Algorithms and Architectures for Quantum Computers

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Overview

This research group seeks to understand and develop the experimental and theoretical potential for information processing and communications using the laws of quantum physics. Two fundamental questions motivate our work: (1) How can a large-scale, reliable quantum computer be realized? (2) What new metrology applications, coding primitives, and models of physical systems are enabled by quantum information?

The first question is primarily experimental. We intend to build a large-scale, reliable quantum computer over the next few decades. Based on our successes with realizing small quantum computers, and after years of testing, modeling, and planning, we have come to understand how this can be achieved by combining fault tolerance techniques developed by von Neumann, with methods from atomic physics. Our main approach is to develop highly integrated trapped ion systems, in which states of single atoms and ions are quantum bits, and logic gates are realized using Coulomb interactions controlled by surface electrode potentials and pulsed laser excitation. This approach of chip-based ion traps also allows cryogenic operation, and integration with solid state quantum devices, such as superconductor based qubits and photon detectors. Trapped ions may also be coupled to high finesse optical resonators, to couple ion qubits with photon qubits.

The second question concerns the future of quantum information, which needs algorithms for more than just factoring, search, and key distribution. Protocols and quantum codes we have discovered in the last decade, point to the possibility of applying quantum information for improved precision measurements, new methods of efficiently encoding and transmitting information, and better ways to understand physical systems. These results drive research into new approaches for realizing fault-tolerant computers, and implementing quantum simulations of complex condensed-matter systems.

We are also leading a novel educational effort at MIT to develop a graduate study program in quantum information science and engineering, funded by an Integrative Graduate Education, Research, and Training grant from the National Science Foundation.

1. Center for Ultracold Atoms

Sponsors
National Science Foundation

Project Staff
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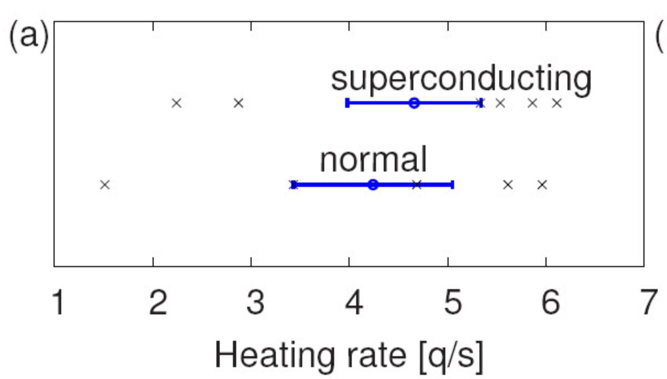
Demonstration of a superconducting microfabricated ion trap

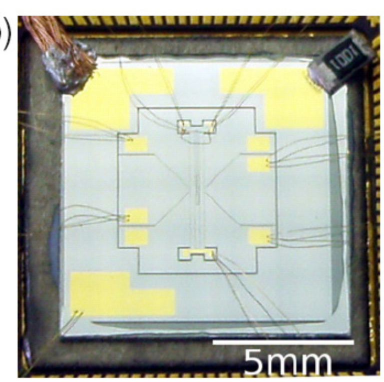
This is joint work with Karl Berggren (MIT RLE) and Eric Dauler (MIT LL)

Microfabricated surface electrode ion traps have significantly advanced the capabilities of trapped ion systems for quantum information processing, by enabling increased level of precision, density, and system integration. The ions trapped in these devices represent quantum bits and are confined by oscillating electric fields. While typical ion traps currently employ aluminum, gold, or doped semiconductor as the electrode material, the anomalous electric field noise affecting such traps provides significant motivation to explore qualitatively different materials for microfabricated ion traps, such as superconductors. In particular, the fact that a superconductor expels electric fields provides an opportunity to test the theoretical understanding that anomalous noise results from surface patch potentials, rather than sources in the bulk, since the bulk noise sources would be screened by the superconductor. A similar approach was taken for neutral atoms, where in superconducting traps it was found that magnetic near-field noise is suppressed resulting in lower heating rate and longer spin-flip lifetimes. For a thin-film superconducting ion trap, blue lasers are typically employed for Doppler cooling and state detection of trapped ions, and the short, 279–422 nm, wavelengths may create quasiparticles in the superconductor, driving it into a normal state. Therefore, verifying that the superconductor employed is actually superconducting during an experiment is required.

