions from each other, using longitudinal rf potentials or by separating using velocity modulation in the cooling systems. We can then operate on these isolated sets of qubits independently. In the storage ring environment, there is potential for multiplexing as well as an ability to work on ions and groups of ions in parallel. **A storage ring could contain thousands of these smaller individual crystals, producing 10's of thousands of qubits**. The many small chains of ions could serve different purposes, depending on the algorithm being employed. For example, we can use some ion chains as quantum memory and some for other purposes, such as for systematic or error analysis. Having many ions and ion chains available opens many possibilities; simultaneous computations, quantum memory, error correction, and more.

Applying accelerator expertise and technology to move quantum information systems to scales needed by particle physics applications means using accelerator science techniques and systems in new and creative ways to allow development of new kinds of quantum computing devices. We propose designing and building a storage ring quantum computer that follows a quantum gate-model architecture. This is a great opportunity to use the advanced methods developed in accelerator science to benefit quantum information science and eventually particle physics.

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