Ion Trap Approaches
to
Quantum Information Processing
and
Quantum Computing

A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Section 6.2

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Compiled by: David Wineland

Editing and compositing: Todd Heinrichs

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List of Acronyms and Abbreviations

C-NOT	controlled-NOT (gate)	QIP	quantum information processing
DAC	digital to analog converter	rf	radio frequency
DFS	decoherence-free subspace	SPD	single-photon detector
GHZ	Greenberger, Horne, and Zeilinger	SPS	single-photon source
MEMS	micro-electro-mechanical systems	TEP	Technology Experts Panel
QC	quantum computation/computing	UV	ultraviolet
QED	quantum electrodynamics		

1.0 Groups Pursuing This Approach

Note: This document constitutes the most recent draft of the Ion Trap detailed summary in the process of developing a roadmap for achieving quantum computation (QC). Please submit any revisions to this detailed summary to Todd Heinrichs (tdh@lanl.gov) who will forward them to the relevant Technology Experts Panel (TEP) member. With your input can we improve this roadmap as a guidance tool for the continued development of QC research.

Table 1-1
Approaches to Ion Trap QC Research

Research Leader(s)	Research Location	Research Focus
Berkeland, D.	Los Alamos National Laboratory	Sr^+
Blatt, R.	Innsbruck	Ca^+
Devoe, R.	Almaden (IBM)	Ba^+
Drewsen, M.	Aarhus	Ca^+
Gill, P.	National Physical Lab (NPL), Teddington, UK	Sr^+
King, B.	McMaster U., Hamilton, Ontario	Mg^+
Monroe, C.	U. of Michigan	Cd^+
Steane, A.	Oxford	Ca^+
Wunderlich, C.	Hamburg	Yb^+
Walther, H.	Max-Planck Institute, Garching	Mg^+, In^+
Wineland, D.	NIST, Boulder	$^9Be^+$, Mg^+

2.0 Background and Perspective

Schemes for ion-trap quantum-information processing (QIP) are derived from the basic ideas put forth by Cirac and Zoller[1]. These schemes satisfy all of the DiVincenzo criteria and most of the criteria have been experimentally demonstrated.

Scalability can be achieved by use of ion-trap arrays that are interconnected with

1. photons[2,3,4,5];
2. a movable "head" ion that transfers information between ions in separate traps[6]; or
3. by moving ions between trap nodes in the array[7,8].

Ion qubits can now be moved between nodes in a multiple-zone trap without decoherence in a time approximately equal to the gate time[9]. Efficient separation of ion qubits for transport to separate nodes will require smaller traps with good electrode surface integrity. This can likely be accomplished with the use of existing micro-electro-mechanical systems (MEMS) or nanofabrication technology. Multiplexing can also be accomplished with optical interconnects; efforts are currently underway at Garching[10] and Innsbruck[11] to develop efficient cavity-quantum electrodynamic (QED) schemes for information transfer between ions and photons.

3.0 Summary of Trapped-Ion QC: The DiVincenzo Criteria

Note: For the five DiVincenzo QC criteria and the two DiVincenzo QC networkability criteria (numbers six and seven in this section), the symbols used have the following meanings:

a) (green) = a potentially viable approach has achieved sufficient proof of principle;

b) (yellow) = a potentially viable approach has been proposed, but there has not been sufficient proof of principle; and

c) (red) = no viable approach is known.

1. A scalable physical system with well-characterized qubits (yellow)

1.1 "Spin" qubit levels are typically chosen to be (1) two hyperfine or Zeeman sublevels in the electronic ground state of an ion or (2) a ground and excited state of weakly allowed optical transition (e.g., Innsbruck Ca^+ experiment).

1.1.1 *Motional-state quantum bus*: Direct interactions between ion qubits are extremely weak because of the relatively large (>1 μm) spacing between ions, which is determined by a balance between the trap potential and Coulomb repulsion between ions. Therefore, quantum information is typically mapped through the motional state to transmit information between qubits [1].