We fabricate superconducting ion traps with niobium and niobium nitride and trap single $^{88}Sr^{+}$ ions at cryogenic temperatures. The superconducting transition is verified and characterized by measuring the resistance and critical current using a four-wire measurement on the trap structure, and observing change in the rf reflection. The lowest observed heating rate is 2.1 (3) quanta/s at 800 kHz at 6 K and shows no significant change across the superconducting transition, suggesting that anomalous heating is primarily caused by noise sources on the surface. This demonstration of superconducting ion traps opens up possibilities for integrating trapped ions and molecular ions with superconducting devices.



Measurement results



Micrograph of ion trap chip

2. Comprehensive Materials and Morphologies Study of Ion traps (COMMIT) for Scalable Quantum Computation

Sponsors
Army Research Office

Project Staff
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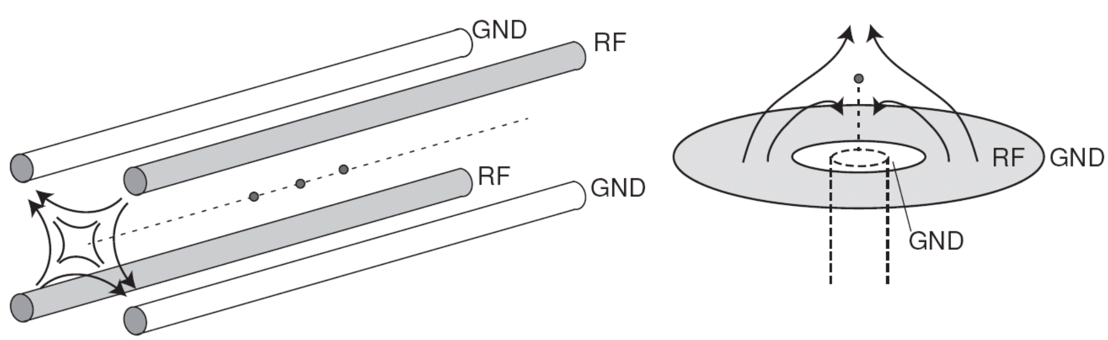
Trapped ion quantum computation is a promising approach for realization of large-scale, reliable quantum computers. However, this approach faces a major challenge to develop the materials and fabrication technology necessary to enable the high fidelity and high gate-count quantum logic ion trap chips which will be necessary. The COMMIT program seeks to advance these goals by evaluating trap materials and morphologies, by evaluating integration technologies, and by implementing a fast turnaround test setup for ion traps, based on cryogenic operation. As part of this program, we have designed and demonstrated a new morphological structure for ion traps, called a point Paul trap.

<u>Demonstration of a surface electrode point Paul trap</u>

This is joint work with Jungsang Kim and Taehyun Kim (Duke University)

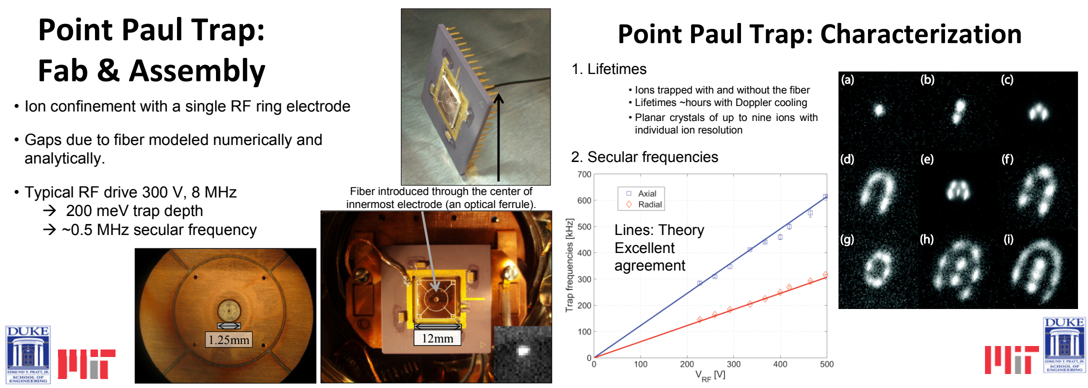
Radiofrequency ion traps have been applied extensively in a large variety of scientific studies over the past 6 decades. Originating from mass spectrometry, they have then been applied in fields such as metrology, quantum information science, and cold molecular physics, to mention but a few. Traditionally, such devices have been rather bulky, three-dimensional structures that required precise machining and careful assembly. Recently, however, the four-rod linear Paul trap has been transformed into a two-dimensional structure, with all electrodes in a single plane, above which ions can be trapped. This new class of so-called surface traps offers a tremendous advantage over their predecessors in that electrodes can be defined lithographically with extremely high precision and that construction can leverage the techniques of microfabrication, with the possibility of incorporating the technology of complementary metal-oxide semiconductor (CMOS) for integrated control hardware. These aspects are particularly attractive to applications in quantum information processing where limitations currently, by a large degree, pertain to the scalability of devices for trapping as well as certain elements of infrastructure such as optics, laser light delivery, and control electronics.

