Introduction to Trapped Ion Computing: Laser Cooling and other key technologies

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ABSTRACT

This paper explores the theory and experimental techniques behind some very keys parts of the trapped ion quantum computer. The paper introduces why trapped ions are leading contenders for quantum computers and how they fulfill the Di Vincenzo criteria of a (potentially) successful quantum computer. The following sections then consider the two key technologies used in trapped ion architecture: laser cooling, Paul traps. The paper examines the fundamental concepts of temperature in the light of laser cooling, Doppler cooling, optical molasses. The paper further explains the physics and optics that go behind the making of qubits and the trapping of ions. Lastly, the paper presents some future challenges that trapped ion computers face and the possible outlook for this technology.

Keywords: Quantum Information, Trapped Ion Quantum Computing, Quantum Computing, Quantum Optics

1. INTRODUCTION

Quantum Computing has become one of the hottest research topics of this decade due to its potential for solving some of the problems that classical computers cannot. There are different approaches that companies and researchers have taken to realize a quantum computer. The two leading contenders range broadly in two categories of superconducting qubits and optical methods. There are specific properties that are needed for successful quantum computing. The generally accepted guidelines were given by David P. DiVincenzo; they are referred to as DiVincenzo's criteria. These criteria/requirements to build quantum computers are as follows: (1) A scalable and controllable physical system with well-characterized qubits (2) The ability to initialize the state of the qubits to a simple fiducial state, such as $|000\ldots\rangle$, (3) Long relevant decoherence times, much longer than the gate operation time (4) A"universal" set of quantum gates (5) A qubit-specific measurement capability.[1]

Trapped ions have proved to be a leading emerging candidate for quantum information science and building quantum computers ever since Cirac and Zoller proposed an implementation of such a device in 1995 using atomic ions.[2] Trapped ions have presented themselves as an ideal candidate. The long lived internal levels of ions serve as qubits; string of ions can be trapped in a linear trap (discussed in section 2). The qubits are easily initialized using lasers for well defined wavelengths given the transition frequencies. These qubits have very high coherence times in the order of few milliseconds. The single qubit gates are implemented using Rabi oscillations between the two levels (ground and excited) with resonant laser pulses. Two qubit gates (or multiple qubit gates) are usually done using motional gates or long range interactions due to coloumb force. The discussion around gates is beyond the scope of this paper.

Thus we can see that these properties make Trapped ion setup an ideal candidate for quantum computing. While all versions of trapped-ion computers (and neutral atom computers) rely on laser cooling to get atoms to temperatures around absolute zero temperatures to reduce the system's entropy and increase the control over qubits, the specific architecture may differ. However, laser cooling and making an array of single qubits that can be manipulated as desired are the key features common to most optical methods in general. This essay focuses on the three critical aspects of the setup: the trapping of ions, laser cooling, and making qubits for this architecture. The paper begins with a section on Paul traps, the traps used for the trapping of ion registers. Then the paper discusses laser cooling and its significance in today's scientific research. Then it discusses the two kinds of qubits used in ion traps –optical and RF qubits (Zeeman and hyperfine qubits) – and their strengths and weaknesses.

2. TRAPPING INDIVIDUAL IONS

The gases are first ionized before trapping as trapping ions for long periods of time is a much easier task than neutral atoms; hence the name trapped ion computing. In ion traps, a time dependent electric field or a combination of electric and magnetic field can be used for localization of ions. Using this, the ions are trapped in free space with these electromagnetic forces (which have very low coupling with the internal degrees of freedom of the ions). In this paper we look at Paul traps, where the ions can form a linear ion chain. A radio frequency potential between two electrodes is applied, these are parallel to the trap axis.[3] The electrodes create a two dimensional oscillating quadruple potential that is translation invariant. The potential of the ideal 3 dimensional Paul Trap is given by the following equation:[4]

$$U = \frac{(U_0 + V_0 \cos \Omega t)(r^2 - 2z^2)}{d^2} \tag{1}$$

In the eq (1), U_0, V_0 are the DC and RF (radio frequency) voltage respectively, m is the mass of the particle, e is the charge of the particle, d is the distance between the electrodes, and Ω is the RF frequency. There are two main configurations of such traps that are used: point traps (RF trapping in all dimensions), linear trap (two dimensional RF trap along with static electric field trapping in the other dimension). The former only has one point where the RF field is zero; on the other hand, linear traps have zero RF field across a line in general. This means that when we load multiple ions in the point traps, the ion chain can suffer micro motion, which can lead to heating of ions. On the other hand in linear traps, since the RF field is 0 across a line, the ions can be trapped without much micro motion across a line.[4]

