Group: 5
Platform: Trapped Ions
Student ID: 490401228

Executive Summary

This report aims to summarise the background and recent developments of quantum computing (QC), and evaluate the attractiveness of investing in this field. By first analysing the history of the field, we are able to aliken the progress of quantum computing to classical computing in its early days. Ion traps are then identified as a highly accurate implementation of small to medium scale quantum computers, with scalability remaining a key issue. Overall, QC is shown to be a rich and rapidly growing field, ripe for large scale investment in several years after the fault-tolerant logical qubit is achieved.

General Background of QC

With technological giants such as Google claiming *'quantum supremacy'* over classical computers, the field of quantum computing (QC) has received a rapidly growing amount of attention. This has made it difficult to separate hype from reality, and to discern real investment opportunities from far-off fantasies.

To effectively evaluate the growth potential of the QC industry and its short-term applications, it is helpful to review the history that has formed the basis of the field's growth.

QC is based on the field of Quantum Physics (or Mechanics), which was popularised by Austrian physicist Erwin Schrodinger in the 1950s, albeit mainly through thought experiments. This scientific field proposes the idea of *'wave-particle duality'* **(Kaloyerou, 2016)**, where every particle (such as an electron) can be described as a 'wave' as well as a particle.

In essence, before we observe a particle, it displays wave-like properties. However, the instant we measure them (for example taking the position of an electron), the waves collapse and they act like a stationary particle. These particles could thus be put in a *'superposition'* of states, where they carry a mix of values. Once we measure the particle, it would only hold one value. Moreover, when their wave functions mix, two quantum particles could become *'entangled'*, with their values exactly correlating upon measurement.

Being an extremely non-intuitive principle, this led physicist Richard Feynman, avid researcher in the field to realise the insufficiency of classical computers to model quantum particles, sparking first talks of a potential *'quantum computer'*. In **1985, David Deutsch** published a paper describing how the first universal quantum computer could actually be built.

While classical bits could only encode 0s and 1s in transistors, quantum particles could hold a superposition of information, allowing much more information to be held in a fewer bits. Once controlled, Deutsch explained that these particles (called qubits) could be manipulated through *'quantum gates'*, which can rotate qubits and manipulate their behaviour.

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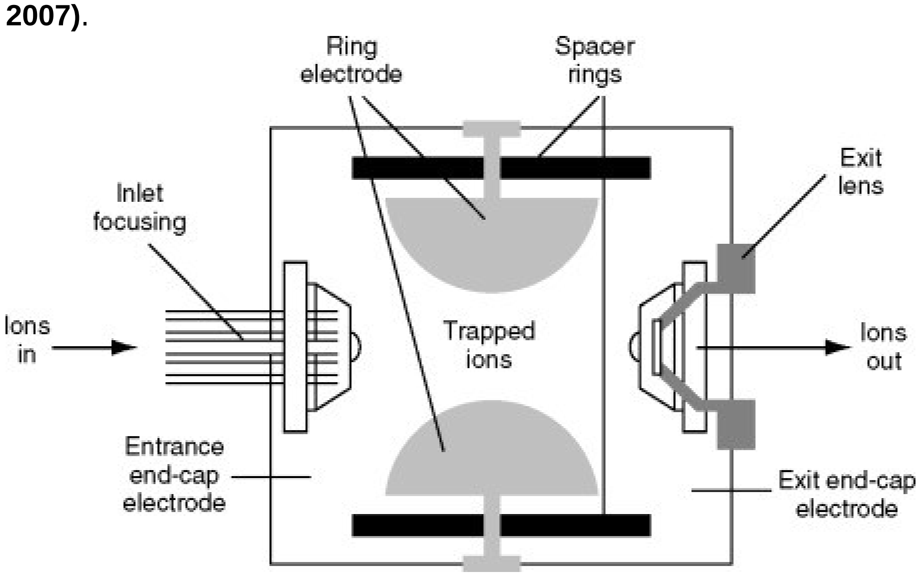
Soon after in 1994, Peter Shor, working for AT&T at the time developed an algorithm which could calculate the prime factors of extremely large numbers using superposition and entanglement of qubits **(Shor, 1999)**. As this would lead to the collapse of many encryption systems, interest in QC boomed. Large scale government investment and interest followed, and through the use of *'trapped ion'* technology, 1995 birthed the first operational, 2-qubit quantum device.

This has sparked more recent breakthroughs in the area of expanding qubit numbers and the quest for *'fault-tolerant'* quantum computers.