1.2 Scalability

1.2.1 Scaling to large qubit numbers can be achieved by using arrays of interconnected ion traps.

1.2.1.1 *Photon interconnections*: Cavity-QED techniques [2–4] can be employed to transfer quantum superpositions from a qubit in one trap to a second ion in another trap via optical means.

1.2.1.2 *Moving-ion qubits*: Ion qubits can be moved from one trap to another by application of time-varying potentials to "control" electrodes [7] or by employing a moveable "head" ion [6].

2. Ability to initialize the state of the qubits to a simple fiducial state (green)

2.1 Spin qubits can be prepared in one of the eigenstates with high probability by using standard optical-pumping techniques (since ~1950).

2.2 Motional state preparation can accomplished by laser cooling to the ground state of motion (since ~1989).

2.2.1 For certain classes of gates, we require only the Lamb-Dicke limit (motional wave packet extent $<<\lambda/2\pi$, where λ is the relevant optical wavelength). Therefore, ground-state cooling is not strictly required. In the 2000 Cirac and Zoller proposal [6], ion confinement can be well outside of Lamb-Dicke limit (see #4 below).

2.2.2 Sympathetic cooling, in the context of quantum computation (QC), has been demonstrated.

2.2.2.1 Cooling of like species (Ca^+) [12].

2.2.2.2 Cooling of different isotopes of Cd^+ [13].

2.2.2.3 Cooling of $^9Be^+$ with Mg^+ (and vise-versa) [14].

3. Long (relative) decoherence times, much longer than the gate-operation time
   3.1 Spin-state coherence
      3.1.1 Spin qubit memory:
         3.1.1.1 Qubit decay times (T_1, T_2) for hyperfine levels can be extremely long (> 10 min observed [15]) compared to typical gate times (< 10 µs). This requires use of first-order magnetic-field "independent" transitions; that is, use of an ambient magnetic field where the spin qubit energy separation goes through an extremum with respect to magnetic field. Natural decay times of hyperfine transitions is typically > 1 year.
         3.1.1.2 Weakly allowed optical transitions can have lifetimes of ~ 1 s (e.g., Ca^+), substantially longer than gate times.
      3.1.2 Spin qubit coherence during operations:
         3.1.2.1 Laser intensity and phase fluctuations and spontaneous emission will cause decoherence and must therefore be suppressed.
   3.2 Motional-state coherence
      3.2.1 Coherence between motional states is currently limited by heating due to stochastically fluctuating electric fields at the position of the ion. Observed single-quantum excitation times typically lie between 100 µs and 100 ms. This heating has so far exceeded that expected from thermal radiation and appears to be related to electrode surface integrity [9].

4. Universal set of quantum gates
   4.1 Single-bit rotations:
      4.1.1 Fidelity of single-bit rotations is not fundamentally limited by internal-state qubit decoherence from spontaneous emission. Certain ions can satisfy fault-tolerant levels (see 5.2.3).
   4.2 Cirac and Zoller 2-qubit controlled-NOT (C-NOT) gate (1995 [1]): A selected mode of motion is cooled to the ground state and the ground and first excited state of this mode are used as a "bus-qubit." The spin qubit state of an ion can be mapped onto the bus qubit with the use of laser beams focused onto that ion. A gate operation can then be performed between the motional qubit and a second selected ion thereby effectively performing a gate between the first and second ion.
   4.3 Cirac and Zoller 2-qubit "push" gate (2000, [6]): Information can be transferred and gates implemented between ions located in an array of traps with a movable "head" ion. This scheme has advantages over the 1995 version [1]:
      a. Ions do not have to be cooled to a definite state or satisfy the Lamb-Dicke criterion. The motional spread of ions need only be negligible compared to their separation.
      b. All ions are separately localized. Therefore, they need not be separated during a computation (as in references [7] and [9]), and individual spin-qubit addressing is easier.

c. In principle, gate speeds need not be limited by motional frequencies. Higher-intensity stability is required for this gate.