We present the design and evaluation of a type of rf surface trap with a high degree of symmetry in its electrode geometry. The generic geometry of this trap, which we shall refer to as the point Paul trap, is shown below, and may consist of any number of concentric electrodes of arbitrary widths to which different voltages can be applied.



This design originated in a study of surface electrode traps, but was subsequently strongly inspired by work on planar Penning traps, where a similar geometry was used to create a static electric quadrupole field that, when combined with a strong homogeneous magnetic field, gave rise to a confining potential above the surface of the electrodes. The point Paul trap also bears close resemblance to the rf ring and the rf hole traps; however, it differs in that the ion is trapped above the surface of the electrodes as opposed to in between, which makes this geometry better suited for microfabrication.

A consequence of the azimuthal symmetry of the electrodes is that the rf field exhibits a nodal point rather that a nodal line as in the linear Paul trap and that the confining fields originate exclusively from the rf potential, rendering the addition of dc potentials nonessential for anything but the compensation of stray charges on the trap. This makes the point Paul trap well suited for confinement of single ions, which may then reside at the rf nodal point where the amplitude of the rapidly oscillating rf field vanishes.



The ability to fabricate these traps in a scalable fashion makes them attractive for realizing large arrays of single ions in independent traps that may be utilized for a quantum processor, provided the individual ions can be interconnected, e.g., through optical fibers. On this aspect, the axial symmetry of the trap lends itself well to integration of such fibers and potentially other optical elements that also possess axial symmetry. The fiber, for instance, may be introduced through the electrodes directly beneath the ions with minimal perturbation of the trapping fields.

Another possible application of this trap is in the field of quantum simulation. While classical computers are unable to efficiently simulate coupled spin systems, such simulations may be implemented using a quantum mechanical system of effective spins, such as a two-dimensional lattice of interacting ions. The resulting potential of the point Paul trap provides ion crystals with exactly the requisite two-dimensional planar structure. As such, the system could be used to simulate, e.g., a frustrated spin system, as was demonstrated recently.

We also find that our trap design is ideally suited for realizing a scheme by which the height of a single trapped ion above the trap surface is varied *in situ*. This capability may prove extremely useful in the search for the origin of anomalous heating in ion traps: a problem currently impeding the advancement of quantum computation with trapped ions. It also provides a general technique by which oven contamination of the trap can be minimized by loading further away from the trap surface and subsequently bringing the ion to the desired trap height.

This work was supported in part by the NSF CUA.

3. Entanglement Transfer & Processing with Photons Interconnecting Atomic and Trapped Ion Ensembles

Sponsors
DARPA

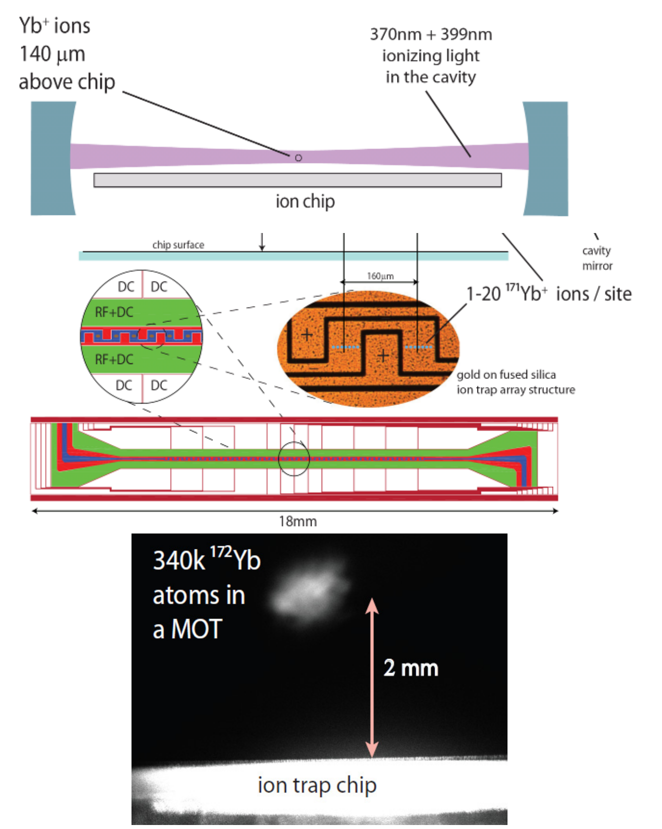
Project Staff
Paul Antohi, Marko Cetina, Arolyn Conwill, Yufei Ge, Andrew Grier, Peter Herskind, Anders Mortensen