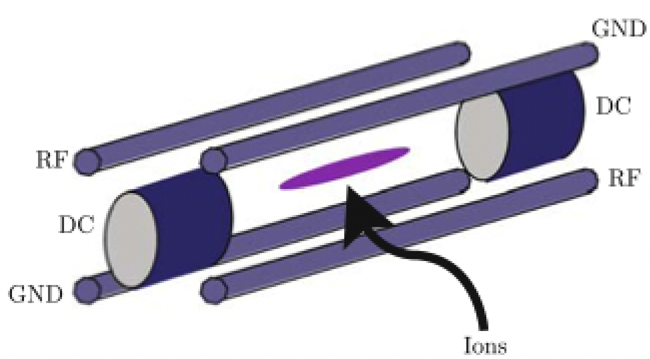

Figure 1. Electrode configuration for Paul traps

The Linear Paul trap setup is shown in Figure 7. The ends of the traps are at static potentials. To operate the trap, we apply a voltage that is RF to two diametrically opposite rods, while the other two are held at RF ground. Using this we can confine the ion in the axis of the node, z in this case. The other two electrodes are DC electrodes in the direction of the trap held at a positive voltage relative to the rods. This pushes, say a positive ion, towards the center. This is the 3D setup, but to scale this trapping method linear traps are preferred. These linear traps can be micro fabricated where the electrodes lie in a plane which are fabricated on insulating substrates.[5] This is shown in Figure 2

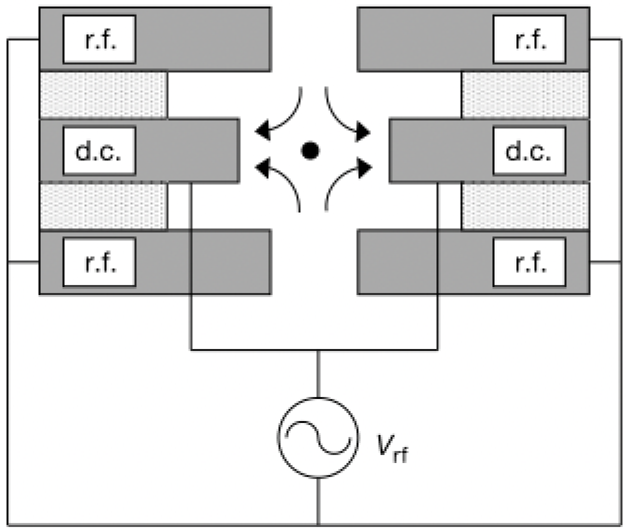

Figure 2. Radio-frequency (r.f.) and static (d.c.) electrode configuration that can be micro fabricated in a chip for scalable quantum computing architecture[5]

In this setup, the dotted region indicates insulating spacers. The RF quadra-pole discussed above is created the same as it is in the 3d trap by applying a high voltage on two RF layers while keeping the two others at the ground, creating a trapping potential pointing perpendicular to the page and is located at the central black dot. For a harmonic potential in this direction, the position of ions is set up the equalization of forces of the trap and the Coulomb repulsion.