4.4 Mølmer and Sørensen 2-qubit gate [16] gate: $\frac{|I,J\rangle \to \left(|I,J\rangle + i|I\oplus 1, J\oplus 1\rangle\right)}{\sqrt{2}\left[I,J \in (0,1)\right]}$

A logic gate can be performed using two (different-frequency) excitation fields—neither of which causes a resonant transition but in combination they cause a coherent two-qubit transition. In comparison to the 1995 Cirac and Zoller gate [1], this gate has the technical advantages that

- it is a one step process,
- an auxiliary internal state is not needed
- individual-ion laser addressing is not needed during the gate (both ions are equally illuminated),
- it does not require motional eigenstates if ions are confined to the Lamb-Dicke limit, and
- the same logic gate can be applied in the (phase) decoherence-free subspace (DFS) using the same physical interaction [7,17].

5. A qubit-specific measurement capability

5.1 State-sensitive laser light scattering can be used to distinguish spin-state qubit levels with nearly unit efficiency ("quantum jump" detection) [18]. Here, one of the qubit levels is driven with light having a polarization such that when it scatters a photon, by radiation selection rules, the ion must decay back in the same qubit level. The other qubit level is detuned from the laser light so that photon scattering is nearly absent. Therefore, if the ion is found in the first level, the photon scattering can be repeated many times so that, even if only a small fraction of the scattered photons are collected and detected, the "bright" state can be seen with very high (> 0.9999) probability.

6. The ability to interconvert stationary and flying qubits

6.1 The basic ideas are laid out in references [2–4]. This overlaps strongly with cavity-QED and the key ideas and experiments are expected to come from that area.

7. The ability to faithfully transmit flying qubits between specified locations

7.1 In principle, qubits transferred between nodes in a multiplexed trap qualify as flying qubits if the transfer distances are small (< 1 μm). This is not relevant for practical quantum communication but can be employed to spread quantum information in a quantum processor as outlined in 1.2.1.2 above.

4.0 What Has Been Accomplished

Note: For the status of the metrics of QC described in this section, the symbols used have the following meanings:

a) = sufficient experimental demonstration;

b) = preliminary experimental demonstration, but further experimental work is required; and

c) = no experimental demonstration.

1. Creation of a qubit

   1.1 Demonstrate preparation and readout of both qubit states.

   1.1.1 Single trapped ions were first observed in 1980 [19]. The ability to distinguish between two spin states with high efficiency was first demonstrated in 1986 [18,20,21,22].

2. Single-qubit operations

   2.1 Demonstrate Rabi flops of a qubit.

   1.2.1 Rabi flops on ensembles of ions and neutral atoms have been observed for decades. Rabi flops on single ions in the context of QC have been observed since 1996 ($\tau_{flop} \sim 0.5\ \mu s$).

   1.2.2 Selective single-spin qubit operations on chain of ions have been demonstrated [23].

   2.2 Demonstrate high-Q of qubit transition.

   2.2.1 The highest observed Q-factor for a microwave transition (suitable for a qubit) is 1.5×10^{13} [15].

   2.2.2 The highest observed Q-factor for an optical transition (suitable for a qubit) is 1.6×10^{14}. Rabi flops have been observed with a laser having line width less than 1 Hz. [24]

   2.3 Demonstrate control of both degrees of freedom on the Bloch sphere

   2.3.1 "Theta" pulses on Bloch sphere are controlled by controlling duration of Rabi flopping pulse time.

   2.3.2 "Phi" pulses can be synthesized from theta pulses with phase shifts inserted between pulses, changing the spatial phase of the ion relative to the laser beams, or in software by shifting phase of oscillator in subsequent operations.

3. Two-qubit operations

   3.1 Implement coherent two-qubit quantum logic operations.

   3.1.1 Coherent Rabi flopping between spin and motional qubits has been demonstrated for hyperfine qubits [25] and optical-state qubits ($\tau_{exchange} \sim 10\ \mu s$) [26].

   3.1.2 A C-NOT gate between motional and spin qubits using Cirac and Zoller scheme [1] was demonstrated in 1995 [27].

3.1.3 A two-spin qubit gate proposed by Mølmer and Sørensen was demonstrated in 2000 (gate time ~ 20 μs) [28].

3.1.4 A simplified C-NOT gate between motional and spin qubits [29] was demonstrated in 2002 [30] (gate time ~ 20 μs).

3.1.5 Experiments are underway which show coupling of spin qubits to photons at the single-photon level [10,11].

3.1.6 Implementing the Deutsch-Jozsa algorithm on an ion-trap quantum computer [31] (new gate demonstrated as part of this).