This is a joint project with Karl Berggren, Jeffrey Shapiro, and Vladan Vuletic (RLE).

Distributed and networked quantum information processing requires effective interconnections between physically separated nodes, where standing qubits (atoms or ions) serve as quantum memory and quantum processing elements. These interconnections will rely on flying qubits (photons) for communication and entanglement transfer. Crucially, such quantum communication and entanglement transfer must involve inter-modal conversion of quantum states, from qubits suitable for processing to qubits good for communication and vice versa. Inasmuch as early implementations of few-qubit processors could well be hybrid architectures, in which different physical modalities are employed for quantum memory and for quantum information processing, it is essential to have fully flexible means for exchanging the high-fidelity entangled pairs between three kinds of qubits, viz., those used for quantum communication, those used for quantum memory, and those used for quantum information processing. This project is addressed to these inter-modal conversion needs.

We have reached one of the project goals, of strongly coupling trapped ions to photons in an optical resonator. The apparatus, shown in the figure on the right, is based on a microfabricated ion trap chip, made of gold on fused silica, with a surface electrode pattern which produces an electric field that confines arrays of ions, each with one to twenty $^{171}Yb^{+}$ ions.

An optical resonator is positioned with its axis aligned with the arrays of ions, 140 μm above the chip. Ions are loaded from a magneto-optical trap positioned above, using a highly efficient photoionization scheme which substantially alleviates issues with contamination of the trap surface by stray atoms and ions. With a cavity finesse of about 7000, unity optical depth is expected for as few as ~100 ions, putting the coupling deeply within the strong coupling regime, where photon-ion qubit exchange will be rapid and efficient.



(top) Ion trap chip and resonator, showing details of the trap electrodes. (bottom) photograph of MOT above ion trap chip, with 300,000 atoms.

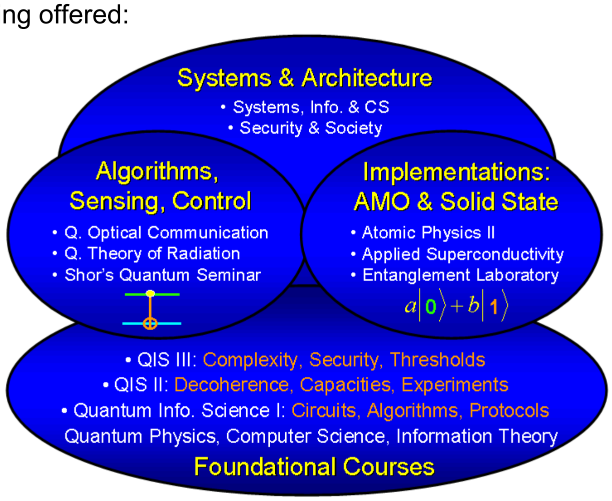
4. IGERT: Interdisciplinary quantum information science and engineering

Sponsors
National Science Foundation

Project Staff
I. Chuang (director); J. Shapiro & S. Lloyd (co-directors); S. Aaronson, K. Berggren, P. Cappellaro, E. Farhi, P. Jarillo-Herrero, L. Levitov, S. Mitter, T. Orlando, P. Shor, J.-J. Slotine, V. Vuletic, F. Wong

This program is a new approach to educating and training students in quantum information science & engineering, based on a unified, interdisciplinary curriculum, crossing traditional barriers between science and engineering, with the goal of nurturing a new generation of students, from education through employment, and of providing a case for a future permanent doctoral program at MIT. The program involves 14 faculty members at MIT, across five departments, and offers Course Q, a comprehensive doctoral program in quantum information; the Fellowship of Quantum Information, a community of graduate students researchers in the field; QIS@MIT, a teaching and seminar program; and InQuIRE, an outreach program connecting government and industrial partners and quantum information research, for students and the public.