3. LASER COOLING

Even after trapping the ions, the noise due to ions being at a high temperature makes them unfit for quantum computation, as it makes them harder to control and manipulate as desired. Atoms at room temperature move very rapidly in a random motion. These velocities can be reduced by cooling but even at the freezing point of helium (4K), the atoms move at the speed (rms) of 90 m/s. Even though the ions are trapped and not moving in free space, they still vibrate at frequencies that make then unsuitable for quantum computation. Thus, they need to be cooled down to almost absolute zero in order to be used for quantum computations. This is done through laser cooling. In this section we discuss the physics behind laser cooling.[6] Laser cooling has been instrumental in various areas of science as it can cool down atoms to micro kelvin levels without the need for any external cryogenic. Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips were awarded the 1997 Nobel Prize in Physics for developing methods to cool and trap atoms with laser light. The setup used by Chu is show in Fig (3).[7] Laser cooling has produced astounding scientific discoveries in the past two decades. The range of application of this technique range widely from high-resolution spectroscopic measurements (for example, in optical clocks based on ultracold atoms), the study of the fifth state of matter (Bose-Einstein Condensates, BEC hereafter), quantum optics, quantum sensing and ultra-precise measurements (of gravitation fields, gyroscopes, accelerometers, etc.), and quantum information science in neutral atom and ion trapping approaches. Other Nobel prizes associated with laser cooling are the 2001 Nobel Prize in Physics awarded to three men involved in creating the first BECs, the 2005 Nobel Prize for the quantum theory of optical coherence, and laser-based precision spectroscopy. This acknowledgment and appreciation highlights the applications of these techniques in fundamental and applied sciences again.

Before describing the workings of laser cooling, it is crucial to understand and define the fundamental concepts.

3.1 Temperature

Laser cooling is known for attaining temperatures around absolute zero levels. However, the definition of temperature is slightly modified from the definition of temperature in thermodynamics. The temperature is defined as a parameter of a closed state that is in equilibrium with its surroundings. However, in laser cooling, this concept does not precisely apply as the system of atoms is a dynamic one that continuously absorbs and scatters light. However, we do borrow the same understanding of temperature, which relates the temperature with the average kinetic energy. Given, this takes place in the Boltzmann regime, the average kinetic energy $\langle E_k \rangle$ is given by $\frac{1}{2}k_bT$, where k_b is the Boltzmann constant and temperature is given by T. Thus, reducing the temperature effectively corresponds to slowing down the atoms.

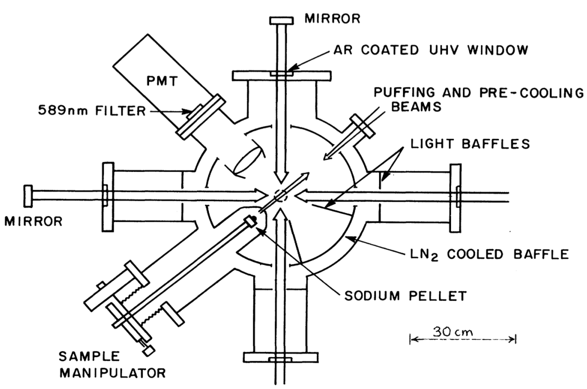

Figure 3. Schematic of vacuums chamber and intersecting counter propagating laser beams used to cool down atoms in an optical trap.[7]

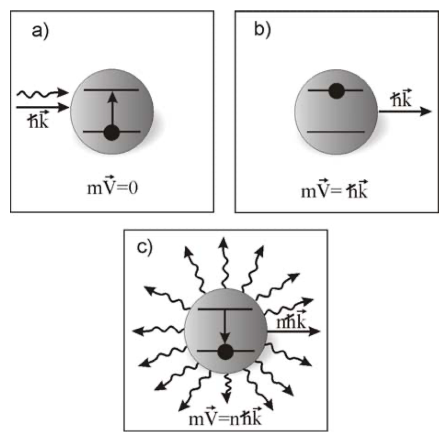

Figure 4. Light pressure acting on a two level atom (a) resonant photos approaching an atom in the ground state (b) momentum kick given by the absorption of the photon (c) recoil momentum due to sponstance emission (which averages out over n cycles).
Wavy arrows depict photons and straight arrows depict momentum's direction.[8]