3.1.7 Realization of the Cirac-Zoller controlled-NOT quantum gate [32].

3.1.8 A robust, high-fidelity geometric two-ion qubit phase gate was experimentally demonstrated [33].

3.1.9 Quantized phase shifts and a dispersive universal quantum gate [34].

3.2 Produce and characterize Bell states.

3.2.1 Violations of Bell's inequalities were established for two entangled ions (same operations as those needed to produce and characterize Bell states) [35].

3.2.2 Fidelity of Bell states produced was 0.71 [36] and 0.97 [33].

3.2.3 Tomography of entangled massive particles using trapped ions [36].

3.2.4 Demonstration of entangled Bell states between atoms and photons [37].

3.3 Demonstrate decoherence times much longer than two-qubit gate times.

3.3.1 Qubit memory coherence times can be much longer than gate times but coherence during gate operations limited by spontaneous emission and laser fluctuations (see DiVincenzo criteria, #3.1 above and #s 2.3 and 2.4 of "Considerations" below).

3.4 Demonstrate quantum state and process tomography for two qubits.

3.4.1 The motional quantum state of a trapped atom was experimentally determined [38,39].

3.4.2 Tomography of entangled massive particles demonstrated with ions [36].

3.5 Demonstrate a two-qubit decoherence-free subspace (DFS).

3.6 Demonstrate a two-qubit quantum algorithm.

3.6.1 The entanglement-enhanced rotation angle estimation using trapped ions was experimentally demonstrated [40].

3.6.2 Simulation of nonlinear interferometers [41].

3.6.3 A technique to generate arbitrary quantum superposition states of a harmonically bound spin-1/2 particle was experimentally demonstrated [42].

3.6.4 Implementation of the Deutsch-Jozsa algorithm on an ion-trap quantum computer [31].

4. Operations on 3–10 physical qubits

4.1 Produce a Greenberger, Horne, & Zeilinger (GHZ)-state of three physical qubits.

4.2 Produce maximally-entangled states of four and more physical qubits.

- 4.2.1 A four-spin maximally entangled state has been experimentally produced [28].
- 4.3 Quantum state and process tomography.
- 4.4 Demonstrate DFSs.
  - 4.4.1 (Phase) DFS for logical spin qubit has been demonstrated [28].
- 4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations etc.) between physical qubits.
- 4.6 Demonstrate quantum error-correcting codes.
- 4.7 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza).
- 4.8 Demonstrate quantum logic operations with fault-tolerant precision.

5. Operations on one logical qubit
   - 5.1 Create a single logical qubit and "keep it alive" using repetitive error correction.
   - 5.2 Demonstrate fault-tolerant quantum control of a single logical qubit.

6. Operations on two logical qubits
   - 6.1 Implement two-logical-qubit operations.
   - 6.2 Produce two-logical-qubit Bell states.
   - 6.3 Demonstrate fault-tolerant two-logical-qubit operations.

7. Operations on 3–10 logical qubits
   - 7.1 Produce a GHZ-state of three logical qubits.
   - 7.2 Produce maximally-entangled states of four and more logical qubits.
   - 7.3 Demonstrate the transfer of quantum information between logical qubits.
   - 7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits.
   - 7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

5.0 Considerations

1. Special strengths
   - 1.1 The long coherence times of spin qubits based on trapped ions imply a robust quantum memory.
   - 1.2 High-efficiency state preparation and detection can be readily implemented (need readout efficiency per qubit ≥ exp(-1/N) for an N-bit processor without error correction or at the level of the noise threshold with error correction).
   - 1.3 Methods to achieve large-scale devices have been outlined.

2. Unknowns, weaknesses
   - 2.1 Motional decoherence caused by stochastically fluctuating electric fields must be reduced. The source of the fields is not known but appears to be due to trap electrode surface integrity [9]; efforts are underway to improve the trap electrode surfaces.
   - 2.2 Multiplexing in trap arrays is not yet operational.