Support is provided by the Integrative Graduate Education, Research, and Training (IGERT) program of the NSF. This IGERT has enrolled over two dozen graduate students as associates, and as of the Fall of 2010, it fully supports 15 students (six women and three under-represented minorities). The academic curriculum has also developed, with a new graduate course in Quantum Complexity Theory offered, and a consistent three-semester sequence in quantum information science being offered:



A new Quantum information Science Teaching Laboratory is also being established, which will offer hands-on experience with quantum optics experiments, including testing fundamental predictions separating quantum from classical mechanics, using entangled photons. And a summer course on Quantum Information Science for Undergraduates, QuISU, has been offered twice, in June, 2009 and 2010, with attendance by almost three dozen students.

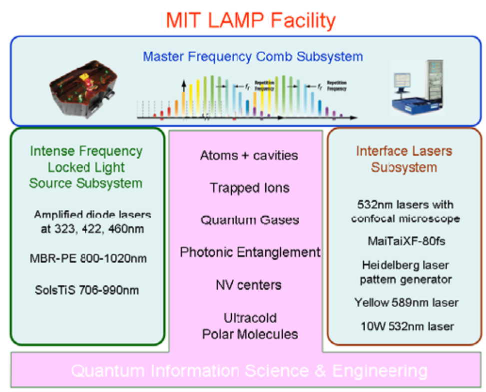
See http://iquise.mit.edu for more information.

5. Laser Acquisition and Modernization Program (LAMP) for Quantum Science and Engineering

Sponsors
National Science Foundation

Project Staff
Isaac Chuang (PI), Wolfgang Ketterle (co-PI), Karl Berggren, Paola Cappellaro, Erich Ippen, Franz Kaertner, Vladan Vuletic, Franco Wong, Martin Zwierlein

Quantum science and engineering is undergoing a rapid and remarkable revolution, exemplified by the realization of small-scale quantum computers capable of high-speed information processing, quantum simulators providing fundamental insight into exotic new materials, and distributed quantum networks, across which secure multi-party communication and computation is possible. A key force driving this revolution is a major advance in coherent laser light sources, which can now reliably provide high intensity and ultra-precise frequencies, with frequency agility across the near-ultraviolet, visible, and infrared spectrum. Such light sources, are made possible by the optical frequency comb (2005 Physics Nobel Prize). Modern lasers are the power supplies of quantum science: they provide the phase coherence and stability needed for direct access to the quantum nature of atoms, molecules, and solid state devices.



This project is an equipment acquisition program, currently underway, to establish the LAMP Facility at MIT, which will provide intense, ultra-stable, optical sources from the near ultraviolet to the infrared frequency range, referenced to optical frequency combs anchored to an absolute frequency standard. The equipment will be composed of three subsystems: the master frequency comb, the intense frequency locked light sources, and the interface lasers, united by assembling off-the-shelf commercial instruments. The master comb will employ Ti:Sapphire laser based combs, fiber laser combs, and existing frequency references; the light sources will employ lasers at wavelengths ranging from 323nm to 1.5μm; and the interface lasers will employ lasers for creation of atomic and solid state systems which can be coherently controlled.

This equipment will address a vital national need, centered at MIT. LAMP builds on two major NSF programs at MIT, the Center for Ultracold Atoms, a Physics Frontier Center, and Interdisciplinary Quantum Information Science and Engineering, an Integrative Graduate Education, Research, and Training program; together, these activities span five departments and involve over ~100 students and staff. LAMP will be vital to the CUA, which last modernized its laser systems over nine years ago, and it will meet the research needs of the large influx of new graduate students arriving through the IGERT program. In addition, LAMP will be available to the local research community.

LAMP will enable major new explorations at the frontier of quantum science, including the realization of new quantum systems made of polar molecules, which have strong dipole-dipole interactions. At nanokelvin temperatures, these molecules may form a new form of matter, a supersolid, allowing studies of nanokelvin chemistry, providing qubits for quantum information science with distinct advantages over other approaches to quantum gates. LAMP will also allow novel manipulations of cold ions in cryogenic ion trap, bringing this research to the next level, the realization of large-scale quantum computers, and long-distance, coherent quantum interconnects.

Publications

Journal Articles

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