3.2 Photon and Atom momentum transfer

When the laser hits the atom, the momentum absorption is given by $\vec{p} = \hbar\vec{k}$ where $\vec{k}$ is the wave vector of the laser field $k = \frac{2\pi}{\lambda}$ where λ is the wavelength of the laser light. This momentum kick due to the absorption of a single photon alters the velocity of an atom by recoil velocity $v_{rec} = \frac{\hbar k}{M}$ where M is the mass of the atom. This velocity is around one cm/s. What follows this absorption is a spontaneous emission of photons. Thus the atom recoils once more to conserve the momentum. This spontaneous emission is isotropic and hence in a random direction, thus imparting no momentum on average. This implies the only net change in momentum is due to the absorption of photons, which in the case of well-directed laser light is given as

$$\vec{F} = \frac{d\vec{p}}{dt} = \hbar k \gamma_p \tag{2}$$

where γ_p is the excitation rate of the atoms This force increases with intensity (as the number of photons increases with intensity). However, one thing to note is that the stimulated emission starts to play a role after a certain point. Higher intensities lead to more (and faster) absorption and faster-stimulated emission (in the same direction as the photon that stimulates this emission); this direction is thus opposite to the direction of the momentum change due to absorption. Thus there is an upper limit of the de-accaleration due to photon atom interaction which is given by $a_{max} = hkfM/\tau$ where τ is the natural time of the excited state.

3.3 Doppler Cooling and Optical Molasses

After reading the previous section, the natural question is that laser cooling works for the atom in one direction, but how does it cool atoms moving in a random direction? Does it not heat the atoms moving in directions other than the one opposite to the direction of the laser beam. The answer lies in an ingenious technique of Doppler cooling. The mechanism is shown in Fig (4).

Consider a detuned laser at frequency ω_L tuned slighted below the resonance frequency ω_0 of the atom resonance frequency. For detuning $\delta = \omega_L - \omega_a$, we have the following relationship, (for full equation refer to[9])

$$\gamma_p \propto \frac{1}{(a+\delta)^2} \tag{3}$$

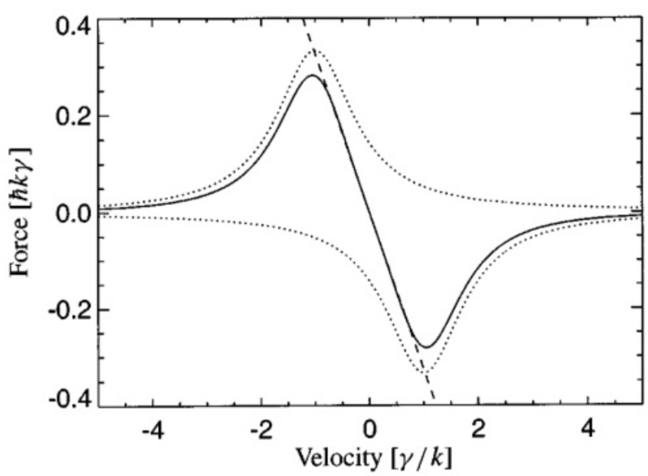

Figure 5. Optical Molasses: Optical damping forces and there dependence on velocity (negative dependence); the straight dotted line shows how this force acts similar to a classical damping force[10]

Thus, the higher the detuning, the lesser the absorption of photons by the atoms. The atoms moving towards the laser beam see reducing detuning due to the doppler effect, and the laser is closer to the resonance frequency ω_a. This increases the probability of absorption for the atoms moving towards the laser beam and reduces the probability of absorption for the atoms moving in other directions. Thus, the atom under- goes an asymmetric influence by the laser beam depending on the direction of its motion. By using two lasers placed in the opposite direction to each other, we can slow down the motion in one dimension, say $\pm\hat{x}$ direction. However, as noted above, atoms move in random directions in 3-D. By using three intersecting orthogonal pairs of counter-propagating laser beams, the above slowing effect can be extended to 3-D (thus covering $\pm\hat{y}, \pm\hat{z}$ directions as well).