2.3 Spontaneous emission [43]:

2.3.1 for Raman transitions, we want large fine-structure splitting to avoid decoherence caused by spontaneous emission (e.g., Sr^+ [24 THz], Cd^+ [74 THz], and Hg^+ [274 THz]) [44].

2.3.2 for optical qubit transitions, we want upper-state lifetime to be ≥1 s (e.g., Sr^+, Ca^+)

2.4 Laser noise

2.4.1 Laser intensity and phase fluctuations can be suppressed efficiently at the site of detection. However, controlling the intensity at the position of the ion qubits is more difficult and needs to be improved.

3. Goals: present–2007

3.1 Improve coherence.

3.1.1 Identify and reduce sources of motional heating. If the motional heating can be reduced sufficiently, this will allow the use of smaller traps thereby increasing gate speed and facilitating ion separation in multiplexed trap scheme.

3.1.1.1 Study different electrode surfaces (e.g., Boron-doped silicon, metallic alloys).

3.1.1.2 Implement *in-situ* electrode cleaning (e.g., sputtering).

3.1.2 Implement logic with "field-independent" spin qubit transitions.

3.2 Multiplex ion traps.

3.2.1 Build trap arrays with "Xs" and "Ts" to facilitate arbitrary qubit positioning [7].

3.2.2 Moving ions between traps [7]:

3.2.2.1 We must parcel out ions located in one trap and deliver to multiple selected traps with minimal heating.

3.2.2.2 Ions must be efficiently re-cooled (preferably to the ground state) using sympathetic cooling.

3.2.3 In the scheme to couple traps with photons [2–4], efficient spin-qubit/photon coupling must be demonstrated.

3.2.4 Generate entanglement between traps using probabilisitic means [5].

3.3 Improve laser stability to reach fault-tolerance limits.

3.3.1 For Raman transitions and single photon optical transitions, this implies controlling the intensity and phase at the site of ions, which is a function of laser power and beam position stability.

3.4 Spin-qubit/photon coupling

3.4.1 Demonstrate a high-efficiency single-photon source (SPS).

3.4.2 Demonstrate coherent transfer of a qubit between a spin and photon state. This may require a miniature optical cavity (under 100 microns) surrounding the ion trap. This implies either special mirror coatings that are low-loss dielectrics in the ultraviolet (UV) domain and conductive at microwave/rf frequencies or the operation of ion traps that are smaller than the cavity (see #s 3.1.1 and 2.1 above).

3.5 Perform algorithms that avoid post selection and pseudoentanglement [45].

3.5.1 Perform repetitive error correction on a single logical qubit "keeping a logical qubit alive."

3.5.1.1 A first experiment could be aimed at correcting only phase decoherence or bit-flip errors.

3.5.1.2 A second experiment would be aimed at correcting both phase and bit-flip errors.

3.5.2 Dense coding

3.5.3 Teleportation

3.5.4 Entanglement-enhanced communication (e.g., Steane's "guess my number" [46])

4. Goals 2007–2012

4.1 Operations on logical qubits

4.1.1 Demonstrate single-bit rotations.

4.1.2 Demonstrate gates between logical qubits.

4.2 Spin-qubit/photon coupling

4.2.1 Demonstrate high-efficiency of coherent exchange between spin qubits mediated by photons.

4.3 Development of integrated optics.

4.3.1 Direct laser light and collect fluorescence using micro-optics that is integrated with the trap structure.

4.4 Assess feasibility of constructing useful large-scale device

4.4.1 Perform fault-tolerant algorithms on multiple qubits.

4.4.2 From the performance of a multiple-node trap array, give an accurate assessment of scaling to arbitrary size.

5. Necessary achievements

5.1 Goals: present–2007

5.1.1 Generic causes and/or generic cures for reduction of stochastic electric field noise must be found. If the noise is, in fact, related to electrode surface integrity and cleanliness, it may not be necessary to know the exact make up of the contaminants that cause the problem, but we must be able to reliably produce "clean" electrodes.