Trapped Ion Technology

Being a relatively new technology, QC has several predominant approaches. The *'trapped ion'* approach to QC is amongst the most promising systems. As it was responsible for the first quantum computer built in 1995 by IBM and several top US universities, investing in trapped ion technology is worth significant consideration.

Proposed by **Cirac and Zoller (1995)**, the trapped ion approach was used to build the first quantum computer soon after Shor's algorithm was derived. The first challenge faced was to make a qubit to be manipulated as described by Deutsch in his blueprint. Researchers thus decided to use atoms with 2 electrons in their outer shell. These would be ionised by removing an electron, granting a slightly positive charge. The ions would be then be held in place electromagnetically through a quadrupole ion trap, as shown in the diagram below **(Yinon, 2007)**.



Electrodes would surround the ions, keeping in place through an oscillating magnetic field. Once supercooled to less than 0.02K through lasers, the ions would have very little motion and thermal energy, hence acting as qubits. They could then be moved and put through quantum gates by altering the strength and direction of the magnetic fields.

These (RF Paul) traps had already been in use since 1980, and resulted in long life-times for the trapped ions. Complex quantum operations such as gates involving multiple qubits have shown to be functional through this method, placing it at the cutting edge of large scale QC.

However, despite the promise shown by trapped ions, any investment into this field must consider its challenges.

In particular, when the number of qubits in ion traps increases, as is required in a full scale quantum computer, the ability to control and measure each qubit individually with high accuracy falls **(Bruzewicz, Chiaverini, Mcconnell & Sage, 2019)**. Hence, while trapped ions may be applied to small and medium scale quantum computers with great success, scalability of this technology remains an issue.

The Future of QC and Trapped Ion Quantum Computers

Since the sunrise of the first quantum computer in 1995, there has been a vast societal shift towards a ‘Quantum Race’ akin the ‘Space Race’. Instead of geographical rivalry, large corporations such as Google and IBM have pushed towards developing more powerful quantum computers with greater practical use.

In **2000, DiVincenzo** outlined 5 key criteria for a quantum information processor (quantum computer), including isolation from the environment and a set of universal quantum gates which can be applied to each qubit. All of these criteria have been fulfilled by ions as qubits since 2004. However, the largest, fully functional *‘quantum register’* of trapped ions only includes 20 qubits, as opposed to Google’s 53 qubit computer powered by superconducting circuits. Therefore, there must be more criteria to be fulfilled when evaluating the viability of ion traps in the QC industry.

In particular, modern QC has reached a turning point. Scalability is now one of, if not the main goal in quantum research, while viability has faded into an assumption. To build a *‘scalable’* computer, the basic computational element, whether bits or qubits, should be able to be increased without suffering a loss of performance. In this sense, no QC technology has yet reached scalability.

However, trapped ions have shown promise with increasing accuracy through continued research. Researchers have even displayed greater than 99.99% accuracy in measurement in trapped ion computers **(Bruzewicz, Chiaverini, Mcconnell & Sage, 2019)**, along with an ion lifetime of up to several months, far surpassing similar technologies such as superconducting qubits. This has positioned ion traps as the leading technology for QC with a smaller number of qubits.

To push to the cutting edge of QC, ions as qubits face two main challenges: slow absolute operation speeds, and scaling past the 300 ion boundary that most traps have shown.

Extending the architecture of ions traps to a 2D array has been proposed as a way to overcome these limitations. While communication between qubits slows down when a 1D array increases in size, as well as accuracy due to information loss, 2D arrays scale much more efficiently.

Moreover, different sections of the ion trap could even serve separate functions, mimicking “memory” in a classical computer **(Bruzewicz, Chiaverini, Mcconnell & Sage, 2019)**. Other research directions such as creating a *‘logical qubit’* that is fault-tolerant (can continue operation even after an error) have also shown great promise.

Societal Impact and Opportunities of QC

Having discussed the recent developments of QC and its limitations, we can see that quantum computers have begun to demonstrate feasibility in their applications. In particular, further developments in fault tolerance and logical qubits, whether through trapped ions or otherwise, would find instant applications in optimization.

If exponential growth is seen in QC as was seen in classical computing in the early days, a full scale, fault-tolerant quantum computer may not be out of sight. However, such a prediction seems overly hopefully given the numerous issues with scalability of quantum computers. The status of QC could be compared to the early days of machine language in classical computers on the hopeful side.

Therefore, significant societal ramifications of QC, such as the application of Shor’s algorithm in revolutionising cryptography may still be several years, or even decades away. Near-term, large scale investment in quantum computing with expectation of commercial benefit would therefore be highly risky and not recommended.

However, the rapidly evolving field of QC is an area to watch over the coming years as fault-tolerant technology begins to emerge.

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