Revisiting the limit of (two-level) Doppler cooling temperatures: In addition to the average force we saw in the section above, we need to include the statistical fluctuations due to the absorption and emission of photons. Even though the $\langle v \rangle = 0$, we see that $\langle v^2 \rangle$ increases linearly with the number of scattered photons (again explaining how higher intensity is not always the best for optimal cooling). Equating the rate of heating and cooling, a steady-state temperature is derived. In the absence of consideration of these statistical fluctuations due to stimulated emission, the minimum kinetic energy of a two level atomic system ($|g\rangle, |e\rangle$), is given by $kT_{min} = \frac{1}{2}\hbar\gamma$, where γ is the full width half max of the absorption line. The T_{min} term is increased by a factor of two if we consider the stimulated emission terms, thus giving $T_{min} = \frac{1}{2}\hbar\gamma$. For sodium, $\gamma = 10\text{MHz}$, which gives us the $T_min = 120\mu K$ if we do not consider the heating due to stimulated emission; however, the doppler temperature limit is given by $2 \times 120\mu K = 240\mu K$. This gives us the theoretical limit for Doppler cooling for two level atoms.

The net effect is a viscous damping force $\vec{F} = \alpha\vec{v}$ with the cooling rate given by $\dot{\vec{v}F} = \alpha\vec{v}^2$. The slowing force is proportional to velocity for small enough velocities, resulting in viscous damping that gives this technique the name optical molasses (OM) as shown in Fig (5),[9].[7]

3.4 Correction by adding complexity to the two-level system approximation

In 1985, further insights were obtained about laser-cooled atoms. In 1988, a National Institute of Standards and Technology group made more accurate measurements that rendered temperatures around six times lower than the doppler limit mentioned above. These results were confirmed at various other places.[11] The groups proposed new mechanics at Stanford and Ecole Normale Superieure (ENS); these mechanics depend on the degenerate sublevels of the ground state, optical pumping between these levels, and the spatial gradient of the polarization of the light and magnetic field (if used). These corrections are beyond the scope of this paper, as we are focusing on the optical trap. However, it is worth mentioning that much lower temperatures can be achieved by carefully designing the experiment by taking into account the polarization of the light field and providing an external magnetic field. These principles have informed the discovery of the Magneto-Optical Traps (MOT), which have become a standard tool for cooling atoms to temperatures around absolute zero.

4. MAKING THE QUBITS

The ions used for ion traps are typically Group-II or Group-II like atoms, the multitude of the states for valence electrons allow us for a lot of choices for qubits. Some of these choices for instances are low lying D levels that form meta state states in the range of sections, non zero spin odd isotopes that produce hyperfine levels due to valence electron and nuclear spin. Instead of D levels one can use low lying F-levels (example in Yb^+). The two most commonly used schemes are optical qubits and rf qubits (Zeeman and Hyper-fine qubits).

4.1 Optical Qubits

For optical qubits, electronic ground states and excited metastate provided by two level systems; these zero spin ions benefit from their relatively simple structure. The transition from ground state to the excited state has a lifetime of about more than a second in Ca^+ ions for $D_{5/2}$. However, to get the optical qubit second scale lifetimes, the laser used to control these must be narrow (around 1 Hz). In addition, the phase changes in the laser can cause decoherence in the qubit. The narrow lasers are hard to commercially produce. With recent advancements, 0.2 seconds coherence times have been registered using 100 Hz commercial lasers.[12] One another advantage of optical qubits is the fact that these metastable and orbitally separated states can allow for very high detection efficiency with relatively fewer optics.[12]

One thing that is to noted about optical qubits is that ions which need resonant lasers in red or near IR wavelengths are favored over the more blue or UV wavelengths. This is because the loss due to scattering in the waveguide is higher for higher frequencies. In addition, redder lights are easier to micro fabricate along with their waveguides, grading waveguied to free space couplers, etc.[12]