5.1.2 Ion separation and transfer between trap nodes in multiplexer must be reliably accomplished.

5.1.2.1 It is expected that sympathetic recooling will be required.

5.1.2.2 Transfer and recooling time must be accomplished in on-the-order-of the logic-gate time.

5.2 Goals 2007–2012

5.2.1 "The" ion must be identified. For example, spontaneous emission dictates that it won't be an ion with a small fine-structure splitting such as $^9Be^+$, although $^9Be^+$ can be used for many test experiments and as a possible cooling ion for sympathetic cooling [44].

5.2.2 Single-bit rotation errors must be further reduced. To reach fault tolerant levels, laser intensity and phase must be stabilized further (power stabilization plus laser-beam position stabilization).

5.2.3 Integrated optics. In contrast to table-top experimental-optics setups currently used, micro-optics integrated with the trap structures must be employed. A lead can be taken from current-neutral atom-manipulation experiments [47] where microlenses, etc. are beginning to be employed.

6. Trophies

6.1 Repetitive error correction

6.2 Demonstrate teleportation of matter states between separate traps (without post selection).

6.3 Morph a qubit from atomic spin to a traveling photon.

7. Connections with other quantum information science technologies

7.1 Motional decoherence caused by stochastic electric field noise may be related to charge/voltage fluctuations in superconducting qubits or surface-state fluctuations. Materials research is needed to reduce this source of decoherence. Low-noise, high-speed DACS will be required in both implementations.

7.2 The construction of smaller traps may require MEMS or related nanofabrication technology.

7.3 Integrated optics will be required for any large-scale processor; this requirement may benefit from any other quantum information technology that employs optics.

7.4 Proposed spin-photon conversion will track advances in cavity-QED and high-finesse optical cavity technology, as optical coating technology gets better and more reliable in the UV and blue region of the spectrum.

8. Subsidiary developments

8.1 Quantum measurement

8.1.1 Entanglement methods from a quantum computer can be used to improve quantum-limited signal-to-noise ratio in spectroscopy and atomic clocks [40,48].

8.1.2 Information-swapping techniques can be used for cooling and state detection in spectroscopy and atomic clocks [49].

8.1.3 If the loss in MEMS resonator systems can be reduced, sympathetic laser-cooling techniques may be useful to enable these systems to reach the ground state of mechanical motion [8].

8.2 Noise measurement

8.2.1 The ion motion is a very sensitive (tunable) detector of surface electric field fluctuations. This feature, which causes motional decoherence in an ion-trap quantum computer, can perhaps find use in the study of fluctuating fields which affect other quantum-information-processing devices.

9. Role of theory

9.1 Hardware-specific algorithm development

9.1.1 Develop algorithms and error-correcting codes tailored to typical sources of decoherence found in ion traps.

9.1.1.1 Incorporate realizable two-bit or multibit gates.

9.1.1.2 Incorporate the parallelism inherent in multiplexed trap arrays.

9.1.1.3 Determine fault-tolerant thresholds for feasible operations.

9.1.1.4 Can gate teleportation be used to increase overall computational speed?

9.1.2 Various noise sources could be modeled and their effects on an ion-trap quantum computer estimated.

9.2 Develop a theory for the sources of observed decoherence (particularly relating to the electric potential noise observed on trap electrodes.)

9.3 Quantum processing using multi-level logic

9.3.1 Electronic ground states of atomic ions (and neutrals) typically have multiple hyperfine Zeeman sublevels in which high coherence could be maintained. Theorists could explore the use of these multilevel systems, as opposed to two-level qubits for QIP.