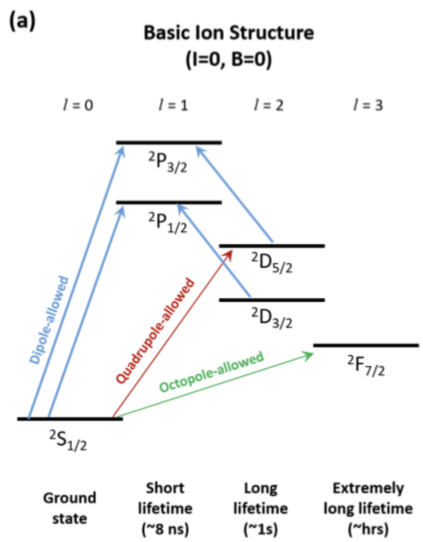

Figure 6. Basic Ion Structure used in Quantum Computing with their lifetime[12]

4.2 Zeeman and Hyperfine Qubits

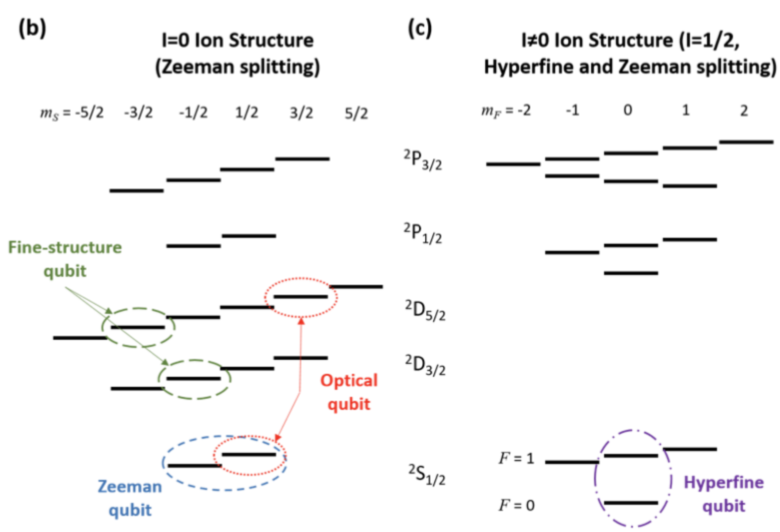

Figure 7. Basic Ion Structure used in Quantum Computing with their lifetime[12]

Zeeman qubits consist of pair of states in the same electron orbital and hyperfine levels, which are seperated by small magnetic fields (low Zeeman perturbations). These are typically mega hertz frequency separations and offer essentially infinite qubit lifetimes. These qubits have a high sensitivity to magnetic field variations ; thus a very expansive shielding is needed to protect these ions from any undesired magnetic interactions to be able to utilize the theoretically accessible long coherence times. Hyperfine states consist of pair of states in the ground state hyperfine manifolds. These can offer comparable timelines to Zeeman Qubits, while being less sensitive to magnetic field variations. While there are other kinds of hyperfine qubits that can be used, the most commonly used ones are the so called "clock states," with the z projection of the Zeeman levels being 0. They offer first order insensitivity to magnetic field. Most Yb based experiments use clock states with very small magnetic field bias (for example, IonQ).

The two main sources of errors that we see in these two qubits are spontaneous scattering in hyperfine qubits that leads to leakage and the sensitivity to magnetic field fluctuations (that de-phase the Zeeman qubits). The magnetic field used in trapping and cooling causes zeeman splitting, where the first order frequency shift due to external magnetic field is given by the following relation[13]

$$\Delta\nu_1 = \frac{g_s\mu_B}{\hbar}\Delta B \tag{4}$$

Here ΔB is the difference between the ideal magnetic field (call it B_0) for the Zeeman levels and the applied field, g_s, μ_B are the g-factors and the Bohr magneton respectively. The second order shift is given by

$$\Delta\nu_2 = \frac{(g_J - g_I)^2\mu_B^2}{2\hbar^2\omega}(2B_0\Delta B + (\Delta B)^2) \tag{5}$$

Here the g_J, g_I are g-factors for electron ad the nucleus, ω is the hyperfine splitting angular frequency. Since the second order (5) separation is so much smaller than the first order (4), the hyperfine levels essentially are unaffected by magnetic field noise. This makes hyperfine qubits a great candidate as qubits. However, not discussed here they do suffer from spontaneous scattering, which can be a problem while working with gates. Despite this, various agencies have embraced them as their qubit of choice (Yb^+ by IonQ, calcium by various universities).

5. CONCLUSION AND OUTLOOK

In the paper, we took a closer look at trapping and cooling of ions, the two fundamental techniques behind the advancement of neutral atom computing. Trapped ion computing is a leading technology for the realization of quantum computing as one an make ion registers of a few hundred qubits (the quantum supremacy lower limit is 50 qubits). Although it is not explored in this essay, there are certain questions that the proponents of ion trap computers have to answer. Even though ions can be trapped for days, sometimes months for deep traps for heavier ions, the lifetime is not infinite. This leads to a loss of ions from the trap and requires reloading. Reloading in an ion trap in the desired location in the 1D ion register can be tricky and is a limiting factor as of now. While single qubit gates in trapped ions are simple and fast as they are essentially just Rabi oscillattions, the two qubit gates are somewhat slower than the other qubit types. They are in the order of micro seconds, whereas we already have gates in the order of 10 nanoseconds in superconducting qubits. Lastly, off resonant lights and (off) photon scattering can reduce the fidelity of states by creating internal states. This is especially apparent in hyperfine qubits.

There are new advances in quantum computing and atomic molecular optics that are pushing the limits of what we know and what we can currently do. Whether we can make quantum computers, are optical methods better than the superconducting counterpart, can the key challenges mentioned above be addressed remain the big questions in front of researchers and companies working in the field. Only time will answer these questions, but the future remains hopeful for trapped ion computers and optical methods to quantum computing in general.

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REFERENCES

[1] DiVincenzo, D. P., "The physical implementation of quantum computation," *Fortschritte der Physik* **48**, 771–783 (Sep 2000).

[2] Cirac, J. I. and Zoller, P., "Quantum computations with cold trapped ions," *Physical review letters* **74**(20), 4091 (1995).

[3] Paul, W. and Steinwedel, H., "Ein neues massenspektrometer ohne magnetfeld," *Zeitschrift für Naturforschung A* **8**(7), 448–450 (1953).

[4] Werth, G., "Basics of ion traps," *Johannes Gutenberg University* .

[5] Kielpinski, D., Monroe, C., and Wineland, D. J., "Architecture for a large-scale ion-trap quantum computer," *Nature* **417**(6890), 709–711 (2002).

[6] Tiwari, V., "Cold atom computing: Laser cooling and other key technologies," (Dec 2021).

[7] Chu, S., Hollberg, L., Bjorkholm, J. E., Cable, A., and Ashkin, A., "Three-dimensional viscous confinement and cooling of atoms by resonance radiation pressure," *Phys. Rev. Lett.* **55**, 48–51 (Jul 1985).

[8] Krzysztof, K., Xuan, K. D., Małgorzata, G., Huy, B. N., Jerzy, S., et al., "Magneto-optical trap: fundamentals and realization," *CMST* (2), 115–129 (2010).

[9] Metcalf, H. J. and van der Straten, P., "Laser cooling and trapping of atoms," *J. Opt. Soc. Am. B* **20**, 887–908 (May 2003).

[10] Lett, P. D., Phillips, W. D., Rolston, S. L., Tanner, C. E., Watts, R. N., and Westbrook, C. I., "Optical molasses," *J. Opt. Soc. Am. B* **6**, 2084–2107 (Nov 1989).

[11] Phillips, W. D., Lett, P. D., Rolston, S. L., Tanner, C. E., Watts, R. N., Westbrook, C. I., Salomon, C., Dalibard, J., Clairon, A., and Guellati, S., "Optical molasses: The coldest atoms ever," **T34**, 20–22 (Jan 1991).

[12] Bruzewicz, C. D., Chiaverini, J., McConnell, R., and Sage, J. M., "Trapped-ion quantum computing: Progress and challenges," *Applied Physics Reviews* **6**, 021314 (Jun 2019).

[13] Brown, N. C. and Brown, K. R., "Comparing zeeman qubits to hyperfine qubits in the context of the surface code: Yb+ 174 and yb+ 171," *Physical Review A* **97**(5), 052301 (2018).