9.4 Multiqubit (>2) and other gate structures in trapped ions

9.4.1 Investigate use of multiple modes of motion to streamline certain logic operations

9.4.2 Investigate use of shaped fields (e.g., with an optical lattice) to simultaneously address many ions.

9.5 Coupling of an entangled system to its environment

9.5.1 The richness of an open system of even a few qubits offers many theoretical challenges.

9.5.2 Investigate optimization of DFS encoding for realistic couplings to the environment.

6.0 Timeline

1. Timeline for 2002–2007

1.1 Refer to the Excel timeline chart below and #3 of “Considerations” (above).

2. Timeline for 2007–2012

2.1 Refer to the Excel timeline chart below and #4 of “Considerations” (above).

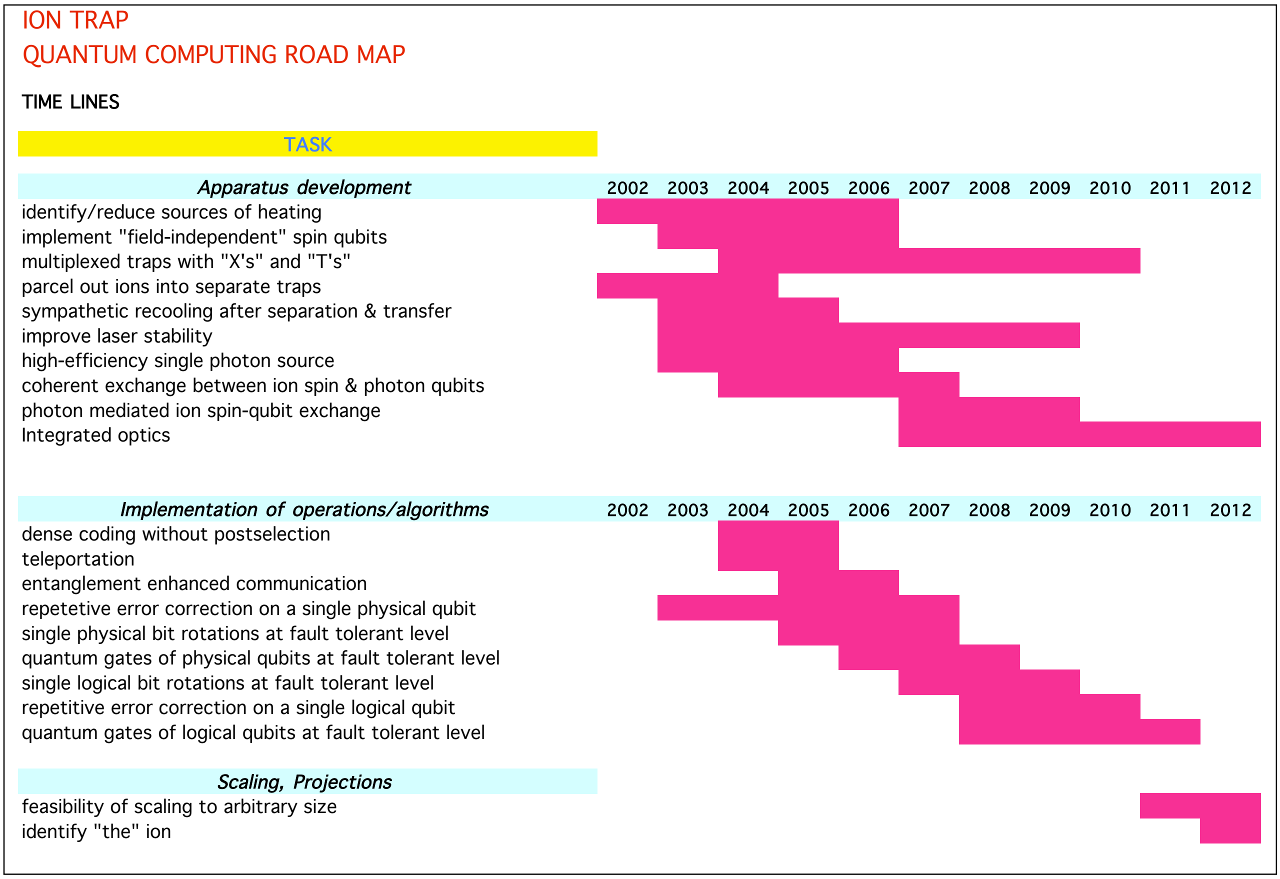

Figure 6-1. Ion trap QC developmental timeline

7.0 Glossary

8.0 References

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